UNIVERSITY OF OXFORD

Discussion Papers in Economic and Social History

Number 20, November 1997

PATH DEPENDENCE AND THE QUEST FOR HISTORICAL ECONOMICS: *ONE MORE CHORUS OF THE BALLAD OF QWERTY*

PAUL A. DAVID

UNIVERSITY OF OXFORD

Discussion Papers in Economic and Social History

1 Hans-Joachim Voth and Tim Leunig, *Did Smallpox Reduce Height? Stature and the Standard of Living in London, 1770-1873* (Nov. 1995)
2 Liam Brunt, *Turning Water into Wine - New Methods of Calculating Farm Output and New Insights into Rising Crop Yields during the Agricultural Revolution* (Dec. 1995)
3 Avner Offer, *Between the Gift and the Market: the Economy of Regard* (Jan. 1996)
4 Philip Grover, *The Stroudwater Canal Company and Its Role in the Mechanisation of the Gloucestershire Woollen Industry, 1779-1840* (March 1996)
5 Paul A. David, *Real Income and Economic Welfare Growth in the Early Republic or, Another Try at Getting the American Story Straight* (March 1996)
6 Hans-Joachim Voth, *How Long was the Working Day in London in the 1750s? Evidence from the Courtroom* (April 1996)
7 James Foreman-Peck, *'Technological Lock-in' and the Power Source for the Motor Car* (May 1996)
8 Hans-Joachim Voth, *Labour Supply Decisions and Consumer Durables During the Industrial Revolution* (June 1996)
9 Charles Feinstein, *Conjectures and Contrivances: Economic Growth and the Standard of living in Britain During the Industrial Revolution* (July 1996)
10 Wayne Graham, *The Randlord's Bubble: South African Gold Mines and Stock Market Manipulation* (August 1996)
11 Avner Offer, *The American Automobile Frenzy of the 1950s* (Dec. 1996)
12 David M. Engstrom, *The Economic Determinants of Ethnic Segregation in Post-War Britain* (Jan. 1997)
13 Norbert Paddags, *The German Railways - The Economic and Political Feasibility of Fiscal Reforms During the Inflation of the Early 1920s* (Feb. 1997)
14 Cristiano A. Ristuccia, *1935 Sanctions against Italy: Would Coal and Crude Oil have made a Difference?* (March 1997)
15 Tom Nicholas, *Businessmen and Land Purchase in Late Nineteenth Century England* (April 1997)
16 Ed Butchart, *Unemployment and Non-Employment in Interwar Britain* (May 1997)
17 Ilana Krausman Ben-Amos. *Human Bonding: Parents and their Offspring in Early Modern England* (June 1997)
18 Dan H. Andersen and Hans-Joachim Voth, *The Grapes of War: Neutrality and Mediterranean Shipping under the Danish Flag, 1750-1802* (Sept. 1997)
19 Liam Brunt, *Nature or Nurture? Explaining English Wheat Yields in the Agricultural Revolution* (Oct. 1997)
20 Paul A. David, *Path Dependence and the Quest for Historical Economics: One More Chorus of the Ballad Of QWERTY* (Nov. 1997)

Path dependence and the quest for historical economics: one more chorus of the ballad of QWERTY

by

Paul A. David
All Souls College, Oxford & Stanford University

First draft: November 1996
Revised: August 1997
This version: November 1997

ABSTRACT

The term *path dependence* (*PD*) here refers to a dynamic property of allocative processes, pertaining to *non-ergodic stochastic systems* -- those whose asymptotic distributions evolve as a function of the history of the process itself. *PD* is shown to be neither necessary nor sufficient for the existence of 'market failure', although the two properties may arise from common structural features. A variety of stochastic models are *PD* and yet exhibit diverse properties in regard to predictability and 'lock-in.' The taxonomy of path dependence proposed by S. J. Liebowitz and S. E. Margolis (1995), along with the latter's interpretation of 'lock-in' and 'accidents of history' are shown at best to be of limited usefulness in the study historical phenomena, and misleading as to the possible implications of *PD* for economic policy analysis.

Keywords: path dependence, non-ergodicity, lock-in, Polya urn processes, reversible spin systems, sunk cost hysteresis, the economics of QWERTY

JEL Classification: B41, C19, D59, D61, D62, D99, O33, O38

Path dependence and the quest for historical economics: One more chorus of the ballad of QWERTY

0. Overture

A decade after it began to be trendy among economists to say that 'history matters,' there are still some things that are less than entirely clear about the possible meanings attached to that phrase, if indeed it is taken to carry any substantive content at all. For me, at least, the term continues to carry a quite precise set of connotations which are associated closely with the concept of *path dependence* — another bit of phraseology that, unfortunately, has come to be invoked more frequently than it is defined. My purpose in this paper, therefore, is simply that of clarifying the meaning and significance of the term 'path dependence' so that others may better appreciate some of the salient implications for our discipline, and the social sciences more generally, of recovering a conceptualization of change as a process that is *historical*. A task so simple to describe is not necessarily so simple to perform. For one thing, much of the training of the modern economist tends to weaken the trainee's natural, intuitive understanding of historical causation, so that some remedial work is required in addressing an audience, some of whose members' advanced education will have left them incapacitated in this particular way.

To put this in different words, it seems to me that neither those economists who casually assign to the influence of 'history' the things for which their analysis does not adequately account, nor those skeptics who say "Sure, history matters, but not for much," are adequately responding to the challenges posed by the general class of dynamical processes in the economy that generate sequences of causally related *events*. One of the things about 'events' that our everyday experience of change seems to confirm is that they 'happen' — and never 'un-happen.' By contrast with the realities of the world around us, recognition of which forces itself implicitly and often only incompletely into the consciousness of practicing economic advisors, much of formal teaching of economic analysis refers to a very different and special class of dynamical processes in which all motion in the long-run is continuous 'locomotion.' That is to say, we've become accustomed to working with models whose dynamics admit perfect reversibility, and in which change may be said to occur without specific, individual 'events' having any causal significance. To then abandon the learned habits of peering at the world of economics automatically and exclusively from the peculiar vantage point afforded by a certain and now certainly antiquated branch of physics, and to be able therefore to take up another and contrary perspective, cannot be simply a matter of 'un-learning.' Something additional, and for many, something new has to be learned — something which can stand alongside neoclassical economic analysis, and so enhance one's appreciation of the special features that distinguish that paradigm from what can be called *historical economics*.

The 'something' in question is an explicit conceptual framework that both defines and delimits what the term 'path dependence' is about, and indicates the lines along which that alternative paradigm might usefully be further developed in theoretical and empirical research.

My purpose here is to try to present such a framework entirely in verbal terms, without recourse to mathematical notation and making only minimal appeal to concepts formalized in statistical theory.

At the same time, however, I want to avoid overly casual expression of these ideas; indeed, to insist on verbal precision in order to clear away the underbrush of confusions and misapprehensions about many conceptual issues connected with path dependence now found in discussions among economists and economic historians. Navigating an exposition between the reefs of mathematical formalism and the shoals of verbal pedanticism demands a sureness of stylistic skill that I am not always able to command. And so, I recognize there are passages in the following where my commitment to steering clear of the first of those hazards threatens to run readers aground upon the latter. The following text may not be imposing the lowest attainable average cost of rendering the actual meaning (or even my construction) of the notion of path dependence accessible for as many of those employing the term as is possible. But, after laboring at this particular task for some while, it is the best that I am able to offer.

Is there really a need to burden our professional discourse with a non-mathematically 'lite' version of what now sounds like a forbiddingly heavy conceptual apparatus? Surely, the 'historical perspective' is one that should be acquired readily enough from even an introductory acquaintance with the writings of economic historians, and equally, students of the evolution of technologies, firm strategies and industry structures. Perhaps that is so, but it is often difficult to induce general principles from a sampling of disparate cases. More troublesome still, it seems that the analytical substance itself has been the first thing to become obscured by the controversies that have been raised over the details of this or that historical case of "alleged" path dependence — of which more will be heard, anon.

Quite possibility, I will allow, the smoke rising from those small conflagrations in the literature (too many of which have involved little more than the incineration of straw men), has not actually obscured anyone's vision at all. The fundamental notions involved in the concept of history 'mattering' perhaps are quite widely shared and understood; they might be immediately and thoroughly accessible to (almost) everyone who pauses to consider the topic of path dependence and its manifestations in economics. If that is so, then the absence of more formal, explicit presentations of those ideas could signify just that it would be more efficient to let them remain part of the tacit, common knowledge context of discussions that are focused upon empirical and normative issues.

Yet my experience has been otherwise. Many people who express interest in the subject seem hard put to supply a quick definition, let along a clear account of the analytical concepts associated with 'path dependence,'— or, more exactly, an account set out in terms that I can recognize. Remarkably, this is so among many of my 'cliometric' colleagues in economic history, who, I am therefore willing to suppose, may draw some clarification from the present theoretically- and methodologically-oriented discussion of the foundations of 'historical economics.' As for other economists, even those outside 'the mainstream' tradition — or some of its larger tributaries — also show surprising signs of uncertainty in their handling of the subject. Consider this sample passage from a recent paper by Oliver E. Williamson, a major contributor to the economics of industrial organization who has declared

himself more than receptive to 'path dependence,' and who, along with many others, identifies the latter with the proposition that 'history matters':[1]

> Transaction cost economics not only subscribes to the proposition that history matters but relies on that proposition to explain the differential strengths and weaknesses of alternative forms of governance....The benefits that accrue to experience are also testimony to the proposition that history matters....More generally, firm-specific human assets of both spontaneous (e.g. coding) and intentional (e.g. learning) kinds are the product of idiosyncratic experience. The entire institutional environment (laws, rules, conventions, norms, etc.) within which the institutions of governance are embedded is the product of history....That history matters does not, however, imply that only history matters. Intentionality and economizing explain a lot of what is going on out there.

Loathe as I am to reproach any who seek to enter the faith, I am left to wonder at the closing juxtaposition, as it seems to suggest an interpretation of path dependence which maintains that 'history matters' only to the degree that 'intentionality and economizing' do not matter. Now, just what Professor Williamson may have had in mind by the phrase 'intentionality and economizing' is itself a matter for possible interpretive misunderstanding. But if those words refer to purposive, optimizing actions on the part of economic agents, then nothing could be further from the truth than to suppose there is some necessary conflict between admitting the existence (indeed, even the preponderance) of such behaviors and the proposition that the outcome of the agent's interactions will be a path dependent process. It does not take much effort to see this for oneself, but perhaps beginning with a sharper conceptualization of path dependence would make it still easier.

Another possibility, of course, is that those economists most interested in, and already most committed to studying history happen to be those who also are least disposed to spend their time on 'the theory of history.[2] Not implausibly, it is the concrete realities of specific

---

[1] See Williamson (1993: pp. 139ff.), who, along with Douglass North (1991) and Joel Mokyr (1992) embraced the term 'path dependency.' The latter is a variant (or, for those inclined to evolutionary modes of discourse, a 'micro-mutant form') that systematically is 'selected against' throughout these pages — wholly on grammatical grounds. Consulting Brown (1993) for the definition of 'dependency,' one is reminded that the noun describes "a dependent or subordinate thing, *esp.* a country or province controlled by another"; whereas, the same authority holds "dependence" to be "the relation of having existence hanging upon, or conditioned by the existence of something else; the fact of dependency on another thing or person." My terminological preference on this minor point, however, ought not be construed as reflecting an adverse judgement upon the substantive merits of what the abovementioned authors have had to say about path dependence.

[2] The *Theory of History* (New Haven, Yale University Press, 1925) was the third work of a trilogy by John Frederick Teggart. It has been belatedly recognized as a precocious and penetrating analysis of the intellectual roots of the separation between studies of history and the nineteenth century formulation of Darwinian evolution as a continuous, event-less dynamical process — a conceptualization that, in addition to its dubious influence upon the field of evolutionary biology, was seen by Teggart to have led social science theorizing in a paradoxically *ahistorical* direction. See the reprinting of Teggart (1977); Eldridge (1985: esp., pp. 22-28) on its significance for modern evolutionary theory and the concept of 'punctuated equilibria. Further discussion of its bearing on the disciplines of economics and economic history may be found in David (1993:"Historical Economics"). Teggart, it is pleasing to note, received his B.A. degree from Stanford University in 1894. In the year of the publication of *The Theory of History* he became the founding Chair and Professor of the Department of Social Institutions at the University of California at Berkeley, and embarked soon thereafter upon what might be described as an early program in 'cliometrics': the results of his systematic statistical studies of patterns in the occurrence of certain classes of events throughout the continent of Eurasia appeared in Teggart (1939).

circumstances that preoccupy applied economists and the majority of economic historians. They would rather leave it to the theorists to consider the more abstract issues involved in characterizing different path dependent phenomena, analyzing various economic mechanisms that might generate them, and deriving such generic propositions about public policy as might follow from the latter's existence. If such an inclination is what keeps the historically inclined among practicing economists silent on these matters, then it needs to be said that placing such a simple trust in the division of intellectual labor within the discipline of economics is probably a mistake. There is no empirical basis for the presupposition that applied economists who have need of a fully articulated and internally coherent set of theoretical concepts and analytical approaches suitable for the study of *historical* dynamics will have those delivered to them by theorists. Such certainly has not been the course of the development of the discipline over the past hundred years, alas, for which the preeminent position of economics among the social sciences is only a partial consolation. One of the serious continuing problems with the state of economics as a scientific discipline is that theorists manage so much of the time to achieve success by writing for one another; and that the same holds among empirical researchers.

Even though at the moment the prospects for real progress in theoretical investigations of historical systems in economics appear to be unprecedentedly favorable, the worry among those who welcome this development must be that the 'history matters' boom may be little more than a bubble; that it will burst, and that all those clever folk will wander off to find another set of formal problems with which to entertain and challenge one another. To avert such a sad denouement, then, requires the creation of conditions that have been found to hold in the production of technical innovations more generally — namely, intense, mutually informed and sustained 'producer-user' interactions.

My not-so-hidden agenda for this occasion, therefore, is to promote more effective communication between economic theorists and students of historical change, by addressing questions that are primarily analytical rather than empirical; and by restating and elaborating my particular understanding of what the concept of path dependence is about, and how it relates to the larger structure of theoretical apparatus that has been, and continues to be imparted in the training of most economists. For this purpose I regard it to be neither necessary, nor, indeed, particularly helpful to enter deeply into a number of on-going debates that have been concerned with historical instances adduced as exemplifying the workings of path dependence, even though some illustrative references to such cases may usefully be made.

Consequently, it is proper for me at the outset to caution those readers who are hopeful of finding herein some further technical details and narrative material on the evolution of typewriter keyboard layouts. Although they are going to be disappointed on that account, there will be another, more suitable place in which to consider my detailed rejoinders to the dubious factual allegations that have circulated concerning the 'true story' of QWERTY.[3] Futhermore, I have not attempted to provide a detailed commentary that does justice to the many statements and arguments advanced in economics books and journals, and on the Internet, too — by either critics and skeptics, or by defenders of the notion that in (some) important economic processes "history really matters." Nor could these pages pretend to

[3] I refer in this regard to Liebowitz and Margolis's (1990) dismissal of the version of the story of QWERTY presented by David (1985, 1986) as "a specious example of market failure borne in part from insufficiently rigorous examination of the historical record." The historical arguments and evidence offered to support that critique are re-examined in my forthcoming paper:'Neoclassical economists at the keyboard: Is there a cure for 'repetitive thought injuries"?'

conduct anything approaching a comprehensive review of the significant theoretical and methodological contributions that have emerged from many quarters on the topic of path dependence during the past decade.

What is on offer here, instead, is one man's modest attempt to untie, and failing that, to cut away conceptual knots and tangles that seem recurrently to ensnare discussions on the subject of path dependence, and so inhibit many from involving themselves in the further development of historical economics. For me to sort out the principal logical muddles that have arisen from what I regard to be misinterpretations of the term path dependence, it has been necessary to make quite explicit the basis of my disagreements with the conceptual and analytical perspective that has been brought to the subject by the recent publications of Professors Liebowitz and Margolis (1994,1995). Most prominent among the misapprehensions that have emerged in the literature during the past decade, at least to my way of thinking, is the notion that the condition of "path dependence" somehow is responsible for "market failures" which, in turn, result in persisting irremediable inefficiencies in the allocation of resources. Professors Liebowitz and Margolis's frequent writings on this and related matters have done nothing to dispel that supposition. Quite the contrary. They therefore are entitled to whatever form of credit may attach to proper recognition for the contributions they have made — including the unnecessary state of confusion (and, in some circles outright anxiety) produced by this backwards construction of the actual analytical relationships concerning path dependence.

