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WORKING PAPER

**ON COMPETING TECHNOLOGIES AND HISTORICAL SMALL EVENTS:
THE DYNAMICS OF CHOICE UNDER INCREASING RETURNS**

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Stanford University

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ABSTRACT

This paper explores the dynamics of microeconomic choice between objects with increasing returns. It finds that such dynamics possess four features: (a) a potential *inefficiency* of aggregate outcome, even where individual choices are perfectly rational; (b) an *inflexibility* of outcome, in that market shares become locked-in--they cannot always be influenced by standard, marginalist policy measures; (c) a *non-predictability*, in that knowledge of supply and demand conditions does not suffice to predict ultimate market shares; and (d) a *non-ergodicity*, in that small historical events are not always averaged away, but can determine the path of market shares. These properties are demonstrated within a simple model where agents choose between technologies competing for adoption.

Choice under increasing returns appears to raise serious questions for policy prescription, for the interpretation of economic history, and for the possibility of constructing models for accurate economic prediction.

ON COMPETING TECHNOLOGIES AND HISTORICAL SMALL EVENTS: THE DYNAMICS OF CHOICE UNDER INCREASING RETURNS

W. Brian Arthur

Attempts to describe the dynamics of markets with increasing returns¹ (or decreasing supply costs) have long been frustrated by an analytical difficulty. Where objects with increasing returns compete, the market outcome is usually indeterminate. It is not difficult to see why. With increasing returns present in a given problem, non-convexities appear, so that multiple equilibria are called into being. Information on preferences, endowments and transformation possibilities enables us to locate these long-run equilibria, but it is often insufficient to tell us *which* one will be "selected". From many initial positions of interest, the system--like a pencil perfectly balanced on its point--is equally "attracted" by several equilibrium outcomes. We cannot say which way it will "fall"; we cannot describe uniquely which path it will follow; hence we cannot pursue conventional analysis.² And theory has little further to say.

As a simple example of this type of problem, consider an island in which cars are introduced, all at more or less the same time. Drivers

1 By contrast, the *statics* of economies with increasing returns is the subject of a vigorous literature. For general increasing-return studies, see among others, Arrow and Hahn (Ch.7, 1971), Beato (1982), Brown and Heal (1976, 1979), Flaherty (1980), Guesneries (1975), Krugman (1980), Scarf (1983), Schelling (1978), Spence (1981), and Weitzman (1982). Economies with increasing returns (or decreasing supply cost) commodities possess several interesting properties: for example, Pareto optima are not always equilibria; conversely, equilibria may satisfy standard first-order conditions, yet be inefficient; and not all endowment distributions permit the attainment of optimality through trading.

2 In the Principles (9th Ed., p.805), for example, Marshall tried to analyze the case where several firms with decreasing long-run cost curves compete for shares of an industry. One firm, he showed, eventually prevails. But *which* one achieves the monopoly he could not determine: the outcome depended on "whichever firm first gets a good start".

are free to choose between the right- and left-hand sides of the road and have no in-built bias toward either. Each side possesses increasing returns: as a higher proportion of drivers chooses one side, the very real returns to choosing that side rapidly rise. Casual thought tells us that we would observe a good deal of randomness to the proportions initially driving on each side, but that, if one side by chance got sufficiently ahead, other drivers would "fall in" on this side, so that eventually all cars would drive on the same side of the road. Of course, the side that "wins"--that comes to "dominate the market"--cannot be deduced in advance. The outcome is indeterminate. And perhaps we must conclude that there is little more to be said in this case.

But notice, in this rather artificial example, four aspects of the outcome in themselves worth investigation. First, in contrast to the usual diminishing-returns situation, the outcome need possess no efficiency properties--the side that "takes the market" need not, from any long-term collective viewpoint, be the better of the two. Second, driving is now locked-in to the "chosen" side. The outcome is structurally rigid, in that marginal inducements to individual drivers to change sides would likely prove ineffective and policy must find other means. Third, even though we know drivers' preferences and possibilities, *ex ante* the outcome would be hard to predict. "Small events" outside the model--perhaps some drivers' reactions, perhaps a dog running into the road, perhaps the timing or" positioning of certain traffic lights--may be crucial in deciding the outcome. And fourth, *ex post*, exact causality would be hard to assign--it would certainly be a mistake to ascribe it to the "superiority" of the outcome.

What of the indeterminacy? One way to bring it within analytical scrutiny would be to make explicit the "small events", add them to the model, and examine in detailed "slow-motion" the dynamic process by which they cumulate into an aggregate outcome. This would be difficult in our imaginary example. But if it were possible in some better-defined case, we should want to ask by what process "small events" tend to make a large difference where there are increasing returns, but not usually where there are diminishing returns, and to what degree knowledge of supply and demand functions enables us to predict market shares.

In this paper we attempt to explore, by way of a mathematically simple model, the dynamics of choice between objects with increasing returns. We find that such dynamics typically possess four features: (a) a potential *inefficiency* of aggregate outcome, even where individual choices are perfectly rational; (b) a potential *inflexibility* of outcome, in that ultimate market shares cannot always be influenced by standard, marginalist policy measures; (c) a *non-predictability*, in that complete knowledge of supply and demand functions does not suffice to predict the path of market shares; and (d) a *non-ergodic property*, in that "small events" at the outset are not averaged out and "forgotten", but may "decide" the path of market shares. Provided the notion of "historical small events" is carefully defined, "indeterminacy" turns out to be both amenable to analysis and interesting in its own right. And we find that choice under increasing returns appears to raise serious questions in the interpretation of economic history, in policy prescription, and in the possibility of constructing models for accurate economic prediction.

To keep the discussion concrete, we set up a model where agents choose between technologies competing for adoption. This use of technologies rather than goods as the objects of choice has a particular advantage. Where most goods show diminishing returns (in the form of increasing supply costs), very many technologies show increasing returns: often the more a technology is adopted, the more it is improved, and the greater its payoff. Assuming each agent's moment of choice to be subject to small, but unknown events, we find that the market share of each technology follows a stochastic process--in this case a random walk. If both technologies show standard diminishing returns, this random walk has *reflecting* barriers. The aggregate outcome is efficient, flexible, predictable, and ergodic. If both technologies show increasing returns, the random walk has *absorbing* barriers. The aggregate outcome is not necessarily efficient, nor flexible, nor predictable, nor ergodic.

