

**A GROWTH RELATED, MULTI-MODE FRAMEWORK
FOR INTERACTION AMONG TECHNOLOGIES**

by

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ABSTRACT

The identification of emerging technologies is a complex problem for which there are no easy or obvious answers. The notion of mortality indicators is proposed as an approach to identifying emerging technologies. Since it is well known that mature technologies are often attacked by emerging technologies, signals in the behavior of a mature technology indicating that it is under attack may help in the search for emerging technologies. The question whether the oscillatory behavior that is often exhibited in the diffusion S-curves of mature technologies is triggered by the emergence of new technologies, and hence that it may serve as such a mortality indicator, is investigated.

This approach lead to an investigation of the mechanisms whereby technologies compete. It was found that technologies seem to have a much more encompassing array of interactions than mere competition. In order to describe and classify these interactions, a multi-mode framework is proposed where the effect that one technology has on another's growth rate is considered as the basis of classification. Three modes of interaction are proposed, viz. pure competition (where technologies have a negative effect on one another's growth rate), symbiosis (where technologies have a positive effect on one another's growth rate) and predator-prey interaction (where one technology has a positive influence on another's growth rate but the second has a negative effect on its benefactor's growth rate). Examples of technologies that interact in each of the various modes are given, together with a motivation why interactions can shift from one mode to another with time. A comprehensive mathematical model, based on modified Lotka-Volterra equations, is developed to simulate the multi-mode framework.

It was found that an emerging technology can contribute to the oscillatory behavior in the S-curve of a mature technology. However, there may also be other significant causes for the oscillations, notably the impact of business cycles. The substitution of plywood by oriented strand board and waferboard is considered as a case study. Alternative explanations for the oscillatory behavior, including chaos theory, are also discussed.

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Deo Gloria

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INTRODUCTION

*“If you can look into the seeds of time and say which grain will grow
and which will not, speak then to me”*

William Shakespeare
Macbeth, Act I, Scene III

There can be little doubt that technological progress is a major driving force in the creation of wealth and welfare for individuals, companies and nations. Technological progress in turn, is driven by *innovation* — a process that I have come to discover as one that can and must be managed to obtain sustained success. This study deals with one aspect of technological innovation, viz. competitive interaction among technologies. The study was inspired by an interesting approach to identify emerging technologies, but soon led to a more encompassing and fundamental investigation of interaction among technologies.

The search for emerging technologies

The ability to identify and track emerging technologies is becoming one of increasing importance, not only for individual companies and industries but also for governments who are starting to recognize its value to initiatives for sustaining global competitive

advantages. The identification of emerging technologies is, however, not a trivial task and certainly not one for which there are easy and obvious solutions. Brief discussions of the importance of the identification of emergence technologies as well as some of the issues surrounding the process are given in Chapter 2. The notion of *mortality indicators* for mature technologies is introduced as a technique that can be deployed in the search for emerging technologies. It is postulated that by focusing on signals that indicate the demise of mature technologies, one can possibly be led to the emergence of new technologies. Once the concept of mortality indicators has been manifested as possible indicators for emerging technologies, questions arise as to which mortality indicators are suitable as such and whether they are reliable and unique. In this thesis we investigate one particular possible mortality indicator, viz. the oscillatory behavior that is often detected in the growth curves of mature technologies. The hypothesis that such oscillations may be triggered by new emerging technologies that are invading the market niches of the mature technologies, is examined.

Interaction among technologies

In order to investigate the causal relationship between oscillations in mature technologies' growth curves and the emergence of new technologies, it was necessary to launch into a much more fundamental investigation of the nature of competition among technologies. Drawing on insights from ecology and organizational ecology, it soon became clear that interaction among technologies encompasses much more than competition. It seems that there is a much broader arena of activity that encompasses not only competition, but also

combinations of mutually advantageous interaction. This realization leads to a focus on reciprocal effects that technologies have on one another's growth rate as a measure of competition. As one progresses along this path, one soon discovers that there are also cases where one technology benefits from the existence of the other, whilst at the same time exerting a negative influence on the growth of its benefactor. Such systems are known as *predator-prey* systems.

In order to accommodate the various modes of interaction among technologies that was beginning to unfold, a growth related, multi-mode framework for interaction among technologies was developed. Three distinct modes of interaction were identified, viz. *pure competition* (where both technologies have a negative influence on each other's growth rate), *symbiosis* (where both technologies have a positive influence on each other's growth rate) and *predator-prey interaction* (where one technology has a positive influence on the other's growth rate, but the second has a negative influence on the first's growth rate). The proposed framework is analogous to ecological frameworks that focus on growth rates, but differs in a few fundamental aspects, primarily the way in which the predator-prey action takes place and the fact that the interaction among technologies can temporally shift from one mode to another.

Although the proposed multi-mode framework is not extensively tested as part of this thesis, several examples are given to motivate the existence of the various modes as well as the notion that the mode of interaction can change with time. It is believed that the

proposed framework establishes a rich setting within which to examine interaction among technologies. Much research remains to be done in this regard however, including investigations into the nature of interaction in the symbiotic and predator-prey modes — areas that seem to have been neglected in the literature — as well as investigations into the transitional effects between the modes and the development of appropriate strategies for the individual modes as well as the transitions. The multi-mode framework for technological interaction is presented in Chapter 3.

In order to simulate the proposed multi-mode framework, a mathematical model was subsequently developed. An introduction to the mathematical modeling of technological competition is given in Chapter 4, where it is shown that many of the traditional models have serious deficiencies when it comes to the modeling of multiple technologies, apart from the fact that they cannot account for the multiple modes proposed in the framework in Chapter 3. The mathematical model for the new framework is described in Chapter 5. It is based on the well-known Lotka-Volterra equations, but has been appropriately modified where necessary to reflect the multiple modes of the framework. A closed form iterative solution for the case of pure competition has also been adapted, thereby enabling one to model all three modes quantitatively. It is shown that the model can be extended to handle any finite number of technologies that interact with one another. As in the case of the framework itself, the model is far from perfect at this stage. In addition to the daunting task of developing a technique whereby the coefficients can be estimated, the greater task of verifying the model in conjunction with the framework remains.

Mortality indicators revisited

In Chapter 6 we return to the oscillatory behavior of the S-curves of mature technologies. The case of the invasion of OSB and waferboard into plywood's market in the light frame construction industry is discussed in some detail as a representative case study. After examining various explanations that have been proposed for the oscillations, including a correlation with business cycles, the application of the model developed in Chapter 5 and chaos theory, the conclusion is drawn that the possibility that the emergence of a new technology can trigger the oscillations cannot be excluded, but that there are certainly also other factors that can contribute to the onset of the oscillations. Nevertheless, one is certainly left with the impression that the entire notion of mortality indicators as signals for emerging technologies and particularly the death knells of mature technologies is an interesting subject that holds the promise of rewarding research possibilities. In Chapter 7 conclusions are drawn and suggestions made for future research projects that have been identified as part of this study. The thesis is concluded with a list of references.

A personal odyssey

The way in which this thesis evolved also tells the story of my personal discovery of the fascinating discipline of technological innovation. Having only recently decided to switch my research interests from the applications of electromagnetic scattering (McNamara *et al.*, 1990) to the management of technology, I was very much under the impression of the strengths and superiorities of rigorous quantitative analysis for attacking research problems. Being particularly interested in the identification and tracking of emerging

technologies within the broader framework of the management of technological innovation, I approached Prof. James Utterback with a few research proposals in this regard. He suggested that I undertake an investigation into the notion that the oscillatory effects that are sometimes observed in the growth curves of mature technologies can be an indicator that an emerging technology is waiting in the wings, ready to attack. The topic seemed ideally suited to my tastes since it held the promise of an interesting application of innovation management combined with the possibility of mathematical analysis. To an electrical engineer the phrase “oscillations” immediately brings visions of harmonic analyses and Fourier transforms to mind — concepts that I was familiar with and which I foresaw as helping my transition from hard engineering research where Mother Nature mercilessly lays down rules that are to be followed with the utmost rigor, to the new world of research in the social sciences where (as I have since discovered) exact and unique answers are far and few between, and the whims of mortals rather the forces of nature play a significant role in the destinies of man and machines.

As my study into the oscillatory behavior of S-curves progressed, I gradually discovered (no doubt due to the gentle nudging of professor Utterback) that the interesting and hard questions, are the qualitative ones. Having ventured into a broad spectrum of the literature of innovation, I started learning about technological competition and strategies for attack and defense. My study took me into the worlds of ecology and organizational ecology where I discovered analogies to technological systems, chaos theory and learned about predator-prey interactions and symbiosis. This led to the formulation of the multi-mode

framework for technological interaction — a framework where reciprocal effects that technologies have on one another's growth rates is the criteria for classification into a mode. It was, however, hard to let go of the urge to quantify and model, and hence a mathematical model for the framework grew in conjunction with the qualitative development of the framework. Gradually the multi-mode framework together with the mathematical model became the main focus of the research, not only due to its inherent interesting aspects, but also due to the number of new and exciting research areas that it suggested. Eventually I returned to the oscillatory behavior of mature technologies' S-curves with the benefit of appreciating that the difficult and interesting questions and answers are the qualitative ones. Having transgressed the circle from incurably attempting to apply meticulous engineering solutions to applications that require a broader understanding and approach, through disciplines where clues are subtle and answers fuzzy, back to the recognition that a motivated balance between empirical observations, rigorous analysis, a lot of experience and sound judgment is to be strived for, I look back upon a very rewarding experience.

THE SEARCH FOR EMERGING TECHNOLOGIES

“Prediction is very difficult, especially about the future”

Niels Bohr

The ability to identify promising emerging technologies at an early stage is without a doubt a tremendous competitive advantage, whether from the vantage point of an individual company, industry or country. Emerging technologies bring not only new opportunities to grasp, but also threaten to replace old ones. It has often happened that new technologies have given rise to entire new industries, as was the case with television and transistors, for example. In an age where technology itself is becoming an increasingly important component of the ability to compete and even survive, the ability of a company, industry or country to identify emerging technologies and take appropriate action is a vitally important issue. There is a growing awareness that the ability to identify emerging technologies is an important element in the innovation process.

The identification and tracking of emerging technologies has important implications for a company from a strategic viewpoint. As major new technological innovations create new industries and destroy old ones, it is essential that firms formulate strategies and deploy resources in a timely fashion. Abernathy, Clark and Kantrow comment that “... The harsh

truth is that our industrial landscape is already littered with the remains of once-successful companies that couldn't adapt their strategic vision to altered conditions of competition" (1983, p.6), whereas Loveridge and Pitt warn against the dangers of *strategic surprise* (1990, p.5). Soukop and Cooper conclude that "... Managers of technologically threatened firms should also recognize that competitive conditions and strategies in the markets based on the new technology are likely to evolve along very different lines from those that prevailed in the traditional industry" (1983, p.226). Foster states that "... most companies need to do a better job of anticipating technological development relatively far in advance. In short they need a distant early warning capability... One way a company can broaden its horizons is to push hard for the identification of technological alternatives" (1988, p.227). New technologies bring with them the requirements for new strategies, new organizational structures and new measures of competitiveness. From the viewpoint of managing a company's R&D effort, for example, early warning of an emerging technology obviously can aid in the selection of projects, indicate which research directions to pursue and which to stay clear from. Similar issues are of concern to directors of public research institutions and policy makers. Barbé *et al.* have done research to examine the way companies perceive new technologies *vis-à-vis* its competitors and the consequences of the companies' responses (1986 as quoted by Moenaert *et al.*, 1990). They found that the earlier a company perceived the threat of a new technology, the more flexible its range of strategic responses were. They conclude that it is important for a company to gather and process information as soon as possible before competitors erect barriers to entry.

On a national level, there is also growing awareness of the importance of identifying and tracking emerging technologies. The US Department of Commerce, for example, recently released a report entitled *Emerging Technologies: A Survey of Technical and Economic*

Opportunities in which twelve emerging technologies which were expected to have the potential of contributing to the development of new or improved products by the year 2000, were identified (1990). In 1992 the President of the United States signed into law a statute that requires the *National Critical Technologies Panel* to submit to the President a biennial report on national critical technical technologies. In October 1992 the *Critical Technologies Institute* was established with the responsibility for the critical technology panels (Branscomb, 1993, p. 49). Although all critical technologies are not necessarily emerging technologies, the law does reflect the concern that new and emerging technologies can have implications on the national security of the nation — not only in a military sense but also with regards to sustained international competitiveness. Similar concerns have been raised in other countries. In May 1993, for example, the British Government published a White Paper entitled *Realising our Potential* in which they emphasize the role of *technology foresight*, charging the *Technology Foresight Steering Group* with the responsibility to “... oversee the collection of information on scientific opportunities and potential market applications from a wide cross-section of experts in academia, industry, finance, consumer research and government” (HMSO, 1993).

Evaluation of the potential impact of emerging technologies is a difficult and complex process. It involves not only skills and techniques for monitoring and scanning but also for interpreting the results in terms of their technological, economic and social implications within the context of the company, the industry as well as in a national and increasingly also in a global setting. In this chapter we are concerned primarily with the process of identifying and tracking emerging technologies, which is only one of the first phases of the larger task of assessing their impact. The process of identification and tracking itself, is a complicated one. Utterback and Brown contend that this process includes the “... search, consideration of alternative possibilities and their outcomes, selection of critical

parameters for observation, and formation of a conclusion based on evaluating the changes in these observations and the implications drawn from them” (1972, p.7).

The identification and tracking of emerging technologies is related to but distinctly different from traditional technology forecasting, the latter which can be viewed as “... a prediction of the future characteristics of useful machines, procedures or techniques” (Martino, 1993a, p.1). In the case of the identification and tracking of emerging technologies, on the other hand, one is interested not so much in the development of the technical characteristics *per se*, but rather in identifying technologies that are emerging as potential competitors for existing technologies, or in filling entirely new market niches. The emphasis is not on predicting technical performance as a function of time or effort expended, but rather on searching for precursors that indicate a high probability of acceptance in the market, usually with associated potential economic success. The problem of the first identification of an emerging technology remains an inherently difficult one. It is akin to identifying a very small signal that is embedded in a noisy environment. Almost by implication there is no obvious place to look and furthermore it is very difficult to determine if something that is detected is actually a new technology that is “emerging”. Once such an emerging technology has been identified, however, there are various ways in which one can keep track of its progress, all with their different strengths and weaknesses.

Relying on chance successes is not a satisfactory way of going about the search for emerging technologies. This is particularly relevant when one considers the fact that new technological innovations very often originate from outside a particular industry which it impacts (see for example Utterback, 1994, p.145). In a similar vein one should also not neglect the potential impacts of complementary products. James Bright remarks, “Does it make sense to commit a nation's research resources on the basis of total inexplicability and

lack of an anticipatory rationale? Surely, industry and government will benefit by earlier anticipation of the probable, possible, and emerging findings of science. By deliberate, explicit analysis, we ought to be able to provide somewhat earlier anticipations of new science and its socioindustrial implications ...Are we content to be 'scientific' about everything but science itself?" (1986, p.1). Utterback and Brown state that, "One of the most difficult problems in managing technological innovation is anticipating the direction and impact of technological change... Attempts to forecast the direction and to assess the impact of technological changes have been incomplete, leaving much to be desired in the terms of method and reproducibility. This, however, is not a valid argument against using the best available information and assessments of technological change" (1972, p.5).

A systematic framework for gathering and processing data is a much more rewarding strategy than grasping for "straws in the wind" as Utterback and Brown put it (1972, p.7). Several structured approaches have been applied in the past in attempts to identify emerging technologies. Porter *et al.* describe a framework for conducting a *technological monitoring* operation (1991, p.114-135). The objectives of the monitoring, as they see it, are much broader than just the detection of emerging technologies, although that can certainly be one of the objectives. Utterback and Brown suggest the use of *signals* to identify technological change (1972, p.6). Even radical technological breakthroughs cast "shadows" that signal their imminence. These shadows are initially manifested in discussions, speculations and suggestions. Later they become more formalized in proposals and technological articles, and later preliminary designs and prototypes appear. One thus finds that "... an innovation may be seen in increasingly refined, enlarged, and more effective material forms long before it achieves widespread use", and that the information incorporated in successful innovations has been available for several years prior to its use (Utterback, 1994). A firm's commitment of resources may, for example,

signal that the idea generation phase of the innovation cycle is over and that a serious development effort is about to commence. Utterback and Brown also suggest that monitoring the pattern in which companies patent new inventions can serve as a rich source of signals (1972, p.13). The tracking and interpreting of such patenting patterns has grown into a niche market for technology consultants. Narin *et al.* (1992) and Mogege (1991), among others, have shown how the patent literature can be used to develop technology indicators.

Martino also discusses strategies to monitor for breakthroughs and suggests that one focuses on signals that act as precursors to a breakthrough (1993a, p.192). He points to the fact that an active monitoring of the environment is required, rather than just a casual scanning for items of interest. The problem is, of course, to identify *a priori* what the precursors are, and where to look for them. Rather than just scanning the technological domain, Martino suggests that one also look at the economic sector, managerial sector, the political sector, the social sector, the cultural sector, the intellectual sector, the religious-ethical sector and the ecological sector. In another publication he shows how Bayesian updates of information pertaining to prior innovations can be used to generate a probability density function which can in turn be used to estimate the time lag between a precursor event and the event to be forecasted (1993b). In a recent textbook he also describes correlation methods that can be used to identify precursors for emerging technologies (1993a).

Rappa has advanced the notion that the emergence of a new technology is coupled to the likelihood of researchers continuing to work in the field (Rappa, 1994a). He postulates that, although any single actor (individual or organization) may have a relatively small

influence on the process of the emergence of a new technology, the collective wisdom of the research community reflects the confidence that they have in the progress of a particular technology — if it is promising they will continue to work in the field and if not they will leave the field for something else. He proposes the notion of calculating hazard functions to express the likelihood of researchers exiting from research in a given technology, and demonstrates the applicability to several cases. In summing up the concept, Rappa notes that just as the price of a share on the stock exchange reflects the common wisdom of the market by aggregating a myriad of possible influencing factors concerning a given company, the hazard rate of the research community aggregates numerous factors that influence individual engineers, scientists and organizations to continue or drop research in a given emerging technology (1994b). Investigating the population dynamics of research communities may thus be another approach to identify and track emerging technologies.

Rather than directing the search at the new emerging technology itself, however, it may be advantageous to use an indirect route by *focusing on the demise of mature technologies*. From the accumulated knowledge base on the processes of technological innovation, especially the diffusion of technology and the substitution of one technology with another, we know that the rise of an emerging technology is often associated with the demise of an older, more mature technology. In this regard, Foster speaks of *attackers* and *defenders* (1986). Relying heavily on S-shaped growth curves, he shows how an older, defending technology can be attacked by a new, emerging technology. Figure 2.1 shows a typical S-curve. In the case where the new technology is attacking an older, established

technology in a particular market niche, one can thus argue that *if it is possible to detect signals that a mature technology is “dying”, such signals may indicate that a new technology is emerging.* If this hypothesis is true, the identification of *mortality indicators* of mature technologies can be a powerful technique to aid in the identification of emerging technologies. It

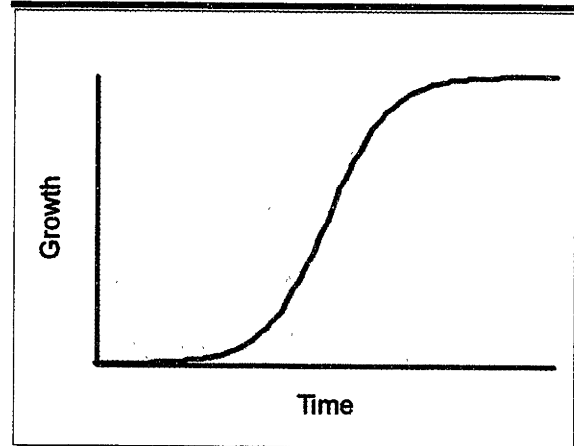


Figure 2.1 A typical S-curve.

will be particularly useful in generating clues where to search for emerging technologies, since the market niche has already been identified. The ability to identify indicators that an older technology is under attack from an emerging technology can be equally useful from the viewpoint of the company that has an interest in the older technology, since they will have to formulate an appropriate and timely response. Mature technologies are usually well-defined and very visible. Their growth is typically well advanced and is either approaching, or has entered, the flattening out phase of the S-curve. In order to pursue this line of reasoning, it thus becomes necessary to investigate the characteristics of mature technologies, particularly with the aim of finding signals that indicate that the mature technology is being attacked by a new, emerging technology.

To illustrate the concept, consider for example Modis and Debecker's findings on patterns of active service contracts in the mini-computer industry (1991). They examined the service life cycle of computers and found that the cumulative sales of computers follow S-shaped curves, but that the service life of the same computers follow so-called *end-of-life* curves. The latter take explicit account of the mortality of products. In their analysis

Modis and Debecker kept track of the number of *active* service contracts for certain generations of computers, noting that hardware maintenance contracts for computers closely follow systems sales. Initially the number of contracts increase at the same rate as sales. However, whereas cumulative sales follow the logistic S-curve, the number of active contracts reach a peak and then start declining as machines age and become obsolete. Modis and Debecker point out that the *graph depicting active service contracts peaks before the cumulative sales does*. As an explanation for this phenomenon, they argue that “... the total number of units sold of a particular product increases with time, reaching a ceiling at the end of the product’s life cycle. The number of products *in use*, however, never reaches the same ceiling as there is a certain mortality among the products sold” (1991, p.573). They found that computer generations are replaced due to technological obsolescence rather than because of aging *per se*, and confirmed the notion that computer models are phased out as a generation, rather than personal cars, for example, that are phased out individually. Computer models thus phase out as their generation becomes outdated, independently of when they were sold. Tracking the number of service contracts or another similar parameter may thus prove to be a mortality indicator for mature technologies.

Although there are certainly many aspects and characteristics of mature technologies that can be investigated as potential mortality indicators, we shall concentrate on one particular phenomenon in this thesis, viz. the *oscillatory behavior that is often detected in the mature phase of the growth curve of technologies*. Figure 2.2 shows an example of this

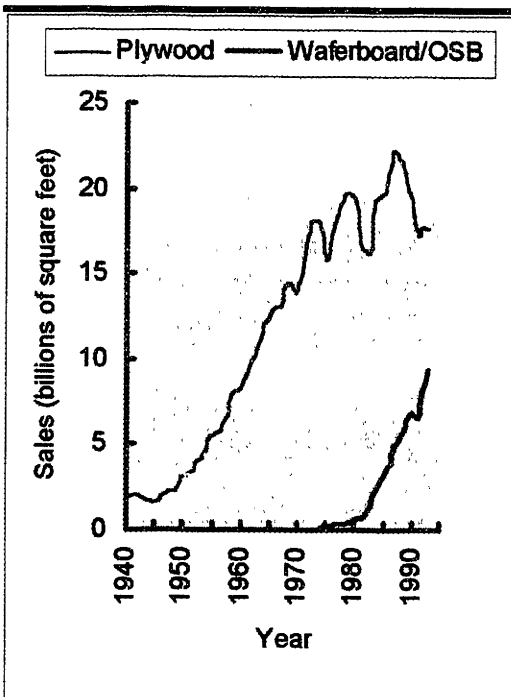


Figure 2.2 Sales of plywood and waferboard/OSB in the US (after Montrey and Utterback, 1990, with additional data from *RISI*, 1993)

type of behavior. It is based on research by Montrey and Utterback and shows the annual sales of plywood in the US as well as the annual sales of waferboard/OSB (1990) with additional data from *RISI* (1993). Note how the emergence of a new technology (waferboard/OSB) coincides with the onset of oscillatory behavior in the S-curve of the mature technology (plywood). In their article Montrey and Utterback suggest that oscillations in plywood's S-curve is triggered by the emergence of waferboard/OSB.

In order to investigate the hypothesis that the emergence of a new technology that attacks a mature technology can trigger oscillations in the mature technology's growth curves, it is necessary to develop an understanding of how technologies compete. In the next chapter we therefore launch into an investigation of technological competition, drawing heavily on ecological analogies. The graphical presentation of the hypothesis in terms of S-curves also suggests that a mathematical model that can aid in the simulation of competition models will be a very useful tool, not only with regard to this particular research avenue, but also as a general managerial aid. Such a model is developed in Chapter 5. In Chapter 6 we return again to address the issue of the oscillatory behavior in

the growth curves of mature technologies and examine their applicability as mortality indicators.

A MULTI-MODE FRAMEWORK FOR INTERACTION AMONG TECHNOLOGIES

“The innovator makes enemies of all those who prospered under the old order, and receives only luke-warm support from those who would prosper under the new”

Niccoló Machiavelli
The Prince

Technological change, substitution and diffusion

The quest for an understanding of the notion of mortality indicators for mature technologies, as discussed in the previous chapter, drives a larger and more fundamental need to comprehend the mechanisms whereby technologies compete. Recall that we are particularly interested in mortality indicators of mature technologies that are brought about by the emergence of new technologies. It is therefore necessary to launch an investigation into the mechanisms whereby technologies compete, particularly the reciprocal effects that the competition has on the competing technologies. In this chapter we thus explore the nature of competition between technologies, drawing heavily on the experiences and insights of the discipline of ecology. It is pointed out that the *growth rate* of a population is a fundamental mechanism whereby growth is regulated and as such seems to play an important role in the reciprocal effect that competing technologies have

on one another. A multi-mode framework, based on the notion of reciprocal effects on growth rates, is proposed as a useful way of thinking about and examining the interaction between technologies.

The term *technological progress* is a very general expression and has been used to describe a widely encompassing array of concepts (see for example Boskin and Lau, 1992; Mokyr, 1990; Freeman, 1986; and Nelson and Winter, 1982), in fact Rosenberg states that technical progress is not one thing, but rather it is many things (1982, p.3). Dosi notes that “... From a longer historical perspective, a view with respectable consensus holds that all the processes of economic growth and social change — at least since the English Industrial Revolution — cannot be explained without reference to the introduction and diffusion of major technological innovations” (1991, p.180). Economists generally agree that technological progress contributes significantly to macroeconomic welfare and growth. The contemporary view that technological diffusion *per se* can contribute to technological and economic progress and can be stimulated by appropriate government and other programs, gives further impetus to the study of diffusion related issues (see for example Kamann and Nijkamp, 1991). In this thesis we shall not direct our attention at the societal and economical effects of technological change, however, but instead consider the effects of competition among technologies on the diffusion of technology.

The view of technological progress that we take is that of *technological change for the better*, i.e. the technology is improved as it changes. Girifalco considers technological change to focus "... on the techniques, their attendant devices, products and processes, and the effects of these on individuals and society" (1991, p.1). The dynamics of technological change is concerned both with the *rates of change* and the *forces* that drive the change. The rate of change is usually considered with respect to time as the independent variable, but other independent variables certainly are also legitimate and have certainly been used, e.g. the research effort expressed in person-hours or dollars. As Girifalco points out, "... Technological change is a dynamic process that encompasses an enormous array of events, influences, motivations, individuals, and institutions. It is a process in the sense that it takes place in time as a series of linked events. While it is often easy to recognize technological change, it is often not so easy to define it with sufficient generality and precision to support a detailed analysis of how and why it occurs" (1991, p.1).

The process of technological change is often described in terms of an innovation paradigm (see for example Utterback, 1994). It is, however, important to distinguish between the concepts of *invention*, *innovation* and *diffusion*. Dosi refers to the Schumpeterian notion that invention concerns the first development of a new artifact or process, whereas innovation entails its economic application and commercial exploitation (1991, p.181). Diffusion, on the other hand, relates to the wide scale adoption users. Our primary

concern is with the *diffusion* aspects of the innovation cycle. As Linstone and Sahal put it, "... The combination of two uniquely human characteristics — intelligence and adaptability — has impelled man to substitute wheels for muscles, agriculture for hunting, aircraft for surface vehicles, and preventive inoculations for disease treatment" (1976, p.xiii). The dynamics of technological change and the subsequent technological progress have been embodied in the substitution of new and better technologies for old ones. However, one can hardly view a new technology as having displaced an older one or being substituted for an older one (e.g. color TV replacing monochrome TV) when a single technologically viable sample of the new technology has been produced or manufactured. In congruence with the innovation paradigm, we therefore consider substitution as *successful substitution in the market place*.

From the substitution viewpoint, the old and new technologies are usually intended to perform the same function, for example the replacement of wood floors by plastic tiles, the replacement of vacuum tubes by transistors and the replacement of sailing ships by steam ships. Often however, the functions do not overlap exactly, i.e. the new and old technologies may serve additional market niches in addition to the common niche. Very often a new technology exhibits capabilities that open new markets that were not accessible to the old technology. Cooper and Schendel estimated in 1976 that 50% of the applications for transistors were for uses that were made possible by transistors (1976, p.63), i.e. that could not be addressed by vacuum tubes. Utterback developed a framework

to evaluate the impact of innovations where one of the classifications he uses is whether the new innovation broadens the market (1994, p.206). He lists, for example, electronic calculators, celluloid film, semiconductor memory and integrated circuits as innovations that broadened the market, rather than just being substitutes. In addition, he points out that radical innovations can also give rise to entire new industries, as in the case of the typewriter, automobile and television. On the other hand, an older technology may serve some market needs that are not addressed by the new technology. This phenomenon is often observed when older technologies that have been supplanted by newer technologies survive on a small scale to serve specialized but limited market niches. Even though transistors replaced valves for practically all switching and amplifying applications, a small market for electronic tubes remains, typically for military customers.

The impact of the widespread proliferation of technology on society has been equally as profound as the advancement in the performance in technology (substitution). We shall refer to this process of proliferation as the *diffusion* of the technology. Rogers defines diffusion as "... the process by which an innovation is communicated through certain channels over time among members of a social system" (1983, p.5). The Schumpeterian view of diffusion is that it is the process whereby the technology (or innovation) is adopted into general use by more and more users (Dosi, 1991, p.181). It is important to realize that the diffusion process is inherently a social one, in the sense that individuals ultimately decide whether to adopt a particular technology or not. The diffusion of

technology has been the subject of extensive research over a protracted period of time. It has attracted the attention of researchers in a wide variety of disciplines, including the management of technology, marketing, sociology, anthropology, education, communication, geography, economics and psychology. A comprehensive history of the development of the research genre of technological diffusion can be found in Rogers (1983). A more recent review is given by Dosi (1991, p.179). From the diffusion viewpoint one is concerned with the rate at which the technology grows toward a saturation limit in the market niche and (according to Girifalco) not overtly concerned about the “divestment or displacement of an old technology” (1991).

The processes of substitution and diffusion are intimately linked, although there are subtle but definite differences between them, depending on how these processes are viewed and defined. Since substitution is exemplified as substitution in the marketplace, it is closely related to the diffusion of technology, which can be viewed as an increase in the spreading of the technology throughout the marketplace or an increase in the number of adopters. In the case of substitution, the battle is fought between two or more technologies for relative share in the marketplace, whereas in the case of diffusion, the battle is for absolute acceptance in the marketplace whether another competing technology is present or not. More often than not, however, there are other competitors. Girifalco draws a distinction between the processes of diffusion and substitution in that he views diffusion as being concerned with “... the rate at which a technology spreads and approaches its saturation

limit”, whereas substitution is concerned with “... the rate at which one technology replaces another” (1991, p.144). In Girifalco’s terms, there is one special case where substitution and diffusion are identical, viz. “... when only two technologies exist for a given market or function and when the market is fully saturated by the sum of the two technologies throughout the time” (1991, p.144).

Rather than measuring technological change in terms of the increase in technical performance of the technology itself (as in technological forecasting), it can also be measured in terms of diffusion and substitution. An increase in the *diffusion* of technology implies that its use is becoming more widespread and hence one can assume that more users are deriving benefit from it. On the other hand, an increase in the *substitution* of one technology for another implies that the market is showing a preference for one technology over another. Although one would intuitively think that this implies that technologically superior products and processes are substituted for inferior ones, it will be shown later that this does not necessarily imply that the market selects the technologically superior product or process, though. Units of analysis are discussed in more detail in the next chapter, but it is appropriate to mention here that substitution data is usually presented in percentage of market share captured, whereas diffusion data is usually presented in a measurable quantity such as sales revenues or the number (rather than the percentage) of households that has adopted an innovation.

The S-shaped curves that are commonly found in studies on technological diffusion and substitution are also often encountered in studies and forecasts relating to technological performance. Hence it is appropriate to point out the relation between technological diffusion and substitution on the one hand and technological forecasting on the other hand. The discipline of technological forecasting is primarily concerned with the estimation of future trends in the *performance characteristics of the technology*, rather than the diffusion or substitution aspects. Langford quotes Lenz (1969, p.2) as defining technological forecasting as "... the prediction of the invention, characteristics, dimensions, or performance of a machine serving some useful purpose for society" and Bright as defining it as "... a probabilistic prediction of future technological attributes, forms, or parameters reproducible according to a system of analysis resting on quantitative relationships or other logic rather than on intuitive opinion" (1969, p.2). Porter *et al.* take a broader view in the sense that they consider technological forecasting to deal with causal elements of any sort, be they social, economic or technological. The focus is, however, on new technologies and changes in existing technologies (1991). Martino defines technology forecasting as "... a prediction of the future characteristics of useful machines, procedures, or techniques" (1993, p.1). In this thesis we are not concerned with the technical performance as such, but rather with the diffusion and substitution of technologies.

Analogies between ecological and technological systems

Interdisciplinary approaches to research can sometimes offer exciting new insights to old problems. If analogies between two fields can be found and there is an empirical base to support such analogies, one is often able to apply the paradigms and solutions of one research area to the problems of a seemingly unrelated other area. Hence we now turn to the field of ecology to explore whether the concepts and principles of that field can offer analogies that might be useful in formulating a framework for evaluating technological competition. In this section we discuss several analogies between ecological and technology systems, the purpose of which is not to develop fully fledged, exhaustive and complete analogies that will stand up to stringent academic scrutiny, but rather to explore concepts that might be applicable to the domain of technological competition and innovation.

Ecology is the branch of biology dealing with organisms' relations to one another and also to their environment (Sykes, 1976). This focus on the interdependence and competition between species as well as inter-species competition makes ecology a very attractive discipline for the study of other fields that deal with related problems. Ecological models are often used to model the growth of inorganic systems, including social systems, political systems and organizational models (see for example Hannan and Freeman, 1989; Van der Ploeg, 1987; Burgelman, 1991; Samuelson, 1971; and Herman and Montroll, 1972). Several researchers have studied applications of ecology and evolution to

technological systems (as opposed to companies involved in technology development or use), among them Basalla (1988), Mokyr (1990), Farrell (1993a, 1993b) and Kwasnicka, Galar and Kwasnicki (1983). Many of the mathematical models that have been developed to model technological growth, in fact, stem from ecological models. In the following chapters we shall consider the applicability of some of the mathematical models that have been proposed to model competition between animate species, to competition between technologies.

Theory of evolution and natural selection

One of the major theories of evolution was formulated by Darwin and is known as *Darwin's theory of evolution* (see for example Hannan and Freeman, 1989). This theory is based on the premise that evolution of species is propagated by survival of the fittest, the fittest being selected by some process of natural selection. Lotka's view that "... The popular and also the scientific conception of evolution contains as an essential feature the element of progress, of development..." (1956) is consistent with our own statement that we view technological progress as technological change for the better. The theory of evolution has since been adapted by various other disciplines. Social scientists, for example, have adopted this theory and as such it has become known as Social Darwinism (Hannan and Freeman, 1989, p.35). In this form it was applied to justify inequality and unequal advantage under industrial capitalism, the argument being that individuals that rose to the top did so because they were the "fittest". Sahal states that "... it is apparent

that the innovation process in a wide variety of fields is governed by a common system of evolution” (1985, p.62).