In straightening out that particular tangle, I will show why path dependence is neither a necessary nor a sufficient condition for market failure. But, I shall also try to elucidate the deeper connections that do exist between those two conditions. In other words, it will be shown that there are certain structural characteristics affecting stochastic dynamical processes in the economy that lead the latter to be subject to market failures, and also cause the affected processes to have the property of path dependence. Once those matters are sorted out, the strengths and limitations of the associated concepts of 'historical accident' and 'lock-in' also will come into clearer focus, along with the way in which wider recognition of path dependence should affect the conduct of economic policy analysis. The ensuing discussion is organized in sections which proceed through the sequence just summarized.

Having said this much by way of introduction and declared intentions, it would be unforgivably coy on my part to try to avoid starting where much of the current discussion of path dependence begins. So, I shall approach my task by way of a little intellectual autobiography, a rather personalized account of 'the story of the story of QWERTY.'[4]

1. Historical reprise: Clio, QWERTY and the path to 'path dependence'

Whatever other interests may be awakened by the revelations that are to follow in this section, they should communicate my view that there is an amazing irony of rhetorical success in the inordinate attention that was captured by one specific illustration of the workings of path

[4] This will provide an opportunity to indicate some of the dispersed locations in which my early publications on conceptual and analytical issues relating to path dependence can be found —. in aid of which a comprehensive listing my papers on those topics is given by the bibliographic references at the end of this essay. The latter citations — a selective inventory of debris scattered alongside the trail that led me to "Clio and the Economics of QWERTY" (1985), and from thence to the present — well may be the most generally useful contribution to emerge from the present undertaking.

dependence, and the consequent significance with which debates over its factual details continues to be endowed. QWERTY, the now-popular emblem of path dependence, has acquired associations in the literature that threaten to obscure the very ideas that it was enlisted to impart to the economics profession. It would be implausible for me to avow very great regret in having contributed to that state of affairs. But, I would accept some blame — for offering an illustration that in the hands of others could turn into a proverbial red-herring, ready for dragging across the trail of path dependence. The proviso is that I am allowed to enter a plea of 'mitigating historical circumstances.'

In the Fall of 1984 I was confronted by a rhetorical challenge. I had involved myself in the plans of Professor William Parker (then of the Yale Department of Economics) to stage a session of the upcoming American Economic Association Meetings — on the need for economists to study (some, more) economic history. I duly had been allotted 20 minutes to have a go at this issue myself. What message, compressed into so brief a timespan, would persuade the economist in the street to turn his or her mind to the possibility that history might matter in what they were doing professionally? Getting attention was a first requirement, and so my talk would start out with references to Sex.[5] Seizing the audience's attention was one thing, but how to keep it? One generally reliable tactic of reinforcement suggested itself: the application of a stimulating shock. What is the subject that jolts economists even more than mention of Sex? Inefficiency! So, I would have to produce a story involving an economic process that could not shake loose from the influence of past events, and one in which rational autonomous agents were led to a shared, collective outcome that would judged to be no better for some, and for others definitely worse than a *feasible* alternative. And if that didn't suffice, more "shock" would have to be applied: show that although all the players individually might wish to choose otherwise were they only able to wipe away the past and start again, it was more than likely that they would go on living with their unsatisfactory (Pareto inferior) situation — because of the difficulties or expense of coordinating the actions that would be needed for them to collectively achieve an escape. I do freely admit to having seized upon the history of typewriter (and computer) keyboard layouts as providing me with just such a rhetorical device.

Whatever novelty may be associated with my paper 'Clio and the Economics of QWERTY' resides largely in the surprising audience response, rather than in either the story's ingredients or its challenging message.[6] As I will be at some pains to show, no great originality attaches to the idea of a sequence of economic choices being conditioned at each moment on the situation that had been created by preceding choices, in a way that the system's asymptotic configuration would be dependent upon the details of the path that it had followed. Nor was it unprecedented to allow for the possibility that each action could reinforce the influence of those which preceded it; and, further, that the actors would not necessarily take into account this consequence of their choice behaviors. From those few analytical elements, which had been recognized by economists as theoretical possibilities, and sometime acknowledged to be present in the background of many of the worldly conditions surrounding us, it was an easy matter to fashion a compact illustrative tale about *path dependence*.

---

[5] Although these eventually had to be excised from the brief paper printed in the *American Economic Review* (1985), they survive in the full text published subsequently, see David (1986).

[6] Another minor but possibly significant novelty consists in its being the shortest paper that I had hitherto put into print.

When stories of that genre have to be told to an audience of economists, it is best that the influence of remote historical events should be seen to become magnified and carried forward to the present time by an intervening sequence of *market* configurations. Of course, the circumstances conditioning those events may themselves be of a transient nature, and quite extraneous, or "orthogonal" to the workings of the dynamical market process in which the agents are participating. Moreover, in the particular case instanced, the existence of positive (e.g. network) externalities affecting behavior in the markets for the interrelated choice-objects (typewriters, courses and manuals on touch-typing, typists skills), provided sufficient grounds to vitiate any rigorous theoretical pre-supposition that the competitive price mechanism would invariably deliver an economically efficient allocative outcome. What would eventuate in that regard would be a matter determined by the events of the historical process.

Now, who could have imagined that when these commonplace elements were assembled in the story of QWERTY, the result would appear to some economists as a surprising anomaly, and to some others as a phenomenon of a sort likely to be encountered only in the history of technological change? Ought I have been able to anticipate that still other readers continue to find in this a threatening tale, perceiving QWERTY as a deceptive Trojan horse built to smuggle the idea of the ubiquity of market failure into the citadel of mainstream economics, along with pernicious beliefs about the general necessity of state intervention? Surely the idea of history would admit of generalization by my audience to realms of economic experience beyond the specifics of the history of typewriters, or the more contemporaneous the rivalry between the VHS and the Sony Betamax formats in the market for videocassette recorders?[7] For many it did, of course, but the generality of the argument was grasped only more gradually by quite a few.

No less plainly, the concept of market failure is a commonplace in modern welfare analysis, even though what should be done when there is a likelihood of market failure is another and more complicated "real-world" policy question. The whole point about my choice of the story of QWERTY for the occasion, as I perceived it, was the unproblematic nature of each of its ingredients. In order to get out its message about "the necessity of history" — compare the subtitle selected for David (1986) — before my 20 minutes at the rostrum were over, I need to avoid having to spend time battering down any analytical doors! Perhaps this was a miscalculation.

On the other hand, it is conceivable that the resistance that subsequently emerged was elicited by slowly emerging perceptions of the more far-reaching implications of the message itself. My goals actually were rather more radical than repeating the many previous notices that the economics literature contains regarding the insubstantiality of a Panglossian faith in the workings of private property and decentralized decision-making in response to perfectly competitive market signals. Some economists might quite properly label as subversive my contribution to that session in the Proceedings of the AEA: after all, it did question the claims of general competitive equilibrium analysis to be capable of instructing us about the dynamic workings of actual markets, even about those that would generally be seen as competitive.

That is a style of radicalism that I willingly have embraced. Indeed, ever since taking up the discipline as an undergraduate, I have looked for ways to make economics *an historical*

[7] At the time it was not possible to draw upon the detailed research subsequently undertaken on the history of the standards rivalry in the VCR market, by Rosenbloom and Cusamano (1987), Baba and Imai (1990), Cusamano, Myolandis and Rosenbloom (1992), and Grindley (1995). Otherwise that might have served as still more 'topical' illustration of the point I wished to make for economists at large.

social science, which, manifestly, it has yet to become. Sometime towards the end of the 1960s I had grown increasingly conscious that this was what my work in economic history really ought to be about. The intuitive discomforts I previously had experienced with the *ahistoricism* of formal economic theory were crystallized in my consciousness by Robert W. Fogel's (1964) pathbreaking work on the economic impact of the railroads. I found myself profoundly unsatisfied by that technically brilliant, highly ingenious, but nonetheless misdirected effort to apply only the techniques of neoclassical analysis in quantitatively assessing the role of the railroads in the nineteenth century development of the U.S. economy.[8]

So, from that point onwards I began to be somewhat more explicit on those occasions where I found it compelling to depart from the implicit and explicit suppositions contained in standard neoclassical microeconomics. An unquestioning and unqualified acceptance of that body of theory, I had seen, would render the writing of economic history paradoxically *ahistorical* — an exercise to illustrate the workings of timeless axiomatically derived theorems and laws, but not a tool for understanding economic change. That much I was able to articulate by the mid-1970s, and it shaped the introduction to my book on *Technical Choice, Innovation and Economic Growth* (1975). There, the concept of non-ergodicity, and its relationship to increasing returns and positive-feedback systems of growth in the tradition of Allyn Young (1928), were set out for those who might be interested in pursuing this way of uniting economics and the study of a significant past. The book sold, and even drew an generously appreciative review article from Jeffery Williamson in the *Journal of Political Economy*. No riots ensued. Why such fuss now? This is a good question for future intellectual historians to ponder.

In participating with Professor Parker in the design of that 1984 AEA Meetings session on the need for neophyte economists to learn some economic history, as well as in writing the paper on QWERTY, I returned to the explicit enunciation of my earlier ideas about historicity in economic processes. I did so with a new sense of purpose: to encourage economists to join in studying economic history, not only because the past does "have useful economics" — which D. N. McCloskey (1976) had firmly told the *Journal of Economic Literature*'s readers — but because the inherent subject matter of 'historicity' poses fascinating and difficult theoretical challenges that have remained largely unexplored by our discipline; and, also, because it had begun to appear that those difficulties might yield to some of the new mathematical concepts and techniques that had been fashioned comparatively recently by probability theorists to deal with the statistics of non-ergodic processes. By such tactics, I thought, it might be incidentally possible to reinvigorate or even rescue my chosen field of research from the intellectually moribund condition that was aptly diagnosed by Robert Solow (1986: p.27), when he quipped that the new economic history seemed to be turning into a specialty pursued by neoclassically trained economists "with a high tolerance for dust and possibly — what is rarer these days — a working knowledge of a foreign language."

The same proselytizing impulse prompted me to organize a subsequent session for the 1989 Meetings of the AEA, on "Path Dependence: The Invisible Hand in the Grip of the Past." The participants in that well-attended gathering (selected papers from which found their way into the May 1990 *Proceedings of the AEA*) included W. Brian Arthur, Stephen Durlauf, James Heckman, Paul Krugman, Paul Milgrom and John Roberts, as well as the faithful sympathizer that the enterprise found in Professor Solow. Fortunately, some of the folk

[8] Compare the expression of those discontents in David (1969).

working at the frontiers of economic analysis had not needed to wait to hear from the physical and life sciences about self-organization, complexity, and non-linear dynamics; they had perceived in other ways that the ahistorical nature of neoclassical theory had become a self-imposed limitation upon our discipline that could and should be discarded.[9]

Whatever the reasons that may be found for it by future historians of economic thought, the most encouraging thing that has happened in economics during the past decade — from my present perspective — is that the idea of path dependence has been taken up so widely, and by people working in so many different branches of the discipline. One of the consequences of the wild-fire spread of the term is that 'path dependence' has now acquired many distinct shades of meaning, not all of which are consistent with one another. Like life, its meaning is being searched for and debated in some quarters. Unlike life, however, it has been seen as disturbing, and has thus acquired critics and even opponents. What an advance has thus been made over the lot that history accorded to William Cunningham and allied members of the English Historical School, who were so quietly ignored and quickly marginalized by Alfred Marshall and his followers at Cambridge just a century ago.[10]

Quite possibly the key to this success (at least in engaging the attention of a substantial number of economists) is the absence of anything resembling a school of thought concerned with path dependence. One of the best and most wonderful things about ideas is that everyone who comes into possession of them is free to construe them as they please, and to make something new of them. Essentialism — and debate about the true nature of path dependence — is as likely to be as unproductive in this realm as in others. Path dependence can be given many different interpretations; each will carry its particular logical implications, and suggest its own fields for empirical inquiry. At the same time, there is some chance of greater coordination and specialization in research if commonly accepted meanings can emerge, not unlike *de facto* communications protocols, to assist in the extension of the network of shared inquiry and discourse. This is something that happens in the process of the emergence and establishment of successful scientific paradigms — around which normal science is able to marshal the intellectual and material resources to advance more swiftly (see, e.g., discussion in David 1997).

We are still some distance away from arriving at that stage, with regard to the prospective discipline of *historical economics*. But, even if the vocabulary and concepts associated with path dependence have not yet stabilized, and even though at times it appears that people are taking the same words to refer to very different things, there is now an interest, curiosity, and even enthusiastic commitment that is vital enough to make it worthwhile trying to establish some terminological consensus in the field. Surely, fixing the language will help to fix ideas, and so support the development of research programs in this area that are in some sense connected, rather than idiosyncratic and self-contained. In any case, that is the hope that has spurred this essay.

---

[9] According to Liebowitz and Margolis (1995: 205), "The path dependence literature comes to us accompanied and motivated by a mathematical literature of nonlinear dynamic models, known as chaos or complexity models...." It will be pointed out below why this is incorrect from a formal standpoint, but it is also misleading as to the intellectual history of the subject, as would be evident from the absence of models of deterministic chaos in the papers on path dependence up to and including the American Economic Association Proceedings (May 1990).

[10] See Koot (1987), Ch.6, and further elaboration in David (1992):"Invisible Hand".

2. Time for re-tuning : Some definitions

Path-dependence, as I wish to use the term, refers to a dynamic property of allocative processes. It may be defined either with regard to the relationship between the process dynamics and the outcome(s) to which it converges, or the limiting probability distribution of the stochastic process under consideration.

At the most intuitive level we may draw a distinction between dynamic processes that are path dependent, and the rest. The latter, path-*independent* processes, may be said to include those whose dynamics guarantee convergence to a unique, globally stable equilibrium configuration; or, in the case of stochastic systems, those for which there exists an invariant (stationary) asymptotic probability distribution that is continuous over the entire feasible space of outcomes — i.e., a limiting distribution that is continuous over all the states that are compatible with the energy of the system.

Stochastic systems possessing the latter properties are said to be *ergodic*, and have the ability eventually to shake free from the influence of their past state(s). In physics, ergodic systems are said to be connected, in the sense that it is possible to transit directly or indirectly between any arbitrarily chosen pair of states, and hence, eventually, to reach all the states from any one of them.

Path dependent processes thus may be defined negatively, as belonging to the class of exceptions from the foregoing set of processes, in which the details of the history of the systems' motion do not matter — because they cannot affect its asymptotic distribution among the states. This leads us immediately to

> ***A negative definition***: *Processes that are non-ergodic, and thus unable to shake free of their history, are said to yield path dependent outcomes.*

In this connection, it may be worthwhile to notice that the familiar homogeneous Markov chain invoked in many applications in economics — models of population migration and spatial distribution, of income and wealth, and occupational and social status distributions, firm size distribution, and so forth — is characterized by an invariant set of state-dependent transition probabilities that are finite (positive), and for convenience in many applications contexts, are specified so as to ensure that the process is *ergodic*. The distributions of the individuals or firms whose motions among the states are governed by Markov chains of this kind will each converge to their respective, invariant asymptotic probability distribution — a distribution that is continuous over the entire feasible state space. (This unique limiting distribution is the one that emerges as the transition matrix operator is repeatedly iterated.) When there is an absorbing state or subset of connected states (from which the probability of escape to the subset of transient states is zero), the system will converge weakly to that single attractor. Such a system's behavior may be said to be pre-destined, and the outcome determinate in the limit.

But, when a state-dependent process has two or more absorbing subsets (that is, distinct regions of equilibria that are locally stable), the homogeneous Markov process becomes *non-ergodic, and its outcomes can be said to be path dependent.* In the trivial case

in which the initial condition of the system was one or the other of the absorbing states, it is plain that whatever governed that selection would fix the limiting position of the system. Further, it is no less self-evident that if there is at least one transient (non-absorbing) state from which the multiplicity of absorbing states can be reached, directly or indirectly, then the realization of the random process at that point in the system's history (on its path) will select one rather than the other outcome(s) to which the system eventually must converge.

For many purposes, however, we would like to say what a path dependent process *is*, rather than what it is not. Help from the probability theorists can be invoked in order to do so in a precise way. Focusing upon the limiting patterns generated by a random process (thus characterizing a dynamic system), we have

> ***A positive definition:*** *A path dependent stochastic process is one whose asymptotic distribution evolves as a consequence (function of) the process' own history.*

This broader definition explicitly takes in processes that possess a *multiplicity* of asymptotic distributions, as generally is the case for *branching processes* — where the prevailing probabilities of transitions among states are functions of the sequence of past transient states that the system has visited. Branching processes that are subject to local irreversibilities share the property of non-ergodicity. The latter therefore characterizes the processes' biological evolution, because speciation constitutes a non-reversible event.

