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Technological Races in Global Industries

(Technology Races)

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Abstract

The starting point of our consideration on technological racing are stochastic models that view corporations as moving objects to approach a stochastic destination. A major focus is the strategic orientation of corporations in participating in such a race , revealing empirically observable phenomena such as 'catchup' and 'leapfrogging', as supported by statistical measurements. Next to the analysis of behavioural patterns on the corporate or industry level is their aggregation on a national scale that extends to racing on economic growth among (groups of) countries. A major conjecture of the paper is that technological racing patterns on a micro scale reinforce globalization and limit control of national and industry policy.

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Motivation and Objectives

a. Motivation

The striking pattern that emerges in firms' innovative activities is that the firms rival for a technological leadership position in situations best described as 'races'. A 'race' is an interactive pattern characterized by firms constantly trying to get ahead of their rivals, or trying not to fall too far behind. In high technology industries, where customers are willing to pay a premium for advanced technology, leadership translates into increased returns in the market. Each race involves only a subset of the firms in the industry, and the activity within each race appears to strongly influence the behaviour of the firms within that race. Surprisingly, the races share broad similarities. In particular, firms that fall behind in their race display a robust tendency to accelerate innovative effort in order to catch up.

Existing theory focuses on the impact of a single innovation at the firm level, or on the effect of a single 'dominant design' on an industry's evolution. Like the dominant design literature, racing behaviour is also a dynamic story of how technology unfolds in an industry. In contrast to any existing way of looking at the evolution of technology, racing behaviour recognizes the fundamental importance of strategic interactions between competing firms. Thus firms take their rivals' actions into account when formulating their own decisions. The importance of this characterization is at least two fold. At one level, racing behaviour has implications for understanding technology strategy at the level of the individual firm and for understanding the impact of policies that aim to spur technological innovation. At another level, racing behaviour embodies both traditions that previous writings have attempted to synthesize: the 'demand-pull' side emphasized by economic theorists and the 'technology-push' side emphasized by the autonomous technical evolution school. It remains an open problem how technological races can be induced endogenously, e.g. by changes in economic variables (such as costs, prices and profitability).

Our stochastic model of a race embraces several features that resemble moving objects towards a stochastic final destination. By exploring 'hypercompetitive' patterns of racing behaviour, in respective industries, we look into racing patterns of individual firms in view of their strategic responses to their racing environment. Among those features we identify is the **speed race problem**, the selection of an **optimal decision point** (t*), to optimize a gradient trajectory (of technological evolution) and to determine the '**stopping line and the waiting region'**. Such a model would be conducive to observations on innovation races in high technology industries, in particular, with race-type behaviours such as leapfrogging and catching-up, striking a balance between moving ahead , waiting and repositioning themselves.. The model can be improved by incorporating constraints . For example, constraints on an innovation path could be given by road blocks such as a bankruptcy constraint or an R&D uncertain payoff constraint. Some of these constraints may be conceptually easy to introduce, others may be tougher such as an investment constraint if the total innovation effort en route to t* plus the worst case would violate it. In such a case one may want to weigh the distant finishing line unproportionately.

Beyond the micro-meso level of explaining changes in industry structures the model also addresses comparable issues on the macro level of global industry change. Aggregation of racing behaviour may result in catchup behaviour among countries that are the second subject level of our exploration.

Simple catchup hypotheses put emphasis on the great potential of adopting unexploited technology in the early stage and the increase in the self-limiting power in the later stage. However, an actual growth path of technological trajectory of specific economy may overwhelmingly be constrained by social capability. And the capability endogenously changes as states of the economy and technology evolve. The success of economic growth due to diffusion of advanced technology or the possibility of leapfrogging is mainly attributable to how the social capability evolves, i.e., which effects become more influential, growing responsiveness to competition or growing obstacles to it on account of vested interests and established positions.

b. Objectives

(a) A key objective is to explore and explain which type of 'racing behaviour' is prevalent in global high technology industries, as exemplified by information technology (computer and telecommunications) industries. The pattern evolving from such racing behaviour would be benchmarked against the frontier racing type of the global technological leaders.

(b) Another objective is to draw policy inferences on market structure, entrepreneurship, innovation activity, industrial policy and regulatory frameworks in promoting and hindering industry frontier races in a global industrial context.

(c) Given the statistical profile of technological evolution and innovation for respective global industries as it relates to competitive racing and rivalry among the leading firms. Among the performance criteria to be assessed are frequency of frontier pushing, technological domination period, innovations vs. imitations in the race, innovation frequency when behind or ahead, nature of jumps, leapfrogging or frontier sticking, inter-jump times and jump sizes and race closeness measures.

(d) An empirical proliferation of racing in these global industries can be explored, comprising of datasets identifying 'relationship between technological positions (ranks) of firms in successive years' (15 year period).

(e) Do observed racing patterns in respective industries contribute to equilibrium and stable outcomes in the world economy ? To which extent are cooperative ventures (global governance) between states justified to intervene? In particular we investigate the claim, as put forward by the Group of Lisbon (1995) that as a likely future scenario triadization will remain 'the prevailing form of economic globalization', in view of observations that increased intensity in racing patterns within key industries could lead to instability and welfare losses in triadization.

(g) More specifically, in an era of ongoing deregulation, privatization, liber- alization and lifting of trade barriers, we explore whether industry racing patterns are sufficiently controlled by open world-wide markets or whether complementary international agreements (regulations, controls) are needed to eliminate or mitigate negative externalities (without compromising the positive externalities that come with industry racing).

