6 Competing technologies and economic prediction

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'Every steam carriage which passes along the street justifies the confidence placed in it; and unless the objectionable features of the petrol carriage can be removed, it is bound to be driven from the road, to give place to its less objectionable rival, the steam-driven vehicle of the day.'

(William Fletcher, *Steam Carriages and Traction Engines*, 1904, page ix.)

In 1890 there were three ways to power automobiles – steam, gasoline, and electricity – and of these one was patently *inferior* to the other two: gasoline. Yet today the entire automotive technology is based upon gasoline. It is possible, of course, that gasoline possessed hidden engineering advantages that were only slowly uncovered. But another, quite different explanation can be put forward.

Very often, technologies show increasing returns to adoption – the more they are adopted the more they are improved, and the more attractive they become. Aircraft designs, for example, improve greatly in structural soundness, maintenance costs, and payload capacity as they accumulate experience through actual airline operation. When two or more increasing-returns technologies compete for adopters, insignificant 'chance' events may give one of the technologies an initial adoption advantage. Then more experience is gained with this technology and so it improves; it is then further adopted, and in turn it further improves. Thus, the technology that by 'chance' gets off to a good start may eventually 'corner the market' of potential adopters, with the other technologies gradually being shut out.

Whether the automotive industry is locked-in to a gasoline technology by historical small events magnified by increasing returns, or by the innate superiority of gasoline engines, is a matter that would require careful historical weighing of evidence together with detailed engineering analysis. If we take the increasing-returns explanation as valid, however, we can see in this example four key features of the dynamics of markets where increasing returns are present.

First, the technology that 'wins' a market does not necessarily have to be the 'best' or most efficient. In the case of the automobile, the steam (Rankine) cycle is thermodynamically more efficient than the gasoline (Otto) cycle. Given as much development as the gasoline engine has undergone over the last ninety years, it is quite possible that a steam engine could have been more economical. (There are several recent steam prototypes that achieve better fuel mileage and have lower exhaust emissions than current gasoline power sources.) In the dynamics of choice under increasing returns, even when individual choices are perfectly rational, there is a potential economic *inefficiency* of outcome.

Second, an industry (or economy) can get 'locked-in' to a technological path that is difficult to get away from. As more and more people choose one technology from a group of competing technologies, that technology becomes more attractive. The other technologies become 'frozen out' of the market and often disappear. To re-establish them, a widening change-over gap would then have to be closed. In cases with increasing returns, there is a potential *inflexibility* where ultimate 'market shares' cannot always be easily altered as a matter of policy.

Third, even with hindsight, the reasons why a particular technology came to be adopted are difficult to pinpoint. Exact causality is hard to ascribe. Where increasing returns are present, it is often a mistake to explain adoption by the 'superiority' of the technology, as is traditional. There is a *non-ergodicity**: historical 'small events' are not averaged out and 'forgotten' but may well decide the path of adoption shares.

Fourth, even if we know all the preferences and possibilities of those choosing, the outcome – the share of the market taken by each technology – is often impossible to predict in advance. If small events can decide the outcome, and if these are in some sense 'too small' for the economist's notice, then with increasing returns there is a *non-predictability*: knowledge of supply and demand usually does not suffice to predict theoretically the share of the market that each technology will take. Of course, with increasing returns we may be able to predict that one technology will come to dominate, we may be able to give odds on each, but we cannot with accuracy say *which* technology will dominate.

DYNAMICS OF CHOICE UNDER INCREASING RETURNS

As one possible, simple model of an adoption process with increasing returns, imagine two technologies, A and B, competing with each other to fulfill a particular economic purpose. They compete in the sense that

* Editors' note: An ergodic process is one in which the initial state is, in the long run, irrelevant. 'Ergodicity' is a term from the mathematical theory of probability, in which a process involving probabilistic transitions between a set of states is described as 'ergodic' if the probabilities of the states tend, in the long run, to values that are independent of the state from which the process begins.

