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When and How Chance and Human Will Can Twist the Arms of Clio

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1 Introduction

The notion of *path-dependence*, despite rather different uses (and misuses!) in diverse disciplines, is nonetheless commonly linked with the idea that "history matters" in the interpretation of whatever phenomenon one would like to explain. Or, putting it another way, in order to understand why a certain entity has become what it is, or why a certain variable has acquired the value that one observes, one needs to bring into the picture, among the explanatory "causes", also the past of that entity or the previous time path of that variable. The bottom line of such intuitive notion is indeed that history matters precisely because *another history* - even holding the causal linkages of the analyzed system invariant - would have possibly yielded a different outcome.

Needless to say, the idea is very appealing and might in fact be a major building block of a new interpretative paradigm, emerging with respect to both natural and social sciences [see Prigogine and Stenger (1984) for a discussion that is also a sort of epistemological manifesto]. If anything, the intuitive appeal for most social scientists (except a few economists!) is such that it is worth asking which are the circumstances under which history does *not* matter.

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Conversely, even when seemingly it does matter, what does it precisely mean? Does it all relate to some differences in the *starting point* of the dynamic process under investigation? Or, does it concern a series of events occurring, so to speak, *along the historical path*? And, how big should these events (or how big should the differences in initial conditions) be in order to reshape the course of future outcomes?

At even deeper, and more philosophical, levels, these issues bear far-reaching implications in terms of *chance* (or *discretionary will*) and *necessity* [to paraphrase a famous book by Jacques Monod]. That is, what are the degrees of discretionality which individual agents, organizations, or collection of them, enjoy in shaping their own future? Is it that "freedom is just the consciousness of necessity" - as the philosopher Baruch Spinoza put it? Or, isn't it an implication of path-dependence that agents may re-set their own paths, albeit within the limits of their historically inherited constraints?

The importance of the difficulty of these background issues are among the motivating reasons of this essay, developing upon previous works in economics on similar subjects: see, among others, David (1975, 1989, 1993, 1996), Arthur (1988, 1994), Dosi and Orsenigo (1988), Dosi and Metcalfe (1991), and Dosi and Kogut (1993). In the hard task of providing within a single essay some reasonably coherent assessment of different notions of path-dependence, in the following we shall start from some archetypical examples and interpretative categories. Building on them, we shall proceed to disentangle some of the sources of path-dependence, different levels of descriptions and different time scales at which path-dependence might (or might not) emerge. Together we shall attempt an admittedly conjectural assessment of the processes by which chance or discretionary human will might de-lock collective histories from particular paths. Notwithstanding some obvious bias in favour of economic and, more broadly, social examples, extensive reference to natural sciences shall help in highlighting the challenging scope of the issues at stake.

2 Path-Dependence, Irreversibilities, and Notionally Alternative Outcomes: Some Illustrative Examples

Some basic conceptual categories and more mundane examples may be useful starting points.

First, note that in order for history to matter, phenomena need to develop along an *irreversible time arrow*, and, together, the *actual outcome* must be only *one of many possible alternative realizations.*

There are plenty of simple examples even from natural history. Consider the formation of a planet system: while the fact that a gas *nebula* would eventually collapse and develop in a planet system is, as a first approximation, an almost sure event, the actual position of planets, which is related to the spatial configuration of initial agglomerations of dust particles, is just one of the (almost infinite) possible dispositions.

The creation of the Lake La Niña in Peru - quite a remarkable event of hydrographic change given that it is now the second in South America for surface size - is an example of the cumulative effect of many meteorological events that are thoroughly changing the conditions in a once desertic territory.

Plenty of illustrations may be taken from, for example, a property of autocatalytic reactions is that they generally have multiple steady states. Even small perturbations of a system resting in an unstable steady state could lead to different (and *a priori* unpredictable) configurations[1].

Regarding biology, in the Darwinian evolutionary paradigm there is a striking tension between selection and mutation: Speciation is an irreversible branching process where the followed path is the outcome of complicated dynamics of mutation and selection among possible developments[2].

And, of course, social sciences are where one is likely to find that the interpretation of most phenomena also implies some account of the courses of history leading to them. This is so because, most often, the structures and constraints inherited from the past, together with human discretionality, select among alternative notional forms of social organization and paths of change.

[1]See e.g. Prigogine (1980).

[2]See Gould (1977).

Second, the proposition that "history matters" intuitively goes together with some sort of *thought experiment* (or *counterfactual*) which can be rarely undertaken through an actual experiment (at least in the social and biological domain).

Any scientists, or for that matter any individual, facing outcomes of contingencies that seem to be determined by particular coincidences of events and/or timing of choices, implicitly or explicitly try to re-run the tape of history, attempting to disentagle the ways big or marginal variations in actions, exogenous events, or timings in the above, might have led to outcomes whose effects could not be washed away by the sheer passing of time.

History as a discipline is largely based on that method, from the conjectures on the macro historical effects exerted by the fascination of the nose of Cleopatra all the way to the causes and effects of the defeat of Napoleon in the Waterloo battle. Here there are micro, random, events (the ravishing beauty of a lady who happened to be there with low probability at a particular time; the rain over Waterloo that prevented the full deployment of the French Artillery; etc...). These phenomena, however, interact with more macroscopic ones: one could argue for example that, given the decadence of Hellenistic Kingdoms, they would have fallen pray in any case of the Roman State, and that Cleopatra's nose influenced, if anything, only the modes and the timing (And *mutatis mutandis*, one could argue the same for Napoleon's political enterprise...)

The long-term impact of micro, normally irrelevant events has intuitively to do with resilience of some higher level collective structures to micro fluctuations. But, at this higher level of observation, a similar question may be posited, namely, could have the Roman State and Hellenistic Kingdoms evolved, with positive probability, along paths wherein, on the contrary, no beauty mattered?