Parallelisms can certainly also be drawn between ecological and technological evolution. It is well known that technologies evolve over time — in fact this is one of the driving forces of technological progress. Technological innovations can be classified in various ways, one of the distinctions being between radical and incremental changes (Utterback, 1984). The theory of evolution is indeed compatible with incremental changes in technology, since one of the characteristics of the unit that has undergone the process of evolution is that it has adapted itself to changing environments as the evolutionary process continued. The question may be posed as to how the adaptation process occurs and what criteria shape and drive the selection of the adaptations. However, as Fisher has pointed out (1930 as quoted by Hannan and Freeman, 1989, p.18), natural selection is just one of the processes whereby evolution can occur. Another could be random genetic events. Perhaps such random genetic events can be equated with more radical breakthroughs in technology, as opposed to incremental improvements.

The concept of the “survival of the fittest” is applicable to the notion of a technology that withstood the test of time. In this case it is compatible with the concept of a dominant design (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; and Utterback, 1994). Utterback describes a dominant design in a product class as “... the one that wins

the allegiance of the marketplace; the one that competitors and innovators must adhere to if they hope to command significant market following” (1994, p.24). In the same vein, Arthur refers to technologies that get “locked-in” (1989).

Natural selection is an optimization process (Hannan and Freeman, 1989, p19) but does not necessary lead to the best biotic solution, just as the dominant design does not necessary represent the best technological alternative. Hannan and Freeman point out that, with respect to organizational ecology, an observable population may be “... very far from ideal in the sense of adaptation, either because good designs have not yet been exposed to selection or because the environment keeps changing faster than the set of organizations can change ... Nothing in the structure of evolutionary arguments supports the assertion that the forms that proliferate are well adapted in an engineering sense. In no sense does the use of a selectivity logic imply that this is the best of all possible worlds ... Selection models insist on the importance of randomness in success” (1989).

The same can certainly be said of technology. One should not assume that the mere existence of a technology is proof of it being well adapted. The QWERTY keyboard is frequently mentioned as a good example of a suboptimum product that has survived as the “fittest”, although it is not the best technological solution (David, 1985)¹. Arthur

¹ Arguments have been made, however, that the QWERTY keyboard may be more optimized than is generally recognized. See for example Liebowitz and Margolis (1990).

mentions narrow gauge British railways, the US color television standards, the programming language FORTRAN and the light water nuclear reactor as other examples of technologies that were widely diffused even though they did not represent the best technological solutions (1989, p.126). It is sobering to take note of Abernathy, Clark and Kantrow's warning that, "... As does a biological species that has become perfectly adapted to a particular environmental niche, mature industries carry with them the implicit threat of extinction or, at least, catastrophe if environmental conditions should suddenly shift (1978, p.6).

MacArthur and Levins suggested that evolution influences adaptive strategies via the investments that are made in each reproductive attempt (1964 as quoted by Hannan and Freeman, 1989, p.118). In the so-called *r-strategy*, fixed resources are spread thinly over many reproductive attempts. Because the resources per reproductive attempt are small, the chances of survival of offspring are slim. However, under favorable conditions, such populations grow rapidly. This strategy hence maximizes the intrinsic growth rate. The fast growth rates offer the possibility of responding swiftly to new opportunities, but at the expense of not being very robust in the face of competition. Environments that change fast and where high mortality rates can be offset by high birth rates, can typically accommodate *r*-strategies. An alternative strategy, the so-called *K-strategy*, calls for a small number of reproductive attempts with a lot of resources invested in every attempt. Offspring thus have good chances of survival so that the species can survive in hostile

competitive environments. Although this is a more robust strategy, the speed of response is very much slower. K-strategies are typically found in environments that change slowly.

The parallelisms between technological innovation and the r- and K-strategies in ecology are remarkable. The r-strategy would correspond to the case where new products are rapidly commercialized with minor changes between different versions. Typically one would expect to learn from market acceptance or rejection which adaptations are necessary for the next product. *First mover* initiatives, which rely on the ability to act quickly, will also be congruent with this approach. K-strategies, on the other hand, would be associated with companies that concentrate on *efficient production*. Hannan and Freeman comment that new companies that use first mover strategies often exploit new technologies and achieve high initial growth rates. However, slower companies that invest in efficient production often compete successfully with the first movers, in some cases taking the market from them (1989, p.119).

Gradualism

Darwin postulated that evolutionary change came about gradually and continuously. Marx, a contemporary of Darwin, supported a similar view with respect to continuous change in technology and particularly to the evolution in machine design. However, referring to the formation of geological formations, Hannan and Freeman contend that there is evidence that most speciation took place in periods that were short on a geological

time scale (1989, p.38). They conclude that, contrary to Darwin's hypothesis, evolutionary change does not appear to be gradual and continuous, but rather "... episodic, with sharp divergence in character in brief geologic periods". Gould and Eldridge (1977 as quoted by Hannan and Freeman, 1989, p.38) and Stanley (1979 as quoted by Hannan and Freeman, 1989, p.38) have advanced the notion that evolution takes the form of *punctuated equilibria*, i.e. where long periods of little change are interrupted by brief periods or punctuations in which there is rapid specialization and great increases in diversity.

There are equally strong viewpoints supporting the discontinuous nature of technological developments, among them Schumpeter (Rosenberg, 1982, p.5). A more contemporary view is that of Tushman and Anderson's cyclical model of technological change in which a period of incremental change is interrupted by a technological discontinuity that gives rise to a period of ferment change culminating in a dominant design (1986; see also Anderson and Tushman, 1990). Utterback states that "... One could generalize that in any product market there are periods of continuity, when the rate of innovation is incremental and infrequent, and periods of discontinuity when major product and process changes occurs" (1994).

In a related issue, one may consider the apparent differences between the evolutionary changes in biological systems and technological systems, the former evolving over millennia whilst the latter can transpire in months or years. Farrell postulates that one of

the factors playing a role is the nature of the mechanism of *transmission*, i.e. the transfer of genetic information from parent to child. In the case of living organisms, gene pools are unique and confined to a particular species. In the case of technology species, on the other hand, he contends that the “gene pools” are contained in the patent literature and other information sources that are available to a broad audience of interested parties (1993b). This free and open access to the genes of different technologies helps along their quick adaptation. Farrell hypothesizes that the genes combine in four basic ways to create new technological artifacts, the ecological parallels of which are hybrids, mutants, recombinants and metamorphs. He describes these as “... hybrid is just an organism that contains characteristics both of parents; ... mutant is the result of small, spontaneous genetic change occurring from one generation to the next, ... recombinant results from a particularly powerful ‘reshuffle’ of genetic material, producing a sum that is greater than its two parts, ... metamorph is the result of a mutation or recombination that causes dramatic, visible physical change in the new generation” (1993b).

Determinism

The issue of *inherent determinism* in the growth of technologies is a controversial one. In commenting on his analyses and forecasts on technological change, Marchetti notes that “... One of the objections almost inevitably popping up when presenting these results to learned societies or to interested bodies, is that the excessive determinism is unpalatable to

a voluntaristic society such as ours ... this determinism is behavioral and intrinsically generated, having nothing to do with external and metaphysical 'fate'." (1983, p.20).

The growth patterns of biotic and organic units are preprogrammed. Hence when a living organism is "born", its growth pattern is already set — there is a determinism in the growth trajectory. However, even though the growth pattern is internally determined, the biotic unit is still dependent on the environment to grow and survive. When a human is born, for example, its physical features are genetically determined, as is its growth trajectory. This pre-determined growth pattern should, however, be viewed as a *potential*, rather than as an embodiment of fate carved in stone. In order to fulfill the potential, it is necessary that the human receive enough nourishment to grow and that it grows up in an environment that can sustain its growth and survival. The environment in which the body grows and circumstances acting upon it in the process will also reflect its actual growth pattern. Hence external factors in the environment are necessary to fulfill the predetermined growth potential. Lotka observes that "... some of the features commonly ascribed to living matter as its peculiar and characteristic attributes seem irrelevant to the point of triviality". This remark applies particularly to the distinction sometimes claimed for living matter, that grows "from within", as distinguished from crystals, which, in a suitable mother liquor, "grow from without" (1956, p.9). He implies that an inherent growth pattern may be instilled in non-living units and offers certain chemical processes as examples.

The question now arises whether a technology also has a predetermined, “genetic” growth pattern. Are there factors that are pre-programmed into the technology that give a certain amount of inevitability to its growth? This question is pivotal not only with regard to the notion of technologies that seem to follow S-shaped growth curves, but also to the chaos formulation of technological growth that is considered later. If we accept that living organisms have a pre-programmed genetic (potential) growth trajectory and we accept Lotka’s assertion that certain non-living structures can also have a pre-programmed growth trajectory (in this case perhaps determined in a larger sense by the external environment), then the issue of whether a structure is *living or not* is not a prerequisite for it to have a pre-programmed growth trajectory. If so, what are the implications for the determinedness of the growth of a technology? The common factor between living beings and the chemical processes that Lotka points out to illustrate his point is that they are both governed by laws of nature. Although technology *per se* is also subject to the physical laws of nature, the diffusion of technology is a social process and consequently one can postulate that the whims of man play a larger and more dominant role than the laws of nature in the diffusion of technology. It is interesting to supplement Lotka’s views with that of Utterback and Suarez when they say that “... Unlike a crystal, the shapes taken by technological change or by industry are not necessary predetermined” (1993, p.1).

Stinchcombe offers an interesting perspective with regard to the determinedness of organizations (1965 as quoted by Hannan and Freeman, 1989, p.xiii). He suggests that

organizations may be “imprinted” with the “... social, cultural, and technical features that are common in the environment when the cohort is founded. Because imprinted characteristics are highly resistant to change, the current characteristics of populations of organizations reflect historical conditions at the time of founding rather than recent adaptations”. Stinchcombe thus suggests that there are some factors that are “present at the birth” of an organization that can have a long lasting influence on the organization and in that sense play a role in the “preprogrammed” destiny of the organization. This implied hysteresis can perhaps account for a certain determinedness in the growth of organizations and hence also in the technologies that they use and produce. One often finds that the nature of business decisions are strongly influenced by the culture created by the founders. Digital Equipment Corporation’s strategies, for example, were determined for a long time by the personal decisions of its founder, Ken Olson. As the nature of DEC’s technology was thus coupled to Olson’s judgments and the latter seemed to have strong convictions about the technology directions to pursue, Stinchcombe’s hypothesis would suggest that DEC’s fate was in a sense predetermined. A similar argument can be made about Henry Ford’s persistence with the Model T when market signals indicated the public wanted something new — a decision that led to the rise of General Motors.

Niche

The concept of a niche is an important one in the field of population ecology. The niche

Niche

The concept of a niche is an important one in the field of population ecology. The niche can be considered to be a resource space, and as such plays an important role in determining competition dynamics between species. In Hannan and Freeman's words, "... the concept provides a useful way to express how environmental variations and competition affect the growth rates of populations ... the niche is the set of conditions in which the population's growth rate is non-negative" (1989, p.95). Hutchinson defines a niche to be "... the set of environmental conditions within which a population can reproduce itself" (1978 as quoted by Hannan and Freeman, 1989, p.95). Hutchinson also advanced the concept of a *fundamental niche* as the set of all environmental states where a population can grow or sustain its level. The fundamental niche will thus characterize the growth rate of an isolated population. The *realized niche*, on the other hand, is the set of environmental conditions in which a population can maintain itself in the presence of competitors. Freeman and Barley refer to a niche as "the population's 'way of earning a living'" (1989, p.95). They refer to an organizational niche as "... that combination of resources that and constraints within which a particular organizational form can arise and persist". The concept of a niche is a very useful element or building block in the theory of competition between two or more species, and since competition between species (or in this case different technologies), is one of the major thrusts of this thesis, it is also an important one in this context.

Carrying capacity

The carrying capacity of ecological systems plays a significant role in the size of the population that can be sustained or supported in a niche. In the case of a herd of cattle or wild antelope, for example, it is well known that a field of given acreage can only sustain a herd of given size, implying that the resources (in this case the grazing) are limited. Freeman and Barley contend that the structure of a niche can be defined in terms of how environmental conditions affect carrying capacity. They also define two populations as being distinct if, and only if, "... their carrying capacities are affected differently by the same environmental conditions or similarly by different conditions" (Freeman and Barley, 1990, p.133) In terms of technology, the total size of the market can perhaps be viewed as the carrying capacity of the niche. Recall, however, from a previous section that the carrying capacity can obviously expand as new innovations broaden the market.

Growth rates and population densities

Before discussing the concept of growth rates, one should settle on a definition of growth itself. This task is certainly not a trivial one. In the case of biotic units one can consider the growth of an individual unit, where the assumption that there is a pre-programmed growth trajectory present, is very strong. From an ecological viewpoint, however, one would also be concerned with *populations* of units rather than just individual units, in which case the determinedness of growth is more complex.

Individual biotic units grow according to some growth rate. In the case of a single unit, the growth rate is an indication of how fast that particular unit grows to maturity as a function of time. Very often the growth rate is not a constant, but rather time dependent. Many cases where the growth of individual units follow an S-shaped curve have been documented (see for example Lotka, 1956). In the study of diffusion, however, one is concerned not so much with the growth of an individual unit, rather than with the growth of populations. Often the growth patterns of populations resemble the growth patterns of individual units. Population density as a unit of analysis is an important concept in ecology and as such has also been applied in organizational ecology. In the study of organizational ecology, the growth rates of interest are the rates of entry and exit of various firms into an industry (see for example Hannan and Freeman, 1989; and Utterback, 1994). In the next chapter growth rates of technological diffusion and substitution will be discussed in more detail.

In a previous paragraph it was stated that the carrying capacity of a certain acreage of grazing land to sustain a certain number of herbivores can be determined. Astute farmers will adhere to such limits. In a natural environment, a given area of bush will also have a carrying capacity, manifested in the number of antelope that it can sustain, for example. In this case the size of the population is regulated not by an astute farmer, but rather by nature itself. As the number of antelope approaches the carrying capacity, nature adjusts the growth rate to slow down the growth of the population of antelope. The ecological

system operates as negative feedback system in regulating the output, which can be considered to be the number of antelope in the population in this case.

The *growth rate* is thus an important mechanism for controlling the population density. Freeman and Barley state that the growth rate usually reflects numerous aspects of the environment (1990). Recall from Chapter 2 Rappa's observation that the hazard rate of research communities can be used as indicator to identify and track emerging technologies since it reflects the collective wisdom of an aggregate of factors and actors, just as the stock price does for a share. In a similar vein, the growth rate would seem to be an analogously basic variable with regard to competition among species, since it aggregates the influences of a large number of factors into a single important variable. In a later section we shall extrapolate this notion to competition among technologies as the basis for establishing a framework to classify modes of interaction between technologies.

Competition

Ecological competition theory was strongly influenced by Gause's experiments in the 1930s on the coexistence of related beetle species (Farrell, 1993a, p.169). The experiments were performed by first observing the growth patterns of the two species separately, i.e. where the two species do not interact and hence their uninhibited growth can be observed. As a next step the two populations were introduced into the same environment in order to observe their interaction. Gause's observations led him to formulate his *principle of competitive exclusion*, which states that two species that occupy the same niche cannot coexist in equilibrium (Hannan and Freeman, 1989, p.97). The

principle has since been shown to be too strong and that equilibriums for coexistence can be found. One can, for example, make the environment more complex by creating subenvironments in which the inferior competitor can hide or find a competitive advantage. In that case the argument can be made, however, that units are no longer competing in the same niche. In the technology domain such refuges can be created by instituting trade tariffs and protections, for example. Alternatively a technology can seek refuge by retreating into a specialized market niche that is out of reach of a more powerful attacking technology. Farrell describes the case of fountain pens that have retreated to the market niche of exclusive and expensive writing instruments as a defense against the attack from ball-point pens (1993a, 1993b). In the process fountain pens had to adapt their nature, changing from primary writing instruments to expensive and specialized instruments serving a niche market.

From an ecological viewpoint, the term *competition* is used to describe the process by which various species or various elements within the same species, vie for the same resources, and as a result have a negative influence on one another's growth rates. In a previous section we explored the notion of carrying capacity, coming to the conclusion that the ultimate population level of a herd of antelope will be limited by the carrying capacity of the acreage on which it grazes. It stands to reason then, that if another herd of a different species of antelope invades the first herd's territory, the two populations vie for the same resources and will therefore influence each other's growth patterns. Since nature regulates the population levels through the mechanism of growth rates, the two herds' influence on one another's growth patterns will be manifested through their influence on the other's growth rates. In this case each herd will have a negative influence on the

other's growth rate, just as a herd that grows very large will impose a declining growth rate on itself.

There are also cases where intra-species interaction can enhance the growth patterns and hence growth rates of each other. The tickbird is a bird that is often found in the same area as herbivores, preying on ticks that live on the herbivores. The interaction between these tickbirds and the herbivores is beneficial for both and hence, in principle, they will have a positive influence on each other's growth. The case where both links are positive is known as *symbiosis*, i.e. where the association of two different organisms living attached to each other or one within the other is to their mutual advantage (Sykes, 1976).²

On the other hand, there are also cases where one population exerts a positive influence on the growth rate of a second, whereas the second has a negative influence on the growth rate of the first. Such interactions are referred to as *predator-prey interactions*. It is important to note that, strictly speaking, predators and prey do *not* compete directly for the same resources. The resource for antelope is the grazing acreage. The antelope in turn, are food resources for predators such as lion, leopard and cheetah. Although the predators eat the prey, they do not eat the prey's food. Ecological predator-prey interaction can thus generally be viewed in terms of reciprocal effects on growth rates rather than as a process of vying for the same resources. This point will be referred to again later when we draw analogies to technological predator-prey systems. Predator-prey interaction has also been identified in organizational ecology. Hannan and Freeman studied the founding and disbanding rates of both craft unions and industrial unions, where they found that,

² The relationship between the related terms *symbiosis*, *mutualism* and *commensalism* is discussed later.

“... Craft unionism suppressed industrial unionism, but the reverse was not true” (1989, p.97).

Hannan and Freeman contend that competition, unlike conflict, is difficult to observe since it is often indirect. This is interpreted to imply that the fact that the competition is occurring is non-obvious and in some cases that the competitors are not identifiable. In order to address the problem, empirical ecologists study competition indirectly in an effort to determine the coefficients of competition. According to Freeman and Barley, they do not use Lotka-Volterra models (that are discussed in a future section), but instead use the relationship between competition theory and niche theory to obtain estimates of competition based on the overlap between niches as defined in terms of observed utilization of resources (1990, p.134). The statement concerning the difficulty to observe competition is in essence the problem statement of this thesis, i.e. the question if there are mortality indicators which signal that a mature technology is under attack by an emerging technology.

The applicability of the analogy between ecological and technological systems

It was mentioned before that the analogies and examples of similarities between ecological and technological systems discussed above are not intended to be complete or exhaustive. The issue of *classification*, for example, has not been addressed here. Nevertheless, the similarities between ecological systems and technological systems that have been pointed out above lend support to the notion that analogies can be drawn between the two fields. Apart from the empirical evidence that technological diffusion often follows the same type of growth trajectories as ecological systems, there is certainly evidence to support a broad based analogy between the two disciplines.

It is important to keep in mind that, even though there may be a strong argument for useful analogies between ecological and technological systems, there are also at least a few inconsistencies where the analogy fails. They can have a profound effect on the applicability of the analogy and should be borne in mind when drawing parallelisms. One of the major issues in this regard is the question of the determinedness that is inherent in biotic units but not in technology. In the case of living organisms there is an inherent ability to reproduce, which is not present in inorganic structures. Another issue is the level of unitariness of the unit of analysis. When considering a predator-prey system of lion and antelope, for example, one can assume for all practical purposes that one lion is as good as another and similarly for antelope. This is certainly not the case for technologies, industries and companies that all have different sizes, characteristics and strategies. From an ecological viewpoint the time constant of a predator-prey interaction with respect to the evolutionary adaptation of a lion is negligibly small, but in the case of technologies, the assumption may not necessarily hold. Even if one can identify a well-defined technological unit-of-analysis, technologies often evolve swiftly over their life cycles. Hannan and Freeman point to similar dissimilarities in attempting to apply ecological theory to the behavior of organizations, viz. in the case of organizations there is no clear-cut parallel to the parent. Moreover, there is no reason why individual organizations cannot live forever. Interestingly, the latter point implies that an organization can *directly* contribute to future generations (1989).

In the next chapter we shall consider mathematical models of technological diffusion, many of which originated in the field of ecology. Even though the diffusion of technology is a social process rather than one governed explicitly by the laws of nature, the qualitative analogies between ecology and technological systems indicate that the use of analogous

quantitative models may also be appropriate. There is certainly a lot of empirical evidence to show that similar patterns occur in ecological and technological diffusion.

A multi-mode, growth related framework for interaction among technologies

The core of technological innovation is embedded in technological change and advances. The whole concept of technological innovation is based on the notion that new technologies emerge that eventually replace older technologies. The various ways in which technological change can come about have been widely studied and various schemes of classifying the change have been proposed. Distinctions are often made, for example, between radical and incremental change, between product and process innovations, between competence enhancing and competence destroying innovations (Utterback, 1994, p.207), or between architectural and modular innovation (Henderson and Clark, 1990). However one chooses to view the changes that come about, clearly the process of technological innovation involves the creation of something new, whether it be products, processes or techniques. As the new innovation invades the market, it will obviously interact with the established technologies that already exist. The interaction is manifested in the diffusion of the new technology when it attempts, and often succeeds, in substituting the mature technology. This interaction between technologies is typically referred to as *competition* in the literature, pointing to the fact that there is a confrontational interaction between the new, emerging technology and the mature, established technology.

As with other growth processes, the new, emerging innovation usually starts as a small entity, often in an environment dominated by mature and established competitors. Very often a new and emerging technology threatens an older, mature technology in the sense that the emerging technology offers the potential of eventually providing enhanced value over the mature technology and thereby luring users of the mature technology over to the emerging technology. This can and often does lead to the eventual demise of the mature technology³, although frequently a small remnant of the mature technology remains to serve a specialized market niche. One frequently encounters the expressions *attack* and *defense* in the literature dealing with the dynamics of interaction between emerging and mature technologies. The setting of technology strategy is thus often concerned with issues relating to the emergence of new technologies and the response of mature technology to the emerging technologies — strategies for attack and defense. Such strategies have been described in some detail by Cooper and Schendel (1976), Cooper and Smith (1992), Foster (1986), Harrigan and Porter (1983), Soukop and Cooper (1983), Utterback (1994) and Williams (1983), among others.

The term *competition* is often used in the context of innovation and industrial economics. The meaning and intent of the term is generally understood even though an exact description of the term is not usually given explicitly. In a seminal paper Abernathy and Clark, for example, developed a framework for classifying innovation and competition (1978). They use the acquisition or development of particular skills, relationships and resources as classification criteria. The nature of the investigation that we are concerned with here, however, demands a definition of the term *competition* that can be applied more

³ Recall that one of the issues that this thesis set out to investigate was whether mature technologies exhibit mortality signals that actually indicate the emergence of a new technology.

rigorously to strategies for attack and defense, particularly if one wants to model the phenomenon of competition mathematically. Furthermore, the interaction between technologies is often not of one of competition in the strict sense of the word. As we shall see, there are many cases where technologies interact in a relationship that is not confrontational.

Following the discussion in the section on ecological analogies, the concept of a *growth rate* offers itself as a suitable and appropriate way of classifying the process of interaction among technologies. As we have seen in a previous section, not only does the growth rate seem to be a fundamental mechanism whereby the growth in populations is regulated, but it also has the ability to account for the aggregate of a multitude of factors. From an economic viewpoint there may be also be an incentive to focus on the growth rate as a classification variable. Blackman notes that "... The extent of investment in technological innovation is related to the perceived rate at which a market will develop for the new technology, and the rate of market development is in turn a function of the dynamics of technological substitution" (1974, p.4). Cooper and Schendel notes that "... It is not enough to judge that someday a new technology will replace an old one. Rates of penetration must be determined. When the Baldwin Locomotive Works was founded in 1831, it would have been of little value to tell the founders that someday their principal product would be obsolete. However, when Sylvania introduced a new line of vacuum tubes for computers in 1957, the rate of improvement of transistors then taking place was extremely relevant" (1976, p.66).

In general, *interaction* can be manifested in the concept of the reciprocal effect that one technology has on another's growth rate. Rather than confining the scope of an

investigation of the relationship between two or more technologies to pure competition it seems fruitful to expand the spectrum of interaction to include predator-prey interaction as well as symbiosis. By considering the possibility that one technology may either enhance or inhibit another technology's growth, one finds that three possible modes of interaction can exist, viz. *pure competition* where both technologies *inhibit* the other's growth rate, *symbiosis* where both technologies *enhance* the other's growth rate and *predator-prey interaction* where one technology *enhances* the other's growth rate but the second *inhibits* the growth rate of the first. A survey of the literature shows that with regard to technologies, pure competition is often discussed, symbiosis sometimes referred to but that predator-prey interaction between technologies is very rarely mentioned.

We can now propose a *multi-mode framework* within which to evaluate the interaction among two or more technologies, where the mode of interaction depends on the effect of the participants' effect on one another's growth rate. Within this framework we distinguish between pure competition, predator-prey interaction and symbiosis. The framework is aimed at providing a setting within which to evaluate attack/defense scenarios and strategies, particularly with regard to emerging versus mature technologies. It is believed that, in contrast to analyses that are bounded in scope to single modes (usually pure competition), the multi-mode framework proposed here provides a richer setting within which to examine the interaction among technologies. Not only do the multiple modes give one the flexibility to examine competition in the various circumstances where the different technologies inhibit and enhance one another's growth, i.e. in the three individual modes, but it also allows an investigation of the transitional effects as the interaction between the technologies transgresses from one mode to another with time.

The multi-mode framework is illustrated in Figure 3.1 for the case of two technologies. In principle, the framework can be extended to any finite number of technologies. Note that although there are three modes, there are two possible predator-prey interactions (depending on which technology is the predator and which the prey), and hence four possible types of interaction. In this thesis, however, we shall refer to three distinct modes.

		Effect of A on B's growth rate	
		Positive	Negative
Effect of B on A's growth rate	Positive	Symbiosis	Predator (A) - Prey (B)
	Negative	Predator (B) - Prey (A)	Pure Competition

Figure 3.1 Multi-mode framework for interaction among technologies.

The concept of considering interaction in terms of the effects that one species has on another's growth rate and the subsequent classifications of pure competition, predator-prey and symbiosis interactions have been recognized by ecologists (see for example Freeman and Barley, 1990, p.133). The use of such a framework to model technological interaction, does however, seem to be new, particularly with regard to the temporal shifts between interaction modes (as defined with regard to growth rates). A subtle difference in the way predator-prey interaction is defined in ecological systems and the multi-mode framework proposed here will also be pointed out in Chapter 5 where the benefit of mathematical rigor can be brought to bear.

Note that competition and symbiosis are cases where two species (or technologies) have the same effect on the other's growth rate. In the case of symbiosis each will have a positive (enhancing) effect on the other's growth rate, whereas in the case of competition each will have a negative (inhibiting) effect on the other's growth rate. One often finds that, where the literature discusses the interaction of technologies or technologically based companies, the discussion is limited to one or both of these cases. Barnett's discussion of the early American telephone industry where he discusses competition and mutualism, is a good example (1990). However, one gets the impression that little research has been done from a technological innovation viewpoint on technological predator-prey relationships.

It is interesting to note the analogy between the multi-mode framework proposed here and the concept of architectural and modular innovation advanced by Henderson and Clark (1990). They formulated the notion that apart from the well-known concepts of radical and incremental innovations (which correspond to the diagonal elements of pure competition and symbiosis in Figure 3.1), two other modes of innovation also exist, viz. architectural and modular innovation. In their paper they show a matrix very similar to that in Figure 3.1, in which architectural and modular innovations also represent non-diagonal elements of a two-by-two matrix (as do the predator-prey modes in Figure 3.1)

Temporal shifts between modes

The notion that the *modes of interaction between two technologies can change with time, differentiates the technological framework proposed here from an ecological one*. In an ecological predator-prey system, for example, lion and antelope will have a relationship where the lion is the predator and the antelope is the prey *ad infinitum*. Until Isaiah 11:6

comes to pass⁴, the nature of this interaction will *not* change. Interactions among technological systems and the related industries and companies, on the other hand, *do* change with time. These changes are manifested in the technology itself, product changes, process changes as well as changes in the structure of the industry and the various companies in the industry.

To illustrate the concept of temporal evolvment, Moenaert *et al.* compares the concepts of a product life-cycle (Figure 3.2) which describes the sales of a product over time, a technological life-cycle (Figure 3.3) which describes the rate of innovation over time and a technological S-curve, which describes the technological performance as a function of time (1990). The implicit notion in the discussion is that all these variables change with

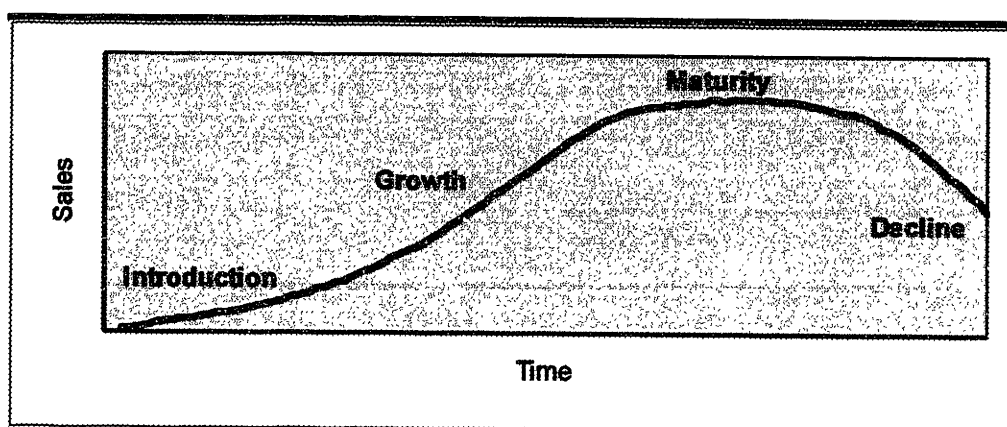


Figure 3.2 Product life-cycle (after Levitt, 1965).

time. The product life-cycle concept was popularized by Levitt (1965). He contends that the "... life story of most successful products is a history of their passing through certain recognizable stages", and defines the stages as market development, growth, maturity and

⁴ "... The wolf will live with the lamb, the leopard will lie down with the goat... the cow will feed with the bear, their young will lie down together and the lion will eat straw like the ox".

decline. The technological life cycle referred to is the Utterback–Abernathy model wherein they describe the evolution of assembled products, non-assembled products and processes with time (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; Utterback,

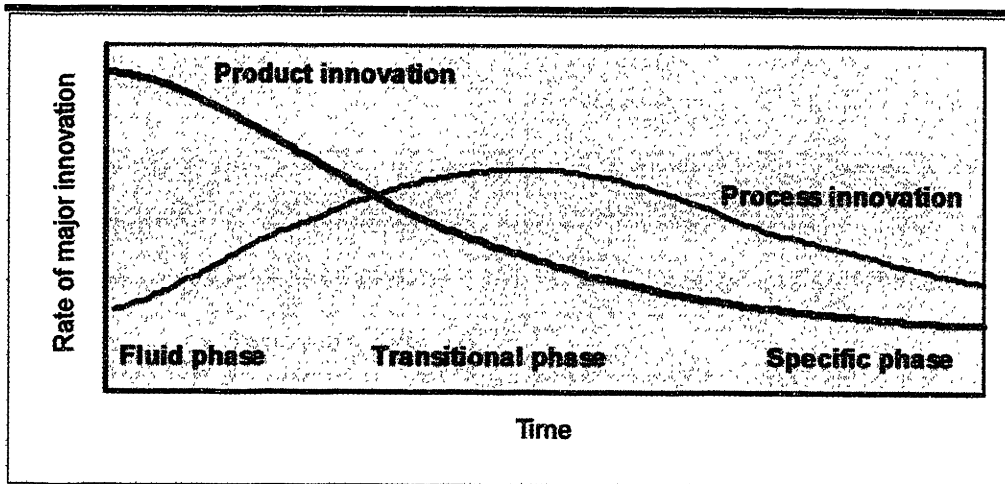


Figure 3.3 Technological life-cycle (after Utterback, 1994, p.83).

1994). They identify three distinct phases of evolution, viz. the fluid phase, the transitional phase and the specific phase. Each one of these phases has very different characteristics. The technological S-curve refers to the observation that the progression of technological development often follows an S-curve as a function of time (where time is the proxy of development effort) (Moenaert *et al.*, 1990; see also Martino, 1993, for a discussion of technological S-curves).⁵ By drawing attention to the three curves, Moenaert *et al.* want to stress not only the interrelationship and differences between diffusion, innovation and technological progress, but also their change over time.

Williams points out that "... Technological change itself is a dynamic relationship over time, but the overall structure of this advance within a competitive segment has a

⁵ Recall that a typical S-curve is shown in Figure 2.1.

generalized pattern” (1983, p.55). Soukop and Cooper stress that the business environment of an industry changes systematically over time as the product technology evolves through its life cycle (1983). Furthermore they contend that the relative evolvment depends on the level of maturity of the industry. To illustrate their case they point to the different scenarios when discrete transistors attacked electronic valves⁶ (which was considered to be a rather mature technology at the time), versus the scenario when integrated circuits attacked discrete transistors a few years later when the discrete transistor was still a relatively young technology. The time constants of change vary significantly from technology to technology and from industry to industry. There are, however, some cases where the change occurred very rapidly. Foster mentions that turbo fans took six years to replace turbo jets, whereas second generation turbo fans took about five years to replace first generation models; integrated circuits gained market share from 20% to 80% in six years; electromechanical cash registers lost market share from 90% to 10% in four years to electronic cash registers; and bias ply tire manufacturers lost 50% market share to radial tires in 18 months (1986). Cooper and Smith refer to CT scanners where four generations followed one another in about four years (1992). The notion that technologies and the industry in which they abide can have different stages has serious managerial implications since it implies that different strategies need to be developed and applied for the different stages (see for example Utterback, 1994). The transitional periods need to be managed with particular care (Loveridge and Pitt, 1990). Later in this section we shall consider possible scenarios for each of the three modes of interaction in the framework. However, *based on the discussion above, one can posit that interaction among technologies will, in general, shift from one mode to another with time.*

⁶ Also known as “vacuum tubes”.

Before we examine the characteristics of the individual modes and temporal shifts between the modes, it is useful to examine a case study that illustrates the nature of interactions from the viewpoint of reciprocal effects on growth rates. However, since the author of the article from which the case study is taken (Barnett) prefers to use the term *mutualism* rather than *symbiosis*, it is useful to discuss some semantical issues with regard to symbiosis and related terms first.

It was stated before that symbiosis is the "... association of two different organisms living attached to each other or one within the other to their mutual advantage" (Sykes, 1976). The concept of symbiosis is closely related to that of *mutualism*, which is "... the doctrine that mutual dependence is necessary for social well-being" and to *commensalism* which is where "...an organism lives harmlessly with or in another and shares its food" (Sykes, 1976). With respect to the technological systems we are interested in, symbiosis seems to be the more appropriate term since it is commensurate with species affecting one another's growth rates. Mutualism implies a necessary interdependence, which may also be present in order for reciprocal enhancement or inhibition of growth rates, but not necessarily so. The subtle difference here is whether the interaction merely enhances or inhibits both technologies' growth rates or whether growth and indeed survival of one of the technologies is dependent upon the other's presence and well being. Commensalism is obviously too weak a term for our purposes. However, we can definitely explore and exploit the commonalties between the terms, and in fact shall use the term *symbiosis* in a sweeping sense wherein the concepts of mutualism and commensalism are also included where appropriate.