The effects of racing patterns on the industrial organization of particular industries are assessed: how does the behaviour of leading firms influence the subcontracting relation between the purchasing firms and their subcontractors that is , which racing pattern induces a strengthening of their vertical links and what behaviour of the parent firm in technological racing encourages their subcontractors to be technologically (and thus managerially) independent?

The paper proceeds as follows. We first review the state of research in the industrial economics of technological racing. Then the model framework identifies the essential elements under which racing patterns will occur. This will be complemented by empirical considerations of the diversity of complexity of racing patterrns, and the measurement problems that result from there.

State of research

Economic models and observations on 'technology races' are the most direct intellectual precursor to this paper (Reinganum, 1989, Scherer, 1991, Tirole, 1988). This follows from the tradition of investigating the varied implications of the notion, first advanced by Schumpeter, that it is the expectation of supernormal profits from the temporary monopoly position following an innovation that is the chief driver of R & D investment. The simplest technology race model would be as follows. A number of firms invest in R & D. Their investment results in an innovation with the time spent in R & D subject to some uncertainty (Gottinger, 1989). However, a greater investment reduces the expected time to completion of R & D. The models investigate how many firms will choose to enter such a contest, and how much they will invest.

Despite some extensive theoretical examination of technological races there have been very few empirical studies on the subject (Lerner, 1997) and virtually none in the context of major global industries, and on a comparative basis. This will be one major focus in this paper.

Technological frontiers at the firm and industry race levels offer a powerful tool through which to view evolving technologies within an industry. By providing a roadmap that shows where an individual firm is relative to the other firms in the industry, they highlight the importance of strategic interactions in the firm's technology decisions.

Does lagging behind one's closest technological rivals cause a firm to increase its innovative effort ? The term 'race' suggests that no single firm would want to fall too far behind, and that every firm would like to get ahead. If a firm tries to innovate more when it is behind than when it is ahead, then 'catchup' behaviour will be the dominant effect. Once a firm gets ahead of its rivals enough, then rivals will step up their efforts to catch up. The leading firm will slow down its innovative efforts until its rivals have drawn uncomfortably close or have surpassed it. This process repeats itself every time a firm gets far enough ahead of its rivals. An alternative behaviour pattern would correspond to a firm increasing its innovative effort if it gets far enough ahead, thus making catchup by the lagging firms increasingly difficult. For any of these forms there appears to be a clear link to market and industry structure, as termed 'intensity of rivalry' by Kamien and Schwarz (1982). We investigate two different kinds of races: one that is a frontier race among leaders and „would-be“ leaders and another, that is a catchup race among laggards and imitators.

These two forms had been applied empirically to the development of the Japanese computer industry (Gottinger,1996), that is, a frontier race model regarding the struggle for technological leadership in the global industry between IBM and 'Japan Inc.' guided by MITI, and a catchup race model relating to competition among the leading Japanese mainframe manufacturers as laggards.[1]

Furthermore, it is interesting to distinguish between two kinds of catchup behaviour. A lagging firm might simply try to close the gap between itself and the technological leader at any point in time ('frontier-sticking' behaviour), or it might try to actually usurp the position of the leader by 'leapfrogging' it. When there are disproportionately large payoffs to being in the technical lead (relative to the payoffs that a firm can realize if it is simply close enough to the technical frontier), then one would expect that leapfrogging behaviour would occur more frequently than frontier-sticking behaviour (Owen and Ulph, 1994). Alternatively, racing toward the frontier creates the 'reputation' of being an innovation leader facilitating to maintain and increase market share in the future (Albach, 1997). All attempts to leapfrog the current technogical leader might not be successful since many lagging firms might be attempting to leapfrog the leader simultaneously and the leader might be trying to get further ahead simultaneously. Correspondingly, one should distinguish between attempted leapfroggings and realized leapfroggings. The leapfrogging phenomenon (though dependent on industry structure) appears as the predominant behaviour pattern in the US and Japan frontier races (Brezis, Krugman and Tsiddon, 1991), Albach (1993) cites studies for Germany that show otherwise.

Leapfrogging behaviour influenced by the expected size of payoffs as suggested by Owen and Ulph (1994) might be revised in compliance with the characteristics of industrial structure of the local (regional) markets, the amount of R&D efforts for leapfrogging and the extent of globalization of the industry. Even in the case where the payoffs of being in the technological lead is expected disproportionately large, the lagging firms might be satisfied to remain close enough to the leader so as to gain or maintain a share in the local market. This could occur when the amount of R&D efforts (expenditures) required for leapfrogging would be too large for a lagging firm to be viable in the industry and when the local market has not been open enough for global competition: the local market might be protected for the lagging local firms under the auspices of measures of regulation by the government (e.g. government purchasing, controls on foreign capital) and the conditions preferable for these firms (e.g. language, marketing practices). When the industrial structure is composed of multi-product firms, as for example, in the Japanese computer industry, sub-frontier firms may derive spillover benefits in developing new products in other technologically related fields (e.g. communications

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[1] A catchup race is likely to occur when innovators fall too far behind in a frontier race or if innovators turn to imitators and follow just one or several leaders. It could also occur in markets that are saturated or technologically mature with a lack of breakthroughs.Therefore, at some point every frontier race can turn into a catchup whereas it is more difficult to imagine that any catchup race will turn into a frontier race.

equipment, consumer electronic products). These firms may prefer an R&D strategy just to keep up with the technological frontier level (catch-up) through realizing a greater profit stream over a whole range of products.