These caricatural examples point indeed, *third*, to the time-scale dimension of path-dependence: i.e. does it relate primarily to the distribution over time of events and to the time scale of processes which however would yield, in the limit, an invariant outcome? Or, on the contrary, are long-term outcomes themselves affected by these sequences of apparently random micro events?

Symmetrically, *fourth*, even when one might observe on some time scale, that history matters only within rather narrow boundaries, seemingly frozen by much more inertial social structures and institutions themselves, what can one infer about path-dependency on longer time scales? Intuitively one has to refer back to the path-dependency properties of these structures and institutions themselves. Indeed, by successive recursions on longer and longer time frames one easily goes back to the questions of path-dependency in the observed biological history, all the way to the initial cosmogony...

Much nearer to our subject, instances where history matters at some of these levels are increasingly studied in economics: In primis, studies of technological change, innovation and diffusion are crowded by such examples, well beyond the celebrated QWERTY keyboard example [David (1985, 1996)][3].

Cowan (1990) argues that the developments of nuclear reactor technology towards light-water reactors (instead of e.g. gas-cooled reactors) was due to a sequence of decisions which favoured first a technology that could have been employed easily by military submarines and later, because of technological developments due to the widespread employment in submarines, could be quickly developed for civil uses. In short, particular historical conditions, related to macro-conditions (the cold war) and micro-decisions (in particular those of a single Admiral of the US Navy) were at the origin of these developments.

Cowan and Gunby (1996) show that developments of chemical or biological pesticides in Texas was quite dependent on sequences of self-reinforcing events that were only partially triggered by the difference in climatic conditions.

The 640K lower memory constraint on DOS-based software was not outcome of any optimization exercise but rather the result of the hasty choices of the IBM designers in order to obtain their first generation of PCs. What would have been the whole software developments had there not been the premium placed on ever better ways to use high-level memory subject to such a constraint?[4]

JVC's VHS and Sony's Beta were commercialized approximately at the same time. According to many studies [see Cusumano et al. (1992) and Liebowitz and Margolis (1994)] none of the two standards has ever been perceived as unambiguously better and, despite their incompatibility, their features were more or less the same, due to the common derivation from the U-matic design. For these reasons the relevant decisions of consumers were likely to be sequential both at the individual and at the collective level. Plausibly, first, a consumer chooses whether or not to adopt a VCR, then,

[3](1995) and West (1994).

[4]See David (1996).

once the adoption decision has been made, turns to the choice of the type of VCR to purchase. The role of the installed base of the two technologies in this market most likely matters: There are strong increasing returns in design specialization and production of VCR models (so that historically all firms specialized just in one single standard) on the supply side, and increasing returns externalities and due to the availability of home video rental services on the demand side [Cusumano et al. (1992)]. Despite technical similarities between the two standards, preferences were strongly heterogeneous, due mainly to brand-name-loyalty type of consumer behavior. The key of JVC's success seems to have been the exploitation of heterogeneity of preferences through Original Equipment Manufacturers (OEM) agreements with European firms characterised by well-established market positions in electronic durable goods: After the invasion of the European market and the consequent reorientation of the home video rentals market, VHS moved towards dominating also the other, quite segmented, Japanese and American markets. However what would have happened had not Sony been misguided by its in-house productive capacity and had they engaged in the same market penetration strategy?

Beyond these simple patterns of competition among technologies, there are a few examples where the emergent monopoly of one technology lasts for a long while until it is discarded by new radical discoveries revitalizing the old technology. For instance Islas (1997) shows how gas turbines got an opportunity to regain a dominant position also in the market of thermal power stations for mass-production of electricity, after barely surviving in the military aircraft market niche. Tell (1997) argues that the fact that direct current electric technology survived in the railway transportation market segment was the key for the rediscovery of that technology as long distance electricity carrier many years later.

Clearly it is doubtful that the new winning technology could be considered just a new version of the old defeated competitor. The re-emergence of gas turbines is an archetypical case: It occurred through the development of different types of combined cycles while at the beginning the gas turbine was only a complementary component of an hybrid technology [White (1956), Auer (1960), Pfenninger and Yannakopoulos (1975), Islas (1997)].

All these examples witness for some critical history-dependence in the subsequent collective selection of some dominant design of product specification or even the dominant knowledge bases and technological paradigms [Dosi (1982)]. At the same time, some of these historical instances illustrate also the possibility of de-locking from some apparently dominant technological trajectories, due to changes in the knowledge bases - on different time scale - in related technological fields.

History looms large also at the broader level of country-specific patterns of growth and specialization in international trade. Indeed an enormous literature, involving sociology, political science and the political economy of growth, has convincingly emphasized the inertia and self-sustained reproduction of institutions and organizational forms as determinants of growth of different nations, showing variegated patterns of catching-up, falling-behind and forging ahead (for some "stylized facts", see Abramovitz (1985), Dosi et al. (1993) and Fagerberg et al. (1995)). Still political and institutional lock-in is almost never complete, and what appeared to be stable "equilibria" for a long period, may be quickly disrupted by a sequence of strongly self-reinforcing, possibly surprising, events. This is the case, for instance, of the collapse of socialist regimes in Eastern Europe[5], but also the case of major technological discontinuities (e.g. Schumpeter's gales of creative destructions), and corporate changes (e.g. Chandler's M-form corporation, Fordism, Toyotism, etc...).

The nature of path-dependent dynamics, the levels at which they might be detected and their sources are the topics of the sections which follow. Clearly, path-dependence must involve some irreversibility of the phenomena under consideration. At the very least, history must matter in some phenomenologically defined short run. Call it a *weak* form of path-dependence. Or in a *strong* form, it might affect also the long-term states the system will eventually obtain.

