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EVOLUTIONARY THEORIES OF TECHNOLOGICAL AND ECONOMIC CHANGE

Roberto Simonetti

CONCEPTS AND TECHNIQUES

- Dynamics versus static efficiency
- Endogenous change
- Creative destruction
- Mutation, selection and variety: population perspective
- Genes, routines and satisficing
- Numerical simulations: Variables, parameters and initial conditions
- Selection and imitation: Effects on efficiency and market structure
- Fitness, selection and optimization: Panglossian arguments and critique
- Increasing returns to the use of a technology: firm (learning) and system (spillovers) level
- Network effects
- Positive feedback, path-dependency and irreversibility
- Stylized facts

LINKS

- The evolutionary theory considered here can be seen as part of institutionalist economics, first considered in relation to one of its pioneers, Thorstein Veblen (Chapter 3)
- Routines, bounded rationality, satisficing behaviour and path-dependency were introduced in Chapter 8. The difference between static and dynamic efficiency was discussed in Chapter 10. Tacit knowledge was introduced in the previous chapter.
- Learning-by-doing and increasing returns to the use of a technology were introduced in Chapters 11 and 15, respectively.

1 Introduction

You saw in the previous chapter that an increasing number of economists and policy makers have been paying attention to technical change as a central feature of capitalist economies and a main determinant of economic growth. Many of these scholars are also dissatisfied with the neoclassical theory of production, which focuses on static allocative efficiency and neglects the sources of new technology. In particular, the assumption of *rational behaviour* and the focus on *equilibrium* adopted in the neoclassical theory of production do not seem appropriate to the study of technical change, which is characterized by severe uncertainty and is dynamic by definition. Some economists, therefore, have felt the need to incorporate a more realistic representation of how firms behave in order to investigate the dynamic processes that characterize technical change.

Two economists interested in innovation and economic dynamics, Richard Nelson and Sidney Winter, reached the conclusion that technological and economic change is best understood within an evolutionary framework (Nelson and Winter, 1977). Their book *An Evolutionary Theory of Economic Change* (1982) is a source of inspiration for an increasing number of economists. Evolutionary theories, although relatively still in their infancy, have offered interesting insights into the relationship between innovation and economic change.

Although evolutionary theories of economic change have only become accepted in recent years, they build on the work of some institutionalist economists, such as Thorstein Veblen (Veblen's theory of consumption is outlined in Chapter 3). In addition, almost a century ago, an Austrian, Joseph Schumpeter, set out a theory of economic development that is a source of inspiration and a reference point for modern evolutionary economists, including Nelson and Winter.

Evolutionary theories in economics are interesting for several reasons. First, they put dynamics at the forefront of their agenda, thereby filling an important gap in economic theory. Second, they raise methodological issues about theoretical and empirical economic analysis. Third, since their view of the economy is radically different from that provided by general equilibrium theory, evolutionary theories provide a new approach to economic policy.

Section 2 lays out the building blocks of evolutionary theories and Section 3 explores the notions of dynamics and path-dependency. You have already met these concepts in the previous chapter; Section 3 introduces economic models that make them explicit. Section 4 briefly reviews some applications of evolutionary theories, while Section 5 discusses the methodological and policy implications of an evolutionary perspective on economic change.

2 Evolutionary theories of economic change

2.1 The Schumpeterian legacy

'The essential point to grasp is that with capitalism we are dealing with an evolutionary process. [...] Capitalism, then, is by nature a form or method of change and not only never is but never can be stationary. And this evolutionary character of the capitalist process is not merely due to the fact that economic life goes on in a social and natural environment which changes and by its change alters the data of economic action; this fact is important and these changes (wars, revolutions and so on) often condition industrial change, but they are not its prime movers. Nor is this evolutionary character due to a quasi-automatic increase in population and capital or to the varieties of monetary systems of which exactly the same thing holds true. The fundamental impulse that acts and keeps the capitalist engine in motion comes from the new consumers' goods, the new methods of production or transportation, the new markets, the new forms of industrial organization that capitalist enterprise creates.'

(Schumpeter, 1987 edn., pp.82–3; originally published 1943)

This statement contains the main theoretical standpoint of the Austrian economist Joseph Schumpeter who was an important source of inspiration for Nelson and Winter.

Question

How do you think Schumpeter (who died shortly before Solow published his analysis of economic growth) would have commented on Solow's results presented in Section 3 of the previous chapter?

It is fair to say that he would not have been surprised. Solow's results showed that innovation was more important than capital accumulation for GNP growth, and in the above quotation, Schumpeter attributes the dynamism of capitalism to 'new consumers' goods' and 'new methods of production' rather than to 'quasi-automatic increase in population and capital'. He therefore stresses that the *qualitative* change that the economy undergoes with economic development is much more important than the quantitative increase in income per capita: '... the contents of labourers' budgets, say from 1760 to 1940, did not simply grow on unchanging lines but they underwent a process of qualitative change' (Schumpeter, 1987 edn., p.83).

Already by the beginning of the twentieth century, Schumpeter had developed a theory of economic development that shared many similarities with modern evolutionary models. He emphasized the importance of *dynamics* and *disequilibrium*, and noted that the main characteristic of capitalism is change from within the system, i.e. *endogenous change*, and the main source of such change is *innovation*. The institution that mainly drives the innovation process is the private firm. In Schumpeter's world, firms do not have access to a public pool of knowledge. They usually follow routinized behaviour while also striving to introduce innovations in order to reap the associated monopoly profits. Like Hayek, another key Austrian economist, Schumpeter embraced the notion of the market as a discovery procedure and creative process (Hayek, 1945). There is no perfect competition, no equilibrium; competition is seen as a process of 'creative destruction' in which successful innovators and some imitators survive, while many other firms disappear (*Changing Economies*, Chapter 6, Section 3). Profits are the reward that entrepreneurs earn for the introduction of innovations, until imitators erode their temporary monopoly. The role of entrepreneurial profit in Schumpeter's theory is very important because entrepreneurs are pushed to innovate by the hope of earning monopoly profits.

In the Schumpeterian theory profits are not seen as a sign of economic inefficiency (see Chapter 15, Section 4) but as the reward that entrepreneurs can earn for successfully introducing innovations. The lure of profits drives the increase in efficiency that stems from the introduction of innovations, and therefore is a major determinant of dynamic efficiency. The price to pay for this dynamism is the static inefficiency that is associated with the temporary monopolies enjoyed by innovators, but it is a price well worth paying in the long run.

The Schumpeterian view of the economy is very different from the picture of an economy in general equilibrium. There are no 'normal profits' nor optimizing agents, and the process of 'creative destruction', in which firms, technologies and industries appear and die, has many similarities with the struggle for survival described in modern evolutionary biology. It comes as no surprise then, that many evolutionary models of 'Schumpeterian competition' have appeared in the literature, and that these models adopt some concepts and mechanisms, such as mutation, selection and fitness, that were originally developed in biology.

Using biological models is not, in fact, a new idea in economics. Alfred Marshall, one of the best known contributors to neoclassical theory, thought that:

> *'The Mecca of economics lies in economic biology rather than in economic mechanics. But biological conceptions are more complex than those in mechanics; a volume on foundations must therefore give a relatively large place to mechanical analogies; and frequent use is made of the term equilibrium, which suggests something of a static analogy.'*
>
> (Marshall, 1948; quoted in Nelson, 1995)

The use of equilibrium as an analytical tool was to Marshall only a first step, dictated by the complexity of dynamic analysis. He believed theories that drew on biology would eventually be better at analysing 'the forces that cause movement' (*ibid.*).

2.2 *Building blocks of evolutionary theories*

Evolutionary theories try to make sense of the evolution of a system, that is, changes in a set of variables that are linked with each other. The approach is necessarily dynamic, as in the Schumpeterian approach. So evolutionary theory is not interested in studying the equilibrium state of a system at a particular point in time, but with understanding the processes by which the variables in a system change. Change and time must, therefore, be explicitly included in the theory.

'Evolutionary', therefore, is not a mere synonym of dynamics. As the British institutionalist Geoff Hodgson points out, evolution in a broad sense can be found in the work of almost all economists, including Walras, the father of the general equilibrium approach (see Chapters 1 and 18; Hodgson, 1993). The types of evolutionary theories that will be considered here study more complex types of dynamics which have two further characteristics. First, they include a mech- (1) anism, *mutation*, that generates variety among the units of analysis. Second, they specify another mech- (2) anism, *selection*, which, in a systematic way, allows only some units to survive and therefore reduces variety. The existence of variety means that evolutionary theories study populations, groups of heterogeneous units. The explicit adoption of a *population perspective*, therefore, differentiates evolutionary theories from simpler types of dynamic analysis. The existence of selection implies that the individual units in the populations studied interact, for instance, they compete in the same market; some survive and expand their share in the population. It should be clear, therefore, that the concept of a representative agent, a concept commonly used in neoclassical economics, is at odds with an evolutionary approach as it is the existence of differences between units that drives evolution. If all units are the same, there is no selection, no evolution.

Drawing from evolutionary biology, Dosi and Nelson (1994) propose four building blocks of evolutionary theories.

1. An evolutionary theory must define some stable units of analysis – like genes in biology.
2. The units of analysis are 'carried' by some individuals or organizations – like organisms in biology – which are the objects of selection.
3. A mechanism of mutation, which includes some random elements, generates new units of analysis, and renews the variety that is destroyed in the selection process.
4. The organisms that carry the 'genes' interact and some are selected at the expense of others – the fittest survive.

An evolutionary view of the economy requires the presence of these four building blocks. Many specific evolutionary models, however, just focus on particular mechanisms and do not specify all four blocks. I now examine each of these building blocks in more detail.

2.3 Firms, routines and genes

Following the Schumpeterian approach, Nelson and Winter (1982) place the firm at the centre of their evolutionary theory. They reject the neoclassical assumption of rational behaviour as maximization, use Simon's concept of bounded rationality and claim that firms cannot maximize and therefore they have to adopt simple procedures – rules of thumb or *routines* – to determine their behaviour (Chapter 8, Section 5). Routines do not themselves change, they are simply adapted or dropped. Routines that yield satisfactory results, for example a minimum level of profits, are followed until changes in the external environment make them unsatisfactory, or until the firm itself innovates, in which case the firm adopts new routines.

Routines determine what firms can and cannot do. Like individuals, organizations learn through experience and acquire tacit knowledge, skills that are embodied in their routines. Firms' skills include the skills of their employees and managers, but also the way individuals interact, the organizational setting (remember the Ford case study in Chapter 10), corporate culture, patents, brands, and so on. Since each organization has a different history, the combination of routines that embodies its knowledge is different from that of other organizations. Therefore, every firm is unique and possesses unique skills; this is what in Chapter 15, Section 7, I call a firm's *capabilities* or *competencies*.

Routines are important not only because they provide an alternative behavioural assumption to the neoclassical rationality, but also because they provide the basic unit of analysis in Nelson and Winter's evolutionary theory. Routines are the equivalent of genes in evolutionary biology, the stable unit of analysis, since, by definition, they cannot change. Further, since firms do not usually try to substitute new routines if the existing performance is satisfactory, firms tend to behave in the same manner over time. Therefore, the economy is characterized by a significant amount of institutional inertia and any hypothetical convergence towards an equilibrium, in which all firms adopt the most efficient routines, is slow and difficult, or may never happen at all.