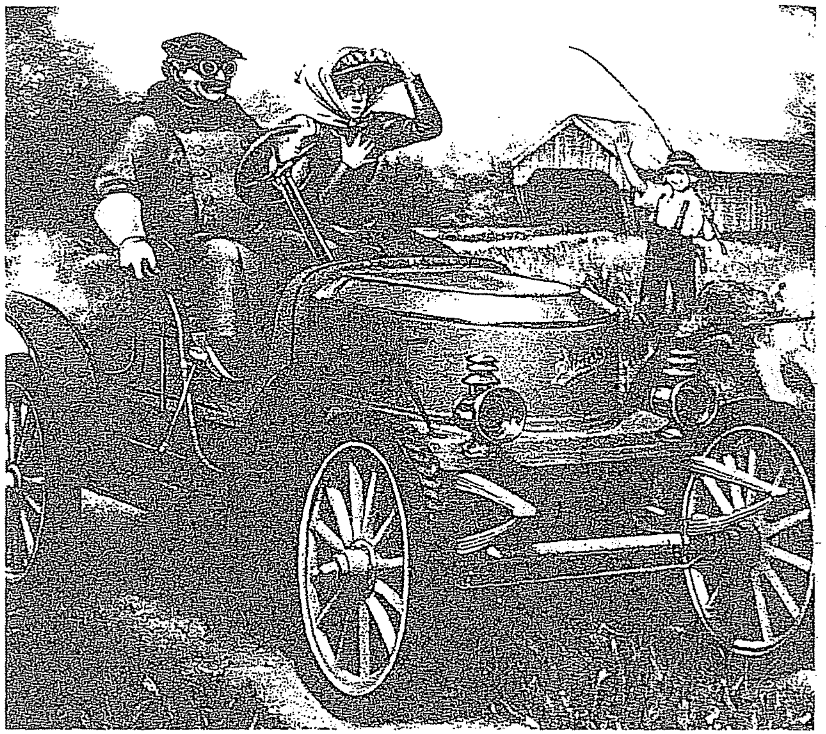

Figure 6.1 Stanley Steamer (reproduced from N. Taylor, *The Stanley Steamer and Other Steam Cars*. © 1981, Bellerphon Books, 36 Anacapa Street, Santa Barbara, California 93101, U.S.A.)

adoption of one will displace or preclude the adoption of the other technology.

Imagine manufacturers – economic agents – having to choose between the two technologies. Once he has chosen a technology, each agent stays with it and his payoff is not affected by future changes. The agents fall into two groups or types, R and S, with equal numbers in each type, but differing in the use to which they put the technologies. Let us say R-agents, initially at least, prefer technology A, and S-agents prefer B.

Now assume that payoff or returns to adopting A or B increase linearly (at a given rate) with the numbers who have chosen A or B respectively. And assume each agent's moment of choice is subject to small, but unknown, events, so that, to us as observers, choice order looks like a binary sequence of R- and S-agent types, with the probability that an R or an S stands in the *n*th position in line equal to one-half.

This is a well-defined, neoclassical model of choice: two types of agents choose between A and B, each agent demands one unit inelastically and the

supply-cost (or returns) are known. The only unknown is the order in which the agents choose; this is subject to 'small events' below the notice of our model. What happens to the market share of the two technologies?

Initially at least, if an R-agent arrives at the 'adoption window' to make his choice he will adopt A; if an S-agent arrives he will adopt B. Thus the difference-in-adoptions between A and B moves up or down by one unit depending on whether the next adopter is an R or an S, that is, it moves up or down with probability one-half. This process is a simple gambler's-coin-toss random walk. There is only one complication. If, by 'chance' a large number of R-types cumulates in the line of choosers, A will then be heavily adopted and hence improved in payoff. In fact, if A gains a sufficient lead over B in adoptions it will pay S-types to switch over. Then both R- and S-types will be adopting A, and only A, from then on. The adoption process is locked-in to technology A. Similarly, if a sufficient number of S-types by

