An Evolutionary Approach to Modelling Technological Change

Thesis
Submitted in conformity with the requirements for the degree of Doctor of Philosophy

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September 22, 1997

0-612-22441-4

Abstract

The purpose of this thesis is to use the biologically inspired techniques of *genetic algorithms* to illustrate some of the biologically inspired predictions of *evolutionary economics* concerning *the process of technological change.*

The process of technological change has been described as 'creative destruction' where the old must make way for the new in order to realize economic progress. However, the current rate and magnitude of technological change has made it difficult for both managers and economists to understand and cope with the significant and pervasive impacts.

Evolutionary economics has emerged as a field that is particularly suited to the analysis of technological change. It views the economy as operating through mechanisms of variety generation, selection of 'good' behaviours, and transmission of those behaviours to other economic agents. It explains economic performance without the problematic assumptions of traditional economics concerning the intelligence, rationality, and motivations of economic agents.

Genetic algorithms are a technique for numerical optimization that manipulates strings of numbers in a manner analogous to the functioning of DNA in biological evolution. They can be used to create computer implemented 'artificial adaptive agents' existing in 'artificial worlds', which mimic the behaviour of economic agents in the real world. These simulations can help in illustrating the predictions of evolutionary economics concerning technological change.

This thesis makes three significant contributions to the study of technological change using evolutionary economics:

1. The introduction of a model which aids in the description and understanding of the process of technological change from an evolutionary point of view;

2. The creation of a computer program which simulates the process of technological change in a simple artificial economy; and

3. The presentation of results from the simulations which illustrate how evolutionary economic systems operate and help in understanding the process of technological change.

Acknowledgements

First, I would like to thank Professor Edwin Neave for his interest and encouragement in this project, especially during the times when I had my doubts. His ability to grasp new ideas and carry them forward is truly amazing.

I would also like to thank Professors Yolande Chan, John Gordon, and Edward Petersen for their time and effort in helping to improve this work.

Hickling Corporation, and in particular Dr. Verne Chant and Dr. David Low, have been most supportive through my leave of absence which has lasted substantially longer than anyone predicted or desired.

I would like to thank my father, William, for some of the things he has given me: a love of learning, eclectic interests, and an introduction to biology (I should have paid more attention).

Most of all, I would like to thank my wife Sheryl. This thesis owes more to her support, understanding and patience than to any effort of mine.

Table of Contents

Table of Figures

1. Introduction

The process of technological change is of vital interest to government, industry, and society because of its significant and pervasive impacts on economic development and social functions. The impacts are great because the old must make way for the new. Schumpeter described this process as 'creative destruction' and placed it at the centre of his theories of economic progress.

Neoclassical economic theory has had difficulty in coping with technological change. It has considered technological change to be exogenous to processes within the economy, and the impact of technological change has typically been defined as the 'residual' in economic statistics. Until recently, this was not a problem. Economic development was dominated by industries where economic growth could be explained by naturally endowed factors of production and where change was usually slow and steady. However, such an approach is inadequate for the new knowledge-based economy. To be sure, neoclassical economics is attacking these problems, and with some success. But in addition, a group of economists are 'adopting new instruments and looking in new places,'[1] inspired by the theory of biological evolution.

Since the development of the theory of evolution in biology, numerous economists have looked to evolution in their search for understanding of economic systems. At the beginning of the century, Veblen, Marshall and Schumpeter considered economics to be an evolutionary process. In his 1950 paper "Uncertainty, Evolution, and Economic Theory", Alchian sketched the parallels between biological evolution and the evolution of industries and economies. And in their groundbreaking work "An Evolutionary Theory of Economic Change" (1982), Nelson and Winter made these parallels explicit by creating a model of the economy which operates using evolutionary principles.

The result of the efforts of these, and many other, economists is the field of evolutionary economics. Evolutionary economics explains economic performance without the problematic assumptions of traditional economics concerning the intelligence, rationality, and motivations of management. The economy is seen to operate through mechanisms of variety generation, selection of 'good' behaviours, and transmission of those behaviours to other economic agents.

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1 "Led by a new paradigm, scientists adopt new instruments and look in new places. Even more important, during revolutions scientists see new and different things when looking with familiar instruments in places they have looked before." (Kuhn 1970, p111)

Economics is not the only field to have been inspired by biological evolution. In the 1960s, John Holland began the development of genetic algorithms. Genetic algorithms are a technique for numerical optimization based on the concepts of biological evolution. They have been used in a wide variety of applications from operations research to engineering design.

The purpose of this thesis is to use the biologically inspired techniques of *genetic algorithms* to illustrate some of the biologically inspired predictions of *evolutionary economics* concerning *the process of technological change.*

This thesis makes three significant contributions to the study of technological change using evolutionary economics:

1. The introduction of a model which aids in the description and understanding of the process of technological change from an evolutionary point of view;

2. The creation of a computer program which simulates the process of technological change in a simple artificial economy; and

3. The presentation of results from the simulations which illustrate how evolutionary economic systems operate and help in understanding the process of technological change.

The thesis is organized as follows:

Chapter 2 explores the similarities between evolution in economic and biological systems. While biological analogies have a long history in economic thought, their use as the foundation for economic theories and models is rather recent. It is argued that this new point of view can provide additional insights for old questions, and may suggest some new questions. However, seeing and accepting what the evolutionary perspective has to offer requires a paradigm shift. It is hoped that this chapter will encourage the reader to try this new point of view.

Chapter 3 examines how evolution in economic systems can be modelled using computer simulations. Simulation is required to analyse evolutionary models because of the special challenges posed by their stochastic, dynamic, and path dependent nature. The concept of artificial worlds is introduced and some of the important approaches to creating artificial economic worlds are summarized. Previous work which uses artificial worlds to model technological change is limited, primarily because the computational tools necessary for their implementation have only recently become readily available.

Chapter 4 introduces a model of the process of technological change. This model is used to structure a discussion of the components of technological change, the determinants of explorative effort, and the dynamics of the process.

Chapter 5 implements the model of Chapter 4 in a computer program, named Bizlife, which simulates the process of technological change in an artificial world. Bizlife has important advantages over previous work in this area in that it: 1) is founded on an explicit model of the process of technological change, 2) uses evolutionary techniques to model evolutionary ideas, and 3) employs powerful computation and visualization software to aid in the generation and interpretation of results.

Chapter 6 presents the computer simulations done with the Bizlife program. Five avenues of investigation were pursued: the impact of imitation and invention, the impact of environmental change, the dynamics of technological change, the division of explorative effort, and entry and exit. For example, results from the simulations have demonstrated the following:

- Industries are able to improve performance even without profit maximizing behaviour by management.

- Management is less able to influence firm performance under conditions of rapid environmental change.

- Invention within industries is important to avoid stagnation and ensure continued adaptation to environmental change.

- Cyclical performance in industries is an emergent and pervasive phenomenon that results from imitative behaviour.

- The natural reaction of an evolutionary system to sudden environmental change is a rapid increase in diversity, followed by a longer period of consolidation.

- Highly inventive organizations, while providing a valuable social function, are unlikely to perform as well as firms with lower rates of invention.

- Contesting a portfolio of products is a more stable strategy than relying on a limited number of products.

Chapter 7 discusses the themes which emerge from the computer simulations of Chapter 6. In particular, two issues are examined: the importance of exploration in evolutionary processes, and the concept of 'efficiency' in evolutionary processes.

Appendices contain a description of a non-linear chemical reaction, a glossary of terms, an introduction to genetic algorithms, a description of the Bizlife computer program, the Bizlife computer code, Bizlife simulation parameter settings, references, and the vita of the author.

2. An Evolutionary Point of View

2.1 *Points of View*

"Somebody once observed to the eminent philosopher Wittgenstein how stupid medieval Europeans living before the time of Copernicus must have been that they could have looked at the sky and thought that the sun was circling the earth. Surely a modicum of astronomical good sense would have told them that the reverse was true. Wittgenstein is said to have replied: "I agree. But I wonder what it would have looked like if the sun had been circling the earth."

"The point is that it would look exactly the same. When we observe nature we see what we want to see, according to what we believe we know about it at the time. Nature is disordered, powerful and chaotic, and through fear of the chaos we impose system on it. We abhor complexity, and seek to simplify things whenever we can by whatever means we have at hand. We need to have an overall explanation of what the universe is and how it functions. In order to achieve this overall view we develop explanatory theories which will give structure to natural phenomena, we classify nature into a coherent system which appears to do what we say it does." (Burke 1985, p11)

"The knowledge acquired through the use of any structure is selective. There are no standards or beliefs guiding the search for knowledge which are not dependent on the structure. Scientific knowledge, in sum, is not necessarily the clearest representation of what reality is; it is the artefact of each structure and its tool." (Burke 1985, p337)

Thomas Kuhn (1970) has articulated the relationship between the structure of current knowledge and the quest for further knowledge. While his theories have been criticised as overly exaggerated and categorical, they have proved to have conceptual appeal in explaining changes in scientific viewpoints.

Kuhn differentiates between 'normal science' and 'scientific revolutions'. He describes normal science as:

> "...research firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice" (Kuhn 1970, p10).

The collection of achievements is termed a 'paradigm' and it defines the legitimate problems and methods for the field. The emphasis in normal science is to add to the scope and precision with which the paradigm can be applied, rather than produce major conceptual or phenomenal novelties.

When research uncovers sufficient anomalies that cannot be explained under the current paradigm, a 'scientific revolution' occurs and a new paradigm emerges. In the process, some previously standard beliefs or procedures must be discarded. More importantly, the world is now viewed in a new way:

"... the historian of science may be tempted to exclaim that when paradigms change, the world itself changes with them" (Kuhn 1970, p111)

Which point of view is correct?[2] In a sense, they all are. Everyone is trying to 'model' the same real world. Models are simplifications that stress certain aspects of the world. Different models provide different viewpoints, different insights. Everyone is right, and everyone is wrong.

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2 It is interesting to examine some of the major 'sciences' to see how their points of view have changed in the recent past:

Scientific Points of View

Science	"Classic" Viewpoint	"Recent" Viewpoint
Biology	Creationist	Evolutionary
Physics	Newtonian	Quantum
Chemistry	Linear	Non-linear
Mathematics	Geometric	Chaotic
Economics	Equilibrium	Evolutionary

The 'recent' points of view all date from this century. While evolutionary biology dates from Darwin's publication of *The Origin of Species* in 1859, it was only in 1996 that the Catholic Church conceded that "the theory of physical evolution is valid". Quantum mechanics dates from 1900 with Planck's theories on energy quanta and 1927 with Heisenberg's uncertainty principle, but up to his death in 1955 Einstein was arguing that "God does not play dice with the universe". Non-linear chemistry dates from 1951 with Belousov's discovery of a chemical reaction which displays oscillatory behaviour, however his submissions for publication of the results were rejected on the grounds that such behaviour would be impossible because it would violate the second law of thermodynamics (it does not). The Belousov-Zabotinski (BZ) reaction is fascinating - both because of the reaction's beauty and its story's poignancy. Appendix A contains a description of the reaction and the history behind its discovery.[2] Chaos theory in mathematics dates from the 1970s with Lorenz's work in meteorology.

All of these 'recent' points of view share a common concession that the universe is more complex than had previously been admitted. Also, each new point of view has opened up new ways of seeing existing knowledge, and posed new questions for research.

This thesis takes an evolutionary viewpoint. This viewpoint is not necessarily better or worse than classical economics, just different. But because it is different, it offers a new view of old questions, and perhaps will suggest some new questions.

This chapter is important because it provides the motivation for the model that will be developed in Chapter 4. In the next section, §2.2, the basic concepts of biological evolution are introduced. The subsequent section, §2.3, considers how these concepts can be applied to the operation of a firm. The final section of this chapter, §2.4, examines the characteristics of a branch of economics known as 'evolutionary economics' which uses these biological analogies as the tenets of its theories.

2.2 Biological Evolution

Humans can only be amazed by the ability of life to continuously develop forms and functions which adapt to the needs of a dynamic and hostile environment. Surprisingly, this is not achieved through a process of optimization, in the sense of a 'directed' search towards the global 'best' solution. Rather, the approach nature takes is one of evolution, a 'random' search for locally 'good' solutions. In nature, there is no best, but good has proven to be very good indeed.

Darwin was the first to suggest how nature adapts in his *The Origin of Species* (1859). The basic requirements of evolution are diverse organisms, a hostile environment, and sexual reproduction. An organism competes with other organisms to survive in its environment. The organism that better meets the needs of its environment has a better chance of surviving and reproducing than its competitors. Organisms that survive pass on their characteristics to their offspring[3]. Thus, through natural selection, successful characteristics have a better chance of being perpetuated than less successful characteristics. This process alone, however, can only sample portions of the search space represented by the current population. New regions of the search space (i.e. new types of organisms) are visited by two means; mutation and sexual reproduction. Mutation is the random change of an organism's characteristics. This was once thought to be the primary engine behind evolution, but it is now known that mutation is incapable of creating enough 'good' new characteristics to account for the speed with which evolution progresses.

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[3] Watson and Crick discovered the chemical structure responsible for the coding of an organism's characteristics. This structure is known as DNA (deoxyribonucleic acid). The physical characteristics of all life are determined by the DNA contained in every cell of each organism (viruses contain only RNA, ribonucleic acid, but require a host cell for reproduction). DNA resembles a ladder twisted into a spiral (a double helix). The rails are made of phosphorus and sugar. The rungs are composed of a sequence of pairs of four amino acids: guanine, cystosine, adenine, and thymine. Guanine always pairs with cystosine and adenine always pairs with thymine. The sequence of amino acids is a code which governs the development of the cell, and hence the organism.

The human DNA is a ladder 2,870,000,000 rungs long. Each human is therefore one point in a search space of order $4^{2,870,000,000}$ (base four because each point in the code can be one of four amino acids). This equals $10^{1,727,912,175}$, an incomprehensibly large number! Life has existed on the earth for about $4 \cdot 10^9$ years. Say 10^{12} new organisms are born each year. Then at most, only $4 \cdot 10^{21}$ points in the search space have been tried; less than one in every $10^{1,727,912,153}$ possibilities.

Sexual reproduction combines the characteristics of organisms in novel ways and has been shown to be an extremely efficient way of searching for new and better organisms.

No organism is perfect, certainly not humans. Yet it is amazing that so many creatures now exist that are good, given the limited time and number of trials it has taken to get it right. There is much in nature which has already been successfully imitated and adapted by humans to improve technology; radar and sonar, robotics, artificial intelligence, medicines, etc. Work is proceeding on a number of naturally inspired approaches to search and optimization such as neural networks and simulated annealing. Surely, the algorithm for the evolution of life itself should prove our most powerful tool yet.

Recent studies of natural history have suggested a number of characteristics of evolution which may be equally applicable to technological change:

- *Balance* - In nature, the evolutionary process allows for simultaneous, but balanced, exploitation and exploration. Exploitation takes advantage of the best of what has been achieved so far in the evolutionary process so that a creature can survive in its environment. Exploration discovers alternative solutions to the survival problem so that future generations can better survive. The balance between these is critical; too much emphasis on exploitation and better solutions will not be found, too much emphasis on exploration and the good solutions will be lost. Nature appears to have been able to strike an excellent balance (Goldberg 1989). Maintaining such a balance is equally important for a firm; exploration is needed to keep pace with the competition, exploitation is essential to fund exploration and keep creditors at bay.

- *Equilibrium* - The traditional view of evolution was that ecological systems adapt to change to maintain a constant state of equilibrium. In fact, equilibrium is often 'punctuated' by periods of rapid change (Eldredge and Gould 1972). The effect is that "mass extinctions are more frequent, rapid, and devastating than formerly imagined ... mass extinctions can derail, undo, and reorient whatever might be accumulating during the 'normal' times between" (Gould 1989, p305). Under these conditions, the reasons for differential survival are qualitatively different from the causes of success in normal times. Under the new regulations, the very best traits, the source of previous flourishing, may now lead to death. This process of punctuated equilibrium in nature is similar to the cycles of the economy and the process of 'creative destruction' described by Schumpeter where the economic structure is revolutionized in discrete rushes which are separated from each other by spans of comparative quiet (Schumpeter 1942, p83).

- *Diversity* - The traditional view of evolution was that the diversity of life increased gradually and consistently. However, more recent evidence is quite different (Gould 1989). It appears that when equilibrium is disrupted, there is a sudden and rapid increase in diversity, followed by long periods of consolidation - early experimentation and later standardization. It has been suggested that perhaps genetic systems 'age' in the sense of becoming 'less forgiving of major restructuring' over time, and this is why diversity does not continue to increase (Valentine 1977). Similar patterns can be seen in technological change. After equilibrium is disrupted, there are initial periods of rapid and radical invention, followed by consolidation into technological trajectories, incremental change, and reliance on imitation.

- *Direction* - The traditional view of evolution was that life moved inexorably towards 'bigger' and more complex; with humans, of course, being the epitome of that. However, the reality seems to be that evolution is a random process without direction (Gould 1996). There is a wall of minimum complexity below which life is not possible; but most of life is bunched just above that, with a long tail towards increased complexity. In fact, by any measure of success, biomass, diversity, habitats, etc., bacteria are the most successful forms of life. There is no evidence that evolution has any more tendency towards increased complexity than to decreased complexity. The view that larger and more complex is better is a homocentric view based on what we find interesting. A similar preoccupation with bigger and more complex can be seen in business research. Most current research concentrates on large firms, while most employment, economic activity, and innovation come from small and medium sized enterprises.

- *History* - The traditional view of evolution was that life develops into 'better' forms in some global sense, and organisms that survive are therefore 'superior' to those that do not. However, 'better adapted' means only 'more suited to changing local environments', not superior in any general sense. The pathways to local adaptation are as likely to restrict as to enhance the prospects for long-term success (Gould 1989). The result is that survival during periods of radical change is very much a random event. As Gould so eloquently put it, being the best adapted fish in your pond is not much use if the pond dries up. History matters, and knowledge of current adaptive success is not a predictor of future success. Historical studies of technology trajectories have reached similar conclusions.

Such comparisons between biology and economics have been suggested before, and are the subject of the next section.

2.3 Biological Analogies of the Firm

The similarities between the evolution of biological organisms and the evolution of economic systems, and the potential for an evolutionary point of view in economic analysis, was noted soon after the development of evolutionary theory. At the end of the nineteenth century, Veblen proclaimed the end of pre-evolutionary economics:

> "Under the stress of modern technological exigencies, men's every-day habits of thought are falling into the lines that in the sciences constitute the evolutionary method" (Veblen 1898, p397).

Heralding the beginning of the twentieth century, Marshall declared that:

> "the Mecca of the economist lies in economic biology rather than in economic dynamics" (Marshall 1898, p318).

It is Schumpeter, however, who is seen a the father of evolutionary thought in economics:

> "The essential point to grasp is that in dealing with capitalism we are dealing with an evolutionary process. It may seem strange that anyone can fail to see so obvious a fact which moreover was long ago emphasized by Karl Marx" (Schumpeter 1942, p82).

Schumpeter emphasized that economic development depends on endogenous technological change as its engine. For Schumpeter, "the evolutionary dynamic of capitalist development has three salient characteristic. It comes from within the economic system and is not merely an adaptation to exogenous changes. It occurs discontinuously rather than smoothly. It brings qualitative changes or 'revolutions', which fundamentally displace old equilibria and create radically new conditions" (Elliot 1980). The stimulus for economic development is the 'innovation' – the new product, method of production, market, source of supply, or form of industrial organization (Schumpeter 1911, p66). The innovation process "incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one. This process of Creative Destruction is the essential fact about capitalism" (Schumpeter 1942, p83). Economic growth, therefore, results from a cyclical development process, in which depressions are, largely, a 'normal' and healthy period of absorption of the bunching of innovations during the preceding prosperity.

Since Schumpeter, a number of authors have drawn explicit biological analogies of the firm. Among them, S. Winter ("Economic 'Natural Selection' and the Theory of the Firm, 1964), G. Becker (Altruism, Egoism, and Genetic Fitness: Economics and Sociobiology, 1976), and J. Hirshleifer ("Economics from a Biological Viewpoint", 1977). However, it was A. Alchian's seminal paper, "Uncertainty, Evolution, and Economic Theory", (published in 1950, the year of Schumpeter's death), which established the foundations for this view. His work is synthesized in this section.

It is worth taking a few moments to examine Alchian's arguments since they foreshadow much of the subsequent work in this field, including this thesis. Alchian pursues the evolutionary analogy "to incorporate incomplete information and uncertain foresight" into economic analysis. He "dispenses with 'profit maximization' ... and does not rely on the predictable, individual behaviour that is usually assumed." (p207)[4].

> "The suggested approach embodies the principles of biological evolution and natural selection by interpreting the economic system as an adoptive mechanism which chooses among exploratory actions generated by the pursuit of 'success' or 'profits'." (p207).

Remember, from the previous section, that the principles of biological evolution consist of:

1. A measure for success,
2. Mechanisms for exploration, and
3. Selection based on success.

The following three sub-sections sketch Alchian's arguments in the context of these principles.

[4] Page numbers refer to Alchian (1950).

A Measure for Success

In biology, an organism is successful if it survives. Similarly, from the evolutionary economic point of view, the true goal of a firm is simply survival. In economics, survival means positive profits, not profit maximization. Alchian states:

> "Realized profits, not *maximum* profits, are the mark of success and viability. It does not matter through what process of reasoning or motivation such success was achieved. The fact of its accomplishment is sufficient. This is the criterion by which the economic system selects survivors: those who realize *positive profits* are the survivors; those who suffer losses disappear." (p210, italics in the original).

This is important because, Alchian says, attempts to maximize profits do not even make sense where there is uncertainty in the firm's environment. The key to positive profits is performance relative to the competition. Alchian goes on to say:

> "Positive profits accrue to those who are better than their actual competitors, even if the participants are ignorant, intelligent, skilful, etc. The crucial element is one's aggregate position relative to actual competitors, not some hypothetically perfect competitors. Even in a world of stupid men there would still be profits." (p210).

Mechanisms for Exploration

A firm does better than the competition by doing things differently. The economist may call this process "optimizing", the biologist calls it "adapting", in both cases it is exploration. In nature, adaptation occurs through sexual reproduction or mutation. The economic analogies are imitation and invention.

Alchian explains imitation as follows:

> "Wherever successful enterprises are observed, the elements common to these observable successes will be associated with success and copied by others in their pursuit of profits or success. 'Nothing succeeds like success'. Thus the urge for 'rough-and-ready' imitative rules of behaviour are accounted for." (p215).

> "Many factors cause this motive to imitate patterns of action observable in past successes. Among these are: (1) the absence of an identifiable criterion for decision-making, (2) the variability of the environment, (3) the multiplicity of factors that call for attention and choice, (4) the uncertainty attaching to all these factors and outcomes, (5) the awareness that superiority relative to one's competitors is crucial, and (6) the non-availability of a trial-and-error process converging to an optimum position." (p216)

Imitation results in uniformity among the survivors. Unchecked, imitation would eliminate diversity and the evolutionary process would stagnate. The solution to this danger is invention.

Invention is 'trial-and-error' adaptive behaviour. While there certainly are those who consciously invent, there are those who, in their imperfect attempts to imitate others, unconsciously invent by unwittingly acquiring some unexpected or unsought unique attributes that under the prevailing circumstances prove partly responsible for their success.

Like biological mutation, invention produces more failures than successes. "Those who are different and successful 'become' innovators, while those who fail 'become' reckless violators of tried-and-true rules." (p216).

Selection Based on Success

It does not matter if firms are consciously trying to adapt or not. In the long run, the natural selection process will ensure that only those firms that have achieved successful strategies will survive. The biological environment chooses for superior fitness; the economic world chooses superior economic efficiency.

Success (survival) accompanies relative superiority, but it does not require motivation and may rather be the result of fortuitous circumstances.

> "Less appropriately acting organisms of the same general class having lower probabilities of survival will find survival difficult. More common types, the survivors, may appear to be those having adapted themselves to the environment, whereas the truth may well be that the environment has adopted them. There may have not been motivated individual adapting but, instead, only environmental adopting." (p211).

> "Success is discovered by the economic system through a blanketing shotgun process, not by the individual through a converging search. Even if each and every individual acted in a haphazard and non-motivated manner, it is possible that the variety of actions would be so great that the resulting collective set would contain actions that are best, in the sense of perfect foresight." (p212).

If all firms are slightly different, those who have characteristics closer to the new, but unknown, optimum position have a greater probability of survival and growth. They will grow relative to other firms and become the prevailing type since survival conditions will push the observed characteristics of the set of survivors toward the unknowable optimum. This will happen by 1) repeated trials, and 2) survival of more of those who happened to be near the optimum - determined *ex post*.

Implications

Alchian believes that the prominent role of uncertainty and fortune in the evolution of economies has implications for management. It is Alchian's argument that, under conditions of uncertainty, luck will play a significant role in determining which firms will succeed and which will fail. He defines two types of environmental uncertainty faced by firms: reducible and irreducible. For decisions involving only irreducible uncertainty, the quality of managers is irrelevant in explaining firm performance. Under such conditions,

> "the greater the uncertainties of the world, the greater is the possibility that profits would go to the venturesome and lucky rather than to logical, careful, fact-gathering individuals." (p210).

If success is the result of fortune, what then is the role of management? Alchian admits that most decision situations do not consist solely of irreducible uncertainty, and "thus a mix of luck and managerial skill at reducing decision-making uncertainty must be employed in explaining the level of firm performance." Alchian says that while sheer chance is a substantial element in determining the appropriateness or viability of a decision, a second element is the ability to adapt[5]. Therefore, individual foresight and action can affect the state of affairs.

> "However, individual behaviour according to some foresight and motivation does not necessarily imply a collective pattern of behaviour that is different from the collective variety of actions associated with a random selection of actions." (p213).

Evolutionary economic theorists like the simplicity of the biological model and identify many parallels between it and the functions of the economy. In fact, Hirshleifer feels that "the biological processes and mechanisms represent more general classes into which the economic ones fall as particular instances". In this, he echoes "Alfred Marshall's view that economics is a branch of biology. Or, in more sweeping terms, of the contention that the

[5] Niccolò Machiavelli says "I conclude, therefore, that as fortune is changeable whereas men are obstinate in their ways, men prosper so long as fortune and policy are in accord, and when there is a clash they fail." (Machiavelli 1514).

social sciences generally can fruitfully be regarded as the sociobiology of the human species (Wilson, 1975)". Alchian is more circumspect: "but as applied to firms, biological reasoning is only a metaphor."

For Alchian, and many others, evolution was a metaphor or analogy that permitted economic problems to be viewed in new ways. However, others have attempted to move the analogy towards a theory of economic behaviour. This new field of evolutionary economics is the subject of the next section.

2.4 Evolutionary Economics

The Revolution

Since the publication in 1982 of Nelson and Winter's "An Evolutionary Theory of Economic Change" (see Section 4.2 for a description of this work), evolutionary economics has been transformed from an interesting analogy to a serious field of economic research. Interest in evolutionary economics has been motivated by what many see as serious faults in neoclassical economics. As Kuhn pointed out:

> "... scientific revolutions are inaugurated by a growing sense, again often restricted to a narrow subdivision of the scientific community, that an existing paradigm has ceased to function adequately..." (Kuhn 1970, p92).

In the case of economics, the evolutionary 'revolution' has been motivated primarily by the difficulties neoclassical economics has when dealing with technological change. Witt (1991) calls evolutionary economics the 'new heterodoxy' and defines it in terms of its opposition to neoclassical economics:

> "The new heterodoxy has a common opposition to the neoclassical world-view which at present dominates economics. The 'hard core' of the latter is a synthesis of the constrained maximization calculus and equilibrium concepts. The opposition's main criticism is that this hard core prevents the neoclassical approach from gaining proper access to the understanding of process and change, the crucial features of modern economic history." (Witt 1991, p 83)

Important objections to neoclassical economic thought have been formulated in, for example, Winter (1971), Nelson and Winter (1982), Day and Eliasson (1986), Dosi et al. (1988), and Hanusch (1988).

Certainly, there has been work to address these concerns within the neoclassical framework[6], but much of this has been perceived as stop-gap measures which do little to rectify the basic structural flaws. Evolutionary economics, for its part, has not yet been able to adequately fill the gap:

6 For example, 'New Growth Theory' (see Romer 1986, 1987, 1990, and Shaw 1992). There are recent signs of cross-fertilization between New Growth Theory and Evolutionary Economics (see Nelson and Romer 1996, and Romer 1996).

> "Unfortunately, the diverse contributions to evolutionary economics have been better at launching criticisms of neoclassical concepts than at developing the reasons for their opposition into a more constructive consensus about alternative core notions" (Witt 1991).

However, the effort to develop evolutionary economics as a discipline continues in an attempt to shed light on questions that are currently dimly illuminated by classical economics. For example: the existence of multiple equilibria, the impact of social values and institutions, the impact of social rules and routines, the creation of novelty and diversity, and the importance of path dependence. This thesis hopes to contribute to that development.

A Description

What, then, is evolutionary economics? Certainly, there are many views (e.g. Saviotti and Metcalfe 1991, Witt 1991, 1992, 1993, Foray and Freeman 1993, Day and Chen 1993, Dosi and Nelson 1994, Andersen 1994). Andersen (1994) calls it a 'rather confusing area'. The following description is a synthesis of the core notions in most views.

In an economic system, economic agents interact with each other and their environment in efforts to control scarce resources. Traditional economic theory holds that these economic agents do so to maximize utility. For a firm, utility maximization is considered to be synonymous with profit maximization. Further, these actions are believed to be rational. Rationality implies the ability of management to make decisions that are fully informed and without error. There is no explanation for differences in choices among firms. The economic system is seen to be in a natural state of equilibrium, unless disturbed by exogenous forces.

As in an economic system, organisms in a biological system interact with each other and their environment in efforts to control scarce resources. However, biologists have been hesitant to credit organisms with the intelligence, rationality, and motivation that economists have assumed for management. Instead, the operation of biological systems is described using the much less restrictive assumptions of evolution. Briefly, evolution has three requirements: diverse organisms, a hostile environment, and adaptation.