What are the implications of the way the firms split cleanly into the two technology races, with one set of firms clearly lagging the other technologically? The trajectories of technological evolution certainly seem to suggest that firms from one frontier cannot simply jump to another trajectory. Witness, in this regards, the gradual process necessary for the firms in the Japanese frontier to catch up with the global frontier firms. There appears to be a frontier ‘lock-in’ in that once a firm is part of a race, the group of rivals within that same race are the ones whose actions influence the firm’s strategy the most. Advancing technological capability is a cumulative process. The ability to advance to a given level of technical capability appears to be a function of existing technical capability. Given this ‘path dependence’, the question remains: why do some firms apparently choose a path of technological evolution that is less rapid than others? We propose two sets of possible explanations, which need not to be mutually exclusive. The first explanation hinges primarily on the expensive nature of R&D in industries like the computer industry which rely on novel scientific discovery for their advancement. Firms choosing the subfrontier will gain access to a particular technical level later than those choosing the frontier, but will do so at a lower cost. Expending fewer resources on R&D ensures a slower rate of technical evolution. The second explanation relates mainly to technological spillovers. Following the success of the frontier firms in achieving a certain performance level, this fact becomes known to the subfrontier firms. In fact, leading edge research in the computer industry is usually reported in scientific journals and is widely disseminated throughout the industry. The hypothesis is that partial spillover of knowledge occurs to the subfrontier firms, whose task is then simplified to some extent. Notice that the subfrontier firms still need to race to be technological leaders, as evidenced by the analysis above. This implies that the spillovers are nowhere near perfect. Firm specific learning is still the norm. However, it is possible that knowing something about what research avenues have proved successful (for the frontier firms) could greatly ease the task for the firms that follow and try to match the technical level of the frontier firm.

A Model Framework for a Simple Stochastic Race

The concept of a race is intrinsic to sports events, crossing the finishing line first is everything to a racer, the rewards may be immense by reaching for the gold. In general, if such a race evolves, the race looks like a sequential machine (finite automaton) acting under resource and time constraints, until a winner clearly emerges. A winner may establish himself at the first trials or runs, leaving very little chance for those left behind to catchup. The situation of competitive rivalry among firms or businesses in high technology industries may resemble more complex paradigms of a race that appear more difficult to describe than a sports event. First of all, the finishing line may not be sharply defined. It could be a greater market share than any of the rivals attain, it may be a higher profitability given the share, or a higher growth potential. In terms of process, it could be even a slow race at the beginning which might accelerate to whatever the finishing line constitutes of. It may be a race that is open to new entrants along the way, in a dormant, low innovation - driven industry that brings changes to this industry. It may allow moves among rivals, unheard of in conventional races, such as "leapfrogging", "take a breath and recharge" or redefining a new race through mergers and acquisitions, in the course of the given one. Races may be endogeneous, induced by changes in innovation patterns, market structures and productivity cycles. All these issues of complexity may justify to set up a racing model that captures many of the essential features. This would be a model of a stochastic race which is proposed. Let us describe the characteristics of such a race on achieving technological and market supremacy , a universal mathematical tretment is given in Gottinger (2000). A finishing line would be ahead of a present technological frontier which would be the common ground for starting the race.

Let *TF*(C) be each racing company's technological knowledge frontier while *TF*(*I*) would be the respective industry's frontier represented by the most advanced company as a benchmark. All firms engage in pushing their frontier forward which determines the extent to which movements in the individual *TF*(*C*) of the racing firms translate into movements of the *TF*(*I*). While a variety of situations may emerge, the extremal cases involve: either one firm may push the frontier at all times, with the others following closely behind or all firms share more or less equally in the task of advancing the *TF*(*I*). The first situation corresponds to the existence of a unique technogical leader for a particular race, and a number of quick followers. The other situation corresponds to the existence of multiple technological leaders. In some industries firms share the task for pushing the frontier forward more equally than in other industries. This is usually the case the more high paced and dynamic is the race in an industry. In any race of the sort "closeness" is an important but relative attribute. The races are all close by construction, however, some might be closer than others. As a closeness measure of the race at any particular time one could define

$$c(t) = \sum_0^N [TF(C_i) - TF(I)]^2 / N(t)$$

where *N*(*t*) is the number of active firms in that industry at time *t*. The measure thus constructed has a lowest value of 0, which corresponds to a ‘perfectly close’ race. Higher values of the measure correspond to races that are less close. Unlike other characteristics such as the domination period length during a race, innovation when ahead versus when behind, leapfrogging versus frontier sticking, which describe the behaviour of a particular feature of the race and of a particular firm in relation to the frontier, the closeness measure is more of an aggregate statistic of how close the various racing parties are at a point in time. The closeness measure is simply an indication of the distance to approach a benchmark, and it does not say anything about the evolution of the technological frontier. To see this, note that if none of the frontiers were evolving, the closeness measure would be 0, as it would if all the frontiers were advancing in perfect lock-step with one another.