The concept of routine is necessarily vague at this general level, and mainly means that firms cannot promptly and constantly adjust their behaviour to ensure that their performance is always optimal. In formal models, however, routines are identified more clearly. They have been defined as 'technologies, policies, behavioural patterns, cultural traits' (Dosi and Nelson, 1994, p.155), depending on what the theory seeks to explain. In the models considered in this chapter, routines are usually defined as technologies and firms as organisms that 'carry' such technologies, which they cannot costlessly or easily change.

It is important to understand that there are two levels of analysis, which correspond to two different populations: genes/routines and organisms/organizations. In Nelson and Winter's theory, routines are the equivalent of genes, whilst the variables that describe the performance of firms, such as profitability, investment and R&D expenditure, are characteristics of organisms.

The second building block in evolutionary modelling is the relationship between these two levels of analysis. In Darwinian biology, organisms cannot change the genes with which they are born during their lifetime. In economies, routines are mostly stable, but this does not necessarily mean that organizations are stuck with their routines in the same way that organisms are stuck with their genes. In most evolutionary models, firms can 'adapt', that is, innovate and/or imitate the routines of successful innovators, although this is not easy and requires expenditure on innovative activities, such as R&D. This is a marked difference between evolutionary theories in biology and economics.

However, imitative efforts are not necessarily successful, just as innovative activities may prove unfruitful. The ease of imitation (and innovation) varies in different theories. If you think of a spectrum, at one end of it you have theories which assume organizations always behave in the same way, and at the other end there are theories which assume organizations immediately adapt their behaviour and quickly adopt the best practice technology. The latter assumption leads towards the neoclassical theory of production, while the former leads to a Darwinian-based economy in which successful routines only increase their share in the population through a Schumpeterian process of 'creative destruction', that is, through the survival and growth of the firms that are lucky enough to have good routines, and the elimination and decline of inefficient firms.

Assuming that firms change routines only rarely (or not at all) might seem quite odd, especially to economists used to the traditional model of the maximizing firm. Nelson, however, points out that 'a number of students of firm behaviour have been impressed that the set of things a firm can do well at any time is quite limited, and that, while firms certainly can learn to do new things, these learning capabilities also are limited' (Nelson, 1995, p.79). Moreover, many empirical studies of firms, technologies and industries regularly show that firms *persistently* differ in a number of features, such as profitability, productivity and innovativeness, and that 'successful firms are often difficult to imitate effectively, because to do so requires that a competitor adopt a number of different practices at once' (*ibid.*).

Some models use just the Darwinian assumption, but the general case allows for situations somewhere along the spectrum. Firms can change their routines, but rarely and slowly. Indeed, you will see that some models include a parameter that specifies the 'ease of imitation', and can study how the results change when the value of that parameter changes.

2.4 Innovation, mutation and variety

Innovation and search routines

Mutation is the mechanism that generates variety, that is, new routines in the population studied – the economy or an industry. The existence of mutation ensures that there is always variety in the pool of routines and in the population of organizations. Indeed, the continued existence of variety is necessary for evolution, so the appearance of new varieties drives the system and gives a meaning to the process of selection. The emphasis on variety, that is, on qualitative differences between technologies and organizations, captures the Schumpeterian emphasis on the qualitative nature of economic change. Not only do productivity and income increase, but also new technologies, firms and industries appear in the economy and compete with existing technologies.

While in biology the creation of variety is achieved through random genetic mutation and sexual reproduction, in the economic models considered here variety is usually created via the innovation process, which, as in the Schumpeterian framework, is influenced by endogenous mechanisms within the model. In some of Nelson and Winter's models the total amount of expenditure on R&D in an industry, which influences the rate of innovation, is not fixed but is determined endogenously from the interaction of competing firms.

Because of the importance of the generation of variety for the theory, evolutionary economists have paid great attention to the innovation process, and have drawn on the literature in various fields in order to identify realistic features of technical change. The works you saw in the previous chapter, historical case studies of technologies, statistical indicators of technical change and studies on the management of innovation, have all contributed to the way in which innovation is conceived and modelled in evolutionary theories. Evolutionary theories stress the importance of tacit knowledge, uncertainty, learning-by-doing and search by trial and error. All regard technology as embodied in a system of institutions, such as firms, universities and government agencies. Indeed, the terms 'national system of innovation' and 'technology system', that you met in the previous chapter, have been developed within an evolutionary framework.

Nelson and Winter embrace the Schumpeterian idea that in capitalist economies the firm is the main source of innovation. However, while Schumpeter, especially in his early writings, mainly attributed the introduction of innovations to the action of the entrepreneur, Nelson and Winter argue that firms have special *search routines* dedicated to the introduction of innovations, that is, of new routines.

You saw in the previous chapter that innovative activity is characterized by severe uncertainty and innovators frequently search by trial and error. The results of the search are partially unforeseeable, and in formal models search can be represented as a random process, as though the outcome was given by, say, the toss of a coin. If firms are lucky they manage to innovate and the greater the resources devoted to innovation, the more likely (but never certain) they are to succeed in innovation. The search, however, is not completely random. Firms employ a set of procedures that involve 'proximate targets, special attention to certain cues and clues, and various rules of thumb' (Nelson and Winter, 1977, p.53). Firms select a small number of projects following certain criteria that include market considerations, cost, and technical feasibility. The last of these, technical feasibility, is influenced by knowledge previously accumulated by the firm and by the network of institutions with which the firm interacts. As with the case of the steam engine, the innovations introduced will not, in general, be complete breaks with the past but changes in one part of what we called in Section 7.7 of the previous chapter, a technology 'system'. Evolutionary theories are, therefore, particularly applicable to situations in which, instead of distinguishing between innovation and diffusion, it is appropriate to talk about the evolution of technological paradigms (Chapter 15, Section 7.4).

2.5 *Economic selection*

Selection, variety and efficiency

The picture of the economy that has been built up so far from an evolutionary perspective shows many heterogeneous organizations that have different, fairly stable patterns of behaviour and different competencies which influence their performance. Private firms seek entrepreneurial profits through the introduction of innovations. Only some firms are successful; the others lose out in the competitive race to sell goods and services. The interaction between firms in the economy generates a process of selection in which the fit firms survive and the unfit ones are eliminated.

Selection operates in the opposite direction to mutation by reducing the variety of organizations existing in the economy through the elimination of organizations and routines that are not fit enough to survive. It is important to note that, although the selection mechanism has an ultimate effect on routines, these are not selected directly in the competitive process. Competition on the market acts directly on the organisms (the firms) which undergo selection according to a measure of their performance, for example profitability. Because a firm's performance depends on a combination of factors, the selection of a particular routine will depend not only on the efficiency that it provides, but also on the other factors that contribute to the firm's performance, including the contribution of other routines.

Selection can assume various forms and can operate on different characteristics of firms. The specification of the mechanism of selection is at the core of any evolutionary theory in economics; different selection mechanisms produce different evolutionary theories. In particular, it is important to define which variables affect the performance of firms, and therefore their fitness. In the models we shall be looking at, I start by assuming that the performance of firms depends just on their technology; I relax this assumption later.

The selection environment in many evolutionary models is the market. Firms compete in order to sell more of their products and expand, but only the most efficient firms expand their output. Note that, in this context, efficiency is a *relative* notion; a firm is efficient if it produces at lower unit costs than its competitors. Evolutionary economists do not assume the existence of a known set of best practices. Firms continually search to improve their efficiency, but their search builds incrementally on their specific knowledge. By contrast, neoclassical economists assume the existence of a known set of best practices, hence a known *absolute* level of technical efficiency that firms may or may not attain. In many evolutionary models, efficiency is achieved through successful innovation or imitation. Efficient firms have lower unit costs and therefore, assuming all firms face the same price, higher profits. These additional profits allow them to finance more investment and, through investment, to grow. The ultimate effect of this process is that the use of successful, that is, productive, technology in the economy grows and the use of less efficient technologies shrinks as the less efficient firms who use them contract or disappear. The average efficiency of the whole economy improves with the increase in the share of efficient technology. Selection, therefore, increases economic efficiency by eliminating inefficient technologies.

I shall now clarify how selection works with some numerical examples. These examples will also introduce you to the *simulation* of economic systems, a technique that is widely used in evolutionary modelling. A formal evolutionary model is a system of equations that describe the economic process under study. For our purposes, we can classify the terms in each equation in two types: variables – the terms which evolve over time – and parameters – the terms that are held constant throughout the simulation run. In simple cases, economists can infer the unfolding of evolution, that is, how the variables change over time, by solving the equations algebraically. In many cases, however, the links between the variables in the system are very complex, and the only way to understand how the economic model 'behaves' is to assign arbitrary values to the variables in the first period (the so-called *initial conditions*) and to the *parameters*, and then to calculate the values of the variables in the following periods using the equations. In this way, economists see how the system evolves, i.e. how the values of the variables change for particular values of the parameters and the initial conditions. By repeating the simulation with different values for parameters and initial conditions, it is possible to have an idea of how the system behaves in a range of situations.

This explanation is rather abstract because the idea of a simulation is not easy to explain in words, the best way is to run one. The following examples should give you an idea of how simulation can be used to help us follow models of how the economy evolves. Models can be very complex, in which case economists have to use computers to simulate the evolution of the economic system under different assumptions. The model we shall examine is simplified, however, so you can 'run' this economic simulation with a calculator, pen and paper.

Although each step of the simulation requires only simple calculations, you may find the density of the formulae and calculations in the next few pages hard going. If you do, carry on reading up to the end of this section only concentrating on the text and the figures in order to understand the basic points illustrated by the simulations. Then, go back through the calculations to gain a deeper understanding of how selection and imitation shape economic competition.

Simulation Run 1: Selection, no imitation

In order to isolate the effect of selection on efficiency, I assume that adaptation, that is, learning or imitation, does not take place; firms are stuck with their technology. I start, therefore, from the Darwinian end of the spectrum that identifies the various types of firm behaviour. In addition, I keep the assumption that the efficiency of the firm, that is, its fitness, depends only on its technology.

Selection dynamics can be very complex. Nelson and Winter use many equations to describe the evolution of an industry. In the simulations that will follow in this section, however, I shall summarize the selection process in a simple equation. Similar selection equations have been used in a variety of dynamic models (see Silverberg, 1998) and the general mathematical structure can be traced back to the biologist R.A. Fisher.

If you consider the population of firms in an industry, the selection equation simply states that the rate of change of the market share of a firm is a function of its *relative fitness* compared with the average fitness of other firms in the industry. The mathematical expression of the law is:

$$G_t^i = \alpha \cdot \left(E_t^i - E_t^{AV}\right)$$

where G_t^i is rate of change of the market share of the ith firm at time t, α is a parameter that measures the intensity (and therefore the speed) of selection, E_t^i is a measure of the fitness of the ith firm at time t, and E_t^{AV} is the average fitness in the industry at time t. Hence, the expression in brackets, (E_t^i - E_t^{AV}) is the relative fitness; that is, the difference between the fitness of the firm and the average fitness of the industry. This equation simply states that those firms that are fitter than average at time t, $E_t^i - E_t^{AV} > 0$, grow, while the others lose market share. The greater the selection parameter α, the greater the effect of a difference in fitness on the changes in market share and therefore the faster the selection. Note that the suffix i in G_t^i (and E_t^i) refers to the ith firm, so for firm A, at time t=1, we have $G_{t=1}^A$ and $E_{t=1}^A$.