Case study: Two technological diffusions in the telephone industry

Barnett did an extensive study on the early history of the American telephone industry (1990). In the study he investigated the effects of two technological innovations, viz. the change from magneto systems to the Hayes's common-battery and the use of line loading, on the type of interaction among early telephone companies. The aim of the study was test hypotheses concerning factors that resulted in competition on the one hand and mutualism on the other hand⁷. Rather than defining competition and mutualism as the reciprocal effect on the growth rate of the technologies *per se*, Barnett considers the effects on the companies as manifested in entry rates, exit rates and survival rates of the telephone companies. He concludes that "... if the density of organizations *with a specific technology* (italics added) increased failure rates, then there is evidence that those organizations generated competition. Conversely, if failure rates decreased as those organizations became more numerous, then there is evidence that they generated mutualism" (p.40). Even though this study is primarily concerned with the organizational ecology aspects of the companies, we can draw useful conclusions from the effects of the two technological innovations *per se* with regard to the proposed multi-mode framework. What is also of significant importance to this study is that Barnett comments that the competition changed form as time progressed, lending support to the notion of a temporal shifting between interactive modes.

Line loading is a technique whereby wire coils are used to change the impedance characteristics of the transmission lines that carry the telephone signals. By using line loading, the distance whereby a signal could be carried was increased drastically from about 30 miles to more than 300 miles. This innovation opened up the whole concept of

⁷ Predator-prey mode interaction is specifically not mentioned in the article.

long-distance telephone systems and gave rise to telephone companies that operated multiple exchanges. The second innovation was the introduction of the Hayes's common-battery. Before this innovation every subscriber had a battery and magneto power source located at the remote telephone. By hand cranking the magneto, a ringing signal was generated. This arrangement had many deficiencies, primarily standardization problems in the form of impedance mismatches of various systems. These mismatches precluded the interconnection of different systems. Furthermore, the operation of the system depended on each subscriber to maintain his/her own battery, something that not everybody did diligently. The common-battery system, on the other hand, replaced the magnetos at the various remote telephones with a common power source located centrally at the exchange. This resulted in standardization as well as improved quality in service.

Figures 3.4 and 3.5 show the number of telephone companies in Pennsylvania that adopted the common-battery system and line loading from 1880 to 1935 (after Barnett)⁸. For the purpose of this study, we can interpret these two graphs to show the diffusion of the two technological innovations. In Figure 3.4 we see that the common-battery is replacing the magneto system as time marches on, even though the diffusion of the magneto system peaks after the introduction of the common-battery system. On the other hand, we see the same diffusion pattern of single switchboard and multiple exchange companies, i.e. companies that did and did not use line loading in Figure 3.5. Since the single switchboard/multiple exchange company unit of analysis is a proxy for the adoption of the line loading technique by telephone companies, we deduce that the same diffusion pattern is followed for line loading versus the alternative, which is not using line loading.

⁸ Note that the multiple exchange companies in Figure 3.5 are used as a proxy for companies that used line loading.

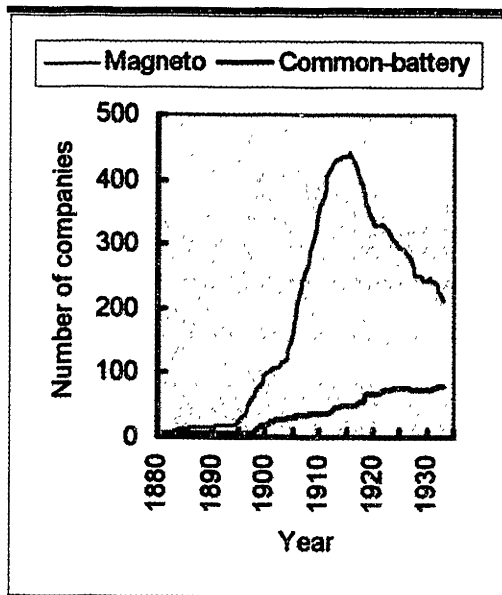


Figure 3.4 Telephone companies in Pennsylvania that used magneto and common-battery systems (after Barnett, 1990).

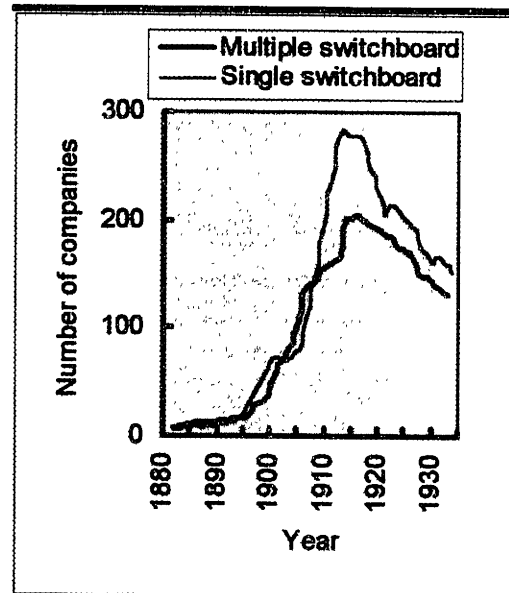


Figure 3.5 Telephone companies in Pennsylvania that used multiple (line loading) and single exchanges (after Barnett, 1990).

From the study Barnett found that there were mutualistic interactions as well as pure competition among companies and by implication, among the relevant technologies. By making and statistically accepting certain hypotheses, he draws the following conclusions:

- Nonstandardized organizations, i.e. those using magneto systems rather than common batteries reduced each other's viability and hence use of the magneto resulted in pure competition. Barnett reasons that, since nonstandardized systems do not work together, they fragment the industry and as a result *all* organizations in the industry are less viable. Use of the magneto created diffuse competition, i.e. competition among *all* firms regardless of their geographical proximity to the magneto firms. As Barnett puts it, "... It was the primitive, nonstandardized technology that inhibited the advanced, standardized innovation. Consequently, not until the numbers of magneto companies declined did the common-battery companies proliferate" (p.41).

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- Differences brought on by technological change bring about mutualism since it makes organizations complementary. The prerequisite is, however, that they must be standardized. If not, they will compete, rather than have a mutualistic interaction. Barnett observed competition as well as mutualism among standardized companies, i.e. those using the common-battery. He accepted the hypothesis that "... among the common-battery companies, the multi-exchange and single-exchange populations each increased its own mortality rate but decreased the mortality rate of the other". Even though Barnett does not mention it, we can also recognize elements of predator-prey interaction here.
 - "... Despite their technological superiority, the common-battery companies do not appear to have generated competition for the less-sophisticated magneto firms. Instead, the common-battery companies increased failure rates only among themselves" (p.55). Furthermore, "... the advanced multi-exchange companies caused the technologically primitive single-exchange company to have a relative survival advantage" (p.51).
 - Standardized companies, i.e. those using common-batteries, that were differentiated, were mutualistic. However, multi- and single-exchange companies, i.e. those using and not using line loading, respectively, were found to have increased each other's mortality rates. Without taking standardization into account, the mutualism effect becomes competitive. Taking the findings together, though, they show that neither standardization nor technological differentiation alone is enough — both must be accounted for simultaneously to show mutualism.

This case of the early American telephone industry illustrates some of the effects of competition and symbiosis between technologies, or at least the secondary effects on the

companies using these technologies. What is important and relative to our study, is that Barnett has identified, albeit in an implied way, competition and mutualism as two distinct modes of interaction brought about by the use of various technologies.

Interaction among technologies

The three modes of interaction that make up the proposed multi-mode framework are all based on the notion of the reciprocal enhancement or inhibition of technologies' growth rate. The combination of enhancement and inhibition between two technologies determines the modes of interaction. In order to investigate the characteristics of the three modes, it is therefore appropriate to examine conditions under which one technology will enhance or inhibit the growth rate of another, as these will serve as building blocks for the three modes in the framework.

In order for a technology to grow to maturity, it has to have a positive growth rate. In the next two chapters we examine various mathematical models for the growth of technologies, but at this point it will suffice to say that there will be factors that influence the growth rate positively and some that influence the growth rate negatively. The multi-mode framework is based on the premise that other technologies contribute to a specific technology's growth rate (together with other factors) by either influencing the technology's growth rate positively or negatively. Rather than create a null-class of

interaction for the trivial case where two technologies do not influence each other, zero influence is considered to be a limiting case of either positive or negative influence.

An interesting extension to the framework can be the case where a new technology emerges that seems to be expanding into a new market niche not previously occupied by a mature technology — a truly new innovation. Eventually, however, newer technologies will come to challenge the pioneer, but there will be a period where the first technology can grow without competition into the niche. One can argue that bar coding is such a technology (Seideman, 1993).

Since the emergence of new technologies and the interaction they have with more mature technologies is of particular interest in this study, consider now the case where a new technology emerges, attacks and eventually replaces a mature technology. Intuitively (and without the benefit of the multi-mode framework), one might want to argue that the two technologies are in competition and hence have negative influences on one another's growth rates. However, this is not necessarily so. There are many examples where the mature technology has actually prospered when the new technology emerged. Poznanski, for example, studied the demise of old steel making processes (notably the Bessemer and open hearth processes) in various countries and found that "... the first years of expansion of new production in all countries were accompanied by a stability or increase in open-hearth output" (1986, p.306). He also refers to a study by Gold, Pierce and Rosegger

(1970) who found that "... output from old technologies grew faster than that from the new ones at certain periods of time, not only in the case of open-hearth, but also of by-product coke, coal cutting, and coal washing...". It might well be argued that this growth of the mature technology was not necessarily caused the influence of the emerging technology. There are, however, specific examples to illustrate cases where the emerging technology does in fact enhance the growth rate of the mature technology. In their study of the electronics component industry, Soukop and Cooper found that "... generally the appearance of a new product technology initially has little or no adverse effect on the market for traditional products, and in fact may increase their total sales by stimulating efforts to improve their performance and/or cost characteristics" (1983, p.221). This "sailing ship effect" is a well-known phenomenon where the mature technology defends itself against a new emerging technology⁹. Once the emerging technology realizes that it is under attack, there is often a vigorous effort on the part of the mature technology to resuscitate itself¹⁰ (see for example Foster 1986, p. 196; Grübler, 1991, p.460; and Utterback, 1994).

Utterback and Kim state that a technology will often only be optimized with regard to its key parameters after a new technology emerges (1985 as quoted by Moenaert *et al.*,

⁹ The term "sailing ship effect" originated from the sailing ship industry that developed fast clipper sailing ships to counter the invasion from steam powered vessels.

¹⁰ Strictly speaking it is of course not the technology itself that reacts, but the companies and institutions that manufacture, develop and use it. As a figure of speech we shall, however, refer to the technology as the actor.

1990). This is a well-known response by mature technologies, as is evident in the literature on defensive strategies referred to above. Utterback mentions, for example, efforts by the gas industry to improve the efficiency of gas lighting when attacked by Edison's electric lamps (1994). Foster refers to the metal manufacturers that have "... limited the use of plastics or ceramics in cars and other products by introducing high-strength, low-alloy steel in metals" (1986, p. 196). Cooper and Schendel mention several other cases where the sales of the mature technology did not decline immediately after the introduction of the new technology, viz. diesel-electric locomotives versus steam locomotives, discrete transistors versus vacuum tubes and jet engines versus propellers (1976, p.64). *Hence we find evidence that an emerging technology can initially have a positive influence on the growth rate of the mature technology that it is attacking.*

Often the new technology enters a niche market rather than the main market of the mature technology, and as such it does not immediately threaten the mature technology. Cooper and Schendel point out that "... some submarkets were insulated from competition for extended periods ... ", and "... The new technology often invaded the traditional industry by capturing sequentially a series of submarkets" (1976, p.63). As the emerging technology grows up, however, it will expand into other markets that will include the main markets of the mature technology as well as new markets that are not served by the mature technology (Utterback, 1994). Once the new technology enters the main markets of the mature technology, it starts having a negative influence on the mature technology's

growth rate as they compete head-on for market-share. The attack of radial ply tires on bias-ply tires illustrates this case (Foster, 1986, p.121). As various technologies were battling for the bias-ply tire cord market in the US in the 1970s, notably polyester and nylon, the French company Michelin invented the radial ply tire. At the time of their first introduction into the US market, radial tires were initially purchased by sportscar enthusiasts who bought the tires as replacements at Sears. Initially the radial tire was not a threat to the main market of bias-ply tires, *inter alia* because of the reluctance of automobile designers to redesign the suspension for radial tires. However, Michelin eventually obtained the tire order for Lincoln Continentals, suddenly became a major competitor for bias-ply tires and soon after drove bias-ply tires from the market. It was mentioned earlier that bias ply tires lost 50% market share to radial ply tires in eighteen months. A large number of other examples of new technologies that have replaced mature technologies in the market have been documented (see for example Foster, 1986; and Utterback 1994). *There is thus evidence that an emerging technology can have a negative influence on the growth rate of the mature technology it is attacking.*

Let us now examine the effect that a mature technology has on the growth rate of an attacking emerging technology. Consider again the case where an emerging technology enters a market niche that is not seriously addressed by a mature technology. One can certainly make a case that the emerging technology's growth rate can be enhanced by the presence of the mature technology. The emerging technology will typically benefit from

factors that advantage followers and imitators in an industry (as opposed to first movers) (see for example Lieberman and Montgomery, 1988; and Kerin *et al.*, 1992). Such factors may include the fact that the mature technology has already established a market. The emerging technology can thus act as free-rider on the mature technology's efforts to open a market, educate customers and establish marketing and distribution channels. The emerging technology only has to persuade the customer to "prefer their brand", since the customer has already bought into "trying the product" (Levitt, 1965, p.83). For example, the first generation electronic computers were originally built with vacuum tubes, notably the ENIAC (Girifalco, 1991). A computer industry started developing where the first customers were the government, although commercial, industrial and academic customers soon followed. Academic disciplines supporting the computer industry started developing. By the time discrete transistors arrived on the scene in the 1950s, there was no need to convince anybody that the computer *per se* was a good idea. Discrete transistors had a ready made market to serve in the computer industry and thus benefited by the presence of vacuum tubes.

An emerging technology can also benefit from the infrastructure that was created to accommodate the mature technology. For example, when diesel-electric locomotives attacked steam locomotives, they benefitted from the existing railway infrastructure, including tracks, stations as well as passenger and freight handling system. When IBM entered the PC market, the market gained significant legitimacy due to the reputation of

IBM (Utterback, 1994), a reputation that was established in large part by IBM's mainframe machines. The PCs thus benefited from the presence of the mainframes. Emerging technologies can also benefit from the mature technology's efforts to gain regulatory approvals and mechanisms. *We can thus argue that a mature technology can have a positive influence on the growth rate of an emerging technology, typically in the early stages of the growth.*

There are many examples of failed innovations (which is actually a contradiction in terms). Although many reasons can be certainly be found for the failures, a case can also be made that some of these emerging technologies failed due to the negative influence that the established mature technologies had on their growth rates. The QWERTY keyboard had its origins in Sholes' typing machine of the 1860s. It was mentioned earlier that the QWERTY keyboard was established as a dominant design even though it was suboptimal. Subsequently several alternatives were introduced to try to displace the QWERTY keyboard. One of the most interesting, the Dvorak Simplified Keyboard (DSK), was introduced in 1932 (David, 1985). Many typing records have been held by the DSK. Nevertheless, the QWERTY keyboard has held its own against all attackers and is still the dominant keyboard. Not too long ago gallium arsenide (GaAs) was hailed as the semiconductor material of the future. Although GaAs has certainly found some applications in certain niche markets, it did not succeed in supplanting silicon as the most prominent semiconductor material in electronics. The Wankel engine, also known as the

rotary engine, was a contender to replace the reciprocal internal combustion engine in automobiles. The engine was commercialized in NSU and Mazda automobiles in the early seventies, its main claim to fame being that it contained fewer moving parts. However, it never gained large scale market acceptance and its use was discontinued. In all of the cases mentioned here, there were mature technologies serving the market niches addressed by the emerging technologies, so that one can surmise that the emerging technologies did not fail because there was not primary demand for a functional product in that niche. It is more probable that the new technologies failed because they could not compete against the established technologies. *We can thus also make a case that a mature technology can exercise a negative influence on the growth rate of an emerging technology.*

We have argued cases to show that under some circumstances emerging technologies can exert positive as well as negative pressures on the growth rates of mature technologies and *vice versa*. The three modes in the proposed framework are manifested in the different combinations of these cases, so that the cases can now be combined to “build” the three modes in the multi-mode framework. In order to have symbiosis, for example, both the emerging technology and the mature technology must have positive influences on the growth rate of the other. In the case of pure competition, both must have negative influences in the growth rates of the other. In the case of predator-prey interaction the mature technology must have a negative influence on the growth rate of the emerging technology and the emerging technology must have a positive influence on the growth rate of the mature technology or *vice versa*.

Although the examples above have been based on the interaction between emerging and mature technologies, the framework itself is of course much more general than that and can be applied to the interaction among any two technologies. In the beginning of this chapter it was stated that the dynamics of technological change is concerned both with the *rates of change* and the *forces* that drive the change. The examples above illustrate some forces that act upon the rates of change. One should keep in mind, however, that the influence that other technologies have on a specific technology's growth rate is just one of many influences. In the next chapter a host of other factors that influence the rate of diffusion are mentioned. The actual rate of diffusion will thus depend on the relative strengths of the different influences (or forces if you will) and not only on their directions. For example, a mature technology may exert a negative influence on the growth rate of an emerging technology but there may be other influences that exert greater positive influences, resulting in a net positive growth rate. In Chapter 5 it will be shown how the interplay between the directions and strengths of the different forces can be captured in a mathematical model for the multi-mode framework.

An interesting possible application of the multi-mode framework is the case where a company's reaction to the emergence of a new technology is to pursue a dual strategy, i.e. the company decides to sustain its presence in the mature technology (with or without renewed effort to actually improve the mature technology) and at the same time develop a position in the emerging technology (see for example Harrigan and Porter, 1983; and Soukop and Cooper, 1983). The multi-mode framework can be applied in the context of the company, where it can be used to model the relationships between the old and new technologies within the company. One can foresee, for example, that in cases where the new innovation builds on previous competencies of the company (Utterback, 1994), that

there will be some symbiotic effects. On the other hand, if one of the technologies bleeds resources from the other or leads to cannibalism, it will result in the exertion of negative influences on growth rates. Depending on the combination of the influences that the new technology has on the growth rate of the old and *vice versa*, the interaction between the two will be pure competition, symbiotic or predator-prey.

Symbiosis

In the case where two technologies have positive reciprocal effects on one another's growth rate, the interaction is considered to be symbiotic. A strong case can be made that computer hardware and compatible software for desktop computing interact in a symbiotic way, as does personal computers (PCs) and hard disc drives. Sahal contends that "... the origin of *revolutionary innovations* lies in certain *metaevolutionary processes* involving a combination of two or more *symbiotic technologies* whereby the structure of the integrated system is drastically simplified" (1985, p.70). He points to jet engines, the three point hitch and control systems for farm tractors as well as the electronic computer as major innovations that came about due to the symbiotic interactions of various other technologies. The advent of the jet engine, for example, was founded in the combination of jet propulsion and the gas turbine. Similarly the modern electronic computer depended on the development of the programmable calculating machine and integrated electronics.

The concepts of *substitutes* and *complementary products* are very useful in the context of the multi-mode framework. One can surmise that a product that is complementary to

another will enhance the growth rate of the second, or at least not inhibit it. For example, the fact that hard disc drives are available for PCs certainly contributed to the popularity and widespread diffusion of PCs. If, for argument's sake, hard disc drives had not been available for PCs their usefulness would have been severely hampered and hence one can postulate that PCs would have experienced a much smaller growth rate. The fact that a large scale infrastructure for charging the batteries of electric cars is not available is probably a major factor contributing to the slow diffusion of electric vehicles. Cooper and Smith argue that in the case of microwave ovens, the lack of complementary products such as cookbooks and cookware could have retarded the market's growth (1992).

The notion of symbiosis and mutualism has also found application in organizational ecology, where researchers study the entry and exit rates of firms. Hannan and Freeman developed their thesis on organizational mortality rates on the basis of population densities (1989). They found that under some circumstances, an increase in density has a negative effect on organizational mortality indicating competition, whereas in others it had a positive effect, indicating symbiosis. Recall also the organizational ecology study on the early American telephone industry done by Barnett (1990).

Pure competition

Pure competition, i.e. where each technology exerts a negative influence on the other's growth rate, is a very prevalent case in an innovation context and has been extensively

covered in the literature. In recent articles, for example, Farrell used a model based on Lotka-Volterra equations to examine pure competition between various technologies, including lead-free versus soldered food cans, woven versus tufted carpets, fountain pens versus ball-point pens, nylon versus rayon tire cords and telephone versus telegraph usage (1993a, 1993b).

Substitutes have been recognized as a powerful force in competition. Porter considers substitutes as one the five forces in his model of industrial competition (1980). Where substitutes address the same market niche as existing products, they will in general have an inhibiting effect on an existing product in the sense that they serve the same niche. One can argue that the emergence of hard disc drives, for example, had an inhibiting effect on the proliferation of floppy drives. Whereas many early PCs (notably the XT) originally had two floppy drives and no hard drives, the emergence of hard drives for the PC market resulted in PCs typically having only one floppy drive and one hard drive, rather than two floppy drives. Similarly, one can argue that the emergence of 3.5" floppy drives has made a major dent in the diffusion of the older 5.25" drives. In the last two cases the inference would thus be that hard drives and 3.5" floppy drives have had a negative effect on the growth rate of 5.25" floppy drives.

Predator-prey interaction

Predator-prey interaction between technologies is an interesting case, both from research and managerial viewpoints. A survey of the literature shows that, except for some cursory references (see for example Porter *et al.*, 1991, p. 196), it has not been addressed seriously as a research topic. There is no obvious evidence of a research effort that has focused on investigating such a relationship between technologies, nor does it appear that work has been done to develop appropriate strategies for technologies and companies that find themselves in a mode of predator-prey interaction.

Considering the examples given above, one can envision, for example, that a predator-prey relationship may exist between an emerging technology and a mature technology where the emerging technology enters a niche market that is not served by the mature technology. In this case the emerging technology will benefit from the presence of the mature technology and the mature technology will thus exert a positive influence on the emerging technology's growth rate. The mature technology may not recognize the threat posed by the emerging technology and hence the emerging technology does not trigger a significant resuscitation or growth spurt, i.e. the sailing ship effect, in the mature technology. At the same time the emerging technology may slowly be stealing market share from the mature technology. Under these circumstances, one can posit that the emerging technology has a negative influence on the growth rate of the mature technology. Hence there is a predator-prey interaction between them, with the emerging

technology the predator and the mature technology the prey. On the other hand, one can also visualize a situation where the emergence of the new technology triggers a sailing ship effect in the mature technology, resulting in de-maturing and new growth (see for example Foster, 1986). This implies that the emerging technology has a positive influence on the mature technology's growth rate. We have also demonstrated that mature technologies can have a negative effect on the growth rate of a mature technology. If that should happen in this case, the two technologies will also have a predator-prey relationship, except that now the mature technology will be the predator and the emerging technology the prey.

Research challenges

In this chapter a multi-mode framework for technological interaction that is based on the reciprocal effects that technologies have on one another's growth as a classification criterion for the three different modes, has been proposed. The framework is rooted in ecological analogies, but several examples from the technological domain were given to illustrate that the framework may, in principle, be applicable to technological interaction. Furthermore we showed that, other than in the case of ecological modes of interaction, the nature of technological interaction changes with time. These changes can sometimes occur very rapidly. There is thus ground to postulate that the interaction between technologies will shift from one mode to the other.

Even though several examples were given to illustrate some of the individual modes and shifts between modes, it would seem that a research project aimed specifically at investigating the usefulness and applicability of the framework will be very fruitful. Such a project will typically begin with a data gathering exercise to investigate interactions in the different modes individually, specifically the symbiosis and predator-prey modes that seem to have been neglected in the literature. Particular attention should also be focused on the transitions between the modes. In order to be useful from a managerial viewpoint, the analysis phase of the research will be followed by a synthesis phase where management strategies are developed and tested. These strategies should be aimed not only at the individual modes, but also on the transitions between the modes. Simulation tools have proved to be very useful, particularly in the synthesis phase of such research, but they are also helpful in interpreting scenarios that unfold in the data gathering and analysis phase. In the next two chapters we embark on an initiative to construct a mathematical model to simulate the multi-mode, growth related framework that has been proposed in this chapter.

MODELING TECHNOLOGICAL COMPETITION

“As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality”

Albert Einstein

Modeling issues

The question might well be asked what the value of a mathematical model for a social system such as the diffusion process of new technology is, and even if it is at all possible to model such systems mathematically. Certainly in the case of phenomena that are governed by the laws of nature, the validity and legitimacy of mathematical models are easy to justify and are readily accepted. In the case of social systems, on the other hand, actions are determined by human behavior and decision making processes rather than by forces of nature. In this chapter we shall see, however, that certain underlying assumptions about such processes can be expressed mathematically and hence that a mathematical model for the system can be formulated. Empirical verification of models eventually leads to an increased confidence in their use. As with all mathematical models, one should keep

in mind that the models are only as good as the fundamental assumptions on which they are based and only the phenomena that are accounted for in the model will influence the result. This may or may not reflect the real situation that is being modeled.

In the case of technological systems, whether it be diffusion processes, substitution processes or with regard to the performance parameters of the technology itself, models have been widely applied for forecasting purposes. However, forecasting the future is a hazardous venture under the best of circumstances and there are an abounding number of technology forecasts that have been proven to be great embarrassments to the forecasters (see for example Schnaars, 1989). The problem is of course that there is such a myriad of factors that can influence an inherently social system that it is very difficult to build a mathematical model to account for them all.

A prudent compromise is to build a model that focuses on specific aspects and models them well, rather than trying to construct a unified model that accounts for all possible exogenous as well as endogenous contingencies. The danger with a limited but focused model is, however, that relevant and important influences and relationships between those variables that are modeled and those that are not may be lost and thereby affect the validity of the model. Given that the environment may also constantly be changing, the assumption that the coefficients and parameters of the models are stationary may not always be valid. Furthermore, unforeseen circumstances and stochastic events will

obviously influence the trajectory of the technology. From a forecasting viewpoint one should thus be very cautious in applying mathematical models to technological systems. In this thesis, however, the emphasis with regard to the models is to aid in the understanding of the characteristics of the system rather than as a forecasting tool.

Let us assume for the sake of argument that a technological system can be modeled mathematically, at least under certain circumstances. Such a model can be very useful as a vehicle for understanding the dynamics of the system. By using the model as a simulation tool, the behavior of the system can be investigated as various parameters are changed. If we can establish which and how real influences affect the modeling parameters and variables, it follows that the system behavior can be simulated as a function of the external influences. Once we understand the dynamics of the system and how changes in the various parameters influence the system's behavior, we can start to develop a strategy for manipulating the behavior of the system since we know what parameters to try to influence and in what direction.

Unit of analysis

In ecological studies the number of units in a population is a natural and almost intuitive dependent variable to use in growth models. The selection of the unit of analysis to describe technology and technological diffusion is, however, a trivial decision. Finding a useful metric to measure technology itself is not easy, due in part to the problem of

defining *technology* (see for example Souder and Shrivastava, 1985; and Van Wyk, 1992). The literature abounds with definitions for technology and innovations, but for the purposes of measuring technological diffusion and competition, they are elusive entities. In an exercise that focuses on technological forecasting, a technical parameter or combination of parameters is typically selected, such as the speed of aircraft or the efficiency of lamps measured in lumens per watt. In the context of this thesis, however, we are concerned with technological substitution and diffusion rather than technological forecasting. In the case of substitution, one can argue that the dependent variable should be market share. The complicating issue then becomes a definition of the scope of the market niche to be considered, an estimate of the size of the market niche, determining the market penetration of the technologies and accounting for the fact that the scope and size of the market niche may change with time.

In the case of technology diffusion, the problem is equally complex, and like technology forecasting, tied to the nature and characteristics of the technology. The term *technology* encompasses such a wide spectrum of artifacts, techniques and processes that make it extremely difficult to define a universal parameter by which to measure diffusion, if we interpret diffusion to be an absolute measure rather than the percentage penetration into a market niche. In the case of manufactured products, for example, one can use the number of units sold as a measure of diffusion. However, Farrell contends that "...census of the species, while important, is not the main determinant for growth". A company selling

soup, for example, is ultimately not so much interested in the number of cans of soup they have sold, but rather in the sales revenue generated by the sales of the soup. He points out that the profit from the sales of the soup provides resources for investment in new production (1993a). On the other hand, Grübler contends, that "... The pragmatic answer to whatever leads consumers to purchase and industry to investment decisions, constitutes an appropriate unit for analysis of diffusion research, would appear rather unsatisfactory from its atheoretical nature" (1991, p.464). Some care should be taken with sales revenues in the case where repeat purchases are possible, however, since the repeat purchases may distort the diffusion pattern. Several other absolute measures of diffusion have been used or proposed, including the capacity and output of steel plants (Poznanski, 1986) and the number of discrete products produced (Bridges *et al.*, 1993; and Harley, 1973).

The notion of the number of units in a population can be extended with some plausibility when we consider firms that are engaged in the manufacture of use of technology, for example. A branch of organizational ecology that studies the entry and exit rates of companies that are involved in technology has indeed successfully applied the concept of the number of firms in this sense (see for example Hannan and Freeman, 1989; and Utterback, 1994). Recall Barnett's study on the early American telephone industry that was discussed in the previous chapter and how he tied organizational characteristics to technology. A subtle but important point to keep in mind is that, whereas the different units in an ecological population are typically very similar, firms usually differ a lot in their

size, modes of response and other important characteristics. Furthermore, companies will also change their technologies from time to time, and more than one firm is often involved in the manufacture and use of a specific technology. Although accounting for the number of firms involved with the manufacture and use of a technology may be relevant and important from an organizational viewpoint, the population of technology-related firms do not map one-to-one to the technology itself and hence presents a problem as a proxy when used as a measure for diffusion of the technology. Barnett notes that "... Often there is no clear boundary around an organization's technology... many technologies can be thought of as systems that cut across formal organizational boundaries" (1990, p.31). Often, the fates of technologies are tied to the firms that use or develop them. Loveridge and Pitt make the point that "... technology innovation (as indeed any form of environmental change) affects firms via the mediating action of the competitive or collaborative context of the industry sector in which it operates" (1990, p.5). They subsequently stress the importance of firm-in-sector analysis.

Rather than using individual companies as a proxy for technology itself, considering the industry in which the technology abides may be more appropriate, specially when considering competition among technologies. Intuitively one would think that using the industry as a unit of analysis would tend to aggregate the idiosyncrasies of the various companies and thus provide a better average. However, as with companies, one finds that there is not a unique mapping between industries and technologies. Furthermore,

Moenaert *et al.*, for example, argue that "... industry maturity and technological maturity are two separate concepts and do not necessarily coincide in time" (1990, p.43). They point to the substitution of latex foam by polyurethane as an example, noting that the latex foam industry was "... still experiencing strong annual growth, but its mature technology offered little prospect for improvement" (p.50).

One can of course also look at diffusion from the demand side rather than the supply side and as such at the number of individuals or companies that have adopted a certain technology. Again the success of this measure will depend on the nature of the technology. Some products are replaced often whereas other are replaced infrequently. If one examines the diffusion of non-assembled products, there is no way to count the number of units manufactured or sold, but we can count the volumes produced or sold, such as tons of ore or square feet of glass pane. In the case of non-tangible innovations, such as process improvements, for example, one probably has to resort to counting the number of adopters in order to measure the diffusion of the innovation. To further complicate the issue, technologies and innovations also change with time. Abernathy and Utterback state that "... the standard units of analysis of industry — firm and product type — are of little use in understanding innovation... the questions raised in this article require that a product line and its associated production process be taken together as the unit of analysis" (1994). Dosi remarks that "... In general, the *speed of diffusion* is inherently hard to judge because there is no precise way to define the ultimate scope of application or

use of a new method of production or a new product” (1991, p.186).

In this thesis we do not intend to make exhaustive conclusions with regard to the unit of analysis that is appropriate to measure technological diffusion and competition. Instead we shall keep in mind that it is a complex issue and that a metric that is suitable for one technology might not be suitable for the next.

Simple growth models

In order to model the growth of a unit mathematically, an expression has to be found that expresses the change of the unit over time. In this section we shall initially consider diffusion models and then extend the analogy to a special class of substitution models. Consider now the function $N(t)$ to represent the population whose growth is to be modeled. The function N can, for example, be the number of units in an ecological population or the size of a biological organism. In the case of a technological system it can, for example, be the number of firms that have adopted a certain innovation, the sales of a given technology or another appropriate unit of analysis for diffusion.

The growth of N can be modeled by setting

$$\frac{dN}{dt} = F(N) \tag{4.1}$$

Hence the growth rate is a function of the size of the population. The function $F(N)$ can be expanded into a Taylor series, yielding (Pielou, 1969, p.20)

$$\frac{dN}{dt} = c_0 + c_1N + c_2N^2 + \dots \quad (4.2)$$

In the case where all coefficients except c_0 are zero, one finds that

$$\frac{dN}{dt} = c_0 \quad (4.3)$$

and hence the growth is *linear*, i.e.

$$N(t) = c_0t + C \quad (4.4)$$

In this and following equations, C is a constant that depends on the initial conditions. Lotka mentions that from an ecological viewpoint one would expect c_0 to be zero, otherwise dN/dt would not vanish with N (1956, p.65). Farrell infers that some technologies do, however, exhibit linear growth patterns (1993a, p.165). His argument to support this statement is discussed in the next section.

In the case where the rate of growth is directly proportional to the population with a constant of proportionality, i.e.

$$\frac{dN}{dt} = c_1N \quad (4.5)$$

the growth is *exponential* (given that $c_1 > 0$), yielding

$$N(t) = Ce^{c_1 t} \quad (4.6)$$

In the case of exponential growth, also known as a pure birth process, the units represented in N are assumed to be immortal and to reproduce at the same constant individual rate (with absolute certainty). Furthermore it is assumed that there are unlimited resources for the units to draw on and that they do not exert any influences on one another. Note that the constant c_1 may also represent the *net* birth rate, i.e. births minus deaths. In cases where members in a population or various populations compete for limited resources, the assumptions of the exponential growth model obviously do not hold and hence the model is unsuitable in such circumstances.

Logistic growth

The growth of any population in an environment that is subject to restricted resources must eventually be inhibited by the scarcity of the resources. A stage will be reached where demands of the current population on the resources preclude further growth and the growth slows. This phenomenon is often manifested in the fact that the population level seems to grow towards a saturation limit. This limit is typically determined by the carrying capacity (or its analogies) as discussed in the previous chapter. In order to account for the influence of limited resources, such as a market of fixed size or a fixed budget, the growth function is expressed in the more general form

$$\frac{dN}{dt} = L(N)N \quad (4.7)$$

The proportionality factor is now no longer a constant (c_1) as in Eq. (4.5), but a function of N that incorporates a limiting influence on the growth of N . Porter *et al.* refer to the

function $L(N)$ as the *market potential*, which is analogous to the biopotential found in ecological systems (1991, p.189). In order for $L(N)$ to exert an inhibitory influence on the growth of N , the derivative of L must be negative, i.e. the larger the population, the more profound the inhibitory effect. A linear function is often assumed for L , i.e.

$$L(N) = a - bN \tag{4.8}$$

with $a, b > 0$, so that the growth equation reduces to

$$\frac{dN}{dt} = N(a - bN) \tag{4.9}$$

This equation is known as the Verhulst or Pearl equation (Pielou, 1969, p.19), and gives rise to the well-known S-shaped curves that are typical of *logistic growth*. The function $N(t)$ itself is given by

$$N(t) = \frac{Cae^{at}}{1 + Cbe^{at}} \tag{4.10}$$

which can also be expressed as

$$N(t) = \frac{(a/b)}{1 + e^{a(t_0 - t)}} \tag{4.11}$$

where

$$t_0 = \frac{1}{a} \ln \frac{1}{Cb} \tag{4.12}$$

It is evident from Eq (4.11) that $N(t)$ will approach the saturation level a/b in the limit as time approaches infinity. At time $t=t_0$, 50% of the market has been captured.