The Problem: On an Euclidean plane let N be a set of n points (x_i,y_i); i = 1,... n ; let n probabilities p_i;i = 1,... , n be given such that $\Sigma p_i = 1$. We use the Euclidean distance on a plane because innovation characteristics are at least two-dimensional, that is, it would apply to so-called system products that consist of at least two components. The probabilities will most likely be subjective probabilities determined by the individual firm’s chances to position itself , endogeneously determined by its distance to the finishing line or its proximity to the next rival in the race. They may be formed by considering the firm’s own position in the race as well as depending on the stochasticity of the rivals’ efforts. As a first approximation we may let the firm’s R&D investment x_i, in relation to the total investment of its rivals $\Sigma\ x_j$, determine the probability $p_i = x_i/\Sigma\ x_j$ .Let a starting point, point (x_0,y_0) or (point 0) also be given; let c(S); S ≥ 0 be a function such that

(1) $$c(0) = 0,$$

(2) $$c(S) > 0; \text{ for all } S > 0,$$

(3) $$c(S + \varepsilon) \geq c(S); \text{ for all } S, \varepsilon > 0,$$

and such that except for $S = 0$, $c(S)$ is (not necessarily strictly) convex and represents the cost of racing at speed S; let $F > 0$ be given (the fixed time value); and finally let $T > 0$ be given (the decision period). It is required to minimize the following function by choosing $t \equiv (x_t, y_t)$ and S (i.e., choose a point t, to be at T time units from now, and a speed S with which to proceed afterwards, so that the expected total cost to cross the 'finishing line' will be minimized):

(4) $$Z(t,S) = FT + c(d(0,t)/T)d(0,t) + (c(S) + F/S) \sum p_i d(t,i)$$

where d(i,j) is the Euclidean distance between points i and j. The Euclidean distance can be seen as a metric how close the destination has been hit. The last term of (4) indicates the mixture of costs of speed racing and the cost of the time resource weighted by the probabilities of reaching alternative stochastic destinations.

We denote the optimal S by S*, and similarly we have t* and Z* = Z(t*,S*). Note that FT is a constant, so we can actually neglect it; the second term is the cost of getting to t during T time units, i.e., at a speed of d(0,t)/T. Now, clearly the problem of finding S* can be solved separately, and indeed we outline the steps toward solution..

The Speed Race Problem

If we look at the list of stipulations for c(S), (1) just means that we can stop and wait at zero marginal cost (which we first keep as a strict assumption to justify the flexibility of the race). (2) is evident, and (3) is redundant, given (1), since if c is not monotone for $S > 0$, then it has a global minimum for that region at some S, say S_{min}, where the function assumes the value $c_{min}<c(S)$ for all $S > 0$. Now suppose we wish to move at a speed of λS_{min}; $\lambda\varepsilon$ (0,1], during T time units, thus covering a distance of $\lambda T S_{min}$; then who is to prevent us from waiting $(1 - \lambda)T$ time units, and then go at S_{min} during the remaining λT time units, at a variable cost of c_{min} per distance unit? As for the convexity requirement, which we actually need from S_{min} and up only, this is not a restriction at all! Not only do all the firms we mentioned behave this way in practice generally, but even if they did not, we could use the convex support function of c as our 'real' c, by a policy, similar to the one discussed above, of moving part time at a low speed and part time at a higher one at a cost which is a linear convex combination of the respective c's. Hence, our only real assumption is that we can stop and wait at zero cost, i.e., (1).

Lemma: let c(S); S>0 be any positive cost function associated with moving at speed S continuously and let (1) hold, then by allowing mixed speed strategies, we can obtain a function c(S); $S > 0$ such that c is positive, monotone nondecreasing and convex, and reflects the real variable costs.

Now, since each time unit cost is F, and we can go S distance units during it, each distance unit's 'fair share' is F/S. To this add f(S), to obtain the cost of a distance unit at a speed of S when the firm knows where it is going, and requires their fixed costs to be covered. (On the other hand, not knowing what it wants to do means that the firm has to lose the F money, or part of it.) Denote the total cost as above by TC(S), or $TC(S) = c(S) + F/S$.

But, F/S is strictly convex in S, and c(S) is convex too, so TC(S) is strictly convex.

Choosing t Optimally

Our problem is to find the point t, or the 'decision point', where we elect to be at the end of the decision period. Then, we will know with certainty what we have to do, so we will proceed at S* to whichever point i is chosen, at a cost of TC(S*)d(t,i). Denoting TC(S*) = TC*, we may rewrite (4) as follows:

$$Z(t) = FT + c(d(0,t)/T)d(0,t) + TC^* \sum p_i d(t,i).$$

Theorem: Z(t) is strictly convex in t.

Proof: Clearly FT is a constant so it is convex. Let $h(w) = c(w/T)w$, hence our second term, c(d(0,t)/T)d(0,t) is h(d(0,t)). By differentiation we can show that h(w) is strictly convex, monotone increasing and nonnegative. d(0,t) is convex (being a norm), and it follows that h(d(0,t)) is strictly convex as well (see Theorem 5.1 in Rockafellar(1970), for instance), As for the third term it is clearly convex (since $\{p_i\}_{i=1, \dots n}$ are nonnegative probabilities), and our result follows for the sum.