The next step is to define what is meant by fitness. In this case, I define fitness as the firm's profit margin - the difference between price (the revenue per unit sold) and unit costs. The greater the profit margin made by the firm compared to the industry's average, the greater the rate of change of its market share as it can finance more investment per unit sold than its competitors. If you assume that all firms sell at the same price, the fitness (profit margin) of each firm depends on its costs, that is, on its technology. Firms with better technology have lower costs and earn more profits; therefore they expand their market share. The greater the differential in efficiency, the greater the difference between rates of change in market share and, in turn, the faster the selection - inefficient firms lose market share more quickly.

We are now ready to run our simulation. First, we have to decide on the number of firms in the industry. For our simulation, I have decided that there will be three firms, A, B and C in the industry and each of them has a different technology and therefore different unit costs, C^i. I now have to assign values to the parameters (the terms held constant), which are each firm's costs, C^i, the values of the selection parameter, α, and the output price P, and the initial conditions (the values of the variables in the first period of the run), which are the market shares of each firm in the first period, $S_{t=1}^i$.

Let us suppose the firms' unit costs are: $C^A = 9$, $C^B = 10$ and $C^C = 11$ and all firms sell at the same price, $P = 15$. Hence, the profit margin of each firm, $\Pi^i = P - C^i$, will be:

$$\Pi^A = 15 - 9 = 6$$

$$\Pi^B = 15 - 10 = 5$$

$$\Pi^C = 15 - 11 = 4$$

Assume that all firms start with the same market share (one third of the market), that is:

$$S_{t=1}^A = S_{t=1}^B = S_{t=1}^C = 0.333$$

and the value of the parameter α is arbitrarily set at 0.5.

Second, the equations that describe the dynamic process we are studying have to be written explicitly. We start from the selection dynamics, which is described by the selection equation, using each firm's profit margin as its measure of fitness. For the ith firm at time t, we have:

$$G_t^i = \alpha \cdot (\Pi_t^i - \Pi_t^{AV}) = 0.5\,(\Pi_t^i - \Pi_t^{AV})$$

where G_t^i is the rate of change of market share at time t, Π_t^i is the profit margin (fitness) of the ith firm at time t, and Π_t^{AV} is the average profit margin (average fitness) of the industry (that is of the three firms) at time t.

We can then use the values of G_t^i to calculate the firm's market shares in the following period, t+1, using the formula:

$$S_{t+1}^i = S_t^i \cdot \left(1+G_t^i\right)$$

where S_{t+1}^i is the market share of the ith firm at time t+1, and S_t^i is the market share at time t. Thus, the market share of each firm at time t+1 is equal to its market share in the previous period multiplied by the factor $\left(1+G_t^i\right)$.

Finally, we need a formula for the average profit margin in the industry, Π_t^{AV}. To work this out we need to weight the profit margin of each firm by its market share because firms influence average profitability according to their market share. The formula is:

$$\Pi_t^{AV} = \sum_{i=A}^{C} (\Pi_t^i \cdot S_t^i) = (\Pi_t^A \cdot S_t^A) + (\Pi_t^B \cdot S_t^B) + (\Pi_t^C \cdot S_t^C)$$

Thus, in order to calculate the average profit margin in the industry we have to multiply each firm's profit margin by its market share and add the results together. So in the first period, the value of the average profit rate is:

$$\Pi^{AV}_{t=1} = (\Pi^{A}_{t=1} \cdot S^{A}_{t=1}) + (\Pi^{B}_{t=1} \cdot S^{B}_{t=1}) + (\Pi^{C}_{t=1} \cdot S^{C}_{t=1})$$
$$= (6 \times 0.333) + (5 \times 0.333) + (4 \times 0.333) = 5$$

All the values of the parameters (apart from $\alpha = 0.5$) and the initial conditions are reported in Table 16.1.

We can now calculate the growth rate of each firm at t=1. For firm A, we have:

$$G^{A}_{t=1} = 0.5 \cdot (\Pi^{A}_{t=1} - \Pi^{AV}_{t=1}) = 0.5 \times (6 - 5)$$
$$= 0.5 \times 1 = 0.5$$

Question

Calculate the rate of change of the market share of firms B and C at t=1, keeping in mind that:

$$G^{i}_{t=1} = 0.5 \cdot (\Pi^{i}_{t=1} - \Pi^{AV}_{t=1})$$

For firm *B*, we have:

$$G^{B}_{t=1} = 0.5 \cdot (\Pi^{B}_{t=1} - \Pi^{AV}_{t=1}) = 0.5 \times (5 - 5)$$
$$= 0.5 \times 0 = 0$$

and for firm *C*:

$$G^{C}_{t=1} = 0.5 \cdot (\Pi^{C}_{t=1} - \Pi^{AV}_{t=1}) = 0.5 \times (4 - 5)$$
$$= 0.5 \times (-1) = -0.5$$

Firm B holds on to its market share because its profits are exactly the same as the average profits of the industry. Firm *C*, however, makes less than average profits so its market share declines in the following period. The market share of firm *A* in period t=2 becomes:

$$S^{A}_{t=2} = S^{A}_{t=1} \cdot (1 + G^{A}_{t=1}) = 0.333 \times (1 + 0.5)$$
$$= 0.333 \times 1.5 = 0.5$$

Question

Calculate the market shares of firms B and C at time t=2, keeping in mind that:

$$S^{i}_{t=2} = S^{i}_{t=1} \cdot (1 + G^{i}_{t=1})$$

For firm *B*, we have:

$$S^{B}_{t=2} = S^{B}_{t=1} \cdot (1 + G^{B}_{t=1}) = 0.333 \times (1 + 0)$$
$$= 0.333 \times 1 = 0.333$$

For firm *C*, we have:

$$S^{C}_{t=2} = S^{C}_{t=1} \cdot (1 + G^{C}_{t=1}) = 0.333 \times (1 - 0.5)$$
$$= 0.333 \times 0.5 = 0.167$$

Since the market shares have changed, we have to calculate the average fitness (profit margin) in period t=2 (the profits are always the same because the price and each firm's costs are fixed for the whole run):

$$\Pi^{AV}_{t=2} = (\Pi^{A}_{t=2} \cdot S^{A}_{t=2}) + (\Pi^{B}_{t=2} \cdot S^{B}_{t=2}) + (\Pi^{C}_{t=2} \cdot S^{C}_{t=2})$$
$$= (6 \times 0.5) + (5 \times 0.333) + (4 \times 0.167) = 5.333$$

Exercise 16.1

Calculate the rates of change of market share for each firm at t=2, their market shares at t=3, and the average industry profit margin at t=3.

Table 16.1 Parameters and initial conditions of the simulation run

	Price	*Unit cost*	*Profit margin*	*Initial share*
Firm A	15	9	6	0.333
Firm B	15	10	5	0.333
Firm C	15	11	4	0.333
Average	15	10	5	–

We can carry on calculating values for many periods, but the dynamics of this simple system are quite clear from the beginning. Firm *A*, the fittest firm, is gaining market share while the others are declining. Table 16.2 shows the values calculated for the variables up to period 13. The results of the run are summarized in Figures 16.1 and 16.2.

Since all firms sell at the same price, the average unit cost for the industry is the price (unit revenue) less the average profit margin as shown in the final column of Table 16.2. This, and Figure 16.1, clearly show the technical gains that result from selection. As *A*, the most efficient firm, gains market share, average unit costs for the industry decrease because the best technology is used to produce a greater share of the output of the industry.

Two other features of the model are also worth mentioning. First, Table 16.2 and Figure 16.2 show that, after 13 runs, the fittest firm has become a virtual monopoly, with a market share of 99.9 per

Figure 16.1 The dynamics of average unit costs and profit margin: Selection and no imitation

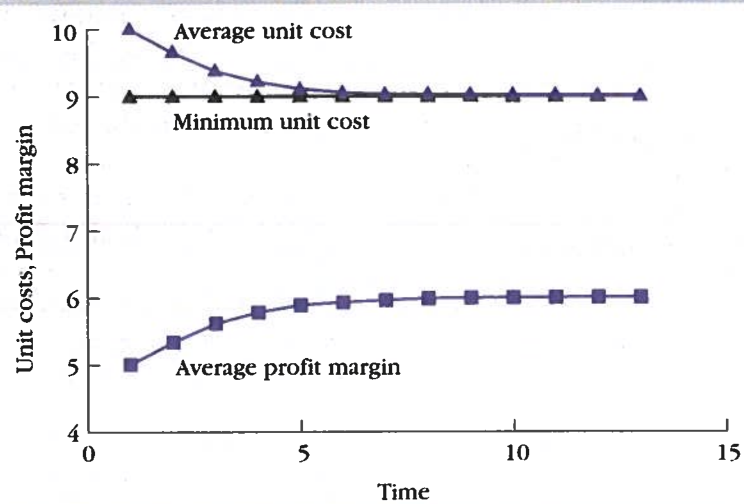
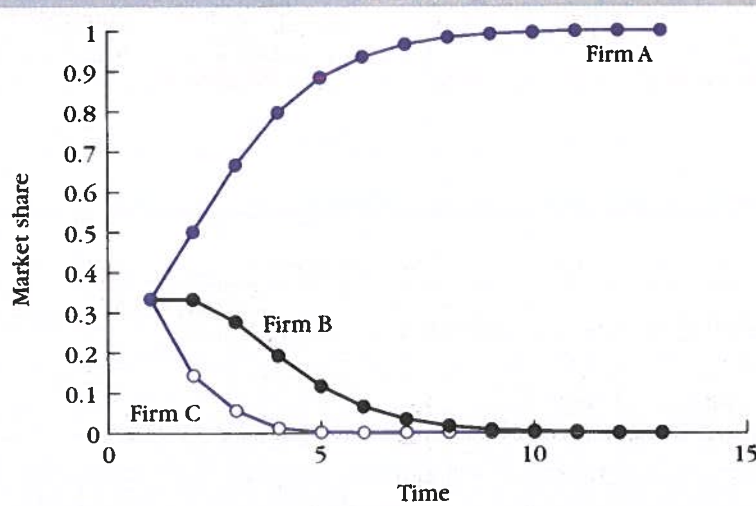


Figure 16.2 The dynamics of market shares: Selection and no imitation



cent, and the other firms have virtually disappeared. Second, since the price is fixed, all the gains in efficiency go to the efficient firm as profit; consumers do not benefit. This result, however, is a necessary consequence of the simple nature of the model, and it is quite easy to set up selection dynamics that do generate benefits to consumers.

Figure 16.2 illustrates well the Schumpeterian process of creative destruction, in which successful firms are rewarded in the market while competitors that do not imitate them in time disappear.

Simulation Run 2: No selection, no imitation

Question

What happens in a second simulation where $\alpha = 0$?