Transition probabilities that are not invariant functions of the current state also are the characteristic feature of so-called inhomogeneous Markov chains. Rather confusingly, however, probability theorists sometimes refer to the latter as having *path dependent transition probabilities*, thereby contrasting them with the more familiar class of homogeneous (or first order) Markov chains whose transition probabilities are (current) *state* dependent.[11] But, as has been seen from the negative definition discussed above, path dependence of the transition probabilities is not a necessary condition for a process that generates path dependent outcomes.

The preceding discussion of what the term 'path dependence' means may be compared with the rather different ways in which it is explicitly and implicitly defined by some economists. For the moment we may put aside all of the many instances in which the phrase "the 'history matters' literature" is simply interchanged with "the 'path dependence' literature," so that while nothing actually gets defined, nevertheless some loose and general connotations are suggested. Actually, much of the non-technical literature seems to avoid

---

[11] Liebowitz and Margolis (1995b: pp. 209-210) fall into just this confusion on the one occasion on which they offer a formal definition of the meaning of 'path dependence'. They say, correctly: "The meaning closest to current use in economics is that of stochastic processes that incorporate some concept of memory." But thereupon draw from the *Encyclopedic Dictionary of Mathematics* (Cambridge, MA: MIT Press, 1987) the following definition of 'path dependence': Letting P(n) be the probability of event E(n) =A(1) on the n-th trial, and (1-P(n)) be the probability of E(n) = A(2) A(1), at that trial, then the general 'response probability' for the sequential process is: P(n+1) = f {P(n), E(n), E(n-1),...,E(1)}. When the function $f = f$ {P(n), E(n), E(n-1),..., E(n-d)}, the response probability is said to be 'd-trial path dependent." In the special case where d=0 it is 'path independent.' The text in Liebowitz and Margolis (1995b: p.210) then goes on to claim, quite erroneously:"The use of path dependence in economics is, for the most part, loosely analogous to this mathematical construction: Allocations chosen today exhibit memory; they are conditioned on past decisions." If 'allocations' are associated with 'events', E(i), and (probabilistic) decisions at moment n are characterized by the pairs [P(n); 1- P(n)], then the foregoing statement does not correspond to the mathematical construction of d-trial path dependence and, more than the latter, corresponds to the generic usage of path dependence in economics.

attempting explicit definitions, resorting either to analogies, or a description of a syndrome — the phenomena with whose occurrences the writers associate 'path dependence.' Rather than telling you what path dependence *is*, they tell you some things that may, or must happen when *there is* path dependence. I can illustrate this with some selections from papers by Stanley Liebowitz and Stephen Margolis (1995a, 1995b, 1995c), whose expositions of the subject recently have begun to attract attention, and adherents. According to these authors

> Path dependence is the application to economic systems of an intellectual movement that has lately come into fashion in several academic disciplines. In physics and mathematics, the related idea is called chaos — sensitive dependence on initial conditions. As chaos theory has it, a hurricane off the coast of Florida may be the fault of a butterfly flapping its wings in the Sahara. In biology the related idea is called contingency — the irreversible character of natural selection. Contingency implies that fitness is only a relative notion: survival is not of the fittest possible, but only of the fittest that happen to be around at the time. [Liebowitz and Margolis (1995c: 33)]

Elsewhere, they propose a slightly more formal explanation, but one that follows the same vein:

> The use of path dependence in economics is, for the most part, loosely analogous to this mathematical construction: Allocations chosen today exhibit memory; they are conditioned on past decisions. It is where such a mathematical process exhibits 'sensitive dependence on initial conditions,' where past allocations exhibit a controlling influence, that it corresponds most closely to the concerns that economists and others have raised as problems of path dependency [sic]. In such a case, 'insignificant events' or very small differences among conditions are magnified, bringing about very different outcomes. It is that circumstance that yields both the 'non-predictability' and 'potential inefficiency'.... [Liebowitz and Margolis 1995b: 210.]

Much could be said about the unsatisfactory nature of these passages — even reading them as descriptive statements, rather than proper definitions. For the present, however, it will be sufficient to notice one thing that they do not say, and three things that they do say. That path dependence is a property of *stochastic* sequential processes is not mentioned, and only the allusion to "contingency" provides any hint of the subject's probabilistic context. Of course, in order to pick up this clue, one would need to suppress the extraneous and misleading surmise that "contingency" has a meaning that is specific to (evolutionary) biology, where it "implies" something about the nature of selections made on criteria of inclusive fitness.[12] But even that slender clue is disguised by the statements associating path dependence

[12] The reference in the passage quoted to "contingency" as the conceptual counterpart in biology of the idea of path dependence is followed by Liebowitz and Margolis's (1995b: 33) statement that "In *Wonderful Life*, Stephen J. Gould applies this intellectual revolution to paleontology." But, it should be shiningly clear from that work by Gould (1989: pp. 282ff, esp.), and really no less from his earlier writings, that he is not drawing upon a recent intellectual revolution: "I regard Charles Darwin as the greatest of all historical scientists. Not only did he develop convincing evidence for evolution as the coordinating principle of life's history, but he also chose as a conscious theme for all his writings...the development of a different but equally rigorous methodology for historical science....Historical explanations take the form of narrative: E, the phenomenon to be explained, arose because D came before, preceded by C, B, and A. If any of these earlier stages had not occurred, or had transpired in a different way, then E would not exist (or would be present in a substantially

with *deterministic* chaos, and the property of "sensitive dependence on initial conditions" that characterizes the dynamical systems of the latter sort. That is the first of the three positive assertions, and it is incorrect. What it reflects is a predilection in the expositions provided by Liebowitz and Margolis (1995b, 1995c) for transposing concepts and arguments that are probabilistic in nature into simple deterministic models.[13]

The second and third things that Professors Liebowitz and Margolis do say point to the reasons they hold path dependence to be a problematical concept for economists: they tell us that a dynamical system in which there is 'memory' will be unpredictable, and worse, characterized by a potential for generating inefficient resource allocations. Like the first of the triad of assertions, these too are inaccurate descriptive statements regarding path dependence *per se*. As I shall show in due course, it is quite important to distinguish between the latter property, and non-ergodic dynamic systems that may (or may not) display additional features which are "troubling" to those wedded to orthodox neoclassical economic analysis.

It is an unfortunate fact that by repeating untrue things often enough, and doing so in a very confident way, you may eventually manage to surround them with an aura of credibility. Yet, we can only wonder why anyone would wish to persist in such a campaign when the subject of the 'dis-information' was as innocuous as a formalization of the already widely held, and very general idea of historical contingency, or 'historicity.' The foregoing instances of the presentation to economists of something which might be called "path dependence according to Liebowitz and Margolis" can be contrasted with the non-technical usages of the same term in some influential recent works of economic history. Economic historians, perhaps not surprisingly, are generally more amenable to the idea of historical contingency, and generally manage to avoid construing the dynamics of path dependent systems in essentially deterministic terms. Douglass North (1990:94) for example, offers this compact explanation when first introducing the term:

> path dependence — the consequence of small events and chance circumstance can determine solutions [where a multiplicity of such equilibria exist] that, once they prevail, lead one to a particular path.

---

altered form, E', requiring a different explanation)....I am not speaking of randomness (for E had to arise, as a consequence of A through D), but of the central principle of all history—*contingency*." [Gould (1989: 282-283)] Further on, Gould (1989:283-284) writes of the universal psychological appeal of the notion of historical contingency, in terms that leave no doubt that this is not a concept specific to evolutionary biology: "Historical explanations are endlessly fascinating in themselves, in many ways more intriguing to the human psyche than the inexorable consequences of nature's laws....Contingency is the affirmation of control by immediate events over destiny....Contingency is a license to participate in history, and our psyche responds. The theme of contingency, so poorly understood and explored by science, has long been a mainstay of literature....Tolstoy's theme in all his great novels." What Gould provides in *Wonderful Life* is a new interpretation of the record of life left in the Burgess Shale, but, as he takes pains to acknowledge, this interpretation "is rooted in contingency" — a very old and far from revolutionary idea.

[13] The latter may then be subjected to criticisms from which the original analysis would be immune. A striking instance of such a switch is to be found in Liebowitz and Margolis's (1995b: 214-215) reproduction and critique of a deterministic payoff tableau, used by Arthur (1989) purely *as a heuristic device* — to convey the possibility that a sequence of myopic adoption decisions under increasing returns to adoption could result in the commitment of the ensemble of adopters to a dominated outcome. In the course of pointing out that the payoff tableau may be read in a way that is inconsistent with the results reported for Arthur's stochastic model, there appears the following commendably candid footnote (pp. 214-215, n. 15): "Actually, Arthur states that this example does not exhibit any 'non-ergodicity,' meaning that it is not path dependent in the sense that small differences in historical sequences play a role in the final equilibrium. In this example the end result is the same no matter the order of initial participants. But it illustrates lock-in very well." I might note that this footnote is the only place I have found in Professor Liebowitz and Margolis's publications on path dependence where the concept is explicitly defined with reference to non-ergodicity, and even it omits reference to probability.

The particular wording in this may be a bit unfortunate, in that it leaves room for the incorrect surmise that 'the path' somehow is 'dependent' upon the selection of a particular equilibrium 'solution.' But, it should be noted, North's formulation conforms with the more rigorous definitions that were provided at the beginning of this section — in not equating the existence of path dependence *per se* with the persistence of economically inefficient outcomes.

Further, and importantly, North also has allowed contingent probabilistic events to have a place throughout the dynamic process. This latter, stochastic aspect of the concept receives very explicit emphasis from the subsequent account that North (1990: 97-98) has given of 'the path-dependent pattern of institutional evolution.' Following an illustrative discussion of the role of the Northwest Ordinance of 1787 (and the precedents in English land law that it embodied) in shaping the nineteenth century pattern of U.S. territorial expansion and settlement, he remarks:

> If, however, the foregoing story sounds like an inevitable, foreordained account, it should not. At every step along the way there were choices—political and economic—that provided real alternatives. Path dependence is a way to narrow conceptually the choice set and link decision making through time. *It is not a story of inevitability in which the past neatly predicts the future*. [North (1990: 98-99), emphasis added.]

A rather different "take" is found in Joel Mokyr's (1990:162-163) attempt to construe path dependence as a specific hypothesis about the sources of a given society's technological creativity: "The view that technological change depends primarily on its own past is known as *path dependency* [sic]."[14] This curious implicit definition is introduced by a brief discussion of some historical observations about sequences of technological development in which techniques learned in one environmental or natural resource context were transferred to other uses:

> A similar phenomenon can be discerned in late medieval Holland, where location determined an affinity with shipping. Starting off as a nation of fishermen, the Dutch learned one thing from another: shipbuilding led to rope- and sailmaking, to the use of wide-driven sawmills, and to the development of provisioning industries.... [Mokyr (1990: 163)]

But, it soon turns out that this unhelpful introduction to path dependence is meant only to affix a label to another in the succession of simplistic straw-man "theories of technical progress" that Professor Mokyr demolishes on his march towards his preferred "evolutionary" account of the dynamics of technological change.[15] And when, in a later chapter of *The Lever of*

---

[14]See endnote 1 on the substitution of 'dependency' for 'dependence'.

[15] It is a general observation that straw men are invariably given labels associated with the work of others than the individuals who construct them. Mokyr (1990:163) begins the paragraph immediately following the passage quoted in the text by observing: "This explanation of technological progress may appear trivial to some and false to others." There follows a review of some "mechanisms for this autocorrelation" in the level of technological creativity, whose inadequacies as guarantors of unbroken chains of innovative success are deftly noted. Says Mokyr (p.164): "...these sequences do not provide a wholly convincing account of technological advance, [as] it is misleading to think that nothing leads to technological progress like technological progress"....Neither nature nor history can lock a society forever into a dead-end technology." Indeed. Of course, it is only Mokyr himself who at this point in his book has mis-labeled what is little more than 'the general theory of the virtuous spiral' with the tag 'path dependence.' A bit further on, Mokyr (pp. 164-165)

Riches (1990), path dependence is reintroduced in an evolutionary context, the author appears considerably more receptive to the (implicitly defined) concept, and cognizant of the stochastic framework within which it acquires significance for students of history:

> To be sure, in a path-dependent world, outcomes are never inevitable, and worlds that could have been but never were might be fruitfully contemplated, much as they may be distasteful to orthodox historians. [Mokyr (1990:285)].

This explicitly acknowledges what the historian of technology George Basalla (1988: 190) has described as "the branched character of technological evolution." The passage of his book, *Technological Evolution*, to which Professor Mokyr makes reference, expresses the conclusion that "the evolutionary perspective on technological change reveals that there are a diversity of paths open for technological exploration and exploitation;" that from "the study of artifact selection" it had become evident that

> [a]gain and again neither biological nor economic necessity determined what was selected....Despite widespread belief that the made world could not be otherwise than it is, in the case of the printing press, railroad, and gasoline engine different choices could have been made. Basalla (1988: 190)

Professor Basalla is willing to go only so far in contemplating counterfactual worlds, but leaves it at just that, refraining from passing judgement one way or the other on the question of the likely comparative optimality of the paths not taken.

By contrast, the economist-economic historian Mokyr evidently accepts the prevailing popular association of path dependence with the issue of potential economic inefficiency and enters the following further qualification of the weak form of Darwinian selectionism that Basalla (1988) embraces:[16]

> Not everything that ever was, was good. But by and large there was order and logic in the evolvement [sic] of techniques, and when necessary the shackles of the past could be broken. Precisely for that reason, path dependency [sic] in biological evolution is much stronger than in technological progress.

The preceding discussion should have served to bring out at least four simple points: (1) path dependence is a special property of stochastic dynamical systems and not just a way of describing state dependent sequences of events; (2) none of the formal definitions of path dependence concern themselves with the question of whether or not economic efficiency is

---

appears to take a different tack when, without explicit notice, he shifts the *explains* of the supposed "path dependent theory of technological change" from the *rate* of inventive activity to its *direction*: "The path-dependent nature of technological change, in which its *course* is explained mainly by its past, can be extended, though caution must be used in applying these models. The links with the past must be specified rather than assumed." [Emphasis added.] From the whole presentation a reader would have to be forgiven were he or she to form the utterly mistaken impression that *path dependence is*: (a) a theory about the sources of technological creativity, (b) the claim that technical progress is temporally auto-correlated, (c) a trivial or false theory, because it says merely that success breeds success, and failure is followed inexorably by more failure — both of which are manifestly not true.

[16] Closely following this, Mokyr's (1990: p.286) comments on the competitive diffusion of technological compatibility standards and conventions, and makes it clear that his evolutionary perspective on technological change does associate the concept of path dependence with 'weak' Darwinian selectionism, and the consequent possibilities of outcomes that may be locally or situationally efficient, yet not globally optimal: "There is no optimality per se in these standards [33 1/3 rpm for playing phonograph records, or driving on the right side of the road] but given that they exist, they have to be accepted, and thus impose a constraint on the techniques that can be used....Yet not all specific behavior has definite adaptive meaning, just as not all technical conventions are necessarily efficient."

attained; (3) the association of path dependence with the general idea of a *contingent* branching process seems to be more immediately congenial, and intuitively significant to economists who are actively engaged in studying economic history; (4) much that continues to be written about path dependence by economists fails to clarify the first two of these points, and does not manage to convey the historical intuition referred to by the third. Misapprehensions about the second point, however, seem to bear special responsibility for the resulting incoherence that has developed in the literature on path dependence, and it is to this problem that I wish to attend more fully.

3. Path dependence 'without tears' (i.e., no market failures!)

The variety of meanings surrounding the term in current usage notwithstanding, it ought to be evident from the definitions already provided (above, at the start of section 2) that the property of path dependence is conceptually distinct from any consideration of the allocational efficiency or other performance characteristics of the dynamical processes in the economy to which it applies. At least, that is the way in which the term has been consistently used in my own work on the subject.[17]

I must admit, however, that a careful reading of even the informed portions of the current literature is required to notice the distinction that it maintains between economic processes that are held to be 'path dependent' and the proper sub-set of those which belong under the heading of "QWERTY-nomics" or "the economics of QWERTY."[18] To the latter category belong the class of stochastic systems that *may* settle into equilibrium states that are Pareto-dominated. Something further is implied logically by the absence of any *definitional* identification between a system's possession of the path dependence property and its being subject to market failure.