The Stopping Line and the Waiting Region

For $T \geq T^*$, we obtain $S = S_{min}$, and by $W(S) = c(S) + Sc'(S)$ it follows that $W(S) = c_{min}$. For $G(t^*) = W(S)$ we have

$$G(t^*) = c_{min}. \tag{6}$$

Now, starting at different points, but such that $G(0) > c_{min}$ and $T > T^*$ as defined for them we should stop at different decision points respectively . Actually there is a locus of points satisfying (6), which we call D as follows

$$D = \{ t \in E^2 | G(t) = c_{min} \} . \tag{7}$$

We call D the stopping line (although it may happen to be a point). Now denote the area within D, inclusive, as C, or

$$C = \{ t \in E^2 | G(t) \leq c_{min} \}. \tag{8}$$

C is also called the waiting area, since being there during the decision period would imply waiting. Clearly $C \subseteq D$, with $C = D$ for the special case where one of the points $N \cup 0$ is the only solution for a large T. In case $C \neq D$, however, we have a nonempty set E as follows

(9) $$E = C - D \text{ (or } C/D).$$

Specifically, there is a point in C, and in E if $E \neq \emptyset$, for which $G = 0$. We denote this point by t_{min}, i.e.,

(10) $$G(t_{min}) = 0.$$

Clearly, in order to identify t_{min}, we do not need any information about the starting point or any of the costs we carry, but just the information on N and $\{p_i\}$

Statistical Measurements of Industrial Racing Patterns

The point of departure for a statistical analysis of industrial racing patterns is that the technological frontier is in fact a reasonable indicator of the evolving state of the knowledge (technical expertise) in the industry. At any point in time the “industry frontier” (ITF) indicates the degree of technical sophistication of the most advanced product in the industry, in a sense described below. Firm level technology frontiers (FTF) are constructed analogously and indicate, at any point in time, the extent of the technical sophistication achieved by any firm until that point in time. The study focusses on the evolution of the European firm and industry level technology frontiers vs. North America and Japan.

In the context of this study we define ‘race’ as a continual contest for technological superiority among some subset of firms within a well defined industry (classification). Under this conceptualisation a race is characterised by a number of firms whose FTF’s remain ‘close’ together over a period of 20 to 25 years. The distinctive element is that firms engaging in a race have FTF’s substantially closer together than the FTFs of any firms not in the race. A statistical analysis should reflect that a race, as defined, may or may not have different firms in the leadership position at different times, may be a tighter race at some times than at others, and in general, may exhibit a variety of forms of industrial behaviour.

We present three cases of high technology industries for which we demonstrate the construction of statistical indicators reflecting racing patterns in those industries, (1) biotechnology, (2) semiconductors/computers and telecommunications equipment. We choose those industries because they are identified as the major components of a technology based network industry reflecting the cutting edge of the science / technology frontier in the world economy. Statistical indicators reflecting the technology race in those industries provide intrinsic information on knowledge leadership position, competitive advantage and level of welfare and wealth creation in the economies involved. Thus, they will be of significant value to policy analysis of economic growth and development. The data set is comprised of product offerings by major European , American and Japanese firms in those industries from the period 1975-2000, assembled from and cross-checked by a range of historical sources, field studies and expert opinions.

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Methodology. Based on previous work on stochastic modelling of innovation races, we look for clusters of firms whose FTFs remain close enough throughout the 25 year period (formal measures of closeness are defined and measured). We identify at least 2 races in progress in the industries throughout the 25 years of duration. One comprises the world frontier race in each of those industries, the other the European frontier race which technically would constitute a subfrontier to the world (sometimes complemented by the Japanese race). Since the data set by no means exhaust the firms in the industry, it is certainly easier to accept that these are the significant technological races in progress. The technology frontier of the firms in a particular race (that is ITF) is constructed in a manner similar to the individual FTFs. Essentially, the maximal envelope of the FTF's in a particular race constitute the ITF for that race. So the ITF indicates, as a function of calendar time, the best achievable performance by any firm in the race.

Characterisation of Statistical Indicators of Industrial Racing

The empirical explorations examine the features of the innovative process that are common to all the races, and those that distinguish between them. This will help us understand some of the similarities and differences between different technology strategies that the races appear to represent. A frontier is 'pushed' forward when the performance level of the technology (for the firm in case of FTF and for the racing group of firms in the case of ITF) is being enhanced.

For example, to which extent are different firms in each race responsible for pushing the frontier forward (i.e. to which extent are movements in the individual FTFs of the racing firms translated into movements of the ITF)?

While a variety of situations are possible, the extremes are the following: (a) one firm may push the frontier at all times, with the others following closely behind, (b) all firms share more or less equally in the task of advancing the ITF. Extreme situation (a) corresponds to the existence of a unique technological leader for a particular race, and a number of quick followers. Situation (b), on the other hand, corresponds to the existence of multiple technological leaders.

(a) Assessment of Frontier Pushing. The relevant statistics for the two races are given in Table 1 in illustrative terms.

TABLE 1: PUSHING THE FRONTIER (ILLUSTRATIVE)

NUMBER OF TIMES EACH FIRMS PUSHES THE FRONTIER

Firm #	1	2	3	4	5	6	total
World frontier	6	3	2	-	-	-	11
EU Subfrontier	4	1	0	2	1	2	10

(b) Domination Period Statistics. Accepting the view that a firm has greater potential to earn rents from its technological position if it is ahead or its race suggests that it would be interesting to examine the duration of time for which a firm can expect to remain ahead once it finds itself pushing its ITF. We define statistically the ‘domination period’ to be the duration of time for which a firm leads its particular race. The domination period tends to be a more uncertain quantity in the world frontier race than in the EU frontier race (as evidenced by the lower domination period standard deviation in Table 2)

TABLE 2 DOMINATION PERIOD STATISTICS (ILLUSTRATIVE)

	Mean (years)	Std. Dev. (years)	n
World frontier	3.44	5.19	9
EU frontier	3.88	2.20	8

(c) Catchup Statistics. If a firm tries to innovate more when it is behind then when it is ahead, then ‘catch up’ behaviour will be the dominant effect. (Evidence that catch up behaviour is the norm is provided by data from the US and Japanese computer industry). Extending this evidence to illustrate our innovation race statistics, we make up Table 3A