The parameter α quantifies the effect that the difference between the firm's and industry's profitability has on the change in each firm's market share. If $\alpha = 0$, differences in profitability do not affect changes in market share, that is:

$$G^i_t = 0 \cdot (\Pi^i_t - \Pi^{AV}_t) = 0$$

and therefore all market shares remain unchanged and the same at one third, as Figure 16.3 shows. Hence, since firms that use inefficient technologies hold on to their market share, average unit cost remains at the initial level of 10, and does not converge towards the minimum level, 9, achieved by the firm with the best technology (see Figure 16.4). Without selection, the average efficiency of the industry does not improve.

Simulation Run 3: Imitation, no selection

Imitation was explicitly ruled out in our model in the first run, so the fate of firms with inferior technologies was sealed from the start. It is possible, however, to build imitation into the model just by adding an equation. We can assume, for instance, that in every period, firms with inferior technologies catch up with the technological leader by reducing their efficiency gap. This process can be modelled by introducing an equation that describes the dynamics of unit costs for each firm. In the previous model, unit costs for each firm were a parameter, that is, fixed over time. This is equivalent to writing $C^i_{t+1} = C^i_t$, where C^i_t are the unit costs of the ith firm at time t.

Table 16.2 Results of the simulation run 1: Selection and no imitation

Time (t)	*Market share (S^i)*			*Average profit margin (in £)*	*Rates of change of market shares (G^i)*			*Average unit costs (in £)*
	Firm A	*Firm B*	*Firm C*	Π^{AV}	*Firm A*	*Firm B*	*Firm C*	Π^{AV}
1	0.333	0.333	0.333	5.000	0.500	0.000	−0.500	10.000
2	0.500	0.333	0.167	5.333	0.333	−0.167	−0.667	9.667
3	0.667	0.278	0.056	5.611	0.194	−0.306	−0.806	9.389
4	0.796	0.193	0.011	5.785	0.107	−0.393	−0.893	9.215
5	0.882	0.117	0.001	5.881	0.060	−0.440	−0.940	9.119
6	0.934	0.066	0.000	5.934	0.033	−0.467	−0.967	9.066
7	0.965	0.035	0.000	5.965	0.017	−0.483	−0.983	9.035
8	0.982	0.018	0.000	5.982	0.009	−0.491	−0.991	9.018
9	0.991	0.009	0.000	5.991	0.005	−0.495	−0.995	9.009
10	0.995	0.005	0.000	5.995	0.002	−0.498	−0.998	9.005
11	0.998	0.002	0.000	5.998	0.001	−0.499	−0.999	9.002
12	0.999	0.001	0.000	5.999	0.001	−0.499	−0.999	9.001
13	0.999	0.001	0.000	5.999	0.000	−0.500	−1.000	9.001

If we allow for the gradual imitation by firms of best practice technology, unit costs become a variable whose dynamics is described by the equation:

$$C^i_{t+1} = C^i_t - \beta \cdot (C^i_t - C^{MIN}_t)$$

where C^{MIN}_t are the best practice (minimum) unit costs at time t. The value in brackets, $(C^i_t - C^{MIN}_t)$, is the efficiency gap of the ith firm, i.e. the difference in the unit costs of the ith firm and the firm that has the best practice technology. This is what all other firms are trying to reduce by imitation. β is a parameter that measures the ease (speed) of imitation; its value varies between 0 and 1.

If $\beta = 0$, there is no imitation:

$$C^i_{t+1} = C^i_t - 0 \cdot (C^i_t - C^{MIN}_t) = C^i_t$$

Figure 16.3 The dynamics of market shares. Simulation run 2: No selection and no imitation

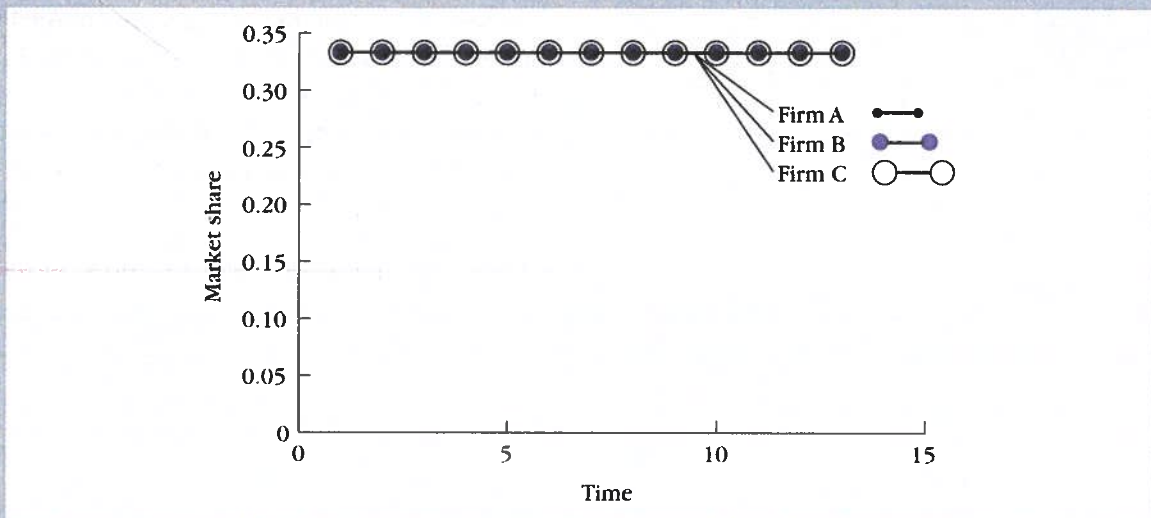
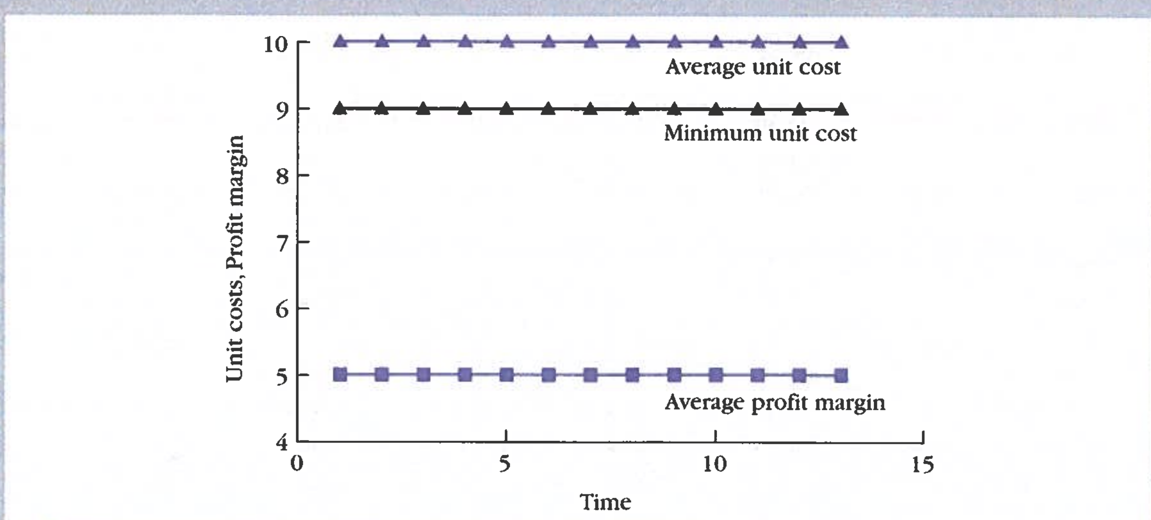


Figure 16.4 The dynamics of unit costs and profit margin. Simulation run 2: No selection and no imitation



If $\beta = 1$, complete imitation occurs in just one period:

$$C^{i}_{t+1} = C^{i}_{t} - 1 \cdot (C^{i}_{t} - C^{MIN}_{t}) = C^{i}_{t} - C^{i}_{t} + C^{MIN}_{t} = C^{MIN}_{t}$$

If $\beta = 0.5$, in each period the ith firm will halve its efficiency gap. For firm C in the first period, for instance, $C^{C}_{t+1} = 11$ whereas $C^{MIN}_{t} = C^{A}_{t=1} = 9$. Firm C's efficiency gap in the first period is $11 - 9 = 2$. So:

$$C^{C}_{t=2} = C^{C}_{t=1} - \beta \cdot (C^{C}_{t=1} - C^{MIN}_{t=1})$$

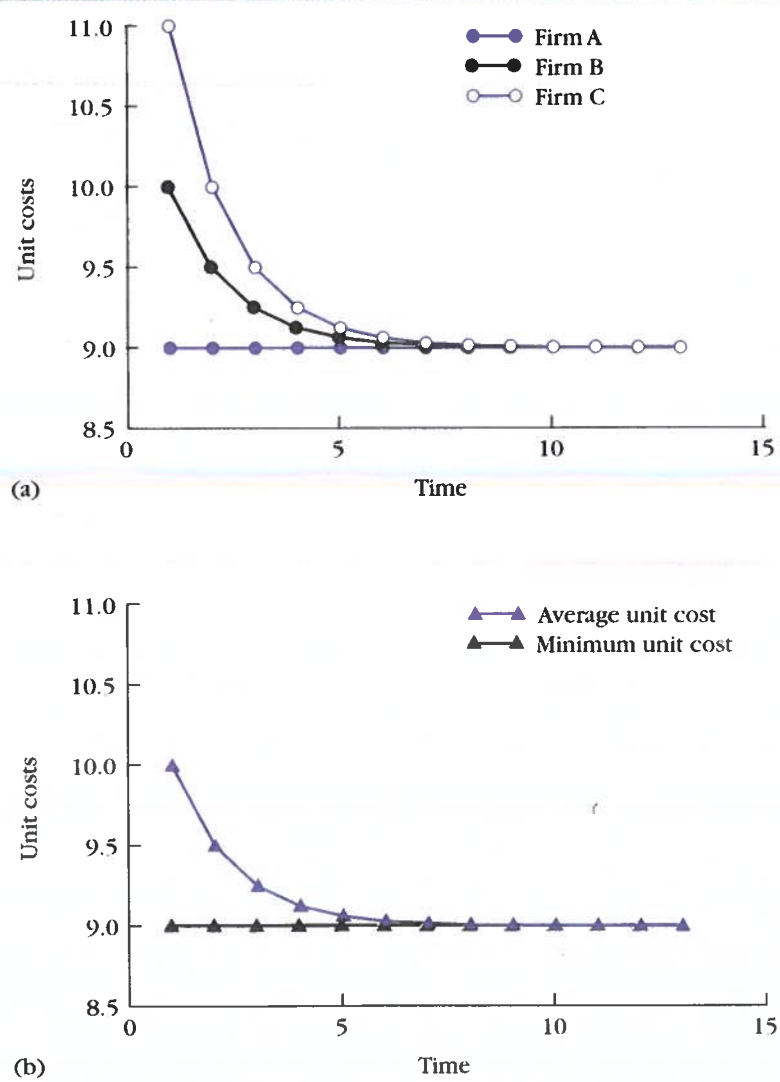
$$= 11 - 0.5 \times (11 - 9)$$

$$= 11 - 0.5 \times 2 = 11 - 1 = 10$$

We start by setting $\alpha = 0$ (as in run 2), so that there is no selection and market shares do not change - the chart of the dynamics of market shares is therefore exactly the same as in Figure 16.3. However, unit costs change each period as less efficient firms catch up with the technological leader, firm *A*. As you can see in Figure 16.5(a), by the time we get to period 10 all firms have virtually the same unit costs, which also correspond to the best practice. For the sake of clarity, average and minimum unit costs are reproduced in Figure 16.5(b). As happened in the first run, the industry average profit margin converges towards 6.

