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The Grip of History and the Scope for Novelty:
Some Results and Open Questions on Path Dependence in Economic Processes

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The Grip of History and the Scope for Novelty: Some Results and Open Questions on Path Dependence in Economic Processes*

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1 Introduction

The very notion of multiple paths of socio-economic change ultimately rests on the idea that history is an essential part of the interpretation of most socio-economic phenomena one observes at any time and place. The property that *history matters* is also intimately related to that of *time irreversibility*. In the socio-economic domain and in many areas of natural sciences as well, one cannot reverse the arrow of time – even in principle, let alone in practice – and still recover invariant properties of the system under investigation. That is, in a caricature, you may get a lot of steaks out of a cow but you cannot get a cow out of a lot of steaks...

Such ideas of irreversibility and history-dependence are indeed quite intuitive and, as Paul David puts it, "would not excite such attention nor require much explication, were it not for the extended prior investment of intellectual resources in developing economics as an ahistorical system of thought" (David (2001)).[1] However, even after acknowledging that "history matters" – and thus also that many socio-economic phenomena are *path dependent*– challenging questions still remain regarding when and in which fashions it does. In tackling path-dependent phenomena, an intrinsic difficulty rests also

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[1] Indeed, it is difficult to find *purely* ahistorical representations even in mainstream economics, except from some breeds of economic theory such as rational expectations or general equilibrium theories.

in the fact that in social sciences (as well as in biology) one generally observes only one of the many possible histories that some "initial conditions" would have allowed. Moreover, is history-dependence shaped only by initial conditions, however defined? Or does it relate also to irreversible effects of particular unfolding of events? How do socio-economic structures inherited from the past shape and constrain the set of possible evolutionary paths? And finally, what are the factors, if any, which might de-lock socio-economic set-ups from the grip of their past?
In this essay, partly drawing on other works by one of the authors (Dosi and Metcalfe (1991) and Bassanini and Dosi (2001)) we discuss some of these questions.[2] In Section 2 we appraise the potential for path dependences and their sources at different levels of observation and within different domains. Section 3 presents a highly introductory overview of the different modeling tools one is utilizing in order to interpret the history-dependence of an increasing number of socio-economic phenomena. Next, in Section 4, we highlight some results and interpretative challenges concerning some path dependent properties of socio-economic evolution. Finally, in the concluding section we discuss the factors underlying the tension, so to speak, between *freedom* and *necessity* in such evolutionary processes.

2 Sources of path dependence and irreversibilities

One indeed observes many potential causes for path dependence from the micro level all the way to system dynamics. Let us review a few of them.

For our purposes here, we refer to a broad definition of path dependence as dependence of the current realization of a socio-economic process on previous states, up to the very initial conditions.

2.1 Irreversibilities related to the decision-making of individual agents

Start by considering quite orthodox decision settings wherein agents hold invariant choice sets and preferences and are endowed with the appropriate decision algorithms. Suppose however that one of the following holds: (i) decisions are taken sequentially over time; (ii) they reflect uncertainty or

[2]Detailed discussions of some of the issues tackled in this essay are in Arthur (1994), David (1988, 2001), Hodgson (2001), Freeman and Louçã (2001), Witt (2003).

imperfect information. Either of these conditions is sufficient for path dependence, in the sense that past decisions or past beliefs determine present and future decision processes.[3]

Individual learning

More generally, a powerful driver of self-reinforcing dynamics for individual agents or collections of them is any process of *learning*. If agents learn, their behaviours depend, other things being equal, also on their memory of the past, i.e. on initial conditions and on the history of their experience. This is a quite general property which holds irrespectively of the purported degrees of 'rationality' attributed to the agents themselves. So it is easily shown to hold under Bayesian learning whereby agents update expectations on some characteristics of the environment or on each other's features.[4] More so, path dependence applies under a wider class of learning processes whereby agents endogenously change also their "models of the world", i.e. the very interpretative structures through which they process information from the environment (cf. the discussion in Dosi, Marengo and Fagiolo (1996)). In all that, path dependence goes hand in hand with irreversibility: all agents with what they know now would not go back to yesterday's beliefs and actions even under yesterday's circumstances.

Local interactions

In many interactive circumstances one is likely to find that individual decisions are influenced by the decision of other agents, in ways that are not entirely reducible to price mechanisms.[5] One famous example concerns segregation phenomena. Suppose that an individual moves to a certain neighborhood only if at least a good proportion of his neighbors is of his same "kind" (wealth, race, or other). If individuals are influenced by each other's decision in this fashion, homogenous neighborhoods tend to form. Hence, very rapidly, the housing configuration will lock into segregation of the different kinds of agents.[6] Similarly, another example of interdependence of prefer-

[3] Of course, path dependence holds, *a fortiori*, if preferences are themselves endogenous (cf. the discussion in Aversi et al. (1999) and the references therein). In these circumstances past events irreversibly change the decision criteria agents apply even under an invariant choice set and invariant information from the environment.

[4] Within the enormous literature, cf. Hahn (1987), Kreps and Spence (1985), Arthur and Lane (1993).

[5] For interaction-based models cf. Brock and Durlauf (2001a), which reports a variety of empirical examples.

[6] Cf. Schelling (1971).

ences is provided by the way fashions, customs or conventions emerge. It suffices that individuals have some tendency to conform to the behaviour of people around them for a common behaviour to spread within the population of agents.[7]

2.2 Increasing returns

A quite general source of path dependence in allocation processes is associated with the presence of some form of *increasing returns* in production or in the adoption of technologies and products. The basic intuition is that production technologies (or collective preferences) in these circumstances entail *positive feedbacks* of some kind.

Recall for comparison the properties of *decreasing returns*, say, in production: in such a case, less input of something – for an unchanged output– means more input of something else, and, if returns *to scale* are decreasing, inputs have to rise more than proportionally with the scale of output. Conversely, under increasing returns, loosely speaking, "one can get more with (proportionally) less" as a function of the scale of production or of the cumulated volume of production over time. In the economists' jargon increasing returns imply "non-convex technologies".

Non-convex production possibility sets may have different origins. They may stem from sheer physical properties of production plants. For example, in process plants output grows with the volumes of pipes, reaction equipments, etc., while capital costs tend to grow with the surfaces of the latter. Since volumes grow more than proportionally to surfaces, we have here a source of *static* increasing returns. Another example, still of "static" kind, involves indivisibilities for some inputs (for example, minimum scale plants). The point for our purposes here is that under non-convex technologies history is generally not forgotten. The production system may take different paths (or select different equilibria) according to its very history.

The property is indeed magnified if one explictly accounts for the role of information/knowledge "impactedness", of untraded interdependences amongst agents and of *dynamic* increasing returns.

Properties of information

The way information is distributed across different agents in a system, say a market or any other environment that provides the ground for economic

[7]For formal models in different perspectives cf. Bikhachandani et al. (1992), Föllmer (1974), Young (1998).

interactions, together with the very properties of information, contribute to shape the consequences of economic interactions themselves.