In recognition of this, it now seems quite important, more important than I had supposed before the attention that has been captured by the economics of QWERTY (see, e.g. Krugman (1994: esp., Ch.9), to re-emphasize the formal existence and economic significance of the neglected complementary sub-set of path dependent processes: those for which *all* the attainable equilibrium states would be efficient in the Paretian sense. To be sure, there are certain structural conditions which violate the assumptions under which it is possible to prove the allocative efficiency of competitive general equilibrium in a Walrasian "tatonnement" market process. This remains an undeniably compelling matter for economic analysis, and one that may not be unconnected with the question of the system's path dependence. Yet, these two issues are logically separable, and are best treated as such. Because that has not been

---

[17] See the bibliographic references for David, and co-authors, especially the publications from 1985 to 1997.

[18] David (1985, 1986) tried out the neologism "QWERTY-nomics" when introducing the analytical elements of the story of the emergence of the QWERTY keyboard format as the de facto standard in the U.S. typewriter industry, but the more transparent phrasing of the titles (the economics of QWERTY") took increasingly firm hold, as in Krugman (1994: Ch.9). Notice that the discussion there, and in Krugman (1991:100), is careful to associate the potential for lock-in to Pareto inferior equilibria with the economics of QWERTY, rather than with the more general phenomena of path dependence. This logical separation has been blurred in part by the rhetorical success of QWERTY, for which David (1985) may be blamed. Some of the credit for the resulting confusion also must be shared, however: the distinction also has been obfuscated by Liebowitz and Margolis's (1990) attempt first to refute the view that the early de facto standardization on QWERTY represented a sub-optimal selection by the market, and subsequently (1995b) to impose a taxonomy in which a particular form of persisting sub-optimality was labeled "third-degree path dependence." The second of these maneuvers is examined in section 5, below.

universal practice in recent discussions among economists and economic historians, some further elaboration on the point seems in order here, to put it mildly.

We might risk starting with an historical case to illustrate the separability of the two issues. In the diffusion of mechanical technologies in Victorian Britain, it has been found, the introduction of types of equipment that would represent "best practice" in newly built plants was effectively blocked by the existence of strong technical complementaries between that equipment and other components of the production system.[19] Although the capital goods involved were of finite durability, and in some instances were comparatively short-lived, the problem was that their service lives had become temporally aligned in an overlapping fashion, so that decisions about replacement of worn-out and obsolete assets tended to occur within the context framed by other, technically interrelated components that were still yielding significant positive quasi-rents. A different history governing investment, and thus the timing of the formation and scrapping dates of the components of these production systems, thus could have resulted in quite a different pattern of cost-minimizing technology choices. Such was the basic situation in Victorian Britain with regard to mechanized grain harvesting on drained arable fields, in cotton textile spinning, and also in the oft-discussed case of railway rolling stock and infrastructure design first cited by Veblen in *Imperial Germany and the Industrial Revolution* (1915).[20] Yet the moral suggested by these historical experiences was not at all about "mistakes" in the choices of technique. Quite the contrary, for the documentation of these cases has been entered in evidence by those who have followed McCloskey (1971, 1974) in disputing the belief that the performance of the British economy in the high Victorian Age suffered as result of irrational managerial resistance to innovation and kindred entrepreneurial failures. Do such matters on that account become devoid of any interest or importance for economists?

I insist that they do not. But the significance of the central theoretical point at issue here also can be exposed in a way that is untinged by the grimy business of rendering economic interpretations of complicated historical actualities. Consider then that favorite, ever-pristine piece of neoclassical general equilibrium analysis which is performed with aid of the Edgeworth Box. In that graphical construct we posit two utility-maximizing agents whose independent indifference sets are specified over a pair of commodities, and whose respective preference functions are continuous and continuously differentiable. A common commodity endowment space is contained in the "box"formed by turning one player's indifference map upside down and superimposing it upon the indifference map of the other. The points of tangency between the two sets of (convex) indifference curves in that space trace *a continuum of equilibria* — the so-called contract locus — along which the agents' respective marginal rates of substitution in consumption are equated. Movements away from that locus would render both of the parties worse off, and hence would not be proposed by either; movements along the contract locus that are favorable to one party must be disadvantageous to the other, and so will not take place voluntarily. Hence, we conclude that all points on this locus constitute locally stable equilibria.

The two fundamental theorems of welfare economics tells us, first, that if the commodities are normal goods (not Giffen-goods) and trading commences from any feasible

---

[19] See, e.g., the discussion in David (1971), or David (1975: Ch.5).

[20] Closer analysis of both the 'naive' and 'sophisticated' economic interpretations of Veblen's (1915) argument, and their treatment in subsequent studies by economic historians may be found in David (1975), Ch. 5.

endowment point in the Edgeworth Box, there exists a unique, market-clearing vector of relative prices; second, these equilibrium prices support a (unique) exchange that moves the pair of agents from their initial endowment point to a point that is somewhere on the contract locus. Computable general equilibrium models use the Scarf algorithm (or equivalent procedures) to find the unique market-clearing relative price(s) and corresponding equilibrium commodity allocation; indeed, such algorithms represent constructive proofs of the existence of a unique and stable equilibrium under the conditions specified. Such solutions, however, assume costless recontracting in the manner of Walras' tatonnement process, in which a number of relative prices are "tried," without any actual exchange being implemented, until the one is found that clears the market — leaving the parties at a (market-clearing) point on the contract locus.

Suppose, instead, that (starting from an arbitrary allocation) one has a *non-tatonnement* market process — involving a sequence of trades, each of which was constrained simply to belong to the momentarily prevailing set of negotiable Pareto-improving exchanges. Various mechanisms, including the purely random, can be specified to select a particular trade from among those in the current negotiation set. We know this process will continue, step by step, until it arrives somewhere on the segment of the contract locus over which the agents' respective utility levels are both either the same, or higher than those which obtained at their initial endowment points. Even when one specifies a particular aboriginal endowment point, therefore, there will exist a multiplicity of locally stable and Pareto efficient equilibria, or attractors for this dynamic system.

Where, precisely, on the contract locus will the final equilibrium solution be located, and what will be the vector of prices that turns out to clear the market? In the general case this is not something we are able to solve for *ex ante*. The answer, obviously, will emerge from the details of the sequence of trades, because each of those exchanges will alter the initial endowment point and thereby re-set the constraints for the next exchange in the sequence. So, here we have a well-known dynamical system that *fully satisfies the definitions of path dependence* — both as to outcome and as to process, if we think of each trade as the realization of an evolving stochastic sub-process that is altering the distribution of possible outcomes.

Theorists concerned with the "disequilibrium foundations of equilibrium economics" (to steal the title of Franklin Fisher's (1983) book on the topic), have certainly been familiar with the characterization of the sequence of irreversible non-tatonnement exchanges as a path dependent process of finding a stable equilibrium. Any economist who would explain the particular equilibrium outcome (among the multiplicity of eligible candidates) towards which this system converges must necessarily have recourse to the historical details of its evolution. By the same token, when computable general equilibrium models are employed — as they have been by applied economists, and economic historians, too — in order to 'solve' for the effects of some policy measure, or of particular 'shocks' attributed to technological innovation or institutional regime change, the implicit specification of a tatonnement-like process suppresses the possibilities that the actual, historical process of market-clearing could select an outcome quite different from the one found by the mathematical algorithm. Yet, no less transparently, there is no market failure here: all of the positions of equilibrium that are reached from any initial endowment point will be equally "efficient" in the Pareto sense.

From the foregoing we see that path dependence, evidently, is not a *sufficient* condition for market failure. And we should be well aware that path dependence is hardly a

necessary condition for market failure, either. Economists have devoted a veritable sea of ink to describing the variety of theoretical conditions (non-convexities in production or indifferent sets, externalities of various kinds, missing markets for state contingent commodities) under which an inefficient allocation would be supported by the relative prices found by a non-sequential market-clearing process conducted by an auctioneer who allowed instantaneous recontracting — entirely in the manner imagined by Walras.

The upshot of the discussion in this section and the one preceding is that the properties of path dependence and market failure cannot properly be thought to be related to each other through conditions of necessity or sufficiency. Given the absence of both necessity and sufficiency, it does seem to be some strange twist of intellectual history for path dependence to have been immediately identified with, much less definitionally equated to the emergence and persisting realization of states that are economically sub-optimal. But this twist in the minds of some economists is not only strangely unwarranted. It has had some seriously misleading analytical sequelae.

4. Deeper connections: Sources of positive feedback, and multiplicity of equilibria

It should be recognized that there are deeper connections, nevertheless, between the possibility that the price system of a competitive economy will not produce convergence to a unique, stable and globally efficient equilibrium, and the presence of certain structural conditions that cause economic dynamics to be path dependent. Put more simply, these two properties of economic systems *may* share common foundations even though it has been shown here that the one certainly can exist without the other. To see that such indeed is the case, one must try to identify the nature of at least some among the set of conditions that contribute both to market failures and to path dependence. Because the attention recently devoted by economists to the phenomenon of path dependence has been closely linked with, and in some considerable measure was initiated by applied policy interests in the potential for the adoption and development of network technologies to be affected by market failures, we might expect that this is a promising area in which to seek common roots of the two properties. It is useful, however, to begin more generally, by reviewing the well-known sources of market failures — leaving to one side the imperfections in the price system that would result from market power and strategic interdependence among agents.

Economists know many answers to the question: How could a competitive market system wind up having made a wrong choice? Some of reasons given would turn on the effects of imperfect information, the absence of complete markets for state contingent claims (insurance), and the impediments to contracting with future generations of agents. The interesting conditions to focus upon at this juncture are more obvious and less esoteric than those, and involve the effects of nonconvexities in supply and positive externalities in demand.

To be concrete here, in a dynamic process, positive feedbacks will be generated by the dominance of indivisibilities and strong technical complementarities on the supply side of markets; and/or the interdependence of customer preferences operating on the demand side. They may thus be seen to arise as well from learning effects and habituation, which constitute forms of unidirectional intertemporal complementarities at the microeconomic level. Even under conditions of complete information, sunk cost effects of rather limited duration can create a plethora of potential macro-level equilibria that are capable of persisting indefinitely. This applies in circumstances — already noticed — where micro-level decisions involving

investments in individual elements of belonging to a set of strongly complementary assets (each having finite physical service lives) are distributed through time, so that the asset structure as a whole resembles a population of overlapping generations. When there are non-convexities such as underlie the phenomenon of thick market externalities, it is quite possible for self-reinforcing income effects, and self-fulfilling expectations to result in the emergence at the system level of lock-in to a sub-optimal equilibrium, despite the existence of other, superior attractors — a condition about which something further will need to be said, anon.

Thus, a number of the classic sources of market failures under conditions of complete information — namely, conditions that show up as nonconvexities affecting supply functions and interdependence of preferences affecting demand functions — also figure in creating the conditions in which we will find positive feedbacks and a multiplicity of equilibria. Under dynamical conditions of sequential state-dependent transitions that have some measure of irreversibility, these micro-level foundations for positive feedbacks can also result in the fact that those (path dependent) episodes of "strong history" may not have happy endings, judged by the welfare optimality criterion of Pareto. But it is the connection between the property of *non-ergodicity* and the inability of a competitive economy's price mechanism to attain an efficient allocation of resources that is critical in this. That much can be established by formal analysis of a stochastic system that is *not* dynamic, and which on that account cannot be thought to possess any 'history' whatsoever. The logical implication of such a demonstration is that even in those specific circumstances the existence of underlying non-ergodicity condition is, strictly, not *sufficient* to connect the properties of "market failure" and "path dependence."

The sort of analysis I ought to have been able to point to, by way of illustration, is this: consider a general equilibrium system in which there are a large but finite number of agents who are initially endowed in an egalitarian fashion with the two goods. Consider too that the goods in question are such strong substitutes that the agents want either as much of one good as they can consume, or of the other, without caring for any of the good that comes second in their preference ordering. Assume, further, that the agents have probabilistic preferences which are interdependent, being affected in an additive manner by their interactions with other agents; in other words, into this random competitive economy introduce *positive (non-pecuniary) externalities* of some sort, such as demonstration effects or peer pressures that exert a mimetic influence on the preferences of interacting agents. It can be proved rigorously that under these conditions, provided that these positive externality effects are strong enough (in a sense that is well-defined), the price mechanism will not enable the economy to attain a unique (probabilistic) equilibrium configuration. There exists no unique price vector that would set the global per capita excess demand of the system to zero, and thereby support a given probabilistic equilibrium configuration of consumption choices. Instead, there will be two pure probabilistic configurations, or phases of the random economy, corresponding to the extremal states in which the agents' preferences become perfectly correlated. To describe the matter more formally, in this model there is a *critical* level of the strength of the positive externalities (additive interactions affecting the agents' probabilistic preferences) which, when surpassed transforms the stochastic economy so that it is non-ergodic and will exhibit behavior akin to the phenomenon of phase transition in physical systems. For this result to hold, it is quite sufficient that each agent's preferences be affected by the choices of *some* others among the ensemble. Local rather the global positive

externalities affecting their (probabilistic) choices will be quite enough to produce the results just indicated.

The foregoing results pertaining to the multiple equilibria of a static random economy actually were established almost a quarter of a century ago by Hans Föllmer (1974); had I been looking in the right places I would have made more of this back in 1975. Since these propositions pertain to the equilibrium properties of a *timeless* economy, however, they cannot logically be conflated with the existence of path dependence and "strong" *history* — as the latter property has been seen to be an inherent feature of sequentially evolving *dynamical* systems. Strictly speaking, then, Föllmer's results pertain to the potentiality of market failure in the presence of positive externalities in consumption. They establish that the latter, through their influence upon the agents' probabilistic preference orderings, destroy the market mechanism's ability to find relative prices that support a given (probabilistic) equilibrium. Föllmer (1974) showed, in addition, that the asymptotic distribution of consumption configurations was one that had (almost) all the probability mass piled up on the equilibria corresponding to the economy's two extremal states. In other words, this random economy with interacting agents exhibits a tendency toward the spontaneous emergence of conformity among the agents in regard to their preference ordering of the available goods, and the consequent realization of *standardization* of consumption behavior across the ensemble.

Although it should be plain enough that one of the pair of pure probabilistic equilibrium phases — which constitute this economy's dominant "attractors" — could well be inferior to the other in a welfare sense, the point may be worth elaborating a bit more fully. Notice, therefor, that the realization of either extremal solution would represent a loss of potential welfare for the individuals whose preference ordering (in the absence of the influence exerted by others in the ensemble) would tend to favor the good that is excluded from the realized extremal equilibrium. Consequently, there is a non-negligible likelihood of an allocative outcome that excludes from the ensemble's consumption a commodity that would have been selected by the overwhelming majority of the agents, had each of them been acting in isolation.

There has been a long-standing awareness on the part of economic theorists that unless nonconvexities and externalities were kept confined in the shadowy fringes surrounding general equilibrium analysis, various problems of "non-existence" would spring forth like hideous monsters to destroy the beautiful propositions that could be proved about a perfect competitive economy. The treatise *General Competitive Equilibrium* by Kenneth Arrow and Frank Hahn (1972), for example, was explicit in acknowledging this threat, and even sought to contain it by arguing that if those effects remained "small" in relation to the size of the economy, the device of taking the latter's convex hull would suffice to prevent such monsters from wreaking too much damage. In the early 1970s, all this already was so familiar that it was sufficient for me simply to allude to it in the Introduction of *Technical Choice, Innovation and Economic Growth* (1975).

My reason for doing so on that occasion was not only to highlight the centrality of dynamic economies of scale and other non-convexities (sources of those pathologies) in the historical experiences of the American and British industries that were recounted in the book, but also to suggest that there could be a bright side to the well known difficulties caused for competitive general equilibrium theorists. It seemed that by coming to grips with the implications of significantly large and irreversible externalities, and large nonconvexities arising from technical complementaries and learning-by-doing, economic theory would be in a

better position to deal with the kind of history that really "mattered." It could begin openly to identify and formally analyze those processes where the influence of events in the past might be transmitted and magnified in their power to significantly and enduringly affect the long-run patterns of resource allocation, for better or for worse.

5. Path dependence and varieties of history, followed by some taxonomic 'fiddling'

The core notion of path dependence has been seen to be concerned with *stochastic processes of historical change* — the probabilistic motions of systems through unidirectional time. Proceeding from that point of departure, a conceptual scheme distinguishing among *varieties of history* was proposed almost a decade ago, in the course of the effort by David (1988) to explain to economists 'how history' mattered. The summary result was a taxonomy based on distinctions involving the degree of strength associated with different notions of the influence of the past in economic dynamics. Consequently, it accorded special place to dynamic processes that exhibited forms of historicity, associated with non-ergodicity and historical contingency. Here is how it went:

- *weak history* goes so far as to recognize "time's arrow" (the rooted sense of difference between past and present) and thus prevents us from supposing all motion to be locomotion — from whence, we in economics are permitted to have the notion of costs being sunk;
- *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 the conditions for path dependence of outcomes, or of transition probabilities and asymptotic distributions of outcomes.