TABLE 3A MORE INNOVATIONS WHEN BEHIND OR AHEAD (ILLUSTRATIVE)
WORLD FRONTIER

Firms #	1	2	3	Total
Total innovations	7	8	3	18
Number when ahead	3	2	0	5
% when ahead *	43	25	0	28
% of time ahead**	81	10	20	

TABLE 3A MORE INNOVATIONS WHEN BEHIND OR AHEAD (ILLUSTRATIVE)
EU FRONTIER

Firms #	1	2	3	4	5	6	Total
Total innovations	9	3	6	5	2	2	27
Number when ahead	2	0	1	1	0	1	5
% when ahead *	22	0	17	20	0	50	19
% of time ahead**	29	47	3	36	18	75	

TABLE 3A MORE INNOVATIONS WHEN BEHIND OR AHEAD (ILLUSTRATIVE)
JAPAN FRONTIER

Firms #	1	2	3	Total
Total innovations	8	6	10	24
Number when ahead	2	2	3	7
% when ahead *	25	33	30	29
% of time ahead**	16	45	52	

One tailed difference of means t test:: % when ahead vs. % of time ahead: t=1.62, d.f.=22, p<0.06

* percentage of innovations occurring when firm leads its race

** percentage of time that a firm leads its race

For each firm, this table compares the fraction of the total innovations carried out by the firms (i.e. the fraction of the total number of times that the FTF advanced) when the firm in question was leading its race with the fraction of time that the firm actually led its race. In the absence of catch-up behaviour, or behaviour leading to a firm increasingly dominating its rivals, we would expect to see no difference in these fractions. Then the fraction of time that a firm is ahead of its race could be an unbiased estimator of the fraction of innovations that it engages in when it is ahead.

The data, however, suggest that this is not the case. Difference of means tests indicate that the fraction of time that a firm leads its race is larger than the fraction of innovations that occur when the firm is ahead, i.e. more innovations occur when the firm is lagging than would by expected in the absence of catch-up or increasing dominance behaviour. Catch-up behaviour is supported by additional observations, as in Table 3B, that the firms make larger jumps (i.e. the FTF advances more) when they are behind than when they are leading the race.

TABLE 3B FIRM JUMP SIZES LARGER WHEN BEHIND OR AHEAD?

	When Ahead		When Behind	
	Mean Jump Size	Number of Jumps	Mean Jump size	Number of Jumps
World frontier	2.37	5	2.92	12
EU frontier	2.84	4	2.82	22
Japan frontier	6.41	7	8.41	17

(d) Leapfrogging Statistics. From this, the distinction emerges between two kinds of catch-up. A lagging firm might simply try to close the gap between itself and the technological leader at any point in time (frontier-sticking behaviour), or it might try to actually usurp the position of the leader by ‘leapfrogging’ it when there are disproportional larger payoffs in being in the technical lead (relative to the payoffs that a firm can realize if it is simply close enough to the technical frontier), then one would expect that leapfrogging behaviour would occur more frequently than frontier-sticking behaviour.

Tables 4 and 5 describe the results of some analyses of this leapfrogging/frontier-sticking phenomenon. All attempts to leapfrog the current technological leader might not be successful since many lagging firms might be attempting to leapfrog the leader simultaneously. Correspondingly, we report both the attempted leapfroggings and the realized leapfroggings. It appears likely that the leapfrogging phenomenon would be more predominant in world frontier than in the EU frontier races.

TABLE 4 NATURE OF JUMPS : LEAPFROGGING OR FRONTIER –STICKING (ILLUSTRATIVE)

	Total Jumps	Attempted Leapfrogs	Realised Leapfrogs
World frontier	18	15 (83%)	11 (61%)
EU frontier	27	13 (48%)	10 (37%)

TABLE 5 INTER-JUMP TIMES AND JUMP SIZES (ILLUSTRATIVE)

	Time and Jump Statistics summarising all FTFs			
	Inter-Jump Times		Jump Sizes	
	Mean	Std. Dev.	Mean	Std. Dev.
World frontier	3.87	3.42	2.87	2.52
EU frontier	3.59	2.76	2.95	1.94
	Time and Jump Statistics summarising ITFs			
	Inter-Jump Times		Jump Sizes	
	Mean	Std. Dev.	Mean	Std. Dev.
World frontier	2.90	2.0 9	2.02	1.02
EU frontier	3.11	2.02	2.14	1.36

(e) Race Closeness Measure (RCM). None of the previous analyses tell us how close any of the overall races are over a period of time. The races are all close by construction, however, some might be closer than others, We define ‘a measure of closeness’ of a race (RCM) at a particular time as follows: $RCM(t) = \Sigma_0^N [f_i (t) - F(t)]^2 / N(t)$ where $f_i (t)$ is the firm's FTF at time t, F(t) is the ITF at time t = max [FTF(t)] and N(t) is the number of active firms at time t.

The measure thus constructed has a lowest value of 0, which corresponds to a ‘perfectly close’ race. Higher values of the measure correspond to races that are less close. Unlike the earlier characteristics (domination period length, innovation when ahead versus when behind, leapfrogging versus frontier-sticking) which investigate the behaviour of a particular feature of the race and of a particular firm in relation to the race frontier, the RCM is more of an aggregate statistic of how close the various racing parties are at a point in time. The closeness measure is simply an indication of parity, and not one that says anything per se about the evolution of the technological frontier. To see this, note that if none of the frontiers were evolving, the closeness measure would be 0, as it would if all the frontiers were advancing in perfect lock-step with one another.