The evolutionary economics approach embodies the principles of biological evolution and natural selection by interpreting the economic system as an adaptive mechanism. The economic environment chooses among exploratory actions of firms generated by imitative and inventive behaviour in the pursuit of 'positive profits', rather than 'maximized profits'. The economic counterparts of genetic heredity, mutations, and survival are seen as being imitation, invention, and survival. Management is boundedly rational and imperfectly informed. Firms are strongly affected by 'chance' events. Firms differ because of their differing exploratory efforts; their differing access to, and interpretation of, information;

and their differing fates at the hand of fortune. The economic system is in a state of perpetual change that is driven by the endogenous activities of its participants.

Witt (1991) defines evolution as *the transformation of a system over time through endogenously generated change.* Andersen (1994) lists typical assumptions and characteristics of evolutionary-economic expianations:

- The agents (individuals and organisations) can never be 'perfectly informed' and they have (at best) to optimise locally rather than globally.

- The decision-making of agents is normally bound to rules, norms and institutions.

- Agents are to some extent able to imitate the rules of other agents, to learn for themselves and to create novelty.

- The processes of imitation and invention are characterised by significant degrees of cumulativeness and path dependency but they may be interrupted by occasional discontinuities.

- The interactions between the agents are typically made in disequilibrium situations and the result is successes and failures of commodity variants and method variants as well as of agents.

- The processes of change, occurring in a context described by the above assumptions and characteristics, are non-deterministic, open-ended, and irreversible.

Of these characteristics of evolutionary economic explanations, there are four which have important implications for how research in this area is carried out. These are:

1. Dynamic - evolutionary economic models examine dynamic processes, rather than static equilibria.

2. Stochastic - evolutionary economic models explicitly acknowledge the stochastic nature of the world.

3. Adaptive - components of evolutionary economic models are continuously influenced by their interaction with other components.

4. Path Dependent - the path taken by an evolutionary economic model is not determinable *a priori*.

Taken together, these characteristics essentially preclude the use of closed form mathematical analyses. Instead, the customary approach in the field has been the use of computer models and simulation. The next chapter examines the need for this approach, discusses some of the significant models which have been used in the past, and examines what is needed in future modelling exercises.

2.5 Summary

In this chapter we have seen that the components of biological evolution are 1) a measure of success, 2) mechanisms for exploration, and 3) selection based on success. Next, we have heard Alchian's arguments that these components exist in the economic world: 1) the measure of success is profits, 2) the mechanisms for exploration are imitation and invention, and 3) selection based on success means the survival of firms with positive profits. Further, we have explored the conclusions Alchian reaches as a result of this evolutionary perspective:

- More successful firms have a higher probability of survival than less successful firms. The metric of success is relative profit, not maximized profit.

- Exploration can be considered to be composed of elements of imitation and invention, which correspond to sexual reproduction and mutation in biology.

- Exploration can result in relative superiority even without motivation or conscious direction. The environment is considered to 'adopt' those who are successful, rather than the successful 'adapting' to the environment. Variety is an important determinant of the success of exploration.

- Fortune plays an important role in determining who is successful. The higher the degree of irreducible uncertainty in the environment, the less ability agents have to determine their destiny, and the greater the role of fortune.

Finally, we have introduced the new field of evolutionary economics that uses the analogy of biological evolution to explain economic processes. The characteristics of evolutionary economic models are:

- Irreducible uncertainty,

- Dynamic, stochastic processes,

- An exogenous determination of success,

- The endogenous creation of novelty and imitation of success, and

- Survival of the more successful, at the expense of the less successful.

In Chapter 4, a model of the process of technological change will be developed which embodies the characteristics of evolutionary economic models. In Chapter 5, the model will be implemented in a computer program which is based on the three components of biological evolution. In Chapter 6, this program will be used to demonstrate Alchian's conclusions regarding the operation of economic systems that behave in a fashion analogous to biological evolution.

3. Evolutionary Approaches to Modelling Technological Change

A model is a simplified description of the real world obtained by making assumptions about how things behave. The model usually takes the form of mathematical or logical relationships. When a model is too complex for direct analytical solution, it can be evaluated using numerical techniques and computer simulation.

Technological change has been modelled using a wide variety of techniques, such as those of traditional economics and game theory. These approaches, however, are preoccupied with equilibrium solutions and do not capture the dynamic aspects of change with which evolutionary models are concerned. Evolutionary models are commonly implemented using computer simulations which Lane (1993a, 1993b) terms 'artificial worlds'.

The classic, and perhaps simplest, artificial world is Conway's game of Life. Life takes place on a grid of cells, each cell touching eight adjoining cells. Each cell can be alive or dead, according to rules which are applied iteratively: a live cell with two live neighbours, or any cell with three neighbours, will be alive at the next time step. Surprisingly complex patterns can develop from these simple rules. The patterns display chaotic behaviour and mimic population dynamics in biological systems.

While there have been numerous implementations of artificial worlds, Lane is the first and only to have described and characterized this class of models. The next section, §3.1, summarizes Lane's (1993a) work. The following section, §3.2, examines two approaches which have been taken to create evolutionary models of technological change using artificial worlds. The final section of this chapter, §3.3, discusses the status of these efforts and suggests improvements for future modelling exercises.

3.1 Artificial Worlds

Lane (1993a) defines artificial worlds (AWs) as "computer implementable stochastic models, which consist of a set of 'microlevel entities' that interact with each other and an 'environment' in prescribed ways" (p90).

Artificial worlds are commonly inspired by biological evolutionary processes and have the following elements:

- Entities - There is a population of entities.

- Attributes - Each entity has attributes chosen from a set.

- Fitness - The fitness of each entity is determined from its attributes and the state of its environment.

- Survival - The survival of the entity into the next time period depends on its fitness.

- Replacement - Entities which do not survive are replaced by new entities which combine attributes of surviving members of the population.

Objectives

According to Lane, "the aim of AW modelling is to discover whether (and under what conditions) histories exhibit interesting emergent properties" (p90). The identification of emergent behaviour depends somewhat on the eye of the beholder, however Lane describes three properties that should be looked for:

- Behaviour which can be described in terms of aggregate-level constructs, without reference to the attributes of specific microlevel entities;

- Behaviour which persists for time periods much greater than the time scale appropriate for describing the underlying micro-interactions; and

- Behaviour which defies explanation by reduction to the superposition of 'built in' micro properties of the artificial world.

AWs are used to help in understanding how large-scale properties of the real world are dependent on the lower-level processes that underlie them. They illustrate both how macro-level complexity arises from the simple interaction of micro-level entities, and how, perversely, macro-level effects can be simple in spite of the complexity of micro-level processes.

The need for computer implementation

AWs are well-defined mathematical models, but Lane feels that, for a number of reasons, it is unlikely that interesting theorems about their emergent properties will be proved with the mathematical tools currently available:

- First, AWs are designed to be open-ended systems. Their emergent properties are only meta-stable, not equilibria or asymptotic states. The mathematical techniques for studying transient phenomena are not well developed.

- Second, emergent properties are necessarily complicated functions of the history of the attributes of the microlevel entities from whose interactions they are formed. It is hard to imagine that the descriptions of emergent properties will be mathematically tractable. There are simple models of cellular automata, for example, wherein the solutions to particular questions are computationally irreducible - the shortest way to analyse the system is to run the complete computation.

- Third, it seems to be a plausible hypothesis that the capability of a system to produce emergent hierarchical organization is a function of its complexity. As a result, the mathematical method of isolation and reductionism to handle complexity will not work.

Thus, it seems likely that the emergent hierarchical properties of AWs will be discovered only by implementing them computationally and observing what happens. For such work, the computer plays a role similar to the role the microscope plays for biology: it opens up new classes of questions and phenomena for investigation.

Advantages

The use of artificial worlds as an approach to studying economic change has some important advantages:

- For the reasons given above, artificial worlds may be the only feasible approach to studying evolutionary processes.

- Like any computer model, artificial worlds allow specific causes and effects to be isolated and examined in detail.

- Artificial worlds provide rich results that can capture some of the complexity and dynamism of the real world.

Problems

However, there is no question that the use of artificial worlds comes with a number of inherent problems. Lane (1993a) and Andersen (1994) point out some of these problems:

- To date, there have been few implementations of artificial worlds which model technological change. As a result, there is no history of what constitutes 'acceptable' models, as there is in neoclassical economics. Therefore, any artificial evolutionary economy is open to criticism on the grounds that its design is arbitrary.

- The more richly detailed a model is, the more intriguing it is to its designers - but the less likely it is to capture anyone else's imagination or interest, which wavers at the first ad hoc and unshared assumption. This produces a real barrier to acceptance and dissemination.

- Without mastering the microlevel details built into an artificial world, it is simply impossible to come to a reasoned judgement on whether an observed aggregate-level property is in fact emergent - or merely a consequence easily derived from the superposition of some particular microlevel features. Such mastery takes considerable effort, but without it, the whole point of the artificial world may be lost.

- Non-evolutionary economists may think that evolutionary simulations are unclear ways of reaching results that can be demonstrated with much more clarity and elegance if substantial rationality is not excluded from the analysis.

- Policy makers may express their disappointment at the lack of clear-cut policy implications.

These criticisms are equally applicable to all artificial economic worlds. In spite of these problems, a few attempts have been made to implement artificial worlds in order to study technological change. These are described in the next section.

3.2 Evolutionary Simulation Models

This section briefly describes the two approaches to evolutionary simulation models that have examined aspects of technological change. However, as Lane (1993b) says, "there really is not such a thing as a short summary description of an artificial economy". The first description is of the Nelson and Winter model. This approach applies an evolutionary strategy to predominately traditional economic equations describing supply and demand. Next, the artificial adaptive agents of Holland and Arthur are considered. This approach uses classifier systems and genetic algorithms as the modelling tool.

Nelson and Winter

Nelson and Winter (1982) were probably the first to create computer programs and calculations which can be interpreted as reflecting the mechanisms of an evolutionary-economic process. They combined:

1. Simon's (and Cyert and March 1963/1992) work on rules and satisficing behaviour,

2. Nelson's and other 'Schumpeterian' work on invention and innovation, and

3. Alchian's and Winter's work on 'natural selection'.

Dosi and Nelson (1994) describe the Nelson and Winter modelling approach. In a series of models, Nelson and Winter examine the actions and interactions of firms. Firms are viewed as the carriers of 'technologies' – practices or capabilities that determine their success in their world. Firms perform search processes in order to uncover new production techniques or to improve prevailing ones. A firm's search process is partly focused on inventing – trying something that is different than what its competitors are doing. But also pays attention to the activities of its competitors and imitates, with a lag, other successful firms in the industry. The search processes therefore both provide the source of differential fitness, and act to produce commonality among the traits of the firms. The population of firms in the industry is viewed as operating within an exogenously determined environment. The environment can be interpreted as a 'market'. The profitability of any firm is determined by what it is doing, and what its competitors do.

The models operate as iterative stochastic systems. Firms are characterized by their resources and prevailing routines (techniques). Decision rules are invoked based on market conditions in the prevailing period. The inputs employed and outputs produced by all firms are determined, and the market determines prices accordingly. Each firm determines how much it expands or contracts. Search routines come up with proposed modifications to each firm's capabilities that may (stochastically) be adopted. The models generate time paths of firm and industry inputs and outputs, wage rates, return on capital, and labour/capital shares.

Nelson and Winter used their models to examine economic growth, inventive strategy, and industry structure. They were able to generate time paths of macro-economic variables that are similar to Solow's 1909 data. They also found: that, in general, innovative R&D was not profitable; that imitation is costly and take time, leading to a gap between average and best practice; and that history and luck matter.

Andersen (1994, 1996) has observed that the Nelson and Winter models have never been fully documented, their differences have never been explored, and that the computer programs have apparently disappeared. Andersen sets to rectify this confusing situation by re-constructing the models and computer programs. He is able to partially replicate the Nelson and Winter results and finds that inventive firms perform best when imitation is difficult. Andersen discusses, but does not implement, extensions which would permit the Nelson and Winter models to examine market share and concentration; satisficing behaviour; exit and entry; industry creation; market behaviour; local markets and National Systems of Innovation; economic growth; and backwardness and catching-up.

Other authors which have used approaches similar to Nelson and Winter's include: Andersen (1994), Silverberg and Verspagen (1994), Englmann (1994), and Chiaromonte et al. (1993). Silverberg and Verspagen create a model of an economy with capital accumulation, wate rates, introduction of new technologies and firms, diffusion of new technologies, and changing innovative behaviour of firms. Invention is achieved by drawing from a normal distribution centred on the current value (i.e. invention is a random walk). Only firms with low profits do imitation. They find: that the rate of technical change is negatively related to the concentration index; that short periods of high variance are interspersed between relatively long periods of market uniformity; that incumbents persist with occasional displacement; and that high levels of competition emerge jointly with high levels of R&D. They make the interesting statement that their model "may not yet be simple enough".

Englmann presents a deterministic disequilibrium model of endogenous innovation and growth. Labour productivity increases via an R&D production function. The model does not assume perfect foresight or rational expectations. The behaviour of agents is governed by routines, not by maximization. Three cases are examined: 1) only one technology is used in production, 2) diffusion of one new technology, and 3) diffusion of various technologies. Simulations show cyclical results for profit, labour productivity, and employment. Also, labour productivity growth increases with the savings rate.

Chiaromonte et al. introduce a model consisting of three sectors: machine production, goods production, and consumption. Both invention and imitation occur. Selection mechanisms act on relative competitiveness. The environment and the agents co-evolve. Chiaromente et al. assume that behavioural norms present a relatively high degree of inertia and, thus, can be taken as parameters. They explore the conditions under which micro-technological learning yields relatively ordered aggregate patterns of growth, and the effect of particular norms of behaviour and interaction among agents upon aggregate dynamics. They present "highly preliminary results" which they find "plausible":

- Innovators may sometimes be 'lambs' whose 'sacrifice' produces a learning externality for the whole system.

- The *form* of micro-diversity affects macro-dynamics, even for unchanged mean values.

- Behavioural heterogeneity is important for progress. What turn out to be 'mistakes' for individual agents might also represent positive externalities for the systems as a whole.

- Some minimum appropriability threshold is a necessary condition for invention, above which the effect is ambiguous.

Lane (1993b) extends the work of Chiaromonte et al., but presents no results.

Artificial Adaptive Agents

Miller and Holland (1991) introduce the concept of artificial adaptive agents (AAA). They start by noting that many economic systems can be classified as complex adaptive systems. Such a system is complex in a special sense: i) It consists of a network of interacting agents (processes, elements); ii) it exhibits a dynamic, aggregate behaviour that emerges from the individual activities of the agents; and iii) its aggregate behaviour can be described without a detailed knowledge of the behaviour of the individual agents. An agent in such a system is *adaptive* if it satisfies an additional pair of criteria: the actions of the agent in its environment can be assigned a value (performance, utility, payoff, fitness, or the like); and the agent behaves so as to increase this value over time. A computer program which mimics the behaviour of such an agent is an AAA, and can be used to investigate the operation of adaptive economic systems.

A wide range of computer-based adaptive algorithms exist for exploring AAA systems, including classifier systems, genetic algorithms, neural networks, and reinforcement learning mechanisms. Current economic studies of adaptive agents rely on genetic algorithms (Axelrod 1987, Miller 1989, Andreoni-Miller 1990) and classifier systems (Marimon et al. 1990, Arthur 1991). The primary application of artificial adaptive agents has been in studying the evolution of strategies in iterated game theory (Axelrod 1984).

Miller and Holland outline an approach to modelling economic systems which uses Holland's classifier system. A *classifier system* (Holland et al. 1986) is an adaptive rule-based system that models its environment by activating appropriate clusters of rules. Each rule is in condition/action form, and many rules can be active simultaneously. The outcome of a competition with other rules that satisfy the current conditions is determined by a strength measure assigned to each rule based on past performance. A 'bucket-brigade' algorithm adjusts rule strengths so that rules which depend on other rules are appropriately rewarded. A genetic algorithm is used for the discovery of new rules.

Classifier systems were originally developed as a technique for a sub-discipline of Artificial Intelligence known as machine learning, and so it is not surprising that they can be used to mimic learning in economic systems. Miller and Holland point out that AAA models, specified in a computer language, retain much of the flexibility of pure linguistic models, while having the precision and consistency enforced by the computer language.

Arthur (1991) calibrates a Holland-type classifier system to reproduce human behaviour in the simple decision context of agents choosing repeatedly among discrete actions with initially unknown, random consequences. What makes this iterated choice problem interesting is the tension between *exploitation* of high-payoff actions that have been undertaken many times and are therefore well understood, and *exploration* of seldom-tried actions that potentially may have higher average payoff. Artificial agents are represented as using parametrized decision algorithms so that the artificial agents' behaviour matches real human behaviour observed in the same decision context. The algorithm is nonlinear in that actions that are frequently taken are further strengthened or reinforced. And it is stochastic in that actions are triggered randomly on the basis of current probabilities, and rewards are drawn randomly from a distribution. Arthur calibrated the algorithm, with some success, against two-choice bandit experiments conducted by Laval Robillard at Harvard in 1952-53.

Other authors who have employed the artificial adaptive agent approach include Bhargava and Mukherjee (1994). They use stochastic cellular automata that interact through Lotka-Volterra competition equations. The simulations examine diffusion of two competing technologies in a two dimensional space. They find that each technology carves out its own niche. Niche formation is slowed by low effectiveness of interaction (high competition).

3.3 The Status of Modelling Technological Change Using Artificial Worlds

The previous section has outlined the two types of approaches to modelling technological change using artificial worlds. Overall, however, there have not been many examples of either approach in the literature. This is probably for two reasons. First, the computing power necessary to create an artificial world has only become inexpensive and easy to use in the recent past. Second, as pointed out in §3.1, there are a number of generic problems inherent in the approaches.

The Nelson and Winter approach suffers primarily from two problems. First, its models tend to be complicated. As a result they are difficult to grasp and seem very arbitrary. Often they are arbitrary in the sense that there is no underlying model of the process of technological change. Second, while evolutionary in implementation, they are neoclassical in design, involving traditional equations for supply and demand, and markets which clear. The use of these equations does little to advance the notion that the evolutionary approach can stand on its own.

The Artificial Adaptive Agent approach suffers, for the moment, from one major problem: lack of model implementation. Existing papers are mostly model descriptions. Where implementation is claimed, results from the model are frequently omitted. This approach does have the major advantage that evolutionary techniques are used to model evolutionary ideas, and neoclassical econometric equations can be avoided.

Whatever approach is taken, it is clear that any artificial world approach requires two things. First, an environment which makes computation relatively easy and fast so that the user can fully investigate the richness and complexity of the model. Second, the richness and complexity of the output requires sophisticated data visualization techniques so that the results can be easily and properly interpreted.

In the next chapter, an artificial world is developed which addresses some of the shortcomings of previous work:

- It is founded on an explicit model of the process of technological change.
- It uses the artificial adaptive agent approach (specifically genetic algorithms) and therefore uses evolutionary techniques to model evolutionary ideas.
- It employs powerful computation and visualization software to aid in the generation and interpretation of results.

4. A Model of the Process of Technological Change

The real world is either random, chaotic[7], or complex; the choice depends on one's faith in humans' ability to make sense of their environment, in spite of 'bounded rationality'. While there is ample evidence supporting the first choice, it does not leave much room for subsequent study. But, even admitting to the second or third choice, human understanding of the world requires that it be simplified, classified, and organized. Models help in understanding the real world by providing such structure.

Technological change is one of the most bewildering aspects of our world. The world economy has been described as undergoing "tectonic shifts" and a "tsunami of transformation" caused by the unprecedented speed and magnitude of technological change (Woodall 1996, Côté-O'Hara 1996). Whether this is for the better or worse will continue to be hotly debated, however there is no question that trying to cope with change is a daunting task for both producers and consumers of new technology. If ever there was a need for help with simplifying and understanding a complex process, it is with technological change.

In this Chapter, a model will be presented to introduce some structure into our attempts at the analysis and understanding of the process of technological change. A glossary of terms used in the model is contained in Appendix B. In Chapter 5, the model will be used as the foundation for a computer program that simulates technological change using an evolutionary approach.

4.1 *Motivation*

The structure of the model is motivated by analogies between the biological and economic worlds. In the biological world, organisms (generically referred to as genotypes) exploit their attributes, in competition with other organisms, to acquire scarce resources from the environment. These resources are used by the organisms to reproduce and perpetuate their genotype. Through sexual reproduction and mutation, different possible attributes of the genotype are explored by successive generations. The economic world can be considered to operate in a similar fashion, with the following correspondences: genotype

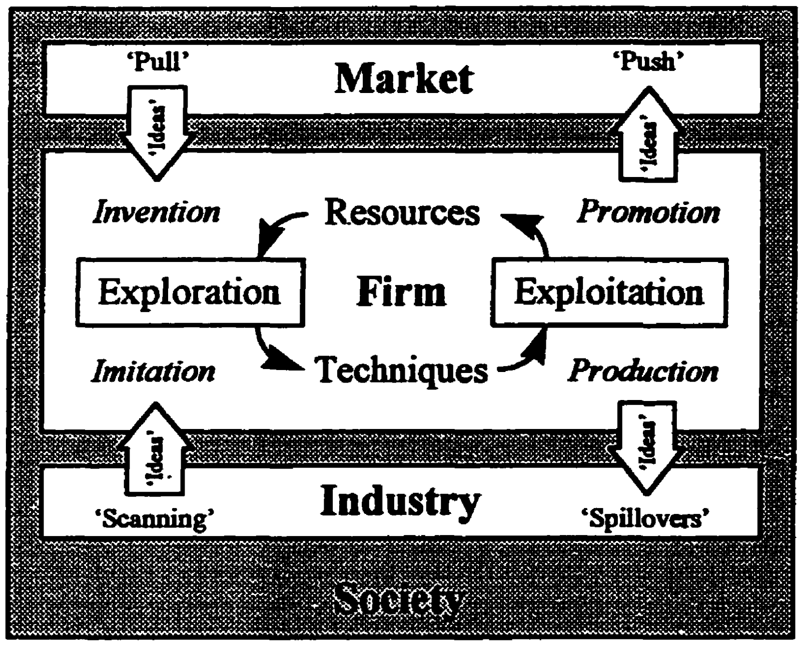
[7] In the popular vernacular, the word 'chaotic' is often used in a sense synonymous with randomness and utter confusion. Here, I am using the mathematical sense of system behaviour which displays discernible patterns in spite of being non-periodic, and is sensitive to initial conditions and small perturbations, but is not random.

↔ firm, resources ↔ resources, attributes ↔ techniques, other organisms ↔ industry, environment ↔ market, sexual reproduction ↔ imitation, and mutation ↔ invention.

4.2 The Structure of Technological Change

Figure 4-1 illustrates the model of the process of technological change developed by the author. Central to this model are the activities of the *Firm* that maintain a dynamic balance between *Exploration* and *Exploitation*. These activities are performed within the context of the *Industry* in which the firm competes, the *Market* which the firm serves, and *Society* which influences the operation of the firm, industry and market. The process of exploration consists of *Imitation* of others in the industry, and *Invention* in anticipation of future market requirements. Exploration produces new *Techniques* for exploitation. The process of exploitation consists of the *Promotion* of techniques (embodied in products) in the market, and *Production* of products (in cooperation and competition with others in the industry). Exploitation produces new *Resources* that can be used for further exploration. New *Ideas* flow into the firm as the result of exploration, and out of the firm as the result of exploitation. These concepts are explained below.

Figure 4-1: The Process of Technological Change



Firm

The term 'firm' has been used because the primary analytical interest is in private sector, profit-seeking organizations. However, much of what will be presented is equally applicable to public sector organizations; though, the mechanisms and outcomes of the processes may be less pronounced if the organization is protected by outside powers.

The purpose of the firm is the standard transformation of inputs to outputs through the application of resources (human and capital) and knowledge. The outputs are generally taken to be products, although the model is equally applicable to services. Those products may have a large technological component, and that is certainly the focus of this work. But, it must be emphasized that everything here is applicable to conditions of change of any type, technological or not.

A fundamental decision for the firm is the appropriate balance between exploration and exploitation. The determinants of this balance depend on both the firm's internal and external environments. External factors include the potential for the firm to appropriate the results of exploration, the market demand for new products, the technical opportunities to create new products (Cohen 1995), the degree of rivalry within the industry (Porter 1990), and the social conditions of the industry and market (e.g. Lundvall 1992). Internal factors include the firm's technical capability, the resources available to the firm, and the ability of the firm to manage project risk. The balance between exploration and exploitation is important in all evolutionary systems (as discussed in §2.2).

The applicability and value of any model depends on the questions that are to be asked of it. The emphasis of this model is at the meso-level of the firm and its interactions with its world. Micro-level details of operations within the firm are not explicitly represented. Similarly, macro-level effects and impacts across industries are not considered. To do so would detract from the particular questions of interest, which consider how the balance a firm achieves between exploration and exploitation relates to its internal and external characteristics.

Industry

The firm is a member of an industry made up of existing rivals, suppliers, and potential new entrants. The firm's industry may be more difficult to define for public sector organizations, but that is not particularly important for the purposes of this study. While relationships among industry members are traditionally viewed as competitive, this does not preclude cooperative activities. The industry is constantly changing as the members individually adapt to changes in the market and among themselves.

One major conclusion of Porter (1990) is that rivalry in an industry is an important driver of explorative activity. The intensity of rivalry increases the opportunity cost of not innovating and results in the competitive matching of R&D investment and new product introductions.

It is sometimes argued that such competition leads to duplication of effort and wasted resources. However, this argument ignores the importance of variety and diversity in the search process. Numerous scholars have suggested that the greater is this diversity within an industry, the greater the rate of an industry's technical advance (e.g. Jewkes, Sawers and Stillerman 1958, Scott 1991). For example, Cohen and Klepper's (1992) probabilistic perspective suggests that the potential technological opportunities that exist will be more effectively exploited when there are simply more firms drawing from the metaphorical urn of possible approaches to innovation.

The benefits of rivalry do depend on some semblance of equality among competitors. If one firm clearly dominates the market, there may be little incentive for others to try to compete. Even Schumpeter envisioned that the market power accruing from successful innovation would be transitory, eroding as competitors entered the field. Therefore, the long-term existence of rivalry requires that an incumbent firm not persist in its dominance.

There are a number of reasons why incumbent firms may have greater success than followers. Phillips (1971) argued that, to the extent that 'success breeds success', concentrated industrial structure would tend to emerge as a consequence of past innovation. There is some evidence of the existence of learning-by-doing in R&D, so successful firms could simply find it easier to make further advances than less successful ones (Phillips 1971). Schumpeter argued that the imperfect nature of capital markets would make it easier for successful firms to finance R&D from internal resources. Existence of network externalities and increasing returns to scale may lock-in (Arthur 1989) incumbent firms and their technologies. Innovation can also affect market structure by increasing or decreasing the efficient scale of production.

Market

The firm's market consists of the consumers of the firm's output. The assumption is that the firm receives resources from consumers in return for its products. But this is not a requirement, as in the case of public sector organizations that receive funding from sources different from the consumers of their services. Markets change, and the firm must continuously adapt to those changes through exploration.

It should be obvious, but all too often seems to be forgotten, that there cannot be any benefit from an innovation unless it its wanted by the market. Once convinced of its ability to satisfy a need, a firm must examine the size and profitability of the portion of the market that it can exploit. Size can be expressed as a volume or rate of growth (Cohen 1995).

The evolutionary literature has moved away from the treatment of market selection as a confrontation between one old and one new technology. Instead, the preferred approach is to consider that at any time there are a variety of technologies available, and diffusion is the outcome of a process of competitive selection across these technologies (Metcalfe 1988). This is the approach which has been taken here.

Exploration

Any operational firm is inherently unstable; the only truly stable condition is bankruptcy[8]. Staying in business, therefore, must be an active process. Of the countless things that a firm must do to survive, exploration is fundamental[9]. If a firm only does what it is has always done, it is vulnerable to the dual threats of changing markets and improving competition. This incessant need to improve results is a pattern of change known as the product life cycle (Abernathy and Utterback 1978, Utterback 1979). The change from one cycle to another is often described in terms of the 'generation' of the technology. The period of the cycle depends on the rate and significance of the change.

Exploration is commonly equated with research and development (R&D), but this is too limiting. A firm can, and does, continuously explore in every aspect of its operations. Exploration includes formal and informal, technical and non-technical, activities. Exploration may concern products or processes.

Exploration activities can themselves be divided into two fundamental types: invention and imitation. Invention is the creation of the novel, imitation is the borrowing of the existing.

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[8] If the operation of a firm is thought of in terms of a Markov process, then the solvency of the firm is equivalent to the gambler's ruin problem. If the firm continues to 'win' it can do no better than obtain monopoly power. However, a monopoly is not stable because the firm must continually adapt to a changing environment. On the other hand, bankruptcy is an absorbing state and therefore, a firm in the long-run will become bankrupt with probability 1.

While the two are commonly separated in both popular and academic thinking (as will be done here), they are in reality inseparable. What is often called invention consists of combining existing techniques (imitation) into new forms. What is often called imitation consists of adapting (invention) existing techniques to new requirements. The pure forms of the two concepts are really the extremes of a grey continuum.

Perhaps the most obvious determinant of explorative effort at the level of the firm is its technical capability. There is a close relationship between inventive and imitative capability. Firms invest in R&D partially to develop new technology (invention), and partially to develop their 'ability to assimilate and exploit existing information' (imitation) which Cohen and Levinthal (1989) call 'absorptive capacity'. A firm's technical capability depends on the *effort* it expends in exploration, its *ability* in exploration, and the *direction* in which it proceeds.

Explorative effort depends on the availability of resources and the willingness to use them for exploration. The availability of resources depends on the many factors influencing the performance of the firm (including past explorative success). Its willingness to expend them in explorative effort depends on conditions external to the firm, and the firm's propensity to explore. Propensity to explore is an intangible concept that is difficult to

[9] For example, Mowery (1983b) found that R&D contributed to firm survival over the period 1921 through 1946.

isolate and quantify. It combines the concepts of curiosity and risk aversion, and is manifested as an element of corporate culture.

Explorative ability is difficult to evaluate. Evaluation difficulty is common to the measurement of all abilities (witness the controversies surrounding IQ tests), but is especially true for explorative ability. This is due to the stochastic nature of technological exploration; who is to say how much credit should be given to ability, and how much to serendipity? However, effort and experience can partially substitute for ability. That is why the accumulation of tacit knowledge is so important in both the imitation and invention processes (Patel and Pavitt 1995).