However, there are two interesting differences. First, while in the 'selection and no imitation' model

Figure 16.5 The dynamics of unit costs. Simulation run 3: Imitation and no selection



we ended up with a monopoly, in this 'imitation and no selection' model, market shares have not changed and industry concentration has not increased. Second, while in the first model technological variety was destroyed by selection *through the elimination of firms* (firms could not change their technology), this time technological variety has been eliminated by the *adaptation of the existing firms.* The 'destruction' of inefficient technologies has occurred inside the firms, not between firms. All firms have become exactly the same in terms of technology. We are now at the neoclassical end of the spectrum, and since all firms are identical it even makes sense to talk about a representative firm that is technically efficient.

Simulation Run 4: Imitation and selection

We can now see in Figures 16.6 and 16.7 what happens when the two mechanisms coexist if we run the model with $\alpha = 0.5$ and $\beta = 0.5$. The imitation process is the same as in Figure 16.5(a) and therefore results in the same fall in unit costs *for each firm*. However, in the early periods, while there are still significant technological differences between firms, selection favours *A*, the most efficient firm. This brings *average* unit costs down faster in Figure 16.6 than in Figure 16.5(b). In Figure 16.6, the dynamics of average unit costs is now clearly visible as they lie below the unit costs of firm *B* in the early periods. Minimum unit costs (best practice technology) still coincide with firm *A*'s unit costs, as in the previous runs.

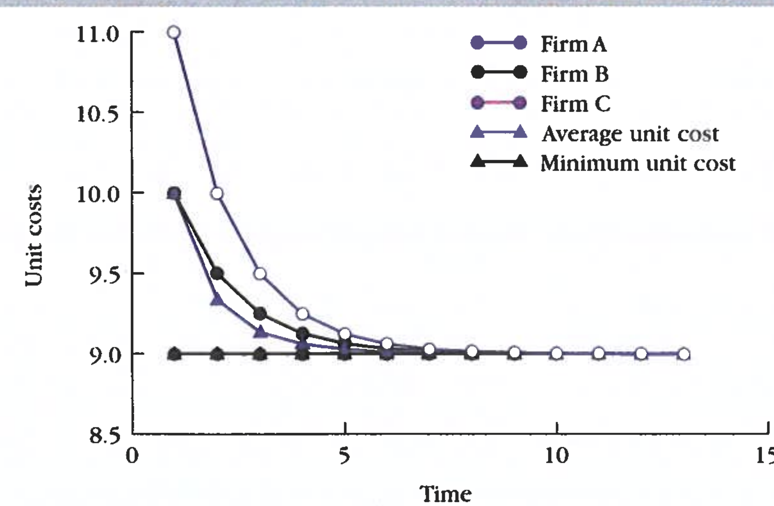
When imitators manage to catch up with best practice unit costs (in Figure 16.6 it happens around $t = 10$), the market shares of the three firms stabilize (see Figure 16.7). Imitators do not regain the lost market shares, but neither are they driven out of the market. The initial cost advantage has given a permanent advantage to firm *A* before market shares become stable again.

Selection, learning and maximization

The mechanisms behind the results of these simulations are quite intuitive. Either selection or imitation can drive improvements in economic efficiency. You have seen, however, that which assumption we make about firms' behaviour changes the evolution of industry structure quite dramatically. If firms cannot change their behavioural traits (in this case technology) quickly and there is a strong selection, concentrated market structures result. On the other hand, fast imitation tends to generate firms that all behave essentially in the same way.

The models just presented are very simple and focus on the importance of selection and imitation. I have completely neglected innovation and other processes that interact with selection and imitation, such as learning-by-doing and other types of first mover advantages. I have also made some assumptions that may be very unrealistic. For instance, I have assumed that one type of routine – technology – is the only determinant of firm performance, and that

Figure 16.6 The dynamics of unit costs. Simulation run 4: Imitation and selection



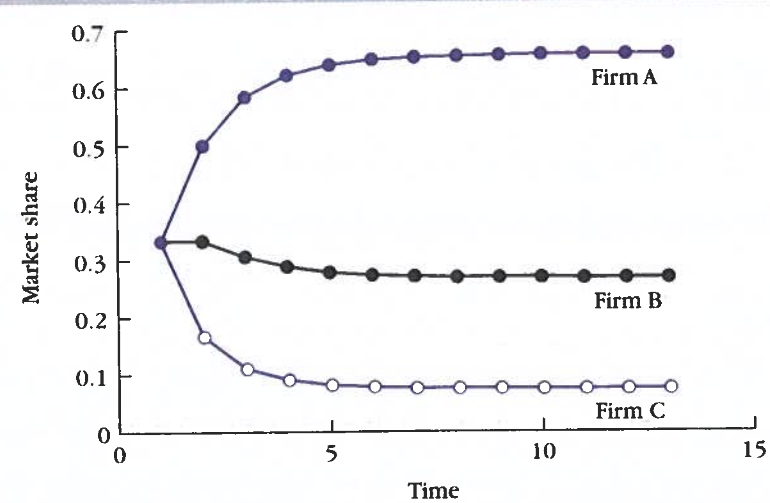
imitation is costless. These assumptions can be relaxed and other mechanisms can be taken into account by including more equations in the model. In some cases, the interaction between different mechanisms can generate surprising results, some of which are mentioned later. It is therefore dangerous to interpret these results as a faithful description of what goes on in the economy; reality is more complex.

Because of their intuitive appeal, however, the notions of learning and 'survival of the fittest' are often mentioned in economic arguments in support of the neoclassical assumption that firms optimize their behaviour. Imitation is a form of learning, and you saw in run 3 (imitation and no selection) that if firms learn quickly and selection is weak then all firms end up behaving in the best possible way, i.e. adopting the best practice technology. The neoclassical concept of technology as public information is also associated with the idea that firms can quickly imitate technological leaders. When adaptation fails, selection comes to the rescue. If some firms do not manage to imitate in time, economic selection eliminates them. A standard neoclassical response to the evidence from case studies that firms follow stable patterns of behaviour rather than maximizing is that it is still correct to model firms 'as if' they maximize because the end result is the same (Friedman, 1953). If they do not learn to behave as if maximizing, firms do not survive - as happened in simulation run 1 of our model, although, unlike in that model, the 'as if' argument assumes that the number of surviving firms is sufficiently large to maintain competition.

Despite its intuitive appeal, however, the 'as if' argument hides some controversial assumptions. First, it implies that selection is faster than mutation, i.e. that competition eliminates inefficient firms faster than it spurs the appearance of new firms and innovations. If variety is generated at least as quickly as it is eliminated, there will always be a significant number of firms that are not using the best technology. This debate can only be solved empirically, and the available evidence offers little support to the 'as if' argument. Evidence that firms are very different, and persistently so, both in terms of behaviour and performance, does not fit with the idea of an economy with strong processes of selection and imitation (Nelson, 1995). On the other hand, many statistical studies of entry and exit of firms strongly support the idea of an economy that continuously eliminates a great number of firms, especially recent entrants (Audretsch, 1995).

The observation that many firms disappear, however, does not necessarily mean that remaining firms behave optimally. In fact, they can even be inefficient in many respects. Our model has reached the conclusion that the firms with the most efficient technology survive and the others are eliminated - either through selection or imitation - only because of the simple assumptions built in it. We have assumed, for instance, that fitness, i.e. profitability,

Figure 16.7 The dynamics of market shares. Simulation run 4: Imitation and selection



depends on one single variable, technological efficiency expressed in unit costs, because the price is the same for every firm. Fitness/profitability, however, often depends on non-technological factors, such as marketing strategies, location, ease of access to customers, luck and special privileges. It is quite reasonable, therefore, to assume that firms may be able to sell products at different prices because of product differentiation. In this case, the final result can be different.

Simulation Run 5: Selection, no imitation and product differentiation

Let us assume, for instance, that firm C, which employs the least efficient technology, has a very successful marketing strategy, and creates a brand name that allows it to sell its product at a higher price, $P = 18$. Firm C is now the fittest; it earns a bigger profit $\Pi_t^C = 18 - 11 = 7$ than the other two, $\Pi_t^A = 15 - 9 = 6$ and $\Pi_t^B = 15 - 10 = 5$, although firm C uses the worst technology. If we run our model setting the parameters as in the first run, $\alpha = 0.5$ and $\beta = 0$, that is, with selection working and without imitation, we find out that firm C expands and dominates the industry, as you can see in Figure 16.8.

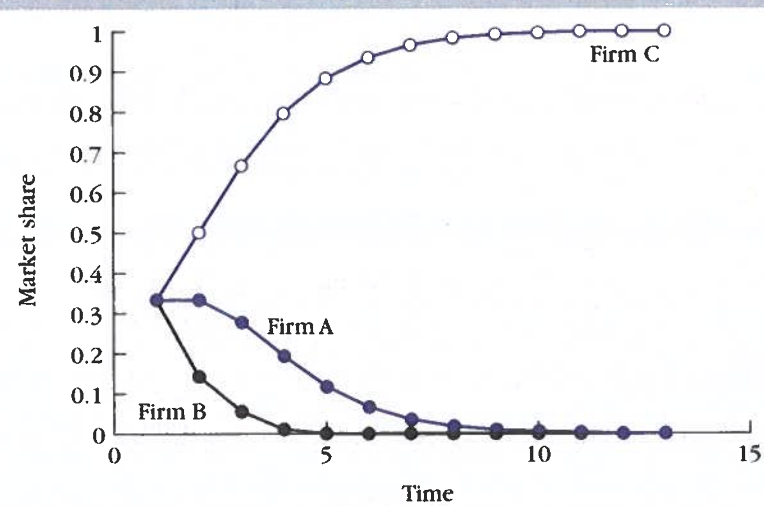
As in the first run, selection generates a concentrated market structure, but this time it is not the firm with the best technology that dominates. The weight of the best technology in the industry shrinks as the market share of the firm which uses it declines. In fact, Figure 16.9 shows that now the worst technology dominates, and industry unit costs increase, as do average price and profits. As a result of selection, average unit costs in the industry have actually increased.

This example shows that firms selected for growth are not necessarily those that behave in an optimal way in all respects. It also sheds light on the meaning of the phrase 'survival of the fittest'. As in the previous cases, the fittest firm survives; firm C is the most profitable. However, the meaning of 'fittest' is open to interpretation as firm C has the worst efficiency. In evolutionary models the fittest firms survive by definition, because we specify it in the model, but this does not entail optimization. In the last run, firm C had the best selling price, but it is quite possible to build a model in which a firm which is not optimal in any feature becomes the market leader.

The message of this example is that you must not confuse fitness and survival with optimization. Economic selection is often (sometimes implicitly) used to support the argument that firms – or, more generally, institutions – that have survived are the best possible. This position is usually called Panglossian, after the philosopher Pangloss in Voltaire's *Candide* who always claimed that we live in the best of all possible worlds, and that anything that happened was for the best.