We begin by introducing the notion of "competing technologies", then go on to set up the simple model of choice.

I. COMPETING TECHNOLOGIES

A. Preliminaries

Usually there are several ways to carry through any given economic purpose. We shall call these "ways" (or methods) *technologies* and we will say that members of the set of technologies that can fulfill a particular purpose *compete*, if adoption of one technology by an economic agent tends to displace or preclude the adoption of another. Competition is meant here in the unconscious, passive sense: technologies, whether incorporated in physical plant or machinery or existing as pure method or pure information, are assumed in this paper to be openly available to all, and not subject to strategic influence or manipulation.³

In this paper competition assumes a stronger form than the standard diffusion case where a new and superior technology competes with an old and inferior one. Here two or more superior technologies compete with *each other* to replace an outmoded horse-and-buggy technology. Thus, in the 1890s, the steam engine, the electric motor, and the gasoline engine competed, in the passive sense, as power sources for the new automobile. In the 1800s and on into this century, spinning mules competed with ring-frames in cotton manufacturing (Saxonhouse and Wright 1983). More recently the nuclear technology "competes" with hydroelectric, coal, and other technologies, for part capture of the electricity generation market. And gallium arsenide competes with doped silicon in the manufacture of fast semiconductors.

In general it need not be the case that the number of technologies competing for a given purpose is few. If we consider the arrangement of the 40 or so keys on a typewriter as a technology, then in principle 40-factorial or 10^{48} possible keyboards compete with the standard QWERTY

³ Patentable techniques, proprietary methods, and "trade secrets" do not fulfill this assumption. They can be transferred at a manipulable price, and they are not open to all.

keyboard. More properly, we should call this typewriter case one of "competing standards" or "competing conventions": here the technological choices are given and fixed.

A technology which is not a mere standard or convention tends to be fluid: it mutates, changing in design and sometimes in use, typically existing in several or many "variants". In 1904, for example, the steam automobile came in several score of forms, among which the better known were the Stanley, the White, the Chelmsford, the Gardner-Serpollet and the Toledo (Fletcher 1904). Choice between competing technologies therefore may involve selection from two or more collections of "variants".

We shall think of a given technology (or variant of it) as combining a certain vector of economic inputs or factors for a given amount of desired "output", so that monetary returns-in-use or payoff to adoption to a particular agent are simply the value of the output less factor cost over an appropriate time horizon. Almost by definition a new technology is subject to uncertainty, so that its monetary return will have a probability distribution. Choice between competing technologies is therefore normally a choice between competing lotteries.

As a particular technology spreads in use, the payoff to adopting it may change considerably. Much of the individual's utility in adopting a standard, for example, depends on the degree to which others have adopted it or will follow suit. In the case of a mutable technology, increased adoption brings a growing accumulation of experience and knowledge; and this "learning by using" (Rosenberg 1982) in turn becomes incorporated into more efficient and reliable variants of the technology. (Supersonic aircraft, for example, improved rapidly after actual designs accumulated in-the-air experience.) Not all technologies, of course, enjoy increasing returns with adoption. The very popularity of a factor-intensive technology may bid its inputs up in price, so that diminishing returns accompany adoption. (Hydroelectric power, for example, becomes costlier with increased use as suitable dam sites become scarcer and hydrodynamically less efficient.) Time itself may of course be a major factor in changing returns to adoption; in our model we will abstract from this and suppose returns to depend only on the numbers who have chosen a technology.

B. A Simple Model with Heterogenous Adopters

Two technologies, A and B , compete for adoption by a large number of economic agents who are currently using an outmoded technology of the one-horse-shay type. (For simplicity we treat the pool of agents as infinite in size.) It pays agent i to retain his obsolete equipment until its demise at time t_i ; but he cannot afford to be without working machinery, so that at this point he adopts either technology A or technology B and holds it thereafter. The variant each agent chooses is fixed or frozen in design at his time of choice, so that his payoff is not affected by future changes in or future adoption of either technology. Agents are rational, they obey the von Neumann-Morgenstern axioms, and they are perfectly informed at their moment of choice: they know of all currently available variants of both technologies and their payoff distributions. Agents fall

into two types, R and S , with equal numbers in each, the two types independent of the times of choice but differing in their preferences, or in their degree of risk-aversion, or in their economic environment.

With these assumptions each agent can form a well-defined scalar utility for each technology or variant of it; when his time comes, he chooses the highest utility variant available and remains attached to it.

For simplicity we suppose the payoff-utility or returns to adopting A or B to vary linearly with the numbers n_A and n_B who have chosen each, as in Table 1.

Table 1. Returns to Adoption⁴

	Technology A	Technology B
R-Agent	$a_R + rn_A$	$b_R + rn_B$
S-Agent	$a_S + sn_A$	$b_S + sn_B$

We can contrast the dynamics of the adoption process under diminishing, increasing, or constant returns regimes by allowing r and s to be simultaneously negative, positive or zero. We assume $a_R > b_R$ and $a_S < b_S$ so that R-agents have a natural preference for A , and S-agents have a natural preference for B . (Later we relax linearity and several of the other simplifying assumptions.)

We now have a well-defined, neoclassical model of choice: two types of agents choose between A and B . The supply cost (or returns) functions are known, as is the demand (each agent demands one unit inelastically). Of interest are the properties of the market outcome--the proportion of the total technologies adopted that belongs to type A or type B as the numbers of adopters increase.

Notice that we have avoided several complexities. Agents are economically forced to choose, hence waiting for returns to rise is not an option; returns to a given adopter do not depend on future choices (but they do depend on past choices), hence expectations are not a problem; and technologies cannot be priced or manipulated, hence game-theoretical strategic maneuvering does not enter. Each of these assumptions could be relaxed at some analytical cost. But in this exploratory paper we deliberately keep the analysis simple.