Explorative direction is partially intuitive based on experience (invention), and partially a reaction to the technological trajectory of industry search (imitation). Malerba (1992) has provided a taxonomy of firm learning and shows that these different sorts of learning affect the kinds of innovative activities pursued by firms.

Technological exploration is an inherently uncertain and risky endeavour. Given that only a small percentage of projects will be successful, a strategy for risk management is diversification. By maintaining a portfolio of projects which pursue different goals using different approaches, a firm will increase its probability of having some success, though at increased cost (McFarlan 1982). The probability of success can be improved further by spending more, though at rapidly decreasing returns to scale.

Large firms may have an advantage over small firms in their probability of long-term survival, since they can diversify to a greater degree and better weather short-term setbacks. Perversely, large firms have an image as being risk adverse. Rosen (1991) rationalizes that larger firms can gain relatively more from safer, more incremental R&D projects that build on existing technologies. This is because, when successful, such projects magnify the firm's existing competitive advantage as well as the advantage that arises from spreading a fixed per unit cost savings over a larger level of output.

A firm can also manage risk by learning from the failures and successes of others in both their innovative and imitative activities. A strategy of imitation, while possibly less risky, and probably less rewarding, is not necessarily less costly. Mansfield et al. (1981) have shown that imitation costs are on average as much as 70% of innovation costs.

Techniques

The results of exploration activities are new techniques for the firm. Techniques are 'ways of doing things'. The concept of a technique includes entities (embodied knowledge), facts (codified knowledge), procedures (social knowledge) and skills (tacit knowledge).

Again, the emphasis here is on the technical aspects of techniques, but the concept is not restricted to that. Techniques require effort and resources to create or assimilate; they cannot be simply bought.

The concept of techniques is an extension of Nelson and Winter's (1982) concept of routines. Technologies are generic combinations of techniques, and products are specific combinations of techniques.

Technologies (and therefore techniques) tend to develop along natural 'trajectories'. This results from the need to cope with, and reduce, the enormous uncertainty inherent in the complex decision problem of formulating explorative strategies (Cohen 1995). Discontinuities in the trajectory result from radical innovations that address 'bottleneck' problems.

Since technological change occurs in an interconnected[10], adaptive system, a change in one part of the system must be compensated for by changes in other parts in order to maintain the dynamic balance. The system, however, is non-linear and its behaviour is chaotic. While tantalisingly familiar patterns develop in technological paths, the actual path of a particular technology is impossible to predict. Subtly different initial conditions

[10] The interconnectedness of all things (Adams 1987)

may lead to radically different outcomes and externally caused perturbations further complicate the path.

Technologies can become 'locked-in' to a particular trajectory under certain conditions (Arthur 1989, 1990, and 1993). First, demand conditions can produce network externalities. A network externality exists when the benefit that a user receives from a technology increases with the number of other users. This can occur when the technology requires compatibility with other products (often producing explicit or 'de facto' industry standards; for example, Microsoft Windows), when use of the technology requires connectivity to others (for example, the phone system), and when the user must make a learning investment (for example, QWERTY keyboards).

Second, supply conditions can produce increasing returns. Increasing returns exist when the profitability of a technology to a producer increases with the amount produced. They can result from economies of scale (for example, larger plants with lower unit costs), learning by doing (for example, experience in production may enable performance and cost improvements), and the ability to disperse high initial costs (for example, the marginal cost of a copy of a software program or movie is insignificant compared to its original production cost). Increasing returns are particularly prevalent in knowledge-based products.

When these conditions exist, the probability of lock-in is enhanced, but which of initially competing technologies will be chosen may be indeterminate *a priori*. This is because of the important role of chance in choosing between potential outcomes. Chance events are 'historically small' and are "outside of the *ex-ante* knowledge of the observer - beyond the resolving power of his 'model' or abstraction of the situation" (Arthur 1989, p118). Therefore, accurate forecasting of technology trajectories may be theoretically, not just practically, impossible.

When lock-in occurs, there is no assurance that the optimal technology trajectory has been selected. An example of this is the victory of VHS videocassettes over the Beta format, which was considered technically superior. Lock-in may also restrict future improvements in a technology. The existence of lock-in destroys the myth that market economies will 'choose' and maintain the optimal outcome.

Classic examples of lock-in include the QWERTY keyboard (David 1985), AC power distribution, the internal combustion engine (Arthur 1990), 'clockwise' clocks (Arthur 1990), and railway track gauges.

Ideas

The firm both influences, and is influenced by, its market and industry. An important mechanism for this influence is the movement of techniques into and out of the firm through the flow of ideas. A firm influences its market by promoting its ideas as embodied in products (technology push). In turn, the firm is influenced by market preferences revealed through choices among the offerings of all the firms in the industry (technology pull).

Schmookler's (e.g. 1966) focus on the role of demand sparked a lively debate among economic historians and others concerning whether 'technology-pull' or 'technology-push' was the primary force behind technological change. It is now generally accepted that both have a role to play, and which dominates depends on the situation. While the suggestion that technological innovations may induce changes in demand (technology push) is obvious to the historian, economists typically consider tastes as given and immutable, and therefore must depend on technology pull.

The firm influences its industry as other firms imitate its ideas (spillovers). Likewise, the firm is influenced by its industry as it observes the behaviour of other firms (scanning).

The topic of spillovers deals with the 'leakage' of new ideas from a firm and their transfer among the members of an industry, what von Hippel (1994) calls the 'stickiness' of knowledge. Spillovers are, in a sense, the flip side of appropriability; they result when appropriability efforts are not wholly successful (see Exploitation below).

Firms 'borrow' different amounts of knowledge from different sources according to their economic and technological distance from them (Kislev and Evenson, 1975). The relevant concept of 'distance' is very hard to define empirically. The 'weighting' function can be interpreted as the effective fraction of knowledge borrowed. Presumably the amount borrowed becomes smaller as the 'distance', in some sense, increases between the firms (Griliches 1995). Patent data confirms that spillovers tend to be geographically localised. This is not surprising, given the importance of tacit (i.e. person embodied, rather than information embodied) knowledge in technical change (Patel and Pavitt 1995).

Time is an important element in the diffusion process. The rate of adoption is the relative speed with which members of a social system adopt an innovation. When the number of individuals adopting a new idea is plotted on a cumulative frequency basis over time, the resulting distribution is an S-shaped curve. There is variation in the slope of the 'S' among innovations, the degree of slope indicating the rapidity of adoption. The top of the 'S' may decline as the technology is superseded by a new generation (Nakicenovic 1989).

The rate and cost of inter-firm diffusion differs across technologies, industries, and countries. On average, little of the original product remains 'private' past ten years (Griliches 1995). Mansfield et. al (1981) examined 48 innovations in four sectors and found that imitation times (measured from the start of applied research to commercial introduction) averaged some 70% of innovation times. The ratio of imitation costs to innovation costs averaged some 65% on average (in only seven of 48 cases did imitation costs exceed innovation costs). The correlation between the ratio of imitation to innovation costs and imitation to innovation times was 0.8 across the 48 innovations.

It has been suggested that the existence of spillovers should be a disincentive to explorative effort. While this may be true as a first-order effect, the net impact of spillovers is more complicated and has an ambiguous effect on industry explorative effort. This is because the level of productivity achieved by a firm or industry depends not only on its own research efforts but also on the level of the pool of general knowledge accessible to it. The simple 'disincentive effect' of spillovers remains, but there is an offsetting incentive to invest in 'absorptive capacity'. Spence (1984) calls the extent to which spillovers enhance technological opportunity the 'efficiency effect'. Therefore, while industry R&D intensity may fall because of spillovers, innovative output may actually increase.

Exploitation

Exploitation activities transform the firm's techniques into the resources it requires for existence. Exploitation is commonly equated with the line business functions of manufacturing and marketing. However, this is only true to the extent that these functions are performing 'routine' activities; they often also participate in exploration.

The fundamental exploitation decision for a firm concerns entry and exit from market products and, ultimately, from industries. Entry and exit are influenced by factors such as market potential, competition, technical capability, product advantage, and resource availability.

Exploitation activities can be divided into two types: promotion and production. Promotion activities are those directed to the consumers of the firm's efforts in the market. Production activities are those directed to suppliers, competitors, and collaborators in the firm's industry.

Appropriability refers to how much of the benefits from exploiting an innovation can be captured by the innovator, rather than by imitators or consumers. Obviously, a firm will be more predisposed to expend resources in exploration if it has reason to expect that it will be able to appropriate a significant portion of the fruits of that effort (Arrow 1962). There are four methods available to firms to increase the benefits they can appropriate from technological advances they initiate. These are patents, secrecy, lead-time, and ancillary capabilities (Geroski 1995).

Inventions are susceptible to leap-frogging by the competition. In such situations, rather than trying to be the first to innovate, each firm may let the others incur the costs of making the discovery and then follow quickly by imitation. There is then a 'free-rider' externality. (Beath et al. 1995)

Resources

Exploitation activities result in the acquisition of additional resources for the firm. Resources include manpower, equipment, and facilities. But resources are, unlike techniques, things that can be acquired and traded. Most of a firm's resources will be required for further exploitation, but the firm has the option to use some of the resources for additional exploration. The expenditure of resources for exploration is both planned, for example the funding of a formal R&D department, and unplanned, for example the production foreman devising an improvement in the manufacturing process.

Availability of resources is a prerequisite for exploration. The degree to which the scarcity of resources is a barrier to exploration is a much studied aspect of public technology policy development. The basic line of inquiry is whether firms under-invest in exploration. This question can be examined from either a social welfare or competitive strategy point of view.

The social welfare view is that exploration benefits the public good by driving economic activity and providing consumers with improved goods and services[11]. However, because of appropriation difficulties (discussed earlier), the incentive for firms to invest resources in exploration is less than would be socially optimal. Therefore, it is argued, there is a need for public intervention to provide resources for explorative activity. Among the many alternatives are the subsidization of firm resources through tax policies, direct funding, loans, and provision of assured markets.

Do firms invest fewer resources in explorative activity than is socially desirable? Changing social attitudes about what is 'desirable' complicates answering this question. Recent changes in attitude about the role of government and government spending, as manifested in public policy, would indicate a public perception that stimulating exploration is not a priority at this time.

[11] In this thesis, the social and economic benefits of technological change are assumed. Admittedly, this may be an uncertain assumption as the existence of these benefits is subject to debate. While technological change is the engine of economic growth in many views (e.g. Schumpeter 1911 and Solow 1957), statistical evidence of this in econometric data can be elusive (Ives 1994). In particular, it has been difficult to show productivity improvements from computer investments: as Solow has said "computers are everywhere but in the economic statistics". The social benefits of technological change are even more uncertain than the economic, and for many have become an emotional issue.

The competitive strategy view is that exploration benefits the competitive position, and therefore profitability, of firms. However, due to inefficiencies in capital markets, the risky nature of exploration, and the short time horizons of investors, resources for exploration may be difficult to obtain. Firms would like to invest more, but are constrained. Again, this leads some to argue for public intervention.

In theory, time and risk concerns should be mitigated through capital markets. However, the inefficiencies caused by information asymmetries can be substantial when dealing with the exploitation of intangibles such as the 'knowledge' which is the currency of exploration. This is why 'traditional' sources of capital, such as banks, are notoriously hesitant to participate in explorative endeavours, and why specialized institutions, such as venture capitalists, are needed to provide the service. These specialized institutions have developed the skills necessary to help deal with information asymmetries.

Are there excessive constraints on the availability of resources for exploration? Certainly there are constraints; resources are never limitless. But the issue of whether the constraints are 'excessive' is tied to how the 'explorer' and 'funder' share risk and reward. Understandably, the 'explorer' desires to keep ownership, control, and possible rewards; unfortunately the 'funder' wants a portion. Myers' (1984) 'pecking order' theory of finance describes the outcome of this situation in the way firms rank sources of finance, preferring to use internal funds first, then external debt, and finally external new equity to fund investments. The evidence would seem to be that any gap in resource availability for exploration is due as much to the perceptions of demand as to a failure in supply (Goodacre and Tonks 1995).

Society

Since the firm's market and industry are specifically identified in this model, the firm's society is then defined as everything else. While that includes a considerable amount, the significant portions are public sector institutions that formulate and implement public policy, and society as a regulator that establishes and enforces social rules and standards.

A number of researchers have highlighted the importance of local social conditions to the competitiveness of firms (Porter 1990, Lundvall 1992a, Nelson 1993, McKelvey 1991, Niosi 1991). This work suggests that there are strong national, regional or local components that influence the opportunities for technological exploration. The interaction of all the conditions influencing exploration in a geographical region has been described as a *National System of Innovation*.

The concept of a National System of Innovation includes the firm, market and industry conditions discussed earlier, but gives special prominence to additional social and political institutions and mechanisms. Examples of important elements include: trade barriers, tax policies, social welfare policies, defence policies, education and training systems, legal systems, labour market relations, and social customs. This moves the theory of industrial innovation from a simple description of the entrepreneur and the isolated firm as innovation units, to a consideration of how all the elements of society contribute to technological change. Therefore, interactions and synergies can be considered which would not be visible in a reductionist analysis of specific firms or competition among firms.

There has been considerable discussion of whether the 'nation' is the appropriate level of analysis. Certainly, the increasing integration of the electronic world, the lowering of trade barriers, and the prevalence of multinational corporations have served to decrease the influence of national conditions. However, the evidence is that the social and political institutions and factors that influence technological exploration still know sovereign boundaries. Perhaps more significantly, distance matters, and while the nation may not always be the correct choice, there is little question that regional differences are significant in the study of technological change.

5. Simulating Technological Change with Genetic Algorithms

In this chapter, the model of the process of technological change of the previous chapter is implemented in a computer program, called Bizlife, which takes an artificial adaptive agent approach to creating an artificial world (as described in §3.2). The description that follows is supported by a description of genetic algorithms in Appendix C, a description of the computer code in Appendix D, and the computer code in Appendix E.

5.1 Bizlife Overview

Bizlife is a computer program that simulates the process of technological change in an artificial economy. The simulation, while simplistic, allows insight into the essential mechanisms of the complex real world. There are two sources of motivation for the program: 1) genetic algorithms that define the structure and operation of the program, and 2) the model of the process of technological change that allows the results from the program to be interpreted in the context of the real world.

Genetic algorithms are a class of techniques for optimization that draw their inspiration from the process by which biological organisms improve their adaptation to their environment[12]. They operate by manipulating strings of numbers. More information on genetic algorithms can be found in Appendix C. The use of genetic algorithms in the context of the Bizlife program is described below.

The model of the process of technological change was described in Chapter 4. The relationship of the program to the model is discussed below. Briefly, all the important aspects of the model have been implemented except for the influence of society and the concept of technology push.

The philosophy used in the development of the program was to avoid logical complexity (i.e. to avoid decision rules). The objective was to see what complexity would emerge from the program, rather than to 'hard wire' that complexity in. Thus, firms in the program have three simple 'desires' (called propensities) – to imitate, invent, and sell products (termed 'contesting' markets) – and do not invoke firm specific decision rules. As a result, firms in the model cannot be considered intelligent or rational.

[12] While Bizlife uses the techniques of genetic algorithms, it is not using them as numerical optimization tools.

The environment does have decision rules that affect the probabilities of program outcomes. These are of two types; first, those dealing with imitation, and second those dealing with entry and exit. However, for the majority of the results reported in Chapter 6, entry and exit are not used. These decision rules are described below.

Bizlife has been implemented using Matlab for the computational engine and the visualization of results. Matlab is a technical computing environment for high-performance numeric computation and visualization. The name Matlab stands for *matrix laboratory*. The basic data element is a matrix that does not require dimensioning.

The basic formulation of the program is very simple – strings of numbers are compared to each other, some elements of those strings are copied to other strings, and other elements are changed randomly. This basic formulation is described in §5.2 and used in the first three results sets of Chapter 6.

A number of extensions to the basic formulation have been implemented. The first extension is the concept of firm distance, which affects the likelihood that two firms will interact. It is described in §5.3 and used in the fourth results set in Chapter 6. The second extension is the concept of resources, which allows the costs and rewards of firm behaviour to be tracked with more precision than the 'performance' measure of the basic formulation. It is described in §5.4 and used in the fifth results set of Chapter 6. The final extension is the concept of entry and exit that allows firms to change the products that they contest based on market forces. It is described in §5.5 and used in the fifth results set in Chapter 6.

In the following descriptions of the basic formulation and its extensions, an informal description is given first, and then a formal mathematical description is contained in a heavy-lined box.

5.2 Basic Formulation

The Bizlife world is composed of strings of numbers and it operates by manipulating those strings in the manner of genetic algorithms. Figure 5-1 shows the structure of the strings. An *Industry* is made up of a number of *Firms*, indicated here by the letters A through G. Each firm can contest a number of products, indicated here by the letters a through i. Each product embodies a combination of *Techniques* out of set of feasible combinations. The techniques chosen by the firms for their products are shown in the body of the table. The performance of a firm is determined by how well its chosen technique combination matches that desired by the *Market* for each product. In each period, firms can engage in *Exploration* through imitation of the techniques of other firms that are performing well, or through invention of new techniques. In each period firms can also engage in *Exploitation*

Figure 5-1: Bizlife Representation

		Products								
		a	b	c	d	e	f	g	h	i
	A	10110			11001	00110	10100	11001	01101	10110
	B	01110	01100	11001	01100	01100	00101			10100
	C		11000	01110	01101	00110	11110	10011	11111	00000
Firms	D		10010	01001	01101	11001	01101	01100	11011	10111
	E	01101	10101	00101				11001	00110	11011
	F	11110		00100	00111	11001	01100	11010		10011
	G	01011	00011	10111	11111	01101	00110	11101	00110	11110
Market		01110	10001	01101	01101	01100	01100	11101	01111	10110

by contesting the market for some products. Firms may not contest some products, indicated in the table by blank cells.

The Bizlife economy progresses over a number of discreet periods. In the simulations of the next chapter, the number of periods is varied to investigate the effect of different time horizons.

Since the program is stochastic, results from a single run may not be representative in general. To smooth the transient effects, results are often averaged over a number of iterations. Most results of the next chapter have been averaged over 20 iterations.

Techniques

In the program, the space of all possible techniques that a firm could employ is represented by a string of numbers of a finite length and cardinality. In the example of Figure 5-1, there are 64 possible combinations of techniques for each product, created from binary strings five positions long. Longer strings, of higher cardinality, create a more 'complex' environment for the firm. In the simulations of the next chapter, technique strings of length 20 and cardinality 5 have been used.

From the technique space, firms 'choose' a technique set to use. Imitation or invention can modify this set (see Exploration below). Typically, the technique string for each firm is initialized by a random assignment. This creates an industry with maximum diversity and is analogous to the primal ooze of biology. In some cases, the initial strings are defined to create special situations.

In the model of §4.2, ideas are the medium of exchange between the firm and its industry and market, and within the industry and market. In the program, ideas and techniques are synonymous. Ideas (techniques) are created by invention and diffuse through the industry by imitation, as described below.

Firm

Each firm is characterized by three attributes: propensity to imitate, propensity to invent, and propensity to contest. A propensity is a measure of a firm's natural 'desire' to do something. The outcome of these propensities in any situation is mitigated by the firm's current environmental conditions. For example, one firm may have high propensity to imitate, but whether it imitates, and which firm it imitates, depends on luck and the performance of the other firms.

Propensities are analogous to instincts (in animals), characters (in individuals), or corporate cultures (in firms). They are persistent and difficult to change in the short run. In the program, the propensities of a particular firm are invariant.

Firms that share the same propensities are of the same 'type'. Firms of the same type are identical in definition, though they may differ in outcomes as a result of stochastic differences in their histories. In the simulations of the next chapter, propensities are varied across firms to investigate the relative importance of imitation and invention to firm performance.

The current products of a firm are represented by a string of techniques (see Techniques above). The firm may not contest all of the products demanded by the market (see Market below). The firm's performance in any period depends on the firm's techniques in relation to those demanded by the market (see Exploitation below). The firm may change its techniques in any period by imitation or invention (see Exploration below).

Industry

The collection of all the firms constitutes the industry. The firms in the industry interact by imitating each other and, in the Resources extension described below, competing for the scarce resources of the market.

By specifying different numbers of firms, different degrees of rivalry can be modelled. The program can simulate the behaviour of large or small industries, monopolies, oligopolies, et cetera. In all of the simulations of the next chapter, the industry consists of 27 firms.

In the program, the number of firms in a simulation does not vary. However, a firm is simply a 'place holder' for data, and firms, in effect, exit the industry if they do not contest any products. The concept of exit is an extension to the basic formulation, and is described below.

Market

The market consists of a string of techniques, grouped into products, in much the same way as for a firm. These techniques represent market demand. The performance of a firm is evaluated as the number of positions in its technique string that match the technique string of the market, averaged over the products that it is contesting.

The number of products demanded by the market can be varied. In the simulations of the next chapter, there are always two products.

The operation of the market in the program is analogous to technology pull, since the market technique string defines what techniques will be successful. The concept of technology push is not captured, since techniques developed by the firm cannot influence the choices of the market. This concept may be implemented in future versions of the program.

Society

The firm's society is not explicitly contained in the program. However, the impact of society is implicit in the parameters of the program that describe the ease with which technology is developed (propensity to invent) and diffused (propensity to imitate and firm distance).

Exploitation

Firms exploit their technique strings by contesting products. The success of exploitation is measured by each product's performance. Performance is calculated by comparing the firm and market technique strings. The performance score of the firm's product is then the number of technique string positions

Figure 5-2: Performance

	Product 'a' Techniques	Performance
Firm A	1 0 $\boxed{1\ 1\ 0}$	3
Firm B	$\boxed{0\ 1\ 1\ 1\ 0}$	5
Market	0 1 1 1 0	

Figure 5-3: Basic Formulation (Performance)

Let $\mathbf{m}_p^r$ be the vector of techniques demanded by the market for product r in period p, and $\mathbf{t}_{f,p}^r$ be the vector of techniques offered by firm f for product r in period p. Then, $\mathbf{t}_{f,p}^{i,r}$ is the i^{th} technique in product r for firm f in period p. Similarly, $\mathbf{m}_p^{i,r}$ is the i^{th} technique demanded by the market for product r in period p. The performance of product r of firm f in period p, $\mathbf{p}_{f,p}^r$, is a measure of the correspondence between the firm and market technique strings, as calculated in equation (1). $\mathrm{X}_{f,p}$ is the set of products being contested by firm f in period p.

(1) $$\mathbf{p}_{f,p}^r = \left\| \mathbf{m}_p^r - \mathbf{t}_{f,p}^r \right\| \qquad \text{for:} \quad r \in \mathrm{X}_{f,p}$$

where: $\|\cdot\cdot\|$ is an operator which measures the distance between two vectors. Here, distance is measured as the number of identical vector elements:

$$\mathbf{p}_{f,p}^{i,r} = \begin{cases} 1 & \textit{if } \mathbf{m}_p^{i,r} - \mathbf{t}_{f,p}^{i,r} = 0 \textit{ for } r \in \mathrm{X}_{f,p} \\ 0 & \textit{otherwise} \end{cases}$$

$$\mathbf{p}_{f,p}^r = \sum_i \mathbf{p}_{f,p}^{i,r}$$

that match those of the market demand for that product as shown in Figure 5-2. The performance of the firm is the average performance of the products that it is contesting. A formal representation of the performance calculations is shown in Figure 5-3.

Exploration

Firms explore their technique space by imitation and invention.

A firm may decide to imitate the technique of another firm for a product that it is currently contesting. This decision is stochastic, and is more likely if the firm has a high propensity to imitate. The choice of firm to imitate is also stochastic.

Imitation is achieved by copying a portion of the techniques from another firm's product as shown in Figure 5-4. The procedure involves copying some technique string position values, chosen at random. This differs from the 'classic' genetic algorithm method of copying using a randomly chosen crossover point, and has been done for ease of implementation.

Figure 5-4: Imitation

	Before	**After**
Firm A	$\boxed{1}$ 0 1 1 0	$\boxed{0}$ 0 1 1 0
Firm B	$\boxed{0}$ 1 1 1 0	$\boxed{0}$ 1 1 1 0

Firm A imitates the first technique of Firm B

A firm may decide to invent a technique for a product which they are currently contesting and for which they have not already imitated another firm. This decision is stochastic, and is dependent on the firm's propensity to invent. Invention is achieved by changing, at random, the value of some positions in the firm's technique string as shown in Figure 5-5. A formal representation of

Figure 5-5: Invention

	Before	After
Firm A	$\boxed{1}$ 0 1 1 0	$\boxed{0}$ 0 1 1 0

Firm A invents a new first technique.

Figure 5-6: Basic Formulation (Imitation and Invention)

In each period, each of a firm's techniques may change through imitation or invention. The probability of such a change is given by the firm's propensity to imitate $\Pi_{f.m}$, and propensity to invent $\Pi_{f.v}$, as given by the probability distribution of equation (2).

$$(2) \qquad \mathbf{t}^{i,r}_{f.p} = \begin{cases} \mathbf{t}^{i,r}_{k.p-1} & \textit{with probability} \left(\Pi_{f.m} \cdot P^{r}_{p-1}(k)\right) \\ \Im & \textit{with probability}\ \Pi_{f.v} \\ \mathbf{t}^{i,r}_{f.p-1} & \textit{otherwise} \end{cases} \qquad \text{for:} \quad r \in \mathbf{X}_{f.p-1}$$

where: $\Pi_{f.m} + \Pi_{f.v} < 1$

$\Im$ is a random integer such that $\Im \in \mathbf{T}$, the set of possible technique choices.

k is the firm to imitate such that $k \in \mathbf{X}^{r}_{p}$, the set of firms in the industry contesting product r in period p.

$P^{r}_{p-1}(k)$ is the relative performance of firm k for product r in period p-1:

$$P^{r}_{p-1}(k) = \begin{cases} \dfrac{\mathbf{p}^{r}_{k,p-1}}{\sum_{k} \mathbf{p}^{r}_{k,p-1}} & \textit{for } k \in \mathbf{X}_{k,p-1} \\ 0 & \textit{otherwise} \end{cases}$$

the imitation and invention calculations is shown in Figure 5-6.

Environmental Change

In the program, the environment is represented by the market techniques. In each period the market techniques may change. This is stochastic and depends on the market technique probability of change. Market technique change is achieved by changing, at random, the value of some positions in the market's technique string. As the market changes, the firms adapt by imitation and invention. A high probability of market change simulates conditions of rapid environmental change. In the simulations of the next chapter, market change probabilities are varied to investigate the impact of environmental change rates. A formal representation of the environmental change calculation is shown in Figure 5-7.

Figure 5-7: Basic Formulation (Environmental Change)

In each period, the environment may be changed by changing some of the market's techniques for each product. The probability of such a change depends on the product's probability of market technique change Π_t^r, as calculated in equation (3).

$$(3) \qquad \mathbf{m}_p^{i,r} = \begin{cases} \mathfrak{I} & \textit{with probabililty}\ \Pi_t^r \\ \mathbf{m}_{p-1}^{i,r} & \textit{othewise} \end{cases}$$

5.3 Extension 1: Firm Distance

The firm distance factor alters the probability of which firm is chosen during imitation so that more distant firms are less likely to be chosen. Firm distance in the program is proportional to the number of positions apart two firms are in the data array. Calculation of the firm distance factor is shown in Figure 5-8. 'Distance' is meant to capture more than just physical distance in the real world. Distance is a concept that describes ease of communication and is affected by culture, language, technologies, and other influences. In the simulations of the next chapter, the choice of firm to imitate is generally distance independent. Firm distance is used in the fourth results set of Chapter 6. A formal representation of the firm distance factor calculation is shown in Figure 5-9.

Figure 5-8: Firm Distance Graph

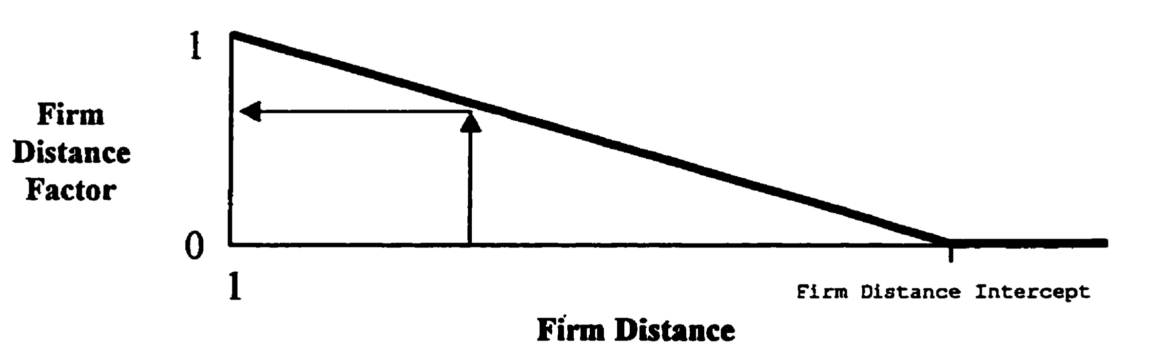


Figure 5-9: Extension (Firm Distance)

In the basic formulation, the choice of firm to imitate is independent of the firm's distance away. The concept of firm distance can be introduced by using a firm distance weighting factor $\Delta_{f,k}$ which changes the probability of firm f choosing firm k to imitate. As implemented here, the relationship is linear, based on the difference between the firms' indicators, as calculated in equation (4).

$$(4) \qquad \Delta_{f,k} = \max\left(0, 1 - \frac{|f-k|}{C_1}\right)$$

where: $|\cdot|$ is an operator which measures the minimum distance between two numbers in modulus arithmetic.

C_1 is a constant representing the firm distance graph intercept.

Then, to implement distance dependence, equation (2) is altered as follows:

$$(2b) \qquad P^r_{p-1}(k) = \begin{cases} \dfrac{\mathbf{p}^r_{k,p-1}}{\sum_k \mathbf{p}^r_{k,p-1}} \cdot \dfrac{\Delta_{f,k}}{\sum_f \Delta_{f,k}} & \textit{for} \quad r \in \mathbf{X}_{f,p-1} \\ 0 & \textit{otherwise} \end{cases}$$

5.4 Extension 2: Resources

Resources are only used in the program to influence market entry and exit decisions, they are separate from the measure of performance.