A serious concern with studying economic change provides the most immediately compelling grounds for doubting the usefulness of any scheme that ignores the qualities of contingency and historicity when classifying forms of path dependence. Yet, remarkably, that is precisely what has been recommended to economists and economic historians by Liebowitz and Margolis (1995b), in whose recent taxonomic proposals three varieties of 'path dependence' are identified. The fundamental basis upon which these authors have proposed to classify different manifestations of path dependence is a determination of the allocative efficiency, or 'economic welfare optimality' of the action leading via a dynamical 'path' to an eventual outcome. Now you might think this could hardly be a practical proposal if one was considering a sequence of actions with probabilistic outcomes, many of which might result in irreversible branching of the 'decision tree' (if we are imagining a single player), or in the generalized 'game tree' (if there are numerous actors).

Cutting through such complications, Liebowitz and Margolis (1995:204-205) start by associating 'path dependence' with the analytical perspective made familiar by the literature on chaos theory, and proceed to discuss deterministic models in which there is another kind of 'dependence,' namely 'sensitive dependence on initial conditions'. This easy elision, although

technically illegitimate, is expositionally convenient for an audience accustomed to having their economic models presented in deterministic terms.[21]

By thus suppressing the explicit stochastic approach that in actuality is a central feature in both theoretical and applied models of path dependent economic processes, Professors Liebowitz and Margolis (1995b) immediately simplify their taxonomic task. Only one (initial) action matters, and inasmuch as it is supposed to be either intrinsically uninteresting or below the level of visibility, or possibly both, all the taxonomic attention naturally becomes directed to the nature of the 'consequences'. Hence, their proposed classification scheme for historical processes is quickly reduced to considering "three possible *efficiency outcomes* when a dynamic process exhibits sensitive dependence on initial conditions."

In each of these imagined kinds of history it is accepted that "initial actions, perhaps insignificant ones [in some sense of 'significance' that remains undefined] put us on a path that cannot be left without some cost...." Liebowitz and Margolis (1995:206-07) say that where the result turns out to be optimal (although not necessarily uniquely so) we can tag the case as being that of *first-degree path dependence. Second-degree path dependence,* they say, may result when an initial 'selecting' action is taken without full knowledge of how alternative paths will turn out, so it is possible that "efficient decisions may not always appear to be efficient in retrospect." This rather inexact formulation does not hold the second-degree form to cover cases in which inefficient allocative outcomes are traceable to 'mistakes' in decision-making. It is apparent that within the Liebowitz and Margolis framework the initial 'selection' of a path implicitly is presumed to involve a conscious choice on someone's part. The category of second-degree path dependence therefore serves to absorb those cases in which a decision under uncertainty can be held to be *optimal in some ex ante expectational sense,* even though *ex post* the 'realized outcome' was dominated by a better one that 'might have been.' That leaves *third-degree path dependence*:

> sensitive dependence on initial conditions leads to an outcome that is inefficient—but in this case the outcome is also *remediable*. That is, there exists or existed some feasible arrangements for recognizing and achieving a preferred outcome, but that outcome is not obtained. [Liebowitz and Margolis (1995: 207). Emphasis in original.]

The details of the foregoing taxonomic scheme are in a sense less noteworthy than is its overall effect, which is to obliterate the distinction between 'path independence' and all path dependent processes other than those giving rise to an inextricable condition of global economic inefficiency. The latter sort, having been promoted to 'third degree' status — perhaps not unintentionally reminiscent of an unpleasant interrogation, or a severe burn — are then more readily presented to economists as the unique, self-evidently arresting form of path dependence with which they might have to contend. That is the form which is associated in Liebowitz and Margolis' (1990, 1995a, 1995b) presentations of path dependence with the term 'lock-in.' Something further will need to be said about this below, inasmuch as this has the effect of restricting the applicability of the notion of 'lock-in' to a condition — 'third-

[21] This is one of those instances in which a casual, heuristic analogy becomes confused with, and actually supplants the thing it had been invoked to explain. From the formal standpoint it is quite inappropriate to bracket the theory of chaos with that of stochastic processes which exhibit path-dependence. Although strong positive-feedback (or, alternatively, additive interactions) will result in the system's inability to shake off its past (non-ergodicity), mathematically the latter is something different from 'sensitive dependence on initial conditions.' See, e.g., Ruelle (1991: Ch.14), Steward (1990).

degree path dependence' — which has been definitionally constructed so as to render it empirically implausible.

What is most important in all this is to recognize that the welfare-analytical taxonomy proposed for path dependence has nothing to do with the 'degree of historicity' characterizing the dynamic processes that are to be thus classified. The approach is rather akin to proposing to categorize civil law cases not according to the nature of the tort alleged, but by whether the judgement was awarded to the plaintiffs or to the defendants, or by the sizes of the damages awarded — criteria that certainly are not devoid of interest, but that are in a sense orthogonal to the process, and applicable equally to title prize fights, or other tournaments in which challengers and defending incumbents can be identified.

By contrast, in my simple taxonomy of the varieties of history for economists (David 1998), no attempt was made to further differentiate the category of "strong history" further, neither according to 'strength' criteria drawn from the nature of the contingencies that might affect the path, nor from some welfare or other evaluation of its allocative and distributional properties. Differentiations of that sort might well prove to be helpful in organizing the material produced by students of economic history, once they have been persuaded to ask the questions that theories of path dependent history suggests it would be feasible as well as interesting to answer. Yet it has always struck me to be less than entirely practical to attempt to implement a classification scheme grounded upon the implicit supposition that what one is observing historically corresponds to the unique and stable equilibria of the market or non-market allocation process in question.

Here is the problem: if 'out-of-equilibrium' motion is an acknowledged possibility, then before applying what are essentially static evaluation criteria, it is necessary for the historical analyst first to determine whether or not a limiting outcome has been reached. Alternatively, if welfare efficiency criteria are to be applied in evaluating not just the attractors of the system, but each of its realized states, we shall then need to work out a far more elaborate welfare-analytic taxonomy to classify the entire dynamic sequence of states, or configurations that constitute the system's path.

Before we start to face up to that challenge, however, there are quite a few more objections that must be lodged against the proposal by Liebowitz and Margolis (1995b) to distinguish among path dependent phenomena on the basis of whether outcomes are or are not Pareto-dominated. The restrictive application of a static welfare criterion exclusively to some notional 'final outcome' as a means of categorizing historical sequences of contingent probabilistic events certainly leaves us a peculiarly narrow aperture through which to regard the richness of past economic experience. But that such a classification scheme is likely inherently to be of limited interest or utility for historians is perhaps not the most telling among the many objections that should be registered against the imposition of this particular set of taxonomic labels. We should then ask why, from the viewpoint of *economists* at large, it is thought satisfactory for the static Pareto efficiency test to thus be elevated to the status of *sole* criterion when deciding how 'important' it is to determine whether a given dynamical system is path dependent?

It is well known that in policy discussions the use of static economic welfare analysis systematically favors the *status quo* — by accepting the existing allocation as somehow 'justified,' and therefore requiring that proposals for change should meet the test of having to provide the wherewithal to fully compensate all who would lose thereby. And that bias can, and sometimes is reinforced by requiring that enough of a surplus should be available to cover

the whole of the entailed transactions costs and administrative costs of the proposed policy intervention, in addition to compensating any adverse income or wealth effects. Liebowitz and Margolis (1995: 207) have followed Williamson's (1993) invocation of this strong formulation of the test of 'remediability,' required before any market outcomes may be pronounced 'inefficient' — and therefore qualifying as worthy of their *third-degree* label.

But what is it that ethically 'justifies' guaranteeing agents their *status quo* level of economic welfare, any more than it justifies subjecting them to its loss? Implicitly some virtue seems to be attached to things that are the product of "history" and we might inquire why that should be so. If it were the case that Dr. Pangloss is right, and the processes of history led inevitability to the best of all possible worlds, that would indeed be a powerful instrumentalist reason for normative presumptions against actions designed to alter the *status quo*. On the other hand, if one sided with those economists who say history is 'important' and needs attending to only on those (rare) occasions when it has produced some inextricably inefficient state of affairs, why, for purposes of deciding on economic policy interventions, should importance automatically be accorded to preserving the consequences of history, for example in the prevailing distribution of income and wealth? Yet, the question of whether or not history tends toward states that are optimal from the standpoint of allocative efficiency is the empirical proposition that is at issue, and so a presumption in its favor cannot be turned into a 'bootstrap'-style rationale for favoring the *status quo* in assaying the evidence.

When one says it is 'best' to leave the situation as it is, because making it better would cost as much as the improvement is worth, that is a judgement which accepts the history that recreated the *status quo*. Should we not consider, instead, the possibility that even if a remedy is not now available, the present state of affairs may well have been avoidable, and in that sense 'regrettable'? This shows how important it is to insist upon distinguishing between 'remediability' *ex post* and *ex ante,* as would seem to be allowed for in the previous passage quoted from Liebowitz and Margolis' (1995b) definition of third-degree path dependence: '...whether there exists *or existed* some feasible arrangements..." It is quite possible that the costs of remedial actions were lower at various points along the path than they subsequently became, in which case the test for 'third-degree-ness' ceases to be so clear-cut.

Now we must come to a second point of clarification concerning the question of 'remediability,' which Professor Liebowitz and Margolis (1995b: 207) attribute to the discussion of path dependence by Oliver Williamson (1993: 140-141). Professor Williamson, however, was very careful to ask first for a test of remediation by 'private ordering' — which I take to refer to private contractual arrangements, or voluntary mechanisms for coordination that are not mediated by market exchanges, and then to observe that 'public ordering' may be feasible when private ordering is not. Here is what he says in the context of market-guided *de facto* compatibility standardization:

> Sometimes, however, public ordering can do better. The issues here are whether (i) the public sector is better informed about network externalities, (ii) the requisite collective action is easier to orchestrate through the public sector (possibly by fiat), and/or (iii) the social net benefit calculus differs from the private in sufficient degree to warrant a different result. Absent plausible assumptions that would support a prospective net gain (in either private or social respects), the purported inefficiency is effectively irremediable.

This important distinction has not been carried over into the taxonomic system set up by Professors Liebowitz and Margolis, so that it is quite possible that their "third-degree path dependence" label is intended to require that both private *and* public ordering are infeasible. What is meant by infeasibility in the latter case, unfortunately, remains obscure. Does it require that the State lacks the machinery to enforce arrangements that would establish by fiat a new coordination point for the market? Or is the test of "infeasibility" passed when it is shown that the incremental resources expended by the State and private parties in carrying through such a dictat would exceed the social gain from shifting to the new equilibrium? Shall we suppose that the State is one that engages in optimal remediation whenever possible, picking the occasion to intervene so that it would satisfy the latter requirement, or should it be admitted that the political and administrative process might fail to act in timely fashion? If the latter is a possibility, it could well turn out that the subsequent costs of remediation would entail a net expenditure of social resources. At that point in time an allocative 'inefficiency' that remained irremediable by private ordering throughout the time period, *ex hypothesis*, would have become irremediable (under Professor Williamson's criterion) also by means of public ordering — although policy measures to alter it might still be justified (or dictated) for other, possibly redistributive reasons.

These last considerations suggest that path dependent phenomena should be something that are to be taken seriously by economists because strictly 'irremediable' failures might arise as a consequence of the failure of feasible state intervention. Were the object of the exercise to free economists from worrying about path dependence, then optimal state intervention would be the course recommended on those as well as on other grounds. In the circumstances properly acknowledged by Williamson (1993) as those in which inefficiencies are not remediable by private ordering, optimally timed State action looks like the best hope for empirical justification of Liebowitz and Margolis's (1995b, 1995c) belief that situations of inextricable, totally irremediable inefficiency are a rare as hen's teeth. Rather miraculously, the logic of Professor Liebowitz and Margolis' recruitment of Williamson's (1993) analysis in their campaign to persuade economists that there's simply nothing to worry about, not even "third-degree path dependence," has led from 'nirvana economics' in which markets work perfectly to a more fanciful 'nirvana political economy' — in which optimal public ordering will be there to save the day when private ordering fails! Somehow one doubts that this was the conclusion these authors' were seeking. That might account for their total silence on the matter of whether remediation is or is not possible through 'public ordering'.

Beyond these purely logical lacunae in the analysis offered by Professors Liebowitz and Margolis, and others who are similarly preoccupied by the question of efficiency, it ought to be accepted that there certainly is more to economic life that is "important." The static efficiency performance of resource allocation mechanisms is not, and ought not to be the only class of questions that commands the scientific interests of economists and economic historians. What about those cumulative processes in which individuals or groups who were disadvantaged become increasingly disadvantaged, whilst those who were the recipients of favors, or good fortune, become differentially advantaged?

Such positive feedbacks, or 'cumulative advantage processes' are known to be capable of generating increasing social and economic stratification, and self-perpetuating inequalities of opportunity as well as of achievement.[22] Is it reasonable to view path dependent processes

[22] See, e.g., David (1988), David (1994:`Positive Feedbacks') and Durlauf (1996).

of economic and social divergence as worth worrying about only when it appears that there has been, in the aggregate, some sizeable net wastage of resources? Is the economics of distributional phenomena to be thereby relegated to the category of the 'not important'? One can hardly suppose that such would be viable as a professional stance for economists who are being asked to explain phenomena such as the persistence of disparate technological and organizational capabilities among firms belonging to a given industry, the differing extent of industrialization characterizing various regions of the world, and the widening relative dispersion of income and wealth in many societies?

Leaving the obvious ethical aspects of the matter to one side, there are some purely instrumental considerations that follow from the distinction between path dependence and path independence. For example, for purposes of public policy *design* it would matter whether one is justified in regarding the prevailing distribution of income, wealth, or health to be the unique and inevitable (stable) result of an ergodic dynamic process, rather than as the emergent, and highly contingent feature of a path dependent historical evolution. In the former case there would be a much stronger presumption that simple amelioration of inequalities would turn out to be only transiently effective, at best; that only through radical structural reforms would a recurrence of the original disparities be prevented. Such determinations as to the nature of the underlying dynamics seems to me to be a matter of real economic importance.

Economists, to be sure, are as free as anyone else to assign greatest weight to whichever aspects of economic performance they care most about. But, if this were to be accepted as a taxonomic principle in classifying dynamic systems in economics, we should be prepared to end up with a continuum of contending taxonomies — one for each analyst on any given day of the year. Economic historians embracing that sort of approach each would be able to assign to the various cases they examined some 'degree' of path dependence in their own scheme of classification, based upon their normative evaluation of the outcome of the stories they were relating. Would that really constitute much of a methodological advance? From the foregoing it will be seen that there simply are no compelling logical grounds, nor any other discernable scientific basis for trying to assign 'degrees of path dependence' *exclusively* by reference to the static welfare properties of the particular equilibrium into whose basin of attraction the system has been drawn. Yet, given the primacy of interest the mainstream of the academic economics profession still places upon static welfare efficiency, one must acknowledge a strong rationale exists in the sociology of scientific knowledge for elevating that principle of classification — as Liebowitz and Margolis (1995b) have done in their most recent discussion of path dependence.

6. Theme and variations in formal models of path dependence

Technical Choice, Innovation and Economic Growth (1975) was written before I was aware of the availability of mathematical techniques for studying stochastic systems that exhibited interesting behaviors (of the path dependent sort) with which my historical investigations were concerned. Formal conditions that rendered stochastic systems non-ergodic, and the investigation of the dynamics of such systems were formerly pretty much the exclusive province of probability theorists studying intersecting Markov chains and the properties of various Markov random field models, including the class that are described as *reversible spin systems,* and *percolation* models. While these particular structures have made some appearances in the mathematical

social sciences literature during the past two decades, many economists will still find them unfamiliar, if not somewhat forbidding.[23]

A typical interacting particle system, such as that described by Liggett (1985:1-2), consists of finitely or infinitely many particles which, in the absence of their interaction, would evolve according to independent finite or countable state Markov chains. Superimposed on this underlying random motion is some type of interaction, as a result of which the evolution of an individual particle can no longer be described simply by reference to its own current state, i.e., the process by which the particle evolved ceases to be Markovian — even though the system as a whole remains Markovian in the same, state-dependent sense.