Figure 4.1 shows a typical logistical S-curve generated by Eq (4.11). Note how the saturation level ($a/b=15$) is approached as time increases and that the 50% level ($a/2b$) is reached at time t_0 ($t=50$). The level of diffusion $N(t)$ extends infinitely into the past as well as into the future, never actually reaching the values of a/b or zero, although they are approached asymptotically. The logistic function and associated S-curves are important from the viewpoint of understanding many of the mechanisms of technological competition and hence an investigation into some of its characteristics is in order.

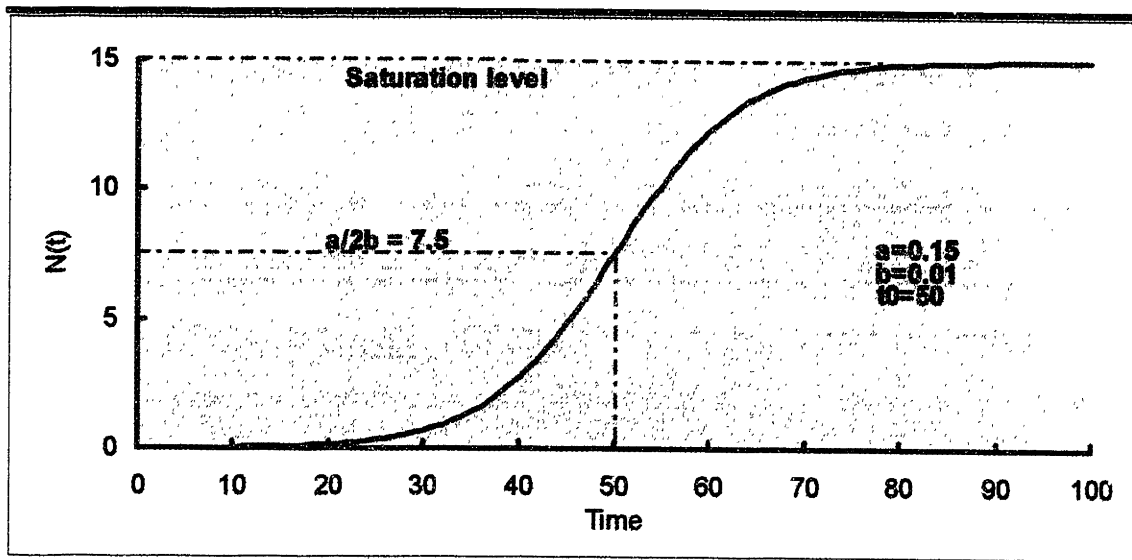


Figure 4.1 Typical logistical S-curve generated by the Pearl equation.

Expanding the differential equation that governs logistic growth, one finds that Eq (4.9) can also be expressed as

$$\frac{dN}{dt} = aN - bN^2 \tag{4.13}$$

The first term on the right hand side of the equation corresponds to that in Eq (4.5) and

hence will give rise to exponential growth. This term represents the growth that will result when resources are unlimited and there is no interference of different units within the population with each other. The second term on the right hand side inhibits the growth rate, and hence the negative sign preceding it. The fact that N is squared can be interpreted as interactions of units of the population with one another. When N is small, the first term will dominate and the growth will be almost exponential. However, as the population increases, the different units in the population will start competing for the limited resources. As N grows, the second term on the right hand side will start dominating the first term, resulting in a slowed growth and a limiting approach of N to the value a/b .

Note that Eq. (4.13) can also be expressed as

$$\frac{dN}{dt} = aN \left[\frac{(a/b) - N}{(a/b)} \right] \quad (4.14)$$

Hence, the rate of change is equal to the potential rate (aN) multiplied by a factor equal to the proportion of the niche that is unfilled, where a/b is considered to be the total size of the niche and $N(t)$ is the current level at which the niche is filled. Alternatively, the differential equation can be expressed as

$$\frac{dN}{dt} = Nb \left(\frac{a}{b} - N \right) \quad (4.15)$$

From this equation it is clear that the growth rate is driven by what has already been achieved (N) and limited by what is still to be achieved ($a/b - N$), i.e. the unfilled market niche. Pielou has also shown that Eq (4.11) can be put into difference form (1969, p.22),

i.e.

$$N(t+1) = \frac{e^a N(t)}{1 + (b/a)(e^a - 1)N(t)} \quad (4.16)$$

In the next chapter it will be shown that the difference form solution is very useful for solving sets of differential equations.

Farrell points out an interesting point concerning logistic growth in the sense that one can also account for the disposal of members of a population with a logistic equation similar to that describing the sales (1993a, p.165). He argues that the census of the population at a specific time is given by the area between the logistic curves representing sales and disposal. He finds that in cases where technologies have long lives or are maintained for a long time, the resulting census at the given time is a linear function. He contends that telephone wire and civil aircraft exhibit such characteristics.

As was pointed out in the previous section, there are subtle but distinct differences between the processes of diffusion and substitution. Even so, there are also marked similarities between the underlying models of the two processes. In substitution analysis the function (f) is used to model market share, i.e.

$$f(t) = \frac{N_n(t)}{N_n(t) + N_o(t)} \quad (4.17)$$

where $N_o(t)$ is the diffusion level of the old technology and $N_n(t)$ is the diffusion level of the new technology. Given that the size of the total market niche is constant, the fraction

(q) of the market that the old technology occupies is given by $1-f$. In the case of two competing technologies, it is evident that

$$\frac{dq}{dt} = -\frac{df}{dt} \tag{4.18}$$

With this model, the growth of one technology is thus inevitably associated with the demise of another.

In a seminal article, Fisher and Pry proposed a simple substitution model based on the principles underlying Eq (4.9) (1971). Essentially setting $a=b=1$, they postulated that the market share of a technology can be expressed as

$$\frac{df}{dt} = 2\alpha f(1-f) \tag{4.19}$$

The function f can be expressed in closed form as

$$f(t) = \frac{1}{1 + e^{2\alpha(t_0-t)}} \tag{4.20}$$

or

$$f(t) = \frac{1}{2} [1 + \tanh \alpha (t - t_0)] \tag{4.21}$$

From Eq (4.19) it is evident that the growth rate at which market share is gained is proportional to the product of the proportion of the market that has already adopted the technology (f) and the proportion of the market that has not adopted the technology ($1-f$).

The product $f(1-f)$ can, however, also be viewed as the interaction between adopters and non-adopters and hence α can be viewed as a coefficient of imitation, reflecting the internal influence or interaction between the adopters and potential adopters. It is inversely related to the *take-over time* (sometimes also referred as Δt in the diffusion literature (Grübler, 1991, p.468)), i.e. the time required for the new technology to grow from 10% substitution to 90%. Recall that the logistic function never attains values of zero and a/b (it only approaches those values in the limit), and hence the need to specify Δt between finite values such as 10% and 90%. Grübler mentions that the Fisher-Pry model is still the predominant model in technological and marketing research and points to work by Mansfield that have demonstrated numerous successful applications of the model (1991, p.458). Even so, the Fisher-Pry model does have some limitations, notably its characteristic as a binary replacement model, i.e. the fact that the technology under investigation is modeled as competing against the market rather than another technology. This problem is discussed again in a later section.

The Fisher-Pry model is only one of a myriad of models that have been proposed since the 1960s to model technological substitution. As time progressed, more generalized models were developed with the intent of improving forecasts that can be made when the models are applied in an extrapolatory mode. Many of the earlier models have been shown to be special cases of the newer, more encompassing models. In examining the plethora of substitution models that have been proposed in the last 30 years or so, one is struck by the fact that many of the models are typified by the addition of more factors and parameters to a single basic equation such as Eq (4.9) above, usually given in closed form solution. Review articles that discuss the various models, their underlying assumptions as well as

the relationships between the different models are published from time to time (see for example Hurter and Rubenstein, 1978; Mahajan *et al.*, 1990; Kumar and Kumar, 1992; and Young, 1993). For the purposes of this paper, however, it is sufficient to take note of the fact that many models have been developed (and applied with varying degrees of success), but in principle they yield S-shaped substitution curves.

The rate of diffusion

The multi-mode framework that was developed in the previous chapter classifies interaction among technologies on the reciprocal effects that they can have one another's growth rate. It was also pointed out, however, that there are many other factors (in addition to the influence from other technologies) that may also influence the growth rate. In the Fisher-Pry substitution formulation of Eq (4.19), for example, this rate of diffusion is embodied in the coefficient α . A multitude of different factors influencing the rate of diffusion (and hence the shape of the S-curve) has been proposed and in fact many of the models have as their *raison d'être* the incorporation of such factors. In this section we examine some of the factors that influence the rate at which a technology is adopted or with which one technology is substituted with another, or alternatively a technology is diffused.

Mansfield suggests that "... the rate of adoption of an innovation is a direct function of the profitability of employing the innovation and a decreasing function of the size of investment required to use it" (1961 as quoted by Linstone and Sahal, 1976, p.59), thereby implying an economic influence on the rate of diffusion. Certainly the technical characteristics of the technology will influence the profitability of employing it and the

investments required, but the economics *per se* is very much an externality. Blackman *et al.* showed that the extent to which resources are allocated also has an influence (1976). Bundgaard-Nielsen suggest that a country's industrial growth plays a role (1976). Davies discusses the influence that knowledge about the product, industry structure and growth and learning curves have on the rate of adoption (1979). In a recent review article Kumar and Kumar cite researchers who have investigated the role of price, advertising, promotion, product interrelationships, market size, repeat purchases and competition on the rate of diffusion (1992). Dosi comments that the rate of diffusion can also depend on the features of the technologies that are to be adopted and substituted, on economic incentives, characteristics of would-be adopters, the information available to them and their technological competence (1991, p.185). He also refers to several other researchers that have shown varying rates of diffusion depending on inter-firm, inter-industry and inter-technology relationships.

Multi-technology competition

The concept of substitution inherently implies that two (or more) technologies are competing, since per definition, one is displacing the other. However, traditional substitution models such as the Fisher-Pry model and its derivatives present us with the dilemma that they do not model two technologies competing against each other, but rather one technology competing against a saturated market or market potential. Due to the fact that a single equation describes the system, the new technology and the rest of the market are coupled in one equation with a few parameters that account for the adoption of the new technology. The formulation yields a solution where the growth of the old technology is accompanied by the decline of the old (given that the size of the market niche stays

constant). Single equation formulations thus do not offer a solution where the older technologies, here represented by the market, has a chance of independently “fighting back”. The mature technology’s response and defense are inevitably coupled to the new, attacking technology’s penetration into the market through Eq (4.18). Grübler comments that “... It appears that much of the debate on the appropriate mathematical model(s) of diffusion, in particular the question of symmetrical versus asymmetrical models, may be the result of looking at innovation from a unary (i.e., an innovation grows into a vacuum) or a binary (the market share of an innovation is analyzed *vis-à-vis* the remainder of the competing technologies) perspective. However, diffusion phenomena generally call for a multivariate approach, which has not yet found wide application in the various diffusion disciplines” (1991, p.452). Diffusions cannot in general be analyzed in isolation. Not only are there usually competing technologies, albeit it emerging or mature technologies, that influence the diffusion process, but often also complementary and enabling technologies. Lieberman and Montgomery state that “... the replacement of technology often appears while the old technology is still growing...” (1988, p.48). In the general case however, one often finds that multiple technologies are vying for market share at the same time and that more than one technology can be growing at the same time.

Girifalco also addresses the issue of multi-technology competition (1991, p.147). He contends that there are two alternative approaches for multi-level substitution, both of which are “... based on reducing the multiple interaction among the technologies to binary competition between technologies or groups of technologies” (p.146). At this point we again run into the subtleties involving the differences between substitution and diffusion. Girifalco’s model is a substitution model and hence it assumes that the market share of all

the technologies involved sums to unity. It will be shown in the next chapter that it is possible to develop a model that does not reduce the technological competition to binary competition between technologies. In the model that is to be presented in the next chapter, each of the competing technologies is modeled with its own equation. However, each equation contains a term to account for the competitive influences of all the other technologies on that particular technology. Nakićenović comments that "... The Fisher and Pry model cannot be used to describe the evolution of primary energy consumption, because evidently more than two energy sources compete for the market simultaneously" (1986, p.311). Alternative models for multi-technology competition have been proposed by Nakićenović (1979 as quoted by Marchetti, 1987). Modis makes the following comment about Nakićenović's model, "... It is imposed that only one competitor is in the saturating phase at any time. Its share is calculated as 100% minus the share of all other contemporaries, each of which traces out a growing or declining trajectory" (1993, p.160). Norton and Bass (1987) and Bridges *et al.* (1993) formulated models to account for the introduction of new generations of products. In all of these cases it would seem that they use the scheme where the sum of the different technologies is unity, i.e. the last technology by default gets whatever is left of the market share.

The differential equation(s) describing the diffusion of a technology must be based on the underlying mechanisms involved. In order to model the diffusion characteristics of a technology, it is therefore necessary that the extent of the resources available be taken into account. Finite resources are often embodied in a market niche of finite size. It was illustrated above that the effect of accounting for finite rather than infinite resources was to change the growth pattern from exponential to logistic. A single equation cannot

however, describe the growth and competition of two technologies simultaneously for it does not account for their respective effects on one another. It can at best model the diffusion of one technology into a market. To model the competition of two technologies, one would need to set up a differential equation for each of the technologies based on the underlying drivers and inhibitors for that technology, together with coupling coefficients that reflect the technologies' effect on one another's growth rate.

In order to mathematically model the multi-mode framework proposed in the previous chapter, the traditional and classic substitution models that are based on single equation formulas are thus inappropriate. It is necessary to model both the mature technology and emerging technology with its own equation. They must then be coupled with coupling coefficients to model the interaction between them. A *system of differential equations* is therefore required. Such a system that is applicable to this problem has been formulated some time ago by the ecologists Lotka and Volterra, but until very recently was not applied to the diffusion of technology. The system of equations that they developed has become known as the *Lotka-Volterra equations*.

Several authors have shown that the Lotka-Volterra equations can be successfully applied to model technological diffusion, among them Bhargava (1989), Farrell (1993a), Marchetti (1987), Modis (1993), Nakićenović (1979 as quoted by Marchetti, 1987) and Porter *et al.* (1991, p.188). This is an important observation and we accept their success as additional justification for pursuing the line of research in the remainder of this chapter. Marchetti comments that "... I am fairly convinced that the equations Volterra developed for ecological systems are very good descriptors of human affairs. In a nutshell, I suppose

that the social system can be reduced to structures that compete in a Darwinian way, their flow and ebb being described by the Volterra equations, the simplest solution of which is a logistic” (1983, p.3).

Even though the Lotka-Volterra equations may be suitable to model technological diffusion and substitution, the question arises however, as to the appropriateness of modeling the oscillatory behavior we are interested in, i.e. oscillatory behavior in the mature phase of the S-curve, with these equations. There are several references in the literature that suggest that the Lotka-Volterra equations may indeed lead to a modeling solution for the oscillatory behavior that we are concerned with here. Porter *et al.* state that “... Oscillatory models are a final class of models accommodated by the Lotka-Volterra equations. Periodic behaviors are commonly found in natural populations and they can be successfully modeled using the Lotka-Volterra equations. Oscillatory behaviors have been observed in consumption and mining patterns in the United States and in car and transportation systems in Europe ... These growths often show a logistic start followed by an overshoot and then oscillation around a supposed limit ... The more complex population models such as Lotka-Volterra, can represent such behaviors if the forecaster has correctly surmised their form... Mathematical modeling using the Lotka-Volterra equations show that oscillatory behaviors occur in certain specially defined systems that are known as predator-prey systems. In the equivalent technological systems, the predator (sic) technology benefits from interaction in a marketplace, while the prey technology loses from interaction. A gain from interaction is modeled with a negative competition coefficient (which subtracts from the available market)” (1991, p.196). The above reference to a logistic equation that overshoots and then oscillates around a limit is

strongly indicative of the type of oscillations that we are interested in, i.e. those that are sometimes observed in the mature phase of a technology. It will be shown in a later section that predator-prey systems can give rise to oscillatory behavior. However, it seems that the primary mode of oscillation that is usually associated with ecological predator-prey systems is *not* that which we are investigating. Commenting on the oscillatory behavior observed in the S-curves of mining production (see Figure 6.3), Marchetti remarks that "... these logistics or quasilogistics can become oscillatory when approaching saturation (a possible solution of Volterra equations often appearing in ecological contexts)" (1983, p.22).

In our endeavor to model the oscillatory behavior that is often observed in the mature phases of technologies, one can be guided by the fact that single equation formulations are clearly inadequate in modeling competition between two technologies and furthermore that there are indications that the Lotka-Volterra system of equations may have the capacity to account for these fluctuations. There is thus justification for exploring the extent to which the Lotka-Volterra equations can account for the multi-mode interaction among technologies and in particular for the oscillations in the mature phases of technological diffusion. Traditionally, the Lotka-Volterra equations have been used to model predator-prey interaction as well as pure competition. It will be shown in the next chapter that they can also be adapted to account for symbiotic interaction.

It should be pointed out that the formulations of the Lotka-Volterra equations for the different modes are different and have very different characteristics. The reader should take note that the nomenclature *Lotka-Volterra equations* has come to be used to indicate

pure competitive as well as predator-prey systems, often without explicitly stating which case is being modeled since it is probably assumed that it should be clear from the context. Some mathematicians refer only to the predator-prey formulation as Lotka-Volterra equations and treat the related equations that deal with pure competition separately (see for example Pielou, 1969; Eisen 1988; and Hirsch and Smale, 1974). As far as modeling technological systems, Porter *et al.* (1991), Farrell (1986a, 1986b) and Bhargava (1989), for example, all refer to the Lotka-Volterra equations in the sense of modeling pure competition. Farrell and Bhargava do not refer to the predator-prey or symbiotic interactions at all. Porter *et al.*, refer to predator-prey interaction in technological systems as per the quotation given previously. Pointing out the distinction between the predator-prey and pure competitive formulations of the Lotka-Volterra equations may seem like petty semantical nit-picking, but to the uninitiated exploring the mathematical subtleties involved, the indiscriminate use of the term *Lotka-Volterra equations* when referring to either predator-prey or pure competitive systems does initially present a certain amount of confusion.

In the next chapter a mathematical model that supports the multi-mode framework and accounts for all three modes of interactive behavior between two technologies, i.e. pure competition, predator-prey interaction and symbiosis, is developed. The model is based on the Lotka-Volterra equations. It will be shown that it easily be extended to more than two technologies.

MODELING MULTI-MODE INTERACTION AMONG TECHNOLOGIES

*“The general who wins a battle makes many calculations
in his temple before the battle is fought.
The general who loses a battle makes but few calculations beforehand.
Thus do many calculations lead to victory, and a few calculations to defeat;
how much more no calculations at all!
It is by attention to this point that I can foresee
who is likely to win or lose”*

Sun Tsu
The Art of War

Modeling the multi-mode framework for technological interaction

One of the thrusts of this thesis is to develop a growth related framework within which one can evaluate interaction among various technologies, particularly with regard to the pure competition, predator-prey and symbiosis interaction modes proposed in Chapter 3 and depicted in Figure 3.1. In this framework the relationship between two interacting technologies is defined in terms of the effect that one has on the other's growth rate. In the case of pure competition, each technology inhibits the other's growth, in the case of symbiosis each technology enhances the other's growth, whereas in the case of

predator-prey interaction, one technology enhances the other's growth whilst the second technology inhibits the first's growth.

It is believed that the proposed multi-mode framework and the mathematical model that supports it give a richer setting within which to examine competition among technologies as opposed to more traditional approaches where competitive interaction among technologies is often evaluated in terms of either pure competition, sometimes symbiosis and very rarely predator-prey interaction. Unifying the three modes into one framework also creates the opportunity for evaluating the dynamics of the interaction as the nature of the competition shifts from one mode to the other. The Lotka-Volterra equations are well suited for adaptation to model the three interaction modes in the framework. The way in which the model is developed in this chapter is to support an understanding of the dynamics of the various modes of interaction that can occur.

In order to simulate the characteristics and dynamics of the multi-mode interaction, a comprehensive mathematical model is developed in this chapter. It is, however, important to keep in mind that the multi-mode framework is the fundamental concept. It exists in its own right as a mechanism for thinking about modes of interaction between technologies and how strategy might be set accordingly. Heeding Linstone's warning against a "... Reliance placed on data and models, and combinations thereof, as the only legitimate modes of inquiry and as a basis for theories" (1991, p.54), and that as a result that the

model becomes an end rather than a means, it is important to realize that the mathematical model is only an approximation that is used to simulate some of the characteristics of the framework, i.e. it is a tool to aid in the understanding of the dynamic responses of the framework that it models. Even though the mathematical model certainly has some deficiencies — many of the immediately obvious ones that are pointed out in this thesis — its imperfections should not detract from the potential usefulness of the multi-mode competition framework and the model.

In this chapter we shall assume that the coefficients of the system are constants. This restriction is to simplify the conceptual development of the model. It is not claimed that the model is ideally suited to describe the interaction between two technologies over their entire life cycles, but we can postulate that at a given time, the relationship between two technologies can be described by the model. One of the strengths of this model is that it allows one to track the dynamics of competition even as the mode changes. Even though there are suggestions in the literature that some socio-technological systems appear stable in time (see for example Marchetti, 1987, p.378; and Norton and Bass, 1992, p.72), there can be little doubt that in general, in a real application the coefficients will vary with time. This has to be the case if the model is to account for shifts from one mode of interaction to another, but in general it will also be the case within the individual modes. Apart from the fact that time dependent coefficients are implied by the logic of the framework itself, their existence is also supported by ample precedents in the literature. Referring to

diffusion models, Kamann and Nijkamp state that "... normally such models are hampered by a major shortcoming, i.e. the presupposed stability of parameters. This is a major flaw in diffusion analysis..." (1991, p.100). Glaziev and Kaniovski note that "... The majority of the present mathematical models treat the diffusion of innovations in a traditional way as a deterministic process, which can be described by means of differential equations or logistic curves.... Without questioning the usefulness of this approach, we must emphasize that the hypothesis about the deterministic character of innovation diffusion is appropriate only for the growth and maturity phase of the innovation life cycle under stable conditions" (1991, p.232). Bretschneider and Bozeman (1986), Easingwood, Mahajan and Muller (1981) and Bhargava (1989) among others have all used time dependent coefficients in models. It will be shown that the model developed in this chapter can easily be adapted to accommodate time dependent coefficients.

The dangers and pitfalls of trend extrapolation as a technology forecasting tool was alluded to in a previous chapter. The model for the multi-technology framework presented here is, however, not intended to be used as forecasting tool in that sense. Rather, it is foreseen that it can be used as a simulation tool to examine various scenarios and possible outcomes as two or more technologies compete and interact. The concept of a technology trajectory on the phase diagram is particularly useful in this regard.¹¹ Understanding how

¹¹ The term *trajectory* is used here to indicate the plot on a phase diagram that shows the relationship between two technologies. It should not be confused with concept of technology trajectories as proposed by Dosi (1982) and Winter and Nelson (1982).

the dynamics and trajectory change as the coefficients and initial values of the system change can, in principle, give some insights into what parameters and issues need to be addressed in order to launch an attack on a mature technology or defend against an emerging technology. The success and usefulness of the model will depend largely on the ability to estimate the coefficients. This can prove to be a very daunting task, given that the various technologies are coupled together through a set of non-linear differential equations and that the coefficients may also be time dependent. In order to further simplify the development of the model, the luxury of arbitrarily choosing coefficients to illustrate the concept will be assumed in this chapter. This approach has the advantage of allowing one to present pathological cases as illustrations. However, in the absence of a very rigorous mathematical analysis, there is always the danger that a special case or characteristic may be missed. Nevertheless, as a first pass and for the purpose of developing the model and a feel for how it behaves, an arbitrary selection of coefficients is an efficient way of starting. In order to apply the model to realistic cases, however, a technique for estimating the coefficients will have to be developed.

Modeling predator-prey interaction

The predator-prey interaction lends itself to a simple illustration of some of the basic concepts that are also applicable in the other two modes, and hence we shall start our treatment of the three interaction modes with the predator-prey formulation.

Consider two populations that are known to have a predator-prey relationship. In an ecological system such an assumption is not difficult to justify, for the nature of lion and

antelope, for example, is well known. However, in the case of technological systems, it may be more difficult to justify a predator-prey relationship *a priori*. In fact, one may have to deduce that the relationship is predator-prey rather than pure competition or symbiotic from the dynamical behavior of the system. The whole concept of predator-prey interaction between technologies has not received much attention in the literature, even though it seems to be an interesting and useful topic to explore. For the purposes of the discussion in this section, we shall confine ourselves to the development of a theoretical framework to model a predator-prey system and examine some of the characteristics of such a system.

Lotka formulated the predator-prey equations as (1956, p.88)

$$\frac{dN}{dt} = -a_n N + c_{nm} NM \quad (\text{predator}) \quad (5.1)$$

$$\frac{dM}{dt} = a_m M - c_{mn} MN \quad (\text{prey}) \quad (5.2)$$

where $a, c > 0$. In this formulation $N(t)$ represents the predator population and $M(t)$ the prey population. Referring to Eq (4.7), we find that the biopotentials for the predator and prey populations are given by

$$L_n = -a_n + c_{nm} M \quad (5.3)$$

$$L_m = a_m - c_{mn} N \quad (5.4)$$

The coefficients c_{nm} and c_{mn} account for the predator-prey interaction between the two populations N and M . Note that when c_{nm} and c_{mn} are both zero, there is no interaction

between the two populations. In that case the prey population will grow exponentially (as was shown in Eq (4.5)), whereas the predator population will decay exponentially. The coefficient a_m is the growth coefficient for the prey population in the absence of predators and under the assumption of unlimited resources, i.e. it reflects the birth rate minus death rate due to causes other than the influence of the predator population. The coefficient a_n is the rate at which the predator will decay in the absence of prey. Note that in the interaction between predator and prey in Eq (5.1), the term MM is the only source of growth for the predator, i.e. it is the only positive factor contributing to the predator's growth. Hence in the model above, the predator feeds *only* off the prey.

Recall that the market potential function L was introduced in the section on logistic growth in the previous chapter to account for the inhibitory effect of limited resources on the growth of a population. The term N^2 in Eq (4.13) was interpreted to model the inhibitory effect on the growth of N (and hence the negative sign) due to interactions between similar units in the same population (and hence the squared term). In the Lotka-Volterra equations above, the same line of reasoning is followed to model the predator-prey interaction. In the case of the prey population (M), growth is inhibited by interaction between units of the prey population and the predator population and hence the presence of the term $-MN$. The coefficient c_{mn} models the efficiency with which the predators hunt the prey. In the case of the predator population, interaction between predator and prey will have a positive (rather than an inhibitory) influence on the growth rate of the predator population (and hence the positive sign associated with the term MM). So far we have not accounted for the inhibiting effect that units within the same population will have on growth in the predator-prey model, but it will be shown later that this effect can easily be added.

Pielou has shown that, in the neighborhood of the equilibrium point (which will be defined shortly), the equations above can be solved to yield (1969, p.69)

$$M(t) = \frac{a_n}{c_{nm}} + \frac{a_n}{c_{nm}} \alpha \cos(\sqrt{a_n a_m} t + \beta) \quad (5.5)$$

$$N(t) = \frac{a_m}{c_{mn}} + \frac{a_m}{c_{mn}} \sqrt{\frac{a_n}{a_m}} \alpha \sin(\sqrt{a_n a_m} t + \beta) \quad (5.6)$$

where α and β are constants. Figure 5.1 shows a typical graphical representation of this form of predator-prey interaction as a function of time. The predator and prey populations have the same period, but that they are a quarter of a cycle out of phase. It is interesting to note that in the region of the equilibrium point, the period depends only on a_n and a_m and not on the coupling coefficients c_{nm} and c_{mn} . The amplitudes of the population curves

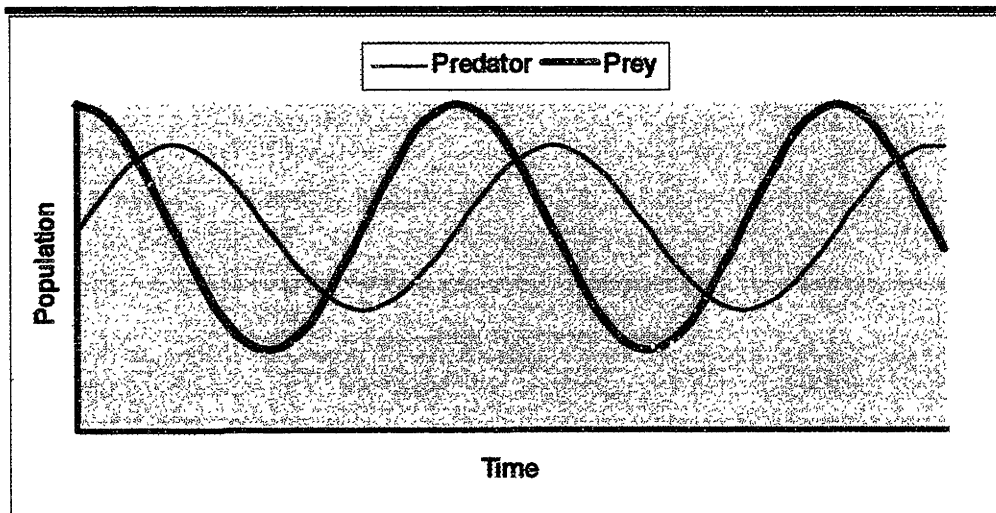


Figure 5.1 Time domain interaction of a simple predator-prey system with no inhibitory effects.

depend on the initial sizes of the populations.

Systems of non-linear differential equations are often displayed in terms of *phase diagrams*, where N is plotted against M .¹² In a phase diagram, time is an implied parameter along the trajectory, but it is typically not labeled or considered explicitly in the phase diagram. Phase diagrams are extremely useful to visualize the trajectory of the two technologies relative to one another. In constructing the phase diagrams, it is necessary to determine the equilibrium regions, i.e. those regions where the growth of the technologies is zero ($dM/dt=0$ and $dN/dt=0$). In the case where only two technologies interact, the equilibrium region for each technology is a line. The two lines sometimes intersect in an *equilibrium point* where the growth rates of both populations are zero simultaneously. Hence, if the trajectory reaches this point, it will not deviate from it again. Note that the terms *equilibrium line*, *equilibrium region* and *equilibrium point* should only be taken literally in the case where the coefficients are constants. As was discussed above, we recognize that in a real situation the constants will be time dependent, and hence so will be the equilibrium lines, equilibrium regions and equilibrium points.

In order to determine the equilibrium region for M , we need to set Eq (5.2) equal to zero.

We find that $M=0$ and that L_m must be set equal to zero in Eq (5.4). It follows that

¹² The author would like to acknowledge the inputs of Dr. Chris Farrell in pointing out the usefulness of the phase diagrams.

$dM/dt=0$ along the line $N=a_m/c_{mn}$ as well as along the N -axis. Furthermore, we find that $dM/dt>0$ in the region $N<a_m/c_{mn}$ and $dM/dt<0$ in the region $N>a_m/c_{mn}$. Similarly we find that $dN/dt=0$ along the line $M=a_n/c_{nm}$ as well as along the M -axis (where $N=0$), with $dN/dt>0$ in the region $M>a_n/c_{nm}$ and $dN/dt<0$ in the region $M<a_n/c_{nm}$. Figure 5.2 shows a typical phase diagram of a predator-prey system based on Eqs (5.1) and (5.2) (after Hirsch and Smale, 1974, p.262)). The equilibrium point is located at the intersection of the lines $dN/dt=0$ and $dM/dt=0$.

Obviously we are only interested in the region $M,N>0$, which can be divided into four subregions in this case. The signs of dM/dt and dN/dt are shown in each subregion in Figure 5.2. The dark arrows in each of the subregions are direction vectors that indicate the directional trends of the trajectory. Since the signs of the growth rates determine the direction in which M and N , respectively, will grow in each subregion, it is possible to determine a generic trajectory of M and N . In general there are many trajectories (since there are many initial values for the populations), but all the trajectories are concentric rings around the equilibrium point $(a_n/c_{nm}, a_m/c_{mn})$, where one travels in anti-clockwise direction around a ring as time progresses (as is evident from the signs of dN/dt and dM/dt) (Hirsch and Smale, 1974, p.262). It can also be shown that the concentric rings are ellipses close to the equilibrium point. It is interesting to note that there is a region where it is possible for both populations to grow at the same time (lower right subregion). Recall that this condition was excluded in the single equation formulations discussed earlier.

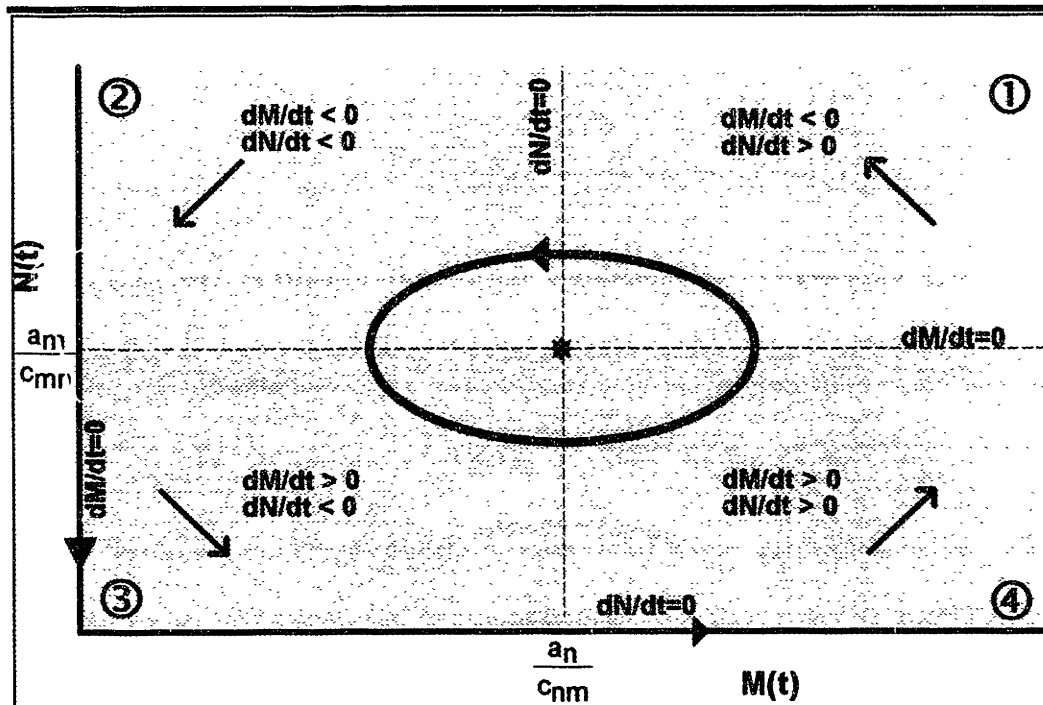


Figure 5.2 Phase diagram for the simple predator-prey system with no self-inhibiting terms. The dark arrows show the direction vectors in the four subregions, the dashed lines show the equilibrium lines and * shows the equilibrium point. Note that the axes are also equilibrium lines (after Hirsch and Smale, 1974).

As an interesting side comment, consider the case where the sign of a_n in Eq (5.1) is positive. This implies that there is no way to contain the growth of N and that the predator feeds on the prey *as well as other sources*. The phase diagram for this case is shown in Figure 5.3. In effect the equilibrium line where $dN/dt=0$ shifts into the (invisible) region ($M < 0$). Note that N grows exponentially whereas M grows and then dies out. The notion that N feeds off other sources in addition to the prey (that can include the same sources that feed M) will be used later when the *modified predator-prey model* is developed.