As the seminal works of Arrow have highlighted (cf. the overview in Arrow (1974)) information is not an ordinary good which can be treated, say, like a machine tool or a pair of shoes. Shoes wear out as one uses them, while information has typically got a high up-front cost in its generation but can be used repeatedly without decay thereafter. Moreover information typically entails a non-rival use, in that it can be used indifferently by one or one million people. These properties entail decoupling of the costs of generation and the benefits of use of information. One could say that the cost of production of Pythagoras' theorem was entirely born by Pythagoras himself, while all subsequent generations benefited from it for free (except for their efforts to build their own *knowledge* enabling them to understand it).

At the same time, information (and more so knowledge[8]) might be appropriable in the sense that other agents might have significant obstacles to access it, ranging from legal protections, such as patents, all the way to sheer difficulty of fully appreciating what a particular piece of information means. This property exerts an influence opposite to the former ones in terms of incentives to profit-motivated investment in knowledge generation. Increasing returns in use and non-rivalry may produce "under-investment" from the point of view of social usefulness, while conditions for appropriability may provide effective incentives for investment.[9] Together, path dependent learning is influenced by the trade-off between "exploitation" and "exploration" (as March (1991) put it), that is between allocation of efforts to refining and exploiting what one already knows and investment in search for new potentially valuable information and knowledge (and equally important, by the beliefs agents hold about them).

Agglomeration economies

A number of case studies have posed the question of why specific production activities have concentrated in certain areas and not in others. The Silicon Valley and many other local industrial districts whose history is associated

[8]The distinction between the two is discussed in Dosi, Marengo and Fagiolo (1996): see also the references therein.

[9]Incidentally note however that the latter investment might turn out of a socially pernicious kind, trading off relatively small private rents against huge collective losses in knowledge accumulation. The current lamentable legal arrangements on so-called Intellectual Property Rights (IPR) are an excellent case to the point (a sophisticated discussion of IPR is in Arora et al. (2001), while a more sanguine but convincing illustration is presented in Coriat and Orsi (2002)).

also with specific economic and technological activities, provide striking examples of "agglomeration economies". The common story starts from initial settlements and, possibly, some favorable conditions for specific activities. Then decisions to locate similar activities in the same region are re-inforced via (partly) *untraded interdependences* supported by spatial proximity. These may include stronger technological spillovers among producers (even when competitors), access to specialized labour force that tends to concentrate in the area and easier interactions with suppliers.[10]

2.3 Dynamic increasing returns

Technological innovation and diffusion are domains frequently displaying *dynamic increasing returns*, that is non-linear and self-reinforcing processes that occur over time.[11]

The process of accumulation of technological knowledge

The processes of accumulation of technological knowledge typically display dynamic increasing returns: new knowledge cumulatively builds upon past one, and it does so in ways whereby in many circumstances yesterday's advances make today's improvements relatively easier.[12] The cumulativeness of technological learning is enhanced by the property of knowledge – as distinct from sheer information– of being partly tacit, embodied in the skills, cognitive frames and search heuristics of practitioners as well as in the collective practices of organizations.[13]

[10]The wide literature includes a variety of models and explanations that also assign different relevance to the initial conditions: see, among others, Arthur (1994), Krugman (1991a) and (1996), Fujita, Krugman and Venables (1999).

[11]Cf. Dosi (1988) for a detailed discussion of the properties of technological knowledge.

[12]This is not to say of course that some forms of "decreasing returns" never endanger knowledge accumulation. Intuition suggests immediately a few historical cases where technological opportunities appear to progressively shrink. However, at a closer look, what generally happens is that increasing returns may well tend to dry out, but one is still a long way from decreasing returns setting in (that is, more formally, one is basically talking about the properties of second derivatives). This applies even in the case of all those resource-based activities such as agriculture and mining which have been for more than two centuries the menacing reference of the mainstream in the economic discipline.

[13]A partly overlapping idea is that learning is typically *local*, in the sense that what agents learn tends to be "near" what agents already know: cf. the pioneering models by Atkinson and Stiglitz (1969) and David (1975) and within the subsequent literature, Antonelli (1995), among others. All this admittedly involves a highly metaphorical notion of "nearness", since we still fall short of any robust topology, or anything resembling it, in the space of knowledge.

Moreover, as one of us argues elsewhere (Dosi (1982)), technological innovations are often shaped and constrained by particular *technological paradigms* and proceed along equally specific *technological trajectories*. In all that, initial conditions— including the economic and institutional factors influencing the selection amongst alternative would-be paradigms—, as well as possibly small seemingly "random" events, affect which trajectories are actually explored. It is a story that one reconstructs at length in Dosi (1984) in the particular instantiation of silicon-based microelectronics, but it appears in different variants across diverse technologies.
Finally, throughout the whole process of establishment of new paradigms and the more incremental patterns of innovation thereafter, the emergence of networks of producers, suppliers, etc. together with other organizations (universities, technical societies, etc.) institutionalizes and so to speak 'solidifies' specific paths of technological learning.

The adoption of technology

Somewhat symmetrically, on the demand side of technological change, i.e. on the side of consumers and technology-users, a wide theoretical and empirical literature has emphasized the relevance of positive feedbacks: for the seminal explorations of the choice problem among alternative products that embody competing technologies, cf. Arthur (1994) and David (1985). Dynamic increasing returns and externalities appear to be at the core of the explanation of why the pool of users/consumers may select technologically inferior standards simply because that technology was the first to be chosen. Indeed, interpretations such as the foregoing ones place a good deal of path dependence weight, together with initial conditions, on "historical accidents" i.e. more formally on small initial stochastic fluctuations that happen to determine the final outcome for the system. The story of the QWERTY typewriter keyboard is a famous one (David (1985)). The keyboard was introduced in 1868. Alternative, more efficient, keyboards were brought to the market later, but did not succeed in replacing the initial one: QWERTY remained the dominant standard due to the 'lock-in' induced by the complementarity between installed base and specificities in the skills of the users.[14] Many other examples can be found when it comes to so-called "network technologies" for which the issue of compatibility among the differ-

[14]The QWERTY story reports on initial events that may constrain long term outcomes. In a different example, David (1992) vividly reports about the individual role played by Thomas Edison in the early battle to win dominance in electricity supply market and discusses in general the power of intentionality in determining historical paths. See also the discussion in Section 5.

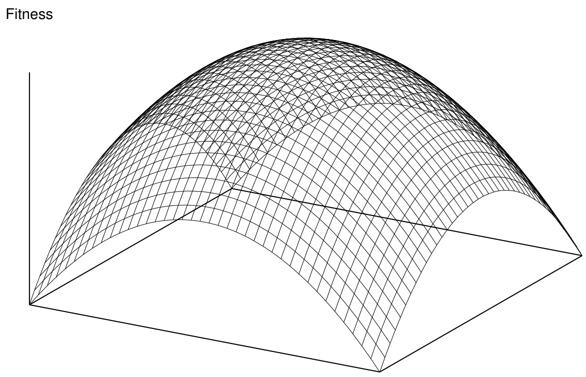

Figure 1: The Fujiyama single-peaked fitness landscape.

ent components of the system is a crucial one (a discussion of some examples is in Bassanini and Dosi (2001)).