To complete the model, it remains to define a set of "historical small events". Recall that in the earlier side-of-the-road example, our lack of knowledge of certain events--drivers' reactions, weather conditions, traffic-light timings--caused the outcome to be indeterminate.

⁴ More in keeping with the learning-effects literature (Steinmueller 1983) we could modify these returns-versus-adoption functions to be log-linear (or exponential) in form: e.g. $\ln(U_0 - U) = a_R - \alpha n_A$ (for technology A) and $\ln(U_0 - U) = b_R - \alpha n_B$ (for technology B). The results that follow would however be the same.

Were we to have infinitely detailed knowledge of such events and conditions, the outcome--the side of the road that would be selected--would presumably be determinable in advance.⁵ We can conclude that our limited discerning power, or more precisely the limited discerning power of an implicit *observer*, caused the indeterminacy. We may therefore define "historical small events" to be those events or conditions that are outside the knowledge of the observer-- beyond the resolving power of his "model" or abstraction of the situation.

To return to *our* model, we assume an observer who has full knowledge of all the conditions and returns functions, *except* the set of times of choice $\{t_i\}$. The observer thus "sees" the choice order as a binary sequence of *R* and *S* types with the property that an *R* or an *S* stands in the n th position in the line with equal likelihood, that is, with probability one half.

In the analysis that follows, we contrast the outcome--the market shares gained by each technology after n agents have chosen--under regimes of constant returns, diminishing returns, and increasing returns.

It is useful to view this choice process as a search procedure--the agents, by their choices, adopting or "exploring" along a path that consists of a mixture of *A* or *B* variants. In principle, at stage n , n out of a total possible $2n$ *A* and *B* variants could be "explored". Accordingly, we shall say that the outcome of the choice process, viewed as a search procedure, is *efficient*, if at each stage n , none of the n choices actually adopted (or "explored") have lower returns to either agent type than the n not adopted. If this is true, the path the choice process takes is not missing good options⁶.

We have built some "small-event" uncertainty into the process--at least as far as the observer is concerned--so that we cannot expect perfect prediction of x_n , the market share of *A* after n choices have been made. But we would hope that historical fluctuations matter less, or average away, as the adoption process proceeds. Accordingly, we will say that the outcome of the choice process is *predictable* if the observer can, *ex ante*, construct a forecasting sequence $\{\hat{x}_n\}$ that comes ever closer to the exact market share, that is, with the property that $|\hat{x}_n - x_n|$ goes to zero, with probability one, as n goes to infinity.

We will say that the outcome is *flexible*, or amenable to marginalist policy intervention, if changing one of the technologies' returns functions by an arbitrary small amount ϵ from any stage n onward, can affect the numbers of agents choosing *A* or *B* at some stage in the future.

⁵ This is not to deny that "God plays dice"; it is merely to take the Laplacian position that, given complete knowledge of the world, the dice become determinate. Randomness follows then from lack of knowledge, and the notion of "pure chance" need not be invoked.

⁶ Except in the constant returns case this "greedy" choice process of adopting the highest-return option at hand does not guarantee maximum aggregate payoff; hence we use this less stringent criterion of efficiency.

Finally, we will say that the outcome is *ergodic* if different sequences of historical small events, in all likelihood, lead to the same market outcome--that is, if two "samples" from the observer's set of possible historical events, with corresponding time paths $\{x_n\}$ and $\{x'_n\}$, have the property that $|x_n - x'_n|$ goes to zero, with probability one, as n goes to infinity. If this is the case, small events average out and become "forgotten" as the market expands.

II. MARKET SHARING AND MARKET EXCLUSION

A. Dynamics and Properties of the Three Regimes

Before looking at the outcome of choices in our R and S agent model, it is instructive to take a glance at how the dynamics would run were all agents of one type only. Here choice order does not matter; agents are homogeneous and indistinguishable; and there are no unknown events so that ergodicity is not an issue. We bypass the trivial constant returns case where agents always choose the higher payoff technology.

Where both technologies show diminishing returns--the standard textbook case--market-sharing in general takes place. As demand increases, adoption follows the composite supply curve obtained from lateral addition of the separate returns curves for each technology.

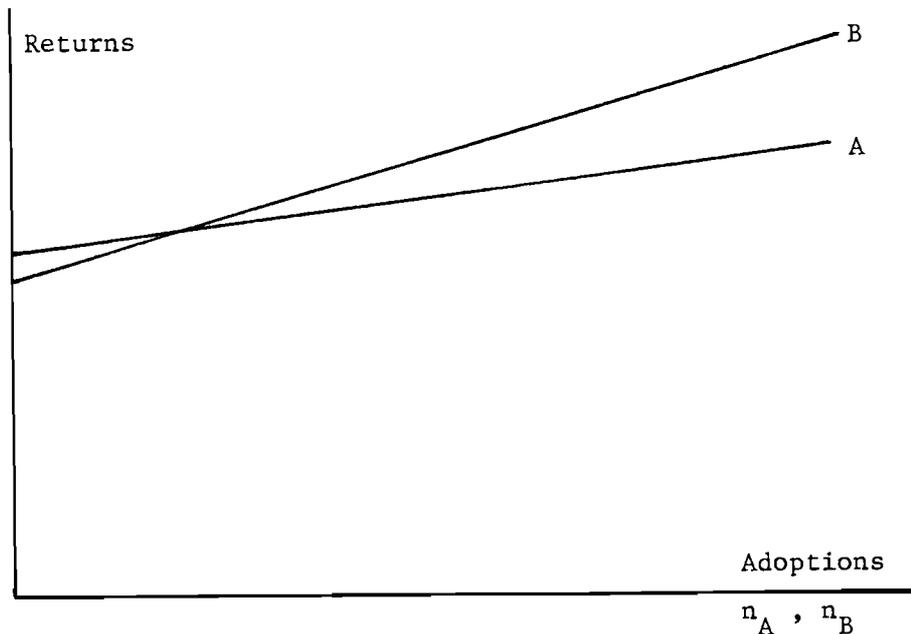


Figure 1.