3 What Is Path-Dependence?

In order to illustrate more rigorously the foregoing points on irreversibility and path-dependence (and the conceptual difference among them), let us start from some natural science examples.

In a closed environment all thermodynamic processes increase their entropy towards a maximum. Entropy can never be decreased[6]. In a sense this

[5]For a different interpretation, although in our opinion short of satisfactory, see Caplin and Leahy (1994).

[6]See Prigogine (1980) for more details on irreversibility of thermodynamic reactions as compared to classical dynamic reactions.

is an archetypical example of an irreversible process, that is a process that develops through history. However, despite its irreversibility, this canonical thermodynamical reaction is a typical example of processes where the effects of history are washed away as time goes by: All systems that have a single maximum of entropy which is also a globally stable steady state (that is systems that admits a Lyapunov function over the whole phase space) converge towards a single asymptotic pattern: history matters and constrains the process during the transition, but the ending point is predictable and unique. If we heat the corner of a physically compact box (and we thermo-insulate it from outside) we can observe an irreversible process of equalization of temperature inside the box. However the system converges towards the unique steady state where the expected value of temperature is the same everywhere in the box.

As an example from economic theory, consider the case of the neoclassical growth model à la Solow [Solow (1956)]: Independently of any initial conditions there is just one possible asymptotic steady state implying, in that model, also absence of per-capita output growth.

In this whole class of systems there is an obvious irreversibility (one cannot "go back in time"). However this implies convergence to an unchange final destiny. In that sense there is no path-dependence.

A general condition for history to matter in terms of asymptotic states which the system might attain is the existence of multiple equilibria reachable under different initial conditions. In turn, it is now well-known that they are likely to appear with reference to the economic domain in the presence of some forms of dynamic increasing returns or collective externalities. Even sticking to otherwise very conventional assumptions on microbehaviors and collective interactions, it can be shown that positive feedbacks of some kind generally yield multiple growth trajectories, multiple specialization patterns in international trade, etc..., depending on initial conditions.

3.1 Path-Dependence in the Presence of Stable Attractors

In mathematical terms the possibility of having many basins of attraction depends on the shape of the function describing its transition dynamics. Just as an example take $x(t)$ as the variable of interest and consider a function $f(.)$ relating its value in the future, e.g. $x(t+1)$, to its current value. Clearly the system is in a steady state only when

$$x(t+1) = f(x(t)) = x(t).$$

Furthermore a steady state x^* can be a (stable) attractor only if in a neighborhood of that point the function $f(x) - x$ downcrosses the x-axis changing its value from positive to negative. In other terms $x(t)$ should display a tendency to increase its value when it is below the (locally stable) attractor x^*, while the opposite holds when it is larger. Clearly if $f(.)$ is linear just one steady state is admissible. In a one-dimensional space, this means that either the process displays a tendency to grow or collapse for ever or it tends to converge to the stable attractor for every initial condition. The possibility of either one pattern depends on the nature of the attractor. However similar properties are shared by functions that cross the 45 degree line no more than twice. For instance all the concave and convex functions belong to this class. Note that the Solow model generates a concave transition function. The Kaldorian growth model[7], on the other hand, has a linear transition. Both these cases are graphically represented in Fig.1.

Insert Fig 2.1: Transition functions in the Solow and the Kaldor growth models. Dotted and Dashed lines identify steady states.

With more complex transition functions (for instance, in a growth model with a nonconvex production possibility set[8]), the possibility of multiple locally stable attractors emerges. Consider the transition function depicted in fig. 2.

Insert Fig 2.2: Transition function with two separate basins of attraction. Dotted line separates basins.

[7]See Kaldor (1957) and Kaldor and Mirlees (1962).

[8]Simple treatments in the context of the growth literature can be found in Majumdar et al. (1989), King and Robson (1993), and Azariadis (1996). More complicated examples come from applications of chaos to economics [e.g. Brock and Malliaris (1989) and Medio (1992)].

A fortiori, multiple growth trajectories are likely to emerge in evolutionary models[9] sustained by the positive feedback structure linking, in probability, technological innovation, profitability, growth and further innovations.

Another broad domain where a multiplicity of equilibria easily appears concerns the processes of selection - being they at the biological or economic levels - among heterogeneous entities, whenever there is some interaction in the contribution of various traits to the "fitness" (in biology) in the "competitiveness" (in economics) of various entities. Consider the relationship in some biological environment between traits and fitness - i.e. what is often called *fitness landscape*.

When the fitness contribution of every gene or trait is independent, the adaptation of biological systems in fixed environments occurs in an highly correlated *Fujiyama single-peaked landscape* (even when fitness contributions are randomly assigned); in such a case whatever the mechanism of adaptation, provided that the fittest has an evolutive advantage, the system converges towards the same maximum from whatever initial condition. The system belongs to the class exemplified by figure 1

.However, whenever *epistatic correlation* appears - i.e. when the fitness contribution of each trait or gene depends also on other ones -, even when the environment is fixed, the landscape tends to become rugged, that is highly non-linear and multi-peaked. A well known example is Kauffman's NK model [Kauffman and Levin (1987), Kauffman (1989,1993)][10]. Even more so, this picture extends to the case when each species landscapes are mutually interdependent [as in the so-called NKC models: see Kauffmann and Johnsen (1991) and Bak et al. (1994)]. Both these models belong to the class exemplified by figure 2.