Because the behavior of interacting particle systems is quite sensitive to the precise nature of the interactions, most of the analytical and computational studies in this field deal with certain structures, or types of models in which the interactions are of a prescribed form. *Spin systems*[24] refer to the class of such models in which each coordinate of the particle is limited to taking on only one of two possible values, and only one of the coordinates undergoes alteration in each (random) transition. In a *reversible* spin system, it is possible for reorientations of the coordinates of the particles to occur in either of the two directions. This corresponds to economic circumstances in which agents are permitted to make mutually exclusive selections at random moments from a binary choice set, and to "recontract" at the next random moment, which is what is envisaged in the probabilistic choice model of Föllmer (1974).

Since the formal structure of this model is quite transparently equivalent to one in which there are positive *local network externalities* affecting agents' preferences among alternative network technologies, it would have provided a natural lead into the theoretical investigation of the economics of technical inter-operability standards, and related issues of "network compatibility." But history, including intellectual history, does not always move forward on straight tracks. Föllmer's work was mathematically formidable, and appeared to deal with a theoretical pathology, the broader economic significance of which remained largely unappreciated among economists at the time. Hence, during the 1980s, when the attention of applied microeconomists in the field of industrial organization turned to the analysis of network externalities in technology adoption, they did not approach the question by investigating the effects those conditions would have in the context of a general equilibrium framework. Further, although some early contributions sought to analyze the outcome of technology choices under the influence of network externalities with the aid of models that were both static and deterministic, researchers soon moved on to consider models that were dynamic and probabilistic.

Thus it was that, through the bringing together of explicit dynamics and conditions that render stochastic systems non-ergodic, the economics profession began to be acquainted with certain formal models of multiple equilibria that could be described properly as path dependent, and be shown also to be susceptible to generating forms of market failure. Of

---

[23] Some will have been introduced to the existence of these by more recent economic applications of interacting particle models whose dynamics are non-ergodic, such as have appeared in Arthur (1988a), David (1988, 1993), Durlauf (1990), and Weidlich and Haag (1983). On spin systems, particularly, see Ligget (1985), and discussion in David, Foray and Dalle (1997). On percolation models, see Grimmet (1989), and other references in David (1988, 1993), with economic applications in David and Foray (1993, 1994, 1995), and David (1997).

[24] The properties of one such spin system, the stochastic formulation of the Ising model of ferromagnetism, were studied thoroughly by Russian probability theorists during the 1960s. Results from that analysis were taken up quite quickly by mathematical general equilibrium theorists working on what at the time were called random economies. The path-breaking paper by Hans Föllmer on general equilibrium in random economies with interacting agents built directly upon those results from Markov random field theory. David, Foray and Dalle (1997) give references and a discussion of the early contributors to this literature.

course, this might also have been achieved through the reformulation of Föllmer's (1974) "Ising economy" model as a *dynamic* random process. And there were other candidate models from the class of "spin systems" that were available for that heuristic role. But still another selection was the one that happened to have been made.

By now it is widely understood that path dependence is a property of the (non-ergodic) stochastic process known as the Polya urn model, a scheme that involves *sequential* sampling from an urn containing balls of different colors, and over-replacing each colored ball that was drawn. The mathematical statistician Georg Polya (1931) proved that rather than a unique limiting distribution of colors being approached when this sampling sequence was extended indefinitely, any one of a multiplicity of equilibrium configurations was to be expected. But the potential sphere of application for this particular stochastic model was greatly enlarged by Arthur, Ermoliev and Kaniovski (1983, 1986): they generalized the results that had been established for the original two-color model formulated by Polya and Eggenberger (1923), and so derived "strong laws" for urn processes of this sort that involved choices among objects of *n* types (colors).

In the subsequent economic formulations by W. Brian Arthur (1988, 1989, 1994), through which the formal aspects of the generalized Polya urn model were introduced to the economics profession, the properties of path dependence and the possibility of equilibria that were "welfare inefficient" came tightly packaged together. The sequentially evolving cumulative frequency distribution of the colors represented in the urn conditioned the current probability of drawing a ball of a given color, and thus took the role of *a global positive externality effect* — one that was formed by the history of events, the antecedent sequence of actual (realized) draws from the urn. Like the introduction of explicit dynamics, the global as opposed to the local character of the externality effects constitutes a difference in specification — distinguishing the Polya process presented by Arthur (1989) from dynamical versions of the stochastic "Ising economy" model formulated by Föllmer (1974).

But the two stochastic structures just mentioned are different again from another among the reversible spin systems, namely the so-called "Voter Model" whose application in economic contexts was first explored by David (1988, 1993). The behavior of stochastic dynamic systems belonging to this interesting class may be briefly summarized:

- The voter model is a Markov random field model that specifies that there are probabilistic local interactions among agents, like the stochastic Ising model.
- Unlike the Polya process, it is a finite population model and may be specified for either a fixed population, or one that is growing 'slowly' in a sense that is well-defined.
- The random interaction effects among neighbors take the form of positive externalities, affecting (in a deterministic way) the index agent's orientation with regard to a binary choice situation.
- When the interaction space is defined in 1 or 2 dimensions, this system exhibits asymptotic convergence to the extremal states, i.e., those where there is perfect correlation among one or the other of the possible orientations of the agents.
- At higher dimensionalities of the interaction space (the local 'neighborhoods'), the system continues to exhibit strong but imperfect correlation of orientations in its asymptotic configurations. In this respect it shares a feature exhibited by Polya models that have multiplicities of non-extremal attractors.

- As its finite population becomes very large, unlike Polya models, the behavior of the voter model has been found to undergo a significant qualitative change: it loses the strict property of convergence to "trapping" states, so that recurrent fluctuations occur between correlated configurations. (The expected sojourn times in the latter, however, are very extended, so that the dynamics of the system mimic the condition of 'punctuated equilibria.')
- The realized equilibria of the finite voter model system are, of course, path dependent and it is quite possible to specify the model in ways that show some of these to be Pareto-dominated.
- Lastly, it is in general possible to predict which of the two possible extremal asymptotic configurations will be realized in this model — from information on its initial configuration. Indeed, to calculate the expectations of one extremum (and that of its complement) it is sufficient to know just the initial proportion of the agents that have the orientation in question; no further information about the initial configuration is necessary.

In this latter feature ("predictability") the voter model differs from the Polya model popularized by Arthur (1989). It is perhaps also worth emphasizing that the Polya model possesses the generic property that each of its multiplicity of asymptotic "attractors" constitutes an absorbing state for the non-ergodic process. By contrast, as was mentioned, in the stochastic Ising economy the price mechanism is unable to *stabilize* the system; it cannot find a price vector to "support" either of the alternative extremal equilibrium phases, nor any of the far less likely distributions that represent "mixtures" of the pure phases in which the agents' respective preferences are highly correlated. It therefore remains a possibility (even though in a large system one that would be realized only very infrequently) that the *persisting random perturbations* of the agents' preferences that are a feature of this model will precipitate a spontaneous "phase change"— or, in other words, a migration of the ensemble from one pattern of correlated consumption choices to the opposite pattern.

Such migrations cannot occur under the Polya process, because as more and more balls are added to the urn, the effect of each increment upon the distribution of colors must become weaker and weaker. The only source of random perturbations affecting that distribution is the sampling process itself, and in the limit, the impact of those effects dies away to order zero. This is what adds the property known as "lock in" to the others (path dependence and market failure) in the package so neatly presented in the economic applications of the Polya urn model by Arthur (1994). This particular feature is not unique to the Polya urn process, as has been seen, for it appears among the properties of the "voter model" that has lent itself to a variety of economic applications.[25] Yet, partly as a consequence of the details of the historical path followed by the evolution of the economic literature on path dependence, one among which was the packaging of a number of arresting features in the familiar Polya model due to Arthur (1989), the meaning and significance of the term 'lock-in' has itself become a matter of some confusion. Consequently, it is necessary now to consider it more closely.

7. Finale - being the meaning of "lock-in" in the historical context of path dependence

[25] See e.g., David (1993a, 1997), David and Foray (1993, 1994).

The current state of imprecision and confusion in discussions of the meaning and significance of the term 'lock-in' has not been alleviated by use of 'lock in' as one among the taxonomic criteria applied to classify path dependent processes in the recent work of Professors Liebowitz and Margolis. Quite the reverse. I must begin by reiterating some doubts as to the coherence of creating a taxonomy for path dependent economic processes that turns upon whether or not it is possible to imagine a system being inextricably 'locked in' to a state that is locally and globally dominated by other allocative arrangements. Yet the latter would appear to be the very condition that is indicated, when the term is taken by Liebowitz and Margolis (1994, 1995b, 1995c) to refer to a situation where all the participating agents know they would derive a *net* gain by arranging by whatever means were necessary, collectively to exchange the *status quo* for some other available configuration.

By 'net gain' in this definition, is meant a surplus over and above the full costs of organizing and implementing the move to another state. *Ex hypothesis* there will be sufficient surplus in the new state to compensate everyone and leave someone better off after absorbing all the costs of negotiation, mechanism design, and insuring credible commitment, that may be required to implement a collective escape. Therefore, in the circumstances thus posited, one would be hard put indeed to see how, if the agents involved were economically rational individuals, the *status quo* could have persisted long enough to be of interest. What is there in the imagined situation that would serve to lock in anyone to so unstable an attractor? Either we accept that people behave rationally and that such situations will be scarce as hens' teeth, or this is a rendering of the notion of 'lock-in' that would oblige economists to acknowledge that sometimes history really matters as a result of the workings of the mysterious, the irrational, or the wildly improbable forces in economic life — or possible all three.

Can it be thought helpful to impose that particularly exacting meaning upon the term "lock-in," and then commend it (thus redefined, virtually, as the null set) to economists as the one and only manifestation of path dependence that would merit being taken seriously? Is it any more helpful than to have attempted exactly the same re-definitional ploy with regard to the concept of "network externality," in order to represent that latter as an empirically empty category? Consider the parallelism of Liebowitz and Margolis's (1994, 1995b) re-definitional distinction between "network effects" and "network *externalities*," by means of which the latter become identified as "an equilibrium in which there are unexploited gains from trade regarding network participation." Then, when the "unexploited gains from trade" implicitly are taken to be reckoned net of the costs to the relevant parties of arranging the transition to a superior state, the indicated equilibrium qualifies for dismissal as an "uncommon tragedy" indeed. These are quite transparent resorts to the stratagem favored by Humpty-Dumpty: "It's not what the words mean, but who shall be Master!"

By contrast, as the term "lock-in" has been used in my work and that of Arthur (1989), it simply is a vivid way to describe the entry of a system into a trapping region — the basin of attraction that surrounds a locally (or globally) stable equilibrium. When a dynamical economic system enters such a region, it cannot escape except through the intervention of some external force, or shock, that alters its configuration or transforms the underlying structural relationships among the agents. Path dependent systems — which have a multiplicity of possible equilibria among which event-contingent selections can occur — may thus become locked in to attractors that are optimal, or that are just as good as any others in

the feasible set, or that take paths leading to places everyone would wish to have been able to avoid, once they have arrived there.

From this vantage point, Arthur's (1989) phrase "lock-in by small historical events" is evidently a gloss that should not be read too literally; it is a convenient contraction of the foregoing reference to the way in which trapping regions may be entered — although somewhat unfortunate, in allowing a hasty reader to suppose that the antecedent events somehow have *created* the local stability, or locked-in state. To be more precise, albeit more cumbersome, one should say that such configurations are self-sustaining (Nash) equilibria; that in the case of a path dependent process some particular historical event caused — i.e., initiated the sequence of transitions that effectively selected — one rather than another among such configurations to be realized as the system's emergent property.

In some circumstances, as in the case of pure coordination games (where there are strategic complementarities in the dynamic interactions among agents) there is no Pareto-ranking of a multiplicity of available equilibria from amongst which a path dependent, branching process can make a selection. *Which* coordination point is reached is a matter of welfare indifference to the parties involved. A coordination equilibrium thus provides us with the paradigmatic situation in which individuals are content to remain doing something, even though they would be happier doing something else if everybody would also do that other thing too. The reason they don't change what they are doing is, generically, that there are information imperfections that make it unlikely that a decentralized process can get everyone coordinated to move elsewhere, collectively.[26] Now notice that while incomplete information may be critical in blocking spontaneous escapes from dominated coordination equilibria, it is not a necessary condition for decentralized market processes to select such states. This is another reason why presenting "lock-in" as a particular (pernicious, and supposedly uncommon) form of "path dependence" is an invitation to further analytical confusions.

This last, important point can be elaborated by observing that the generic problems of escaping from lock-in of the system to a globally inferior (but locally stable) attractor are rooted in "pure" coordination costs. Such costs may be very high, however, especially if the individual agents are expected to act spontaneously under conditions of incomplete information. Hence, the nature of the *ex post* coordination problem generally is not the same as the problem of arranging coordination with agents who do not yet exist, or who have yet to recognize the complementaries between their interests and capabilities and those initiating the action. The sources of *ex ante* market failure that allow the system to be led into a globally inferior equilibrium are not necessarily the ones that make it very hard to get out.

Of course, if and when the structure of economic incentives and constraints bearing upon the process under study is altered by events that, for the purposes of the analysis may reasonably be regarded as "exogenous innovations" (in the state of relevant knowledge, or in the regulatory institutional regime), the previous attractor(s) may be destroyed, freeing the system to endogenously begin to evolve some new configurations. Thus, the advent of microwave transmission technologies in the 1950s may be seen to have undermined the prevailing regulatory regime governing the U.S. telecommunications industry (which had itself emerged through a path dependent process); and the denouement, in the event of the AT&T

[26] For discussion of this in the context of technical compatibility standards, see, e.g., David and Greenstein (1990); on social conventions, organizational routines and formal institutions, David (1994, Les Standards), and David (1994, Institutions).

divestiture, brought into being a liberalized regulatory regime and new market structure that may be said to have formed new "attractive paths," for the evolution of digital telecommunications technologies. But to claim that the evidence of change itself is sufficient to dispose of the notion of a persisting inefficient "lock-in" is tantamount to supposing that Schumpeter's gale of "creative destruction" is blowing continuously at full force, through every niche, nook and cranny of the economy. Indeed, it is a way of losing one's sense of the variations in the flow of events through time which makes history of interest.

Strategic re-definitions, playing with words to avoid the force of the concepts with which they were originally associated, is a form of rhetoric that is essentially obscurantist. By the purely semantic trick of re-defining path dependence to come in various degrees of seriousness, and by associating the most "serious" form to be — not a process, but a particular outcome state gauged in terms of allocational efficiency, it is possible to give superficial plausibility to the claim that no serious economic consequences are associated with the phenomenon of path dependence. This has been the taxonomic gambit tried by Professors Liebowitz and Margolis, who reserve their "most serious" form of path dependence (third degree) to be the state in which the *status quo* is Pareto-dominated *even after all transition and adjustment costs are considered.* They can then ask, rhetorically, why should one suppose that we would ever find a situation of "serious path dependence" — where people refused to make themselves individually and collectively better off, after paying all the bargaining, transactions and information costs of arranging their escape from a bad situation?

Why indeed? If one insists that the only sort of sub-optimality worth worrying about is the kind so wasteful as to justify escaping at any finite cost, then one is implicitly accepting the actual or equivalent loss of all the remedial expenditures (the costs of undoing the effects of outcomes we collectively prefer not to live with). Is it not pertinent for economists advising private and public agencies to consider the likelihood that some substantial portion of those costs were consequences of the path dependence of the dynamic process through which "regrettable" outcomes were "selected?"

Strategic re-definition and the deployment of taxonomic *non-sequiturs* may be clever moves in rhetorical games, but playing these generally is an unproductive way for scientists of any sort to spend their time. Such pursuits do often succeed in generating some noise and heat, yet those outputs are rarely accompanied by much light. Worse, in the case at hand, the effect has been that of obscuring what new illumination might be gained by acknowledging the phenomena's *potential* economic importance and considering how one might empirically ascertain those aspects of the workings of the economy where that potential tended to be actualized most frequently and fully.

Suppose, for the moment, that the significant economic question to be addressed in regard to the possibility of "lock-in" is this: How can we identify situations in which it is likely that at some future time individuals really would be better off had another equilibrium been selected *ab initio*? By that we must mean that an alternative outcome would be preferred in some collective sense (perhaps by application of a compensation test) to the one that they are now in, and that they also (collectively) be ready to incur some substantial costs to rectify the situation — assuming it was feasible to do so. Were it possible to answer that question by saying that such conditions will never obtain, then economists could well afford not to bother with the distinction between dynamic processes whose outcomes were path dependent and those which were path independent. It would be a distinction that might interest students of history, but would otherwise be inconsequential for economic policy. But such would be true

only if multiple equilibria could be shown never to exist outside the context of pure coordination games (i.e., where none are Pareto-dominated), or if it could be shown that it would never be possible to identify the structural conditions that give rise to other multiple equilibrium situations. We have no impossibility theorems of this sort, and neither of these propositions is likely to be established empirically.