2.4 Properties of selection

Selection processes among heterogenous entities, both at the biological and economic levels, are another important source of path dependence. In the economic arena, selection occurs in multiple domains, concerning e.g. products (and indirectly firms) on product markets; firms, directly, on financial markets; technologies, indirectly through the foregoing processes and directly via the social dynamics of inter-technology competition.[15] In fact selection processes may entail multiplicity of outcomes for the system[16] if different *traits* (or maybe, *genes*, in biology) – i.e. idiosyncratic characteristics of the composing entities of any agent –, contribute in interrelated ways to the *fitness* (in biological terms) or to the *competitiveness* (in economic terms) of agents. This happens for example when there are complementarities between specific characteristics.

One way to represent the relationship between traits and fitness is in

[15] One of the formal representations of such competitive processes is through so-called replicator dynamics: cf. Metcalfe (1998), Silverberg (1988), Young (1998), Weibull (1995), and the pioneering Winter (1971) (we offer a basic intuition in the Appendix).

[16] Using the terminology that will be more formally defined in the next section we can define this property in terms of "multiplicity of equilibria".

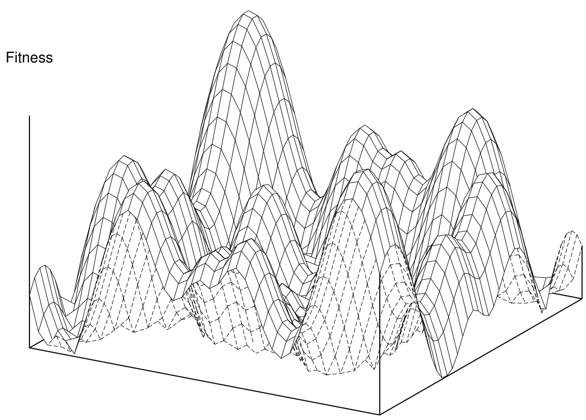

Figure 2: A fitness landscape with several local maxima peaks (Schwefel's function) .

terms of *fitness landscapes*.

When the fitness contribution of every trait or gene is independent, the fitness landscape looks like a so-called *Fujiyama single-peaked landscape* (see Figure 1). Under the assumptions that higher fitness corresponds to evolutionary advantage in the selection process and that the biological or economic agents adapt in a fixed environment, then the system converges to the single maximum peak whatever the rule of adaptation and whatever the initial condition.[17]

However, as soon as the fitness contributions of some traits depend on the contributions of other traits, i.e. *epistatic correlations* appear, then the fitness landscape becomes *rugged* and *multi-peaked*. In this case the initial positions in the landscape and the adaptation rules that underly the movement of individual entities in the landscape together determine which (local) peaks are going to be attained by the system.[18]

[17]Even in this case, things might not be so simple. For example, the irrelevance-of-initial-conditions property may well turn out to rest on very demanding assumptions, including the presence of the 'best' combination of traits from the very start and its survival throughout the ('disequilibrium') process of adaptation/selection. For an insightful discussion cf. Winter (1975).

[18]A general introduction to 'rugged landscape' formalizations is in Kauffman (1989).

2.5 The nature of corporate organizations

Organizations typically compete on a rugged landscape because of complementarities in the organizational components that contribute to their "fitness" (or "competitiveness"). Adaptation over rugged competitive landscapes may often yield lock-ins into different fitness peaks. And, indeed, interrelated technological and behavioural traits are likely to be a primary cause of the path dependent reproduction of organizational arrangements (Marengo (1996), Levinthal (2000)).

More generally, an interpretatively challenging view of economic organizations (*in primis* business firms) depicts them as *history-shaped behavioural entities*, carriers of both specific problem-solving knowledge and of specific coordination arrangements amongst multiple organizational members holding (potentially) conflicting interests.

Individual organizations carry specific ways of solving problems which are often hard to replicate also because they have a strong tacit and partly collective component. Organizational knowledge is stored to a significant extent in the organization's *routines*[19], that is in the operating procedures and rules that firms enact while handling their problem-solving tasks. Relatedly, the accumulation of technological and organizational knowledge is, to a good degree, idiosyncratic and cumulative.

Business organizations may be viewed as entities which *imperfectly* evolve mutually consistent norms of incentive-compatible behaviours and learning patterns.

Together, (i) the complexity (and non stationarity) of the environments in which firms operate; (ii) multiple 'epistatic correlations' amongst behavioural and technological traits; and (iii) significant lags between organizational actions and environmental performance-revealing feedbacks, all contribute to render utterly opaque the link between what firms do and the ways they are selectively rewarded in the markets where they operate. After all, 'epistatic correlations' on the problem-solving side blur straightforward attributions of blames and credits ("...was it the R&D department that delivered the wrong template in the first place, or did the production department mess it up along the way?..."). And so do far less than perfect spectacles interpreting environmental signals ("...are we selling a lot, notwithstanding some temporary fall in profitability, precisely because we are on the winning track, or just because we badly forgot the relation between prices and costs...?"). In these circumstances path dependence is likely to be fueled by both behavioural ('procedural') and 'cognitive' forms of inertia.

[19] Cf. Nelson and Winter (1982), Cohen et al. (1996), Coriat and Dosi (1998a), Dosi, Nelson and Winter (2000), among others.

This is also another aspect of the fundamental "exploitation/exploration" dilemma mentioned above. Within uncertain, ill-understood, changing environments, reasonably favorable environmental feedbacks are likely to reinforce the reproduction of incumbent organizational arrangements and behaviours, irrespectively of whether they are notionally "optimal" or not.

2.6 Institutions

In fact these latter properties are part of a more general point which applies to many other formal organizations, in addition to business firms – e.g. public agencies, trade unions, etc. – and to many institutional arrangements including ethical codes, 'habits of thoughts', etc.[20] As argued by David (1994), *institutions* are one of the fundamental *carriers of history.* They carry history in several ways. First, they carry and inertially reproduce the architectural birth-marks 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 this sense, one could say that institutions contribute to shape the very fitness landscapes for individual economic actors and their change over time. Third, at least as important, they tend to reproduce the *collective perceptions and expectations*, even when their mappings into the "true" landscapes are fuzzy at best. At the same time, fourth, institutions also represent social technologies of coordination: as argued by Nelson and Sampat (2001), they are a source of (path dependent) opportunities for social learning.