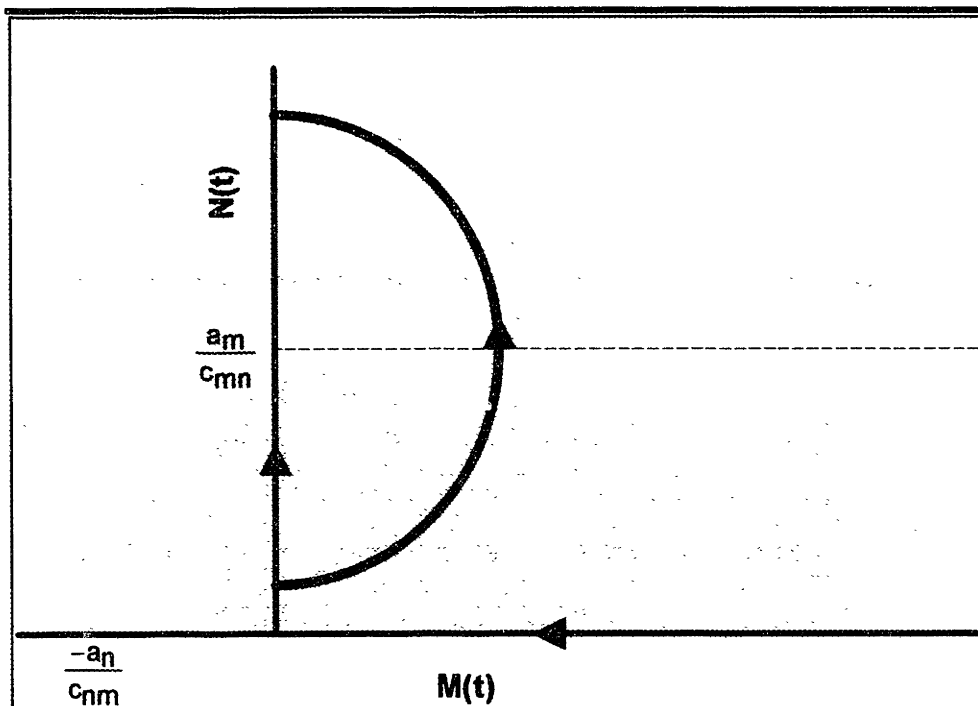


Figure 5.3 Phase diagram for the simple predator-prey system where the predator feeds from the prey as well as other sources.

It is clear from these results that although the predator-prey formulation discussed here does lead to oscillatory behavior, the oscillations shown in Figure 5.1 are *not* of the type we are interested in, i.e. the oscillations that are often detected in the mature phase of logistic growth. The oscillations that the system exhibits here are those of the population curves themselves that oscillate rather than follow a logistic growth. Since there is no logistic growth (and hence no S-curve behavior) here, one should not expect oscillations in the mature phase since there is no mature phase. The lack of logistic growth in this case should not surprise us, however. Recall from the previous section that logistic growth resulted when an inhibiting term proportional to the population itself was added, and so far this has not been done here.

The effect where units within the same population start interfering with one another when the population grows can easily be accounted for by taking a cue from Eq (4.13) and adding additional terms ($-b_n N^2$ and $-b_m M^2$) to Eqs (5.1) and (5.2), respectively. These terms account for the intraspecific interference where resources are limited, as discussed in the section on logistic growth. The model can thus be extended to

$$\frac{dN}{dt} = -a_n N - b_n N^2 + c_{nm} NM \quad (\text{predator}) \quad (5.7)$$

$$\frac{dM}{dt} = a_m M - b_m M^2 - c_{mn} MN \quad (\text{prey}) \quad (5.8)$$

where all coefficients are positive constants. A phase diagram for this system can be constructed in a similar fashion as above by setting the potential functions equal to zero. We find that $dM/dt=0$ along the N -axis and the line $a_m - b_m M - c_{mn} N = 0$. Furthermore, $dN/dt=0$ along the M -axis and the line $-a_n - b_n N - c_{nm} M = 0$. The coordinates of the equilibrium point are given by

$$M^* = \frac{a_m b_n + a_n c_{mn}}{b_n b_m + c_{mn} c_{nm}} \quad (5.9)$$

$$N^* = \frac{a_m c_{nm} - a_n b_m}{c_{mn} c_{nm} + b_n b_m} \quad (5.10)$$

Two possible solutions exist, depending on whether there is an equilibrium point in the region $M, N > 0$. Given that we are only interested in this region, there will be an equilibrium point only if the two lines intersect in the region $N > 0$.

Consider now the case where the equilibrium point exists in the region $N > 0$. This condition will hold if $N^* > 0$, i.e. $a_m c_{nm} > a_n b_m$. As before, the regions where $dN/dt = 0$ and $dM/dt = 0$ are lines that are found by setting the potential functions equal to zero, i.e.

$$-a_n - b_n N + c_{nm} M = 0 \tag{5.11}$$

$$a_m - b_m M - c_{mn} N = 0 \tag{5.12}$$

The phase diagram for this case is shown in Figure 5.4. The signs of the rate of growth in the various subregions indicate that the technology trajectories will be similar to those of the previous case. However, in this case the trajectory will spiral towards the equilibrium point.

Consider now the case where $N^* < 0$, i.e. where the two lines do not intersect in the region $M, N > 0$. The phase diagram is shown in Figure 5.5 (after Hirsch and Smale, 1974, p. 263). Note that in this case the predator population (N) inevitably dies out and the prey population stabilizes to a level of a_m/b_m . This level should be expected. Once the predator population has died out, the prey population should follow a logistic growth. We know from the section on logistic growth that the population eventually approaches a limiting level of a_m/b_m . Other than in the previous case, however, there is no region here where the two populations can grow simultaneously.

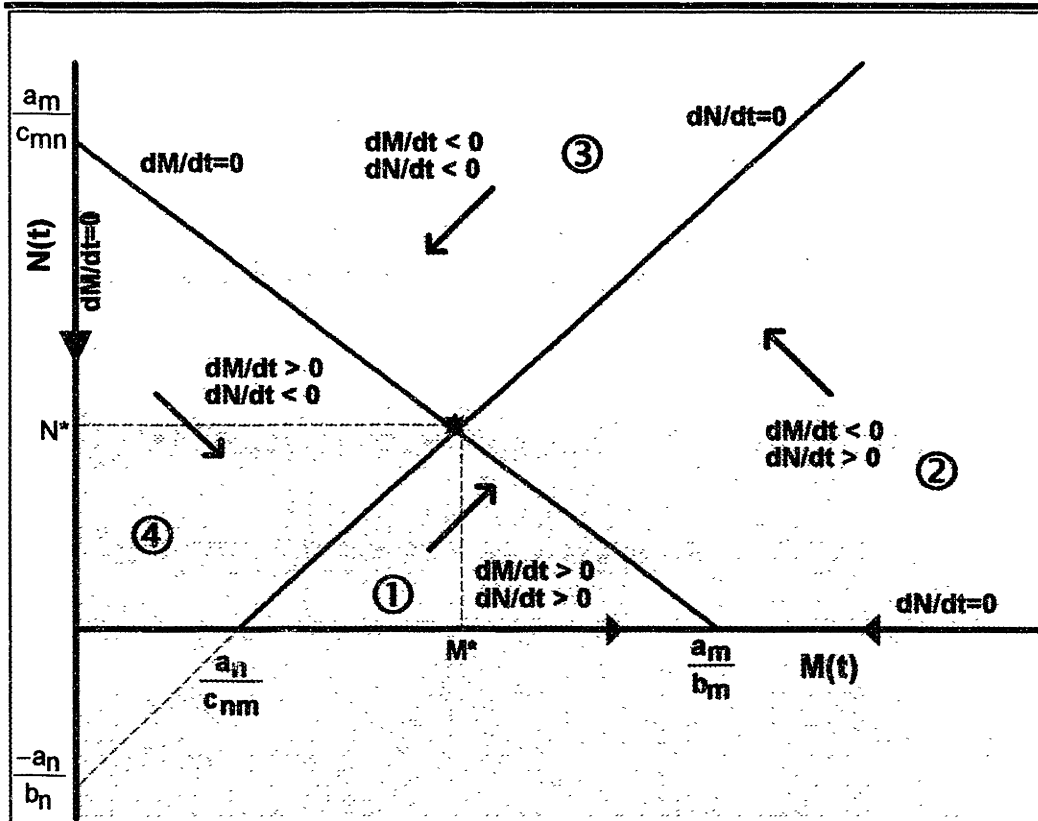


Figure 5.4 Phase diagram for the predator-prey system with limited growth and an equilibrium point in the region $M, N > 0$.

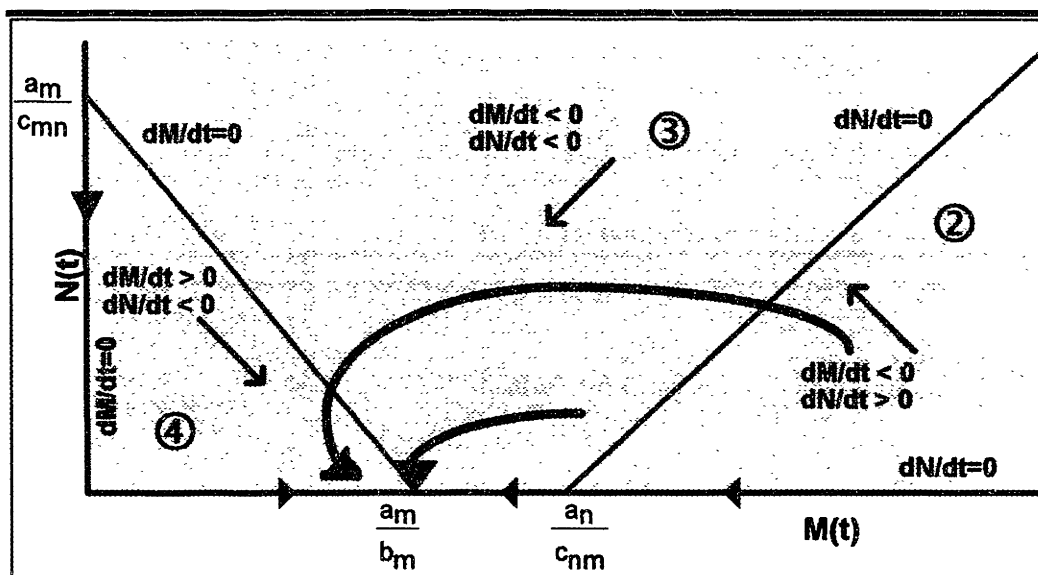


Figure 5.5 Phase diagram for the predator-prey system with limited growth and no equilibrium point in the region $M, N > 0$.

Hence we find that also in the case of limited growth examined here, the predator-prey formulation of the Lotka-Volterra equations does not seem to yield an obvious solution that exhibits oscillations in the mature phase of a logistic growth in one of the populations. Keep in mind the inherent assumptions that were made, however, particularly concerning constant coefficients.

The question may well now be asked how to interpret the predator-prey formulation of the Lotka-Volterra equations with regard to technological systems rather than ecological populations. In principle, the concept is clear. Consider the case where the presence of the mature technology has a positive influence on the growth of the emerging technology, but the presence of the emerging technology has a negative influence in the growth of the mature technology.¹³ The mature technology (M) can be represented by the equation for the prey population as given by Eq (5.8). The first two terms on the right hand side correspond with those that give rise to the logistic equation described earlier. The third term on the right hand side represents the inhibitory effect that the emerging technology (N) has on the growth rate of the mature technology. Note that this term is proportional to the interactions between emerging and mature technologies, just as the second term is proportional to interactions between units of the same technology. If one accepts the premises of the logistic equation (upon which the Fisher-Pry model is based), then the

¹³ Recall from the discussion in Chapter 3 that there are also cases where the emerging technology can be the prey and the mature technology the predator, but for the sake of argument we shall consider here the emerging technology to be the predator and the mature technology the prey.

formulation of this equation for the mature technology should not present a conceptual problem.

The emerging technology is modeled by Eq (5.7). Note that in this case the only source of growth for the emerging technology is proportional to its interactions with the mature technology. In the case of an ecological predator population whose only food is the prey, it is easy to interpret this term. In the case of technological systems, however, the mature technology does not act as the “food” for the emerging technology. Instead the emerging technology and the mature technology vie for the same resources in the market, i.e. the “food” can be interpreted to be the resources in the market, rather than the other technology *per se*. Perhaps the interaction term should not be taken so literally then, but instead be interpreted in a sense that the mature technology influences the emerging technology’s growth in a positive manner. Examples of this type of behavior were given in Chapter 3.

The term $-a_n N$ can be interpreted literally to be the rate at which the emerging technology will decline in the absence of the mature technology. One can certainly argue that a technology that is no longer manufactured will have a gradual rather than an abrupt (step function-like) decline. Certainly the number of, say, the 1980 model of a particular type of

car that one sees on the streets will probably decline in this fashion¹⁴. Recall, however, that in the discussion of exponential growth, the coefficient c_1 in Eq (4.5) (corresponding to a above) was the *net* birth rate. In the case of technologies there is no general inherent reason why the term a_n should have a negative sign, indicating a net decline. If there is reason to believe that the mere presence of a technology will stimulate growth of that technology, then one can certainly postulate that this term should have a positive sign. The case of fax machines is a good example. If only a few individuals or organizations own fax machines, they are not very useful. However, the more people who own them, the more useful they become. Hence it is not unreasonable to postulate that the growth rate for the diffusion of fax machines will be proportional to the population of fax machines. The case of a positive sign for a_n is in fact the basis for the Pearl equation that regulates logistic growth.¹⁵ Many other mathematical models, including the Fisher-Pry model discussed in Chapter 4 are based on positive a coefficients.

Modeling modified predator-prey interaction with a system of differential equations

Guided by our understanding of the underlying principles that give rise to the predator-prey formulation, we can now propose a model to describe two technologies that behave in the *normal logistic manner in the absence of one another, but have a predator-prey relationship when in the presence of one another*. Although such a formulation deviates

¹⁴ Recall Modis and Debecker's findings that computer systems are often retired as a generation and not one by one as is personal cars.

¹⁵ In the general case positive and negative signs for a_n can be argued.

from the classical predator-prey formulation and its resulting characteristics, the positive sign for the term a_n that is used in such a formulation is well motivated. Hence we can now postulate a *modified predator-prey formulation* as one of the three modes in the interaction matrix shown in Figure 3.1. The system of equations describing the *modified predator-prey mode*¹⁶ can be expressed as

$$\frac{dN}{dt} = a_n N - b_n N^2 + c_{nm} NM \quad (\text{predator}) \quad (5.13)$$

and

$$\frac{dM}{dt} = a_m M - b_m M^2 - c_{mn} MN \quad (\text{prey}) \quad (5.14)$$

As before, N represents the predator, M represents the prey and all coefficients are positive. Note that a_n now has a positive sign. The equations describing the equilibrium lines where $dN/dt=0$ and $dM/dt=0$, respectively, are given by

$$\frac{dN}{dt} = 0: \quad N = \frac{a_n}{b_n} + \frac{c_{nm}}{b_n} M \quad (5.15)$$

¹⁶ In the rest of this thesis the expression *predator-prey* shall imply *modified predator-prey* as defined here, i.e. when the sign associated with a is positive but the sign of c depends on whether the technology is a predator or a prey.

$$\frac{dM}{dt} = 0; \quad N = \frac{a_m}{c_{mn}} - \frac{b_m}{c_{mn}} M \quad (5.16)$$

In addition, the N -axis (where $M=0$) is also an equilibrium line for M , and similarly the M -axis (where $N=0$) is also an equilibrium line for N . Note that the sign of the coefficient c determines whether a technology is a predator (as in (5.13)) or a prey (as in (5.14)). The presence of b ensures that the growth of a technology will not be unbounded exponential growth, but rather limited logistic growth. It can be shown that the coordinates of equilibrium point are given by

$$M^* = \frac{a_m b_n - a_n c_{mn}}{b_m b_n + c_{nm} c_{mn}} \quad (5.17)$$

$$N^* = \frac{a_m c_{nm} + a_n b_m}{c_{mn} c_{nm} + b_n b_m} \quad (5.18)$$

Again we find that there are two possible cases, depending on whether there is an equilibrium point in the region $M, N > 0$. The phase diagrams for the two cases are shown in Figures 5.6 and 5.7 respectively. It is obvious that an equilibrium point will exist in the region $M, N > 0$ if $a_m b_n > a_n c_{mn}$. Note that these two cases (with and without the equilibrium point in the region $M, N > 0$) are very similar to the regular predator-prey interaction with limited growth discussed earlier.

It would seem that in the case where the equilibrium point exists in the region $M, N > 0$, the technology trajectory will approach this point, sometimes in a spiraling fashion and

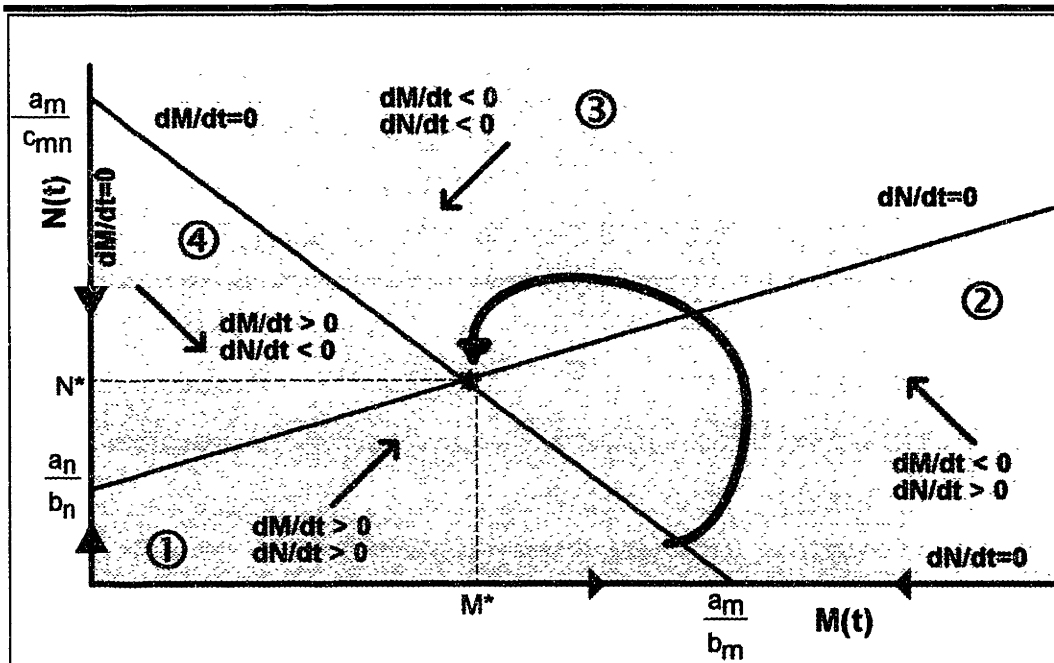


Figure 5.6 Phase diagram for the modified predator-prey system with an equilibrium point in the region $M, N > 0$ (Case 1: $a_m b_n/a_n > c_{mn}$).

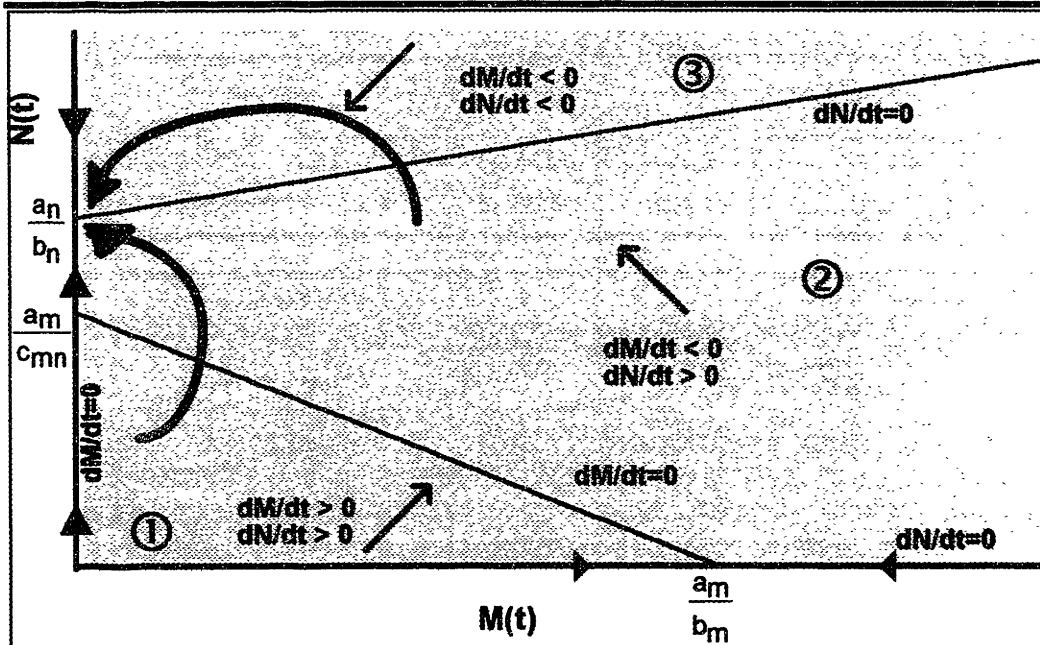


Figure 5.7 Phase diagram for the modified predator-prey system without an equilibrium point in the region $M, N > 0$ (Case 2: $a_m b_n/a_n < c_{mn}$).

sometimes in a more monotonic way. In this case $N^* > a_n/b_n$, so that the limiting value of the predator population is larger than what it would have been if there had been no predator-prey interaction (a_n/b_n). On the other hand, we find that $M^* < a_m/b_m$, so that the limiting value of the prey population will always be less than what it would have been if there had been no predator-prey interaction (a_m/b_m). In the case where there is no equilibrium point in the region $M, N > 0$ (as depicted in Figure 5.7), the prey population will die out and the predator population will eventually settle at a level of a_n/b_n . Again this value is to be expected, since in the absence of prey, the predator follows a regular logistic growth, which has been shown to approach the limiting population a_n/b_n . Note that in this formulation the predator can survive without the prey since it can “feed” off other resources as well (as manifested in the positive sign of a_n).

Although there are several statements in the literature that the Lotka-Volterra equations and particularly the pure competition formulation, cannot be solved explicitly (see for example Porter *et al.*, 1991, p.197; and Hannan and Freeman, 1989, p.101) they can be solved numerically. Pielou has also shown that the equations can, in fact, be solved in difference form (1969, p.59). He has solved the case of pure competition, but it will be shown that his solution can be adapted to apply to the modified predator-prey case formulated above as well as the symbiotic case, the difference being in the sign of the coefficients c_{nm} and c_{mn} . In the next section it will be shown that in the case of pure competition, c_{nm} has a negative sign, whereas in this case it has a positive sign.

Pielou's solution for the pure competitive case can now be duly modified to account for this sign change that is mandated by the modified predator-prey model above, yielding the solution for Eq (5.13) as

$$N(t+1) = \frac{\lambda_n N(t)}{1 + \beta_n N(t) - \left(\frac{c_{nm}}{b_n}\right) \beta_n M(t)} \quad \text{(predator) (5.19)}$$

where

$$\lambda_n = e^{a_n} \quad (5.20)$$

$$\beta_n = \frac{b_n(e^{a_n} - 1)}{a_n} \quad (5.21)$$

and similarly for Eq (5.14) as

$$M(t+1) = \frac{\lambda_m M(t)}{1 + \beta_m M(t) + \left(\frac{c_{mn}}{b_m}\right) \beta_m N(t)} \quad \text{(prey) (5.22)}$$

where

$$\lambda_m = e^{a_m} \quad (5.23)$$

$$\beta_m = \frac{b_m(e^{a_m} - 1)}{a_m} \quad (5.24)$$

Note the negative sign in the denominator of the equation for $N(t+1)$. This is where the solution for the modified predator-prey formulation deviates from Pielou's solution for the pure competition case.

At the risk of jumping the gun on the discussion of the case of pure competition, we note that Eq (5.14) represents the equation of the pure competition system of equations, with the solution given by Eq (5.22). Comparing Eq (5.22) with the difference form solution of the Pearl equation given by Eq (4.16), we note that Eq (5.22) contains an additional term in the denominator that accounts for the interaction among the two technologies. The term a_m/b_m in Eq (5.24) represents the maximum level at which the market niche is saturated in the absence of competition (as was discussed in the section on logistic growth). The saturation level is brought about by the inhibiting effect of similar units vying for the same limited resources and is manifested by the term $-b_m M^2$ in the differential equation. The factor $(c_{mn}/b_m)\beta_m$ in the denominator of Eq (5.22) in effect thus replaces a_m/b_m with a_m/c_{mn} as a “saturation level” associated with the inhibitory effect that results from the competition between the two technologies (as represented by the term $-c_{mn}MN$ in the differential equation).

There are no obvious references to or descriptions in the literature of the modified formulation of the predator-prey equations proposed above (except for the cursory reference to generic predator-prey interaction by Porter *et al.* (1991, p.196)) and therefore it warrants a more intensive discussion here. As an example to illustrate some of the characteristics of the modified predator-prey system, consider the case where the interaction among the two technologies is described by

$$N(t) = N (0.1 - 0.01N + c_{nm}M) \quad (5.25)$$

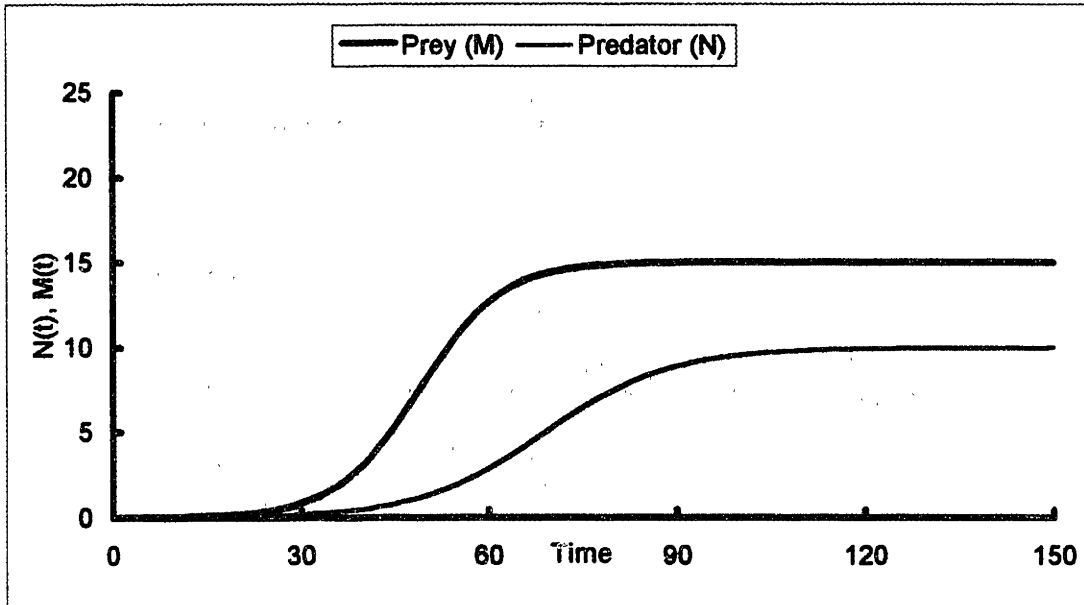
$$M(t) = M (0.15 - 0.01M - c_{mn}N) \quad (5.26)$$

It should be stressed again that we are arbitrarily choosing coefficients as a convenient way of investigating the behavior of the system.

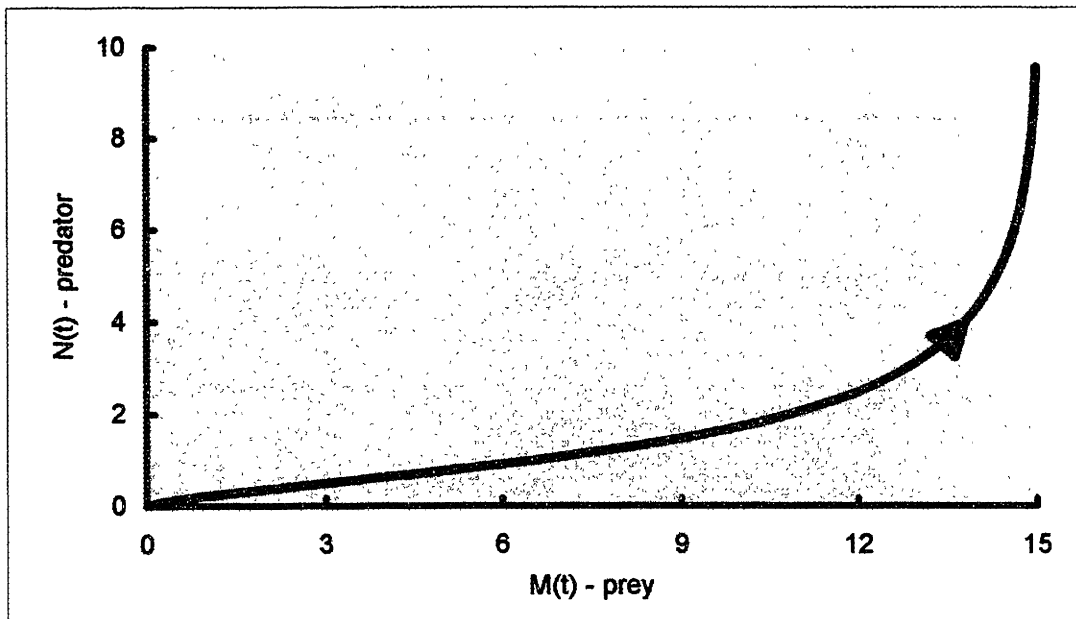
In order to set the predator-prey interaction in perspective, let us first consider the case where there is no interaction between M and N . This is accomplished by setting the coefficients c_{nm} and c_{mn} equal to zero in Eqs (5.25) and (5.26). Figure 5.8 shows M and N as a function of time as well as the trajectory on the phase diagram. Note that in this case where $c_{mn}=0$, M is the same as that depicted in Figure 4.1. As expected both technologies exhibit logistic growth. In the limit as time approaches infinity, the prey (M) tends to the limit a_m/b_m (15 in this case) and similarly the predator (N) tends to the limit a_n/b_n (10 in this case), as one would expect in the case of logistic growth.

In this example, the initial values $M(0)$ and $N(0)$ have both arbitrarily been chosen close to the origin. It is appropriate to reflect for a moment on the initial values of N and M . In the case where a new technology (N) attacks an mature technology (M), one would assume that $N(0)$ would be small since N is still young and that $M(0)$ would be large, since M is mature and established. As was mentioned before, one intuitively feels that the emerging technology should be the predator and the mature technology the prey, but it was shown through examples in Chapter 3 that this is not necessarily the case. M and N could, for example, have coexisted for a long time whilst addressing different market niches. If either M or N decides to switch strategies and attack the market niche of the other (whether in a positive or negative way) interaction between M and N will then commence.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0$	$N(0)=0.01$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0$	$M(0)=0.01$



(a)



(b)

Figure 5.8 No interaction between technologies (a) time domain (b) phase diagram.

In general, $t=0$ indicates the time when the interaction between M and N starts. In the case just mentioned there are two mature technologies that start interacting at $t=0$, and hence both $M(0)$ and $N(0)$ will have large values at that time. A similar argument can be made to motivate a case where both $M(0)$ and $N(0)$ will have small values. It is implied that in the general case both M and N have grown in some fashion to obtain the values $M(0)$ and $N(0)$ at $t=0$ when they start interacting. Within the time reference used here, this growth took place during the period $t<0$. In order to include the most general behavior of the model, we shall therefore consider various combinations of initial values in the examples that are considered in this chapter. From Figure 5.6 it is evident that there are two cases in the (modified) predator-prey mode, since $a_m b_n > a_n c_{mn}$ or $a_m b_n < a_n c_{mn}$. We now proceed to investigate each of these cases.

Case 1: $a_m b_n > a_n c_{mn}$

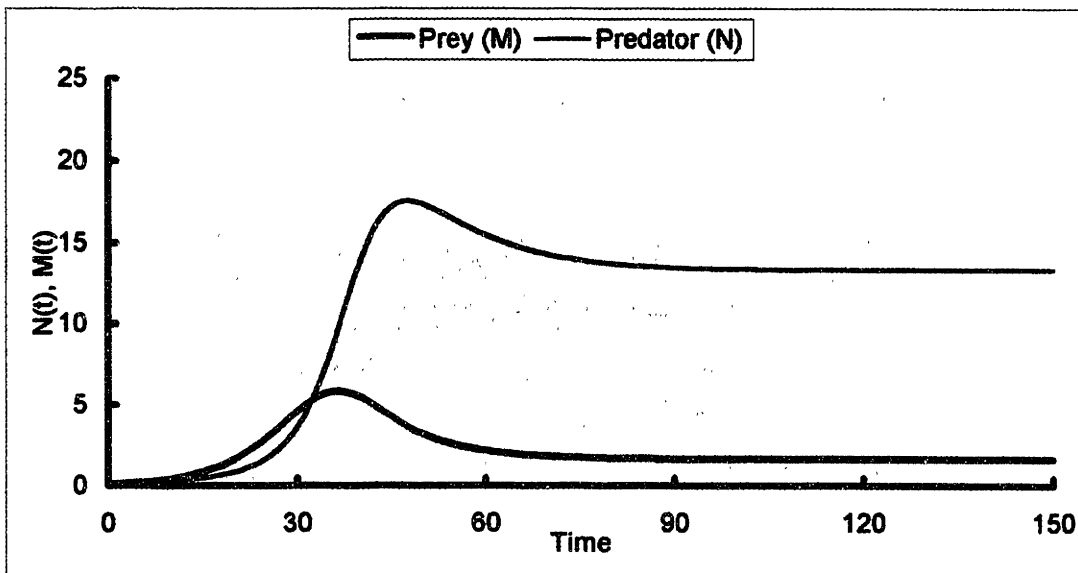
Consider the case where an equilibrium point exists in the region $M>0$. In order for this to happen, it is evident from Eq (5.17) that it is required that $a_m b_n > a_n c_{mn}$. In the example defined by Eqs (5.25) and (5.26), there will thus be an equilibrium point in the region $M>0$ if $c_{mn} < 0.015$. To illustrate this case, arbitrarily select $c_{mn} = 0.01$ and $c_{nm} = 0.02$. The other coefficients are the same as in Figure 5.8. Figure 5.9 shows M and N as a function of time as well as the trajectory on the phase diagram. The equilibrium lines where $dM/dt=0$ and $dN/dt=0$ are also shown on the phase diagram as well as the equilibrium point, which is located at (1.67, 13.33). The two lines indicating the equilibrium regions where $dM/dt=0$ and $dN/dt=0$, respectively, are given by $N=15-M$ and $N=10+2M$. Recall that the axes are also equilibrium lines. Note that the trajectory spirals towards the equilibrium point, and it does so in an anti-clockwise sense. Furthermore, notice that the trajectory is vertical where it crosses the $dM/dt=0$ line at point A and horizontal where it crosses the $dN/dt=0$

line at point B (as it should be since these lines represent regions where the derivatives with respect to the horizontal and vertical directions are zero). Turning our attention to the time domain plots of the two technologies, we see that both plots deviate substantially from the S-curves that resulted when there was no interaction among the two technologies (as shown in Figure 5.8). As time approaches infinity, both technologies now approach the levels corresponding to the levels of the equilibrium point (M^* and N^*) rather than the a/b -level that is characteristic of logistic growth.