The Panglossian argument has two main flaws. First, better institutions that are possible might not

Figure 16.8 The dynamics of market shares. Simulation run 5: Selection, no imitation and product differentiation



have actually appeared. If the creation of variety happens rarely then better institutions are not very likely to appear although they are possible. Second, selection is a complex mechanism that does not guarantee optimization. We have seen a 'perverse' result, from a technological perspective, which occurred because fitness also depends on variables other than technological efficiency. Since selection works on fitness, which may depend on attributes of the organism that are not genetically determined, selection does not always ensure that the best genetic material, the best technologies, survive. In other words, when imitation is weak, the fate of the technologies is strictly linked to that of the organizations which 'carry' them.

3 Path dependency and economic evolution

3.1 *Modelling innovation*

Now that you have explored the building blocks of evolutionary theories, we can think how simple models of selection and adaption could be extended. We could start by adding innovation to our model of economic selection.

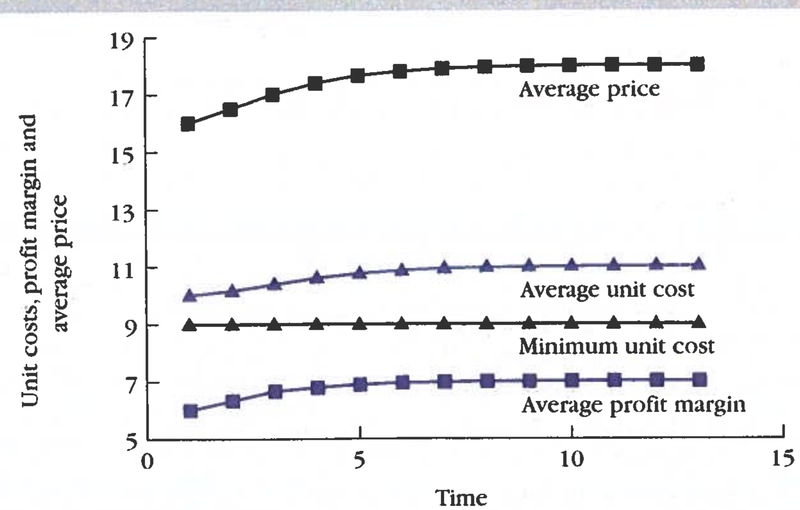
Question

How would you include innovation in the models of economic selection seen in the previous sections?

To capture the unpredictability of the outcome of innovative activities, innovation is often represented in formal models as the output of a random process, such as the toss of a die. In our model, unit costs could be made to depend on such a random variable. If the result of the toss is, say, 6, the lucky firm innovates and becomes the technological leader, otherwise costs follow their usual dynamics.

Modelling innovation in this way, however, conforms to the traditional ideas of exogenous technical change; innovation just 'falls from the sky'. In fact, the output of innovative activity is influenced by economic factors, such as the amount of resources devoted to innovation and the ease with which firms can appropriate the returns to innovation. The fact that the same technology can have different effects on profitability across firms should also be taken into account. Some firms might be able to exploit the opportunities offered by a technology more fully if they have complementary assets, or might use the technology with increasing efficiency as they learn more about them over time. Representing technical change as just a one-off shift in unit costs neglects

Figure 16.9 The dynamics of industry unit costs, profit margin and price. Simulation run 5: Selection, no imitation and product differentiation



phenomena which generate dynamic increasing returns to use such as learning-by-doing (see Chapter 11, Section 2.2; Jovanovich and Nyarko, 1995).

Further, it should be possible to distinguish, for instance, between discontinuities due to changes of paradigm and incremental technical change within a paradigm (Chapter 15, Section 7). This distinction is useful as it takes into account the fact that technical change is characterized by increasing returns to use for the economy as a whole and overcomes the somewhat artificial distinction between innovation and diffusion (Dosi, 1988). Since the knowledge produced in the innovative process is also used as an input for future innovations, the more a technology (a paradigm) is adopted in the economy, the better it becomes, as firms and other institutions (suppliers, customers, universities) learn about it; many adoptions are therefore also incremental innovations that improve the technology. The time of adoption of a technology, therefore, becomes an important variable. More developed evolutionary models have provided a useful framework for analysing the economic effects of such increasing returns to use in a variety of contexts at the individual firm, industry and economy level.

3.2 Increasing returns and competition between technologies

Increasing returns to use of a technology operate both at the firm level, as each firm uses a technology more efficiently, and at the system level, as many institutions adopt the technology and therefore improve it. Some models have explored both mechanisms while others have concentrated on just one of them.

Variety, selection and diffusion: Silverberg, Dosi and Orsenigo's model Silverberg *et al.* (1988) have built a model of the diffusion of two competing technologies, which includes many of the features of technical change just mentioned. In their model, the existing dominant technology (paradigm) has exhausted its potential for improvement, and a new technology, which has a large *potential* for improvement, becomes available for all firms to adopt. The *actual* efficiency of the new technology, however, is low at the start, and only adoption by pioneers can improve it. Firms that adopt the technology develop it and learn to use it more efficiently with time, and therefore they gain first mover advantages against later adopters. This favours the firms that adopt early – as in Scherer's study of learning-by-doing in the semiconductor industry that was discussed in Chapter 11, Section 2.2. Some of the improvements, however, spill over into the system, and some competitors can start learning about the new paradigm from a higher level of efficiency (for instance, they might share some suppliers). Since these 'early followers' have not borne the expenditure to develop the technology, they can be more profitable than the pioneers and expand faster.

The authors run the model under different conditions. The outcome of the simulations is influenced by the relative strength of two factors, learning by an adopting firm and spillover effects to other firms. If learning is fast and early adoption generates high efficiency advantages, pioneers gain a substantial lead on competitors who will not be able to catch up, and will go on to dominate the market – this is Scherer's case. However, if appropriability is weak, that is, there are significant spillovers and competitors benefit without spending, pioneers pay for the substantial expenditure incurred to develop a technology which also becomes accessible to competitors for free (this is the problem identified by Arrow, see Chapter 15, Section 4). Pioneers will, therefore, lose market share. When the run starts, firms do not know how fast they will learn and how much knowledge will spill over to other firms, and therefore form different expectations about the relative strength of the two processes. Depending on their expectations, they adopt the next technology at different times. If they think that first mover advantages outweigh spillovers, they adopt early, otherwise they wait.

Various results are possible depending on the values given to the parameters for learning and appropriability. If learning is fast and appropriability strong, the first adopter dominates the industry. For a wide range of values of the two parameters, however, firms that adopt just after the earliest pioneers – early followers – end up dominating the industry, as they exploit the spillovers generated by the pioneers but also start learning early enough. Firms that adopt only when the new technology has overtaken the old technology in productivity, cannot catch up.

This result is very interesting for a number of reasons. First, you can see that there are increasing returns to the adoption of the technology at both the firm and the industry level. Each firm enjoys increasing returns due to learning-by-doing, and the efficiency of the technology improves with the number of adopters.

Second, and more interestingly, when early followers dominate against pioneers and late adopters, the technology would not have come to dominate the industry without the existence of pioneers. At the beginning of the run, the actual efficiency of the new technology is so low that most firms are not ready to invest in it. The early followers adopt the new technology only after its actual efficiency has risen because of prior investment in it by over-optimistic pioneers, who wrongly thought that first mover advantages would outweigh spillovers. Quick followers would not have adopted the technology if nobody else had started the development first, and therefore the actual efficiency of the new technology would not have grown enough to overtake the old dominant technology. The unlucky pioneers, who unwillingly end up paying for their excessive optimism, are necessary for the final success of the new technology. However, they would not have invested in it had they known the real balance between first mover advantages and spillovers.

The intriguing conclusion of Silverberg *et al.*, therefore, is that a potentially better technology might not be developed – or might be developed much later – without the presence of over-optimistic pioneers. Two factors contribute to the success of the new technology. First, firms lack information about the future efficiency of new technology and about the extent of learning and spillovers; they guess. Second, firms are heterogeneous so they have different expectations about the technology and make different guesses. But heterogeneity implies that some over-optimistic firms can exist. If all firms guess correctly, nobody would adopt the new technology, knowing that the first adopters would fail.

The results are certainly not Panglossian, and the mechanism is not neoclassical. A potentially better technology may not come to dominate, and, even if it does, it may have been initially adopted only because firms are different and some get it wrong. Instead of perfect foresight and perfect knowledge about new technology we have a variety of expectations and firms that get it wrong are destroyed. Adaptation is slow, and selection is a driving force in the evolution of the new technology.

Random events, network externalities, irreversibility and path-dependency: Arthur's model

Another very influential model that puts increasing returns to use at its core has been developed by Brian Arthur, an economist interested in the evolution of complex systems (Arthur, 1989). In his model, two new technologies compete, and the returns to the adoption of each technology increase with the number of agents (firms or customers) that adopt it. There is positive feedback to the adoption of either technology. Arthur's model shows how increasing returns affect competition between technologies, and, more importantly, provides a very clear example of path-dependency at work. Since path-dependency has been mentioned in several parts of the course, it is worth looking at it more closely here, using a numerical example. In order to do so, I shall develop a very simplified version of Arthur's model and carry out a simple simulation.

Let us consider a model with two types of agents, H and T, who have to choose between two technologies, A and B. You can think of them as customers that have to choose between two computer operating systems, for instance, Mac and Windows, or as firms that have to choose between two new process technologies. The decision as to which technology to adopt depends on the returns to the adoption of each of the competing technologies, which are, in turn, influenced by two factors. First, agents naturally prefer one of the two technologies because they gain higher returns from the adoption of one technology; in particular, H-agents naturally prefer technology A, and T-agents naturally prefer B. Second, the returns to adoption of each technology also depend on the number of agents that have adopted the technology at the moment of the agent's decision. If most of the agents have chosen a particular technology, it is sensible to make the same choice for a number of reasons; more resources are devoted to the improvement of widely-adopted technology, and the uncertainty that surrounds its effectiveness declines as its familiarity increases; there are more users of the same technology with whom (as in the case with computer systems) to share information (this mechanism is called the *network effect*, or sometimes *network externalities*, as the returns to the adoption of a technology depend on the decision of a network of users); there are *economies of scale*, both static and dynamic, to exploit as producers can sell to a large market; as a technology becomes more common a *complementary infrastructure* appears (as with petrol stations with the diffusion of cars driven by internal combustion engines).

Network effect

This occurs when an agent's returns to the adoption of a technology changes with the number of agents that adopt that technology.

It is reasonable to assume that the difference in the number of adopters only matters when the lead of one technology is large enough. In the model we are considering, I have arbitrarily decided that a lead of ten adopters is the threshold. If neither technology leads by more than ten adoptions, agents choose their naturally favourite technology (H-agents choose A, T-agents choose B). However, if one technology leads by more than ten adoptions, there is positive feedback and *all* agents choose the leading technology, that is, the agents that naturally prefer the other technology switch their allegiances.