There is, however, another way to look at the question. It may be that the selection of Pareto-dominated equilibria in positive feedback systems are never allowed to become serious enough (in the Liebowitz-Margolis sense) to impress the contemporary observer who can imagine clever if costly mechanisms for organizing collective escapes from locally sub-optimal situations. This, indeed, is a cogent point, and deserves closer attention than it usually receives from economists who challenge the champions of historical economics to look around and find a "really important" example — by which they seem to mean, a case of path dependent dynamics leading to a grossly inefficient equilibrium. Instead of imagining that history is played out without anybody noticing what is happening, and then when an equilibrium appears to be reached, that people gather around and assess its optimality, we must allow for the process to encompass possibilities and consequences of incremental *path-constrained meliorating actions* being taken by observant, intelligent agents.

The static framework of welfare analysis within which too many economists are still being taught to do their thinking tends to suppress the natural disposition to conceptualize the whole flow of current economic life as contingent upon the results of antecedent choices. Seen in truly historical perspective, a great deal of human ingenuity, especially the sort that is said to be "mothered by necessity," is devoted to trying to cope with "mistakes" that are threatening to become "serious" in their economic consequences; to assuring, somehow, that their more pernicious effects will be moderated if not abated altogether. This is done *ex post*, by contriving technological "fixes" and "patches," by commandeering temporary task forces to handle emergencies that established organizational structures are discovered to be handling badly, by sustained efforts at "reforming" (not reinventing) long-standing institutions, and, yes, by concerted educational campaigns to untrain people who have acquired dysfunctional habits of one sort or another.

We like to refer to all of that activity as "progress" and, in a historically local sense, that is just what it is: melioration. But the meliorative options are more often than not quite tightly bounded by the existing critical situation: it is the existing software code that threatens to malfunction badly when the year 2000 rolls around, not some other programs and data formats that were not implemented, although they might well have been trivial to modify. The resources spent in such perceived loss-avoidance activities are part of what we are happy to consider productive investments, adding to the net product, whereas some part of it could equally well be thought of as the deferred costs of regrettable decisions made in haste to be remedied at leisure, and sometimes for great profit. They might equally be called regrettable economic opportunities.

Most of the situations in which the discomforts of remaining in a bad coordination equilibrium could be really large are those in which the institution, or technology, or a behavioral norm has become highly elaborated and deeply embedded in numerous activities throughout the economy. One must then must contemplate a counter-factual world in which the whole general equilibrium course of evolution would have been very different. Consideration of the implications of general purpose technologies is one of the ways in which

economists today are coming to grips with this sort of systems analysis. Little wonder, then, that economic historians have been and should be concerned primarily with such questions.

8. One more chorus of QWERTY ... staying 'on key' right through the policy refrain

As I have already confessed, the story of QWERTY provided the simplest heuristic device I could find that might provoke economists to take seriously the ways in which past events have shaped the world around us. QWERTY turned out to be an effectively emblematic case, partly because it exhibited all the elements of much more important and complicated examples, and perhaps also because economic journalists could relate to its subject matter in a very immediate personal way.

Whether Dvorak is or is not ergonomically better than the QWERTY keyboard arrangement, and whether the pre-Dvorak contender, the Ideal keyboard, was superior to QWERTY as its champions claimed, of course, are questions that remain intensely interesting for some specialists concerned with the acquisition of motor skills, and also continue to be debated among aficionados of the history of the typewriter industry. It is important to try to get the story's technical details as right as is possible, because that is what writers of history are supposed to do — which is why I have thought it best to respond to some of the empirical assertions made in criticism of my historical narrative, albeit in another place.

But, there should be no doubt that it is the underlying issues concerning the micro-level sources of non-ergodicity, positive feedbacks and path dependence, and their association in this case with the potential for market failures, that imparts significance to the instance of QWERTY, rather than the reverse. The case for the existence of path dependence in the evolution of economies cannot be thought to turn upon the verdict that psychologists and experts in keyboard ergonomics may deliver about the magnitude of the net gains or losses that would result from switching the world's typists to some keyboard(s) other than the ones to which they have become accustomed.

Nor is the existence of lock-in phenomena thrown into doubt by the counter-argument that were the Dvorak standard for keyboard layouts economically more efficient (Pareto superior), an entrepreneur would be making a fortune marketing it today. Nobody argues that QWERTY is ergonomically superior to, or even close in that respect to the Maltron keyboard, or still other, newer entrants such as the VELOTYPE system introduced by a Swedish firm in the late 1980s. Yet, the companies who are trying to market these alternatives today don't seem to be making money at it. To explain this by saying that the savings made available to individuals by those systems don't make unilateral switching worthwhile in a world where QWERTY is the existing coordination standard, is simply to refuse to understand what a coordination equilibrium is about in the first place. But that has been precisely the core of the conceptual objections (as distinct from the empirical allegations) raised by Liebowitz and Margolis (1990) against the rendering of the story found in David (1985, 1986).

The point made previously about the possibilities of path-constrained meliorative action is worth returning to in this connection. As the believers in the market system rightly contend, people can and do make money by adaptations designed to remove or circumvent gross inefficiencies in the workings of institutions and technological systems that their society has inherited from the past. And, once the fact that the economy is becoming committed to a particular trajectory of development is recognized, it makes sense for innovators to go with

the flow and elaborate it further in ways that improve its performance. Electrically activated keyboards, and ergonomically improved layouts have much reduced the stresses originally imposed on manual typists by the QWERTY layout. Similarly, to take another familiar technological illustration, one may consider the 640K lower memory constraint on all the DOS-based programs that have ensued (up to Windows 95), and ask: How would the whole software industry have developed had there not been the premium placed on clever ways to use high-level memory subject to the lower memory constraint? Recall further that the latter was not the product of a carefully considered optimization, but was created by the choices made (myopically) by IBM design team in their rush to get out their first PCs.

The foregoing hardly exhausts the examples that can be readily produced in the same vein. Although AC current would make the operation of all our electronic technologies infeasible, today we enjoy the benefits of having learned over many decades to make smaller and smaller and more and more efficient DC converters, which are built into all our radios, TVs, computers, etc.—to the point that we don't even notice them. Suppose we had not had to do that, because we distributed DC locally to begin with. If we distributed DC, further, we could store it using batteries and have done research to make the latter more efficient. And then, having electricity that was not a "perishable," as AC was, we would not have had to figure out peak load management techniques and pricing schemes, etc., etc. (on which one might consult David 1990, 1991 for further details).

Analogously, nuclear power generation system designs based on light-water reactor technology rather than gas-graphite reactors have imposed similar costs of adaptation, which remain burdensome to this date, especially in countries like the US that use their nuclear plants as base-load capacity. Light-water reactors must be periodically shut down for refueling. This hardly appeared to be serious drawback in submarines, where, championed by the U.S. Navy's Captain Hyman G. Rickover, the initial applications work with nuclear power was undertaken.[27] Conventional submarines could not operate continuously, as they had to surface periodically to recharge their batteries; by comparison, the nuclear power plant design would extend underwater running times. The light-water reactor thus presented the only immediately available working design for a nuclear power plant at the end of the 1950s, when, in the wake of the Cold War propaganda crisis created by the launch of Sputnik, the AEC moved quickly to realize the promise of a civilian use for atomic energy. From that choice of a plausible, yet truly sub-optimal starting point, there followed much subsequent expenditure of engineering effort and construction cost in order to deal with the problems of containment for land-based use of light-water reactors, curtail costly down-time during refueling, and mitigate the hazards of catastrophic failures that are at their greatest during startups and shutdowns of these facilities.[28] Progress? Certainly. But, was this particular technological trip necessary?

The same point can be made in regard to another complex evolutionary process, one that step-by-step brought about the widespread dependence upon high-yield systems of agricultural production. These now entail the technically interrelated use of chemical

[27] A career engineer officer, Rickover intially had been seconded to Oak Ridge to do a paper study of a liquid-metal-cooled reactor for a destroyer, and in 1948 work on sodium-cooled reactors was underway at the Argonne Laboratories, and in the General Electric facility at Knolls, near Schenectady; but once Rickover's attention shifted to the application of nuclear propulsion in submarines, the liquid sodium designs were rejected in favor of developing a light-water pressurized water reactor. For other details, see the history related by Cowan (1991).

[28] On the latter, and, in the instance of the accident at Three Mile Island, another illustration of hysteresis effects in the industry, see, e.g., David, Maude-Griffin and Rothwell (1996).

fertilizers, monoculture, and heavy applications of fungicide/pesticide sprays. The associated structure of private costs and private returns is sustaining a situation of lock-in with whose perceived deleterious environmental consequences we currently are having to cope — as has been shown recently by Robin Cowan and Philip Gunby's (1996) exemplary analysis of the difficulties impeding a large-scale spontaneous escape back into organic farming.

In considering the nature of the policy lessons that might be drawn from the foregoing view of the incremental evolutionary development of complex technological systems, some remarks on the putative role played by "historical accidents" in path dependent processes are now very much in order. Unfortunately, the use of that phrase itself is prone to cause misunderstandings. It is quite misleading to take it to suggest that some original economic irrationality, or implementation error (accident) must be implicated whenever we find that positive network externalities have given rise to a sequence that turned out to be other than a globally optimal path. Indeed, only those who are hostile to the very idea of path dependence would repeatedly insist upon a literal interpretation of the phrase "accidents of history." Doing so suggests that the essential feature of such processes is that the original actors in the drama — whether as contributors to the design of a technical system, or an institutional rule structure, or a particular form of business organization, or as the initial adopters of such innovations — had to have been acting arbitrarily, or irrationally in the context of their economic circumstances. Such an interpretation is not only logically unwarranted; it obfuscates an important but widely overlooked feature common to the histories of many network technologies, and one that has some bearing upon the way public policy might be approached in that area.

The facts of all the technological instances recently under re-examination — QWERTY, 640K lower memory in the IBM PC, AC vs DC electrical current, light-water reactors, and VCR formats, too — are quite consistent with the view that the behavior of the initiating actors of the drama, generally, was quite deliberate (not at all random in the sense of remaining inexplicable to the historian); and furthermore, reasonably conformable to the urgings of the profit motive. Yet, generally, their actions also were bounded by a parochial and myopic conception of the process in which they were engaging — in the sense that these decision agents were not concerned with whether the larger system that might (and was) being built around what they were doing would be optimized by their choice.[29] In most cases they can be held to have failed entirely to foresee the complementary innovations and investments that would be influenced by their initial commitment to one rather than another course of action. In other words, their failure of imagination took the form of not thinking systemically about the technological and industrial structures that they were engaged in developing. Thomas Edison, of course, being a systems inventor par excellence, was an exception in that particular regard; yet, as has been shown by David (1991), Edison's business strategy in the context of the 'Battle of the Systems' — including his sudden decision to withdraw from the flourishing electrical supply systems industry altogether — appears to have been driven by quite different, rather myopic, but nonetheless rational economic considerations.

In general, what was difficult for the pioneers in any area to foresee were the complementaries that would emerge subsequently, and in so doing open the possibilities of developing a more complex, distributed system whose components were not produced or purchased integrally. The Remington Co. engineers who put the finishing touches on the first

[29] See, e.g., David (1987, 1990); David and Bunn (1988), Cowan (1991).

commercially successful typewriters to carry QWERTY into the world did not dream of the possibility of touch-typing manuals; Edison had not anticipated that anyone would devise an efficient and economical converter to link DC electrical supply facilities with distant users by way of polyphase AC networks. Similarly, in more modern times, neither of the rival vendor groups behind the Sony Betamax and VHS cassette formats in the early VCR market had anticipated the commercial importance of pre-recorded movies and video rental stores.[30] Nor were the IBM engineers in Texas, as they rushed to create a readily producible personal computer, concerned with the amount of random access memory that would be needed to load a word-processing program like WordPerfect whilst keeping an Excel spreadsheet and a LAN-modem open and running in the background.

The point here is not that these folks ought to have seen the shape of the future. Rather it is that the shape of the larger systems that evolved was built upon their work, and thus in each case preserved, and was in some respects much constrained by it — even in the way that they coped with the legacies of those initial decisions, taken quite deliberately, but with quite other and in some measure more evanescent considerations in mind.

Whatever the intended purpose of misconstruing the economic analysis of path dependence as requiring that sheer accidents or irrational economic action plays a critical role, its effect is to set up a rhetorical strategy in which a superficial appearance of doubt may be cast upon this approach — by simply pointing to evidence that the principals involved in the early stages of the (technological, or other developmental) process actually had not acted in some random and economically irrational manner. As if anyone had claimed otherwise![31] Myopia, and lack of prescient imagination are not synonyms for lack of calculation and inconsistencies in the behavior of individual economic agents. The building and demolition of straw men is a form of mental exercise too well-practiced among academics. Unfortunately, like many other kinds of public calisthenics, it creates a spectacle that generally proves unedifying for the audience.

From the foregoing it may be seen that a proper understanding of path-dependence, and of the possibilities of externalities leading to market failure, is not without interesting implications for economic policy. But those are not at all the sorts of glib conclusions that some critics have alleged must follow if one believes that history really matters — namely, that government should try to pick winners rather than let markets make mistakes. Quite the contrary, as I began trying to make clear more than a decade ago.[32] One thing that public policy could do is to try to delay the market from committing the future inextricably, before enough information has been obtained about the likely technical or organizational and legal implications, of an early, precedent-setting decision.

In other words, preserving open options for a longer period than impatient market agents would wish is the generic wisdom that history has to offer to public policy makers, in all the applications areas where positive feedback processes are likely to be preponderant over negative feedbacks. Numerous dynamic strategies can and have been suggested as ways of

---

[30] Compare the detailed analyses of the VHS market in Baba and Imai (1990), Cusamano, Myolandis and Rosenbloom (1992) and Gridley (1992), none of which are noticed in Liebowitz and Margolis (1994), or the latter authors' subsequent references to this case.

[31] Compare, e.g., the critical discussion of the early history of VCRs in the discussion of network externalities by Liebowitz and Margolis (1994, 1995a, 1995b, 1995c).

[32] Especially in David (1987), David and Bunn (1988), David and Greenstein (1990) and, most forthrightly in David (1992).

implementing this approach in various, specific contexts where public sector action is readily feasible. Still more sensible and practical approaches will be found if economists cease their exclusive obsession with traditional questions of static welfare analysis, and instead of pronouncing on the issue of where state intervention would be justified in the economy, start to ask what kind of public actions would be most appropriate to take at different points in the evolution of a given market process.

The "first best" public policy role in these matters, therefore, is not necessarily the making of positive choices, but instead the improvement of the informational state in which choices can be made by private parties and governmental agencies. In the context of the recent literature on sunk cost hysteresis and options theory, one may see that the more history matters — because complementaries create irreversibilities in resource commitments — the more worthwhile it is to invest in being better informed prior to leaping. There is an evident opportunity cost in giving priority to investments in further information acquisition; quite standard economics can be relied on to balance the expected value of waiting (searching) for further "news" against the anticipated costs to the current generation(s) of not allowing markets to make choices on the basis of the knowledge that is presently available. Obviously, some assessment of the rate at which the relevant information states are capable of evolving will turn out to be of critical importance in determining when a stage has been reached where it no longer is best to defer irreversible resource commitments.

9. Coda - Overcoming intellectual sunk cost hysteresis

The cluster of ideas that are now identified with the concept of path dependence in economic and other social processes probably would not excite such attention, nor require so much explication, were it not for the extended prior investment of intellectual resources in developing economics as an ahistorical system of thought. For many economists, their own costs sunk in mastering that discipline have produced a facility for reasoning that suppresses natural, human intuitions about historical causation. They thus have a "learned incapacity" (in Thorstein Veblen's apt phrase) to see how historical events could exert a causal influence upon subsequent outcomes that would be economically important. Perhaps unknowingly, such folk have fully internalized Aristotle's teleological principle of explanation, which rejected the method of reference to antecedents, and so escaped infinite explanatory regress by substituting forward-looking functionalism (as we would describe it). This was undoubtedly useful, even though it has had the intellectual side effect, in many disciplines, of encouraging the formal suppression of the intuitive impulse to refer to pre-existing states and intervening "events" when asked to account for the way things are today.