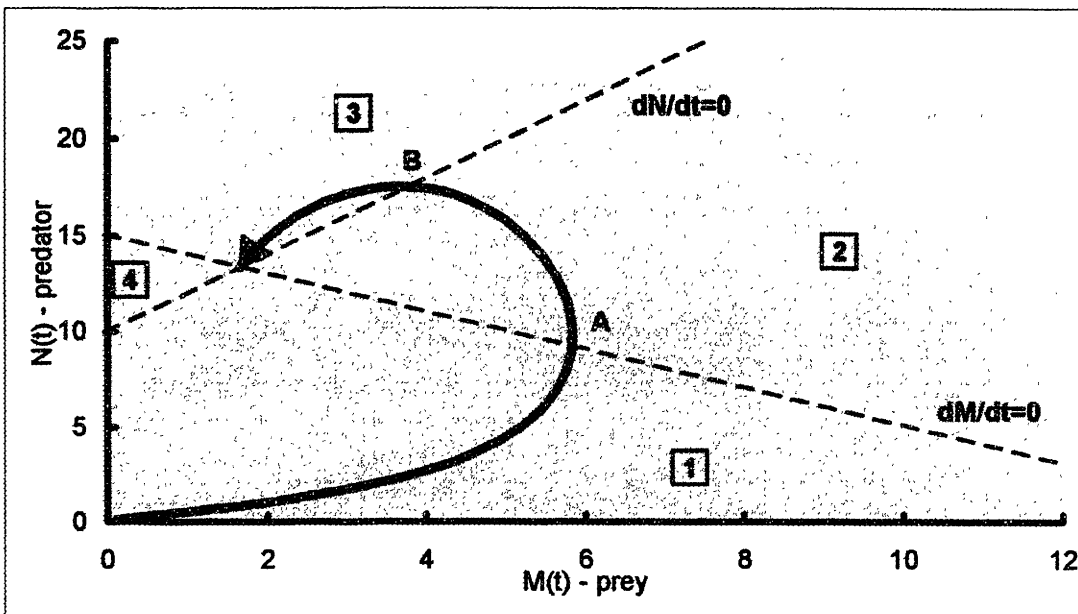
Comparing Figure 5.9(a) to Figure 5.8(a), it is evident that in this case the predator (N) has certainly benefited from the interaction. Not only is its final value higher than in the case where there is no interaction, but there is also a growth spurt that corresponds with the growth in M . In addition, the slope of the growth phase of the predator's S-curve is higher than in the case when there is no interaction. The prey, on the other hand, is inhibited by the growth in the predator. After an initial growth that follows the first phase of the S-curve of the case where there is no predator-prey interaction, the prey population declines as the predator interaction stunts its growth. As the prey declines, so does the super growth of the predator. Note that the prey does not vanish completely, but settles to a final level that is much smaller than that attained in the case where there is no predator-prey interaction.

We now shall now investigate the effect that different combinations of initial values have on the path of the trajectory. Figure 5.10 shows the case where the prey population (representing the mature technology) has a large initial value and the predator population (representing the emerging technology) has a small initial value. The trajectory

Predator	$a_n=0.1$	$b_n=0.01$	$c_{mn}=0.02$	$N(0)=0.01$	$N^*=13.33$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=0.01$	$M^*=1.67$
	$a_m b_n / a_n = 0.015$				



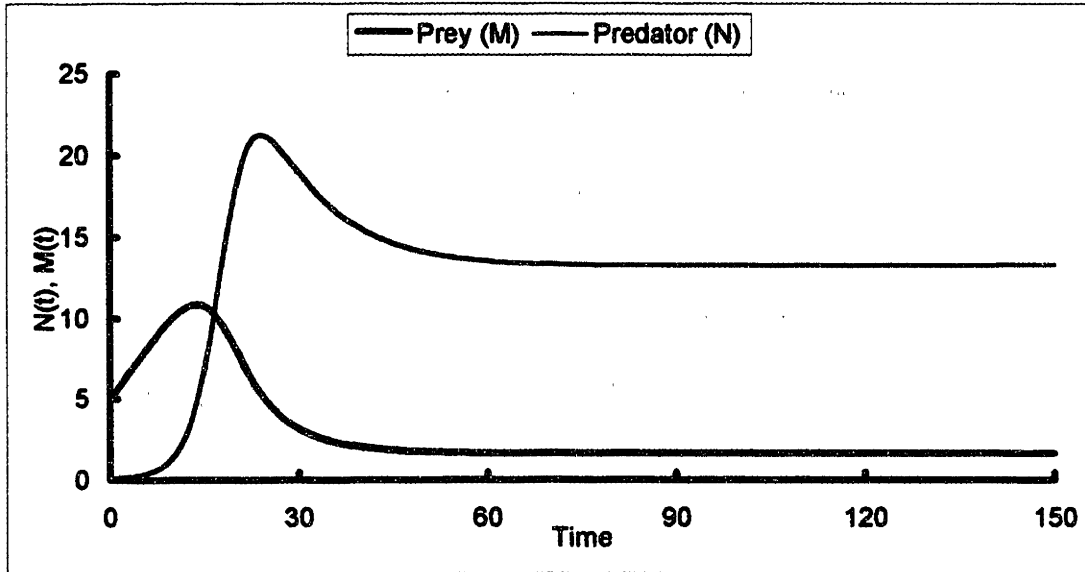
(a)



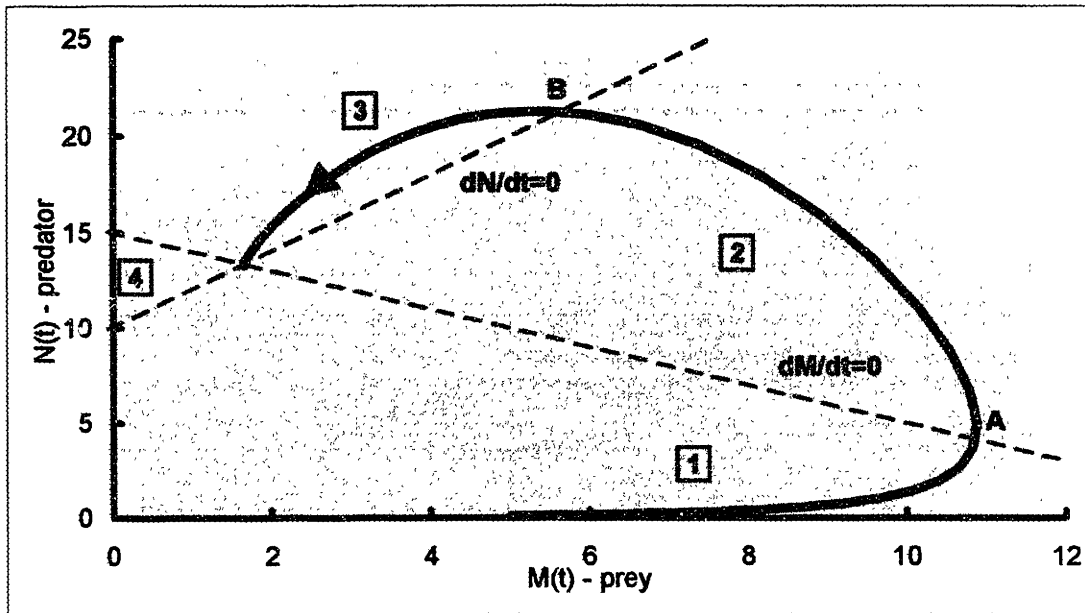
(b)

Figure 5.9 Modified predator-prey interaction (Case 1: $a_m b_n / a_n > c_{mn}$) with $N(0)=0.01$ and $M(0)=0.01$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=0.01$	$N^*=13.33$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mm}=0.01$	$M(0)=5$	$M^*=1.67$
	$a_m b_n / a_n = 0.015$				



(a)



(b)

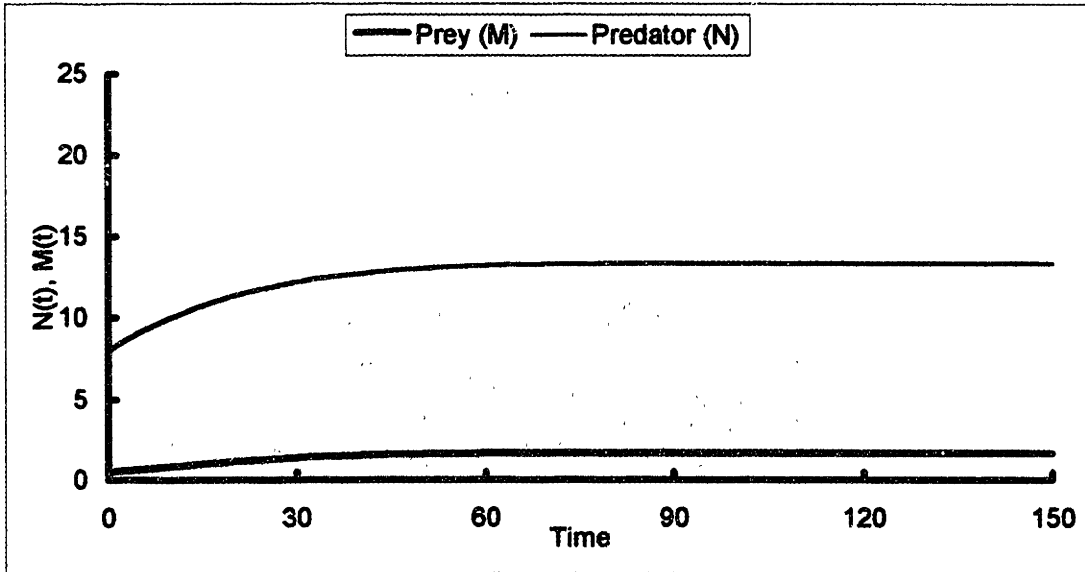
Figure 5.10 Modified predator-prey interaction (Case 1: $a_m b_n / a_n > c_{mn}$) with $N(0)=0.01$ and $M(0)=5$ (a) time domain (b) phase diagram.

and interaction of the two technologies are, however, very similar to the case where both initial values are in the proximity of the origin.

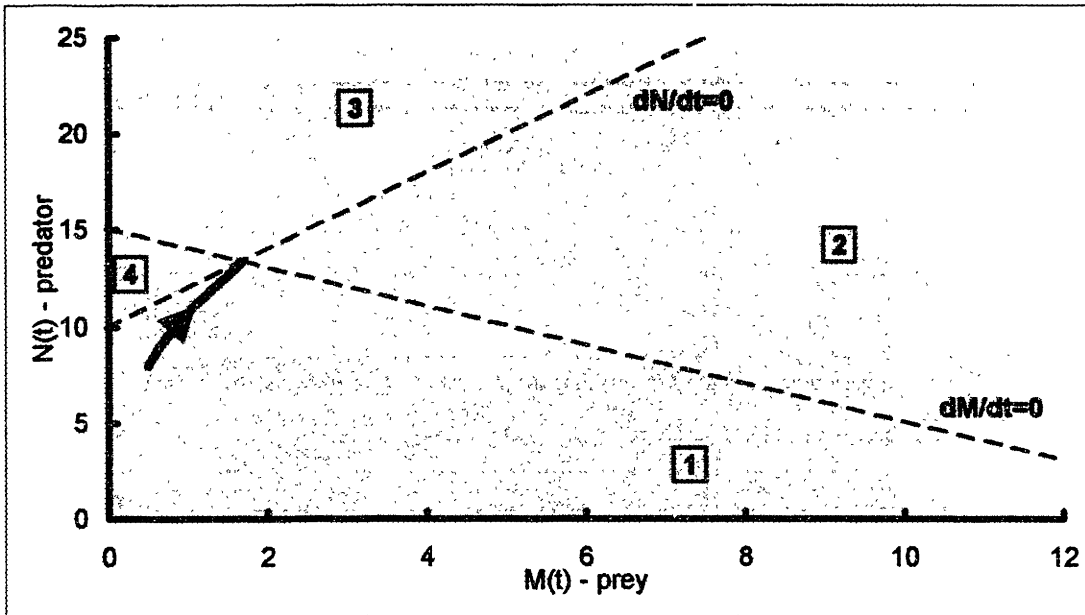
It is obvious that the initial values of the two populations influence the trajectory significantly, even when all the coefficients of the model are unchanged. Keep in mind that in this case the trajectory on the phase diagram evolves in an anti-clockwise direction as time progresses and that the trajectory in each of the subregions has to obey the direction vectors shown in Figure 5.6. In Figure 5.9 where the initial values of both technologies are close to the origin, we find that the trajectory spirals towards the equilibrium point through subregions 1, 2 and 3. In that case the prey population (M) reaches a maximum value at point A (where it crosses the line $dM/dt=0$) before the predator population (N) reaches its maximum value at point B (where it crosses the line $dN/dt=0$). The spiraling motion of the trajectory also explains the overshoot of the time plot of the predator, i.e. the predator grows in subregions 1 and 2, but subsides again in subregion 3 (since its growth vector is negative in that subregion) in order to eventually terminate in the equilibrium point. The prey population grows in subregion 1, but subsides in both subregions 2 and 3.

Consider now two additional cases designed to investigate the effect of the initial values on the trajectory. In both cases we keep the coefficients of the system the same but change the initial values of the two populations. Figure 5.11 shows the case where the initial values are $M(0)=0.5$ and $N(0)=8$. Note that the starting point is still in the first subregion as in the previous two figures. However, in this case the trajectory does not spiral towards the equilibrium point through other subregions in an anti-clockwise sense. The trajectory still obeys the growth vectors of the first subregion, but now grows monotonically in a

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=8$	$N^*=13.33$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=0.5$	$M^*=1.67$
	$a_m b_n / a_n = 0.015$				



(a)



(b)

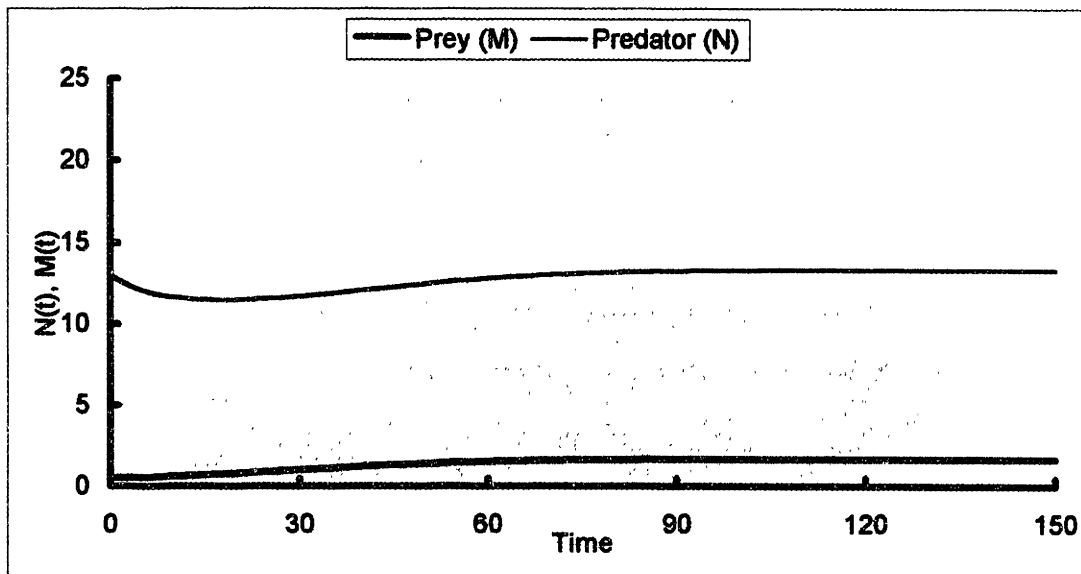
Figure 5.11 Modified predator-prey interaction (Case 1: $a_m b_n / a_n > c_{mn}$) with $N(0)=8$ and $M(0)=0.5$ (a) time domain (b) phase diagram.

clock-wise sense towards the equilibrium point with the entire motion in the first subregion. In the corresponding time domain plots we thus observe monotonic growth in both technologies. Since there is no spiral through other subregions, there is also no overshoot in either technology. Figure 5.12 shows the case where the initial values are $M(0)=0.5$ and $N(0)=13$, i.e. the starting point is in the fourth subregion. The trajectory now spirals through the fourth and first subregions in order to reach the equilibrium point. Hence the predator population first declines and then grows to stabilize at the value of the equilibrium point. The prey population shows a monotonic growth. *We conclude that the trajectory and corresponding interaction between the two technologies depend not only the coefficients of the system but also on the initial values.*

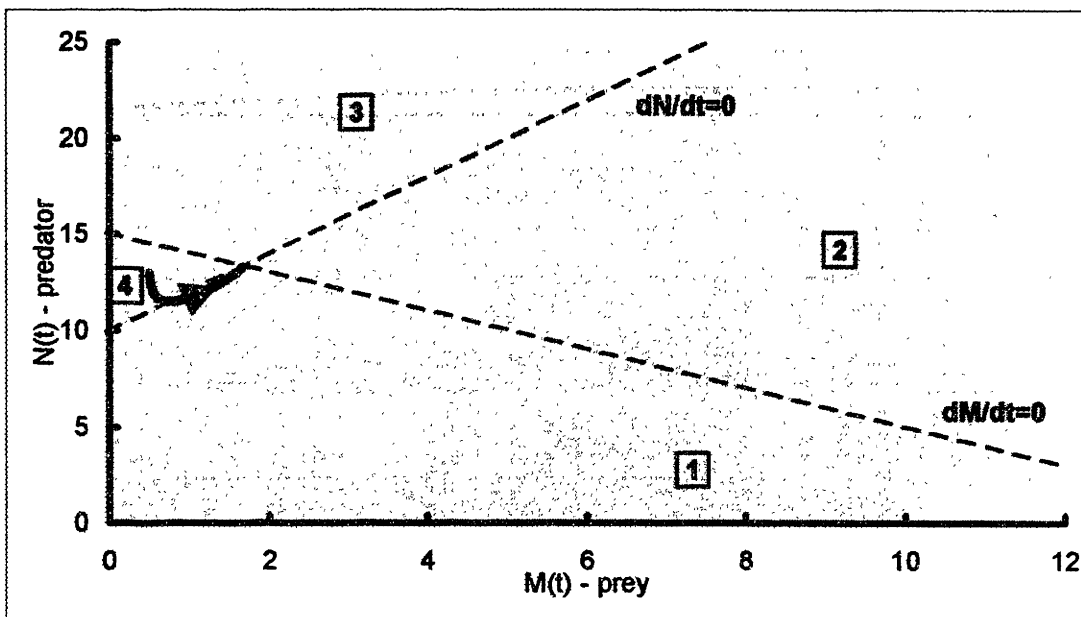
Let us now investigate the effect that the coefficients have on the dynamics of the system in the case where the equilibrium point is in the region $M, N > 0$. The coefficients a and b are logistic parameters and as such their influences are well known. We shall therefore concentrate on the effects of the competition coefficients c_{mn} and c_{nm} .

Consider first c_{mn} , i.e. the coefficient that determines the extent to which interaction with the predator (emerging technology) will inhibit the growth of the prey (mature technology). We expect that an increase in this coefficient will be detrimental to the prey's growth. From Eq (5.16) we know that the intersection of the line $dM/dt=0$ with the N -axis as well as its slope are both inversely proportional to c_{mn} . Referring to Figure 5.6, it is evident that increasing c_{mn} will thus decrease the slope of the line and move the point of intersection with the N -axis down the axis. These effects are captured by investigating c_{mn} 's effect on the equilibrium point. From Eqs (5.17) and (5.18) it is clear that increasing c_{mn} will decrease both M^* and N^* . In Figure 5.6 we can see this effect as the line

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=13$	$N^*=13.33$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=0.5$	$M^*=1.67$
	$a_m b_n / a_n = 0.015$				



(a)



(b)

Figure 5.12 Modified predator-prey interaction (Case 1: $a_m b_n / a_n > c_{mn}$) with $N(0)=13$ and $M(0)=0.5$ (a) time domain (b) phase diagram.

$dM/dt=0$ slides down the $dN/dt=0$ line, moving the equilibrium point downwards and to the left in the process. In the extreme case where $a_m b_n / a_n < c_{mn}$, one finds that $M^* < 0$ and the prey population dies out. This case is discussed separately in a following paragraph (as Case 2 of the modified predator-prey interaction).

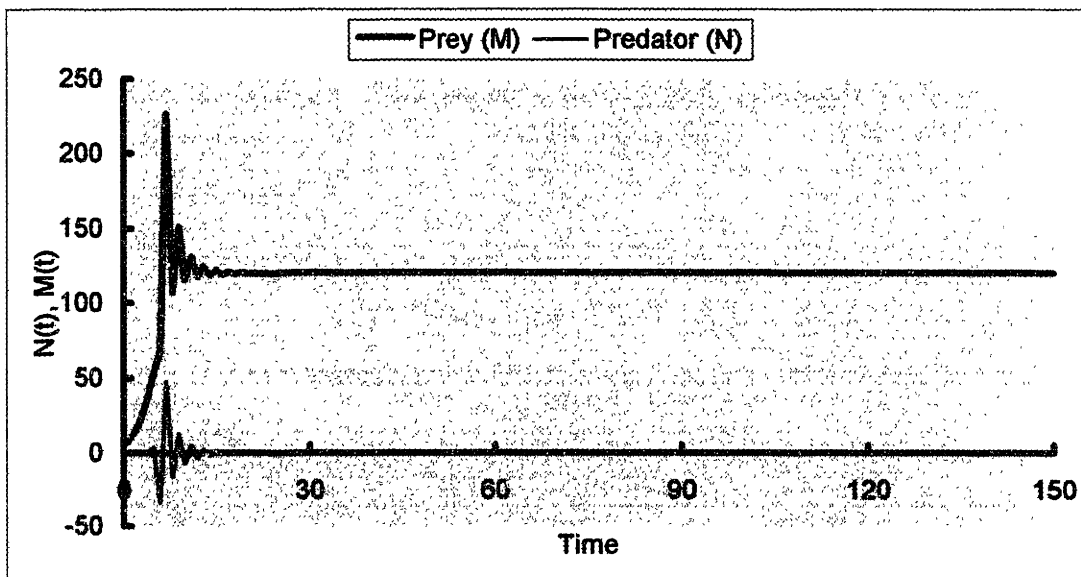
Consider now c_{nm} , the coefficient that determines the extent to which the predator benefits from interaction with the prey. One would expect that increasing c_{nm} will benefit the predator's growth. Note from Eq (5.15) that this coefficient determines the slope of the line $dN/dt=0$ since the slope is proportional to c_{nm}/b_n . From Figure 5.6 it is clear that increasing c_{nm} will slide the equilibrium point left and upwards along the line $dM/dt=0$, thereby increasing the limiting value of N (N^*) and decreasing the limiting value of M (M^*). In the limit as c_{nm} approaches infinity, the equilibrium point moves to the point a_m/c_{mn} on the N -axis. At this point the prey population also dies out. From Eq (5.15) we know that b_n and c_{nm} work in opposite directions and hence the effect of an increase in c_{nm} can be countered by increasing b_n .

It is interesting to note that increasing c_{mn} decreases both M^* and N^* , whereas increasing c_{nm} increases N^* but decreases M^* . There is thus an asymmetry in the effects of the two competition coefficients. Since the purpose of the model is to be a simulation tool for the multi-mode framework and therefore also an aid to managerial decision making, this is an important observation. In a later discussion we shall examine how the setting of an attack/defense strategy relates to the coefficients of the model. In that regard it is important to be aware of the characteristics of the coefficients such as the asymmetry of the competition coefficients.

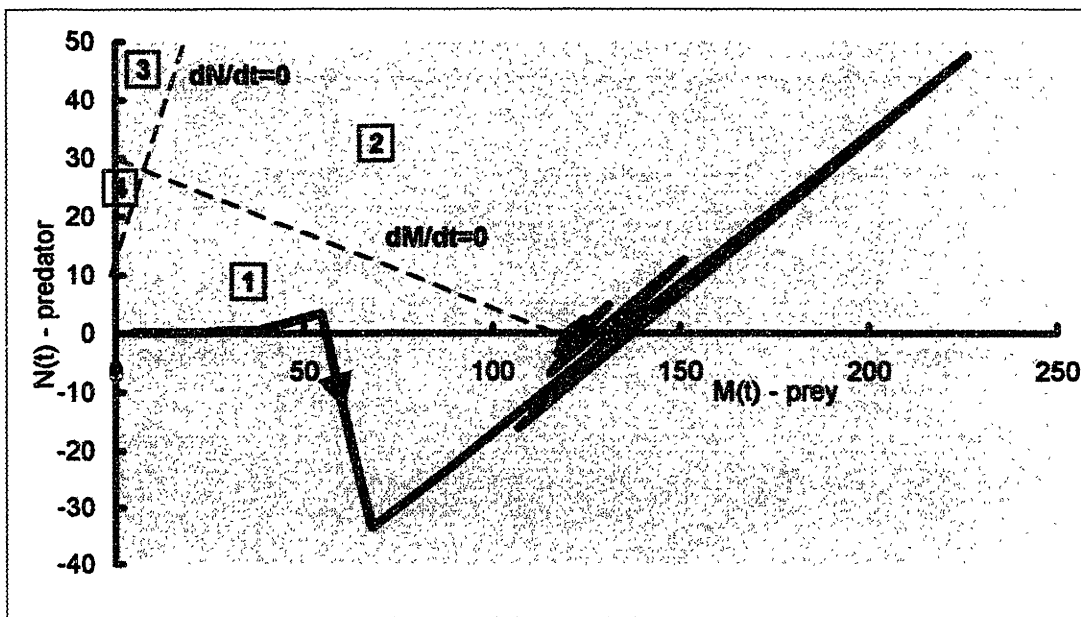
A very interesting phenomenon is observed as the value of $a_m b_n / a_n$ is increased. The S-curves of both technologies break into chaos-like oscillations in the mature phase of the prey population as illustrated in Figures 5.13 and 5.14. The behavior in these two figures *do not* conform to the notion that the trajectory approaches the equilibrium point. Unrealistic negative values of $N(t)$ are also produced. From the viewpoint that motivated our original investigation into the Lotka-Volterra equations, i.e. the oscillatory behavior in the mature phase of an S-curve, this is a very encouraging result, even though the model produces a result that obviously does not conform to reality. A similar phenomenon is observed in the case of symbiotic interaction, where this chaos-like behavior will be discussed in more detail.

A theory advanced by Modis and Debecker that the oscillations in the mature phase of a technology's S-curve are chaotic in nature (1992) is discussed in Chapter 6. In the same article Modis and Debecker also comment on a phenomenon they call the *catching-up effect*, in which the S-curve of a technology exhibits "overshoot" when it enters the mature phase (p.117). They refer to Marchetti's work in this regard, and quote him as describing the "... sudden release of pent-up energy following a 'technical' delay in the early evolution of a population. It is manifested as growth at an accelerated rate until the logistic trajectory is reached". Turning our attention back to Figure 5.9, we notice that the overshoot phenomenon of the predator corresponds exactly with the overshoot Modis *et al.* refer to. It will be shown that a similar effect occurs in symbiotic interaction. The model developed in this chapter therefore suggests that the catching-up effect in a technology's S-curve can perhaps also be related to the boost it receives from another technology that is in symbiotic or predator-prey interaction with it.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=0.1$	$N^*=27.78$
Prey	$a_m=0.6$	$b_m=0.005$	$c_{mn}=0.02$	$M(0)=5$	$M^*=8.89$
	$a_m b_n / a_n = 0.06$				



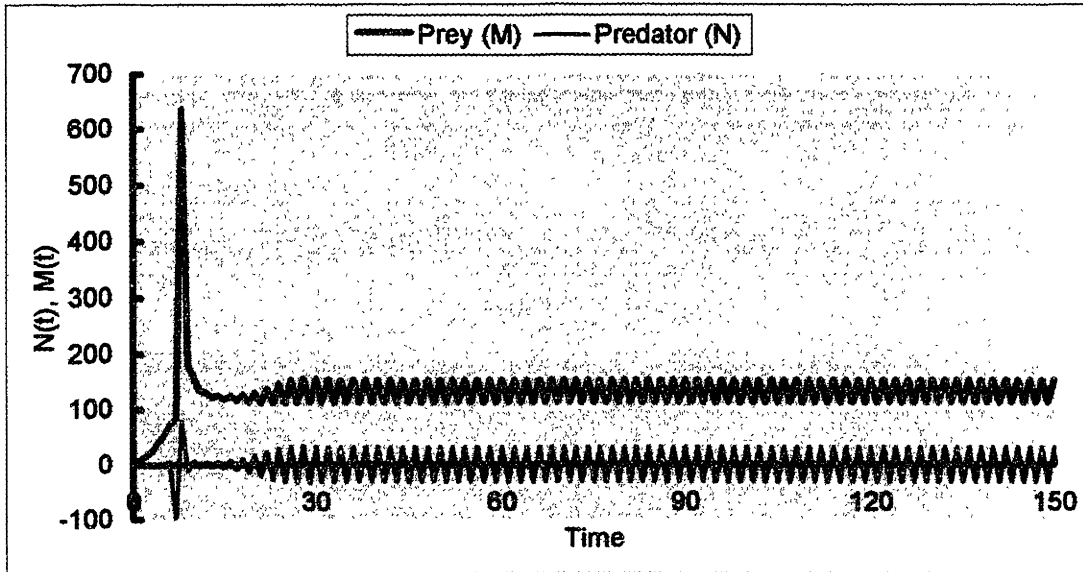
(a)



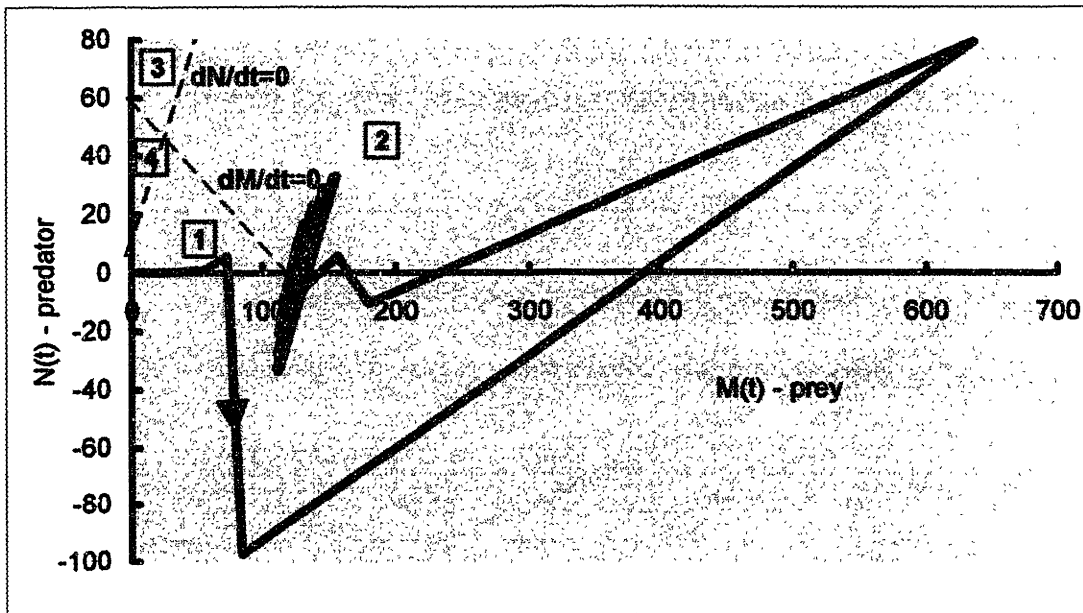
(b)

Figure 5.13 Modified predator-prey interaction (Case 1: $a_m b_n / a_n > c_{mn}$) with $N(0)=0.1$ and $M(0)=5$ (a) time domain (b) phase diagram. Note the seemingly chaotic oscillations.

Predator	$a_n=0.05$	$b_n=0.01$	$c_{nm}=0.015$	$N(0)=0.1$	$N^*=46.25$
Prey	$a_m=0.6$	$b_m=0.005$	$c_{mn}=0.01$	$M(0)=5$	$M^*=27.50$
	$a_m b_n / a_n = 0.12$				



(a)



(b)

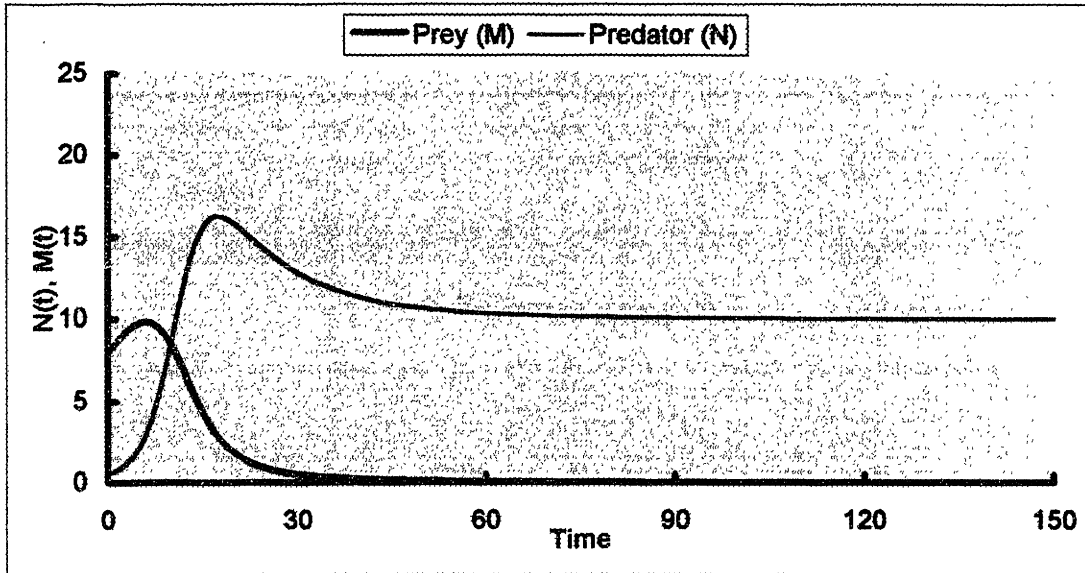
Figure 5.14 Modified predator-prey interaction (Case 1: $a_m b_n / a_n > c_{mn}$) with $N(0)=0.1$ and $M(0)=5$ (a) time domain (b) phase diagram. Note the seemingly chaotic oscillations.

Case 2: $a_m b_n < a_n c_{mn}$

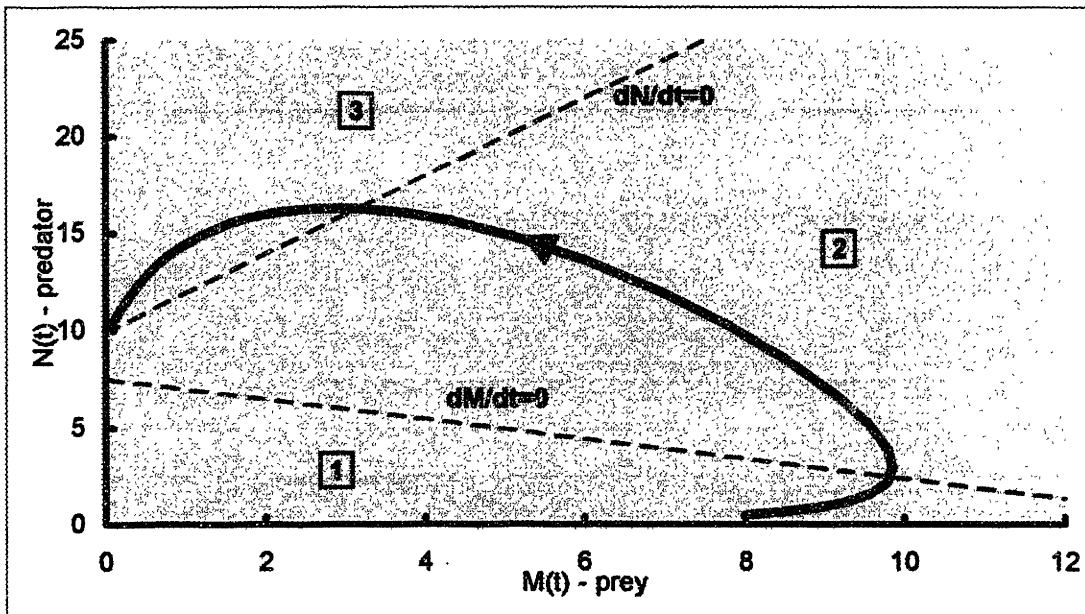
Consider now the second case of the modified predator-prey interaction (with regard to the phase diagram landscape) where there is no equilibrium point in the region $M, N > 0$, i.e. where $M^* < 0$ or $a_m b_n < a_n c_{mn}$. Recall that the phase diagram for this case is shown in Figure 5.7. One finds that in this case the trajectory will converge to the intersection of the line $dN/dt=0$ and the N -axis. Hence the prey population dies out and the predator population settles to its limiting value for the case where there is no predator-prey interaction (a_n/b_n). Figure 5.15 shows the case where the parameters are the same as in Figures 5.9-5.12, except that $c_{mn}=0.02$. Figure 5.16 shows the effect where c_{mn} is increased even more, this time to 0.08. Note that the line $dN/dt=0$ is not affected by the change in c_{mn} , but that the line $dM/dt=0$ has changed its intersection with the N -axis as well as its slope. In the time domain plots we see the prey growing initially, but then dying out. The predator initially benefits from interaction with the prey, but as the prey dies out, the predator's population approaches the limiting level where there is no interaction. Note again the overshoot in the case of the predator population in Figure 5.15.