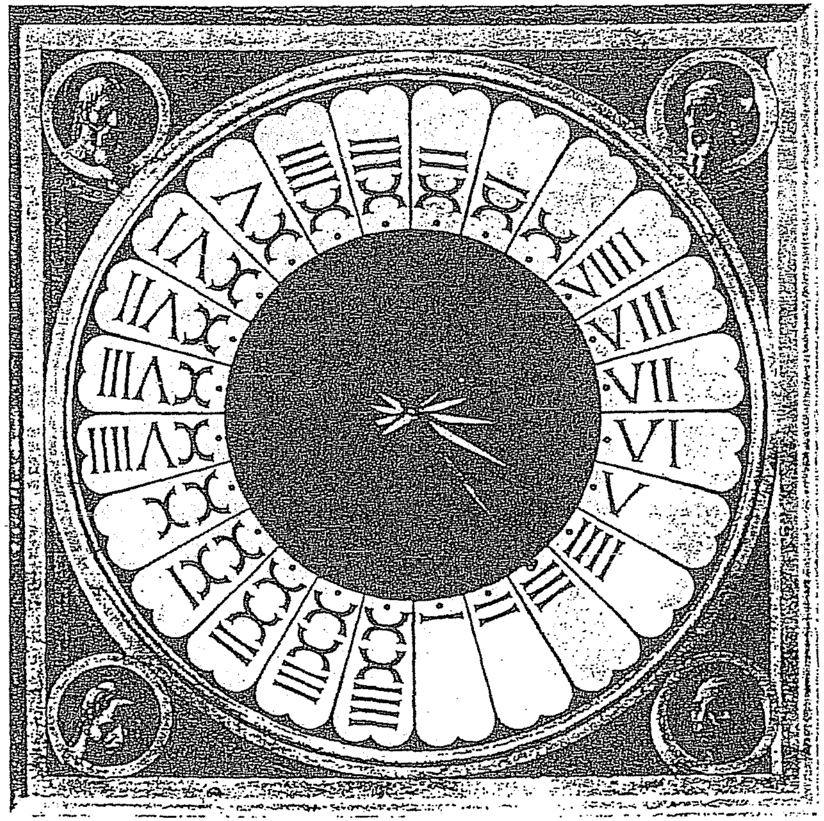

Figure 6.2 Clock by Paolo Uccello, Florence, Italy (Casa Editrice Giusti di Becocci)

Table 6.1 Properties of the three regimes

	Necessarily efficient	*Necessarily flexible*	*Predictable*	*Ergodic*
Constant returns	Yes	Yes	Yes	Yes
Diminishing returns	Yes	Yes	Yes	Yes
Increasing returns	No	No	No	No

'chance' arrives to adopt B over A, B will improve sufficiently to cause R-types to switch over. The process will then lock-in to B. Our random walk is really a random walk with absorbing barriers on each side, the barriers corresponding to the lead in adoption it takes for each agent-type to switch its choice.

All this is fine. We can now use the well-worked-out theory of random walks to 'prove' the properties I pointed to earlier. The important fact about a random walk with absorbing barriers is that absorption occurs eventually with certainty. Thus in the model I have described, the economy *must* lock-in to one of the two technologies, A or B. But *which* technology is not predictable in advance. Also, the order of choice of agents is not 'averaged away'; on the contrary, it decides the eventual market outcome. Thus the process is non-ergodic. Nor is it flexible. Standard policy measures of favoring one technology over another by tax or subsidy merely shift the barriers. But if the process has become locked-in, the leading technology is constantly improving, so that after a certain time any given boost to the payoff of the excluded technology will not be sufficient. Further, it is easy to construct examples in which this 'greedy algorithm' of each agent taking the technology that pays off best at his time of choice may miss high rewards to the future adoption and development of the excluded technology. Economic efficiency is not guaranteed.

These results are drastically altered in the standard textbook diminishing-returns case. Here technologies, as they become adopted, exert pressure on scarce resources, so that their returns fall with adoption. Hydroelectric power, for instance, becomes more expensive with increased use as the more suitable dam sites are taken up. It is easy to show that the market shares of technologies in the diminishing-returns case are governed by a random walk with reflecting barriers. Here the market for the two technologies is usually shared: the outcome is predictable, as it is the same regardless of the 'small events' sequence; it can always be changed as a matter of policy; and it is always economically efficient.

Where technologies remain the same in payoff regardless of the numbers of adopters – the constant-returns case – the dynamics are governed by a random walk without barriers. Table 6.1 summarizes the properties of the three contrasting regimes.