Firms acquire resources in each period from products that they are contesting according to their performance relative to other firms. Products have market sizes that determine the amount of resources available for acquisition. Firms receive a share of the resources proportional to their performance relative to the other firms contesting the product.

Resources are expended by a number of activities: imitation, invention, contesting a product, and entering a new product. The relative costs of these activities can be varied to investigate how cost influences the balance between exploration and exploitation.

The calculation of resources in period p+1 is shown in Figure 5-10. In the simulations of the next chapter, resources have only been used in the fifth results set of Chapter 6. A formal representation of the resource calculations is shown in Figure 5-11.

Figure 5-10: Resources

+	Resources_p
+	Revenue_p
-	Cost of Entry_p
-	$\text{Cost of Contesting}_p$
-	$\text{Cost of Imitation}_p$
-	$\text{Cost of Invention}_p$
=	Resources_{p+1}

In each period, the market size may change. This is stochastic and depends on the market size probability of change. Market size change is achieved by changing the market size by a random percentage. In the simulations of the next chapter market size change has not been used. A formal representation of the market size change calculations is shown in Figure 5-12.

Figure 5-11: Extension (Resources)

In the basic formulation, resources are not explicitly accounted for. The concept of firm resources can be introduced by keeping track of a firm's revenue and costs. As implemented here, a firm's revenue from a product is proportional to its relative performance. A firm's costs are proportional the number of times it contests a product, enters a new product, imitates a technique, and invents a technique. These are calculated in equation (5).

$$(5)\quad \mathbf{r}_{f,p} = \mathbf{r}_{f,p-1} + \sum_{r \in X_{f,p}} \left(\frac{\mathbf{p}^r_{f,p}}{\sum_f \mathbf{p}^r_{f,p}} \cdot \mathbf{s}^r_p \right) - C_2 \cdot N_{c,f,p} - C_3 \cdot N_{e,f,p} - C_4 \cdot N_{m,f,p} - C_5 \cdot N_{v,f,p}$$

where: $\mathbf{r}_{f,p}$ are the resources of firm f in period p.

$\mathbf{s}^r_p$ are the resources available in the market from product r in period p.

C_2, C_3, C_4, and C_5 are constants representing the costs of contesting products, entering new products, imitating techniques, and inventing techniques, respectively.

$N_{c,f,p}$ is the number of products contested by firm f in period p.

$N_{e,f,p}$ is the number of products entered by firm f in period p.

$N_{m,f,p}$ is the number of techniques imitated by firm f in period p.

$N_{v,f,p}$ is the number of techniques invented by firm f in period p.

Figure 5-12: Extension (Market Size Change)

In each period, the resources available in the market for a product may change. The probability of such a change depends on the market's probability of size change Π^r_s, as calculated in equation (6).

$$(6)\qquad \mathbf{s}^r_p = \begin{cases} \mathbf{s}^r_{p-1} \cdot \delta & \textit{with probabililty } \Pi^r_s \\ \mathbf{s}^r_{p-1} & \textit{othewise} \end{cases}$$

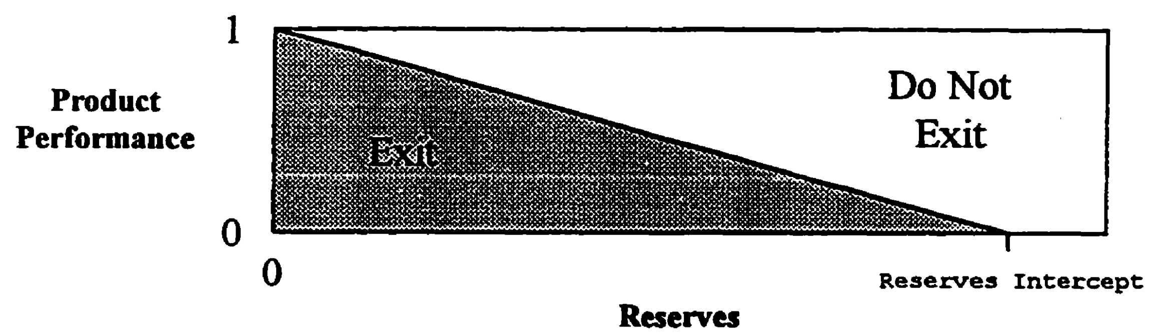
where: δ, as implemented here, is a random real number between –1.1 and +1.1.

5.5 *Extension 3: Entry and Exit*

Exit

A firm may decide to exit from a product that it is currently contesting. This decision is stochastic, and is dependent on the firm's propensity to contest, whether the anticipated payback from the product is sufficient, and the firm's reserves. A firm's reserves represent the number of periods that a firm could sustain contesting a product without additional revenue. A product's payback represents the number of times the cost of entry will be recovered from product revenues. Product exit may occur in the 'Exit' region of Figure 5-13.

Figure 5-13: Product Exit Graph



In the simulations of the next chapter, product exit has only been used in Results Set 5. A formal representation of product exit is shown in Figure 5-14.

Figure 5-14: Extension (Product Exit)

In the basic model, the set of products that a firm contests is static. The concept of exit from a product by a firm can be introduced by reducing the products a firm contests. The probability of such a change depends on the firm's propensity to contest $\Pi_{f,c}$, the firm's reserves in period p $\varphi_{f,p}$ relative to product performance, and the product's expected payback in period p σ_p^r relative to a minimum, as calculated in equation (7).

$$(7) \qquad \mathrm{X}_{f,p} = \begin{cases} \mathrm{X}_{f,p-1} \sim r & \textit{with probablity } (1-\Pi_{f,c}) \\ \mathrm{X}_{f,p-1} & \textit{otherwise} \end{cases} \quad \text{for:} \quad \begin{array}{l} r \in \mathrm{X}_{f,p-1} \\ r \in \left[\sigma_p^r < C_6\right] \\ f \in \left[\mathrm{p}_{f,p}^r < 1 - \dfrac{\varphi_{f,p}}{C_7}\right] \end{array}$$

where: ~ is an operator which removes product r from the set of products contested by firm f.

$\varphi_{f,p}$ is the firm reserve, representing the number of periods that a firm could sustain contesting a product without additional revenue:

$$\varphi_{f,p} = \frac{\mathrm{r}_{f,p} - C_3}{C_2}$$

σ_p^r is the product payback, representing the number of times the cost of entry will be recovered from product revenue:

$$\sigma_p^r = \frac{\dfrac{\mathrm{s}_p^r}{N_{c,p}^r} - C_2}{C_3}$$

$N_{c,p}^r$ is the number of firms contesting product r in period p.

C_2, C_3, C_6, and C_7 are constants representing the cost of contesting a product, the cost of entering a product, the minimum payback, and the product exit graph intercept, respectively.

Entry

A firm may decide to enter into a new product that it is not currently contesting. This decision is stochastic, and is dependent on the firm's propensity to contest, whether it has sufficient reserves, the performance of nearby (and therefore related) products which it is already contesting, and the anticipated payback from the product. Calculation of Product Distance is similar to the calculation of firm distance discussed previously (see Exploration above). Calculation of the Product Distance Factor is shown in Figure 5-15. Product

Figure 5-15: Product Entry Graph

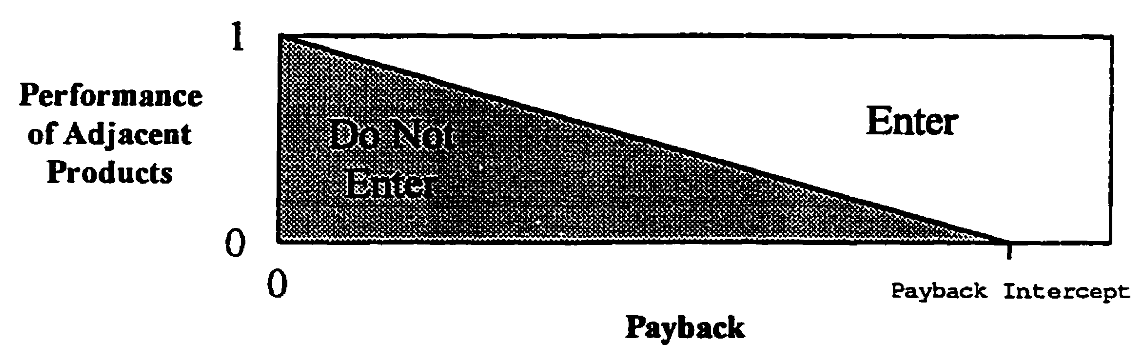
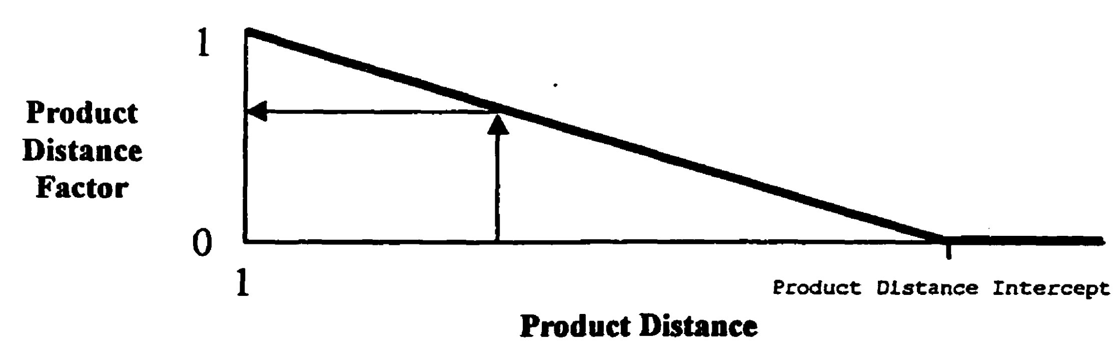


Figure 5-16: Product Distance Graph



entry may occur in the 'Enter' region of Figure 5-16. Techniques for new products are selected by imitation or invention, as described above. In the simulations of the next chapter, product entry has only been used in the fifth results set. A formal representation of product entry is shown in Figure 5-17.

Figure 5-17: Extension (Product Entry)

The concept of product entry can be extended to product exit in a similar manner. The probability that a firm will enter a product depends on the firm's propensity to contest $\Pi_{f,c}$, the firm's reserves in period p $\varphi_{f,p}$ relative to a minimum, and the product's expected payback in period p σ_p^r relative to the performance of adjacent products, as calculated in equation (8).

$$\text{(8)} \qquad X_{f,p} = \begin{cases} X_{f,p-1} \cup r & \textit{with probablity } \Pi_{f,c} \\ X_{f,p-1} & \textit{otherwise} \end{cases} \qquad \text{for: } r \notin X_{f,p-1}$$

$$f \in \left[\varphi_{f,p} > C_8\right]$$

$$r \in \left[\frac{\sum\limits_{i \in X_{f,p}, i \neq r} \left(p_{f,p}^i \cdot \Lambda^{r,i}\right)}{C_{10} \cdot \Lambda^r} > 1 - \frac{\sigma_p^r}{C_9} \right]$$

where: $\cup$ is an operator which adds product r to the set of products contested by firm f.

$\Lambda^{r,i}$ is the product distance factor for product i relative to product r. As implemented here, the relationship is linear based on the difference between the product indicators:

$$\Lambda^{r,i} = \begin{cases} 1 & \textit{if distance independent} \\ \max\left(0, 1 - \dfrac{r-i}{C_{11}}\right) & \textit{if distance dependent} \end{cases}$$

C_8 is a constant representing the minimum reserve.

C_9 is a constant representing the product entry graph intercept.

C_{10} is a constant representing the number of techniques per product.

C_{11} is a constant representing the product distance graph intercept.

$\varphi_{f,p}$ is the firm reserve (calculated previously).

σ_p^r is the product payback (calculated previously).

5.6 *Advantages and Limitations*

The artificial world as implemented in Bizlife has a number of advantages over previous work in this area:

- It is founded on an explicit model of the process of technological change. It is simple in concept, and therefore easily understood, but produces complex effects. It has wide applicability across many industries and can be adapted to study a variety of situations.

- It uses the artificial adaptive agent approach (specifically genetic algorithms) and therefore uses evolutionary techniques to model evolutionary ideas. With the exception of entry and exit decisions, there are no equations governing activity. Imitation and invention are the only processes.

- It employs powerful computation and visualization software to aid in the generation and interpretation of results. Variables can be manipulated easily, and effects can be isolated precisely. The speed of the program means that investigations can be extensive and detailed.

However, there are certainly limitations inherent to the chosen approach. Generic problems have been discussed in §3.1. Additional limitations include:

- There is no way to translate program inputs or outputs to measures in the real world. This means that the model cannot be used for predictive purposes. It will also make acceptance of the model difficult for some people. However, it should be realized that the link to the real world of most economic models is often exaggerated.

- The model is currently quite simplistic. While there is a certain fascination in seeing how much of the world's complexity can be captured with a few simple concepts, there will be pressure in the future to increase the model's complexity in order to accommodate various 'perceptions' of how the world works.

- The approach is not translatable into neoclassical terms, and therefore will require effort on the part of the traditional academic community to be understood and appreciated.

5.7 Assumptions

Since no other models of technological change based on genetic algorithms have been published, many of the assumptions in the Bizlife program are ad hoc, without foundation in previous work. Typically, capabilities within the program have been implemented in the simplest manner possible – in keeping with the program's philosophy of avoiding complexity.

The most fundamental assumption of the program is that *genetic algorithms are a useful metaphor for the process of technological change in the economy.* This assumption means that a firm can be modelled as a set of choices from a large number of possible 'ways of doing things' (techniques). This is in keeping with Nelson and Winter's concept of 'routines' which has been used by many subsequent models (for example Englmann 1994 and Andersen 1996). Other assumptions related to how genetic algorithms operate follow from this one. For example, how techniques are discovered and diffused through the industry. These assumptions may require a 'leap of faith' or 'suspension of disbelief' to accept, supported of course by the analogies between technological change and biological evolution painted in Chapter 2.

Other important assumptions are:

- *A firm can be characterized by its propensities to imitate, invent, and contest products.*

  This assumption has been made to succinctly describe the characteristics of a firm pertinent to the process of technological change. These concepts are capable of encompassing a large variety of influences on the activities of a firm. Chiarmonte et al. (1993) also use 'behavioural norms' to describe their agents.

- *A firm's propensities do not change.*

In reality, a firm's propensities change slowly relative to the rate of change of its techniques. Not allowing propensities to change is a first approximation. Future versions of the program will allow propensities to change in response to environmental factors. Chiaromonte et al. (1993) also assume that behavioural norms present a relatively high degree of inertia and, thus, can be taken as parameters. In contrast, Silverberg and Verspagen (1994) have firms imitate only when profits are low.

- *A firm's activities can be described by a string of numbers.*

This is in keeping with von Neumann's concept of cellular automata and the belief that any organism can be reduced to a string of instructions.

- *Firms know the relative success of their competitors, but not specifically which techniques are producing that success.*

This is reasonable, given that even a firm's competitors will rarely have a clear understanding of what they have done right or wrong to influence performance. Financial reports, for example, provide a clear indication of a firm's overall performance, but not which of the firm's decisions have been the correct ones.

- *The environment is exogenously determined. Firms cannot influence market demand.*

This is reasonable for some avenues of investigation. However, many other interesting questions will only be answered by allowing firms to influence market demand in the program. This capability will be incorporated in future versions of the program.

- *Revenue is proportional to relative performance.*

The idea that revenue is positively related to performance is a fundamental premise of capitalistic economics. The assumption that the relationship is proportional is a simplification made in the absence of information to the contrary.

- *Firm distance is a linear function of firm rank order.*

The assumption that a measure of 'distance' between firms is important when examining technology diffusion is widely accepted (Rogers 1983, Karahenas and Stoneman 1995). The assumption that the relationship is linear is a simplification made in the absence of information to the contrary. Bharagava and Mukherjee (1994) use a 'coefficient of interaction' for the same purpose.

- *Product distance is a linear function of product rank order.*

The product distance assumption is similar to the firm distance assumption. The idea that the success of new products will be dependent on that of existing products is related to the concept of core competencies (Prahalad and Hamel 1990). The assumption that the relationship is linear is a simplification made in the absence of information to the contrary.

- *Imitation and invention can be seperated.*

As has been explained in §4.2, imitation and invention are extremes of a continuum. Separation of the concepts in the model permits analysis of relative positions on the continuum. Nelson and Winter (1982), Silverberg and Verspagen (1994), and Chiaromente et al. (1993) also have agents which invent and imitate.

- *Invention is random trial and error.*

This assumption follows from the previous one. In the extreme, pure invention can be thought of as search without reference to what has gone before, and in this view must be random. While invention changes techniques at random, this does not mean the product change in random. Since a product is made up of many techniques, and since invention changes only a few techniques each period, a product is very similar to its self in previous periods. Thus, products evolve over time and do not jump discontinuously. In a similar fashion, Silverberg and Verspagen (1994) achieve invention by drawing from a normal distribution centred around the current value. Both approaches make invention a random walk.

- *Market technique changes are random.*

While market techniques change at random, this does not mean that the products demanded by the market do. Since a product is made up of many techniques, and since the techniques change relatively slowly, products in each period are very similar to products in previous periods. Thus market demand (the environment) evolves over time and does not jump discontinuously.

- *Market size changes are random percentages.*

This assumption allows market size to change in a simple way. It has been done for ease of implementation.

- *Firms are myopic in the sense that they do not look beyond the current period when determining which activities to pursue.*

  This is reasonable, given that the complexity and rate of change of the environment makes it so difficult to forecast the future. This assumption is standard in models of this type (for exampie, Nelson and Winter 1982, Silverberg and Verspagen 1994, Chiaromonte et al. 1993, and Englemann 1994).

- *The influences of many factors, such as society, are secondary and can be ignored.*

  Every model must make choices about what to include. Other factors may be necessary to answer specific questions and will be incorporated into future versions of the program as needed.

- *Economic systems are stochastic – luck matters.*

  This is a fundamental premise of evolutionary economics, and all models that claim to be evolutionary have stochastic elements (for example, Nelson and Winter 1982, Chiaromonte et al. 1993, Bhargava and Mukerjee 1994, Silverberg and Verspagen 1994).

5.8 Validity

Models can be either descriptive or prescriptive. Prescriptive models are meant to predict the future and thus support decisions. They must be complete and therefore tend to be complicated. For this type of model the establishment of validity is an important step in the application of the model and the standards of credibility are high. Typically validity is demonstrated by comparing model results with historical data, or with other models which have previously established their validity.

Descriptive models, on the other hand, are more concerned with describing the past. They often are used as frameworks to categorize items, guides for conducting analyses, or illustrations that offer insights and understanding. Often, the value of the model is in its simplification of the complexity of the real world, rather than a complete or accurate description. Validation of this type of model is less important, and therefore less onerous, than for a prescriptive model.

Fortunately, the model and program of this thesis is descriptive. They are meant to promote a new way of looking at the process of technological change, and to illustrate what such a viewpoint might reveal. For such a task, face validity (verasimility) is sufficient. If the reader can be convinced that the model is reasonable, in a specific and narrow way, then the results from the model will have some persuasive power.

Since there is no direct correspondence between the parameter values in the program and metrics in the real world, the model cannot be calibrated and establishing validity with historical data is not possible. However, if the development of the model has persuaded the reader that it is reasonable, that is enough to fulfil its intent.

6. An Evolutionary Simulation of Technological Change

The following sections investigate the behaviour of the Bizlife program. In doing so, they reveal some of the interesting implications which emerge from the evolutionary economics point of view of the process of technological change. Parameter values for the runs illustrated in this chapter can be found in Appendix F.

The investigations of this chapter progress in steps that begin with a basic implementation of the program and sequentially build in complexity. At each step, parameters are varied independently and investigations build on previous results. In this fashion, an understanding of the model can be built incrementally, and causes and effects are effectively isolated.

This approach is in contrast to an alternative in which all of the capabilities of the program are utilized immediately and together using 'reasonable' parameter settings. With such an approach, even with the relatively simple model used here, it would be extremely difficult to understand the reasons for outcomes given the program's dynamic and stochastic nature.

Therefore, the temptation to dive too deeply, too quickly, into the use of the program has been avoided. The majority of the runs presented here do not use the full capabilities of the model. However, it is the results from the simplest implementations of the model that are the most subtle and profound.

The first results set examines how imitation and invention work separately and together as exploration processes that improve industry performance. This is done assuming a static environment, homogenous firms, and costless processes.

In the second results set, the assumption of a static environment is relaxed and the impact this has on the relationship of imitation and invention levels to performance is examined.

In the third results set, the dynamics of the previous results are examined more closely to understand how firms interact within the industry over time.

In the fourth results set, the assumption of homogeneous firms is relaxed in order to examine how the division of explorative effort impacts the overall performance of the industry and the relative performance of individual firms.

In the final results set, the assumption of costless processes is relaxed and the dynamics of entry into, and exit from, product markets is examined. At this point, the full capabilities of the program are operational.

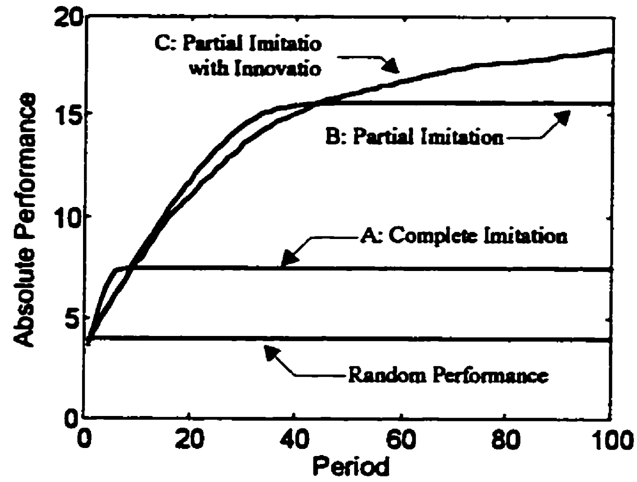
6.1 Results Set 1: The Impact of Imitation and Invention

Findings

In this set of runs, the impact of imitation and invention propensities in a static environment is investigated. The model has been kept very simple: all firms are identical, there is no entry or exit, and costs are ignored. Results have been averaged over 20 iterations to suppress the dynamics of individual runs resulting from the stochastic nature of the model.

Figure 6-1 shows the average performance of the firm population, by period, for three model runs. The 'Random Performance' line indicates the performance level that would be expected from the random selection of firm techniques and is the baseline from which to judge performance improvements. Note that since firms are initially seeded with techniques at random, their initial performance starts at this line.

Figure 6-1: Static Environment



First, consider run 'A: Complete Imitation'. In this run, each firm imitates another firm completely in every period. Since the probability is higher of imitating better performing firms, improvement is initially very rapid. However, after only about five periods improvement abruptly ceases. The reason for this is called 'premature convergence'. Because of the high rate of imitation, all of the firms soon become identical and there is no diversity left from which to select better techniques.

This loss of diversity can be seen by comparing Figure 6-2 and Figure 6-3. The figures show firm techniques (rows in the main body of the matrix) against the market techniques (the row above the matrix). The colour of each cell indicates the technique that has been chosen. The objective of the firms is to match their techniques with the market techniques. Figure 6-2 shows the initial period. There is significant diversity, but low performance. Through imitation, the firms copy the better performing firms. Later, performance has improved, but now all of the firms' technique choices are identical, as shown in Figure 6-3. Imitation can no longer improve performance.

Figure 6-2: Diversity

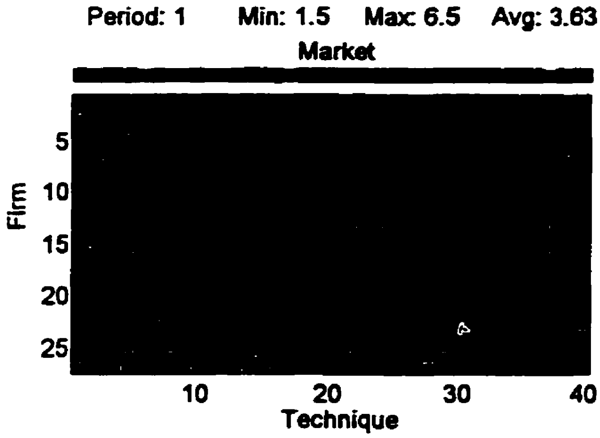
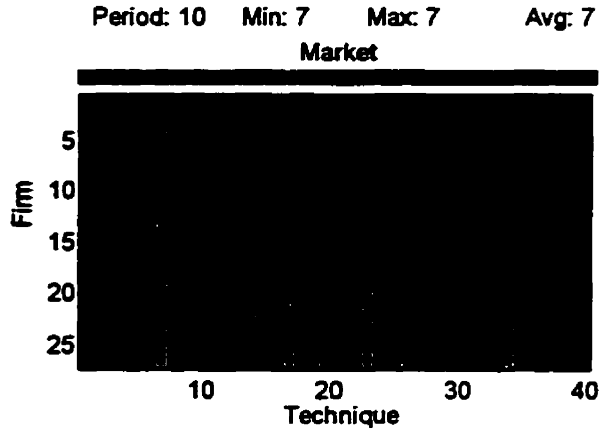


Figure 6-3: Convergence



Next, consider run 'B: Partial Imitation' in Figure 6-1. It is identical to run 'A', except that the rate of imitation has been reduced. Imitation is now no longer perfect. When a firm imitates, it now only chooses bits and pieces of another firm's techniques. As a result, imitation is capable of searching new regions because it combines existing ideas in novel ways. The result is evident. Improvement proceeds at a slower rate, but continues much longer and ultimately achieves a higher performance level. However, convergence still eventually occurs, and once it does there can be no further improvement.

Finally, consider run 'C: Partial Imitation with Invention' in Figure 6-1. It is identical to run 'B', except that now firms invent as well as imitate. Again, performance improves quickly at first, though not as quickly as in run 'B' because invention results in many poor technique choices which decrease performance. However, invention prevents the firms from converging and therefore allows improvement to continue beyond what would be possible without invention. While it is invention which is generating the improvements in the later periods, imitation is still very important because it allows successful inventions to diffuse to the rest of the firms.

Figures 6-4 and 6-5 show, from two different angles, the surface which is generated by taking the parameters of run 'C' in Figure 6-1 and varying the imitation rate across the range of possibilities. In general, lower rates of imitation slow performance improvement. Clearly there are disadvantages to both too low and too high a rate of imitation, but performance is relatively insensitive to the choice in the mid to high range.

Figure 6-4: Propensity to Imitate (left view)

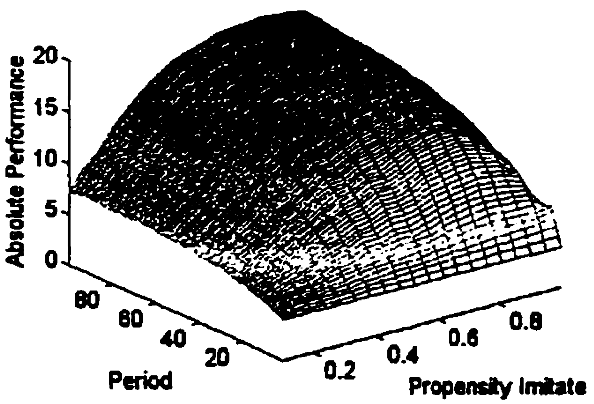


Figure 6-5: Propensity to Imitate (right view)

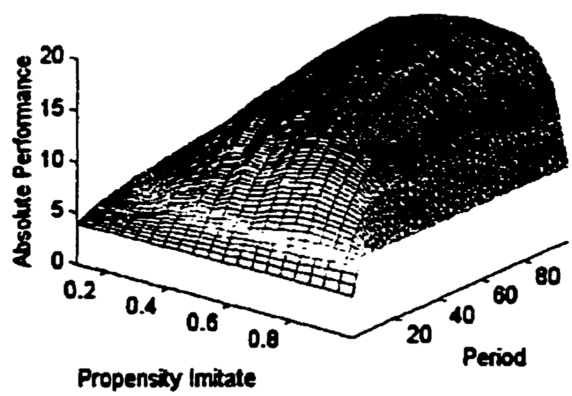


Figure 6-6 and 6-7 are similar to Figures 6-4 and 6-5, except that this time it is the invention rate which has been varied over a range of values. The shape of this surface is very different. While some invention is better than none, it is evident that too much invention is counterproductive.

Figure 6-6: Propensity to Invent (left view)

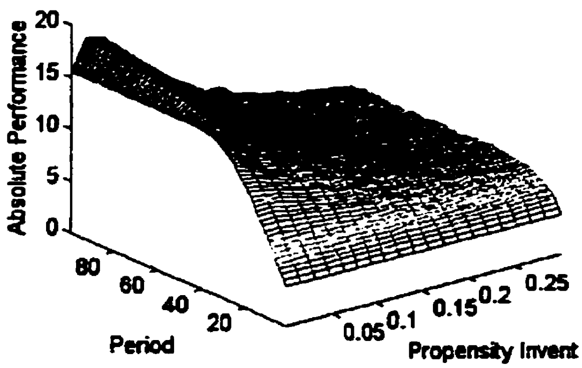
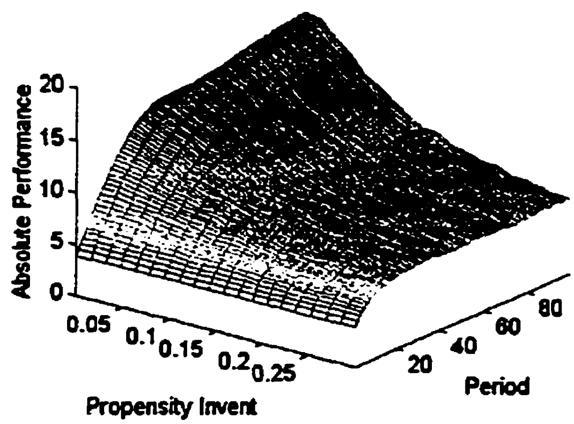


Figure 6-7: Propensity to Invent (right view)



Implications

1. *The performance of firms and industries can improve through evolutionary processes without any requirement for rationality or motivation on the part of management.*

This is the most fundamental conclusion from the evolutionary perspective of change. If the three components of evolution exist, 1) a measure of success, 2) mechanisms for exploration, and 3) selection based on success, then the performance of a system will improve over time. Note that the agents in the system do not require intelligence, motivation, goal oriented behaviour, or other similar attributes. Search can be undirected and, in the local sense, purposeless, and still produce global improvements in performance.