Interestingly, there are many analogies between these models of biological evolution and the evolution of complex organizations [Levinthal (1998a,1998b)]: Heterogeneity of organizational patterns, as well as inertia in the face of changing environmental conditions, can emerge as properties of adaptative search in rugged fitness landscapes due to complementarities among or-

[9] The classic reference for such type of models is Nelson and Winter (1982). An example where such multiplicity of growth paths is explicitly analyzed is in Dosi et al. (1994). A more detailed discussion of the relationship between evolutionary processes and path-dependence is in the chapter of this book by Vernon Ruttan and, with a somewhat different view, in Dosi (1997).

[10] Kauffman's analysis has mainly a statistical character: General properties of NK models are studied through random assignment of fitness contributions.

ganizational components.Contrary to contingency theories of organizations [Lawrence and Lorsch (1967)] claiming a high plasticity of organizational traits with respect to the requirements of changing competitive environments, Levinthal (1998b) convincingly argues that adaptation over rugged competitive landscapes may yield lock in onto different fitness peaks, even when the competitive conditions change. Hence both organizational variety at any point in time and organizational inertia over time.

3.2 Small and Big Events

An economic system may be affected by big events (plagues, catastrophes, wars, major innovations, policy reforms, etc...), with very strong and persistent effects but usually very low frequence, and small events (weather conditions, incremental innovations, adoption choices, etc...), such that the analyst's filter cannot finely detect the linkage between single event and overall economic effects. Most of economic models take into account only the first type of events: In deterministic models with multiple steady states, history just selects the initial condition from which the attainable steady state is univoquely determined. As Costas Azariadis puts it in his survey on multiple equilibria and growth:

> "An alternative working hypothesis [...] takes the growth process of nations to be fundamentally the same except for differences in *history*, e.g., in the circumstances from which the growth process begins. These are chiefly the starting stocks of human and physical capital, and the state of technology" [Azariadis (1996), p.452].

For instance, in the modern theory of international trade history looms very large but its representation is mainly reduced to initial conditions[11].Similar considerations apply to deterministic equilibrium models of endogenous growth[12]

[11]Examples are Krugman (1981, 1987, 1991b), Ethier (1982) and almost all the works in the Kaldorian tradition [such as Thirlwall (1979), Fagerberg (1988), Cimoli and Soete (1992), Amable (1993) and McCombie and Thirlwall (1994)].

[12]In endogenous growth theory multiplicity of equilibria has generally more to do with coordination of decentralized decision-making rather than with history [as shown by Benhabib and Perli (1993), this is the case in Lucas (1988) and Romer (1990)]. Still, as in the foregoing quotation, when a role for history is underlined, this is reduced mainly to the selection of initial conditions [e.g. Becker et al. (1990), Azariadis and Drazen (1990), Boldrin (1992), Brezis et al. (1993), Cozzi (1997), and Boldrin and Levine (1998)].

Basically, a deterministic approach suffers from the limitation that it cannot represent the dynamic process which makes the whole unfolding history relevant: Everything historically relevant is over when the analyst's camcorder is switched on, and it doesn't help much to watch the crime scene when all the facts has already happened. Phenomena that are related to timing, potential repetition and correlation of historical events are formally ruled out. All this nothwithstanding the verbal acknowledgement of the dynamic importance of timing and repetition of events:

> "Are the poor merely the victims of the circumstances in which they are initially placed by chance, environment or history? If the answer to the last question is yes, can a small or *temporary* improvement in the opportunities of persistently poor groups result in a large or permanent betterment of their lifetime income?" [Azariadis (1996), p.451, italics added].

and

> "Even temporary events, if they are strong enough, can permanently wrench an economy away from underdevelopment. If *temporary events lead to favorable initial conditions*, the economy continues to grow even without the stimulus of major additional innovations or other events similar to those that got the process started" [Becker et al. (1990), p.33, italics added].

In general, the possibility of temporary events occurring along any historical path which have permanent effect on the future path itself can hardly be treated within a deterministic framework. Conversely a stochastic approach allows a more natural representation of both big and small events throughout the history of the system[13].

Arthur (1989) models of emergence of technological lock-in through a sequence of individual adoption choices is a classical example of path-dependence

[13]This statement should be qualified by considering also deterministic chaotic systems. While all the forgoing remarks still apply on the fact that history is "squeezed" into initial conditions, chaotic systems imply *sensitive dependence* on initial conditions themselves, so that two systems starting with arbitrary close initial conditions may exhibit increasingly diverging trajectories.

emerging through a sequence of small stochastic events. The standard story told by authors' developing this class of competing technology dynamics models is the following[14]. Every period a new agent enters the market and chooses the technology which is best suited to its requirements, given its preferences, information structure and the available technologies. Preferences are heterogeneous and a distribution of preferences in the population is given. Information and preferences determine a vector of payoff functions (whose dimension is equal to the number of available technologies) for every type of agent. Because of positive (negative) feedbacks, these functions depend on the number of previous adoptions. When an agent enters the market it compares the values of these functions (given its preferences, the available information, and previous adoptions) and chooses the technology which yields the maximum perceived payoff. Which "type" of agent enters the market at any given time is a stochastic event whose probability depends on the distribution of types (e.g. of preferences) in the population. Because of positive (negative) feedbacks, the probability of adoption of a particular technology is an increasing (decreasing) function of the number of previous adoptions of that technology. These assumptions often lead to multiple asymptotic behaviors, none of which is certain at the beginning.

In essence, in deterministic (non-linear) models only initial conditions are the carriers of history, while in a stochastic framework it may well be that it is the whole sequence of events that determines which limit state is attained, and, conversely, from the same initial conditions the system may evolve towards many different end states.

Continuing with our one dimensional graphic example we can illustrate this with figure 3.

Insert Fig 2.3: Transition functions corresponding to two different values of the underlying stochastic variable. There are two separate basins of attraction. Dotted and dashed lines separate basins.