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

Such path-dependent properties are indeed magnified by the widespread *complementarities* amongst different institutions which make up the socio-economic fabric of particular countries: cf. the evidence and interpretations put forward from different angles, including "institutionalist" political economy (Hollingsworth and Boyer (1997), Hall and Soskice (2001), Streeck and Yamamura (2001)), game-theoretic inspired institutional comparisons (Aoki (2001)) and historical institutionalism (North (1990)). A thorough discus-

[20]More detailed discussions of the nature of "institutions" by one of us are in Dosi (1995) and Coriat and Dosi (1998b).

sion of political institutions is in Pierson (2000) who has recently argued that politics is characterized by a prevalence of specific ("political") versions of increasing returns. The major roots are traced, among others, in the collective nature of politics (making for the political equivalent of network externalities), in the complexity of political institutions and in the possibility of using political authority to enhance asymmetries of power. All this, together with the usually short time horizon of political actors and the inertia of political institutions, makes the cost of reversing a specific course of events particularly high, and thus tends to induce widespread lock-in phenomena.

To repeat, complementarities generally induce "rugged" selection landscapes. So, at this level of analysis, there is no unequivocal measure of any particular mode of organization of e.g. labour markets or financial markets or State/business firm relations...
Revealed performances depend on the degrees of complementarity between them. But the other side of the same coin is the frequent presence of "local maxima" in the admittedly rather metaphorical space of institutional arrangements where countries path-dependently converge.

Take an example among many and consider the institutional arrangements governing national systems of innovation and production. A recent literature has rather convincingly argued that they are major ingredients in shaping growth patterns of different countries and their specialization in international trade (Lundvall (1992), Nelson (1993), Archibugi et al. (1999)). Moreover, an enormous literature, involving sociology, political science and the political economy of growth, has powerfully emphasized the inertial and self-sustained reproduction of institutions and organizational forms as determinants of specific growth patterns of different nations, showing variegated patterns of "catching up, falling behind and forging ahead".[21] Still, political and institutional lock-ins are 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. So, even when looking at growth performances across countries, recent history has shown the rise of new (sometimes unlikely) actors in the international economic scene as well as the decline of seemingly unlikely others.

Indeed, secular comparisons between the fates of e.g. the UK, Germany, and the USA; Russia and Japan; Argentina and Korea; etc., entail major challenges to the analysts irrespectively of their theoretical inclinations. So, for example, while there is hardly any evidence on long-term convergence patterns in e.g. technological capabilities, labour productivities, per

[21]For some stylized facts, cf. Abramovitz (1986), Dosi, Freeman and Fabiani (1994) and Meliciani (2001), among others.

capita incomes, etc., equally, there is no easy story on the "drivers of convergence/divergence" that may be mindlessly applied across different countries. "History" – both economic and institutional –, in our view, most likely matters a lot. But it does so in ways that certainly go well beyond any naive "initial condition" hypothesis. For example, Korea in the late 40's had educational levels, (population-normalized) capital stock, etc., comparable to the poorest countries in the world and certainly of orders of magnitude worse than Argentina, but also of India. Given that, what are the differences in the socio-economic processes and in their forms of institutional embeddedness, if any, which account for such striking differences in revealed performances?

2.7 From micro behaviours to system dynamics, and back

In this section we have tried to flag out a few of the very many likely sources of history- (or, equivalently, in our jargon here, path-) dependence. Some of them straightforwardly pertain to the dynamics of individual agents and, more metaphorically, individual organizations. Conversely, other properties have to do with *system dynamics*, i.e. they concern some properties of the dynamics of *collections of interacting agents*.

The relationship between the two levels of observation however turns out to be a tricky one. Admittedly, economists still do not know a great deal about all that. Two relatively robust properties appear however to stand out.

First, system dynamics is generally shaped by the characteristics, beliefs, expectations of micro actors, even when such beliefs are evidently at odds with any reasonable account of the environment wherein agents operate. Hence, there is often ample room for "self-fulfilling" expectations and behaviours, obviously entailing multiple *expectation-driven* equilibria or dynamic paths. A good case to the point is the wide literature on "sunspot equilibria".[22] The punchline is the following. Suppose some agents in the system hold the view that some "weird" variables (e.g. sunspots or, for that matter, patterns in beauty contest winners or football scores, etc.) bear lasting influences on economic dynamics. What will happen to the dynamics of the system itself? The answer (obviously overlooking here a lot of nuances) is that the dynamics, or analogously, the equilibrium selection will most often depend upon the distribution of beliefs themselves, no matter how "crazy" they are.

[22] The original reference is Cass and Shell (1983); for a recent survey cf. Benhabib and Farmer (1999).

A *second* robust result concerns aggregation and the general lack of isomorphism between micro- and system-level behaviours. So, for example, distributions of stationary ("routinized") micro rules may well engender an apparently history-dependent dynamics as a sheer result of statistical aggregation over a multiplicity of agents (Forni and Lippi (1997)). In a similar vein, seemingly "well behaved" relations among aggregate variables – e.g between prices and quantities – are shown to be the outcome of sheer aggregation over heterogenous, budget-constrained, agents (Hildenbrand (1994)).

For our purposes here, these latter properties imply also that one may conceive different combinations between "flexible", reversible, micro behaviours and powerful system-level path dependences, and vice versa (one proposes a taxonomy in Dosi and Metcalfe (1991)).

Last but not least, note that one ought to account for the importance of *macro-foundations* of micro behaviours. Collective norms, institutions, shared habits of thoughts, etc. have a paramount importance in shaping micro "mental models", preferences and behavioural patterns: in that, all history frozen in incumbent institutions exerts its self-reproducing effects.

3 Theoretical representations of path dependent processes

In the history of the economic discipline one finds lucid early accounts of path dependent increasing returns. Adam Smith's story on the "pin factory" is a famous one. In brief, the efficiency of pin production grows with the division of labour, the degrees of mechanization of production and the development of specialized machinery, which in turn depend on the extent of the market, which in turn grows with production efficiency....

Indeed throughout the last two centuries a few seminal contributions have addressed positive feedback processes in knowledge accumulation and economic growth.[23] (Recall also that, as already noted, increasing returns are not necessary for the occurrence of path dependence.[24]) Nonetheless, it is fair to say that increasing returns *and* path dependence have been stubbornly marginalized by the mainstream of economic theory for reasons that is impossible to discuss here.[25] At the same time, a facilitating condition for

[23]Outstanding examples include A. Young, N. Kaldor and G. Myrdal. See the discussion in Arthur (1994), chapter 1.

[24]Cf. the thorough discussions in David (1988, 1993, 2001). Moreover, in Bassanini and Dosi (2001) one shows that under certain conditions increasing returns are neither sufficient for path dependence (see also below, Section 5).

[25]On different facets of the epistemology of a paradigm which, for a long time, has

such a lamentable state of affairs has been for long time the lack of formal instruments accounting for path dependent processes. However, things have recently changed in this latter respect.

3.1 Formal tools

A set of powerful formal results in mathematical modeling tools has provided new ways of representing both non-linear deterministic dynamics and stochastic ones. Let us provide here a brief, very simple, overview of some helpful formal tools.