The outcome is predictable--our observer can determine in advance market shares after n choices exactly in this situation--and it is easy to show it is efficient. It is also flexible: marginal adjustment of either returns curve will shift the composite supply curve and hence market

share.

Where both technologies show increasing returns, the result is more interesting. The first agent chooses the more favorable technology, *A* say. This enhances the returns to adopting *A*. The next agent *a-fortiori* chooses *A* too. This continues, with *A* chosen each time, and *B* incapable of "getting started". The end result is that *A* "corners the market" and *B* is excluded. This outcome is trivially predictable, and efficient if returns rise at the same rate. Notice though that if returns increase at different rates, the adoption process may easily become inefficient, as a cursory inspection of Fig. 1 shows. In this instance, not only are unadopted options better, but choices of *B*'s only would have produced higher aggregate returns. But this situation cannot, in general, be corrected by marginalist policy; after *n* choices the finite gap between the returns to *A* after *n* adoptions and the returns to *B* at the starting point would have to be closed. Flexibility is not present; and choice becomes increasingly "locked-in" to *A*.

Now let us return to the case of interest, where the unknown choice sequence of two types of agents allows us to include some notion of historical "small-events". Begin with the constant-returns situation, and let $n_A(n)$ and $n_B(n)$ be the number of choices of *A* and *B* respectively, when *n* choices in total have been made. We write the difference, $n_A(n) - n_B(n)$, as d_n . (Note that through the variables d_n and *n*--the difference and total--we can fully describe the dynamics of the adoption of *A* versus *B*: in particular x_n , the market share of *A*, is $0.5 + d_n/2n$.) In this constant returns situation *R-agents* always choose *A*, and *S-agents* always choose *B*, regardless of the number of adopters of either technology. Thus the way in which adoption of *A* and *B* cumulates is determined simply by the sequence in which *R* and *S* agents "line up" to make their choice, $n_A(n)$ increasing by one unit if the next agent in line is an *R*, $n_B(n)$ increasing by one unit if the next agent in line is an *S*, with the difference in adoption, d_n , moving upward by one unit or downward one unit accordingly.

To our observer, the choice-order is random, with both agent types equally represented. Hence to him, the "state" d_n appears to perform a simple coin-toss gambler's random walk with each "move" having equal probability 0.5.

In the diminishing-returns situation, these simple dynamics are modified. Figure 2 illustrates the returns functions of each agent type.

Observe that, although at the outset *R-agents* will choose the higher-returns (to them) technology *A*, adoption bids its returns downward, so that future *R-agents* will switch their preference to *B* if the numbers using *A* become sufficiently greater than the numbers using *B*. That is, *R-agents* will "switch" their preferred choice in our model if

$$\begin{aligned} d_n = n_A(n) - n_B(n) &> \Delta_R \\ &= \frac{(a_R - b_R)}{\tau} \end{aligned} \tag{1}$$

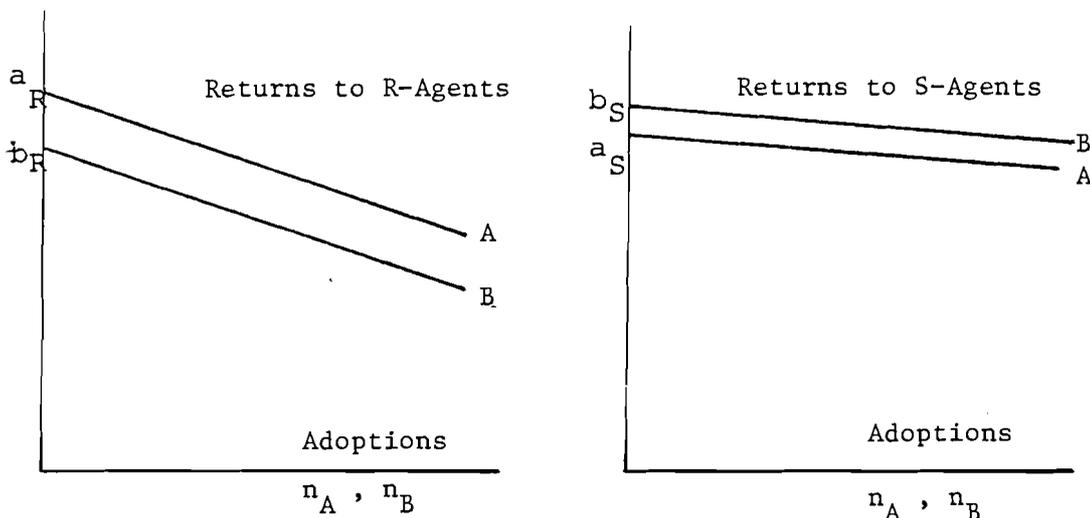


Figure 2

Similarly *S-agents* will switch preference to *A* if numbers adopting *B* become sufficiently ahead of the numbers adopting *A*, that is, if

$$d_n = n_A(n) - n_B(n) < \Delta_S = \frac{(a_S - b_S)}{s} \quad (2)$$

We see now (in Fig. 3) that there are three distinct regions in the d_n, n plane where the directions of choice differ. In region I, where adoption of both technologies shows little difference R-types choose *A* and S-types choose *B*. But in regions II and III both agent types choose the same technology--the one that is "behind". Thus d_n may wander at will in region I but cannot enter regions II or III. The competitive choice process with diminishing returns appears to our observer as a random walk with reflecting barriers.

We obtain slightly different dynamics in the increasing returns situation. Now R-agents, who start with natural preference for *A*, will "switch allegiance" if adoption pushes *B* far enough *ahead* of *A* in numbers and in payoff. Similarly, S-agents, with a natural preference for *B*, will switch their choices to *A* if adoption pushes *A* far enough ahead of *B*. Regions of choice again appear in the d_n, n plane (see Fig. 4), defined by inequalities similar to (1) and (2). Once region II or III is entered, both agent types choose the same technology, but in this case the difference is that they will choose the technology that is "ahead", with the result that this technology further increases its lead. The choice process is "locked into" either region II or region III from then on. In the d_n, n plane the boundaries of these regions become barriers which "absorb" the process. Once either is reached by random movement of d_n , the process ceases to involve both technologies--it is "locked-in" to one technology only.