Mainstream economics is not alone among the social sciences in providing a way to explain an existing state of the world by reference to the purpose or end (*telos*) that it serves, rather than to the conditions from which it may have evolved.[33] This has proved a source of deep insights into many matters, but not to all matters of concern to economists and students of broader cultural phenomena, such as the spread of languages and social communication norms.[34] Nor, for that matter, does it suffice to provide good accounts of biological phenomena. In modern Darwinian evolutionary theory there is a beautiful, productive tension

[33] See David (1993, Historical Economics) for more on the teleological mode of analysis in economics.

[34] For further discussion of the latter topics, see, e.g., David (1994), David and Foray (1993).

between the teleological principle of natural selection according to inclusive fitness, and the antecedents principle, viz., that the possibilities of evolution are tightly constrained at every moment by the current contents of the gene pool, which is the product of species' history. Perhaps that is why we might be drawn towards evolutionary biology as "the Mecca for economics."

Modern economics in its ahistorical, convergence model formulation serves some intellectual purposes very well, and the perpetuation of the methodological *status quo* can be seen to serve still other rational private ends. Nevertheless, if that style of explanation was entirely satisfactory in accounting for all economic and social phenomena without reference to legacies from the past, some of us would not presently be so exercised by trying to adjust contemporary economic thinking to the notion that history matters — nor would others be strenuously resisting that adjustment. Path dependence is a concept requiring explication for many today, simply because so much of economics has committed itself to theories that would make the results of choice behaviors consistent in the sense of being path independent. But there is no compelling reason to regard that as an exclusive and binding commitment.

Path dependence, at least to my way of thinking, is therefore about much more than the processes of technological change, or institutional evolution, or hysteresis effects and unit roots in macroeconomic growth. The concepts associated with this term have implications for epistemology, for the sociology of knowledge, and cognitive science as well.[35] Nevertheless, it would be quite wrong to imagine that positive feedback dominates all aspects of economic life (let alone 'life'), just as it is unwarranted to proceed on the supposition that economic dynamics everywhere are intrinsically characterized by the operation of stablising, negative feedback systems. Considering the possibility that the former framework is the one most relevant in a particular context does not rule out the opposite conclusion, or preclude appropriate resort to the latter framework — the familiar convergence models of neoclassical economics. These really are not necessarily mutually exclusive tool-sets, or incompatible standards, that cannot be integrated into a larger intellectual system. Even though we should be aware of the workings of strong social processes — familiar in the sociology of knowledge – that can turn normal science procedures into exclusionary dogmas, it is not necessary for social and behavioral scientists to adopt positions that exacerbate and amplify those tendencies.

Once the concept and the ideas surrounding path dependence are properly understood, there can be no reason to construe them as necessarily corrupting the discipline of economics, or to fear that once admitted they would be subversive of all *laissez-faire* policies. There are simply no good grounds to go on actively resisting these ideas, which if accepted will lead us into previously little-explored regions of theoretical and empirical enquiry. Nor is there even a sound precautionary case for seeking to contain their spread until it can be determined what would become of the grand edifice of economic analysis as we know it, once the assumed global dominance of negative feedback processes were discarded. The logic of sunk cost hysteresis has a legitimate place in the conventional theory of optimal investment behavior. Yet, when it is carried over and applied to the field of *intellectual* investments in new tools of

[35] On these epistemological topics, see, e.g., the stochastic models developed in David (1997), and David and Sanderson (1997).

economic analysis, the result is a self-defeating orthodoxy of thought and surely not the optimal progress of our discipline.

Citations to Works by Paul A. David

A chronological listing of publications dealing explicitly with conceptual and methodological aspects of path dependence, macro-level irreversibilities and hysteresis in economic processes.

Transport Innovation and Economic Growth: Professor Fogel On and Off the Rails, *Economic History Review*, Vol. 22, No. 3, December 1969, pp. 506-525.

The Landscape and the Machine: Technical Interrelatedness, Land Tenure and the Mechanization of the Corn Harvest in Victorian Britain, in *Essays on a Mature Economy*, D. N. McCloskey (ed.), London: Methuen, 1971, pp. 145-205.

Technical Choice, Innovation and Economic Growth: Essays on American and British Experience in the Nineteenth Century, Cambridge: Cambridge University Press, 1975.

Clio and the Economics of QWERTY, *American Economic Review*, 75 (2), May 1985.

Understanding the Economics of QWERTY: The Necessity of History, in *Economic History and the Modern Economist*, W. N. Parker, ed., London: Basil Blackwell, 1986

Some New Standards for the Economics of Standardization in the Information Age, in *The Economics of Technology Policy*, P. Dasgupta and P. L. Stoneman, eds., London: Cambridge University Press, 1987.

Path Dependence: Putting the Past into the Future of Economics, *Institute for Mathematical Studies in the Social Sciences Technical Report 533*, Stanford University, November 1988.

The Economics of Gateway Technologies and Network Evolution: Lessons from Electricity Supply History, (with **Julie A. Bunn**), *Information Economics and Policy*, Vol. 3, Winter 1988, pp. 165-202

When and Why Does History Really Matter? *A Presidential Address to the Economic History Association,* Delivered at the Smithsonian Museum of Science and Technology, Washington D.C., September 1989. [Department of Economics Working Paper, Stanford University, October 1989.]

Heros, Herds and Hysteresis in Technological History, *Journal of Industrial and Corporate Change*, Vol. 1 (1), 1990.

The Economics of Compatibility Standards: An Introduction to Recent Research, (with S. Greenstein), in *Economics of Innovation and New Technology*, 1(1 & 2), Fall 1990: 3-42.

The Hero and the Herd: Reflections on Thomas Edison and the 'Battle of the Systems,' Ch.2 in *Favorites of Fortune: Technology, Growth, and Economic Development Since the Industrial Revolution*, P. Higonnet, D.S. Landes and H. Rosovsky, eds., Cambridge, MA: Harvard University Press, 1991.

'Path Dependence and Economics' — The 1991-1992 Marshall Lectures delivered at the University of Cambridge, April 28-29, 1992. *Lecture I*: 'The Invisible Hand in the Grip of the Past'; *Lecture II*: 'Models of Non-Ergodic Economic Dynamics, and their Implications for Policy.' [Center for Economic Policy Research Working Paper, Stanford University, August, 1992]

Path Dependence in Economic Processes: Implications for Policy Analysis in Dynamical System Contexts, *Background Paper — Rosselli Foundation Workshop on Path Dependence*, Torino, Italy, 29-30 May, 1992. [Center for Economic Policy Research Working Paper, Stanford University, August, 1992.]

Path dependence and Predictability in Dynamic Systems with Local Network Externalities: A Paradigm for Historical Economics, in *Technology and the Wealth of Nations*, D. Foray and C. Freeman, eds., London: Pinter Publishers, 1993.

Historical Economics in the Long Run: Some Implications of Path Dependence, in *Historical Analysis in Economics*, G.D. Snooks (ed.), London: Routledge, 1993.

Intellectual Property Institutions and the Pandas Thumb: Patents, Copyrights, and Trade Secrets in Economic Theory and History, in *Global Dimensions of Intellectual Property Protection in Science and Technology*, M. Wallerstein, et al., eds., Washington, DC: National Academy Press, 1993.

Percolation Structures, Markov Random Fields and the Economics of EDI Standards Diffusion, (with **Dominique Foray**), in *Global Telecommunication Strategies and Technological Change*, G. Pogorel, ed. Amsterdam: Elsevier Science Publishers, 1993.

Dynamics of Technology Diffusion through Local Network Structures, (with **Dominique Foray**) in *Evolutionary Economics and Chaos Theory: New Developments in Technology Studies*, L. Leydesdorff (ed.), London: Pinter Publishers, 1994.

Positive Feedbacks and Research Productivity in Science: Reopening Another Black Box, Ch. 8 in *Technology and Economic Change*, O. Grandstrand and P. Jacobson, eds., Amsterdam: Elsevier, 1994.

Les standards des technologies de l'information, les normes de communication et l'etat: un problem de biens publics, Ch. 10, in *L'analyse economiques des conventions*, A. Orleans, ed., Paris: Presses Universitaires, 1994.

Why Are Institutions the 'Carriers of History'? Path dependence and the Evolution of Conventions, Organizations and Institutions, *Structural Change and Economic Dynamics*, vol.5, no.2 1994: pp.205-220.

Dépendence du sentier et économie de l'innovation: Un rapide tour d'horizon, (with **Dominique Foray**), *Revue d'Economie Industrielle*:Numéro Exceptionnel:Economie industrielle—développments récents, 1er trimestre, 1995: pp.27-51

Making Use of Treacherous Advice: Cognitive Progress, Bayesian Adaptation and the Tenacity of Unreliable Knowledge, (with **Warren C. Sanderson**), Ch. 12 in *Frontiers of the New Institutional Economics*, eds. J. V. Nye and J. Drobak, San Diego, CA: Academic Press, 1996.

Marshallian Externalities and the Emergence and Spatial Stability of Technological Enclaves, (with **Dominique Foray and Jean-Michel Dalle**), *Economics of Innovation and New Technologies* (Special Issue on Economics of Localized Technical Change, ed. C. Antonelli), vol.4(2&3), 1997.

Communication Norms and the Collective Cognitive Performance of 'Invisible Colleges', forthcoming in *Creation and Transfer of Knowledge: Institutions and Incentives*, eds., G. B. Navaretti, P. Dasgupta, K.-G. Maier and D. Siniscalco, Heidelberg: Physica-Verlag, 1997.

Other Works Cited

Arthur, W. B. (1988). Self-Reinforcing Mechanisms in Economics, in *The Economy as an Evolving Complex System* (Santa Fe Institute Studies in the Science of Complexity, **5**), Redwood City, CA: Addison-Wesley.

Arthur, W.Brian (1989). Competing Technologies and Lock-in by Historical Small Events, *Economic Journal*, 99 (March): 116-131.

Arthur, W. Brian (1990). Industry Location Patterns and the Importance of History, *Mathematical Social Sciences*, 19: 235-251.

Arthur, W. Brian (1994). *Increasing Returns and Path Dependence in the Economy*, Ann Arbor: University of Michigan Pres.

Arthur, W. B, Ermoliev, Yu. M. and Kaniovski, Yu. M (1983). A generalized urn problem and its applications, *Kibernetika*, 19: 49-57 (in Russian). Translated in *Cybernetics*, 19: 61-71.

Arthur, W. B, Ermoliev, Yu. M. and Kaniovski, Yu. M (1986). Strong Laws for a Class of Path-Dependent Urn Processes, *Proceedings of the International Conference on Stochastic Optimization, Kiev 1984*, Arkin, Shiryayev, Wets (eds.), New York: Springer (Springer Lecture Notes in Control and Information Sciences, 1986, 81.

Baba, Y. and Imai, K. (1990). Systemic Innovation and Cross-Border Networks: The Case of the Evolution of the VCR Systems. Paper presented to the Schumpeter Society Conference on Entrepreneurship, Technological Innovation and Economic Growth, held at Airlie House, VA, June 3-5, 1990. (April).

Basalla, G. (1988). *The Evolution of Technology*, Cambridge: Cambridge University Press.

Brown, L. (1993), *The New Shorter Oxford English Dictionary, On Historical Principles*, Oxford: Clarendon Press.

Cowan, R. (1990). Nuclear Power Reactors: A Study in Technological Lock-in, *Journal of Economic History*, 50(3), September : 541-67.

Cowan, R. (1991). Tortoises and Hares: Choice among Technologies of Unknown Merit, *Economic Journal*, 101(407), July : 801-14.

Cowan, R. and Gunby, P. (1996). Sprayed to Death: Path Dependence, Lock-In and Pest Control Strategies, *Economic Journal*, 106(436), May : 521-42.

Cusumano, M. A., Mylonadis, Y. and Rosenbloom, R. S. (1992). Strategic Maneurvering and Mass-Market Dynamics: The Triumph of VHS over Beta, *Business History Review*, 66(Spring): 51-94.

David, P. A., Maude-Griffin, R. C. and Rothwell, G. S. (1996). Learning by Accident? Reductions in the Risk of Unplanned Outages in U.S. Nuclear Power Plants After Three Mile Island, *Journal of Risk and Uncertainty*, vol. 12: 175-198, 1996.

Durlauf, S. (1990), Non-ergodic Economic Growth and Fluctuations in Aggregate Output. *American Economic Review*, **80** (3).

Durlauf, S. (1996), Neighborhood feedbacks, endogenous stratification, and income inequality, in *Dynamic Disequilibrium Modelling*, Cambridge: Cambridge University Press.

Eldridge, N. (1985), *Time Frames: The Rethinking of Darwinian Evolution and the Theory of Punctuated Equilibria*, New York: Simon and Schuster.

Fisher, F. M. (1983), *The Disequilibrium Foundations of Equilibrium Economics*, New York: Cambridge University Press.

Fogel, R. W. (1964), *Railroad and American Economic Growth*, Baltimore: The Johns Hopkins Press.

Föllmer, H. (1974). Random Economies with Many Interacting Agents, *Journal of Mathematical Economics*, 1: 51-62.

Gould, S. J. (1989). *Wonderful Life: The Burgess Shale and the Nature of History*, New York: W. W. Norton & Company.

Grimmet, G. (1989). *Percolation*, New York: Springer-Verlag.

Grindley, P. (1992). *Standards, Business Strategy and Policy: A Casebook*. London: London Business School.

Koot, G. M. (1987). *English Historical Economics, 1870-1926*, Cambridge: Cambridge University Press.

Krugman, P. (1991). *Geography and Trade*, Cambridge MA: MIT Press.

Krugman, P. (1994). *Peddling Prosperty*, New York: W. W. Norton and Company.

Liebowitz, S.J., and Margolis, Stephen E. (1990). The Fable of the Keys, *Journal of Law and Economics*, 33(1), April: 1-25.

Liebowitz, S.J., and Margolis, Stephen E. (1994). Network Externality: An Uncommon Tragedy, *Journal of Economic Perspectives*, 8(2), Spring : 133-50.

Liebowitz, S.J., and Margolis, Stephen E. (1995a). Are Network Externalities a New Source of Market Failure? *Research in Law and Economics*, 17(0):1- 22

Liebowitz, S .J., and Margolis, Stephen E. (1995b). Path Dependence, Lock-in, and History, *Journal of Law, Economics, and Organization*, 11(1), April :205-26.

Liebowitz, S. and Margolis, Stephen E. (1995c). Policy and Path Dependence: From QWERTY to Windows 95, *Regulation: The Cato Review of Business & Government*, 3:33-41.

Liggett, T. M. (1985) *Interacting Particle Systems (Gundleheren der mathematischen Wissenschaftern **276**)*, Berlin: Springer-Verlag.

McCloskey, D. N., ed. (1971). *Essays on a Mature Economy*, London: Methuen.

McCloskey, D. N. (1974). Victorian Growth: A Rejoinder to Aldcroft, *Economic History Review*, Second Series, 27(2), May: 275-277.

McCloskey, D. N. (1976). Does the Past Have Useful Economics? *Journal of Economic Literature*, 14(2), June: 434-461.

Mokyr, J. (1990), *The Lever of Riches: Technological Creativity and Economic Progress*, New York: Oxford University Press.

North, D. N. (1990), *Institutions, Institutional Change and Economic Performance*, Cambridge: Cambridge University Press.

Solow, R. M. (1986). Economics: Is Something Missing?, in *Economic History and the Modern Economist*, William N. Parker, ed., Oxford: Basil Blackwell: pp. 21-29.

Ruelle, D. (1991) *Chance and Chaos*, Princeton: Princeton University Press.

Steward, I. (1990), *Does God Play Dice? The New Mathematics of Chaos*, London: Penguin.

Teggart, F. J. (1977). *Theory and Processes of History* (Second Paperback printing of the 1941 Edition of *Theory of History* (1925) and *TheProcesses of History* (1918), published in one volume), Berkeley, California: University of California Press.

Teggart, F. J. (1939). *Rome and China, a Study of Correlations in Historical Events*. Berkeley, California: University of California Press.

Williamson, O. E. (1993), Transaction cost economics and organization theory, *Industrial and Corporate Change*, **2**(2):pp. 107-156.

Discussion Papers in Economic and Social History

are edited by:

Liam Brunt
Nuffield College, Oxford, OX1 1NF

James Foreman-Peck
St. Antony's College, Oxford, OX2 6JF

Susannah Morris
Nuffield College, Oxford OX1 1NF

Avner Offer
Nuffield College, Oxford, OX1 1NF

papers may be obtained by writing to
Avner Offer, Nuffield College, Oxford, OX1 1NF email:avner.offer@nuffield.ox.ac.uk