Nonlinear dynamics and chaos

Suppose one can represent system dynamics through a *transition function* f that determines the value of the variable at time $t+1$ in relation to its value at time t:

$$x_{t+1} = f(x_t) \tag{1}$$

Define a *steady state* as a point x^* for which $x^* = f(x^*)$, i.e. a point where the system settles. If the transition function is linear, there exists only one steady state (whether stable or unstable). Multiplicity of steady states occurs as soon as the transition function presents non linearities (an example is shown in Figure 3). In a deterministic setting, the steady state to which the system will eventually converge is going to be determined solely by initial conditions. An important property of this system is its full predictability. Given the initial condition and the transition function, one in principle knows the final state to which the system will get and also the exact path followed to reach it.

The growing understanding of the properties of non-linear dynamic systems has brought new insights and tools of analysis.[26] Moreover, as widely shown in fields like physics, chemistry and molecular biology, non-linear processes can result in "self-organization" of systems as a far-from-equilibrium property. Highly complex behaviours can arise even with very simple transition functions, the best known example being the logistic function. Such systems however may be highly sensitive to small disturbances in initial conditions and display a multiplicity of patterns in their long-term behaviour. Arbitrarily small initial differences can result in cumulatively increasing differences

stubbornly focused on the properties of history-independent equilibria, cf. Freeman and Louçã (2001), Hodgson (2001) and Nau and Schefold (2002).

[26] Cf. Brock and Malliaris (1989), Haken (1981), Prigogine (1980), Prigogine and Stengers (1984), Rosser (1991).

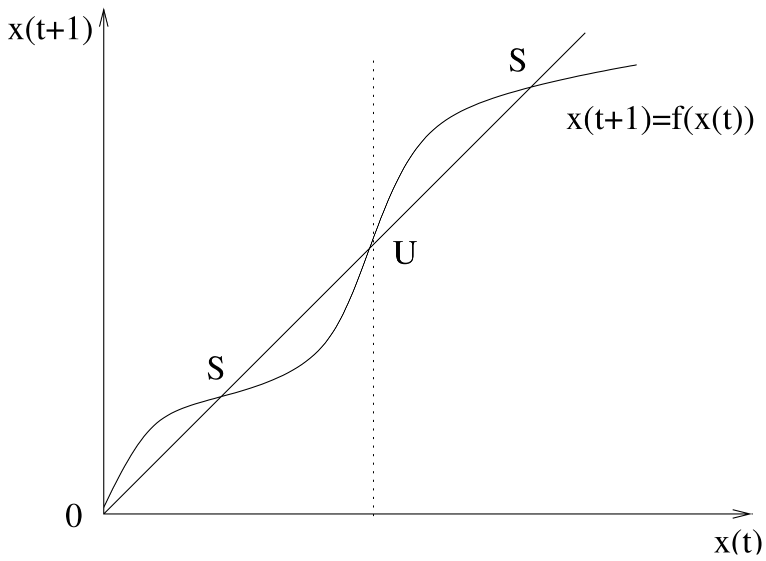

Figure 3: A non-linear transition function that implies multiple steady states. Stable and unstable steady states are indicated with S and U, respectively.

in the historical trajectories *via* self-reinforcing dynamics. The best known examples are *chaotic* dynamics.
A definition of chaos rests on the sensitive dependence of the underlying dynamical systems on initial conditions, in the sense that arbitrarily small differences lead to increasingly divergent paths in the system dynamics. Hence, chaotic patterns are those whereby the path of the dynamical system is fully unpredictable in the long term, yet with a characteristic structure that differentiates it from a purely casual behaviour and allows short term predictability.

Stochastic processes

A distinct potential source of path dependence in the dynamics relates to the impact of *ex-ante* unpredictable shocks occurring throughout the process. The property is captured by various types of stochastic models, possibly with time-dependence or state-dependence of probability distributions of shocks themselves.[27]
David (2001) provides two complementary definitions of path dependent pro-

[27]A good deal of the formal tools can already be found in classics such as Feller (1971) and Cox and Miller (1965). However their economic application (with some significant refinements) is a more recent phenomenon.

cesses, namely:

> "*A negative definition:* Processes that are non-ergodic, and thus unable to shake free of their history, are said to yield path dependent outcomes.
> ... *A positive definition:* A path dependent stochastic process is one whose asymptotic distribution evolves as a consequence (function of) the process' own history." (David (2001))

The key concept here is that of *ergodicity*. Intuitively, a process is ergodic if in the limit its underlying distribution is not affected by events happened "along the way" (we provide a more formal definition in the Appendix). This means that in the long run, initial history does not affect the likelihood of the different possible states in which the system may end up. The opposite applies to *non-ergodicity*.

In the theory of stochastic processes, *Markov processes* provide a sort of benchmark for analysis. In a canonic Markov process the "transition probabilities" that define the dynamics of the system depend only on the current state of the system, regardless of the whole history of previously visited states. Think of the simple case of a "random walk", which can be thought to describe the motion of a particle along a line. The particle can either jump up or down, with respective probabilities p and q. These transition probabilities characterize the motion from t to $t + 1$ and only look at one time step, irrespectively to the previous positions occupied by the particle.[28] Conversely, history of previous events is relevant in non-Markovian processes, which have been exploited to model path-dependent economic phenomena. We provide two illustrative examples that also relate to previously discussed sources of path dependence.

The first example concerns *Polya urn processes.*[29] Arthur et al. (1983) have utilized them to model increasing returns in adoption of alternative technologies when the incentive to adopt each technology depends on the number of previous adopters. The setting involves an urn containing balls of different colors. Basically, one can think of different colors as alternative technologies. Each agent draws a ball and then inserts a ball of the same color back in the urn. Then every time that a technology is chosen, the probability that the same technology is chosen at the next time step increases. One can then prove that under rather general conditions the limit state of the system is the dominance of one of the technologies. Being the limit state an absorbing

[28] An important feature is however worth mentioning: even for the simplest random walk the state at time t embodies the full memory of all shocks which drove it from its very beginning.

[29] See the appendix for some formal definitions and results.

one, this formally defines a process of lock-in in one technological monopoly. The second example is provided by the so-called *voter model*.[30] The model entails random local interactions between agents in a finite population. The basic idea is that agents vote depending on the voting frequencies of their "neighbours". In one and two dimensional spaces, it can be proved that the system clusters into an homogenous setting where agents all vote for the same party. Local positive feedbacks represent the key for explaining locking in this irreversible state. At the same time, initial conditions and the particular unfolding of micro-choices determine which of the states is attained within any one "history" (David (2001) discusses the socio-economic importance of the model).

4 Understanding path dependence in economic evolution: some results and challenges

The foregoing examples of formal modeling of path dependent economic processes ought to be taken as promising even if still rather rudimentary attempts to grasp some fundamental properties of economic dynamics. They certainly fall short of any thorough account of socio-economic evolution (compare for example the 'grand' evolutionary research program as outlined in Dosi and Winter (2002) which in turn builds upon the seminal Nelson and Winter (1982)). However, they already offer precious insights, and together, interesting interpretative puzzles.