This correlates with the trajectory's presence in region 3. This case is similar to that observed in Figures 5.9 and 5.10, except that here the prey population dies out and the predator's limiting value is that of the no-interaction case, i.e. a_n/b_n rather than the equilibrium value. In Figure 5.16 the intersection of the line $dM/dt=0$ with the N -axis drops down lower and the slope becomes shallower. Since the trajectory does not enter region 3, there is no overshoot in the case of the predator. Note that the trajectory changes its sense of rotation as it propagates. It starts with an anti-clockwise sense and then changes to a clock-wise sense.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nn}=0.02$	$N(0)=0.5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mm}=0.02$	$M(0)=8$
	$a_m b_n / a_n = 0.015$			



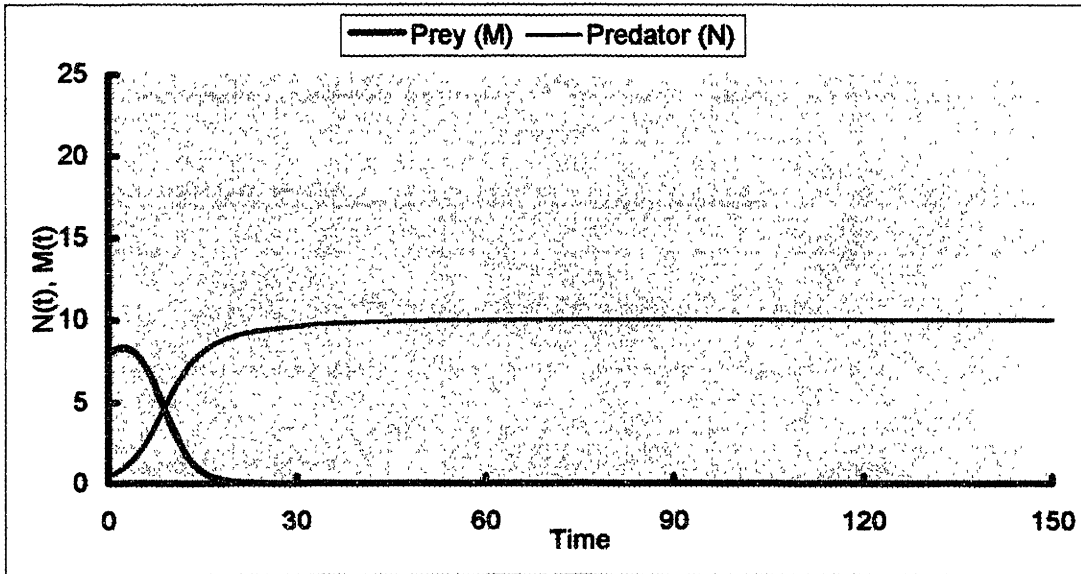
(a)



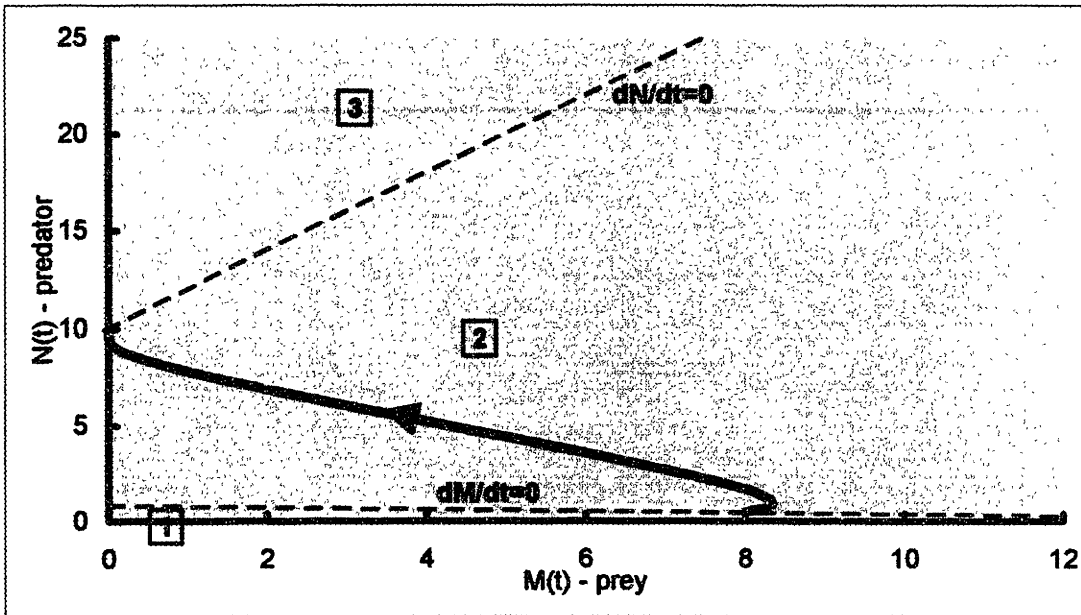
(b)

Figure 5.15 Modified predator-prey interaction (Case 2: $a_m b_n / a_n < c_{mn}$) with $N(0)=0.5$ and $M(0)=8$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=0.5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.08$	$M(0)=8$
	$a_m b_n / a_n = 0.015 < c_{mn}$			



(a)



(b)

Figure 5.16 Modified predator-prey interaction (Case 2: $a_m b_n / a_n < c_{mn}$) with $N(0)=0.5$ and $M(0)=8$ (a) time domain (b) phase diagram.

Modeling pure competition with a system of differential equations

We turn now to the issue of modeling pure competition between two technologies with a set of differential equations, one for each technology. In this case, each technology will have an inhibiting effect on the other's growth. As in the case of the predator-prey formulation, we can take a cue from Eq (4.13), and set up an equation for each of the two technologies (N and M) by adding a third term to the right hand side of each equation to account for the inhibiting effect that one technology has on the other, , i.e.

$$\frac{dN}{dt} = a_n N - b_n N^2 - c_{nm} NM \tag{5.27}$$

$$\frac{dM}{dt} = a_m M - b_m M^2 - c_{mn} MN \tag{5.28}$$

with $a, b, c > 0$. The coefficient c now plays a similar role to that of b for both technologies, in the sense that both reflect an inhibitory effect on growth. The formulation above is often referred to as the Lotka-Volterra equations when the pure competitive mode is implied (see for example Porter *et al.*, 1991; Farrell, 1993a; and Bhargava, 1989). Note that the difference between this formulation and the modified predator-prey formulation discussed in the previous section is the sign of the coefficient c_{nm} . The market potential functions referred to earlier are now given by

$$L_n = a_n - b_n N - c_{nm} M \tag{5.29}$$

$$L_m = a_m - b_m M - c_{mn} N \tag{5.30}$$

and the equations of the equilibrium lines where $dN/dt=0$ and $dM/dt=0$ are given by

$$\frac{dN}{dt} = 0: \quad N = \frac{a_n}{b_n} - \frac{c_{nm}}{b_n} M \quad (5.31)$$

$$\frac{dM}{dt} = 0: \quad N = \frac{a_m}{c_{mn}} - \frac{b_m}{c_{mn}} M \quad (5.32)$$

As before, the axes are also equilibrium lines, i.e. $dN/dt=0$ on the M -axis where $N=0$ and similarly for M . In this case we can use Pielou's difference form solutions for both N and M in their original form (1969, p.59), i.e.

$$N(t+1) = \frac{\lambda_n N(t)}{1 + \beta_n N(t) + \left(\frac{c_{nm}}{b_n}\right) \beta_n M(t)} \quad (5.33)$$

where

$$\lambda_n = e^{a_n} \quad (5.34)$$

$$\beta_n = \frac{b_n(e^{a_n} - 1)}{a_n} \quad (5.35)$$

and similarly

$$M(t+1) = \frac{\lambda_m M(t)}{1 + \beta_m M(t) + \left(\frac{c_{mn}}{b_m}\right) \beta_m N(t)} \quad (5.36)$$

where

$$\lambda_m = e^{a_m} \quad (5.37)$$

$$\beta_m = \frac{b_m(e^{a_m} - 1)}{a_m} \tag{5.38}$$

In order to illustrate the behavior of this case we can, for the sake of argument, consider N to be the attacking, emerging technology and M to be the defending, mature technology. Farrell refers to the term c_{nm}/b_n in Eq (5.33) above as the *defender's advantage* (1993b, p.6). The corresponding term c_{mn}/b_m for technology M 's equation will be the *attacker's advantage*. The terms *defender's advantage* and *attacker's advantage* were popularized by Foster in his qualitative analysis of technological competition (1986). Note that when the defender's advantage is large, one finds that

$$c_{nm} \gg b_n \tag{5.39}$$

in Eq (5.33), in which case the defending, mature technology (M) will have a larger inhibiting effect on the attacking, emerging technology (N) than the interactions of similar units within N . Although this is an interesting and useful metric, we shall show later in this chapter that by taking into account the interplay of *all* the coefficients, one can gain good insight into the dynamics of the system. Farrell has investigated several attack-defend scenarios in which he has successfully applied the system of equations described above, including light bulbs, lead-free food cans, carpets and pens (1993a, 1993b).

Porter *et al.* discuss the conditions under which the pure competition formulation of the Lotka-Volterra equations as manifested in the set of differential equations above can approximate, or reduce to, other well known single equation diffusion models such as linear, exponential, decaying exponential, Pearl and Gompertz models (1991, p.191). It is evident that when the competition coefficients in Eqs (5.27) and (5.28) are zero or negligibly small, the equations reduce to the Pearl formulation given in Eq (4.9).

Intuitively one would want to refer to the mature, defending technology as the prey and to the emerging, attacking technology as the predator. In the case of pure competition, however, the distinctions between predator and prey become less distinct than in the predator-prey modes. In this section on pure competition we shall retain the nomenclature of predator and prey, but for the purposes of discussing the model the names should not be taken too literally, especially not in the case of pathological examples that are chosen to illustrate special cases. From a phase diagram viewpoint, there are four possible cases to consider, depending on whether $c_{mn} > a_m b_n / a_n$ and $c_{nm} > a_n b_m / a_m$. The four cases are shown in Figures 5.17, 5.22, 5.26 and 5.32, respectively (after Pielou, 1969, p.56). Note that $dM/dt > 0$ below its equilibrium line and $dM/dt < 0$ above its line, and similarly for N . Note also that in Cases 3 and 4 shown in Figures 5.26 and 5.32, there are equilibrium points in the region $M, N > 0$. The coordinates of the equilibrium point are given by

$$M^* = \frac{a_m b_n - a_n c_{mn}}{b_n b_m - c_{nm} c_{mn}} \quad (5.40)$$

$$N^* = \frac{a_n b_m - a_m c_{nm}}{b_n b_m - c_{mn} c_{nm}} \quad (5.41)$$

As would be expected, the terms in the expressions for M^* and N^* above are the same as those for the predator-prey formulation in Eqs (5.17) and (5.18), although there are of course differences in the signs.

In order illustrate the four cases of pure competition, consider now the system

$$N(t) = N(0.1 - 0.01N - c_{nm}M) \tag{5.42}$$

$$M(t) = M(0.15 - 0.01M - c_{mn}N) \tag{5.43}$$

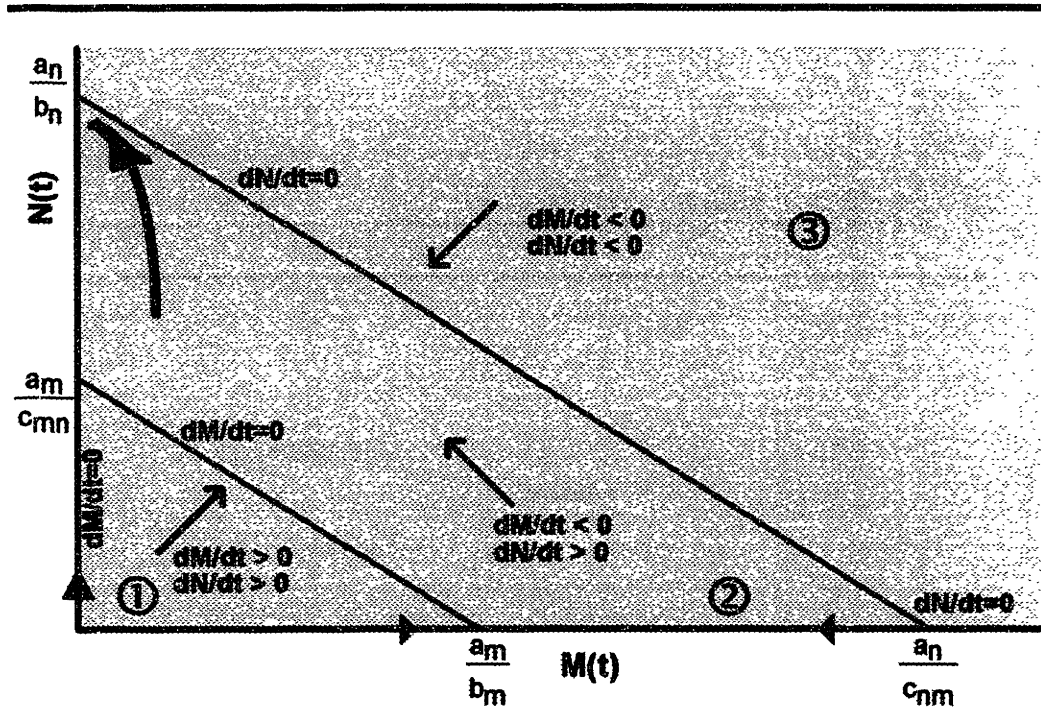


Figure 5.17 Phase diagram for pure competition system without an equilibrium point in the region $M, N > 0$ (Case 1: $c_{mn} > a_m b_n / a_n$ and $c_{nm} < a_n b_m / a_m$).

Case 1: $c_{mn} > a_m b_n / a_n$ and $c_{nm} < a_n b_m / a_m$

To illustrate this case, we select $c_{mn}=0.02$ and $c_{nm}=0.005$. The other coefficients are the same as in the previous cases. Figure 5.17 shows the phase diagram with the equilibrium lines for this case as well as the signs of dM/dt and dN/dt in the various subregions. The equilibrium lines divide the region $M, N > 0$ into three subregions. We find that in this case the trajectory converges to the point $(M=0, N=a_n/b_n)$. Hence M dies out and N converges to the limiting value it would have obtained under regular logistic growth.

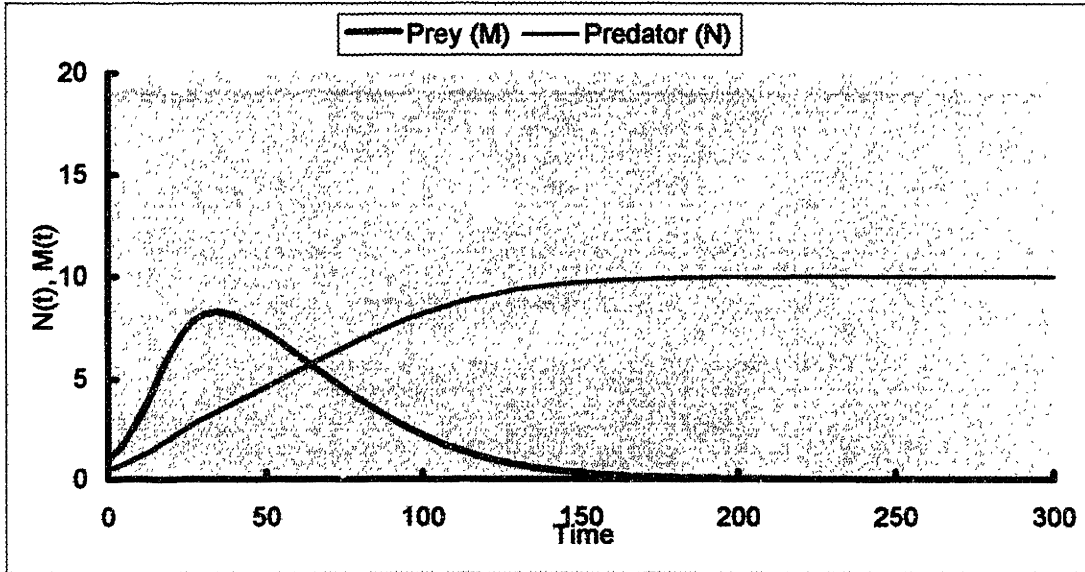
Figures 5.18-5.20 show the trajectories and growth curves as a function of time for initial values in each of the three subregions. Even though the model and coefficients are exactly the same, the trajectories for the three cases are very different, illustrating again the major influence that the initial conditions have on the trajectory.

In several of Farrell's examples he assumes that $c_{nm}=0$ (or in his notation, $D=0$, where he refers to D as the *defender's advantage*) (1993a, p.170). Setting $c_{nm}=0$ is a special case of the present case we are considering ($c_{mn} > a_m b_n / a_n$ and $c_{nm} < a_n b_m / a_m$). The effect is to change the slope of the line $dN/dt=0$ to zero as shown in Figure 5.21. The equilibrium line where $dM/dt=0$ is not affected. Comparing Figures 5.18 and 5.21 (where the initial conditions as well as the coefficients are the same except for c_{nm} that is set equal to zero), we see that the new equilibrium line gives the trajectory more "room to maneuver". By setting $c_{nm}=0$, the inhibiting effect that the prey (M) has on the predator's growth (N) is eliminated. As expected, we see an accelerated growth in the predator and decelerated growth in the prey.

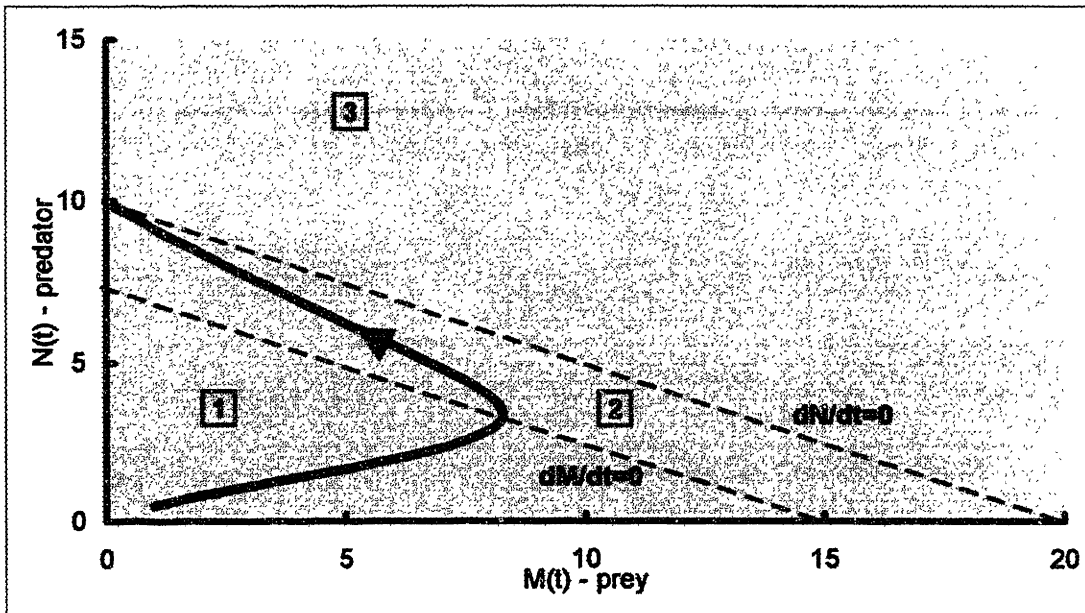
Case 2: $c_{mn} < a_m b_n / a_n$ and $c_{nm} > a_n b_m / a_m$

To illustrate this case, we select $c_{mn}=0.01$ and $c_{nm}=0.02$, but again keeping the other coefficients the same as before. Figure 5.22 shows the phase diagram with the equilibrium lines for this case as well as the signs of dM/dt and dN/dt in the subregions. The equilibrium lines divide the region $M, N > 0$ into three subregions. We find that in this case the trajectory converges to the point $(M=a_m/b_m, N=0)$. Hence in this case N dies out and M converges to the limiting value it would have obtained under regular logistic growth. Figures 5.23-5.25 show the trajectories and growth curves as a function of time for initial values in each of the three regions.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=0.5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=1$
	$a_m b_n / a_n = 0.015$		$a_n b_m / a_m = 0.0067$	



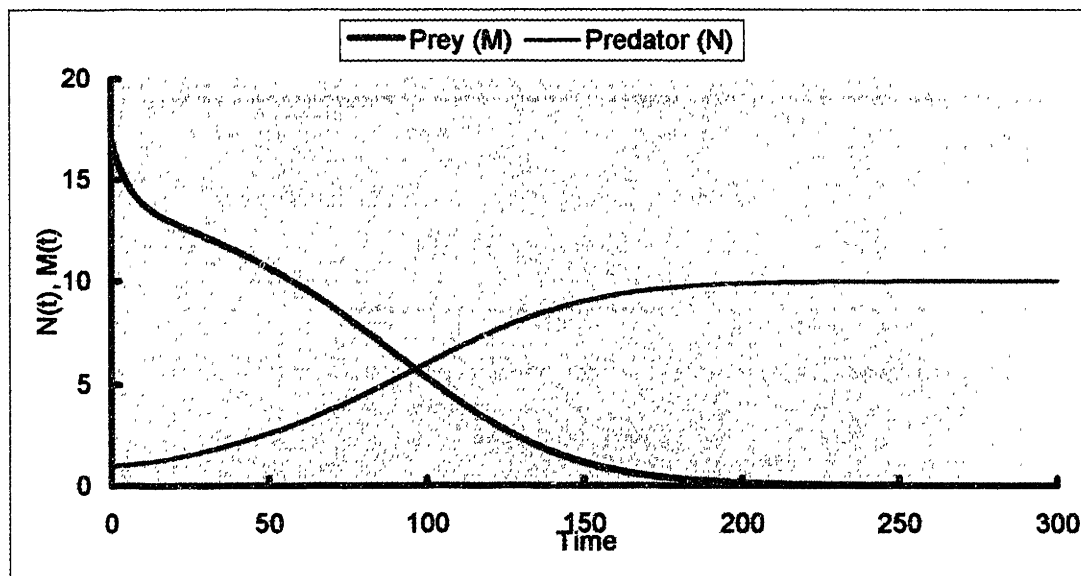
(a)



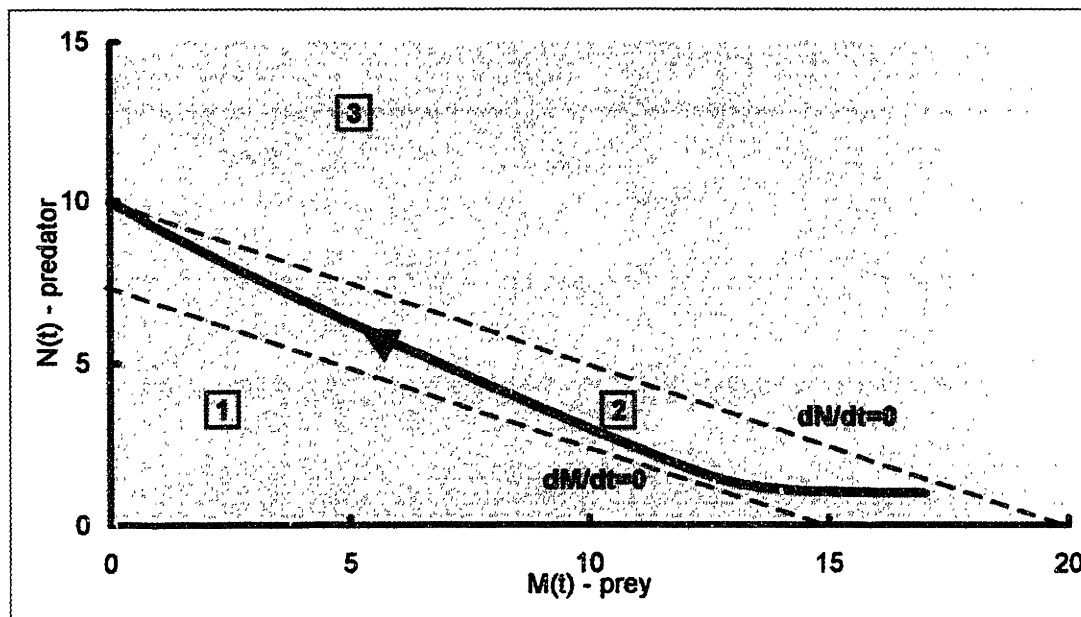
(b)

Figure 5.18 Pure competition interaction (Case 1: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m > c_{nm}$) with $N(0)=0.5$ and $M(0)=1$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=1$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=17$
	$a_m b_n / a_n = 0.015$		$a_n b_m / a_m = 0.0067$	



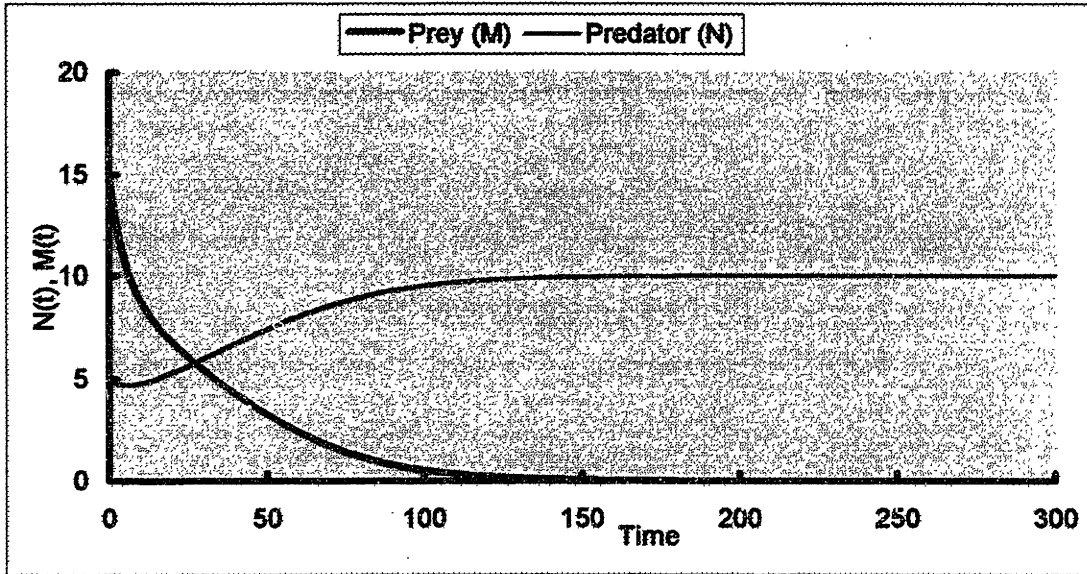
(a)



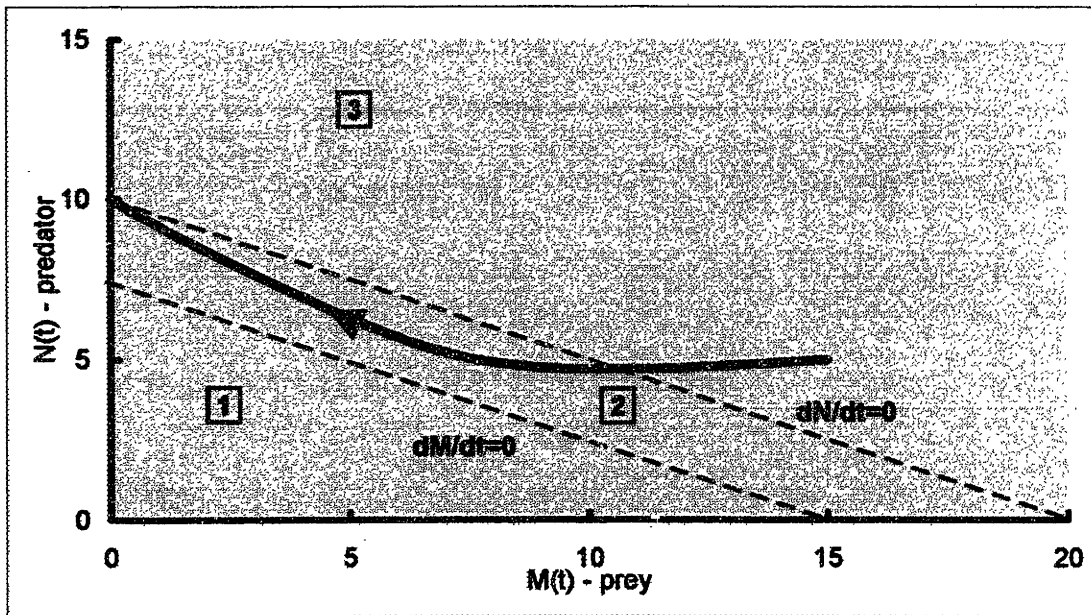
(b)

Figure 5.19 Pure competition interaction (Case 1: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m > c_{nm}$) with $N(0)=1$ and $M(0)=17$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=15$
	$a_m b_n / a_n = 0.015$		$a_n b_m / a_m = 0.0067$	



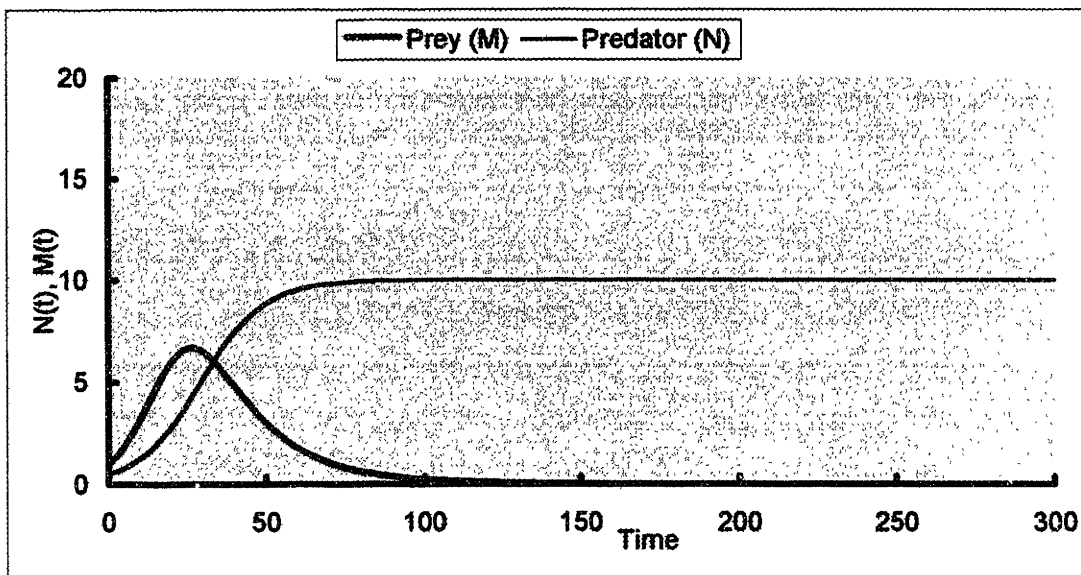
(a)



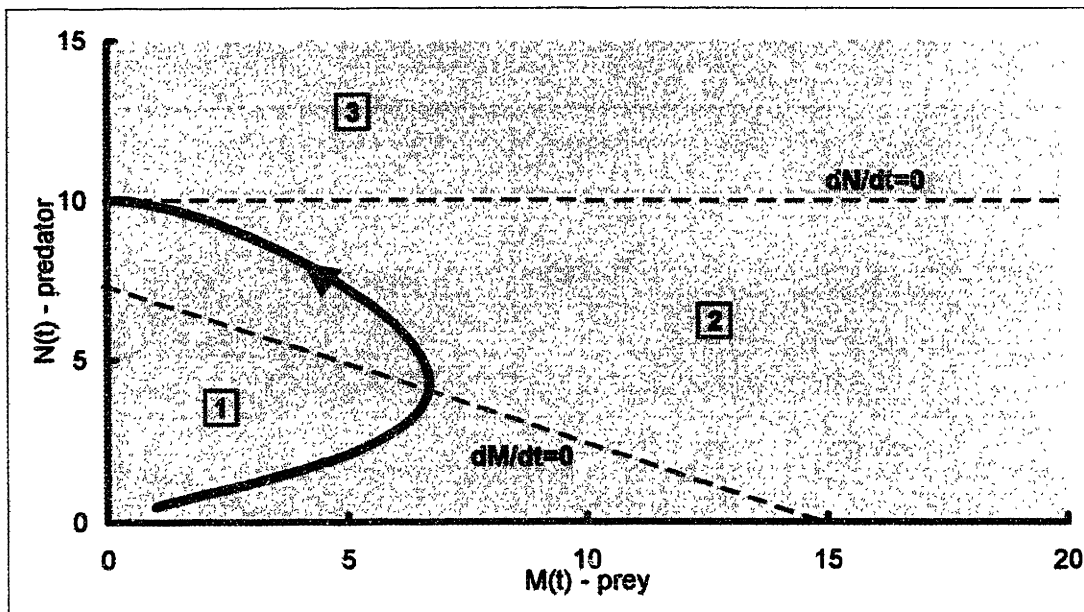
(b)

Figure 5.20 Pure competition interaction (Case 1: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m > c_{nm}$) with $N(0)=5$ and $M(0)=15$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0$	$N(0)=0.5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=1$
	$a_m b_n / a_n = 0.015$		$a_m b_m / a_m = 0.0067$	



(a)



(b)

Figure 5.21 Pure competition interaction (Case 1: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m > c_{nm}$) with $N(0)=0.5$ and $M(0)=1$ (a) time domain (b) phase diagram. Defender's advantage=0.