Table 16.4 Competition between technologies: Simulation results

Total adoptions (1)	*Agent drawn (2)*	*No. of H-agents (3)*	*No. of T-agents (4)*	*Adoptions of A (5)*	*Adoptions of B (6)*	*Lead of A (7)*
1	H	1	0	1	0	1
2	H	2	0	2	0	2
3	T	2	1	2	1	1
4	T	2	2	2	2	0
5	H	3	2	3	2	1
6	T	3	3	3	3	0
7	H	4	3	4	3	1
8	H	5	3	5	3	2
9	H	6	3	6	3	3
10	H	7	3	7	3	4
11	T	7	4	7	4	3
12	H	8	4	8	4	4
13	H	9	4	9	4	5
14	H	10	4	10	4	6
15	T	10	5	10	5	5
16	H	11	5	11	5	6
17	H	12	5	12	5	7
18	H	13	5	13	5	8
19	T	13	6	13	6	7
20	H	14	6	14	6	8
21	T	14	7	14	7	7
22	T	14	8	14	8	6
23	H	15	8	15	8	7
24	H	16	8	16	8	8
25	T	16	9	16	9	7
26	H	17	9	17	9	8
27	H	18	9	18	9	9
28	H	19	9	19	9	10
29	H	20	9	20	9	11
30	T	20	10	21	9	12
31	T	20	11	22	9	13
32	H	21	10	23	9	14

There is one adoption each round and in each there is an equal probability that the adopting agent is of type H or of type T ($p = 0.5$).

I can now run the simulation using a coin to determine which type of agent makes the decision each round: an H-agent (T-agent) is selected when a head (tail) is shown. You can run your own simulation by simply tossing a coin and recording the results in a table. My results are recorded in Table 16.4:

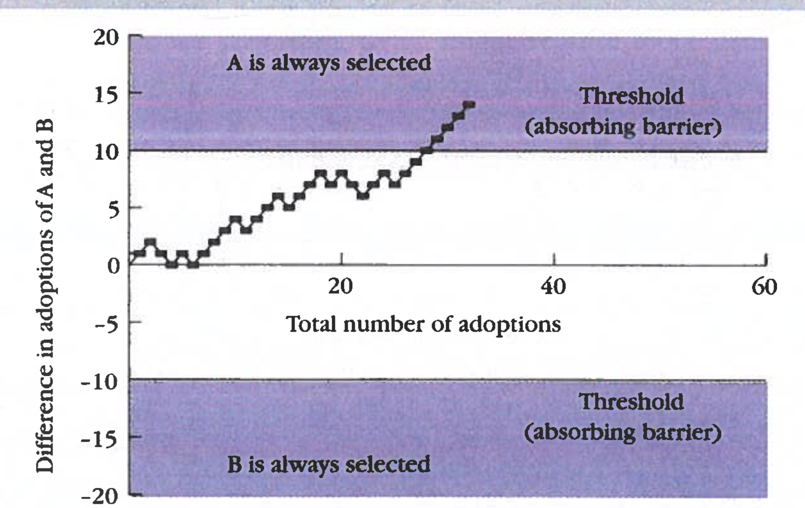
- column 1 shows the number of rounds (adoptions of either technology)
- column 2 reports the result of each toss H (head) or T (tail)
- columns 3 and 4 indicate the total number of H-agents (T-agents) drawn up to that round
- columns 5 and 6 report the total number of adoptions of each technology; these are the same as columns 3 and 4 until one of the two technologies leads the other by more than ten adoptions; after that the leading technology is always chosen, and so just increases its lead
- column 7 shows the lead of technology A; it is calculated by subtracting the figure in column 5 from that in column 6. When B leads, the figure is negative.

In the simulation presented in Table 16.4, the first toss of the coin (H) indicates that the first adopter is an H-agent. So technology A leads by one adoption. The process is repeated until the 29th round, when the 20th adoption of technology A gives it a lead of 11 adoptions with a total of 20 against the 9 adoptions of B. From this round onwards, all T-agents switch their preference to technology A, as in rounds 30 and 31, and therefore the lead of A increases with every round. Nobody chooses B anymore, and the industry is 'locked into' technology A.

The results of the run are shown in Figure 16.10, which shows the lead of technology A. The thresholds beyond which each technology is always adopted are represented by horizontal 'absorbing barriers'. Once one of the barriers is crossed, there is no return. One technology, in this case A, wins and the other is subsequently never adopted again.

Note that we could have easily had the opposite result: the system could have been locked into technology B if more T-agents had adopted early. The decision of a few firms to be early adopters, which is modelled as a random variable in this model, has determined which technology succeeds. Either technology could have been selected; the success of one depended on a *sequence* of small random events which determined the *path* that the process followed. History – the sequence of events – matters. For this reason, the process is said to be *path-dependent*. Taken to the limit, one can imagine a situation in which the decision of a single agent makes a dramatic difference.

Figure 16.10 Adoption with increasing returns



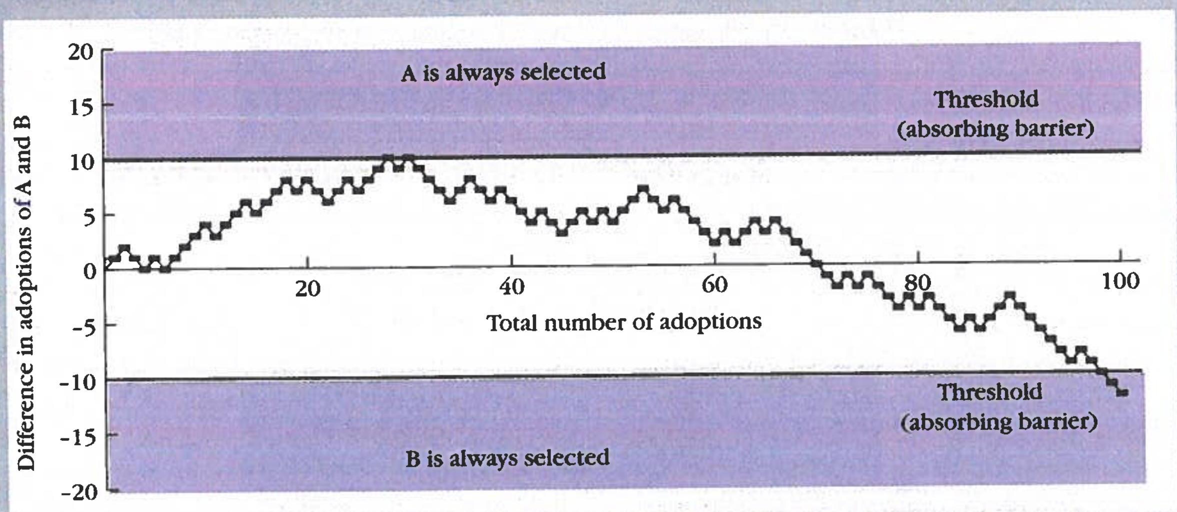
Imagine a run similar to the one described in Table 16.4, but with the sequence of adoption in rounds 29 and 30 inverted. As shown in Table 16.5, technology A does not reach the threshold after which increasing returns make all firms choose to adopt it, and the system is not locked in. By round 34, if T-agents continue to be the next to adopt, as in Table 16.5, A's lead drops to six and the competition becomes wide open again.

Figure 16.11 shows a run in which technology B ends up winning the 'race'. The switch between an H-agent and a T-agent in rounds 29 and 30 has changed the whole picture. Note that the total number of agents adopting each technology in the first 32 rounds has not changed; only the *order* in which they appear. The action of one agent deciding to adopt the technology one round later, can, unknowingly, change the destiny of the whole system.

Table 16.5 Competition between technologies: Simulation results with a new sequence

Total Adoptions (1)	*Agent drawn* (2)	*No. of H-agents* (3)	*No. of T-agents* (4)	*Adoptions of A* (5)	*Adoptions of B* (6)	*Lead of A* (7)
1	H	1	0	1	0	1
...	...	...	...	...	...	...
27	H	18	9	18	9	9
28	H	19	9	19	9	10
29	T	19	10	19	10	9
30	H	20	10	20	10	10
31	T	20	11	20	11	9
32	T	20	12	20	12	8
33	T	20	13	20	13	7
34	T	20	14	20	14	6
...	...	...	...	...	...	...

Figure 16.11 Adoption with increasing returns: a new sequence



Reflection

If you are deciding between cable or satellite TV, the fate of broadcasting technology may depend on your decision!

A consequence of path-dependency is *non-predictability*. It is impossible to know in advance which technology will succeed because the sequence of values that the random variable will assume cannot be predicted – by definition, they are random.

More importantly, in the presence of increasing returns, processes that are path dependent can generate inefficiency in the long run. Let us assume, for instance, that technology B is better than technology A in the long run, but its superiority is only revealed after at least 30 agents have adopted it. Until the 30th adoption of B, agents base their decision only on their natural preferences and on the number of adopters. In our original run, B never gets the chance to be adopted 30 times because the system is locked-in to A by the time B has been adopted only nine times. Technology B, which is *potentially* better, never diffuses far enough to show it.

Increasing returns also make the *timing* of the introduction of a technology very important. In the model, I assumed that both technologies started at the same time. A technology that has an early start, however, could corner the market straightaway even if another technology is potentially better in the long run.

Note that without increasing returns to use such inefficiency could not occur in this model. If there are constant returns, the returns to the adoption of a technology do not change with the number of adopters, and agents always choose according to their natural preference. There are no absorbing barriers. Sooner or later, technology B will be adopted by 30 agents and its superiority will be revealed. Technology B will also end up dominating in the case of diminishing returns to use, which are represented by 'reflecting barriers'. If a technology leads by more than ten agents, all agents adopt the other, so no technology corners the system until technology B proves superior. Diminishing returns to use occur when scarce resources are needed to use a technology. Arthur (1989), for instance, mentions the case of hydro-electric technology which required a scarce resource, suitable dam sites, to work effectively.

4 Methodological issues: theory and evidence

The models you saw in the previous section are interesting because they show that market selection does not necessarily produce optimal results. So a question comes to mind: How frequently do these 'mistakes' happen? How many 'inferior' technologies have been adopted just because of historical accident?

A number of studies have argued that these 'mistakes' are more frequent than you might think. The history of the QWERTY keyboard (*Changing Economies*, Chapter 15) is one of the first examples of inferior technology locked in by positive feedback, but some other examples include the competition between VHS and Betamax in VCR technology, between four technologies – light-water, gas-cooled, heavy-water and sodium-cooled reactors – in nuclear energy, between chemicals and integrated pest management in pest control, and, believe it or not, between internal combustion (petrol) and steam technology in automobile engines.

Many of these case studies are very convincing, but the issues often remain unresolved as it is often possible to argue that the successful technology was, in fact, the best one. The problem is that it is impossible to find irrefutable evidence of what 'could have happened' if a few small events had been different. You can run a simulation many times and find out the average behaviour of a complex system, but real history occurs only once.

The possibility that small historical events can dramatically shape history also means that a theoretical model of economic and technical change might require more detailed knowledge of all the events that might have affected the evolution of the process and of their timing, than we can possibly have in such circumstances. There is the danger of giving too much importance to anecdotal evidence that is, in fact, irrelevant. Some technologies might be so much better than the competition that they would end up being successful in any case. It is important, however, to look with suspicion on Panglossian positions that argue the superiority of a technology, a firm or, more generally, of an institution just because it has survived against the competition. Survival alone is not a proof of optimality.

That they warn us that better worlds might be possible is not the only merit of evolutionary theories.