Imagine that there is an underlying stationary stochastic variable (e.g. weather conditions) that takes only two values that affect production differently (say, rain or sunshine). Figure 3 represents the transition functions

[14] See Arthur et al. (1987), Arthur (1990), Cowan (1990), Glaziev and Kaniovski (1991), Dosi et al. (1994), Dosi and Kaniovski (1994), and Kaniovski and Young (1995).

relative to the different realizations of the stochastic variable in each time. When the system lies to the right of the dashed line or to the left of the dotted line only one steady state is attainable with positive probability. If initial conditions are between the two lines the system initially fluctuates in this region, but eventually will trespass one of the lines and with certainty never cross it again. Both lines can be trespassed with positive probability. The dotted and dashed lines represents two absorbing barriers[15]. Obviously, still, there are some sets of initial conditions (metaphorically speaking, some sets of big events) that determine the long run outcome with certainty[16].

Furthermore notice that, when the system fluctuates in the middle region, the nearer it gets to one barrier the higher the probability to be absorbed by that barrier. The engine that is at work here is some kind of positive feedback or self-reinforcing mechanism. Positive feedbacks (at least of local nature) are actually necessary to create local instability, and therefore multiple long-run patterns that can be selected by history. Indeed, in our view, a good deal of economic processes driven by knowledge accumulation and innovation share these basic characteristics [for discussions, especially with reference to evolutionary models of economic change, see Dosi (1997) and Nelson (1995)].

Let us recall the main points set forth in the previous subsections: Essentially a path-dependent phenomenom is an irreversible dynamic process where there is a multiplicity of potential long-run outcomes, due to some kind of non-linearity, in the functions describing transitional dynamics. Furthermore, a complete description of the role of history can be accomplished if the whole sequence of relevant historical events is taken into account: From the point of view of formal modeling this calls for a stochastic approach.

For expository reasons, until now we have considered only set-ups where dynamical systems eventually settle into a "resting" state: the foregoing examples consider situations wherein the asymptotic pattern is a steady state. This do not need to be the case. Actually many examples from the evolu-

[15]Let us clarify what we mean with stochastic steady state when the process admits more than one basin of attraction. In fact by definition there is at most one asymptotic distribution for every initial state (that is, more than one probability distribution of limit states of the process conditional to events at time 0). A set of states is said to be a *closed set* if no outside state can be reached with positive probability through a finite sequence of steps from any state inside the set. We consider as stochastic steady states each invariant distribution defined for each irreducible subprocess with initial conditions inside each closed set, since there is only one invariant distribution for every such set.

[16]But this need not to be the case when the state space is multi-dimensional - see David (1975) and Bassanini (1997).

tion of institutions, organizations, and technologies suggest a world wherein temporary "resting" states are "metastable" in the sense that on longer time scale they are persistently overcome by new developments leading to new "temporary" resting states. Therefore we need to broaden the definition of path-dependence to encompass the case where there is no convergence to any asymptotic behavior.

3.3 Path-Dependence Without Asymptotics

Consider the irregular motion performed by a pollen grain suspended in liquid. Its irregularity was first noted by the Scottish botanist Robert Brown in 1828. The motion was later explained by the random collision with the molecules of the liquid and described as a stochastic process which closely resembles a random walk (actually a random walk in continuous time and over a continuous state space: a Brownian motion). The trajectory followed by the pollen grain is an irreversible phenomenon and still, even if we could take the liquid surface as approximately infinite, history would not matter asymptotically: Two pollen grain would come arbitrarily close to each other in finite time, and an infinite number of times afterwards; the position of a grain in a time instant is all that matters in order to know the probability distribution over future trajectories (Markovian nature of the process); thus differences in the two pollen grain's histories are eliminated in finite time.

Note that foregoing observation about the motion of particles over a surface does not apply to the motion of particles in a volume: It is a well-known property of random walks in more than two dimensions that two realizations do not cross with certainty. In this latter case we are actually facing a true instance of path-dependence.

In terms of a general definition of path-dependence, able to encompass cases of path-dependence without asymptotics, we can say that a dynamical system is path-dependent whenever the trajectories described by two possible realizations do not come arbitrarily close to each other infinitely many times with certainty. If the dynamical system is described by a Markov process (such as a random walk) this statement reduces to the following: the trajectories described by two possible realizations do not cross with certainty.

Path dependence without any asymptotic lock-in is even more likely if one allows the endogenous change of the state space in which the dynamics are nested. This is, after all, the case of many biological, economic and technological phenomena.

In biology the evolution of species is the result of a branching process which often displays alternation of stages of convergence to a (approximately invariant) local fitness landscape followed by stages of temporary permanence in the neighborhood of local maxima until disruption of the equilibrium occurs and a new pattern of convergence towards a different fitness peaks along a reshaped fitness landscape takes place. Simulation of the NKC model with local interactions [see Kauffman and Johnsen (1991)] gives an easy way to visualize this process. If interactions are local, for every single species there is an alternation of stages of landscape stability and instability due to mutation of the interacting species. The ruggedness of the global landscape (that is the landscape referred to the whole bundle of genes, independently of their species), may generate rapidly diffusing "avalanches" of change, even after mutation of only one species. Representing graphically the spatial structure of interactions, regions of mutating species and regions of species in a "resting" state can be observed[17].