(f) Interfrontier Distance. How long does ‘knowledge’ take to spillover from frontier firms to subfrontier firms. This requires investigating “interfrontier distance”. One measure of how much subfrontier firms’ technology lags the frontier firms’ technology could be graphed as “subfrontier lag” in terms of calendar time. At each point in time , this is simply the absolute difference in the subfrontier performance time and the frontier performance time. The graph would clearly indicate that this measure has been declining or increasing more or less monotonically over the past 25 years to the extent that the subfrontier firms have been able/unable to catch up with the frontier firms. A complementary measure would be to assess the difficulty of bridging the lag. That is, how much longer does it take the subfrontier to reach a certain level of technical achievement after the frontier has reached that level. Thus it might very well turn out that the interfrontier distance may be decreasing though the difficulty in bridging the gap is increasing.

Another reason to analyze interfrontier distance is that it provides some indication of technological obsolescence in the industry. Another measure of interfrontier distance(a bridging difficulty measure) provides a lower bound on how long a technology lasts in the industry. This is so since a technology is actively used in the industry at least from the time that a frontier firm introduces it to the time that a subfrontier firm introduces it. The measure is a lower bound , since the actual life of a technology will exceed this measure for a number of reasons. For one thing, firms that lag the frontier of their respective races will use the same technology later than the firms at the frontier. For anothe, recall that the FTFs were constructed using each firm’s most technically sophisticated product. The technology will presumably be around for quite a while in less advanced products that the firm puts out (intra-firm diffusion of technology).

Further Discussion

The model sets out to examine and measure racing behaviour on technological positions among firms in high technology industries, as exemplified by the globally operating telecommunications equipment,semiconductor and computer industries . In measuring the patterns of technological evolution in these industries we attempt to answer questions about whether and to which extent their racing patterns differ from those firms in respective industries that do not operate on a global scale. Among the key issues we want to address is the apparent inability of technology oriented corporations to maintain leadership in fields that they pioneered. There is a presumption that firms fail to remain competitive because of agency problems or other suboptimal managerial behaviour within these organizations. An alternative hypothesis is that technologically trailing firms, in symmetric competitive situations, will devote greater effort to innovation, so that a failure of technological leaders to maintain their position is an appropriate response to the competitive environment. In asymmetric situations, with entrants challenging incumbents, research could demonstrate whether startup firms show a stronger endeavour to close up to or leapfrog the competitors. Such issues would highlight the dynamics of the race within the given market structure in any of the areas concerned. We observe two different kinds of market asymmetries bearing on racing behaviour: (a) risk-driven and (b) resource based asymmetries.

When the incumbents' profit are large enough and do not vary much with the product characteristics, the entrant is likely to choose the faster, less aggressive option in each stage as long as he has not fallen behind in the race. The incumbent's behaviour is influenced by what is known as the 'replacement effect' (Tirole, 1988). The conventional 'replacement' effect says that, in an effort to maximize the discounted value of its existing profit stream, the incumbent (monopolist) invests less in R & D than an entrant, and thus expects to be replaced by the entrant (in the case where the innovation is drastic enough that the firm with the older technology would not find it profitable to compete with the newer technology). In one of our models, when the incumbent's flow profit is large enough, the same replacement effect causes the incumbent to be replaced only temporarily (if the innovation is drastic). Subsequently, she is likely to regain a dominant position in the market since she has a superior version of the new technology.

In view of resource based asymmetries, we observe, as a firm's stage resource endowment increases, it could use the additional resources to either choose more aggressive targets or to attempt to finish the stage quicker, or both. This hypothesis suggests two interpretations, suitable for empirical exploration: (a) if the demand for new products displays different elasticities for different local/regional markets, then we might expect there to be only imperfect correlation between aggressiveness and resource richness when products from different markets are grouped together, (b) if, however, demand for these products is not inelastic enough, then we would expect resource rich firms to aim for both higher speed in R&D and greater aggressiveness.

A further point of exploration is whether chance leads result in greater likelihood of increasing lead, or in more catchup behaviour. Previous work in this regard (Grossman and Shapiro, 1987; Harris and Vickers, 1987) has suggested that a firm that surges ahead of its rival increases its investment in R&D and speeds up while a lagging firm reduces its investment in R&D and slows down. Consequently, previous work suggests that the lead continues to increase. However, based on related work for the US and Japanese telecommunications industry (Gottinger, 1996) when duopoly and monopolistic competition and product system complexity for new products are accounted for, the speeding up of a leading firm occurs only under rare circumstances. For example, a firm getting far enough ahead such that the (temporary) monopoly term dominates its payoff expression, will always choose the fast strategy, while a firm that gets far enough behind will always choose the slow and aggressive approach. Then the lead is likely to continue to increase. If, on the other hand, both monopoly and duopoly profits increase substantially with increased aggressiveness then even large leads can vanish with significant probability.

Overall, this characterization highlights two forces that influence a firm's choices in the various stages: proximity to the finish line and distance between the firms. This probability of reaping monopoly profits is higher the farther ahead a firm is of its rival, and even more so the closer the firm is to the finish line. If the lead firm is far from the finish line, even a sizeable lead may not translate into the dominance of the monopoly profit term, since there is plenty of time for the lead situation to be reversed and failure to finish first remains a probable outcome. In contrast, the probability that the lagging firm will get to be a monopolist becomes smaller as it falls behind the lead firm. This raises the following question. What kind of actions cause a firm to get ahead? Intuitively, one would expect that a firm that is ahead of its rival at any time t, in the sense of having completed more stages by time t, is likely to haven chosen the faster, less aggressive strategy more often. We will construct numerical estimates of the probability that a leading firm is more likely to have chosen a strategy less aggressively (faster) to verify this intuition.