4.1 Degrees of history dependence and their detection

David (2001) offers the following categorization of the degree of "historicity", i.e. of the strength of the influence of the past in economic dynamics:

> "*weak history* goes so far as to recognize "time's arrow" (the rooted sense of difference between past and present)...;
> *moderate to mild history* acknowledges that instantaneous transitions between discrete states have high and possibly infinite adjustment costs, so that it would take time and a sequence of motions to attain a terminal state (family size, capital stock, reputation, educational or skill level)– whence we have the notion of a dynamic path being an object of choice;
> *strong history* recognizes that some dynamical systems satisfy

[30] For details, cf. the original model Holley and Liggett (1975) and Liggett (1999).

> the conditions for path dependence of outcomes, or of transition probabilities and asymptotic distributions of outcomes. " (David (2001), italics added)

Within the broad class of processes displaying *some* forms of history dependence, *how much* does history actually matter? Which one of the foregoing 'degrees of historicity' apply to which phenomena?

In order to address such questions, a major methodological issue immediately springs up. Social scientists (to repeat, as well as biologists) most often observe just one historical path. When very lucky, evolutionary biologists neatly catch – as Darwin was able to do – just some independent (on biological scales, rather short) branches of the same evolutionary process. Social scientists find it even harder to observe and compare alternative sample paths. Hence, how can one be sure that what one seemingly detects in the actual history was not the only feasible path given the system constraints?

For sure, anthropologists have a rich comparative evidence, but it is very hard to bring it to bear on the issues of path dependence discussed here. A comparatively more modest, albeit still daunting, task concerns the analysis of technological and institutional dynamics within the domain of modern, mostly 'capitalist', history. Have they been the only feasible paths given the system constraints? Or, conversely, can one think of other dynamics – notionally feasible on the grounds of initial conditions – whose exploration has been ruled out by any actual sequence of events?

Even more specifically, why have historically observed technologies been chosen? Were they "intrinsically" better in ways increasingly transparent to the involved actors? Or, conversely, did they become dominant as a result of multiple (mistake ridden) micro decisions, piecemeal adjustments, co-emergence of institutional structures, etc. – irrespectively of the presence of notionally "superior", relatively unexplored activities? (Of course similar questions apply to the emergence and persistence of particular institutions, forms of corporate organizations, etc.)

Competing answers to this type of questions and competing methodologies of investigation clearly fold together.

At one extreme, a style of interpretation focuses on the final outcome of whatever process, and – when faced with notional, seemingly "better" alternatives – it tries to evaluate the "remediability" of the *status quo*. Under high or prohibitive remediation costs and in absence of striking "irrationalities" along the past decisions history, one next declares the absence of path dependence. This extreme view tries to justify and explain any end-state of the system as being the best possible outcome given the (perceived) constraints by imperfectly informed but fully 'rational' agents along the whole path. The

view, emphatically illustrated in Liebowitz and Margolis (1990) and (1995)[31] basically aims at rationalizing whatever one observes as an equilibrium and, at the same time, at attributing rational purposefulness to all actions which led to any present state.
On all that, David (2001) and Dosi (1997) coincide in the skepticism about any Panglossian interpretations of history as "the best which could have happened", mainly "proved" by the argument that "rational agents" would not have allowed anything short of the optimal to happen (compared with Voltaire's *Candide* on the virtues of Divine Providence).
Conversely, a distinct perspective rather bravely tries to face the *challenge of counter-factuals* ("...what would have happened if..."): hence it focuses on the actual thread of events, on the possible amplification mechanisms linking them, and together, on the (varying) potential leverage that individuals and collective actors retain of influencing selection amongst future evolutionary paths.
A good part of such exercises is inevitably "qualitative", based on case studies, circumstantial comparisons across firms and countries displaying different evolutionary patterns, etc.[32] However, complementary investigations address some path dependent properties on more quantitative grounds, concerning, e.g. real and financial time series.

A complementary task: detecting non-linearities

Early examples of statistical tools devised for detecting forms of path dependence are those trying to detect chaos. While *chaos* can be easily obtained out of economic models, not much supporting evidence has been collected so far. Limitedly to high-frequency financial time series, there is some evidence of chaotic behaviour,[33] but there is hardly evidence for other economic series.[34] Brock et al. (1991) formally test for chaos in a number of economic and financial datasets. This is done by applying the "BDS" test, presented in Brock et al. (1996) in order to detect low-dimensional chaos. At the same time, as Brock (1993) himself critically discusses "...chaos is a very special species of nonlinearity..."; so that it is misleading "...to conclude that weak evidence for chaos implies weak evidence for non linearity." (p.7).
Moreover, note that the apparent linearity/predictability/lack of path depen-

[31] For critical assessment see David (2001) and Dosi (1997).

[32] An interesting exercise, involving a few respected historians is Cowley (1999).

[33] For a survey of the literature on chaos in macroeconomics and finance see LeBaron (1994), and previously Kelsey (1988).

[34] A more optimistic view on the pertenance of chaotic dynamics for economic phenomena is in Chen (1993, 2003).

dence on some time scale does not rule out "deeper", possibly "slower" path dependent dynamics. So, for example, under conditions resembling what in biology are called "punctuated equilibria"(Elredge and Gould (1972)) phase transitions between apparent steady states might occur infrequently, rather abruptly, unpredictably triggered by particular chains of events,[35] while possibly still leaving linear structures of the time series in the (quasi) equilibrium phases.

4.2 Path dependence in economic evolution

Granted all that, how do such different degrees of path dependence show up in the 'grand' evolutionary interpretation of economic change? The latter, as outlined in much greater detail in Coriat and Dosi (1998a) and Dosi and Winter (2002), entails at the very least as fundamental building blocks:

(i) heterogenous, 'boundedly rational' but innovative agents;

(ii) increasing returns in knowledge accumulation;

(iii) collective selection mechanisms, including of course market interactions;

(iv) multiple forms of social embeddedness of the processes of adaptation, learning and selection.

The late S. Gould has reminded us (originally addressing evolution in the biological domain) that an illuminating angle to interpret evolutionary dynamics is by trying to identify what would remain unchanged if "the tape of evolution would be run twice" (Gould (1977)).

It is indeed a very challenging question for social scientists too.
Needless to say, "running the tape" all over again most likely would change the identities of who is "winning" or "losing"; who survives and who does not; who is getting at the top and who is getting at the bottom of the social ladder. However, this should not come as such a big surprise. After all, it is much more plausible to think of *system-level* path-*independent* or path-dependent equilibria, irrespectively of individual destinies.
Hence, what about system-level dynamics? One must sadly admit that evolutionary arguments have too often been used as *ex post* rationalizations of whatever observed phenomena: again, the general belief is that "explaining

[35] An insightful germane discussion, building on the 'long waves' debate on economic growth' is in Freeman and Louçã (2001).

why something exists" has too often meant showing why in some appropriately defined space "whatever exists is a maximum of something" and this is the reason why it inevitably exists...