The economics of innovation and diffusion of technologies is full of examples of apparent convergence to a dominant technology, intertwined with the arrival in the longer term of a new one which displaces the old, etc... For instance the competition between the bloomery and the puddle steel production processes, leading to the dominance of the latter around mid-nineteenth century, was disrupted by the introduction (around 1860), and subsequent dominance of the Bessemer and later open hearth processes, followed by the introduction of two new competitors (electric and oxygen processes) during the second half of the twentieth century [Nakicenovic and Gruebler (1991), Gruebler (1991)]. Such dynamics can be interpreted in terms of the theory of dominant designs [Abernathy and Utterback (1978), Anderson and Tushman (1990), and Henderson and Clark (1990); see Tushman and Murmann (1998) for a comprehensive survey of the literature], or, almost equivalently, in terms of technological paradigms yielding relatively ordered technological trajectories of more incremental change [Dosi (1982, 1988)].

Whatever interpretative lenses are chosen, however, the path-dependence of such processes of innovation and diffusion entail some more subtle questions. At one extreme one could argue that the whole pattern of emergence of a paradigm or design, its diffusion, dominance, time-consuming displacement by a new one, etc..., is in fact a story of the successive discovery and establishment of knowledge bases and products which are "objectively better" -

[17] See Kauffman and Johnsen (1991), figure 7.

on some technological and economic measures - of the one they are displacing and of any other one which could compete with them at that particular time. Hence of course irreversibility, but not much path-dependence. Were it not for the persistent arrival of new (and superior) paradigms the system would indeed lock into an asymptotic state, and it would do so independently of initial conditions and/or early stochastic fluctuations. In the language above, for any state of technological knowledge the system displays a single peaked landscape.

Conversely, at the opposite extreme, a few scholars claim an overwhelming driving role to history - especially in the form of social and political factors -. A good summary of this view (indeed still far from more radical "social constructionists") is by Tushman and Murmann (1998) who suggest that

> [...] dominant designs are not driven by technical or economic superiority, but by sociopolitical/institutional processes of compromise and accomodation between communities of interest moderated by economic and technical constraints. The more complex the product, the more accentuated these institutional forces intrude in the emergence of a dominant design [Tushman and Murmann (1998)].

In our earlier language, that implies evolutionary process over landscapes which - at least in terms of technical efficiency - are for a good portion flat and, thus, lock or de-lock as a result of individual and collective wills and politics.

The view we tentatively suggest here does indeed share with the latter the appreciation of the importance of social factors in the selection among notionally alternative technological paradigms and archetypical artifacts, *when such alternative exists, and especially in the early history of a technology* (what in Dosi (1982) is called the pre-paradigmatic phase). Here in our view is where path-dependence primarily rests. Seen from the symmetric angle of social discretionality in governing the future course of events, it is the phase of early emergence of new technological paradigms which provides the primary "window of opportunity" - as David (1987) and Perez and Soete (1988) puts it - for social governance and choice.

However, we do share with the former view, first, the idea that often technical constraints might be overwhelmingly binding (that is, caricaturally, to repeat again a famous sentence by Keith Pavitt "we would never want to fly on an airplane that is only a social construction!"). Second, irrespectively of the drivers in the early process of selection (and also of the long-term notional opportunities of technologies which could have been but have not been chosen), we believe that technological learning does indeed display local (paradigm-specific) dynamic increasing returns to knowledge accumulation. Hence, as time goes by the peaks in the landscape associated with the dominant technologies become higher and higher, so that, most often, major discontinuities are associated with the emergence of radically new knowledge bases (e.g. electricity vs. steam power, semiconductors vs. thermoionic valves, etc...) which radically change the space of exploration for further advancement.

4 Sources of Path-Dependence

As discussed in the foregoing section, some combinations of irreversibilities and non-linearities are the essential determinants of path-dependence. Let us expand upon the factor accounting for these irreversibilities and non-linearities themselves.

In general, at micro level, some irreversibility condition emerges whenever the past irremediably influences the behavioral framework of the agents: for example, their choice set and payoff structures depend upon time and past decisions; their problem-solving competencies, preferences and models of the world changes in history dependent fashion; or, much more trivially, irreversibility just takes the form of an unchanged decision algorithm that agents carry with them since their birth. Note that situations where the decision process of one or many agents is sequential typically generates some kind of irreversibility.

In general, we shall say that there is path-dependency at an individual level whenever history influences irreversibly the choice set and the behavioural algorithms of the agents so that e.g. if the system at some future time, $t+\tau$, is suddenly reversed back to its macroscopic state at t, the microscopic identities and behaviours of the agents would remain irreversibly changed as compared to those present at t.

At system level, irreversibility entails, somewhat loosely speaking, a decreasing probability, as time goes by, of going back to a state that the system visited before or switching over to a state that the system could have attained had it had another history up to that time[18].

[18]More detailed discussions by one of us of these and related issues is in Dosi and

Non-linearities, both at the local and at the global level, stem out of some kind of dynamic increasing returns which puts in play some process of "cumulative causation" in the dynamics. Dynamic increasing returns can emerge on the supply side because of economies of scale, irreversibility of investment, asymmetry of information. More generally, they are likely to be a common property of learning and accumulation of technological capabilities with their typical features of locality and cumulativeness[19]. Widely studied phenomena such as learning-by-doing, learning-by-interacting and learning-by-using all entail positive feedbacks[20].

The dynamical interactions between knowledge accumulation, market expansion, reduction of the (hedonic) price of goods are common features of diffusion processes of particular technologies and dominant designs. and they are indeed what drives specific technological trajectories. As illustrative examples think of the well documented dynamics of information-processing capabilities, speed and prices in microelectronics [Malerba (1987) and Dosi (1984)]. Or, even, at the level of a single (dominant) artifact, consider the case of Boeing 727, 737 and 747, for example, which have been on the jet aircraft market for years, have undergone constant modification of the design and improvement in structural soundness, wing design, payload capacity and engine efficiency as they accumulate airline adoption and hours of flight [Rosenberg (1982)]. Similar observations can be made for many helicopter designs [Saviotti and Trickett (1992)].