This does not preclude agents from having these attributes – and it would be expected that in most situations they would be advantageous – however, their existence is only of relative importance when comparing performance among agents, not in explaining the underlying reasons for economic and technological progress. As Alchian put it so well in §2.3, "Even in a world of stupid men, there would still be profits".

The degree to which human economic agents can be assumed to act rationally in the real world is open to debate. Certainly, this ability is dependent on a variety of circumstances specific to the situation. The impact of environmental change on this capability will be investigated later.

This result will not be surprising to evolutionary biologists who have never considered intelligence necessary for biological development. However, this result should give pause to economists and business schools.

In economics, capitalistic economic growth is thought to be driven by the self-interest of individual economic agents pursuing personal gain. This view is not inconsistent with the evolutionary view, but it is also not necessary. As this program has shown, similar economic outcomes are possible in a system which has mechanisms for variety generation, removal of poor performers, and transmission of 'good' behaviours to other economic agents – all without any particular motivation or capability on the part of any agent.

Similarly, business schools owe their existence to the belief that if managers are well trained, they will create successful, profitable businesses. Again, it may well be true. But if business is simply a lottery, there will always be some who win more than others. Will we be able to distinguish luck from skill?

2. *Imperfect imitation is a form of exploration that combines existing ideas in novel ways. It is capable of improving performance of both firms and industries, to a point, without invention.*

This is an important, and perhaps not obvious, point. The basis for technological change is exploration. The common view of exploration is one of invention, of radical change. However this result emphasizes the importance of imitation as a search mechanism. When imitation combines portions of different ideas, new ground is in fact being explored. Typically, this produces incremental change, but this is very powerful because the probability is high that the short-term exploitation of the results will be successful since portions of the new idea have been successful in the past.

The power of imitation as a mechanism for exploration has implications in the real world. If exploration is improved by having a large imitative compenent, then research organizations should ensure that scanning of previous efforts, both inside and outside the organization, be given sufficient attention and resources.

3. *Perfect imitation (as in cloning) maintains existing performance, but cannot improve performance.*

While imitation can be a powerful search mechanism, its power is derived from the ability to combine successful concepts into novel ideas. If imitation is perfect, then nothing novel is produced and exploration has not occurred. While perfect imitation may have immediate exploitation benefits, long term improvement cannot be achieved.

The shortcomings of perfect imitation have long been understood by the biological world and explain the predominance of organisms that use sexual reproduction. In the economic world the dangers of perfect imitation are generally not significant since it is so difficult to achieve. The important point is that the optimal level of imitation is something less than perfect and something more than none. The appropriate level is, then, an empirical matter.

4. *Invention can improve performance beyond what imitation alone can achieve.*

The previous points have established the importance of imitation as a mechanism for improvement in an evolutionary system. However, that is only part of the story. The simulations have also demonstrated that invention is important to the long-run success of exploration in order to ensure that diversity is maintained. Without invention, there is the danger that continued imitation will lead to premature convergence of the population members at a local, sub-optimal, solution. Invention prevents convergence and allows more of the search space to be explored and, eventually, a better solution to be found. As discussed in §4.2, convergence can lead to 'lock-in' to sub-optimal technological trajectories.

The more important role of invention in adjusting to a changing environment will be investigated in Results Set 2.

5. *Imitation and invention need to be appropriately balanced. Imitation is the more efficient search method, and should predominate. However, some invention is important.*

   The simulations show that invention should be, relatively, a much less active component of the exploration process than imitation. This is because, for local search and short-term improvement, imitation is more efficient than invention. This also explains why imitation is more 'socially accepted', but invention more highly regarded when succesful. As Alchian said in §2.3, "Those who are different and successful 'become' innovators, while those who fail 'become' reckless violators of tried-and-true rules".

6. *Exploration and exploitation need to be appropriately balanced. In the short-run, exploration can decrease exploitive performance; in the long-run exploration improves performance.*

   This point is another fundamental conclusion for the evolutionary perspective of change. The balance between exploration and exploitation is a recurring theme in evolutionary systems. Biological organisms owe their survival to the achievement of the correct balance (as discussed in §2.2). Genetic algorithms are excellent numeric optimization tools because they also achieve this balance (as discussed in Appendix C).

Firms, too, must balance the opposing demands of keeping pace with the advances of their competitors and keeping creditors at bay.

6.2 *Results Set 2: The Impact of Environmental Change*

Findings

The results of the last section were obtained under conditions of a static environment. However, we know that this assumption is not very realistic in most real-world situations. What happens when the environment presents a moving target for firms' efforts to choose techniques?

Figure 6-8: Changing Environment

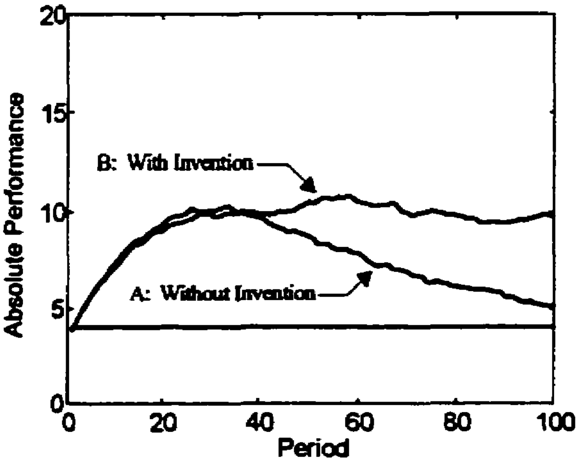


Figure 6-8 shows the impact on performance of environmental change. The conditions in Figure 6-8 are the same as those in Figure 6-1 run 'C', except that now there is some change each period in the techniques desired by the market. In run 'A' of Figure 6-8 the firms do not invent. As before, there is initial improvement in performance. However, at the point where the firms reach convergence in techniques, performance begins to decline. This is because once all of the firms are homogenous, there is no diversity left with which to cope with environmental change.

The solution to this problem is invention. Figure 6-8 run 'B' is the same as run 'A' except now the firms invent. Because of invention, initial performance improvement is not quite as steep. But now, convergence does not occur. The firms can cope much better with the changing environment and their performance does not decline.

How well can firms cope with environmental change? Figures 6-9 and 6-10 show how average firm performance varies with the rate of change in the environment. The conditions here are the same as in Figure 6-8 run 'B'. Obviously, the best performance

Figure 6-9: Environment Change (left view)

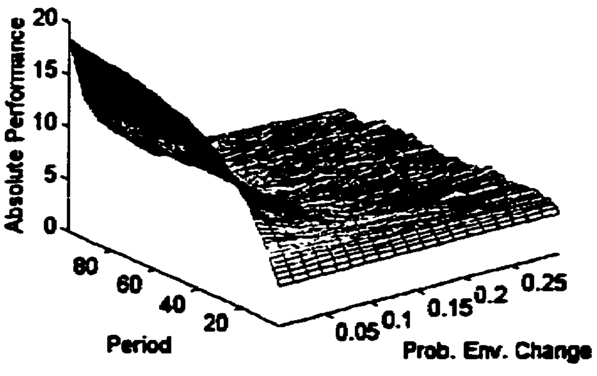
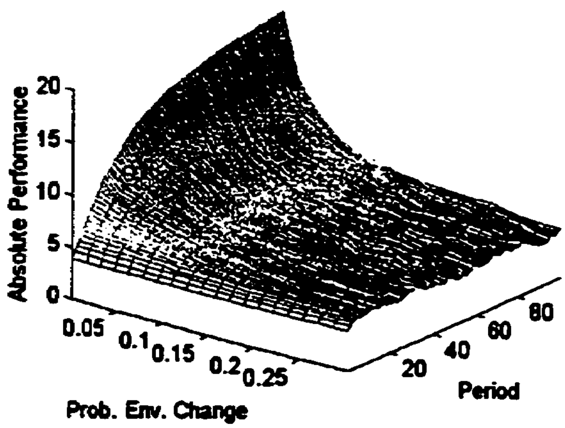


Figure 6-10: Environment Change (right view)



occurs when there is no environmental change. Performance then decreases quickly and finally levels off.

The conditions in Figures 6-11 and 6-12 are the same as Figures 6-4 and 6-5, except that there is environmental change. The surface is now flatter and less smooth since it is more difficult to adapt to the changing environment. Also, the maximum occurs at slightly higher levels of imitation.

Figure 6-11: Propensity to Imitate (left view)

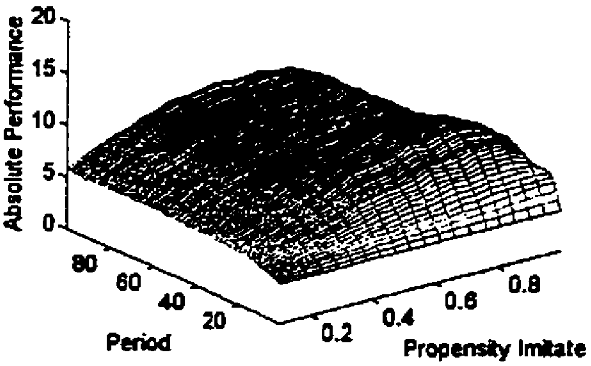
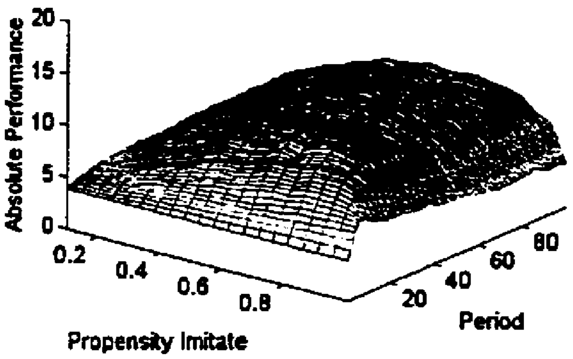


Figure 6-12: Propensity to Imitate (right view)



The conditions in Figures 6-13 and 6-14 are the same as Figures 6-6 and 6-7, except that there is environmental change. Again the surface is flatter and less smooth as the firms experience more difficulty in the changing environment. While the maximum occurs at about the same level of invention, performance is now not nearly as sensitive to its value.

Figure 6-13: Propensity to Invent (left view)

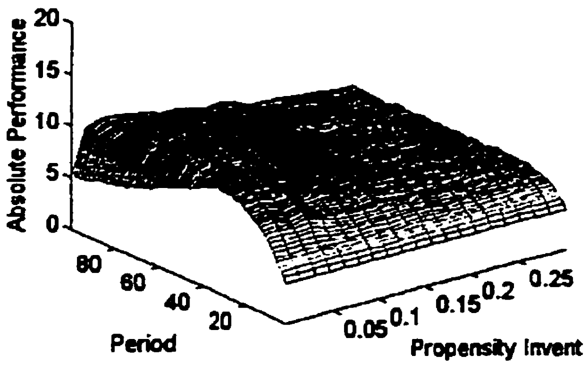
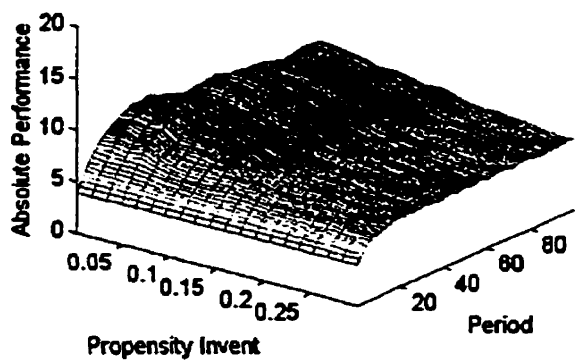


Figure 6-14: Propensity to Invent (right view)



Implications

1. *Invention is vital for coping with environmental change because it maintains diversity.*

We saw in the previous results set that invention increased performance in the long run because it delayed convergence. The real value of invention, however, is in dealing with environmental change. Imitation can only work by re-combining elements that currently exist. In a static environment this may be satisfactory. But if the environment changes, there may be a need for a capability that has never existed in the past. This is when invention becomes vital. As was pointed out in §2.2, being the best adapted fish in your pond is not much use if the pond dries up.

2. *Environmental change decreases the absolute performance that can be expected.*

This is in some sense the most obvious finding of the results. However, it is worth examining its implications. In the real world (but not in the program), technological change acts to change market demand (technology push). As a result, firms are constantly adapting to a changing environment that is of their own making – i.e. technological change is autocatalytic.

This finding, then, provides another possible explanation for the 'productivity paradox', discussed in §4.2. The paradox questions why, if technology is meant to increase productivity, that economic productivity has been improving at a decreasing rate? The answer may be that, in the quest for increased productivity, technology has changed the environment at a rate that negatively impacts performance.

3. *Under conditions of rapid environmental change, management decisions matter less, and luck plays a larger role in success.*

A previous finding has indicated that management intelligence is not a necessary condition for improvements in industry performance. However, whatever benefit management intelligence has, its impact must be less when the future is less certain. In §2.3, Alchian argues that, under conditions of irreducible uncertainty, the quality of managers is irrelevant in explaining firm performance. A lesson from natural history, discussed in §2.2, is that survival does not imply superiority. Managers who survive are not necessarily better in any general sense, just lucky to be better suited to the environmental requirements of the moment.

This result is supported by Nelson and Winter (1982) who found that history and luck matter.

6.3 Results Set 3: The Dynamics of Technological Change

Findings

The previous two sets of results have presented runs that are averaged over 20 iterations in order to smooth the variations of individual runs produced by the stochastic nature of the model. While this helps to show tendencies in behaviour, it hides some of the interesting dynamics. It is often these dynamics which are the source of concern about technological change in the real world.

Figure 6-15 shows a single iteration of run 'A' in Figure 6-8 with environmental change and no invention. The range of performance values in the initial periods indicates the diversity which exists in the population of firms. The performance of individual firms varies considerably but is bounded. The performance of the industry as a whole improves. However, in the middle periods, the diversity within the population can be seen to decrease and the performance of the firms becomes less variable. Finally, the firms converge and their performance becomes identical. At this point, the performance of the industry begins to decrease.

Figure 6-15: No Invention

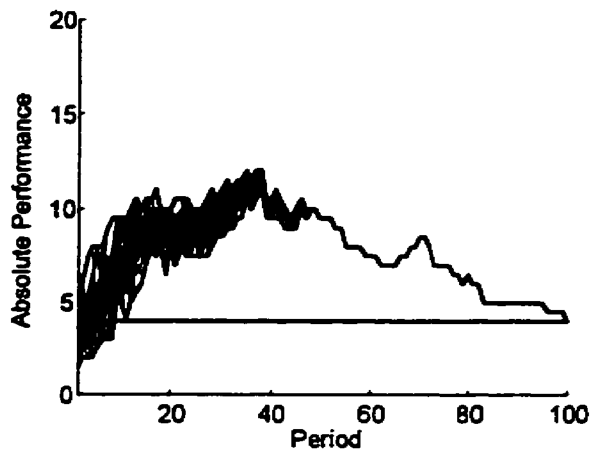


Figure 6-16: With Invention

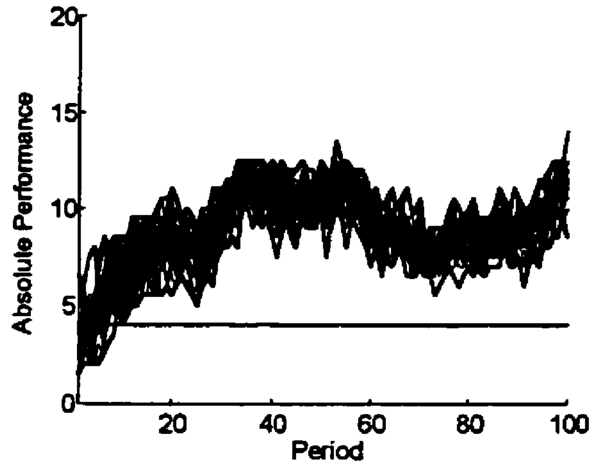


Figure 6-16 shows a single iteration of run 'B' in Figure 6-9 with environmental change and invention. The initial level of diversity is maintained throughout the simulation and as a result performance does not permanently decrease.

Figure 6-17: Variation in Diversity

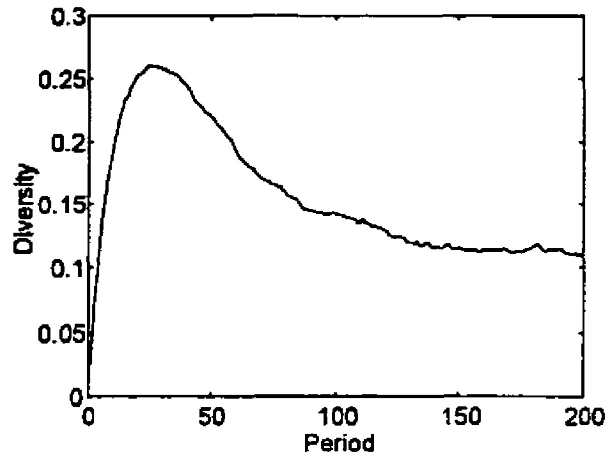


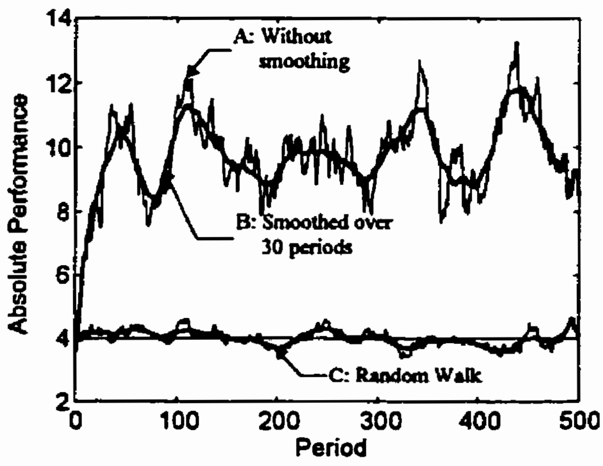
Figure 6-17 shows how diversity in the population reacts to a sudden environmental change. Diversity is measured using the Herfindahl concentration index that is the sum of the squares of the proportion of each technique[13]. Initially, the population is homogenous in its techniques. This can be thought of as a population that has achieved equilibrium with its environment. At the start of the simulation, the environment suddenly changes, but then remains static. In response, the diversity of the population rapidly increases through invention. As successful techniques for the new environment are discovered, the diversity of the population slowly decreases. Figure 6-17 shows the average of 100 iterations to smooth the variations of individual runs produced by the stochastic nature of the model. This

[13] The Herfindahl concentration index is defined as $H=\Sigma f_i^2$, where f_i is the proportion of the ith technique in the population. It ranges from $1/n$, for n equally common techniques, to 1, for complete convergence (Silverberg and Verspagen 1994). The number plotted here is 1-H to measure diversity rather than concentration.

effect replicates the findings from the study of both biology and technological change. It was obtained without any special manipulation of the model and appears to be an emergent behaviour of systems using imitation and invention.

Notice in Figure 6-16 that there are obvious performance cycles at many time scales. The performance of individual firms varies considerably and at high frequency. Industry performance displays small, short cycles. This could easily be attributed to the stochastic nature of the model. However, the larger, longer cycles are more difficult to dismiss.

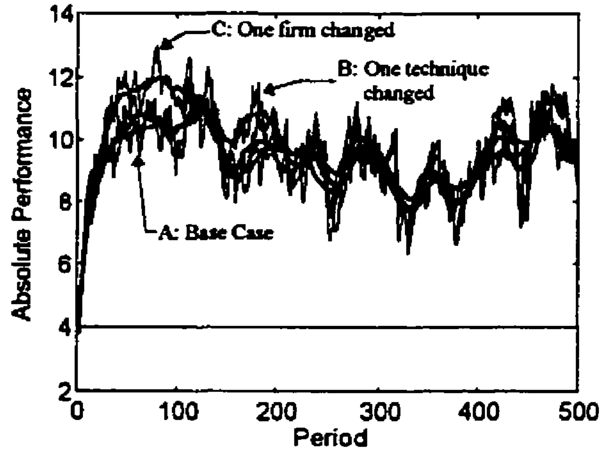
Figure 6-18: Business Cycles



To investigate this effect further, the number of periods in the run of Figure 6-16 was extended by a factor of five. The result is shown in Figure 6-18. Line 'A' is the average performance of the industry in each period. It shows both short and long-term cycles. To bring out the long-term cycles, the results were smoothed using a 30 period moving average in line 'B'. It shows significant cyclical behaviour.

Is this cyclical behaviour the result of a simple random walk? Line 'C' in Figure 6-18 shows a random walk obtained by 'turning off' imitation. The remaining invention is purely random. As can be seen, the cyclical behaviour of the random walk is not nearly as pronounced. There is no question that a random walk underlies the cyclical behaviour of lines 'A' and 'B', but the imitation accentuates the effect by increasing the time scale of the walk.

Figure 6-19: Evidence of Chaotic Behaviour



The self-similarity of the cyclical behaviour at different time scales has been previously mentioned. Is the behaviour chaotic in the mathematical sense? Chaotic behaviour is difficult to prove, however the primary indicator is sensitivity to initial conditions (Lorenz 1993). Figure 6-19 shows three runs. Take line 'A' as the base case. Line 'B' has exactly the same initial conditions, except a single technique for a single firm has been changed by one unit. This is the smallest possible change that can be made to the model. This small change has produced a completely different trajectory in the path of the run. Line 'C' is also has the same initial conditions as line 'A', except that now all of the techniques for a single firm have been changed by one unit. Line 'C' also follows a different path. With different initial conditions, the line 'B' case may not diverge from the line 'A' case. This is not surprising given the discreet nature of the model; for example, the single technique difference may be quickly erased by an imitation and therefore not persist and influence future behaviour. However, in all cases of initial conditions investigated, line 'C' diverges from line 'A'. The evidence is that the system is chaotic.

Implications

1. *Diversity implies variation in performance among firms over time.*

   This is another obvious finding with subtle implications. There is a natural desire on the part of governments to pick winners. The selection of success is, after all, a necessary condition for evolutionary improvement. However, variation in performance implies diversity of approaches. And it is this diversity which fuels the economy and permits it to adapt to change. Therefore, from a social welfare viewpoint, unsuccessful, but innovative, firms may, in the long run, benefit the economy. This result is supported by Chiaromonte et al. (1993) who find that behavioural heterogeneity is important for progress. What turn out to be 'mistakes' for individual agents might also represent positive externalities for the system as a whole.

2. *Sudden environmental change results in a rapid increase in diversity, followed by gradual consolidation. This is an emergent phenomenon.*

This is an exciting result from the program. The variation of population diversity in response to environmental change has been of particular interest to both biologists and sociologists. As noted in §2.2, in both biology and technology, when equilibrium is disrupted (punctuated equilibrium, as discussed in §2.2) there has been found to be a rapid increase in diversity followed by longer periods of consolidation. This is in contrast to the traditional, and perhaps intuitive, view that diversity should increase gradually and consistently. That this phenomenon should emerge from the simple model used here indicates how common and pervasive the effect is. The effect seems to result from the interaction of inventive and imitative behaviour. This result is supported by Silverberg and Verspagen (1994) who find that short periods of high variance are interspersed between relatively long periods of uniformity.

3. *Cyclical performance in industries is an emergent and pervasive phenomenon that results from imitative behaviour.*

This is also an exciting result. The cyclical behaviour of the economy has long been recognised. However, the underlying reasons for the cycles have been poorly understood. This result indicates that cyclical performance comes, fundamentally, from imitative behaviour in a changing environment. As discussed in §2.3, such cycles were of particular interest to Schumpeter who felt that cycles were caused by technological change and 'creative destruction'. This result is supported by Englmann (1994) who finds cyclical behaviour for profit, labour, productivity, and employment.

4. *Industries display chaotic behaviour in that their performance paths are i) self similar at different scales, ii) bounded, iii) sensitive to initial conditions, and iv) not predictable.*

It is known that the economy displays chaotic characteristics. This is perhaps not surprising, given its complexity and extensive feedback mechanisms. However, it is interesting that the program should display chaotic behaviour, given its simplicity. This finding indicates that chaotic behaviour is to be expected from any system that operates in an evolutionary manner. This result is supported by Chiarmonte et al. (1993) who find that the *form* of micordiversity affects macro dynamics, even for unchanged mean values.

The finding that technological change produces chaotic behaviour in economic systems further strengthens the argument that technological futures are impossible to predict and that, therefore, the influence of management in preparing for those futures must be limited.

6.4 Results Set 4: The Division of Explorative Effort

Findings

The previous results sets use populations of firms which are identical in their propensities. Since division of labour was one of Adam Smith's primary mechanisms explaining economic progress, it makes sense to examine how the division of explorative effort among the firms in an industry would impact performance. This was done by preventing all but one firm in an industry from inventing. The one special firm had a high rate of invention, and physically was placed in the middle of the population. The firms had normal rates of imitation and the rate of environmental change was normal. To accentuate the geographical impact of this situation, the distance away that a firm looks for firms to imitate was reduced. In previous results sets, firms looked to all firms in the population equally. Also, the technique choices of the population were initially homogenous, in contrast to previous sets where the initial technique choices were diverse. This situation is analogous to an industry with a low rate of internal invention that relies on a public research institute for new technology.

First, examine Figures 6-20 and 6-21, which are the front and rear views of the same performance surface. This run is the average of 100 iterations, significantly more than the 20 of previous sets, in order to smooth transient dynamics. Also, the scale of the performance axis has been increased in order to magnify the effects.

Figure 6-20: Division of Effort (front view)

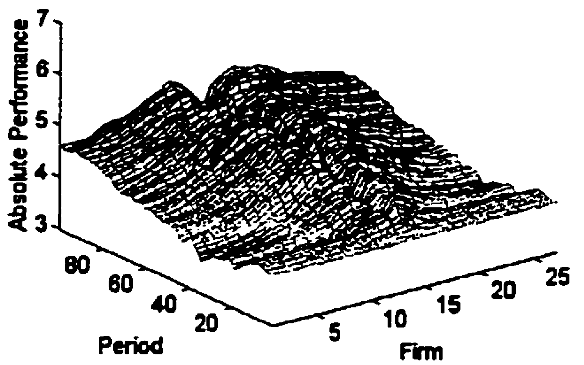
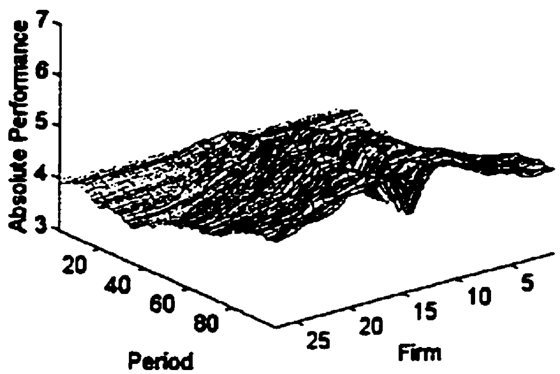


Figure 6-21: Division of Effort (rear view)



Initially, the firms are homogeneous, and so the front edge of the surface is level. The inventing organization is in the middle, and it is in this region where performance is the first to increase. Meanwhile, at the edges performance of firms decreases, since they have no diversity with which to respond to environmental change. Over time, the inventions are diffused from the middle to the edges. As this happens, the performance of firms further from the middle begins to increase. The maximum increase is seen near, but not next to, the inventing organization. The inventing organization displays relatively poor performance.

Relative performance is an important metric, since this is primarily how organizations are evaluated in the real world. Figures 6-22 and 6-23 introduce a relative performance view. Relative performance is measured as the difference between the firm's absolute performance and the mean for the industry during the period. This view dramatically accentuates the differences among the firms. The poor performance of the inventing organization and the distant firms can be seen clearly.

Figure 6-22: Relative Performance (front view)

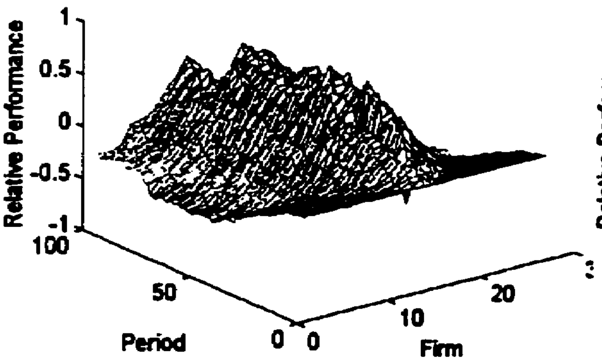
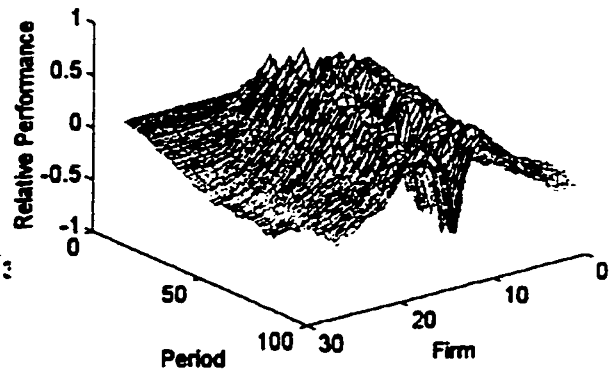


Figure 6-23: Relative Performance (rear view)



The development of the different performance levels among the firms can been seen by comparing Figures 6-24 and 6-25. The first figure is from a very early period. The inventing organization is the middle row. It and its neighbours are the first to display diversity. Much later, as shown in the second figure, the diversity has spread outwards. However, even then the diversity remains higher near the inventing organization.