Moving away from the firm-led race patterns revolving in a particular industry to a clustering of racing on an industry level is putting industry in different geoeconomic zones against each other and becoming dominant in strategic product/process technologies. Here racing patterns among industries in a relatively free trade environment could lead to competitive advantages and more wealth creating and accumulating dominance in key product / process technologies in one region at the expense of others. The question is, whether individual races on the firm level induce such like races on the industry level and if so, what controlling effects may be rendered by regional or multilateral policies on regulatory, trade and investment matters.

Similar catchup processes are taking place between leaders and followers within a group of industrialized countries in pursuit of higher levels of productivity. Moses Abramovitz (1986) explains the central idea of the catch-up hypothesis as the trailing countries' adopting behaviour of a 'backlog of unexploited technology'. Supposing that the level of labour productivity were governed entirely by the level of technology embodied in capital stock, one may consider that the differentials in productivities among countries are caused by the 'technological age' of the stock used by a country relative to its 'chronological age'. The technological age of capital is an age of technology at the time of investment plus years elapsing from that time. Since a leading country may be supposed to be furnished with the capital stock embodying, in each vintage, technology which was 'at the very frontier' at the time of investment, 'the technological age of the stock is, so to speak, the same as its chronological age'. While a leader is restricted in increasing its productivity by the advance of new technology, trailing countries 'have the potential to make a larger leap' as they are provided with the privilege of exploiting the backlog in addition of the newly developed technology. Hence, followers being behind with a larger gap in technology will have a stronger potential for growth in productivity. The potential, however, will be reduced as the catch-up process goes on because the unexploited stock of technology becomes smaller and smaller. This hypothesis explains the diffusion process of best-practice technology and gives the same sort of S-curve change in productivity rise of catching-up countries among a group of industrialized countries as that of followers to the leader in an industry.

Although this view can explain the tendency to convergence of productivity levels of follower countries, it fails to answer the historical puzzles why a country, the United States, has preserved the standing of the technological leader for a long time since taking over leadership from Britain in around the end of the last century and why the shifts have taken place in the ranks of follower countries in their relative levels of productivitiy, i.e., technological gaps between them and the leader. Abramovitz poses some extensions and qualifications on this simple catch-up hypothesis in the attempt to explain these facts. Among other factors than technological backwardness, he lays stress on a country's 'social capability', i.e., years of education as a proxy of technical competence and its political, commercial, industrial, and financial institutions. The social capability of a country may become stronger or weaker as technological gaps close and thus, he states, the actual catch-up process ‘does not lend itself to simple formulation’.This view has a common understanding to what Mancur Olson (1996) expresses to be ‘public policies and institutions’ as his explanation of the great differences in per capita income across countries, stating that ‘any poorer countries that adopt relatively good economic policies and institutions enjoy rapid catch-up growth’. The suggestion should be taken seriously when we wish to understand the technological catching-up to American leadership by Japan, in particular, during the post-war period and explore the possibility of a shift in standing between these two countries. This consideration will directly bear on the future trend of the state of the art which exerts a crucial influence on the development of the world economy.

Steering or guiding the process of racing through the pursuit of industrial policies aiming to increase competitive advantage of respective industries, as having been practised in Japan (Gottinger, 1996), in that it stimulates catchup races but appears to be less effective in promoting frontier racing. A deeper reason lies in the phenomenon of network externalities affecting high-technology industries. That is, racing ahead of rivals in respective industries may create external economies to the effect that such economies within dominant industries tend to improve their international market position and therefore pull ahead in competitiveness vis-a-vis their (trading) partners.

As P. Krugman (1991, 1997) observed: ‘It is probably true that external economies are a more important determinant of international trade in high technology sectors than elsewhere’.

The point is that racing behaviour in leading high technology industries by generating frontier positions create cluster and network externalities pipelining through other sectors of the economy and creating competitive advantages elsewhere, as supported by the ‘increasing returns’ debate (Arthur, 1996). In this sense we can speak of positive externalities endogenizing growth of these economies and contributing to competitive advantage.

It is interesting to speculate on the implications of the way the firms in major high technology markets, such as telecommunications, split clearly into the two major technology races, with one set of firms clearly lagging the other technologically. The trajectories of technological evolution certainly seem to suggest that firms from one frontier cannot simply jump to another trajectory. Witness, in this regard, the gradual process necessary for the firm in the catchup race to approach those in the frontier race. There appears to be a frontier ‘lock-in’ in that once a firm is part of a race, the group of rivals within that same race are the ones whose actions influence the firm’s strategy the most. Advancing technological capability is a cumulative process. The ability to advance to a given level of technical capability appears to be a function of exisitng technical capability. Given this path dependence, the question remains: why do some firms apparently choose a path of technological evolution that is less rapid than others. Two sets of possible explanations could be derived from our case analysis, which need not be mutually exclusive. The first explanation lingers primarily on the expensive nature of R & D in industries like telecommunications and computers which rely on novel discovery for their advancement. Firms choosing the catchup race will gain access to a particular technical level later than those choosing the frontier, but will do so at a lower cost.

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