Quite a few applications of "evolutionary games" to both economics and biology are dangerously near such an interpretative archetype. And so is a good deal of 'socio-biology' (a bit more of a discussion by one of us in Dosi and Winter (2002)). Admittedly, even relatively sophisticated evolutionary interpretations of economic change tend to overlook the possible history dependence of specific evolutionary paths.

Conversely, a few (mostly qualitative) analyses – already mentioned above – of the properties of national systems of production and innovation and of the "political economy" of growth powerfully hint at underlying path dependencies. And the conjecture is indirectly corroborated by several formal results, from different theoretical fields. They include, as already mentioned, path dependent selection amongst alternative institutional arrangements (Aoki (2001)), models of selection amongst alternative technologies, and also path dependencies in the statistical properties of growth processes of stylized industries and economies – even under unchanged initial conditions – (cf. Winter et al. (2000) and Dosi and Fagiolo (1998)).

Certainly, most of the work of exploration of the possible properties of history dependence in incumbent models of economic evolution still awaits to be done. At the same time, an equally urgent task regards the development of broader interpretative frameworks explicitly addressing *hierarchically nested evolutionary processes*, allowing for e.g. (on average, slowly changing) institutions which in turn structure (on average, faster) dynamics of social adaptation, technological explorations, etc.. (A fascinating template of such an exercise concerning biology is presented in Fontana (2003), this volume.)

4.3 Selected histories might be quite 'bad': the painful acknowledgment of the distinction between interpretative and normative analyses.

"Evolution" as such, both in the biological and socio-economic domains, does generally involve at least "weak to mild" history dependence – in the foregoing definitions –. However, a much trickier question regards the properties of those very evolutionary processes as judged against any normative yardsticks. Does "evolution" entail some notion of "progress" in some appropriately defined space?

As already mentioned, the general notion of history dependence of any socio-economic process is in principle quite separate from any normative evaluation

of the "social quality", however defined, of the outcomes which history happens to choose. As David (2001) argues in detail, one may think of quite a few circumstances easily involving multiple *neutral* equilibria or paths which turn out to be (roughly) equivalent in normative terms. On formal grounds, the original Polya urn example is a good case to the point. The whole set of reals on the interval $[0, 1]$ happens to be fixed points satisfying the condition $f(x) = x$, where x may stand for frequencies of e.g. technologies, behaviours, strategies, organizational forms, etc. and $f(x)$ for the probabilities of their social adoption, without any distinct normative feature attached to them.
Further suggestive examples come from biology hinting at the widespread occurrence of *neutral drifts* in the genotypical space mapping into diverse but fitness-equivalent phenotypical structures.
At the same time, it equally holds that many path-dependent processes do entail the possibility of lock-in into equilibria or paths which are "dominated" in normative terms (i.e. intuitively are "socially worse"), as compared to other notional "better" ones which *could have been explored* given some initial conditions but ultimately turn out to be unreachable under reasonable switching costs at later times[36] (the argument is forcefully presented in Arthur (1994)). In this respect, a few analyses have focused so far upon rather simple cases of choices amongst technologies and social conventions, often highlighting the path dependent properties of the underlying selection processes. However, the relevance of path dependent selection of relatively "bad" institutional set-ups and technologies remains a highly controversial question. One inclination is to depart from any naive notion of evolutionary dynamics leading – notwithstanding painful detours and setbacks – "from worse to better". In many respects such a "progressive" view is shared by a whole spectrum of scholars, ranging from Karl Marx to contemporary neoclassical economists.[37] Empirically, as Nelson (2002) has recently suggested, it may well be that "physical technologies" tend to often display more "hill-climbing" features as compared to "social" technologies, due to our relatively higher ability in the former domain to test hypotheses and codify solutions to the problems at hand. So, for example, while e.g. electricity or antibiotics or vaccines happened to be rather uncontroversial technological advancements, one seldom finds crisp matching examples in the social domain.
Come as it may, history is full of cases of collective dynamics irreversibly

[36]Formally, one can show that asymptotic switching costs may well be infinite, *under dynamic increasing returns* even from an "inferior" to a (notionally) "superior" technology/organizational form, etc.

[37]Indeed, many economists, even among the most sophisticated ones, are inclined to read history as a painstaking process driving – notwithstanding major setbacks – toward market ("capitalist") economies: see for example Hicks (1969).

leading *from better to worse*: in our view, the story of Easter Island vividly depicted in Diamond (1995), far from being an odd outlier, is indeed an archetype of common processes of transitions to worse and worse coordination equilibria. The decadence of many civilizations probably belongs to that same class of collective dynamics: institutions and microbehaviours coevolve in ways such as to yield recurrent transitions to "worse and worse" social arrangements.

5 Locking and de-locking: some conclusions on the tension between freedom and necessity

It follows from our foregoing discussion that two somewhat complementary mechanisms are always at work. On the one hand, specific histories of competence-building, expectation formation, emergence of particular organizational structures, etc. together yield relatively *unique* and hence *heterogenous* micro histories.

On the other hand, broader mechanisms of alignment of individual and organizational decisions, together with convergence to dominant technologies and institutions, tend to reduce such a diversity among agents and bring about relative consistency of behaviours, practices, expectations.

More precisely, mechanisms at the heart of aggregate "coherence" include: (i) social adaptation by individual actors; (ii) the path-dependent reproduction of a multiplicity of institutions governing interactions amongst agents; (iii) selection mechanisms (comprising of course market-selection dynamics). These processes contribute to explain locking into specific "socio-economic paths". But lock-ins seldom have an absolute nature: 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 "windows of opportunities" – using again Paul David's terminology – which allow de-locking and escaping from the past.

Let us outline some of the forces that work as potential factors of "de-locking".

First, a straightforward mechanism of "de-locking" is related to *invasions*. They can be literal ones as it has often happened with past civilizations, and also more metaphorical ones, i.e. the "contamination" with and diffusion of organizational forms, cultural traits, etc. originally developed elsewhere. Sticking just to organizational examples, think of e.g. the worldwide "invasion" of Tayloristic principles of work organization – originally developed in the US, or more recently the diffusion of "Japanese" management practices. *Second*, social adaptation is never complete, at least in modern societies. However, precisely the gap between social norms and prescribed roles, on the one hand, and expectations, "mental models", identities which agents actually hold, on the other, may be an extremely powerful source of "unlocking" dynamics: within an enormous literature, see the fascinating comparative analysis of the riots of obedience and revolt by B.Moore (1978), and also, from the economists' camp, the formal explorations of some implications of "cognitive dissonance" including Akerlof and Dickens (1982) and Kuran (1987, 1991). *Third*, and relatedly, non-average ("deviant") behaviours may well entail, under certain circumstances, what natural scientists call "symmetry breaking" and phase transitions to different collective structures (Allen (1988)).