Figure 6-24: Period 5

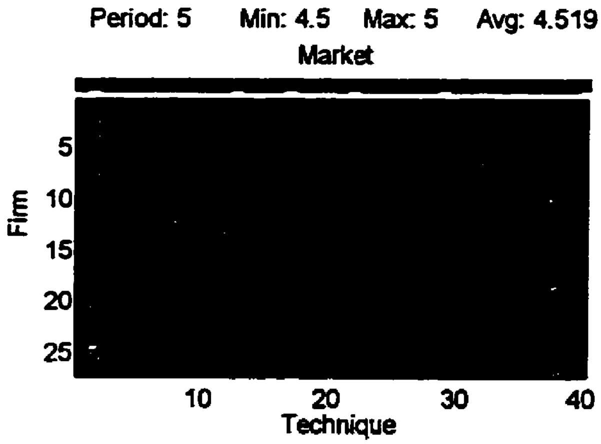
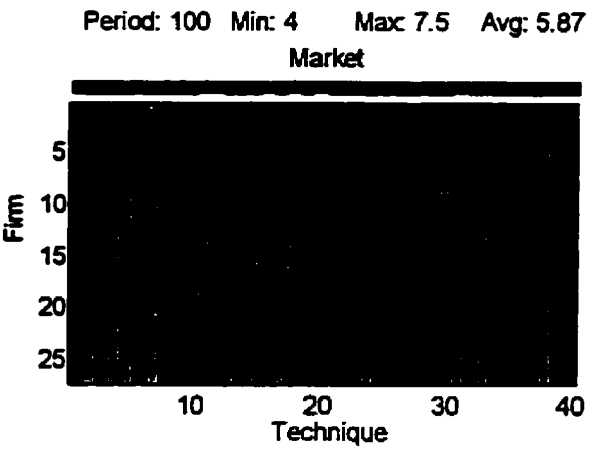


Figure 6-25: Period 100



As a side note, an interesting and unexpected effect can be seen at the edges of the population during the early periods of Figures 6-20 and 6-21. Remember that this run represents 100 iterations to smooth transient effects resulting from the stochastic nature of the model. In spite of this, cyclical patterns can clearly be seen among the firms that have not yet been affected by the invention. The interaction of the imitating behaviour of the firms and the changing nature of the environment cause these patterns.

Implications

1. *There can be variations of inventive effort in an industry, as long as the results are widely disseminated.*

There have been a variety of opinions about who should perform research (invent) in the economy. At various times in history small firms, large firms, universities, public laboratories, and private laboratories have driven research. Also in question is whether research should be centralized in purpose driven establishments, or distributed among the users of the results.

While these results do not directly answer these questions, they do provide some guidance. The simulations show that, with adequate dissemination, it is not necessary that all organizations in an industry invent. However, dissemination requires an absorptive capacity (discussed in §4.2) and this implies some degree of research capability. The points below consider the organization of research within an industry and how the results are disseminated.

2. *Highly inventive organizations, while providing a valuable social function, are likely to under-perform firms with lower rates of invention. This justifies the role of publicly funded research organizations.*

Not surprisingly, high rates of invention can reduce the performance of a firm. This is because invention, by its very nature, is rarely productive and detracts from short-term exploitation. However, invention is important to long-run survival in a changing environment.

This result is supported by Nelson and Winter (1982) who find that, in general, innovative R&D was not profitable. Anderson (1996) finds that inventive firms perform best when imitation is difficult (appropriability is high). Chiaromonte et al. 1993) find that innovators may sometimes be 'lambs' whose 'sacrifice' produces a learning externality for the whole system.

How then, can exploration and exploitation be balanced? One approach is for all organizations to do some invention. An alternative is for the majority to subsidize the low performance caused by invention of few organizations. This is traditionally done by the use of tax dollars in public, or publicly funded, research organizations. The justification for public intervention has been discussed in §4.2. More recently, private consortia have developed for the purpose of pre-competitive research.

3. *Firms at a 'distance' from the inventing source will under-perform firms closer to the source. Distance implies ability to assimilate inventions. Physical distance is only one contributor to this ability.*

The simulations demonstrate that the concept of 'distance' is an important element in the dissemination of research. As discussed in §4.2, distance implies more than geographical proximity and includes many aspects governing the ability to communicate. This result is supported by Nelson and Winter (1982) who find that imitation is costly and takes time, leading to a gap between average and best practice.

From a public policy point of view, dissemination of innovations is a benefit to industry and the economy. An important role of government is therefore the provision of an infrastructure that promotes diffusion. Of course, from the perspective of an individual firm dissemination can reduce the portion of the proceeds from their explorations that they can appropriate. Once again, balance is important – this time between short-term individual interests and long-term common interests.

6.5 Results Set 5: Entry and Exit

Findings

This set of runs introduces the concept of entry and exit for products. First, however, it is important to describe how entry and exit has existed in a very real sense in the model runs up to this point. While the number of 'place holders' for firms in the simulations does not change from period to period, the definition of those firms changes through imitation and invention of techniques. Thus, sets of techniques can be viewed as undergoing entry and exit. New techniques enter through invention, and if successful, diffuse to other firms through imitation. Old techniques exit, if unsuccessful, as they are superseded by more successful entry techniques. Since a firm is defined by its techniques, firms are changing, and in effect entering and exiting, every period.

What differs in this section is a firm's decision to contest a product. Up to now, all firms contested all products. Now, firms will be allowed to enter and exit products as the economics of the current period suggest is appropriate. To do this, we must introduce some additional parameters which allocate costs and revenues. The most important of these is market size which represents the total resources available for distribution to competing firms. Firms will receive these resources in proportion to their relative performance. Poorly performing firms (in terms of resources) may decide to exit from a product. Firms which see an opportunity to earn a share of available resources may enter into a product. (Appendix D describes the details of these calculations).

Figure 6-26: Large Market

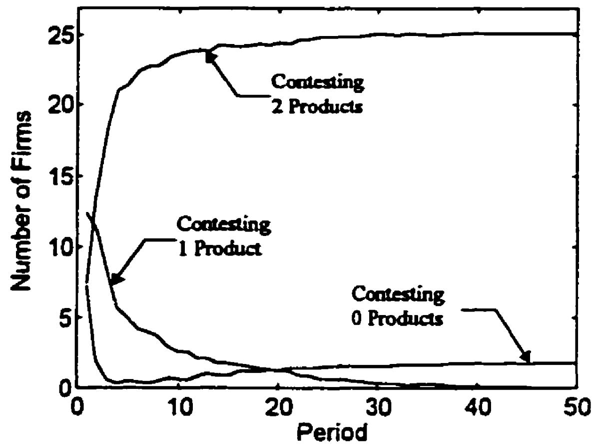


Figure 6-26 shows the number of firms contesting products over time in a two product market. The results have been averaged over 20 iterations. Initially, firms have a 50% probability of contesting each product. If there were sufficient resources in the market to support all of the firms, they would all move directly to contesting two products. However, in the run of Figure 6-26 there are not quite enough resources available to support all of the firms. Some firms are successful and move to contesting two products. The unsuccessful firms exit from both products.

Note that contesting a single product is unstable in the long-term. This makes sense. In these runs, the firms and products are homogeneous. Therefore, there is no particular reason that one firm would be more likely to achieve success in either product, compared to any other firm. But there are benefits to contesting two products, since a diversified portfolio allows the firm to weather temporary setbacks in either product. Therefore, contesting two products is more stable than one.

Figure 6-27 shows what happens as the market resources available to the firms are reduced. Not surprisingly, the market now supports fewer firms. Figure 6-28 carries this to the extreme, where only a couple of firms can survive in a very small market. Figure 6-29 summarizes the relationship between the number of firms contesting products and market size.

Figure 6-27: Medium Market

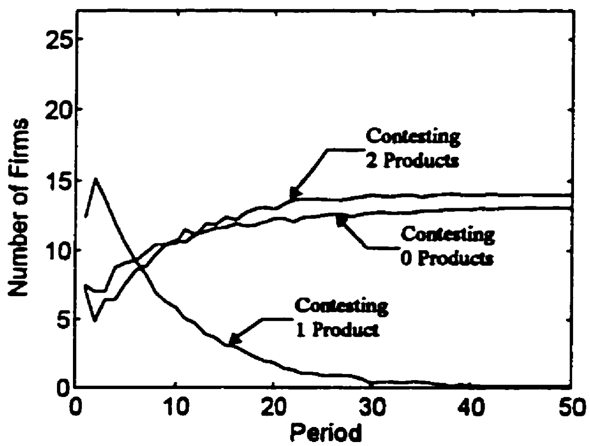


Figure 6-28: Small Market

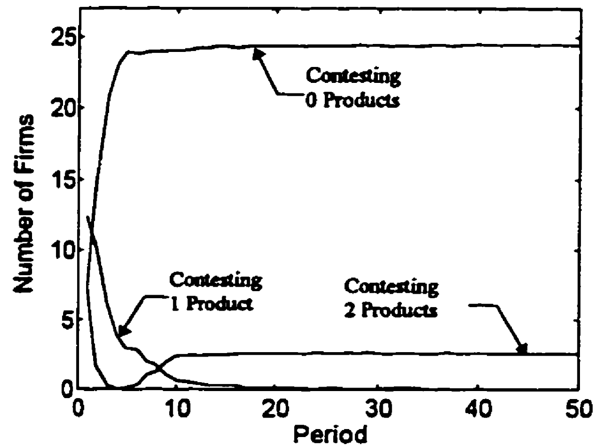
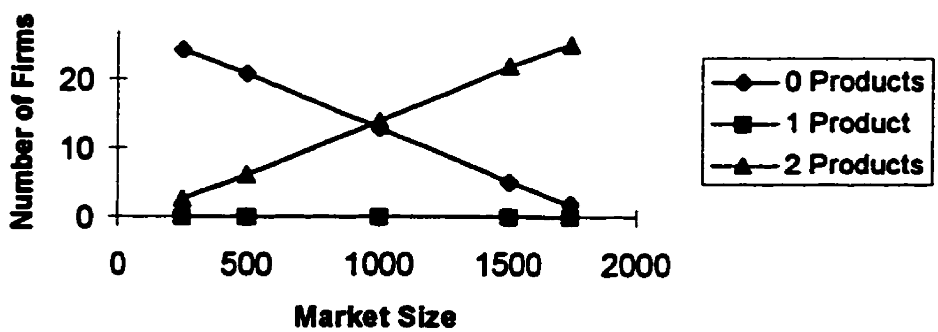


Figure 6-29: Effect of Market Size



Implications

1. *Contesting a portfolio of products is a more stable strategy than relying on a limited number of products.*

The simulations support the perception, discussed in §4.2, that portfolio diversification is a sensible strategy to maximize the probability of long-term survival. Under the conditions of these simulations, the stability is sufficient to exclude firms from entering the market again after exiting completely. This supports the idea of the dominance of incumbent firms discussed in §4.2. This result is supported by Nelson and Winter (1982) who find that success breeds success leading to industry concentration. Also, Silverberg and Verspagen (1994) find that incumbents persist with occasional displacement.

6.6 Limitations and Future Work

In the most limited sense, the results presented in this chapter do nothing more than demonstrate how the methods of genetic algorithms manipulate numbers. Interest in the results from the perspective of technological innovation depends critically on the analogy between the real world and its representation in the artificial world of the computer program. The limitations associated with this approach have been discussed previously in

§3.1, §5.6 and §5.8. As for any model, the acceptance of this model requires a 'leap of faith' based on the reasonableness of the model given experiences in the real world. Hopefully, the strength of the analogy in this model will increase as the findings of other investigators confirm those presented here.

The results presented in this thesis have not begun to exhaust the research potential of the Bizlife computer program. Within the confines of its current capabilities, the effects of a number of parameters have been chosen for investigation. Other parameters, and the questions they address, that have not yet been examined include:

- Industry size.

  The effect of number of firms on innovative behaviour, industry concentration, and the diffusion of new ideas.

- Number of products.

  The effect of product portfolio size on innovative behaviour, industry concentration, and niche market strategies.

- Number of technique choices.

  The effect of environmental complexity on innovative behaviour and a firm's ability to compete.

- Number of techniques per product.

  The effect of environmental complexity on innovative behaviour and a firm's ability to compete.

- Entry, contesting, imitation, and invention costs.

  The effect of relative costs on innovative behaviour and a firm's ability to survive.

- Conditions controlling entry and exit.

  The dynamics of entry and exit from products in response to changes in the environment, and niche market strategies.

In addition, further research questions could be addressed by increasing the capabilities of the program. Immediate plans for augmentation of the program include investigation of:

- *Evolutionary markets* – making market demand endogenous to the program by having a population of consumers who operate in a manner similar to firms in the current model. This will allow technology push to be examined.

- *Adaptive strategic behaviour* - the response of firms to environmental change when their strategies for imitation and invention are allowed to vary.

- *Risk* - the relationship between variance and magnitude of returns for different imitative and inventive strategies.

- *Niche markets* - the possibility of increasing survival probabilities by occupying specific niches in the market and utilizing specific strategies.

- Number of techniques per product.

  The effect of environmental complexity on innovative behaviour and a firm's ability to compete.

- Entry, contesting, imitation, and invention costs.

  The effect of relative costs on innovative behaviour and a firm's ability to survive.

- Conditions controlling entry and exit.

  The dynamics of entry and exit from products in response to changes in the environment, and niche market strategies.

In addition, further research questions could be addressed by increasing the capabilities of the program. Immediate plans for augmentation of the program include investigation of:

- *Evolutionary markets* – making market demand endogenous to the program by having a population of consumers who operate in a manner similar to firms in the current model. This will allow technology push to be examined.

- *Adaptive strategic behaviour* - the response of firms to environmental change when their strategies for imitation and invention are allowed to vary.

- *Risk* - the relationship between variance and magnitude of returns for different imitative and inventive strategies.

- *Niche markets* - the possibility of increasing survival probabilities by occupying specific niches in the market and utilizing specific strategies.

7. Discussion

This thesis has been a journey in search of discovery and understanding. It began by noting the similarities between the evolution of economic and biological systems. These similarities provided a new perspective from which to view the process of technological change and its effect on economic and business decisions. Using this perspective, a new model of the process of technological change was developed which captures its essential characteristics: the balance between exploration and exploitation, the role of invention in creating new techniques for trial, the role of imitation in diffusing and combining successful techniques, and the market as a mechanism for deciding between successful and unsuccessful techniques. The evolutionary point of view stresses the stochastic, dynamic and path dependent nature of technological change, and these characteristics require that computer simulation be used for the analysis of the model. A computer program was created for this purpose. The computer program was used in wide ranging investigations which examined the behaviour of the model and revealed some interesting implications of the evolutionary point of view.

This thesis has followed a number of themes from their biological origins, through their economic analogies, to their simulations using the computer program. The results have implications not only for our understanding of technological change, but also for our understanding of economic processes, and the relationship between complexity and simplicity. Some of these themes are:

- Macro-level effects can be simple in spite of the complexity of micro-level processes.
- Macro-level effects can be complex in spite of the simplicity of micro-level processes.
- Evolutionary processes balance exploitation and exploration.
- Evolutionary processes balance creation of diversity and consolidation.
- Evolutionary processes are discontinuous and chaotic.
- Evolutionary processes can operate without intelligence, rationality or motivation.

In examining these themes, this thesis has made three contributions:

1. *The introduction of a model which aids in the description and understanding of the process of technological change from and evolutionary point of view.*

The model of the process of technological change developed here has helped in categorizing participants, defining the characteristics of an innovation system, and describing the interactions within the system. While the model is not strictly evolutionary in design, the implementation of the model in the computer program is. Certainly, the structure of the model is due both to its evolutionary inspirations and the requirements of the computer program. There are no similar models that would have served this purpose adequately.

2. *The creation of a computer program which simulates the process of technological change in a simple artificial economy.*

There have been few computer programs which model technological change using an evolutionary approach. The program developed by Nelson and Winter (1982), which was described in §3.2, is certainly an inspiration for the program developed here. Conceptually, there are many similarities between the two works. However, the Nelson and Winter program differs in some important respects. Most significantly, the Nelson and Winter program employs extensive and complicated rules of behaviour for its agents. Also, their program is more neoclassical in nature, assuming, for example, that there are two factors of production, that markets clear, and that prices are in equilibrium in each period. The same can be said of other programs based on the Nelson and Winter approach, such as the works by Andersen (1994), Silverberg and Verspagen (1994), Englmann (1994), and Chiaromente et al. (1993). In contrast, the philosophy of this program has been to use evolutionary techniques to model evolutionary processes.

In the Artificial Adaptive Agent tradition, there have been a few programs based on cellular automata (Arthur 1991, Bhargava and Mukherjee 1994). However, there have been no published models based on genetic algorithms.

3. *The presentation of results from the simulations which illustrate how evolutionary economic systems operate and help in understanding the process of technological change.*

Of course, the results from the computer simulations of the artificial world in Chapter 6 are illustrative of the process of technological change in the real world only to the extent to which the analogies between the two worlds are accepted. However, given that these analogies hold, the implications of the simulations are:

- Industries are able to improve performance even without profit maximizing behaviour by management.

- Management is less able to influence firm performance under conditions of rapid environmental change.

- Invention within industries is important to avoid stagnation and ensure continued adaptation to environmental change.

- Cyclical performance in industries is an emergent and pervasive phenomenon that results from imitative behaviour.

- The natural reaction of an evolutionary system to sudden environmental change is a rapid increase in diversity, followed by a longer period of consolidation.

- Highly inventive organizations, while providing a valuable social function, are unlikely to perform as well as firms with lower rates of invention.

- Contesting a portfolio of products is a more stable strategy than relying on a limited number of products.

As was argued at the outset of this thesis, the evolutionary point of view requires a paradigm shift. Once that shift has been accomplished, all management decisions can be seen in a new light. It is hoped that the simulations of the previous chapter and the discussions of this chapter have helped the reader to appreciate the evolutionary perspective.

The following sections discuss how the findings from the computer simulations could be applied to real-world management decisions in the private and public sectors. These discussions are at best an introduction to an evolutionary interpretation of business. All interpretations are personal, and the discussions here are presented to provoke thought and reaction. Others will certainly have their own interpretations.

7.1 The Importance of Exploration in Evolutionary Processes

The preceding chapter has illustrated the importance of exploration in a changing environment. This will not be surprising to anyone involved in technologically intensive sectors of the economy, and there are few sectors left which are not being buffeted by technological change.

It is clear that competitiveness requires exploration. This is true at both the levels of the firm and the nation. Not always clear, however, is the appropriate balance between exploration and exploitation. The simulations show, not surprisingly, that there can be too much exploration, as well as too little. The simulations also indicate that the rate of environmental change is a determinant of explorative effort; higher environmental change calls for more exploration. Unfortunately, the model cannot be calibrated to specify actual investments for real-world organizations.

In the model of technological change presented in this thesis, exploration is separated into inventive and imitative components. While invention is commonly accepted as an exercise in exploration, the explorative aspects of imitation are not often realized. However, in an evolutionary process, imperfect imitation is actually the most important component of exploration. This has very important implications for real-world organizations. All parts of an organization should continuously scan for new and better ideas. Benchmarking is one way of achieving this. Imitation is particularly important for the R&D sections of organizations. It bears repeating that one of the most important purposes of the R&D department is to act as a capable receptor for ideas from outside.

In spite of the dominance of imitation as an explorative activity, the simulations also illustrate the importance of invention. Without invention, industries can stagnate. From a competitive standpoint, this may be acceptable as long as the status quo is maintained. However, if one firm is able to break out of the mould, they may be able to obtain a temporary advantage. In a rapidly changing environment, temporary advantages may be all that are ever available. If first-mover advantages are not critical, the simulations show that all firms can benefit from the inventive activities of a few.

The simulations show the difficulty in appropriating the benefits of inventive effort. In fact, highly inventive firms are likely to be at a competitive disadvantage. However, the simulations also show that the overall performance of an industry (and therefore the social good) is improved by inventive effort. The problem of appropriation for the individual firm, coupled with the potential industry-wide and social welfare benefits of inventive activity, suggest that it may be attractive to perform inventive activity in cooperation with others. Since the benefits of an invention are likely to be appropriated by others, the costs and risks might as well be spread also. There are a number of ways of achieving this. The traditional means is to tax firms, and use the proceeds to fund public sector research organizations and universities. Firms can also contract-out research to private, semi-private, and public research institutions[14]. This serves to spread the capital costs, if not the marginal costs and risk, of research. A more recent approach is the formation of research consortia[15] where firms contribute funds for pre-competitive research. These

[14] In Canada, private research institutions are few. Semi-private research institutions consist of recently privatized organizations such as BCRI and ORTECH which receive some public funding. Public research institutions such as the National Research Council (NRC), the Alberta Research Council (ARC), government laboratories, and many universities are increasingly doing research on a cost recovery basis.

[15] In Canada, examples of such research consortia include the National Centres of Excellence (robotics and intelligent systems, innovative structures, tele-learning, forest management, microelectronics, telecommunications, and a variety of health and biotechnology topics), the Ontario Centres of

approaches trade off wide applicability and investigative freedom on the one hand, and targeted relevancy and control on the other.

7.2 The Concept of 'Efficiency' in Evolutionary Processes

In the current fiscal climate of 'doing more with less', the efficiency of both public and private operations has come under close scrutiny. A large part of the solution has been seen to be the elimination of duplication. How does this attitude mesh with the 'efficiency' of evolutionary processes?

Evolutionary processes are inherently wasteful for two reasons. First, there is duplication as multiple agents compete with each other to find better solutions to the problems imposed by the environment. Second, many of these agents do not survive and the result of much of the effort that they have expended is then lost from the system. It might seem that by coordinating the actions of all agents, efficiencies should be easily obtained. Coordination is indeed an option in situations where the future can be predicted - either because it will be similar to the past (static environments), or because the coordinator has perfect information and unbounded computational capabilities to predict the future.

Excellence (manufacturing and materials sciences, information technologies, telecommunications, space sciences, ground water, laser technologies), Paprican (pulp and paper), and Forintek (forestry).

Of course, in the real world, neither of these conditions exists and coordination has frequently been found wanting compared to evolutionary alternatives. The best evidence of this is the success of free-market economies (which are evolutionary) over communist economies (which are coordinated). Other evidence includes the benefits that have come from the de-regulation of public monopolies, and the trend towards internal competition among business units of companies. Still, coordination obviously predominates within organizations and in some parts of the public sector. Why are duplicative inefficiencies preferred in some situations, but not in others?

The answer comes from understanding how evolution utilizes duplication and when it is necessary. An evolutionary approach does not imply that duplication *per se* is beneficial; it is competition for limited resources which drives evolution, and no strategy which wastes resources will be successful in the long-run. When evaluating the value of duplication, the following points should be kept in mind:

- Duplication is used by evolution to explore many points in the search space in parallel. This strategy has been shown to be optimal in large, noisy, search spaces (Goldberg 1989); it is not appropriate in other situations.

- Duplication is only beneficial in exploration. Most of what an organization or economy does is not explorative, and duplication in these other activities is <u>not</u> beneficial.

- Duplication refers to the number of simultaneous attempts to reach similar goals, not the paths that are taken. Exploration along a particular path should still be done as efficiently as possible.

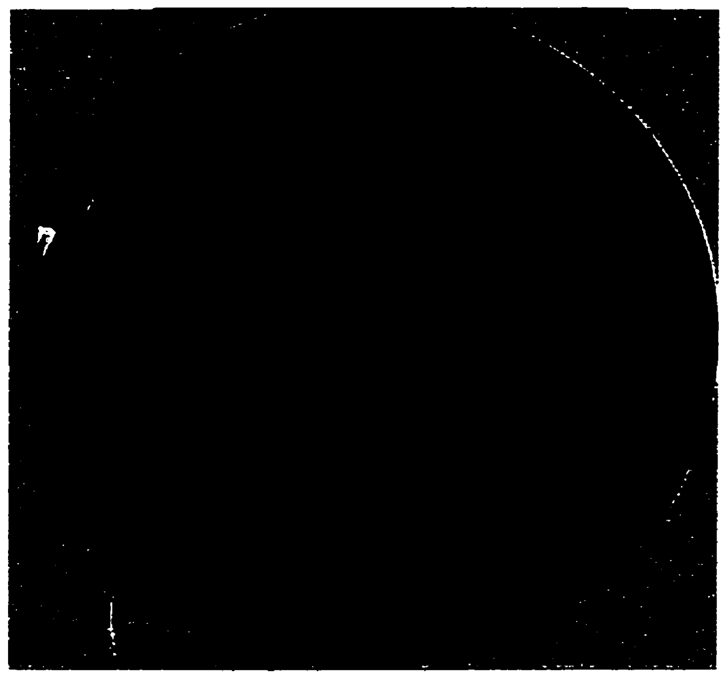
- Duplication serves no purpose if it is exact. 'Cloning' of explorative approaches has no benefit; it is diversity in the approaches which produces the power of evolutionary search.

- As has been shown in the previous chapter, and by experience in the real world, diversity should be initially high in order to explore a large portion of the search space, and then diversity should decrease as 'good' solutions are discovered.

While evolutionary exploration may be shown to be efficient in a global sense, there is no question that the process creates hardships for individual agents. Diversity implies variation in performance, and ultimately there must be many failures for every success. There is a desire in society to ease the transitions for the 'losers'. This will be beneficial if the resources and experience from unsuccessful explorations can be saved for future efforts. However, it must be remembered that in an evolutionary world poor performance cannot be condoned, and good performance must be rewarded. Attempts to 'save' poor performers will only serve to inhibit the evolutionary process.

Appendix A: The BZ Reaction

Figure A-1: The BZ Reaction



One variation of the Belousov-Zabotinski reaction is produce in a mixture of sodium bromate, sulfuric acid, sodium bromide, malonic acid, and a phenanthroline redox indicator. The mixture is initially a uniform reddish colour. In a few minutes, patches of blue will form and these will develop into concentric rings of red and blue. The rings grow and join intc surprisingly intricate patterns. There is a spontaneous formation of temporal and spatial order, from random beginnings. (Cohen and Stewart 1994).

Boris Pavlovich Belousov (1893-1970) was a chemist and head of the biophysics laboratory in the USSR Ministry of Health when he discovered the oscillatory reaction.

Although there had been scattered evidence of oscillatory chemical reactions since 1921, chemists remained sceptical of such claims. His initial submission for publication in 1951 was rejected with the request that he produce additional evidence. He worked for another six years and submitted a revised manuscript to another journal, but that editor insisted that the paper be shortened to a letter. Belousov decided to give up on publishing his work and had no further involvement in the reaction's study.

In 1961, Anatol Zhabotinski, a graduate student in biophysics at the Moscow State University, became aware of Belousov's work and began looking at similar systems. The reaction came to the attention of the Western world at a 1968 conference on Biological and Biochemical Oscillators in Prague where Zhabotinski presented some of his results. The biology community was more receptive to these ideas than the chemistry community since they were accustomed to working with self-organizing systems. The publication of the proceedings in English brought the BZ reaction to the attention of Western chemists.

Before, and even during, the development of the BZ reaction, a number of papers were being written in the West on why true homogeneous oscillating reactions were impossible based on erroneous application of the 2nd law of thermodynamics. By the late 1970's many chemists were aware of oscillating reactions and agreed that they were genuine and even interesting.

In 1977, Ilya Prigogine was awarded the Nobel Prize in Chemistry for his explanations of nonequilibrium systems. In 1980, the Lenin Prize was awarded to Belousov, Zhabotinski, V.I. Krinsky and G.R. Ivanitsky for their work on the BZ reaction. Belousov had died in 1970. (Tyson 1976).

Appendix B: Glossary

The following definitions are specific to their use in this thesis.

Appropriability	A measure of the benefits from exploiting an innovation that can be captured by the innovator, rather than by imitators or consumers.
Chaos	A dynamic system which is sensitive to initial conditions and small perturbations, and displays discernible patterns in spite of being non-periodic.
Environment	Everything external to the firm. Often used to refer to general market conditions.
Evolution	A process by which a system adapts to its environment. Evolution requires 1) a measure of success, 2) mechanisms for exploration, and 3) selection based on success.
Exploitation	The process by which a firm uses its techniques to acquire additional resources. Exploitation consists of promotion and production.
Exploration	The process by which a firm investigates its environment to find new techniques. Exploration consists of imitation and invention.
Firm	An organization which controls techniques, exploits those techniques to acquire resources, and explores for new techniques.
Genotype	An organism as defined by its blueprint (DNA) in theory (see also phenotype).

Ideas	The medium by which techniques are transmitted among firms, and between firms and the market.
Imitation	One of two idealized forms of exploration (see also invention). Imitation involves copying the techniques of other successful firms.
Industry	A collection of firms that interact with each other to control scarce resources.
Innovation	A generic term for the result of exploration.
Invention	One of two idealized forms of exploration (see also imitation). Invention involves creating new techniques.
Market	The source of resources for a firm. Resources are exchanged for techniques embodied in products.
Phenotype	An organism as it is realized in fact (see also genotype).
Production	One of two idealized components of exploitation (see also promotion). Promotion involves all activities necessary to transform techniques into products.
Products	Specific collections of techniques which can be exchanged for resources in the market.
Promotion	One of two idealized components of exploitation (see also production). Promotion involves all activities necessary to exchange products for resources in the market.
Rationality	The ability to make decisions which are fully informed and without error. Where there is uncertainty about future conditions, the possible outcomes are fully described by probability distributions.
Resources	Things which can be traded or transformed through exploration into techniques. Resources include manpower, equipment, and facilities.

Society	The environment of a firm other than its industry and market. Society includes public sector institutions and the social rules and standards under which a firm operates.
Techniques	Ways of doing things. Techniques include entities, facts, procedures, and skills.
Technologies	Generic collections of techniques that can be combined to create products.

Appendix C: An Introduction to Genetic Algorithms

Chapter 2 discussed the ability of biological systems to explore and exploit extremely complicated search spaces. There are many situations in human endeavour where this capability is needed. In fact, the greatest limitation of traditional search and optimization techniques is that problems often must be reduced to almost trivial simplicity before they can be solved. Genetic Algorithms (GAs) are a class of techniques for optimization which draw their inspiration from the process by which biological organisms improve their adaptation to their environment (Davis 1991, Goldberg 1989, Holland 1992a, 1992b). They have been found to be versatile, robust, and fault tolerant.

GAs have been applied with a great deal of success in a surprisingly wide array of applications for optimization, control, and machine learning. Traditional operations research examples include the travelling salesman problem, graph colouring, the prisoner's dilemma, scheduling, and bin packing. More novel examples include gas pipeline control, communication networks design, medical imaging, gas turbine design, and evolvable computer software and hardware (chips that alter their circuitry to adapt to their environment).

The foundations of the GA approach to optimization were in place thirty years ago. However, it is only in the last ten years that GAs have received widespread attention. In that time, GAs have been applied to an eclectic variety of problems. In the process, much has been learned about the strengths and weaknesses of GAs, and how to make GAs perform better in particular situations.