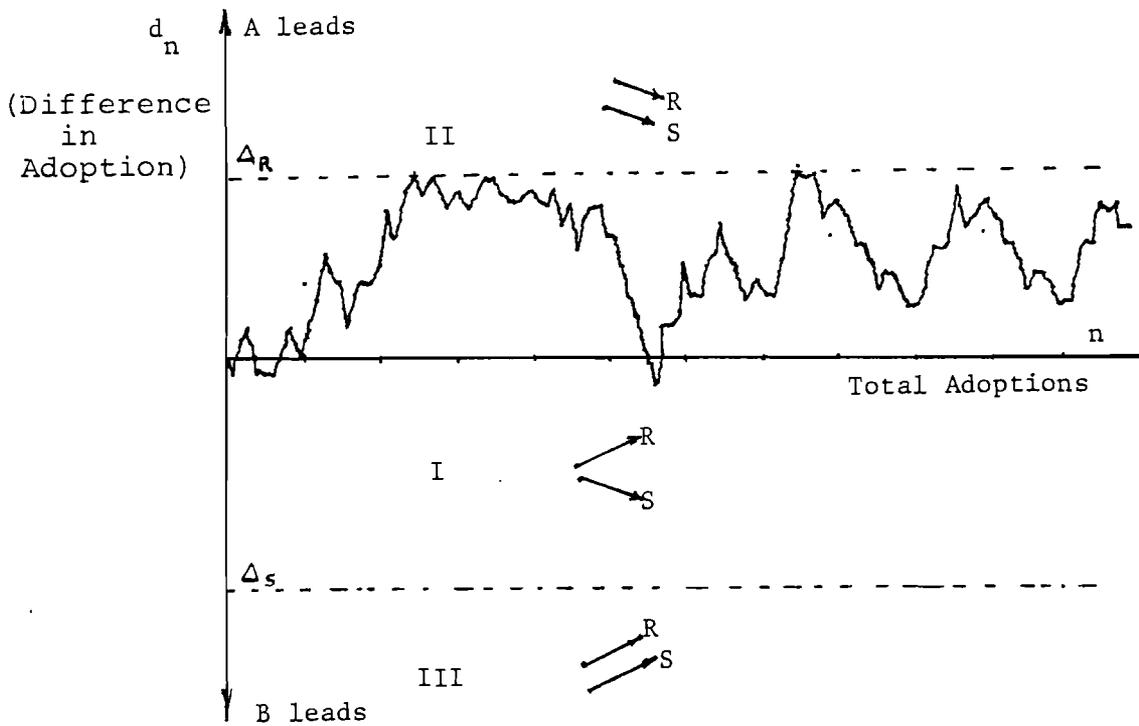


Figure 3.

We are now in a position to use the elementary theory of random walks (as in Karlin and Taylor 1975 say) to derive the properties of this choice process under the different linear returns regimes. For convenient reference we summarize them in Table 2.

Table 2. Properties of the Three Regimes

	Necessarily Efficient	Necessarily Flexible	Predictable	Ergodic
<i>Constant Returns</i>	Yes	No	Yes	Yes
<i>Diminishing Returns</i>	Yes	Yes	Yes	Yes
<i>Increasing Returns</i>	No	No	No	No

In the increasing-linear-returns situation, we know that d_n becomes absorbed with probability one—that is, that the market share of *A* *must* eventually become zero or one, so that the two technologies cannot coexist indefinitely and one *must* exclude the other. But as in the side-of-the-road example, our observer cannot *ex ante* predict *which* technology will predominate. He can predict that one technology will take the market; if he knows random walk theory he can predict that it will be *A* with probability $r(a_S - b_S) / ((s(a_R - b_R) + r(a_S - b_S)))$; but he cannot