Richard Nelson (1995) argues that evolutionary theories are preferable to those based on equilibrium theorizing because they frequently provide a better explanation of the phenomena studied.

But what does 'better' mean? Nelson specifies that better does not mean that the predictive power of evolutionary theories is greater than that of neoclassical theories, or the statistical fit of regression analyses based on evolutionary models is systematically higher. The complexity of evolutionary theories, which tackle out-of-equilibrium dynamics of complex systems and confer a crucial role on small historical events, can actually reduce their predictive power relative to explanations based on equilibrium. However, 'the advocate of an evolutionary theory might reply that the apparent power of the simpler theory in fact is an illusion' (Nelson, 1995, p.85) when reality is, in fact, complex.

> *'Instead, by 'better explanation' one means that it is consistent with informed judgements as to what really is going on ... [and] ... those informed judgements reflect inferences drawn from a broad and diversified body of data. [...] This said, it is clear that one of the appeals of evolutionary theorizing about economic change is that that mode of theorizing does seem better to correspond to the actual processes, as these are described by the scholars who have studied them in detail.'*
>
> (*ibid.*)

Nelson's reference to the need to support theory with a 'broad and diversified body of data' is particularly interesting, and leads to two important considerations. First, economic processes are complex, and a single research methodology cannot fully capture this complexity. Economic theories must be evaluated using different types of 'data', by which I do not only mean the statistics used in traditional econometric work, but also evidence from historical research, case studies, interviews, ethnographic research and other research methods. The importance of qualitative differences in evolutionary theories means that quantitative research methods might miss some important aspects of the phenomena studied. Indeed, historical work and case studies have been important sources of knowledge about innovation, and new data sets have been generated in order to carry out quantitative analyses of phenomena that have been originally investigated with qualitative research techniques. For instance, the measurement of appropriability in the Yale survey on innovation, which has been used in econometric studies (Levine *et al.*, 1985), has its roots in qualitative and theoretical research.

Second, Nelson claims that theories should be evaluated by how well they explain a variety of *stylised facts* that have been identified by empirical studies. The notion of a set of stylised facts was originally put forward by Nicholas Kaldor (1978). He argued that the first step in the construction of a theory is the identification of some facts that the theory seeks to explain. However, since facts, as they are recorded in actual data, reflect historical contingencies, the economist should first identify some 'broad tendencies' that the theory should explain. Stylised facts are, therefore, recorded facts filtered from historical contingencies. The theorists should then formulate a hypothesis to account for these stylised facts. Kaldor, for instance, built a theory of capital accumulation and economic growth in industrialized countries that tried to explain some stylised facts; the continued increase of capital per worker, the roughly steady rate of profit on capital, steady capital-output ratios, and the absence of a falling rate of productivity growth.

However, the definition of stylised facts can be a source of controversy because the distinction between broad tendencies and historical contingencies is always debatable. Dosi *et al.* (1995), for instance, seem to identify stylised facts with empirical regularities, results that have been found in a number of studies, and argue that, for a model, 'accounting for a multitude of regularities *together* is certainly a point of analytical strength' (Dosi *et al.*, 1995, p.22, emphasis in the original).

Although evolutionary theories have been quite capable of explaining large sets of stylised facts, currently their use is still largely restricted to explaining technical change in circumstances in which the market operates selection. The evolution of science, and of technologies in sectors where market forces are weak, such as for military and medical technologies, has not been tackled. Evolutionary theories are also less useful in situations in which agents have all the relevant information they need and change is slow; then equilibrium theorizing can produce an acceptable approximation to reality. In these cases, neoclassical theory and game theory may provide the researcher with more useful tools of analysis.

5 Conclusion: economic experiments and economic growth

This chapter has introduced you to evolutionary theories, which adopt a dynamic view of the economy, emphasize the importance of technical change, and treat uncertainty as a central feature of economic life. In a world full of uncertainty, agents cannot maximize and do not possess perfect foresight. Instead, they make mistakes and stick to satisfactory behavioural patterns, while, at the same time, they learn slowly and attempt to innovate in order to survive in the Schumpeterian gales of creative destruction.

Creation and destruction dominate the evolution of the economy. The innovation mechanism generates new technologies, firms and institutions, while selection and adaptation eliminate institutions that are clearly unfit, and favour those that are good enough; failure at the micro level is widespread but necessary for progress at the system level. Pioneer losers are also sometimes necessary for the successful development and diffusion of superior new technologies.

An evolutionary view of the economy implies a notion of economic progress, although progress is achieved at the high price of a number of individual tragedies and we do not live in the best of all possible worlds. The ultimate source of this progress is the creative development of new technologies and new organizational forms that replace those eliminated by selection. The stunning performance of capitalism described at the start of Chapter 15 is ultimately due to its ability to create organizational diversity, by what Nathan Rosenberg (1992) calls 'economic experiments'. He argues that:

> *'... the history of capitalism involved the progressive introduction of a number of institutional devices that facilitated the commitment of resources to the innovation process by reducing or placing limitations upon risk while, at the same time, holding out the prospect of large financial rewards to the successful innovator. [...] Technological achievements were thus based upon capitalist legal institutions, especially with respect to contracts and property rights, that legitimized the right to experiment with the new organizational forms as well as with new technologies.'*
>
> (Rosenberg, 1992, pp.190–1)

The emergence of financial institutions has been crucial to the success of capitalism and continues to influence the efficiency of the economy (Chapter 17). Institutions such as limited liability, insurance and the stock market favour the accumulation of capital for investment and innovation, and limit the risks associated with experiments.

Drawing on Marx, Rosenberg also stresses the importance of the rise of the bourgeoisie, which 'is the first ruling class whose economic interest are inseparably tied to change and not to the maintenance of the status quo' (Rosenberg, 1992, p.184). In capitalist societies, authority is decentralized and economic agents have the incentive and are free to chase what Schumpeter called 'entrepreneurial profit' from innovation. The knowledge accumulated by the institutions in the economy through the outcomes of economic experiments has contributed to the success of capitalism. Even failures are important in the long run as they indicate which avenues should not be pursued, thereby limiting the waste of future resources. Indeed, Rosenberg even argues that the failure of socialism in the twentieth century is a consequence of an institutional structure that did not promote, and even hindered, the emergence of new organizational forms.

After so much praise of innovation, evolution and capitalist progress, a warning now is necessary. Although economic growth is not the same as improving welfare and the quality of life, we can reasonably say that the standard of living in capitalist economies has never been so high. However, evolutionary theories teach us that evolution is myopic, and technologies that are more environmentally sustainable might be locked out of the economy while irreversible damage is done (Cowan, 1996). Environmental criteria, after all, rarely determine the selection mechanisms. Industrialization is rapidly increasing in the world, and the levels of pollution and population are reaching levels that worry an increasing number of scientists. Global warming is just one example of a by-product that has been generated, or at least accelerated, by capitalism's economic success. As a final note of caution, when we praise the achievements of capitalism, it is worth keeping in mind what the palaeontologist Stephen Gould wrote about dinosaurs' stupidity:

'The remarkable thing about dinosaurs is not that they became extinct, but that they dominated the earth for so long. Dinosaurs held sway for 100 million years while [...] people, on this criterion, are scarcely worth mentioning [...] a mere 50,000 years for our own species, Homo Sapiens. *[...] Try the ultimate test within our system of values: Do you know anyone who would wager a substantial sum, even at favourable odds, on the proposition that* Homo Sapiens *will last longer than* Brontosaurus?'

(Gould, 1980, pp.220–1).

Further Reading

Background reading on evolutionary theories and technical change include:

Dosi, G., Freeman, C., Nelson, R., Silverberg, G. and Soete, L. (eds) (1988) *Technical Change and Economic Theory*, London, Pinter.

Schumpeter is constantly quoted by evolutionary economists:

Schumpeter, J.A. (1961) *The Theory of Economic Development* (first edition 1911, second edition 1926), New York, Oxford University Press.

Schumpeter, J.A. (1987) *Capitalism, Socialism and Democracy* (first British edition 1943), London, Unwin Paperbacks.

The following articles discuss path dependency and locked-in inferior technologies:

Arthur, W.B. (1988) 'Competing technologies: an overview', in Dosi *et al.*, pp.590-607.

Cowan, R. (1996) 'Sprayed to death: path dependence, lock-in and pest control strategies', *Economic Journal*, 106, pp.521-42.

The mathematically minded might be interested in two formal evolutionary models of the evolution of technology and market structure:

Winter, S.G. (1984) 'Schumpeterian competition in alternative technological regimes', *Journal of Economic Behavior and Organization*, vol.5, pp.287-320.

Dosi, G., Marsili, O., Orsenigo, L. and Salvatore, R. (1995) 'Learning, market selection and the evolution of industrial structures', *Small Business Economics*, vol.7, pp.1-26.

For those who don't mind trespassing into biology, Gould's work provides a good critique of the Panglossian perspective in biology:

Gould, S.J. and Lewontin, R.C. (1979) 'The spandrels of San Marco and the Panglossian paradigm: a critique of the adaptionist programme', *Proceedings of the Royal Society*, vol.205, pp.581-98.

Gould, S.J. (1980) *The Panda's Thumb*, Harmondsworth, Penguin.

Answers to Exercises

Exercise 16.1

Rates of growth at $t = 2$

Firm *A*:

$$G^{A}_{t=2} = 0.5\cdot(\Pi^{A}_{t=2} - \Pi^{AV}_{t=2}) = 0.5 \times (6 - 5.333)$$
$$= 0.5 \times (0.667) = 0.334$$

Firm *B*:

$$G^{B}_{t=2} = 0.5\cdot(\Pi^{A}_{t=2} - \Pi^{AV}_{t=2}) = 0.5 \times (5 - 5.333)$$
$$= 0.5 \times (-0.333) = -0.167$$

Firm *C*:

$$G^{C}_{t=2} = 0.5\cdot(\Pi^{A}_{t=2} - \Pi^{AV}_{t=2}) = 0.5 \times (4 - 5.333)$$
$$= 0.5 \times (-1.333) = -0.667$$

Market shares at $t = 3$

Firm *A*:

$$S^{A}_{t=3} = S^{A}_{t=2}\cdot(1 + G^{A}_{t=2}) = 0.5 \times (1 + 0.3334)$$
$$= 0.5 \times (1.334) = 0.667$$

Firm *B*:

$$S^{B}_{t=3} = S^{B}_{t=2}\cdot(1 + G^{B}_{t=2}) = 0.333 \times (1 - 0.167)$$
$$= 0.333 \times (0.833) = 0.277$$

Firm *C*:

$$S^{C}_{t=3} = S^{C}_{t=2}\cdot(1 + G^{C}_{t=2}) = 0.167 \times (1 - 0.667)$$
$$= 0.167 \times (0.333) = 0.056$$

The average fitness (profit margin) in period 3 becomes:

$$\Pi^{AV}_{t=3} = (\Pi^{A}_{t=3} \cdot S^{A}_{t=3}) + (\Pi^{B}_{t=3} \cdot S^{B}_{t=3}) + (\Pi^{C}_{t=3} \cdot S^{C}_{t=3})$$
$$= (6 \times 0.667) + (5 \times 0.277) + (4 \times 0.056) = 5.611$$