The use of GAs in this thesis, however, is not as a numerical optimization technique. Here they will be used in the manner of Holland's artificial adaptive agents described previously in Section 3.2. Whether for optimization, machine learning, or the simulation of artificial worlds, though, the mechanics of GA operation are similar. This section provides an introduction to the basics of GAs for optimization.

Genetic Algorithm Fundamentals

As researchers search for ways to improve GAs, many variations on their operations are being tried. This description of GA fundamentals covers what is considered to comprise a 'classic' GA. The mechanics of a simple genetic algorithm are surprisingly simple, consisting of nothing more complex than copying strings and swapping partial strings. There are five basic operations:

Representation: The first operation is to represent the problem as a string of finite length, consisting of a finite alphabet. Typically, the alphabet used is binary and there are theoretical reasons why this is preferable. Representation is the most difficult aspect of using GAs and is somewhat of an art requiring experience and inspiration. Fortunately, it has been found that the performance of GAs is insensitive to the representation choice.

Initialization: The second operation is the creation of a population of strings. Typically, the initial population is created randomly. This is analogous to the 'primal ooze' from which life on earth is thought to have evolved. A random initial population ensures that the entire search space has the potential to be represented. Using heuristics to seed the initial population may speed the convergence of the GA to a local optimum, but not necessarily the global optimum because some portions of the search space may have been excluded from the initial genetic material.

Evaluation: The third operation is the evaluation of the 'fitness' of each string in the population relative to the others. In practice, this means decoding the string representation and determining its performance in the problem domain. This, and the string representation, are the only parts of the GA procedure which are problem specific.

The GA does not require any information about 'why' or 'in what way' one string is better than another; just the outcome from the evaluation procedure.

Selection: The fourth operation is the selection of strings that will survive to the next generation. Survival is probabilistic. A string has a better chance of survival if it had a high relative performance in the evaluation operation. One string may see many of its type survive, while another dies out.

Reproduction: The fifth operation is reproduction that combines the information contained in two strings to create two new strings. This enables the GA to test regions it has not previously sampled. Very occasionally during the reproduction operation, mutation will occur. The mutation operation randomly changes one of the elements in a string. It enables new genetic information to be added to the population.

The last three operations (evaluation, selection, and reproduction) are iterated. Each iteration searches many points in the search space in parallel; many more than the population size. In fact, the number of points searched is of the order of the cube of the population size. Typically, each iteration results in a population with improved characteristics. The process is, however, stochastic, and the performance of the population may remain static or regress for periods.

There is no set rule for stopping the procedure. Without mutation, or something similar, the process will eventually converge so that all strings in the population are identical. The process may be run until convergence, run for a set number of iterations, or run until there is no longer an apparent improvement in the performance of the population. The last option is dangerous because GAs often run for many iterations at one level of performance, and then suddenly improve dramatically.

A Genetic Algorithm Example

The operation of a GA is best illustrated through a simple example. We wish to find a 'good' string of five binary numbers. For the moment we will assume that we can evaluate the fitness of a string, but we do not know the form of the function which is being optimized. We randomly generate a population of four strings, calculate their fitness, and determine how many of each string will survive:

Population		Fitness			Survival
		Value		%	
1.	0 1 1 0 1		169	14.4	1
2.	1 1 0 0 0		576	49.2	2
3.	0 1 0 0 0		064	05.5	0
4.	1 0 0 1 1		361	30.9	1
		Total	**1170**		
		Max	**576**		
		Avg	**293**		

The survival calculation can be thought of in terms of a weighted roulette wheel. The wheel is divided into four segments, each segment's area is proportional to the percentage of each fitness value to the total fitness. The wheel is spun four times and the segment that is chosen each time represents the string that survives. In this case, string 2 is 49.2% of the total and we would expect it to do well; as it does with two of its kind surviving. In contrast, string 3 does poorly at 5.5% of total fitness and none of its kind survive. Since survival is probabilistic, it would have been possible, though unlikely, that, for example, 2 of string 3 could have survived, while none of string 2 survived.

The surviving strings then reproduce. Adjacent strings are mated and a crossover point for each pair is chosen at random. The substring before the crossover point of the first string in the pair is combined with the substring after the crossover point of the second string in the pair to form a new string. Similarly, the substring after the crossover point of the first string in the pair is combined with the substring after the crossover point of the second string in the pair to form another new string. This is repeated with the second pair of strings to form another two new strings:

	Population	After Crossover		Fitness
1.	0 1 1 0:1	0 1 1 0 0		144
2.	1 1 0 0:0	1 1 0 0 1		625
3.	1 1:0 0 0	1 1 0 1 1		729
4.	1 0:0 1 1	1 0 0 0 0		256
			Max	**729**
			Avg	**439**

Notice that the best string and the average of all the strings have both increased compared to the original population above. In a GA this process of evaluation, survival, and reproduction would be continued for many iterations. While the maximum and average fitness of the population may temporarily decrease, they will generally improve; quickly at first and then more slowly.

The problem in this case was optimization of the function $f(x) = x^2$. It is significant the GA did not require any information about the function. There are many problems in the real world, especially in the business world, where outcomes are known, but the function is not. For example, a manager can observe the success of his or her marketing decisions, but knows very little about the process by which the business environment interacts with those decisions to determine his or her fate. In fact, the operation of a GA in finding 'good' solutions is analogous to Simon's description of the 'satisficing' behaviour of managers.

Appendix D: Bizlife Program Description

Program Operation

Operation of the program is as follows:

1. *There is a population of firms.*

   The number of firms in the population is set by the user. Larger populations of firms in the model are analogous to industry size in the real world. Within each population of firms, there are sub-populations of firm types. Firms of the same type share propensities to imitate, invent and contest (see Points 6 and 7 below).

2. *There is a set of techniques that each firm uses in products.*

   The technique set for each product is represented by a string of numbers. Initially, this string is randomly chosen for each firm. The number of techniques (the length of the string) and the number of choices for each technique (the cardinality of the alphabet used to create the string) are set by the user. Together, these two parameters are analogous to the complexity of the environment.

3. *There is an optimal set of techniques determined by the market of an industry.*

The market is represented by a string of numbers of the same length and cardinality as used for the firm technique set. This string represents the market demand set.

4. *Time progresses in discreet periods.*

Evaluations and changes are made in each period. The user defines the length of the simulation. Different time periods can be examined to compare the short and long-run performance of firms.

5. *In each period, the performance of the firm is evaluated.*

The performance of a firm is determined by the number of its techniques that correspond to the market demand. The score that would be expected as a result of random chance is equal to the string length divided by the cardinality.

6. *In each period, a firm may change some of its techniques by imitating other firms.*

The firm knows the performance of other firms in its industry in the last period, but it does not know which techniques are the right ones. The firm is more likely to imitate firms that have performed well. The probability that a firm will imitate is set by the user. Based on this probability, for each technique a firm will decide whether or not to imitate. If it decides to imitate, it will copy the technique of another firm chosen randomly, weighted by performance. This is analogous to such concepts as benchmarking where firms try to learn from the actions of industry leaders.

7. *In each period, a firm may change some of its techniques by invention.*

The probability that a firm will invent is set by the user. Based on this probability, for each technique, a firm will decide whether or not to invent. If it decides to invent, it will randomly change the technique. This is analogous to invention in the real world through processes such as research and development.

8. *In each period, a firm may exit from some products that it is currently contesting.*

Firms are more likely to exit from a product if the firm has a low propensity to contest, has few remaining resources, the product is performing poorly, and the product has poor prospects for profit.

9. *In each period, a firm may enter some products which it is not currently contesting.*

Firms are more likely to enter a product if the firm has a high propensity to contest, has abundant resources, is currently contesting similar products, and if the product has good prospects for profit.

10. *In each period, the resources of the firm are evaluated.*

Resources are augmented by revenue from products, and reduced by the expenses of contesting products, entering products, imitating techniques, and inventing techniques.

11. *In each period, the market may change.*

The probability of market change is defined by the user. Based on this probability, techniques in the market demand are changed randomly.

Program Structure

In this section, user defined parameters and options are signified by a `different font`.

Figure D-1 shows the structure of the Bizlife program. There are six major routines: input, initialization, exploration, exploitation, market change, and output. The exploration, exploitation, and market change routines are iterated for the number of periods in the simulation. The following sections describe each of the program routines.

Figure D-1: Program Structure

- Input
- Initialization
- Exploitation
    - Firm Performance
    - Product Revenue
    - Product Entry
    - Product Exit
- Exploration
    - Imitation
    - Invention
    - Firm Costs
- Market Change
- Output

Input

The following are user-defined parameters. Their use is described in subsequent sections.

- `Random Number Seed` - Integer
- `Number of Periods` - Integer
- `Number of Firms` - Integer
- `Number of Products` - Integer
- `Number of Techniques` - Integer
- `Techniques per product` - Integer
- `Market Size` - Integer
- `Propensity to Contest` - Real
- `Propensity to Imitate` - Real

- Propensity to Invent - Real
- Firm Resources - Integer
- Cost of Entry - Integer
- Cost of Contesting - Integer
- Cost of Imitation - Integer
- Cost of Innovation - Integer
- Probability of Market Technique Change - Real
- Probability of Market Size Change - Real
- Payback Intercept - Integer
- Minimum Payback - Integer
- Reserves Intercept - Integer
- Minimum Reserves - Integer
- Firm Distance Intercept - Integer
- Product Distance Intercept - Integer

The following are user-selected options. Their use is described in subsequent sections.

- Firm Distance - Logical
- Product Distance - Logical
- Products Contested - Logical
- Market Size - Logical
- Market Change - Logical
- Firm Propensities - Logical

Initialization

Random number generator - The random number generator is initialized with the random number seed. Because Bizlife is stochastic in operation, different random number seeds will produce different results.

Market techniques - The vector of market techniques is the `number of products` in length times `techniques per product` and contains randomly generated integers between one and the `number of techniques`.

Market sizes - The vector of market sizes is the `number of products` in length. There are three options for initialization of market demands, set by the `market size option`. With the first choice, all market demands equal the `market demand`. With the second choice, market demands are randomly generated integers between one and the `market demand`. With the third choice, market demands are evenly distributed in increments of `market demand` / `number of products`.

Market technique and demand change probabilities - Both the vector of market technique change probabilities and the vector of market demand change probabilities are the `number of products` in length. There are three options for initialization of market change probabilities, set by the `market change probability option`. With the first choice, all market technique change probabilities equal the `probability of market technique change`, and all market size change probabilities equal the `probability of market size change`. With the second choice, the market technique change probabilities are randomly generated real numbers between zero and the `probability of market technique change`, and market demand change probabilities are randomly generated real numbers between zero and the `probability of market size change`. With the third choice, the market technique change probabilities are evenly distributed in increments of `probability of market technique change` / `number of products`, and the market size change probabilities are evenly distributed in increments of `probability of market size change` / `number of products`.

Firm resources - The vector of firm resources is the `number of firms` in length and each element equals the `firm resources`.

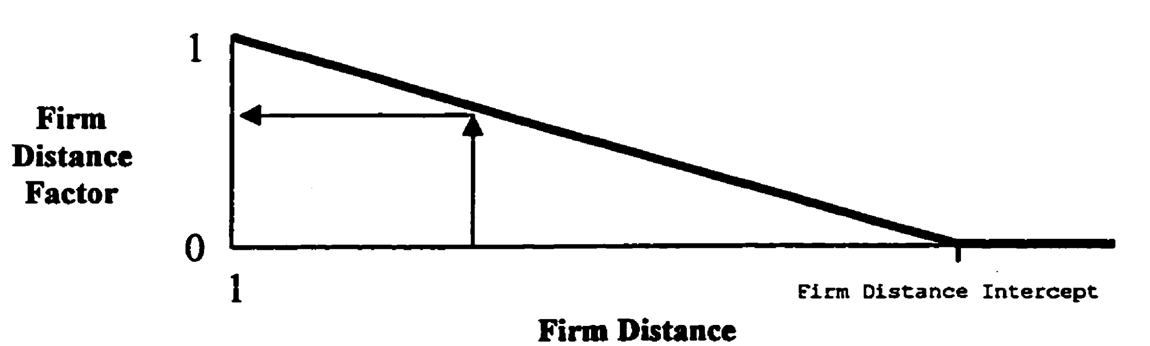
Firm propensity to contest, imitate, and invent - The three vectors of firm propensities to contest, imitate, and innovate are the `number of firms` in length. There are three options for initialization of the firm propensities. With the first choice, all firm propensities equal the `propensity to contest`, `propensity to imitate`, and `propensity to invent`. With the second choice, firm propensities are randomly generated real numbers between zero and `propensity to contest`, `propensity to imitate`, and `propensity to invent`. With the third option, firm propensities are evenly distributed.

Firm techniques - The matrix of firm techniques is the `number of firms` by the `number of products` times the `techniques per product` in size and contains randomly generated integers between one and the `number of techniques`.

Products contested - The matrix of products contested is the `number of firms` by the `number of products` in size. There are two options for the initialization of products contested, set by the `products contested option`. With the first choice, all products are contested by all firms and the matrix of products contested is filled with ones. With the second choice, the products contested are chosen randomly based on the firm propensity to contest calculated earlier, and the matrix of products contested is filled with ones and zeros, as appropriate.

Firm distance factors - The matrix of firm distance factors is square, the `number of firms` in size. There are two options for the calculation of firm distance factors, set by the `firm distance option`. With the first, the matrix of firm distance factors is filled with ones and calculations using the firm distance factor will be independent of distance. With the second, adjoining firms have a factor of one, and more distance firms have a factor of less than one as defined by the `firm distance intercept` of the firm distance graph

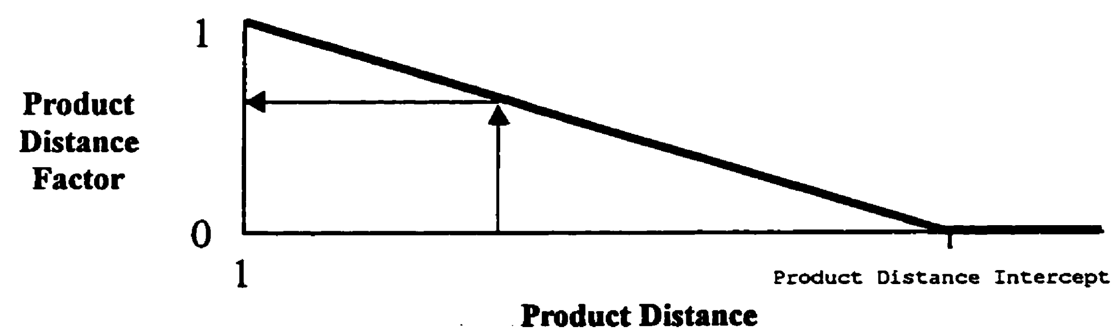
Figure D-2: Firm Distance Graph



(Figure D-2).

Product distance factors - The matrix of product distance factors is square, the `number of products` in size. There are two options for the calculation of product distance factors, set by the `product distance option`. With the first, the matrix of product distance factors is filled with ones and calculations using the product distance factor will be independent of distance. With the second, adjoining products have a factor of one, and more distance products have a factor of less than one as defined by the `product distance intercept` of the product distance graph (Figure D-3).

Figure D-3: Product Distance Graph



Firm records - Nine matrices are used to record the results of the firms for each period. These are `number of firms` by the `number of periods` in size. They record: firm performance, products contested, products entered, products exited, products imitated, products innovated, firm resources, firm revenue, and firm cost. They are initialized to zero.

Product records - Six matrices are used to record the results of the products for each period. These are `number of products` by the `number of periods` in size. They record: product performance, firms contesting, firms entering, firms exiting, firms imitating, and firms innovating. They are initialized to zero.

Market records - One matrix is used to record the results of the market for each period. This is two by the `number of periods` in size. It records: number of market technique changes and number of market demand changes. It is initialized to zero.

Exploitation

Performance - The performance of a firm for each of the products in which it contests is equal to the number of positions in the firm and market technique strings which match. For example, consider the case where techniques are described as a binary string with five positions. The firm's technique is `01011` and the market technique is `11001`. The strings match in the second, third, and fifth positions, so the performance is `3`. These individual performances are averaged over products for each firm, and averaged over firms for each product.

Revenues - A firm's revenue from a product is a portion of the total revenue available for the product (`market size`) based on the firm's performance for that product as a proportion of the performance of all firms contesting that product. For example, consider the case where a firm scores 8, the total of all firm's scores for the product is 32, and there are 100 resource units available from the product. The firm will receive (8/32)x100=25 in revenue from that product.

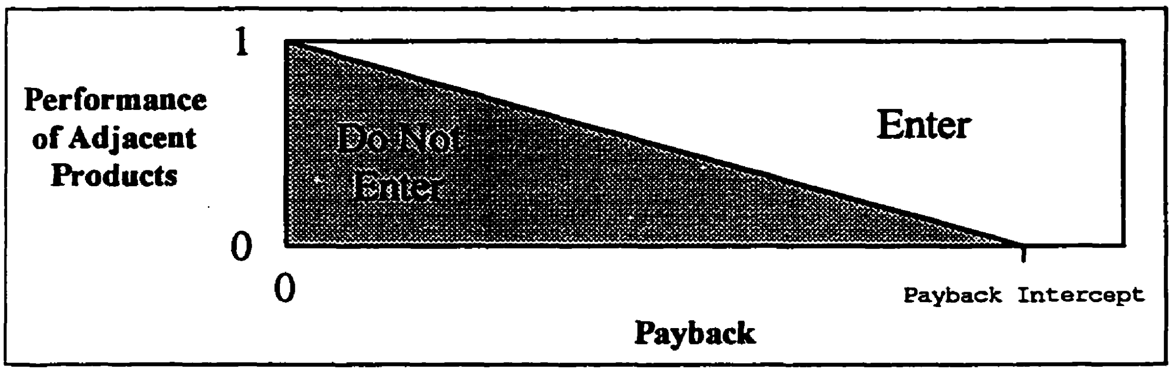
Costs - A firm incurs costs for entering new products, contesting existing products, imitation, and innovation. The number of products affected in each of these ways is multiplied by the respective factor: `cost of entry`, `cost of contesting`, `cost of imitation`, and `cost of innovation`.

Resources - A firm's resources in the next period are equal to its resources in the last period, plus revenues, minus costs.

Product Entry - A firm will enter a new product if four conditions are met. First, the firm cannot be already contesting the product. Second, the firm's reserves must be greater than `minimum reserves`. A firm's reserves represent the number of periods that a firm could sustain contesting a product without additional revenue. It is calculated as the firm's resources, minus the `cost of entry`, divided by the `cost of contesting`. Third, a stochastic choice, based on the firm's `propensity to contest`, must be true.

Fourth, the anticipated payback from the product must be greater than the minimum defined by the product entry graph (Figure D-4). This calculation does not consider what others might do in the same, or future, periods.

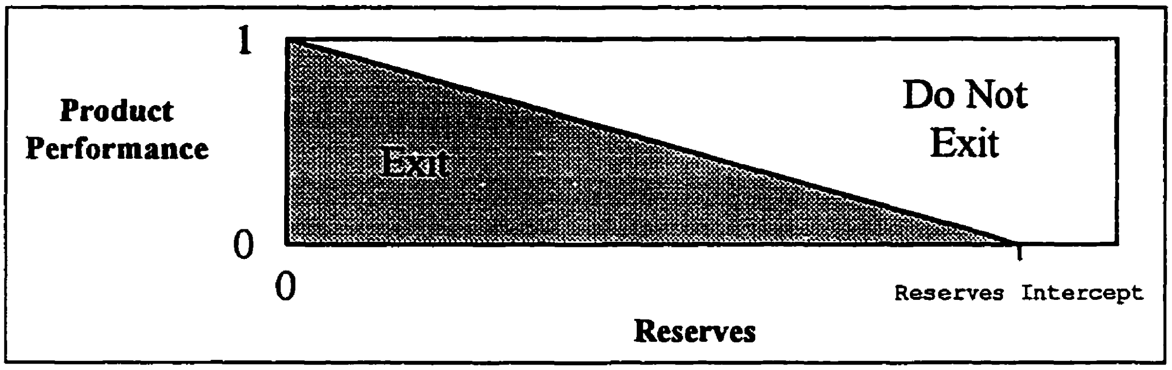
Figure D-4: Product Entry Graph



The anticipated payback represents the number of times the cost of entry will be recovered from product revenues. It is calculated as `market size`, divided by number of firms contesting the product, minus the `cost of contesting`, divided by the `cost of entry`. The performance of adjacent products is calculated by weighting the absolute performance of each product by its product distance factor calculated previously. If the product payback, adjacent product performance intersection falls within the white area of the graph, the product meets the minimum payback criteria for product entry.

Product Exit - A firm will exit from a product if four conditions are met. First, the firm must be currently contesting the product. Second, the product's anticipated payback must be below `minimum payback`. Payback is calculated as described in Product Entry above. Third, a stochastic choice, based on one minus the firm's `propensity to contest` (i.e. propensity to exit), must be true. Fourth, the firm's reserves must be lower than the maximum defined by the product exit graph (Figure D-5).

Figure D-5: Product Exit Graph



The firm's reserves are calculated as described in Product Entry above. If the reserves/product performance intersection falls within the grey area of the graph, the product meets the maximum reserve criteria for product exit.

Exploration

Imitation - A firm will imitate another firm's technique if two conditions are met. First, the firm must be currently contesting the product. Second, a stochastic choice, based on the firm's `propensity to imitate`, must be true. If both of these conditions are met, imitation is achieved by copying some of the technique string positions for the product of another firm. The choice of firm for imitation is stochastic based on the performance of the other firms, weighted by the firm distance factor calculated earlier.

Invention - A firm will invent a technique if three conditions are met. First, the firm must be currently contesting the product. Second, the firm cannot already have imitated this product in the current period. Third, a stochastic choice, based on the firm's `propensity to invent`, must be true. If these conditions are met, innovation is achieved by changing some of the product technique string positions to a number between one and the `number of techniques`.

Market Change

Market technique change - The decision to change a market technique is stochastic based on the `probability of market technique change`. If the decision is made to change, this is achieved by randomly changing some of the market technique string positions to a number between one and the `number of techniques`.

Market size change - The decision to change a market size is stochastic based on the `probability of market demand change`. If the decision is made to change, this is achieved by randomly choosing a number between one and the `market size` as the new size.

Output

The following information is stored for each period.

By firm:

- Firm Performance
- Number of Products Contested
- Number of Products Entered
- Number of Products Exited
- Number of Techniques Imitated
- Number of Techniques Invented
- Firm Resources
- Firm Revenues
- Firm Costs

By Product:

- Product Performance
- Number of Contesting Firms
- Number of Entering Firms
- Number of Exiting Firms
- Number of Imitating Firms
- Number of Inventing Firms

For the Market:

- Number of Techniques Changed
- Number of Demands Changed

Appendix E: Bizlife Computer Code

Program: Bizlife

This is the main program from which functions are called. To use the program, first specify the dynamic graph choice variable (graph1=1 to display the dynamic graph) and the input file name (inputfile='imputfile_name) on the Matlab command line. Then invoke the Bizlife program on the command line.

```
%bizlife
if exist('graph1')==0;
graph1=0; end;
if exist('inputfile')==0
disp('specify inputfile'); return; end;
load dasound;

eval(['minput=dascan(''' inputfile ''');']);
[r,c]=size(minput);

for g=1:c;
tic;

if minput(1,g)~=1;
```

```
disp('next')
else;
vinput(:)=minput(:,g);
```

This section transfers the input file data to the program parameters.

```
%INPUT
filenum=vinput(2);                                      %file number
para=vinput(3);                                         %vary parameter
paravary=vinput(4);                                     %parameter to vary
paramax=vinput(5);                                      %maximum parameter value
paramin=vinput(6);                                      %minimum parameter value
paranum=vinput(7);                                      %number of parameter values
randseed=vinput(8);                                     %random number seed I[0,?]
iter=vinput(9);                                         %number of iterations I[1,?]

snperi=vinput(10);                                      %number of periods I[1,?]
snfirm=vinput(11);                                      %number of firms I[2,?]
snprod=vinput(12);                                      %number of products I[2,?]
sntech=vinput(13);                                      %number of choices I[2,?]
snleng=vinput(14);                                      %number of techniques I[1,?]

snsize=vinput(15);                                      %market size (opt 4) I[1,?]
sptech=vinput(16);                                      %probability technique change (opt 6) R[0,1]
spsize=vinput(17);                                      %probability size change (opt 6) R[0,1]

spcont=vinput(18);                                      %propensity to contest (opt 7) R[0,1]
spimit=vinput(19);                                      %propensity to imitate (opt 7) R[0,1]
spinno=vinput(20);                                      %propensity to innovate (opt 7) R[0,1]
snreso=vinput(21);                                      %initial firm resources I[0,?]

scentr=vinput(22);                                      %cost of entry I[1,?]
```

```
sccont=vinput(23);                       %cost of contesting I[1,?]
scimit=vinput(24);                       %cost of imitation I[0,?]
scinno=vinput(25);                       %cost of innovation I[0,?]

sgextint=vinput(26);                     %product exit reserves intercept I[0,?]
sgentint=vinput(27);                     %product entry payback intercept I[0,?]
sgextmin=vinput(28);                     %product exit minimum payback I[0,?]
sgentmin=vinput(29);                     %product entry minimum reserves I[0,?]

sgfirdis=vinput(30);                     %firm distance factor (opt 1) I[1,snfirm-1]
sgprodis=vinput(31);                     %product distance factor (opt 2) I[1,snprod-1]

%Options
vopt=zeros(7,1);                         %initialize options
vopt(1)=vinput(32);                      %firm distance factor L[0/1] 0=all
vopt(2)=vinput(33);                      %product distance factor L[0/1] 0=all
vopt(3)=vinput(34);                      %products contested L[0/1] 0=all 1=rand 2=none
vopt(4)=vinput(35);                      %market size L[0/1/2] 0=equal 1=rand 2=dist.
vopt(5)=vinput(36);                      %entry and exit L[0/1] 0=disable 1=enable
vopt(6)=vinput(37);                      %market prob.L[0/1/2/3]0=equal 1=rand 2=dist.
3=read
vopt(7)=vinput(38);                      %firm prop. L[0/1/2/3] 0=equal 1=rand 2=dist.
3=read
vopt(8)=vinput(39);                      %firm tech. L[0/1] 0=random 1=same
```

This section intializes program parameters.

```
%INITIALIZATION
if para==1;
paraname=dapara(paravary);
recvfirperf=zeros(snperi,paranum);       %initialize firm performance record
recvfirnrev=zeros(snperi,paranum);
recvtecimit=zeros(snperi,paranum);
```

```
recvtecinve=zeros(snperi,paranum);
recvprocont=zeros(snperi,paranum);
recvtecherf=zeros(snperi,paranum);
vparaval=zeros(1,paranum);
incr=((paramax-paramin)/(paranum-1));
eval([paraname '=' num2str(paramax) '+incr;']);
else;
paranum=1;
incr=0;
clear recvfirperf recvfirnrev recvtecimit recvtecinve;
clear recvprocont recvtecherf vparaval;
paraname='no_parameter';
end;

for h=1:paranum;                                 %loop for parameter varied

if para==1;
eval([paraname '=' paraname '-incr;']);
eval(['vparaval(h)=' paraname ';']);
end;

recfirperf=zeros(snperi,snfirm);                 %initialize firm performance record
recfirnrev=zeros(snperi,snfirm);                 %initialize firm revenue record
rectecimit=zeros(snperi,snfirm);                 %initialize technique imitation record
rectecinve=zeros(snperi,snfirm);                 %initialize technique invention record
recprocont=zeros(snperi,snfirm);                 %initialize products contested record
rectecherf=zeros(snperi,snprod*snleng);          %initialize herfindahl number record

clear mfirm mfirtech2 mmarket perfsum
```