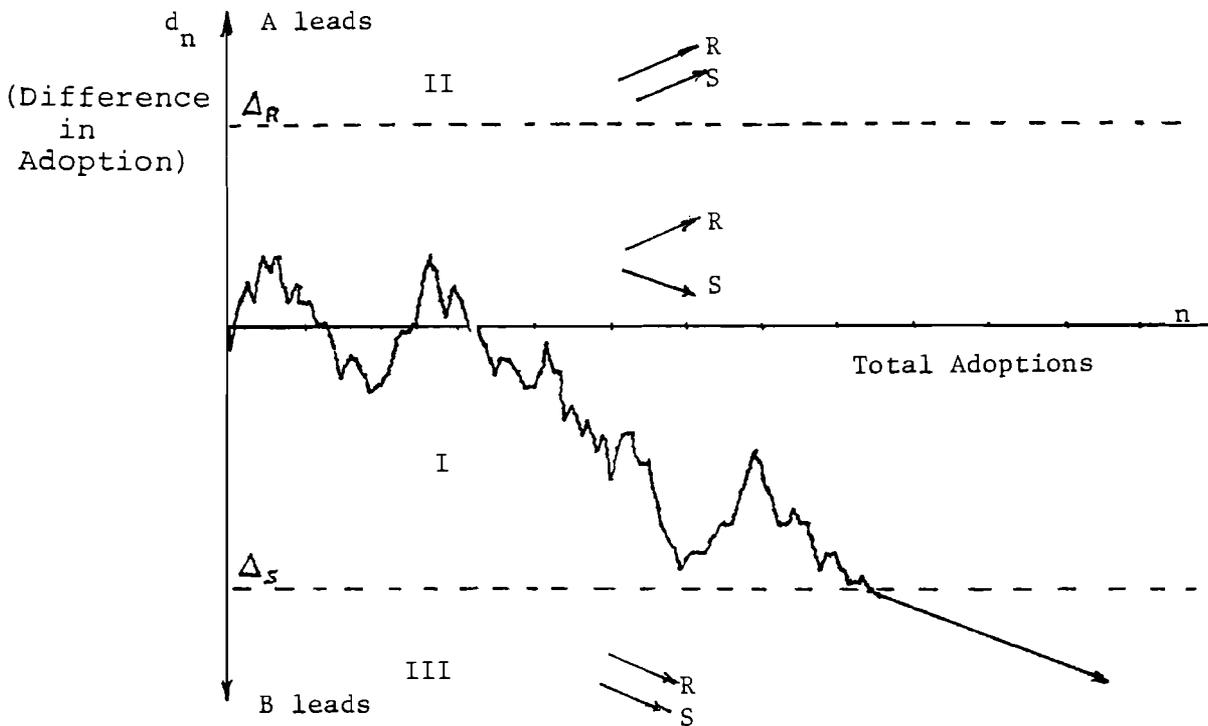


Figure 4.

predict the actual market-share outcome with any accuracy at all--in spite of his knowledge of supply and demand functions. This state of affairs is quite different where returns are constant, or diminishing. In the constant-returns case (no barriers), the standard deviation of d_n increases with \sqrt{n} , so that d_n/n tends to zero, with probability one, as n increases; and in the diminishing returns situation (reflecting barriers) d_n is trapped between finite constants, so that again d_n/n tends to zero as n increases. In both cases our observer can predict that market shares will become asymptotically equal with probability one, the fifty-fifty market split resulting from the inherent symmetry of the problem in this case.

Ergodicity follows easily in the constant and diminishing returns cases. Any sequence of historical events--any line-up of the agents--drives the market to fifty-fifty in the diminishing returns case; and only truly extraordinary happenstance events (for example, twice as many R-agents as S-agents joining the line indefinitely) with associated probability zero can cause deviation from fifty-fifty in the constant returns case. The line-up caused by the historical timing of agent choices therefore has no effect on eventual market shares, and the process is ergodic--it forgets its small-event history. In the increasing returns case the situation is quite different. A sizeable proportion of the choice sequences causes the market outcome to "tip" toward A, the remaining proportion causes it to "tip" toward B. (The extraordinary line-ups--say S followed

by R followed by S followed by R and so on indefinitely--that cause market sharing, have proportion or strictly speaking, measure, zero.) Thus, the historical sequence of the choices (which depends on the small events $\{t_i\}$) *decides* the path of market shares, and the process is non-ergodic-- it remembers its small-event history.

Marginalist policy adjustments to the returns trivially have no effect in the constant-returns situation. In the two other cases they correspond to a marginal shift of one or both of the barriers. Once the increasing-returns process is "locked-in" to A or B , however, the same technology is chosen with an ever widening returns-to-adoption difference between it and other, and marginal subsidies or taxes can have no purchase on the dynamics of choice in the future. They must however affect future choices in the diminishing-returns situation (in absolute numbers, if not in market shares), because reflecting barriers continue to influence the process (with probability one) at times in the future.

The efficiency issue is different, having nothing to do with randomness. It is simple to show that choices are always efficient in the diminishing-returns case. But with returns increasing, it is very easy to construct a low-payoff "locked-in" market that leaves options unadopted that deliver a higher payoff. Increasing returns do not guarantee efficiency.

B. Extensions and Variations

Would these results have been materially different if we had made weaker assumptions in our model? The answer is a qualified no.

To begin with, we can easily show that the same qualitative results hold for N technologies in competition, and for agent types in unequal proportions (here the random walk "drifts"). Where agent numbers are finite, the "extraordinary paths" occupy a definite proportion of the possible paths, so that absorption or reflection now have probability somewhat less than one and properties that assert themselves asymptotically may no longer fully hold. Where returns to one technology depend also on the numbers adopting the *other* technology, switching barriers again appear, causing corresponding behavior in the dynamics.

Our linear-returns results extend to the nonlinear case, providing the returns functions are "parallel" - in the sense that d_n causes "switching" to occur always at the same numerical difference in adoption between the two technologies. (The log-linear learning-curve returns of footnote 4 are parallel in this sense, for example.) Then the associated barriers are constant, and the random-walk results above again obtain. In the more general case, where returns have no common pattern besides a similar monotonicity, the results are weaker. Here the cross-over point at which the difference in adoption d_n causes switching may vary as total choices n increase. The barriers may widen or narrow with n , and if they widen at a sufficient rate no switching may occur at all. Market-sharing is still guaranteed in the diminishing-returns case; but

⁷ Switching occurs, with probability one, only if the non-constant barriers lie within iterated-logarithm-law limits, from some finite stage onward.

market-exclusion no longer, in the increasing-returns case. For example, if the increasing payoffs to learning-by-using become exhausted so that returns to adoption level off at different levels for each technology, the situation gradually becomes akin to constant returns. Both technologies can, in this case, share the market.

Three variations that merit further study are worth some speculative comments. Consider first a variation where *all* agents differ in preferences, in risk aversion, or in economic circumstances (see David 1969). There is now a distribution of agents over returns at any stage in the adoption process. It appears that this increased heterogeneity changes little the mechanism that causes market-sharing or market exclusion. The hard barriers between regions of choice now disappear, to be replaced by a gradation where more and more agents have switched preference as d_n becomes larger. The same random walk appears, but now with changing step probabilities instead of barriers. Market sharing and market exclusion can again be shown under appropriate conditions, but more sophisticated machinery is needed⁸.

In a quite different variation, we might suppose that adoption does not necessarily mean a technology will be improved, it merely increases the *chances* that it will be improved (see Sahal 1981, David 1975, and Nelson and Winter 1982, for example). There may be a wide class of such "probabilistic increasing-returns" models, with "small-events" now becoming the discovery of improved variants. Exact market-exclusion or market-sharing conditions would depend on the nature of the model.