IMPLICATIONS

There are several implications of the increasing-returns mechanism I have sketched out here. If this type of mechanism is valid, we would expect past history to contain a 'fossil record' of technologies that could have been as good as, or, given equal development, might have been better than, the technologies which were eventually adopted. One example is the direction of motion of the hands on the Uccello clock in the Cathedral in Florence, Italy. They turn anti-clockwise. The Uccello clock was constructed in 1433: it wasn't until after 1550 or so that the clockwise movement became standard.

We would also expect to see technologies which are patently inefficient but which we are 'stuck with'. The U.S. color television system, the driving-on-the-left convention in Britain (bad for car exporters) and the extreme longevity of the 1950s' programming language FORTRAN are examples. The 'standard' keyboard on typewriters is a case in point. Before 1873, early typewriters came with a variety of keyboard arrangements. But in that year, Christopher Scholes, together with his brother-in-law, a schoolteacher, designed a keyboard to overcome mechanical problems with sticking key-bars. The first six letters on the upper row of Scholes' keyboard were QWERTY. The Remington Sewing Machine Company of New York started mass-producing typewriters on the Scholes model – with the QWERTY keyboard. An international meeting in 1904 was supposed to decide on one keyboard among the many alternatives to become the standard. No agreement was reached, primarily because of opposition to any change from typing teachers. QWERTY keyboards are now used in all but 3 of the 45 nations with Roman alphabets and superior competitors to the QWERTY system – the Dvorak system and the Maltron system –have had trouble in gaining a footing.

Policy measures are generally straightforward in the diminishing-returns and constant-returns cases. Here it is usually best to leave the adoption process alone and let the market find its way to an efficient mix of technologies. But where competing technologies show increasing returns to adpotion, the 'fittest' of the technologies may not survive. The government may then need to step in, to encourage and protect infant technologies that, if sufficiently adopted and developed, may pay off handsomely. But there are difficulties. Eventual returns to a technology (think of solar energy, for example) are hard to ascertain; so that while there are obvious dangers and costs of missing out on a potentially superior technology, there are equally obvious costs to exploring large numbers of unknown technological paths.

The argument here implies that we should be careful in interpreting economic history. We usually look for reasons why a predominant technology was superior, and how this 'innate' superiority eventually led to adoption. But this line of reasoning is valid only for cases of constant and diminishing returns. Where technologies exist potentially in ever more improved designs, superiority becomes a function of adoption or use. To return to our gasoline versus steam engine example, it is quite possible that gasoline was indeed innately superior. The matter has never been settled. But it is equally possible that a series of small events at the turn of the century gave gasoline a temporary lead that subsequently proved unassailable. In the North American case, we can, among other small events, single out an 1895 horseless carriage competition sponsored by the Chicago *Times-Herald*. This was won by a gasoline-powered Duryea – one of only two cars to finish out of six starters – and has been cited as the possible inspiration for R. E. Olds to patent in 1896 a gasoline power source, which he subsequently mass-produced in the 'Curved-Dash Olds'. Gasoline thus overcame its slow start. Steam continued viable as an automotive power source until in 1914 there was an outbreak of hoof-and-mouth disease in North America. This led to the withdrawal of horse troughs – which is where steam cars could fill with water. It took the Stanley brothers about three years to develop a condenser and boiler system that did not need to be filled every thirty or forty miles. But by then it was too late. The steam engine never recovered. Where increasing returns are present, it is often the missing 'horseshoe nail' that decides the technological path that is followed.

I have argued that, with increasing returns, the later development of an industry or economy may depend on 'small events' beyond the resolution of an economic observer or his model. Similar arguments have been applied in the last decade to the theoretical possibility of accurate meteorological forecasting. It has been proven that an observational net of weather ships would theoretically have to be finer than the radius of the smallest eddy for weather developments to be forecastable; otherwise these 'small events' become amplified by inherent positive feedbacks into large uncertainties. Given the inevitable presence in the economy of increasing returns to adoption or to allocation, we can speculate that an econometric model that predicts perfectly accurately is not just a practical, but also a *theoretical*, impossibility.

NOTE

Further development of Professor Arthur's argument can be found in W. Brian Arthur (1994) *Increasing Returns and Path Dependence in the Economy*. Ann Arbor, MI: University of Michigan Press.