This section is iterated to average results over a number of runs.

```
for i=1:iter;                                    %iteration loop

rand('seed',randseed+i);                         %initialize random number generator
colormap(hsv(sntech));                           %initialize color map
```

```
snteclen=snprod*snleng;                                    %total technique length

temp1=eye(snprod);                                         %
temp2=ones(snleng,1);                                      %
m=1;                                                       %
for n=1:snprod;                                            %
perfsum(m:m+snleng-1,:)=temp2*temp1(n,:);                  %firm performance sum matrix
m=m+snleng;                                                %
end;                                                       %

vfirreso=ones(snfirm,1)*snreso;                            %firm resources

%Option 8 - firm techniques 0=random 1=identical 3=read
if vopt(8)==0;
mfirtech=ceil(rand(snfirm,snteclen)*sntech);               %firm techniques
%save biztech.mat mfirtech;
elseif vopt(8)==1;
mfirtech=ones(snfirm,1)*ceil(rand(1,snteclen)*sntech);
else;
load('biztech.mat');
end;

vmartech=ceil(rand(1,snteclen)*sntech);                    %market techniques

%Option 1 - firm distance factor 0=distance independent 1=slope function 2=step function
if vopt(1)==1;                                             %
temp1=max((sgfirdis-[0:snfirm-1])./(sgfirdis-1),0);        %
temp2=max((sgfirdis-fliplr([1:snfirm-1,0]))...             %
      ./(sgfirdis-1),0);                                   %
temp1(1)=0;                                                %
temp2(1)=0;                                                %
mfirdist=max(toeplitz(temp1,temp2),toeplitz(temp2,temp1)); %firm distance factors
elseif vopt(1)==2;
temp=min(sgfirdis,snfirm-1);
temp1=[0 ones(1,temp) zeros(1,snfirm-temp-1)];                     %
```

```
temp2=[0 zeros(1,snfirm-temp-1) ones(1,temp)];
temp1=(temp1|temp2);
mfirdist=toeplitz(temp1)                                    %firm distance factors
else; mfirdist=ones(snfirm,snfirm); end;                    %firm distance independant


%Option 2 - product distance factor 0=distance independent
if vopt(2)==1;                                              %
temp1=max((sgprodis-[0:snprod-1])./(sgprodis-1),0);         %
temp2=max((sgprodis-fliplr([1:snprod-1,0]))...              %
      ./(sgprodis-1),0);                                    %
temp1(1)=0;                                                 %
temp2(1)=0;                                                 %
mprodist=max(toeplitz(temp1,temp2),toeplitz(temp2,temp1));  %product distance factors
else; mprodist=ones(snprod,snprod); end;                    %product distance independant

%Option 4 - market size 0=equal for all products 1=random 2=distributed
if vopt(4)==1;
  vmarsize=ceil(rand(1,snprod)*snsize);                     %market sizes vary
elseif vopt(4)==0;
  vmarsize=ones(1,snprod)*snsize;                           %market sizes equal
else;
  vmarsize=(ceil(snsize/snprod):ceil(snsize/snprod):...     %...
             ceil(snsize/snprod)*snprod);                   %market sizes distributed
  if snsize==0; vmarsize=zeros(1,snprod); end;              %distribution does not work for zero
end;
mmarket(:,1)=vmarsize';

%Option 6 - market change probabilities 0=equal for all products 1=random 2=distributed 3=read
if vopt(6)==1;
  vmarptec=rand(1,snprod)*sptech;                           %market technique change prob. varies
  vmarpsiz=rand(1,snprod)*spsize;                           %market size change prob. varies
elseif vopt(6)==0;
  vmarptec=ones(1,snprod)*sptech;                           %market technique change prob. equal
  vmarpsiz=ones(1,snprod)*spsize;                           %market size change prob. equal
elseif vopt(6)==2;
```

```
  vmarptec=(sptech/snprod:sptech/snprod:sptech);              %market technique change prob. dist.
  if sptech==0; vmarptec=zeros(1,snprod); end;                %distribution does not work for zero
  vmarpsiz=(spsize/snprod:spsize/snprod:spsize);              %market size change prob. distributed
  if spsize==0; vmarpsiz=zeros(1,snprod); end;                %distribution does not work for zero
else;
fid=fopen('bizprod.in');
temp=fscanf(fid,'%g %g',[2 snprod]);
vmarpsiz=temp(1,:);
vmarptec=temp(2,:);
fclose(fid);
end;
mmarket(:,2)=vmarpsiz';
mmarket(:,3)=vmarptec';

%Option 7 - allocation of propensities 0=equal for all firms 1=random 2=distributed 3=read
  vfirtype=ones(snfirm,1);                                    %firm type indicator
if vopt(7)==1;
  vfirpcon=rand(snfirm,1)*spcont;                             %firm propensity to contest vary
  vfirpimi=rand(snfirm,1)*spimit;                             %firm propensity to imitate vary
  vfirpinn=rand(snfirm,1)*spinno;                             %firm propensity to innovate vary
elseif vopt(7)==0;
  vfirpcon=ones(snfirm,1)*spcont;                             %firm propensity to contest equal
  vfirpimi=ones(snfirm,1)*spimit;                             %firm propensity to imitate equal
  vfirpinn=ones(snfirm,1)*spinno;                             %firm propensity to innovate equal
elseif vopt(7)==2;
  vfirpcon=(spcont/snfirm:spcont/snfirm:spcont)';             %firm propensity to contest distributed
  if spcont==0; vfirpcon=zeros(snfirm,1); end;                %distribution does not work for zero
  vfirpimi=(spimit/snfirm:spimit/snfirm:spimit)';             %firm propensity to imitate distributed
  if spimit==0; vfirpimi=zeros(snfirm,1); end;                %distribution does not work for zero
  vfirpinn=(spinno/snfirm:spinno/snfirm:spinno)';             %firm propensity to innovate distributed
  if spinno==0; vfirpinn=zeros(snfirm,1); end;                %distribution does not work for zero
else;
fid=fopen('bizfirm.in');
temp=fscanf(fid,'%g %g %g',[4 snfirm]);
vfirpcon=temp(1,:)';
vfirpimi=temp(2,:)';
```

```
vfirpinn=temp(3,:)';
vfirtype=temp(4,:)';
fclose(fid);
end;

%Option 3 - products contested 0=all 1=rand 2=none
if vopt(3)==1;                                                   %
mfircont=rand(snfirm,snprod)<vfirpcon*ones(1,snprod);            %some products contested
mfirtech=mfirtech.*(mfircont*perfsum');                          %new firm techniques
elseif vopt(3)==0;
mfircont=ones(snfirm,snprod);                                    %all products contested
else;
mfircont=zeros(snfirm,snprod);                                   %no products contested
mfirtech=zeros(snfirm,snteclen);
end;

mfirm(:,1)=vfirpcon;
mfirm(:,2)=vfirpimi;
mfirm(:,3)=vfirpinn;
mfirm(:,4)=vfirtype;

mfirentr=zeros(snfirm,snprod);                                   %firm products entered
mfirexit=zeros(snfirm,snprod);                                   %firm products exited
mtecimit=zeros(snfirm,snteclen);                                 %firm techniques imitated
mtecinno=zeros(snfirm,snteclen);                                 %firm techniques innovated
```

This section is repeated for each period.

```
%MAIN
for j=1:snperi;                                                  %loop for periods
```

This section calculates firm performance, revenue, entry and exit.

```
%EXPLOITATION
%Application
%--Performance
tempa=~(mfirtech-ones(snfirm,1)*vmartech);                   %
mfirperf=tempa*perfsum;                                      %firm performance
vfirperf=(sum(mfirperf'))'./max((sum(mfircont'))',1);        %average firm performance
vproperf=sum(mfirperf)./max(sum(mfircont),1);                %average product performance

%--Revenue
temp=max(sum(mfirperf),1);                                   %
vfirreve=mfirperf*(vmarsize./temp)';                         %firm revenue

%Option 5 - entry and exit 0=disabled 1=enabled
if vopt(5)==1;
vfirrese=(vfirreso-scentr)/sccont;                           %firm reserves
vpropayb=(vmarsize./(sum(mfircont)+1)-sccont)/scentr;        %product paybacks
%Competition
%--Product Entry
temp1=~mfircont;                                             %not currently contested
temp2=(vfirrese>sgentmin)*ones(1,snprod);                    %sufficient reserves to contest
temp3=rand(snfirm,snprod)<(vfirpcon*ones(1,snprod));         %propensity to contest
temp4=ones(snfirm,1)*(1-vpropayb/sgentint)<...               %graph comparing payback to...
      (mfirperf*mprodist)/(sum(mprodist(:,1))*snleng);       %performance of adjacent products
mfirentr=temp1&temp2&temp3&temp4;                            %products for entry
tempa=ceil(rand(snfirm,snteclen)*sntech);                    %innovated techniques
mfirtech=mfirtech+(tempa.*(mfirentr*perfsum'));              %new product techniques (will imitate)
%--Product Exit
temp1=mfircont;                                              %currently contested
temp2=ones(snfirm,1)*(vpropayb<sgextmin);                    %insufficient payback to contest
temp3=rand(snfirm,snprod)>(vfirpcon*ones(1,snprod));         %1-propensity to contest
temp4=(1-vfirrese/sgextint)*...                              %...
      ones(1,snprod)>mfirperf/(sntech);                      %graph comparing reserves to performance
mfirexit=temp1&temp2&temp3&temp4;                            %products for exit
mfircont=mfircont-mfirexit;                                  %products contested after exit
```

```
end;
```

This section determines imitative behaviour, inventive behaviour, costs, and final resources.

```
%EXPLORATION
%Imitate
tempa=mfircont*perfsum';                              %techniques currently contested
tempb=rand(snfirm,snteclen)<(vfirpimi*ones(1,snteclen));  %propensity to imitate
mtecimit=tempa&tempb;                                 %old techniques to be imitated
mtecimit=mtecimit+(mfirentr*perfsum');                %all techniques to be imitated

mfircont=mfircont+mfirentr;                           %products contested after entry

if sum(vfirperf)==0;
   'All firms are bankrupt'
   return;
end;

m=1;                                                  %technique location indicator
for n=1:snprod;                                       %loop for products
tempa1=mfirperf(:,n)*ones(1,snfirm).*mfirdist;        %performance, distance weights
tempa1=tempa1-(ones(snfirm,1)*min(tempa1));           %normalize
tempa2=cumsum(tempa1./(ones(snfirm,1)*...
       ((sum(tempa1)==0)+sum(tempa1))));              %weighted selection matrix
temp=dalook(tempa2,rand(1,snfirm));                   %choice of firms to imitate (da's function)
mfirtech2(:,m:m+snleng-1)=interp1(1:snfirm,...
                          mfirtech(:,m:m+snleng-1),temp);  %imitated techniques
m=m+snleng;                                           %increment technique location indicator
end;

mfirtech=(mfirtech.*(~mtecimit))+(mfirtech2.*mtecimit);   %firm techniques after imitation

%Innovate
```

```
tempa=mfircont*perfsum';                                %techniques currently contested
tempb=~mtecimit;                                        %techniques not imitated
tempc=rand(snfirm,snteclen)<(vfirpinn*ones(1,snteclen)); %propensity to innovate
mtecinno=tempa&tempb&tempc;                             %techniques to be innovated

tempa=ceil(rand(snfirm,snteclen)*sntech);               %innovated techniques
mfirtech=(mfirtech.*(~mtecinno))+(tempa.*mtecinno);     %firm techniques after innovation

%--Costs
vfircost=sum((mfircont*sccont+mfirentr*scentr)')'+...   %...
         sum((mtecimit*scimit+mtecinno*scinno)')';      %firm costs

%--Resources
vfirreso=vfirreso+vfirreve-vfircost;                    %revised firm resources
```

This section determines market change.

```
%MARKET
vmartechc=rand(1,snteclen)<...                          %...
          reshape(ones(snleng,1)*vmarptec,1,snteclen);  %market techniques to change
vmartech=vmartech.*(~vmartechc)+...                     %...
         ceil(rand(1,snteclen)*sntech).*vmartechc;      %new market techniques
vmarsizec=rand(1,snprod)<vmarpsiz;                      %market size to change
vmarsize=vmarsize.*(~vmarsizec)+...                     %...
         vmarsize.*(1+(rand(1,snprod)*2-1)*.1).*vmarsizec; %new market size

mfirtech=mfirtech.*(~(mfirexit*perfsum'));              %techniques after exit

%HERFINDAHL NUMBER
for x=1:sntech;
  temph(x,:)=sum((ones(snfirm,snteclen)*x)==mfirtech);
end;
rectecherf(j,:)=rectecherf(j,:)+sum((temph/snfirm).*(temph/snfirm));
```

This section records the period's results.

```
%RECORD
if para==1;                                                          %vary parameter
recvfirperf(j,h)=recvfirperf(j,h)+mean(vfirperf);
recvfirnrev(j,h)=recvfirnrev(j,h)+mean(vfirreve-vfircost);
recvtecimit(j,h)=recvtecimit(j,h)+mean(sum(mtecimit')');
recvtecinve(j,h)=recvtecinve(j,h)+mean(sum(mtecinno')');
recvprocont(j,h)=recvprocont(j,h)+mean(sum(mfircont')');
recvtecherf(j,h)=recvtecherf(j,h)+mean(rectecherf(j,:));
else;
recfirperf(j,:)=recfirperf(j,:)+vfirperf';                           %firm performance
recfirnrev(j,:)=recfirnrev(j,:)+vfirreve'-vfircost';                 %firm net revenue
rectecimit(j,:)=rectecimit(j,:)+sum(mtecimit');                      %techniques imitated
rectecinve(j,:)=rectecinve(j,:)+sum(mtecinno');                      %techniques invented
recprocont(j,:)=recprocont(j,:)+sum(mfircont');                      %products contested
end;

%DYNAMIC OUTPUT
if graph1==1;
daimage(vmartech,mfirtech,j,min(vfirperf),max(vfirperf),mean(vfirperf));
end;


%FINISH
if fix(j/10)==j/10;
status=['run ' int2str(g) ', parameter ' int2str(h) ' of ' int2str(paranum)];
status=[status ', iteration ' int2str(i) ' of ' int2str(iter)];
status=[status ', period ' int2str(j) ' of ' int2str(snperi)];
disp(status),
%pause;
end;
```

```
end;                                                            %period loop
end;                                                            %iteration loop
end;                                                            %parameter loop
```

This section displays the status of the run and stores the results.

```
data=[inputfile ' ' int2str(g) ', ' num2str(toc/60) ' min., ' date];
disp(['Time ' num2str(toc/60) ' min.']),

if para==1;
recvfirperf=recvfirperf/iter;
recvfirnrev=recvfirnrev/iter;
recvtecimit=recvtecimit/iter;
recvtecinve=recvtecinve/iter;
recvprocont=recvprocont/iter;
recvtecherf=recvtecherf/iter;
dasave(vinput,data,recvfirperf,recvfirnrev,recvtecimit,...
       recvtecinve,recvprocont,recvtecherf,vparaval,mfirm,mmarket);
else;
recfirperf=recfirperf/iter;                                     %firm performance
recfirnrev=recfirnrev/iter;                                     %firm net revenue
rectecimit=rectecimit/iter;                                     %techniques imitated
rectecinve=rectecinve/iter;                                     %techniques invented
recprocont=recprocont/iter;                                     %products contested
rectecherf=rectecherf/iter;                                     %herfindahl number
dasave(vinput,data,recfirperf,recfirnrev,rectecimit,...
       rectecinve,recprocont,rectecherf,'dummy',mfirm,mmarket);
end;

sound(snd,fs);

end;                                                            %run if
end;                                                            %run loop
```

Program: Bizgraph

This program graphs the results of a run.

```
%bizgraph
if vinput(3)==0
 %daplot(matrix2,vinput,'Product');
 daplot(matrix1,vinput,'Firm');
 %dasurf(matrix2,[1:vinput(12)],vinput,'Product');
 dasurf(matrix1,[1:vinput(11)],vinput,'Firm');
 if vinput(37)==3;
  matrix3=matrix2-(ones(vinput(12),1)*mean(matrix2'))';
  daplot2(matrix3,vinput,'Product');
 end;
 if vinput(38)==3;
  matrix4=matrix1-(ones(vinput(11),1)*mean(matrix1'))';
  daplot2(matrix4,vinput,'Firm');
 end;
else;
 subject=dapara2(vinput(4));
 dasurf(matrix1,matrix2,vinput,subject);
 dasurf(matrix1,matrix2,vinput,subject);
 view(37.5,30);
 daplot(matrix1,vinput,subject);
end;
```

Program: Bizprint

This program prints the results of a run.

```
%bizprint
fid=fopen('print.tmp','a');
fprintf(fid,'\n \r \t BIZLIFE PARAMETERS \n \n \r');

fprintf(fid,'\t File number:                 \t %g \n \n \r',vinput(2));

fprintf(fid,'\t Vary parameter:              \t %g \n \r',vinput(3));
fprintf(fid,'\t Parameter to vary:           \t %g \n \r',vinput(4));
fprintf(fid,'\t Maximum parameter value:     \t %g \n \r',vinput(5));
fprintf(fid,'\t Minimum parameter value:     \t %g \n \r',vinput(6));
fprintf(fid,'\t Number of values:            \t %g \n \n \r',vinput(7));

fprintf(fid,'\t P1. Random number seed:      \t %g \n \r',vinput(8));
fprintf(fid,'\t P2. Number of iterations:    \t %g \n \n \r',vinput(9));

fprintf(fid,'\t P3. Number of Periods:       \t %g \n \r',vinput(10));
fprintf(fid,'\t P4. Number of firms:         \t %g \n \r',vinput(11));
fprintf(fid,'\t P5. Number of products:      \t %g \n \r',vinput(12));
fprintf(fid,'\t P6. Number of choices:       \t %g \n \r',vinput(13));
fprintf(fid,'\t P7. Number of techniques:    \t %g \n \n \r',vinput(14));

fprintf(fid,'\t P8. Market size:             \t %g \n \r',vinput(15));
fprintf(fid,'\t P9. Prob. market tech, change: \t %g \n \r',vinput(16));
fprintf(fid,'\t P10. Prob, market size change: \t %g \n \n \r',vinput(17));

fprintf(fid,'\t P11. Propensity firm contest:  \t %g \n \r',vinput(18));
fprintf(fid,'\t P12. Propensity firm imitate:  \t %g \n \r',vinput(19));
fprintf(fid,'\t P13. Propensity firm innovate: \t %g \n \r',vinput(20));
fprintf(fid,'\t P14. Initial firm resources:   \t %g \n \n \r',vinput(21));
```

```
fprintf(fid,'\t P15. Cost of entry:           \t %g \n \r',vinput(22));
fprintf(fid,'\t P16. Cost of contesting:      \t %g \n \r',vinput(23));
fprintf(fid,'\t P17. Cost of imitation:       \t %g \n \r',vinput(24));
fprintf(fid,'\t P18. Cost of innovation:      \t %g \n \n \r',vinput(25));

fprintf(fid,'\t P19. Prod. entry intercept:   \t %g \n \r',vinput(26));
fprintf(fid,'\t P20. Prod. entry minimum:     \t %g \n \r',vinput(27));
fprintf(fid,'\t P21. Prod. exit intercept:    \t %g \n \r',vinput(28));
fprintf(fid,'\t P22. Prod. exit minimum:      \t %g \n \n \r',vinput(29));

fprintf(fid,'\t P23. Firm distance factor:    \t %g \n \r',vinput(30));
fprintf(fid,'\t P24. Product distance factor: \t %g \n \n \r',vinput(31));

fprintf(fid,'\t Opt. firm distance factor:    \t %g \n \r',vinput(32));
fprintf(fid,'\t Opt. prod distance factor:    \t %g \n \r',vinput(33));
fprintf(fid,'\t Opt. products contested:      \t %g \n \r',vinput(34));
fprintf(fid,'\t Opt. market size:             \t %g \n \r',vinput(35));
fprintf(fid,'\t Opt. entry and exit:          \t %g \n \r',vinput(36));
fprintf(fid,'\t Opt. market change prob.:     \t %g \n \r',vinput(37));
fprintf(fid,'\t Opt. firm propensities:       \t %g \n \r',vinput(38));
fprintf(fid,'\t Opt. firm techniques:         \t %g \n \n \r',vinput(39));

fprintf(fid,'\f \n \r \t FIRM CHARACTERISTICS \n \n \r');
fprintf(fid,'\t Contest \t Imitate \t Innovate \t Type \n \r');
fprintf(fid,'\t %g \t \t %g \t \t %g \t \t %g \n \r',mfirm');

fprintf(fid,'\n \r \t MARKET CHARACTERISTICS \n \n \r');
fprintf(fid,'\t Size \t \t Size Change \t Tech Change \n \r');
fprintf(fid,'\t %g \t \t %g \t \t %g \n \r',mmarket');
fprintf(fid,'\n \r');
data=['     ' data];
fprintf(fid,data);

fclose(fid);
!print print.tmp
delete 'print.tmp';
```

Function: daimage

This function is called by the Bizlife program to dynamically plot the technique array during a run.

```
function daimage(matrix1,matrix2,p,m1,m2,m3);
figure(1)
clf
axis('off')
text(...
   'position',[0 1],...
   'string',['Period: ', num2str(p)]);
text(...
   'horizontalalignment','right',...
   'position',[1 1],...
   'string',['Avg: ', num2str(m3)]);
text(...
   'position',[.55 1],...
   'string',['Max: ', num2str(m2)]);
text(...
   'position',[.3 1],...
   'string',['Min: ', num2str(m1)]);
a1=axes('position',[.11 .77 .8 .025],...
   'drawmode','fast');
image(matrix1);
title('Market')
axis('off')
a2=axes('position',[.11 .15 .8 .6],...
   'drawmode','fast');
image(matrix2);
xlabel('Technique')
ylabel('Firm')
drawnow;
return;
```

Function: dalook

This function is called by the Bizlife program to choose which firm another firm will imitate.

```
function matrix3=dalook(matrix1,matrix2);
[m1,n1]=size(matrix1);
matrix3=zeros(m1,1);
for i=1:m1;
  if matrix1(m1,i)==0;
    matrix3(i,1)=ceil(rand*m1);
  else;
    for j=1:m1;
      if matrix2(1,i)<=matrix1(j,i);
        matrix3(i,1)=j;
        break;
      end;
    end;
  end;
end;
return
```

Function: dapara

This function is called by the Bizlife program to translate the parameter number to be varied in a simulation to a parameter name. This is done because Matlab cannot read characters from a file.

```
function name=dapara(number);
if number==1; name='randseed';
elseif number==2; name='iter';
elseif number==3; name='snperi';
elseif number==4; name='snfirm';
```

```
elseif number==5; name='snprod';
elseif number==6; name='sntech';
elseif number==7; name='snleng';
elseif number==8; name='snsize';
elseif number==9; name='sptech';
elseif number==10; name='spsize';
elseif number==11; name='spcont';
elseif number==12; name='spimit';
elseif number==13; name='spinno';
elseif number==14; name='snreso';
elseif number==15; name='scentr';
elseif number==16; name='sccont';
elseif number==17; name='scimit';
elseif number==18; name='scinno';
elseif number==19; name='sgextint';
elseif number==20; name='sgentint';
elseif number==21; name='sgextmin';
elseif number==22; name='sgentmin';
elseif number==23; name='sgfirdis';
elseif number==24; name='sgprodis';
else name='error';
end;
return;
```

Function: dapara2

This function is called by the Bizgraph program to title the axis of a graph.

```
function name=dapara(number);
if number==1; name='Random Number';
elseif number==2; name='Iterations';
elseif number==3; name='Number of Periods';
elseif number==4; name='Number of Firms';
elseif number==5; name='Number of Products';
```

```
elseif number==6; name='Number of Choices';
elseif number==7; name='Number of Techniques';
elseif number==8; name='Market Size';
elseif number==9; name='Prob. Env. Change';
elseif number==10; name='Prob. Market Change';
elseif number==11; name='Propensity Contest';
elseif number==12; name='Propensity Imitate';
elseif number==13; name='Propensity Invent';
elseif number==14; name='Firm Resources';
elseif number==15; name='Cost of Entry';
elseif number==16; name='Cost of Contesting';
elseif number==17; name='Cost of Imitation';
elseif number==18; name='Cost of Invention';
elseif number==19; name='Exit Intercept';
elseif number==20; name='Entry Intercept';
elseif number==21; name='Exit Minimum';
elseif number==22; name='Entry Minimum';
elseif number==23; name='Firm Distance';
elseif number==24; name='Product Distance';
else name='error';
end;
return;
```

Function: daplot

This function is called by the Bizgraph program to produce two dimensional graphs of the absolute performance results.

```
function daplot(matrix,vinput,subject)
%vinput(10) is snperi
%vinput(14) is snleng
figure
axis([1 vinput(10) 0 vinput(14)]);
xlabel('Period');
ylabel('Absolute Performance');
```

```
title(['File number: ' int2str(vinput(2)) ', ' int2str(vinput(9)) ' iterations, ' subject]);
hold on
plot(matrix);
plot(max(matrix'),'y','linewidth',1.5);
plot(mean(matrix'),'r','linewidth',1.5);
plot(min(matrix'),'m','linewidth',1.5);
plot(ones(size(1:vinput(10)))*(vinput(14)/vinput(13)),'w','linewidth',1.5);
%legend('y','Max','r','Avg','m','Min','w','Rand ');
drawnow;
return;
```

Function: daplot2

This function is called by the Bizgraph program to produce two dimensional graphs of the relative performance results.

```
function daplot2(matrix,vinput,subject)
%vinput(10) is snperi
%vinput(14) is snleng
figure
axis([1 vinput(10) -vinput(14) vinput(14)]);
xlabel('Period');
ylabel('Relative Performance');
title(['File number: ' int2str(vinput(2)) ', ' int2str(vinput(9)) ' iterations, ' subject]);
hold on
plot(matrix);
plot(max(matrix'),'y','linewidth',1.5);
plot(mean(matrix'),'r','linewidth',1.5);
plot(min(matrix'),'m','linewidth',1.5);
legend('y','Max','r','Avg','m','Min');
drawnow;
return;
```

Function: darelper

This function graphs the relative performance of the firms in the industry.

```
function m=darelper(matrix);
[p f]=size(matrix);
m=matrix-(ones(f,1)*mean(matrix'))';
mesh(m);
xlabel('Firm');
ylabel('Period');
zlabel('Relative Performance');
return;
```

Function: dasave

This function is called by the Bizlife program to save the results of a run.

```
function dasave(vinput,data,recfirperf,recfirnrev,rectecimit,...
       rectecinve,recprocont,rectecherf,vparaval,mfirm,mmarket);
filename=num2str(vinput(2));
filename=['biz' filename '.mat'];
disp(filename),
eval(['save ''' filename ''' vinput data recfirperf recfirnrev rectecimit rectecinve recprocont rectecherf
vparaval mfirm mmarket']);
return;
```

Function: dascan

This function is called by the Bizlife program to read the input file.

```
function a=dascan(filein);
fid=eval(['fopen(''' filein ''')']);
a=fscanf(fid,'%*s %g %g %g %g %g %g %g %g %g %g',[10 inf]);
a=a';
fclose(fid);
return;
```

Function: dasmooth

This function performs moving average smoothing on results.

```
function vector2=dasmooth(vector1,n);
[l,m]=size(vector1);
vector2=zeros(1,m);
vector2(1:n-n/2-1)=vector1(1:n-n/2-1);
vector2(m-n/2+1:m)=vector1(m-n/2+1:m);
for i=n:m;
 vector2(i-n/2)=sum(vector1((i-n+1):i))/n;
end;
```

Function: dasurf

This function is called by the Bizgraph program to produce three dimensional surface meshes of results.

```
function dasurf(matrix,vector,vinput,subject);
```

```
%vinput(10) is snperi
%vinput(14) is snleng
figure;
%surf(vector,[1:vinput(10)],matrix);
mesh(vector,[1:vinput(10)],matrix);
amin=min(vector);
amax=max(vector);
axis([amin amax 1 vinput(10) 0 vinput(14)]);
xlabel(subject);
ylabel('Period');
zlabel('Absolute Performance');
%title(['File number: ' int2str(vinput(2)) ', ' int2str(vinput(9)) ' iterations, ' subject]);
colormap(hsv(64));
%shading faceted;
shading interp;
drawnow;
return;
```

Appendix F: Simulation Parameter Settings

	Figure	5-1A	5-1B	5-1C	5-2	5-3	5-4 5-5	5-6 5-7	5-8A 5-15	5-8B 5-16	5-9 5-10	5-11 5-12	5-13 5-14	5-18 A&B	5-20 5-21 5-22 5-23	5-24 5-25
	File number	2000	2003	2004	2001	2002	2005	2006	2010	2011	2007	2013	2014	2012	3008	3009
	Vary parameter	0	0	0	0	0	1	1	0	0	1	1	1	0	0	0
	Parameter to vary						12	13			9	12	13			
	Max parameter value						1	0.3			0.3	1	0.3			
	Min parameter value						0.1	0			0	0.1	0			
	Number of values						20	20			20	20	20			
P1	Random number seed	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
P2	Number of iterations	20	20	20	20	20	20	20	1	1	20	20	20	1	100	1
P3	Number of periods	100	100	100	100	100	100	100	100	100	100	100	100	500	100	100
P4	Number of firms	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
P5	Number of products	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
P6	Number of choices	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
P7	Number of techniques	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
P8	Market size	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P9	Prob. technique change	0	0	0	0	0	0	0	0.03	0.03		0.03	0.03	0.03	0.03	0.03
P10	Prob. size change	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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	Figure	5-1A	5-1B	5-1C	5-2	5-3	5-4 5-5	5-6 5-7	5-8A 5-15	5-8B 5-16	5-9 5-10	5-11 5-12	5-13 5-14	5-17	5-18 5-19 5-20 5-21	5-22 5-23
P11	Propensity firm contest	1	1	1	1	1	1	1	1	1	1	1	1	1		
P12	Propensity firm imitate	1	0.5	0.5	1	1		0.5	0.5	0.5	0.5	0.5	0.5	0.5		
P13	Propensity firm invent	0	0	0.03	0	0	0.03		0	0.03	0.03	0.03	0.03	0.03		
P14	Initial firm resources	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P15	Cost of entry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	Cost of contesting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P17	Cost of imitation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P18	Cost of invention	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P19	Product entry intercept															
P20	Product entry minimum															
P21	Product exit intercept															
P22	Product exit minimum															
P23	Firm distance factor														2	2
P24	Product distance factor															
O1	Firm distance factor	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
O2	Product distance factor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O3	Products contested	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O4	Market size	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O5	Entry and exit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O6	Market change probability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O7	Firm propensities	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
O8	Firm techniques	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
	Number firm type 1														26	26
	Number firm type 2														1	1

	Definitions:					Propensity										
				Contest		Imitate		Innovate								
		Firm type 1		1		0.5		0								
		Firm type 2		1		0.1		0.1								

More Parameter Settings

	Figure	5-17	5-18C	5-19A	5-19B	5-19C
	File number	5031	4012	4010	4011	4013
	Vary parameter	0	0	0	0	0
	Parameter to vary					
	Max parameter value					
	Min parameter value					
	Number of values					
P1	Random number seed	2	2	2	2	2
P2	Number of iterations	20	1	1	1	1
P3	Number of periods	200	500	500	500	500
P4	Number of firms	27	27	27	27	27
P5	Number of products	2	2	2	2	2
P6	Number of choices	5	5	5	5	5
P7	Number of techniques	20	20	20	20	20
P8	Market size	0	0	0	0	0
P9	Prob. technique change	0	0.03	0.03	0.03	0.03
P10	Prob. size change	0	0	0	0	0

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	Figure	5-17	5-18C	5-19A	5-19B	5-19C
P11	Propensity firm contest	1	1	1	1	1
P12	Propensity firm imitate	0.5	0.0	0.5	0.5	0.5
P13	Propensity firm invent	0.03	0.03	0.03	0.03	0.03
P14	Initial firm resources	0	0	0	0	0
P15	Cost of entry	0	0	0	0	0
P16	Cost of contesting	0	0	0	0	0
P17	Cost of imitation	0	0	0	0	0
P18	Cost of invention	0	0	0	0	0
P19	Product entry intercept					
P20	Product entry minimum					
P21	Product exit intercept					
P22	Product exit minimum					
P23	Firm distance factor					
P24	Product distance factor					
O1	Firm distance factor	0	0	0	0	0
O2	Product distance factor	0	0	0	0	0
O3	Products contested	0	0	0	0	0
O4	Market size	0	0	0	0	0
O5	Entry and exit	0	0	0	0	0
O6	Market change probability	0	0	0	0	0
O7	Firm propensities	0	0	0	0	0
O8	Firm techniques	1	3	3	3	3
	Initial technique matrix		#1	#1	#2	#3

Appendix G: References

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