Finally, where conventions or standards compete, returns usually become a function of future as well as past adoptions, so that technological expectations (Rosenberg 1982) enter.⁹ We cannot say much in this case without further information on how expectations form and are modified as returns change. But it is likely that in most cases increasing returns again cause market exclusion: given sufficient increasing returns, expectations of what is likely to prevail, even if founded on very little, can become self-fulfilling, so that the fundamental market instability is further exacerbated.

⁸ Such as the path-dependent strong law theorem of Arthur, Ermoliev and Kaniovski (1983). Market exclusion here appears to depend crucially on the extent to which agents have correlated preferences for the two technologies.

⁹ For an analysis of the expectations case, see the forthcoming dissertation of Hanson.

III. DISCUSSION

A. Some Technological Examples

In our various theoretical models, the economy, under circumstances of increasing returns, can become "locked-in" to a future technological path that is neither guaranteed to be efficient nor entirely predictable in advance. The most common real-world case actually conforms to none of the above illustrative models. A technology is initially adopted as most suited to prevailing conditions; but after some time these conditions change. Because users and ancillary machinery have become accommodated to this technology, however, it is now locked in¹⁰. Better alternatives cannot make a start. The 1950's programming language FORTRAN; the excessively narrow gauge of British railroads¹¹; the U.S. color television system--all technologies initially adopted for sound engineering reasons--show that initial adoption can carve an inefficient groove that the future finds hard to escape.

The QWERTY typewriter keyboard, manifestly inefficient for modern touch-typing, is a case in point. Before 1873, early typewriters displayed a variety of keyboard arrangements, the most common being alphabetical order for easy reference. In 1873, however, Christopher Sholes found that this arrangement caused his up-strike key mechanism to jam. After considerable experimentation and on the advice of his brother-in-law, a school teacher and mathematician, Sholes minimized jamming by selecting a keyboard that caused the typing bars to come up from different directions on most words. The first six letters were "QWERTY". Approximately 1000 of these "type-writers" were mass-produced in the Remington sewing-machine factory in New York. In due course, employers bought QWERTY; typists learned QWERTY; and teachers taught QWERTY; so that "...other manufacturers adopted the arrangement with only slight variations. Those who failed to do so disappeared without a trace." (Beeching 1974)¹².

Examples need not be confined to engineering standards nor to trivial technologies. If road and rail "compete" as alternative possibilities for a sizeable portion of freight transported, if each mode exhibits increasing returns in the form of long-run decreasing costs per ton-mile as its freightage increases, and if each starts with roughly similar costs, then small events --a timely lobbying effort perhaps, or the opening up of a new industrial region--may favor freightage on one mode, causing its costs to fall and customers to switch their patronage towards it. Freight density on this favored mode further increases and its costs fall further.

¹⁰ We could treat this case within our framework as one of myopic homogeneous agents operating in an R-environment that at some time changes to an S-environment; or equivalently, as a finite sequence of R-agents, followed by an indefinite sequence of S-agents.

¹¹ Veblen writes in 1915 of "the silly little bobtail carriages used in British goods traffic; which were well enough in their time, before American or German traffic was good for much, but which have at best a playful air when brought up against the requirements of today." (See also Frankel 1955.)

¹² Not quite. The Dvorak keyboard, invented in 1932, and reported to be 35% faster than QWERTY, still struggles on. But of forty-five nations using Roman-alphabet languages, only Belgium, Portugal and Turkey today possess standard alternatives to the QWERTY keyboard. (See the Olympia International standard keyboards in Beeching 1974.)

Eventually the advantaged mode comes to dominate much of the market, but *which* mode this is may differ in different countries. Under these suppositions¹³, where road is relatively healthy, rail would be chronically under-invested, requiring periodic subsidies to maintain some degree of efficiency; and vice-versa.

This is not to say, of course, that every case of competing technologies shows tendencies toward market exclusion. Most power-generation technologies, for example, are factor-intensive and show eventual diminishing returns. We would expect these to share the market in a more-or-less predictable and efficient way. Similarly, ring and mule technologies shared the cotton-spinning market up to the 1920s. The ring could spin successfully from a narrow range of cotton grades, whereas the mule, although less efficient, could perform over a wider range (Saxenhouse and Wright 1983), with the result that manufacturers' different access to qualities of raw cotton maintained a shared market.

If it is true that competing technologies are often of the increasing-returns type, then we would expect the past to contain a "fossil record" of discarded or excluded technologies that would have been as good as, or, given equal development, might have been better than, those that eventually predominated. As a pure example of this, consider that in the past, the hands on certain clocks (the Uccello clock of 1433 in Florence cathedral, for example) turned *anticlockwise*. (See also Cipolla 1967, p.65.) After about 1550 this convention was excluded.

B. On Historical Explanation

The argument of this paper suggests caution in the interpretation of economic history. Often, where we observe the predominance of one technology over its competitors--say gasoline over steam as the propulsion device for automobiles--we tend to look for reasons why the predominant technology was superior, and for the means by which this innate superiority came to be translated into adoption. But this form of reasoning is valid only for constant and diminishing returns technologies. Where technologies exist potentially in ever more efficient variants, superiority becomes itself a function of adoption or use. Although we should be cautious about engineering claims, recent evidence (Burton 1976; Strack 1970) suggests that had the more efficient steam-cycle been properly harnessed and developed for automotive transport, it might well have been preferable to the gasoline technology (see also Fletcher 1904)¹⁴. Gasoline in North America seems to have gained its decisive edge between 1896 and 1898 when one or two variants of the gasoline technology appeared that were temporarily superior to contemporary steam variants. Larger entrepreneurs like Ransom Olds "switched" into

¹³ In practice, of course, this simple mechanism would be somewhat complicated by government regulation, cartel agreements, inter-regional differences, and the multi-product nature of freight. Note however that from 1970 onward, econometric studies "all give strong evidence of increasing returns" to U.S. railroad freight density (Keeler 1983).