More generally, *fourth*, a fundamental role in preventing irreversible socio-economic lock-ins is played by various forms of heterogeneity among agents – in terms of e.g. technological competences, behavioural repertoires, strategies, preferences, etc. –.[38]

Fifth, "de-locking" possibilities might be a byproduct of those very mechanisms which tend to induce path dependence in the first place. Indeed many organizational forms, behavioural patterns, etc. tend to be selected over multiple selection domains, possibly characterized by diverse selection criteria. So, for example, as one argues in Coriat and Dosi (1998a), organizational routines entail possibly uneasy compromises between their problem-solving efficacy and their properties in terms of governance of conflicting interests. Complementarity of functions, as discussed above, is likely to induce multiplicity of equilibria and path dependence. However, such equilibria may well be "meta-stable", entailing the possibility of de-locking induced by increased inadequacies in some of the affected domains (i.e. over some "selection landscapes"). A good case to the point is the increasing mismatching between formal hierarchies, incentives and actual decision powers driving toward the collapse of centrally-planned economies (Chavance (1995)).

Finally, *sixth*, a major de-locking force has historically been the emergence of radical technological innovations, new knowledge bases, new sources of technological opportunities (i.e. what one calls in Dosi (1982), new techno-

[38]In fact heterogeneity of agents can help also in explaining why "locking" might not occur: instead one might observe market sharing of different technologies or organizational forms. As shown in Bassanini (1999) and Bassanini and Dosi (2003), convergence to monopoly of a technology, an organizational form, etc. may in fact not occur even under conditions of increasing returns if the degree of heterogeneity of agents is high enough. Similarly Herrendorf et al. (2000) prove that heterogeneity of agents is a condition for avoiding multiple or indeterminate equilibria in GE models.

logical paradigms): on the powers of 'Unbound Prometheus' of technological change cf. the seminal works of Landes (1969), Freeman (1982) and Rosenberg (1976). Ultimately, as we have tried to argue in this essay, human affairs always involve a tension between the tyranny of our collective past and the apparent discretionality of our wills. Admittedly, one is still rather far from getting any robust understanding even of the basic mechanisms underlying this tension. However, it is a fundamental exercise if one wants to handle the uncountable problems of collective action we continously face and try to (imperfectly) shake free of the grip of the past and shape our future.

Appendix

Ergodicity in stochastic processes

Take the family of *Markov processes* as baseline reference for the stochastic processes of interest here. Given the set of possible states in which the system may find itself, one is in general interested in the probability distribution over the states, possibly different at different points in time. For (time invariant) Markov processes:

$$Pr(X_t = y|X_{t-1} = x, ..., X_0 = x_0) = Pr(X_t = y|X_{t-1} = x) = p_{x,y} \qquad (2)$$

i.e. the probability of being in state x at time t conditional on all states visited in the past reduces to the probability conditional only on the state visited in the previous time $t-1$. The probability $p_{x,y}$ is called the transition probability from state x to state y[39] and together with the distribution on the initial states, fully determines the joint (unconditional) probability distribution over the set of possible states. Moreover, one can partition the set of all possible states into *transient* and *recurrent* states depending on the probability that the stochastic process returns to the states after a first visit. A stochastic process is *ergodic* if one can obtain a probability distribution over the recurrent states that in the limit does not depend on the initial state of the system.
Non-Markovian processes do not satisfy condition (2), implying that the whole path of previously visited states is relevant in determining the probability of finding the process in a specific state at any given time.

Polya urn processes

Assume an urn of infinite capacity containing balls of two colors, say, white and black. At every draw a number c of balls of the same color as the drawn ball is added to the urn. (In the generalized urn scheme there are k different ball colors.) If c is greater or equal to one, the process entails positive feedbacks: if a color is drawn once, then the likelihood of drawing that same color at the next time step is higher. If $c = 0$ the process reduces to independent Bernoullian draws, when c is negative the process accounts for negative feedbacks. It can be proved that when $c \geq 1$ such a process converges with probability one to the dominance of one single color of the

[39] Here we take the transition probability to be time-invariant. One could generalize to time-dependent probabilities.

balls. This limit state is *absorbing*, meaning a zero probability of leaving it.[40]
In the case of an urn with two colors, let X_t be the proportion of white balls in the urn at time t. Consider the case when one ball is added into the urn at time steps $t = 1, 2, ...$ The probability that the new ball is white is a function of the share X_t, say $f_t(X_t)$, where $f_t : [0, 1] \rightarrow [0, 1]$. The new ball is then black with probability $1 - f_t(X_t)$.
One can then represent the dynamics of X_t as

$$X_{t+1} = X_t + \tfrac{\xi_t(X_t) - X_t}{t+n} \quad \text{with } t \geq 1 \quad \text{and} \quad X_1 = \tfrac{n_w}{n} \tag{3}$$

where n_w is the proportion of white balls at the initial time and ξ_t are independent random variables with binary outcome defined by

$$\xi_t(X_t) = \begin{cases} 1 & \text{with prob } f_t(X_t) \\ 0 & \text{with prob } 1 - f_t(X_t) \end{cases} \tag{4}$$

$f_t(X_t)$ represents the average of $\xi_t(X_t)$. Call $\psi_t(X_t) = \xi_t - f_t(X_t)$ the difference between $\xi_t(X_t)$ and its mathematical expectation, so that $E[\psi_t(X_t)] = 0$. The we can rewrite Eq. 3 as

$$X_{t+1} = X_t + \tfrac{[f_t(X_t) - X_t] + \psi_t(X_t)}{t+n} \quad (t \geq 1)$$

Under this formulation the realization of the process at time $t + 1$ is given by the realization at time t plus a term with two components. The first component, $f_t(X_t) - X_t$, is a systematic one, the second component is the zero-mean noise $\psi_t(X_t)$. Then the limit points of the sequence X_t have to belong to an appropriately defined set of zeros of the function $f_t(x) - x$ for $x \in [0, 1]$.
The outlined case is indeed the most general one, without conditions on the continuity of the f function. For discussions and formal proofs of the limit results see Arthur et al. (1983), Dosi and Kaniovski (1994), Hill et al. (1980).

Replicator dynamics

Evolutionary theory developed in biology rests on two main elements: (i) perpetual generation of novelty; (ii) selection of 'superior' species, given heterogenous populations.
The original mathematical representation of the selection mechanism via the so-called *replicator dynamics*, is through the Fisher equation (more on economic applications in Metcalfe (1998)). Assume the existence of n types of

[40]For an overview of the state-of-the-art in generalized urn schemes and hints on their economic applications, cf. Dosi and Kaniovski (1994).

entities in the population. Call x_i the fraction of the population of type i and call F_i its fitness. Then the Fisher equation in the linear continuous simplification reads:

$$\dot{x_i} = cx_i[F_i - \bar{F}]$$

where $\bar{F}$ is the weighted fitness average in the population:

$$\bar{F} = \sum_i x_i F_i$$

The way such simple version of the replicator dynamics operates is such that the relative frequency of types with higher-than-average fitness grows, while the proportion of types characterized by below average fitness shrinks. If the fitness measure is constant over time the system is bound to converge to the dominance of the fittest type. More general formulations allow for non linear interactions amongst traits which contribute to overall fitness and for changes of fitness landscapes themselves (cf. Silverberg (1988) for a discussion of various selection models).

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