Demand side positive feedbacks are equally important. Network esternalities [see, e.g., Katz and Shapiro (1994)] have been receiving much attention in the last two decades. For example, telecommunication devices and networks, as a first approximation, do not tend to provide any utility per se but only as a function of the number of adopters of compatible technologies with whom the communication is possible [more formal analyses of this intuitive property can be found in Rohlfs (1974), Oren and Smith (1981), Economides (1996)]. The benefits accruing to a user of a particular hardware system depend on the availability of software whose quantity and variety may depend

Metcalfe (1991) and Dosi and Kogut (1993).

[19]Quite diverse but complementary empirical and theoretical arguments supporting the "cumulative causation" view, can be found with a large literature, in Myrdal (1957), Kaldor (1981), Zeckhauser (1968), Atkinson and Stiglitz (1969), David (1975), Nelson (1981, 1995), Dosi (1988), Levin et al. (1985, 1987), Antonelli (1995), Stoneman (1995), Arthur (1994), Freeman (1994), Rosenberg (1976).

[20]See Rosenberg (1982), Arrow (1962) and Lundvall (1993).

on the size of the market if there are increasing returns in software production. This is the case of VCRs, microprocessors, hi-fi devices and in general systems made of complementary products which need not be consumed in fixed proportions [Cusumano et al. (1992), Church and Gandal (1993), Katz and Shapiro (1985, 1994)].

More generally, network externalities of some kind (on the demand and/or on the supply side) and the development of commonly shared standards all entail some sort of positive feedback, and, thus also a potential source of path dependence. In this respect , the story of the dominance of the QWERTY keyboard, discussed by David (1975, 1996) is only the most celebrated example. Moreover, on the demand, side all phenomena of endogenous evolution of preferences with social imitation, conformity and bandwagon effects are likely to involve non-linear feedbacks between collective interactions and microbehaviors [, Dosi and Metcalfe (1991), Bernheim (1994), Brock and Durlauf (1995, 1998), Duesenberry (1949), Aversi et al. (1997)].

Another quite general source of positive feedbacks is related to the emergence of social customs, conventions and collectively shared norms. Their development implies also the change in rewards and penalties facing individual decisions and the evolution of cognitive patterns and behavioral algorithms supporting these norms and customs themselves. And with that goes a non-linear self-reinforcing process.

Indeed, as argued by Paul David (1995), *institutions* are one of the fundamental *carriers of history*. In fact they carry history in several ways. First, they carry and inertially reproduce the birthmarks of their origin and tend to persist even beyond the point when the conditions which originally justified their existence, if any, cease to be there. Second, they generally contribute to structure the context wherein the processes of socialization and learning of the agents and their interactions take place: in that sense one could say that institutions contribute to shape the fitness landscapes for individual economic actors and their changes over time[21].

In brief, institutions bring to bear the whole constraining weight of past-history upon the possible scope of discretionary behaviors of individual agents, and relatedly, contribute to determine the set of possible worlds which collective dynamics attain, given the current structure of the system. At the

[21] These telegraphic points are presented in more details in Dosi (1995), and Coriat and Dosi (1998); for germane arguments, Granovetter (1985), Boyer (1996) and Nelson and Sampat (1998).

same time they also represent social technologies of coordination - as Nelson and Sampat (1998) argue: as such , alike technologies *strictu sensu*, they are also a source of path-dependent opportunities for social learning.

5 Levels at Which Path-Dependence May Occur

It should be clear from the foregoing discussion that we believe that path-dependence is a rather common property at different level of observation - ranging from individual behaviors to business organizations all the way to the whole economies -, and within different domains - including technological change, economic growth and institutional dynamics. However it is important to emphasize that there need not be any isomorphism in the degrees of irreversibility and path-dependence across different levels of observation [the issue is discussed at greater length in Dosi and Metcalfe (1991)]. For sake of illustration one may think of two extreme archetypes. In the first one, the behavior of heterogeneous micro entities is trivially path-dependent in the sense that an initial condition (say, their genes at birth) makes them repeat endlessly the same behavioral repertoire (e.g. in the language of game theory, they might deterministically play a single pure strategy). Still, the system dynamics might or might not be path-dependent: This will be determined by the nature of the interactions and the related fitness landscape (cf. above). Indeed, in the simplest case of a selection dynamics on a single-peaked landscape, under relatively weak assumptions, it can be shown that the system converges to the unique evolutionary stable strategy equilibrium[22]. Hence, there is an irreversible system dynamics which however is not path-dependent. Conversely, at the other extreme, one may easily think of systems composed of agents who do not embody any long-lasting effect of their idiosyncratic histories upon their own behavior which nonetheless exhibit strong collective path-dependence.

A conceptually distinct issue regards the aggregate properties of a collection of path-dependent processes. Consider an economy with an increasing number of identical sectors, without intersectoral input/output linkages or intersectoral knowledge spillovers. Even if each sector displays path-dependent dynamics, due to the law of large numbers the limit of that economy exhibit

[22]See e.g. Foster and Young (1990), Fudenberg and Kreps (1993).

ergodic patterns. In this case we are conceptually in the presence of a repeated sample of independent observations drawn from the same population: Whatever the aggregating rule we employ, the asymptotic value of this variable can be known with certainty from the parameters of the model.

Ultimately the properties of the aggregate as compared to the properties of its constituent parts depends on the structure of interactions among the latter. In Bassanini and Dosi (1999) we examine the international diffusion of competing technologies, formalizing the idea that convergence to the same technology or standard depends on the relative weight and strength of international spillovers as compared to nationwide (or regional) esternalities. Aggregate vs. local path-dependence seems therefore to depend on the structure of interactions. When local interactions are strong (i.e. every unit depends on each other with intensity above a certain threshold) path-dependence at local level induces path-dependence at global level. Still, no conclusive results have ever been provided to define a "minimum" interaction threshold below which no path-dependent aggregate outcome is observable.