¹⁴ The Rankine (steam) cycle is thermodynamically more efficient than the Otto (gasoline) cycle. In a 1970 NASA study Strack concluded that a "steam propulsion system could be designed to weigh approximately the same as a conventional automobile propulsion system. The overall fuel cost would be no greater, and perhaps less, than today's average case."

gasoline, and magnified its prevalence in production runs. Gasoline gained a small temporary lead that subsequently proved unassailable (May 1977).

Seen from our analysis, the issue in historical interpretation of choice of technology is not quite "market determinism" versus "historical accident"¹⁵. More precisely it is whether the outcome is built in *a-priori* to the endowments, opportunity sets, and preferences existing in the economy, with aggregate choice being guided to an inevitable conclusion by an invisible hand of market determination, or whether unavoidable fluctuations--small events outside the given economic conditions--can cumulate to sway the future technological structure of the economy. The former case, ergodicity, obtains in constant and diminishing returns regimes¹⁶. Small events are "averaged away" and forgotten--the dynamics do not "notice" the presence or absence of headaches and horseshoe-nails, and causality lies with the superiority of the market outcome. But while this is comforting, history here is reduced to the status of mere carrier--the deliverer of the inevitable. The latter case, non-ergodicity, obtains in increasing-returns regimes. Micro-events become magnified by positive feedbacks; their cumulation decides the outcome and forms the causality. Insignificant circumstances become cemented into the technological structure of the economy; and history, in a sense, becomes destiny.

Historical explanation, we can conclude, should be different in the different returns regimes.

C. Policy and Prediction

The two main regimes of diminishing and increasing returns call for different policy action. In the diminishing returns case of two objects of choice competing for the market, it is usually best to let the superior aggregate choice, or the superior mix of choices, reveal itself in the outcome that eventually dominates. But if this policy is applied in the increasing returns case there is no guarantee that the "fittest" (in the long run sense) will be the one that survives. Further, if government seeks to maintain a healthy balance between increasing-return choices (road and rail, say) by subsidizing the choice that has fallen behind, it pushes policy onto a razor-edge. Small subsidies to the excluded choice will not re-establish it; large subsidies, on the other hand, will swing the market and drive the dominant choice out.

¹⁵ Positions on this ancient debate run all the way from Engels, 1894 ("In default of Napoleon, another would have filled his place, ...") to Croce, 1921 ("The material of history ... [is] the fleeting network of a human world which drifts like clouds before the wind and is often totally changed by unimportant events."). Modern historiography (e.g. Conrad and Meyer 1964) takes a comfortable compromise position that causality is part deterministic, part "random". Interestingly we find in our variable-returns models no such compromise. Causality resides either deterministically within the given economic structure, or "randomly" in the small events and circumstances outside the given structure. Strictly speaking, "random events" are not invoked or defined in this paper--only circumstances that lie outside the main description of the dynamic structure.

¹⁶ For an earlier recognition of ergodicity as a useful concept in economic history see David (1975, p.16)

More effective policies in the increasing-returns case would be predicated on the nature of the market breakdown: in our model agents myopically chose the best variant at hand; there was no inter-agent market to induce them to explore promising but less-developed infant technologies. One possibility then, would be the assignment of limited rights to compensation by later users. But this is only partially effective. Restricting such "patents" to tightly defined variants allows easy bypass by latecomers; widening it to whole technologies (steam propulsion, for example) restricts exploration by others. As a second possibility, the central authority could itself underwrite adoption and exploration along promising but less popular technological paths. But again such policies can be problematic. Eventual returns to a technology may be hard to ascertain --witness the controversy over solar energy subsidies, for example. And while there are obvious costs to being locked-in to an inferior technology, there are equally obvious costs to exploring large numbers of unknown technological paths. Where government does have a clear favored outcome, the best course is to "tilt" the process economically toward the favored technology at the outset, this being especially effective if events are running close to locking-in the preferred choice. With increasing returns, events at only certain times influence the outcome so that timing becomes all-important, whereas with diminishing returns timing matters little.

Finally, a word or two about economic prediction. We have seen, in the illustrative model, that where increasing returns are present, much of the later development of an economy may depend upon "small events" beneath the resolution of an observer's model and so may be impossible to predict with any degree of certainty. This suggests that there may be theoretical limits, as well as practical ones, to the predictability of the economic future. Suppose we grant econometricians, for a moment, full knowledge of future wars, of the timing of earthquakes, of the formation of cartels, and of the technological possibilities over the horizon. Suppose we grant them consummate skill in finding correct econometric descriptions of supply and demand functions and market conditions. Suppose the economy contains processes of choice which operate subject to increasing returns. And suppose that econometric models--whether computer-based or not--are of finite size and hence of finite resolution, so that there are real-world micro-events that lie beneath their notice. Then the inherent potential amplification of these unnoticeable small events may bring into being a corresponding region of uncertain outcome¹⁷. We can speculate that an econometric model that predicts accurately with certainty is, under these most favorable circumstances, an impossibility.

¹⁷ Similar arguments apply (Leith 1966; Lorenz 1963) to the theoretical possibility of accurate meteorological forecasting. The observational net would have to be finer than the radius of the smallest eddy, else these "small events" become amplified by inherent positive feedbacks into large uncertainties.

IV. CONCLUSION

In this paper we constructed a simple theoretical model of competing technologies that showed the dynamics of choice under increasing returns to have several important properties: historical small events can determine the future technological path of the economy; knowledge of preferences, endowments, and transformation possibilities is not always sufficient to predict the path the economy will follow; and the economy can over time become locked in to a rigid and not always efficient technological structure.

There remains a large number of open questions, to which the conceptual framework developed here might apply. Do these properties obtain in all increasing returns dynamics? If not, can we characterize the situations where they do? What happens when we allow strategic manipulation, as would be likely with competing products? What happens if returns depend also on future choices? What difference does it make if agents can wait for returns to increase? Under what circumstances would we see similar, increasing-returns properties in the dynamics of international trade, of economic development, or of industrial structure? What policies might prove effective in particular cases?

Whether the theoretical properties obtained in this paper apply to some portion of the actual economy remains to be empirically proven; if they do standard conventions in policy prescription, historical interpretation and economic prediction may have to be revised.

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