As an empirical illustration of the point, compare the case of the VCR market with that of computer keyboards. In the former, historically, gaining leadership in the European market, with the consequent bias in the related home video market, was crucial to VHS to resolve in its favor the battle for leadership in the Japanese market as well [Cusumano et al. (1992)]. Keyboards tell a different story: while in all the English-speaking world the QWERTY keyboard represents the standard, in the French-speaking world a slightly different version (the AZERTY keyboard) is by far the more adopted one. Clearly, geographical areas with the same language tend to be reflected in spillover clusters due to free "migration" of typists, similar training institutions, etc....

However, no conclusion can be drawn from the observation of the absence of a global monopoly of a technology about the ergodicity or path-dependence in the worldwide diffusion process. Or putting it another way, what would be the outcome, in terms of world market shares, of running the tape twice? In general, no strong result, to our knowledge, has been achieved on the relationship between structures of interactions and distributions of asymptotic states [a more detailed discussion can be found in Bassanini and Dosi (1998)].

6 Locking Into and Escaping from Path-dependencies

In a nutshell, the thrust of our foregoing argument is that, even confining ourselves to social phenomena, there are some very general sources of path-dependency intimately associated with i) the cumulative characteristics of knowledge accumulation; ii) the nature of organizations (in general, including of course business organizations) with their "epistatic correlations" in behavioural traits, mechanisms of coordination, routines, patterns of organizational learning, etc.; iii) the externalities and dynamic increasing returns which the process of economic growth most often entails; iv) the network of social relations path-dependently constraining and shaping the action sets, decision algorithms and preferences of agents; and more generally: v) the very nature of institutions as "carriers of history".

As such, the ubiquitous presence of path-dependency implies - as argued above - a view of socio-economic phenomena deeply tainted by irreversibility and various forms of "lock-in" into particular organizational structures and/or trajectories of changes. The tape cannot re-run twice (except in the gedankenexperiment of the analyst) and the only one history that actually occurred provides all the constraints, as well as all the opportunities, that social agents face at any particular time.

But "lock-ins" seldom have an absolute nature, and the unfolding of history while closing more or less irremediably opportunities that were available but not seized at some past time is also a source of new "possible worlds" and hence, in some sense, a "window of opportunities" - using again P.David's terminology - which allow "de-locking" and escape from the tyranny of the past.

Some factors operating to this effect have been already discussed, when considering path-dependence without asymptoties.

In particular, *first*, at technological level, the emergence of new technological paradigms, we have seen, do represent a major source of "de-locking", which in turns often involves the emergence of a new se of business actors, a new knowledge base, new communities of practitioners (e.g. scientists, engineers, etc.) and even new forms of corporate organization.

Second, *heterogeneity* among agents and *imperfect adaptation* of agents themselves with organizations and broader social networks do represent a persistent source of variety and in a sense a sort of insurance that the system will never completely lock into a trajectory or behavioural mode (more on this issue in Coriat and Dosi (1998a)). More than that: under some circumstances, non-average behaviours may yield *symmetry breaking* effects on the distribution of traits in the population and yield macroscopic (i.e. system level) transitions (see, among others, Allen (1988)).

Third, the co-evolutionary nature of many processes of socio-economic adaptation is as argued above a source of lock-in but also entail a potential for "de-locking" and major discontinuities. Often, technologies, behavioural traits, organizational forms are selected in multiple landscapes, and according to different criteria of "fitness". For example, as discussed in Dosi and Coriat (1998b), organizational routines are selected both in relation to their problem-solving efficacy and their ability to represent mechanisms of organizational governance and social control. That is, they can been seen as the outcome of adaptation in two different landscapes.

In turn, increasing "mis-adaptation" in one of the multiple domains in which the fitness of routines, technologies etc. are evaluated may entail far-reaching discontinuities and, so to speak, re-open the process of search also for new relatively path-independent combinations.

Finally, *fourth*, entrenched path-dependencies might be broken by "invasions": new organizational forms originally developed in other contexts which spread and become at least for a period, new dominant paradigm. Think, in this respect of the diffusion from the USA throughout the world of the M-form, "Fordist" corporation or more recently, the spreading of Japanese industrial practices, also implying organizational de-locking from older established organizational forms.

7 Conclusions

The attempt of accounting in a thorough and rigorou way for the role of history in soci-economic phenomena is fascinating enterprise which is only at its beginning. However, some lessons can already be drawn also on normative levels.

As B.Arthur, (1989), puts it, path-dependent processes may (although not always do) display properties of (i) sub-optimality (in the sense that other ex ante attainable historical paths would have implied socially superior outcomes); (iii) potential inflexibility (i.e. increasing lock-in, irremediable from the point of view of ex-post discretionary intervention by agents); and ex ante unpredictability.

In such worlds, it is precisely in the phases of early "seeding" and development of path-dependent processes that the scope of discretionary - individual and collective - choices is higher, while later on, the weight of the past history may well bind freedom to rather narrow boundaries. In essence, it is in the subtle relations among path-creations, path-dependencies and the various forms of de-locking mechanisms discussed above that one sees the inevitable tension between freedom and necessity characteristic of many social phenomena. A more detailed, historical and formal, study of path-dependent processes will allow us also to develop sorts of "theories of the possible worlds", defining the notional states which are attainable, given all the weight of an irreversible past, and thus also - paraphrasing March (1991) - determining the scope of what one may explore and what one has to exploit, or just inevitably swallow.

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