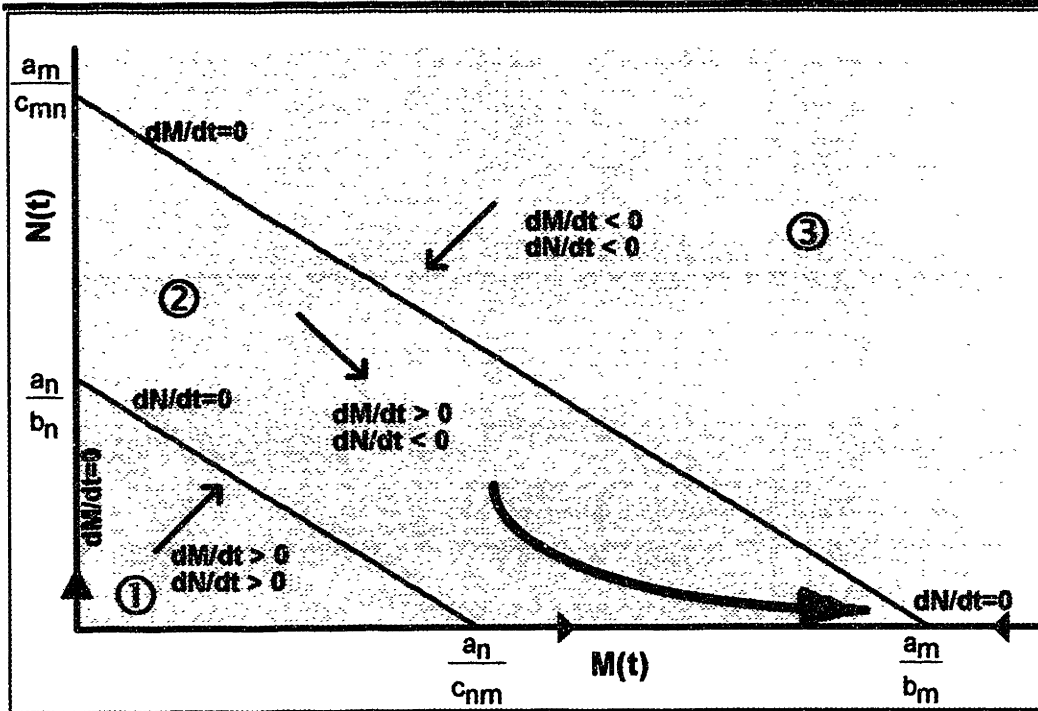
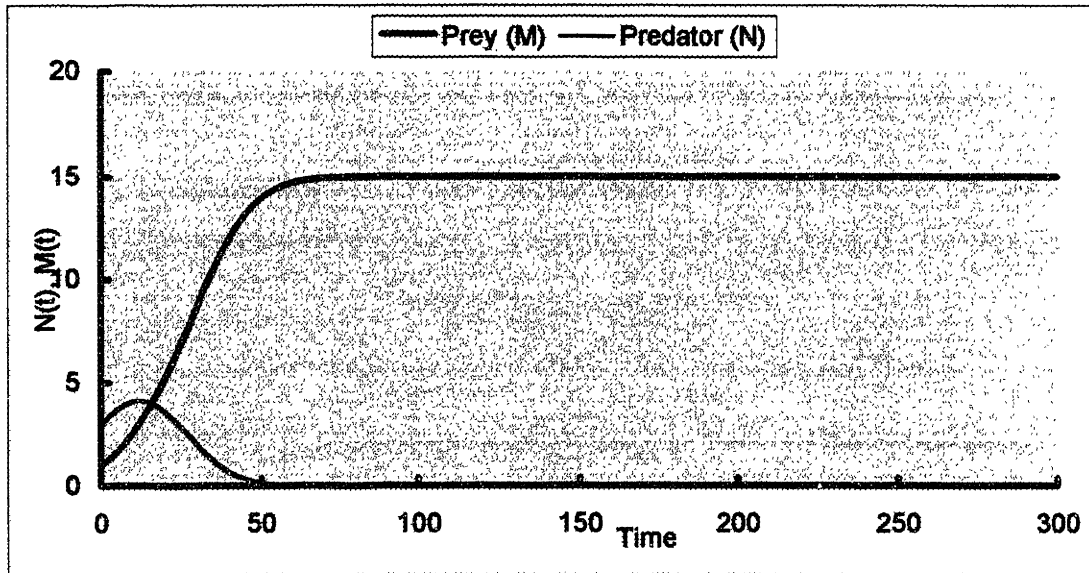


Figure 5.22 Phase diagram for pure competition system without an equilibrium point in the region $M, N > 0$ (Case 2: $c_{mn} < a_m b_n / a_n$ and $c_{nm} > a_n b_m / a_m$).

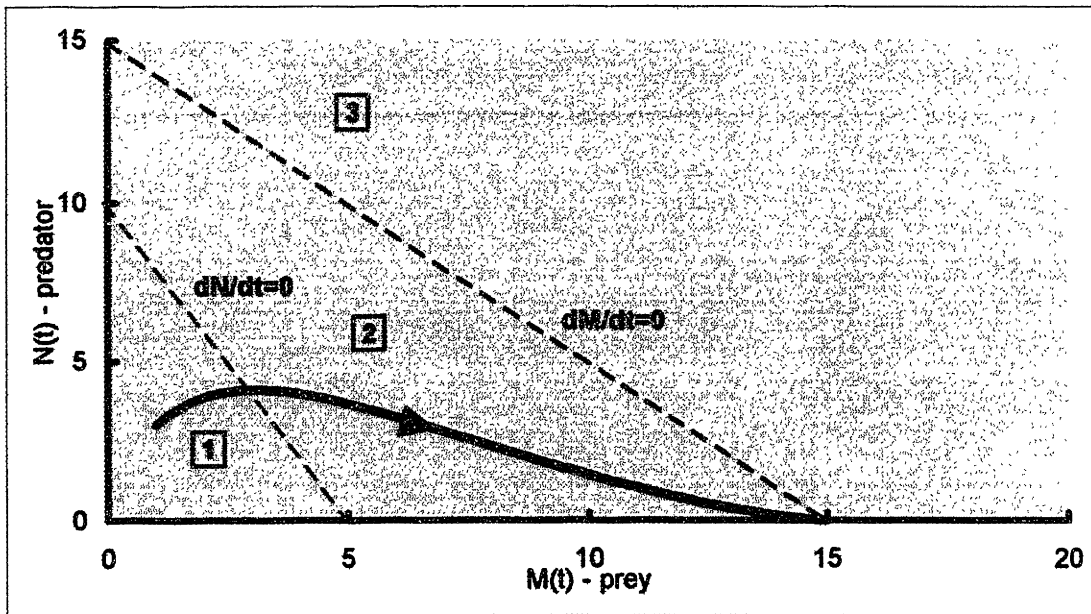
Case 3: $c_{mn} < a_m b_n / a_n$ and $c_{nm} < a_n b_m / a_m$

To illustrate this case, we select $c_{mn}=0.01$ and $c_{nm}=0.005$. Figure 5.26 shows the phase diagram with the equilibrium lines for this case as well as the signs of dM/dt and dN/dt in the various subregions. The equilibrium lines divide the region $M, N > 0$ into four subregions. There is an equilibrium point in the region $M, N > 0$, and we find that in this case the trajectory converges to the equilibrium point. Figures 5.27-5.29 show the phase diagram trajectories and time domain growth curves for three sets of initial values in the first subregion. Note that the trajectory can progress in either an anti-clockwise or clockwise direction. Figures 5.27 and 5.28 show that the equilibrium point is approached from an anti-clockwise direction for two starting positions in subregion 1, whereas Figure 5.29 shows that the equilibrium point is approached from a clockwise direction for

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=3$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=1$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_m = 0.0067$	



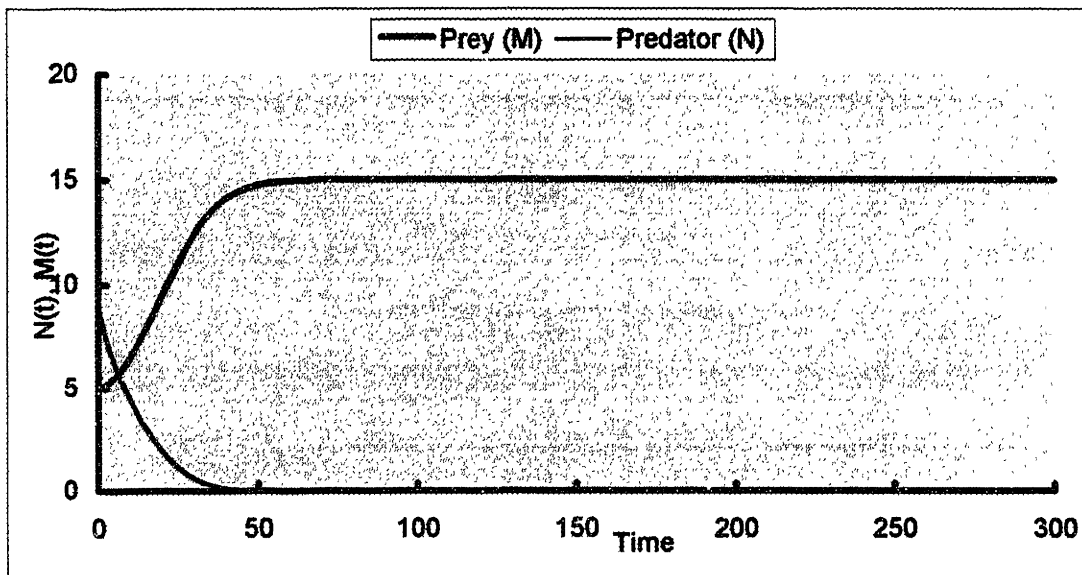
(a)



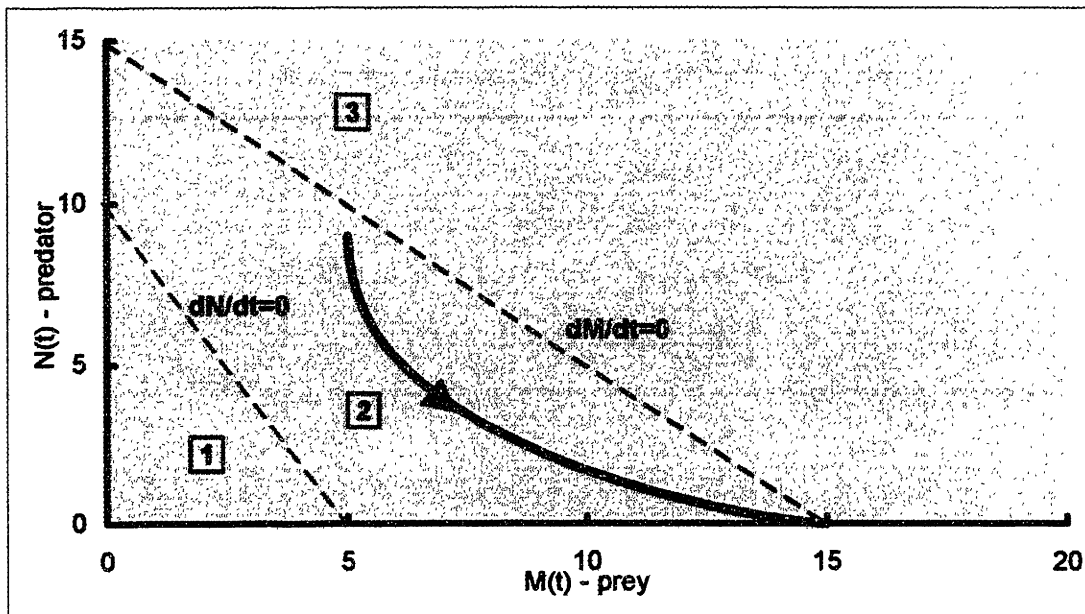
(b)

Figure 5.23 Pure competition interaction (Case 2: $a_m b_n / a_n > c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=3$ and $M(0)=1$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=9$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=5$
	$a_m b_n / a_n = 0.015$		$a_m b_m / a_m = 0.0067$	



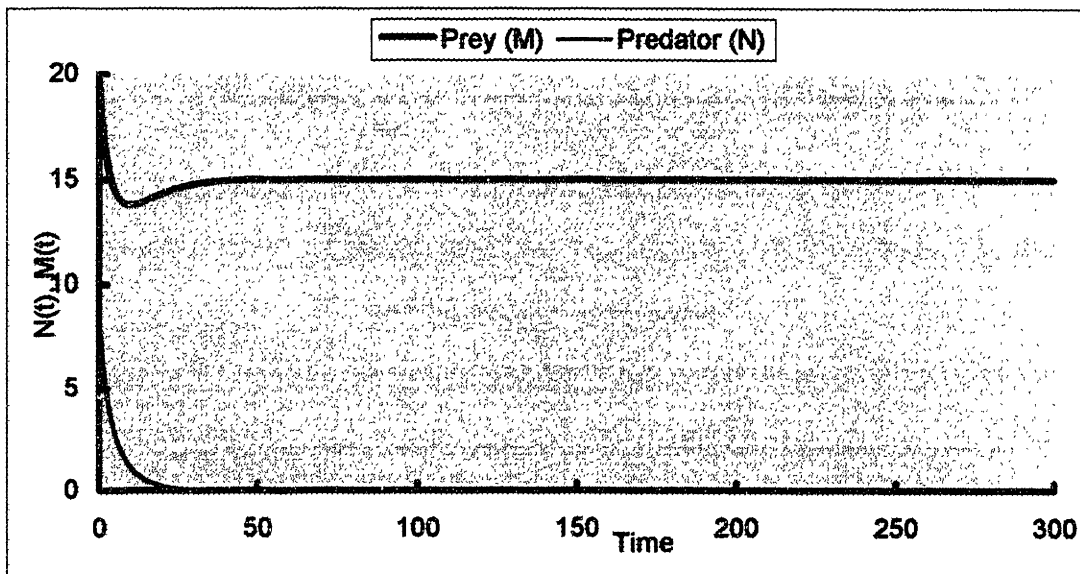
(a)



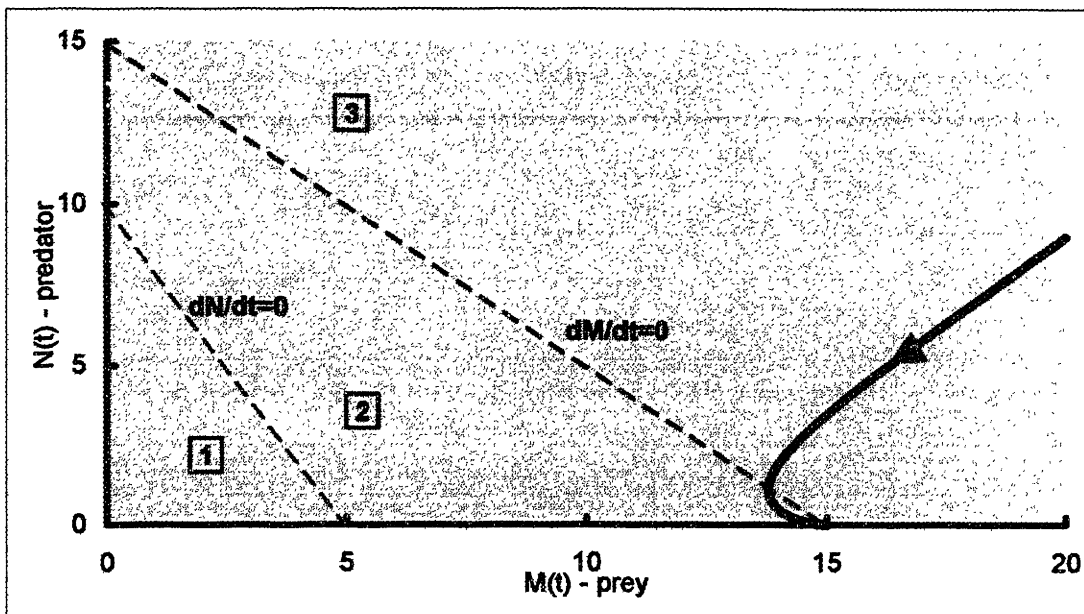
(b)

Figure 5.24 Pure competition interaction (Case 2: $a_m b_n / a_n > c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=9$ and $M(0)=5$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=9$
Frey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=20$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$	



(a)



(b)

Figure 5.25 Pure competition interaction (Case 2: $a_m b_n / a_n > c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=9$ and $M(0)=20$ (a) time domain (b) phase diagram.

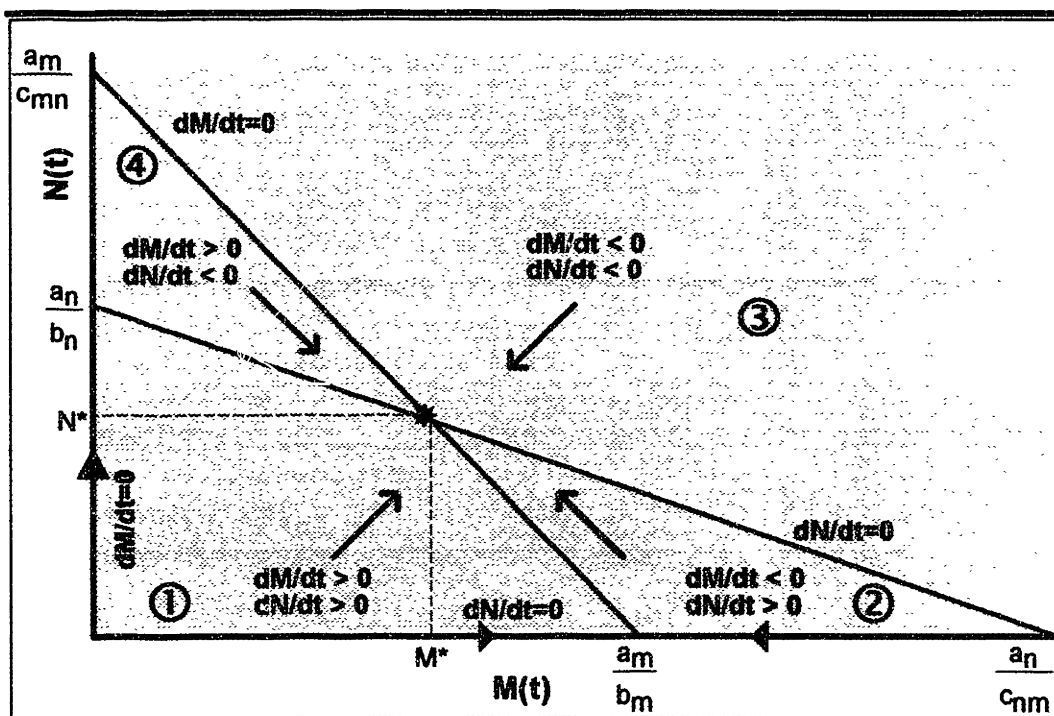
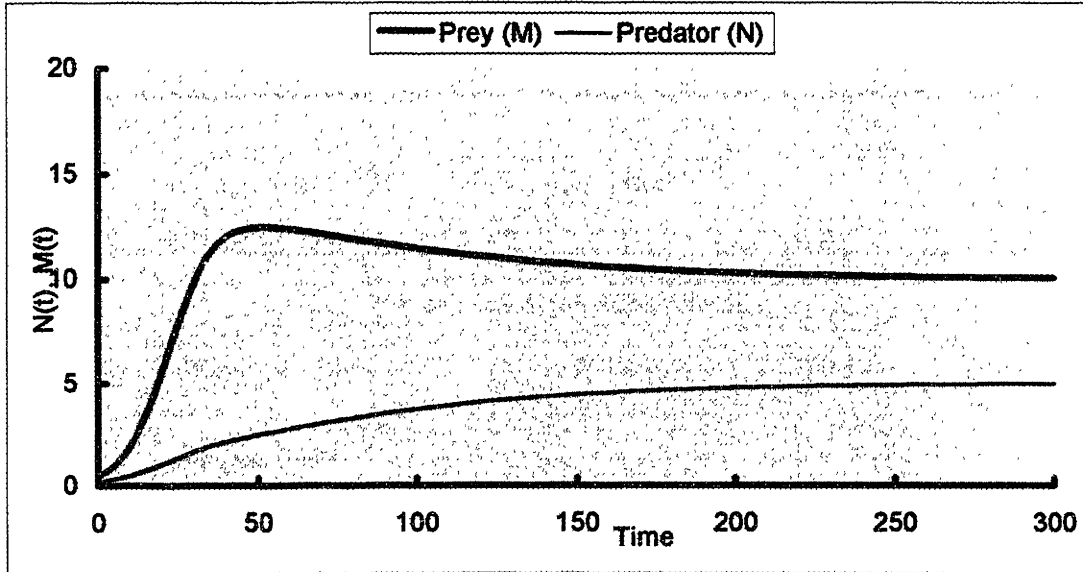


Figure 5.26 Phase diagram for pure competition system with equilibrium point in the region $M, N > 0$ (Case 3: $c_{mn} < a_m b_n/a_n$ and $c_{nm} < a_n b_m/a_m$).

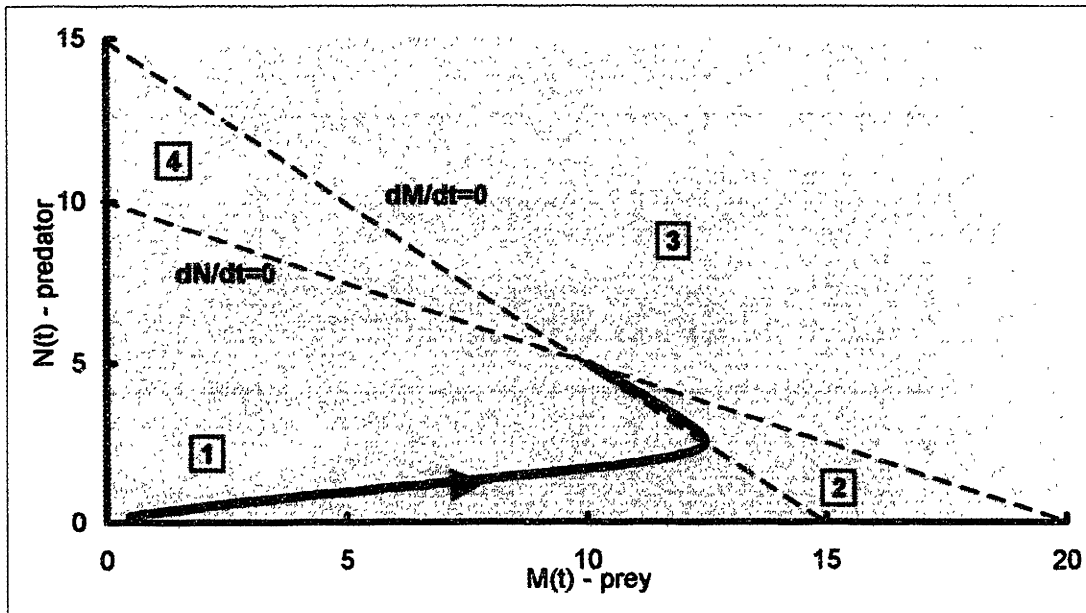
another initial value also in subregion 1. It would seem that the direction that the trajectory follows is determined by the relative strengths of dM/dt and dN/dt at the starting point. This is the only one of the four cases of pure competition where both technologies ultimately survive, with the final values being those of the equilibrium point (M^* and N^*). Figure 5.30 shows how the equilibrium point is approached from an initial value in the second subregion.

Note the differences between this case and the modified predator-prey case that also contained an equilibrium point in the region $M, N > 0$ (as shown in Figure 5.6). In both cases the trajectory converges upon the equilibrium point. The way in which that happens, however, differs substantially between the two cases. The major difference

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=0.2$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=0.5$	$M^*=10$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$		



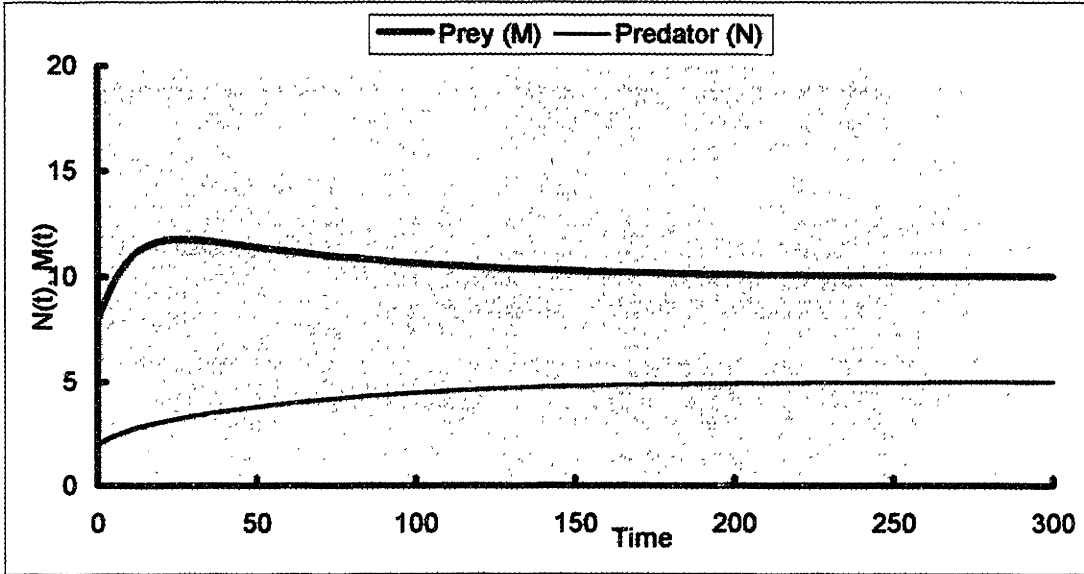
(a)



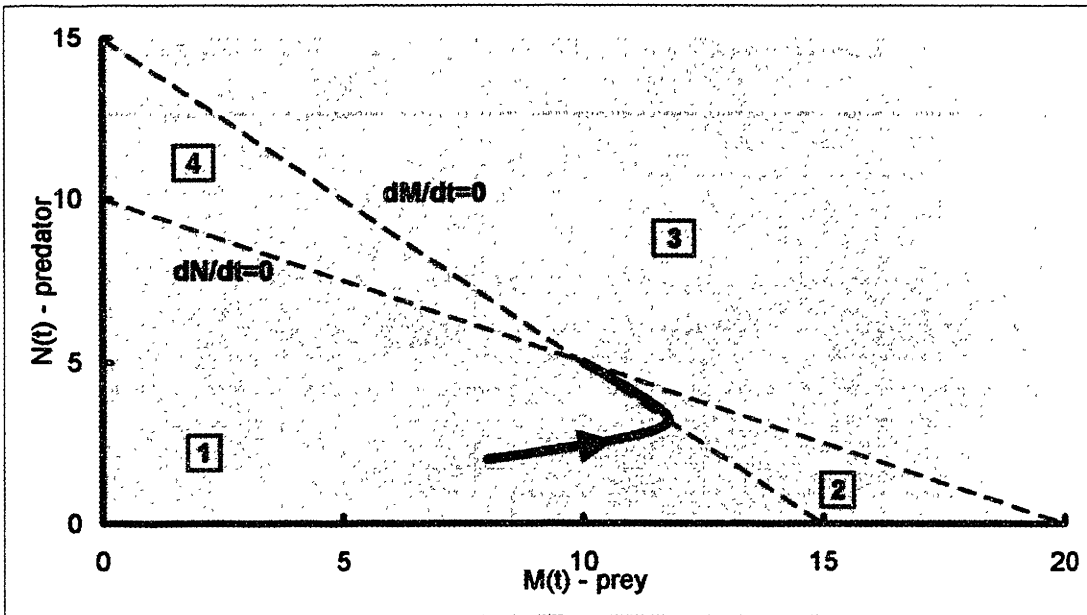
(b)

Figure 5.27 Pure competition interaction (Case 3: $a_m b_n / a_n > c_{mn}$ and $a_n b_m / a_m > c_{nm}$) with $N(0)=0.2$ and $M(0)=0.5$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=2$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=8$	$M^*=10$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$		



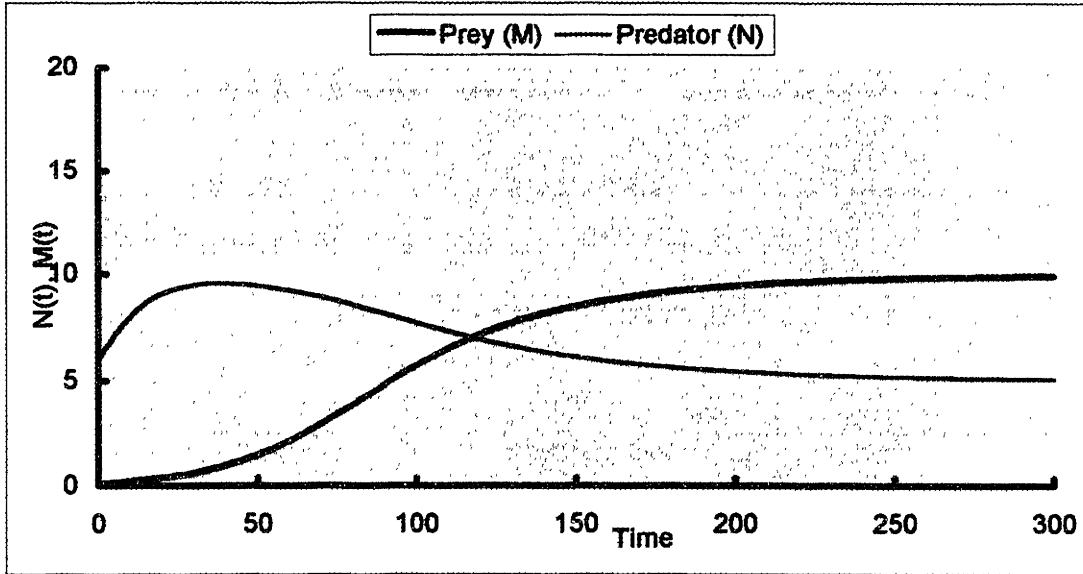
(a)



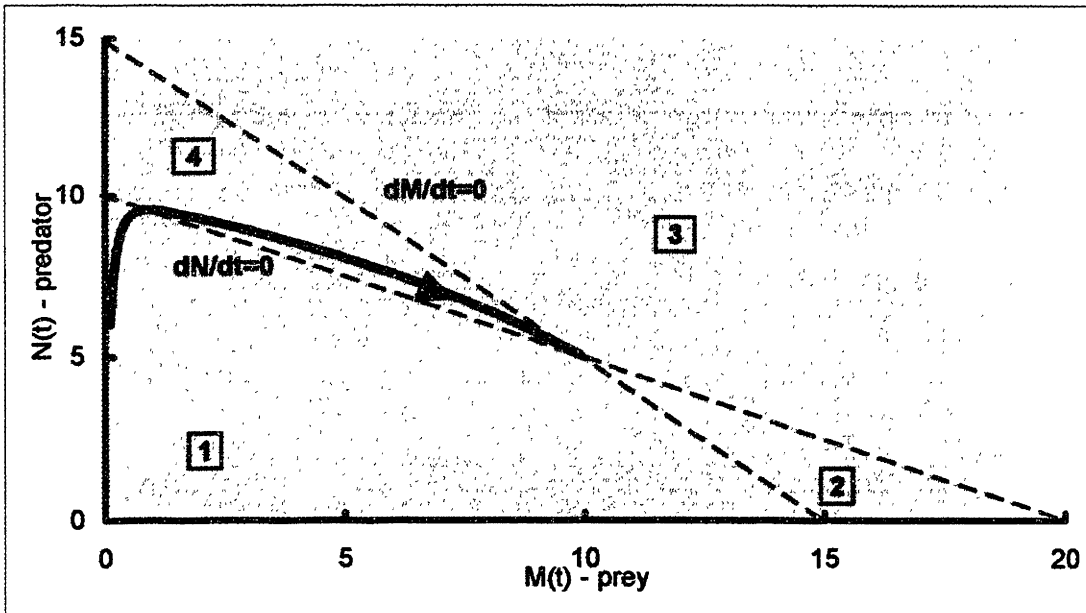
(b)

Figure 5.28 Pure competition interaction (Case 3: $a_m b_n / a_n > c_{mn}$ and $a_n b_m / a_m > c_{nm}$) with $N(0)=2$ and $M(0)=8$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=6$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=0.1$	$M^*=10$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$		



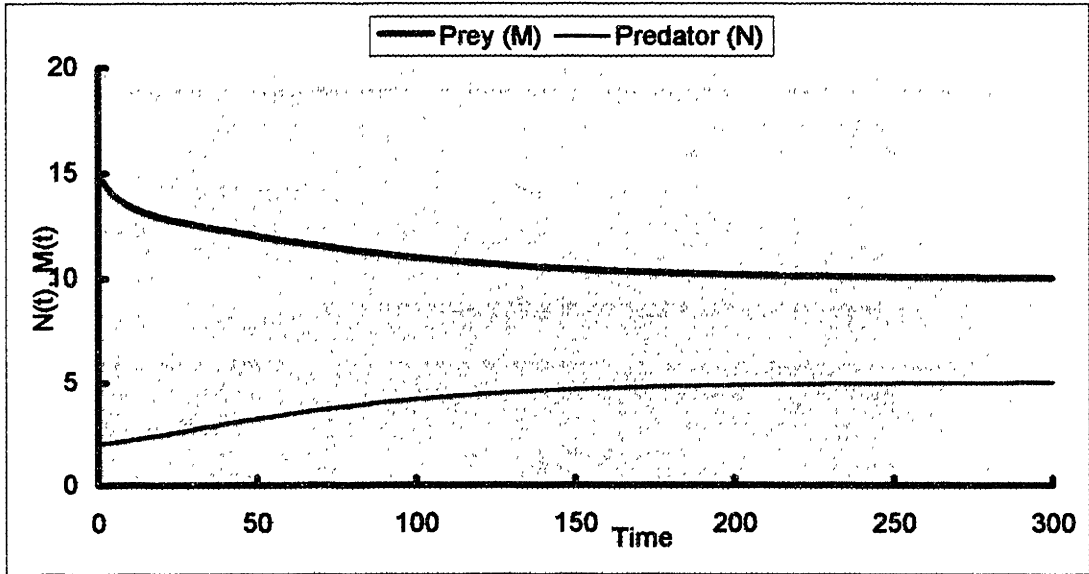
(a)



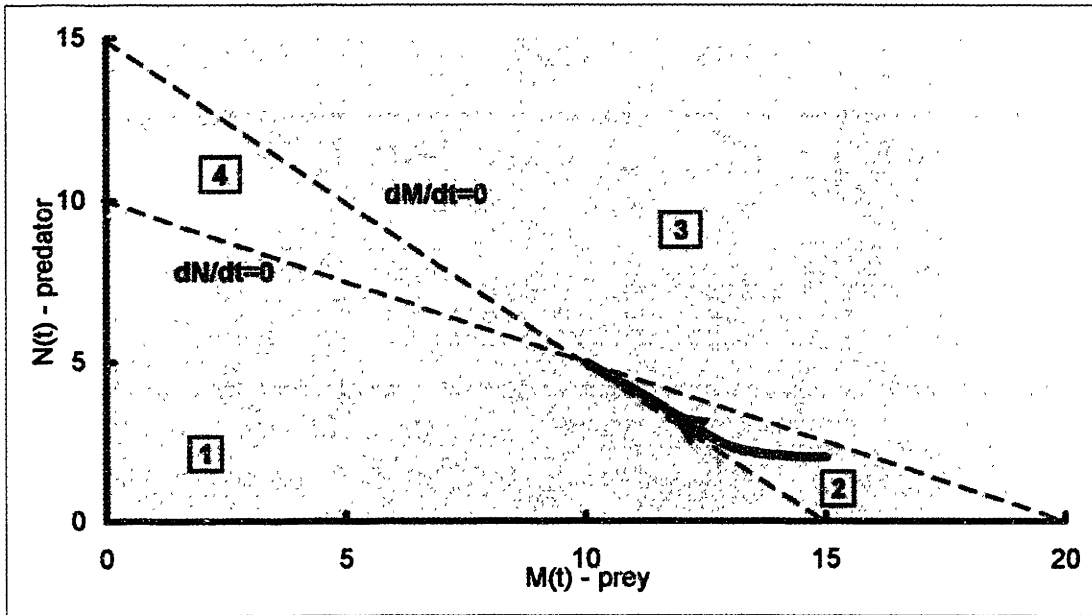
(b)

Figure 5.29 Pure competition interaction (Case 3: $a_m b_n / a_n > c_{mn}$ and $a_n b_m / a_m > c_{nm}$) with $N(0)=6$ and $M(0)=0.1$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=2$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=15$	$M^*=10$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$		



(a)



(b)

Figure 5.30 Pure competition interaction (Case 3: $a_m b_n / a_n > c_{nm}$ and $a_n b_m / a_m > c_{mn}$) with $N(0)=2$ and $M(0)=15$ (a) time domain (b) phase diagram.

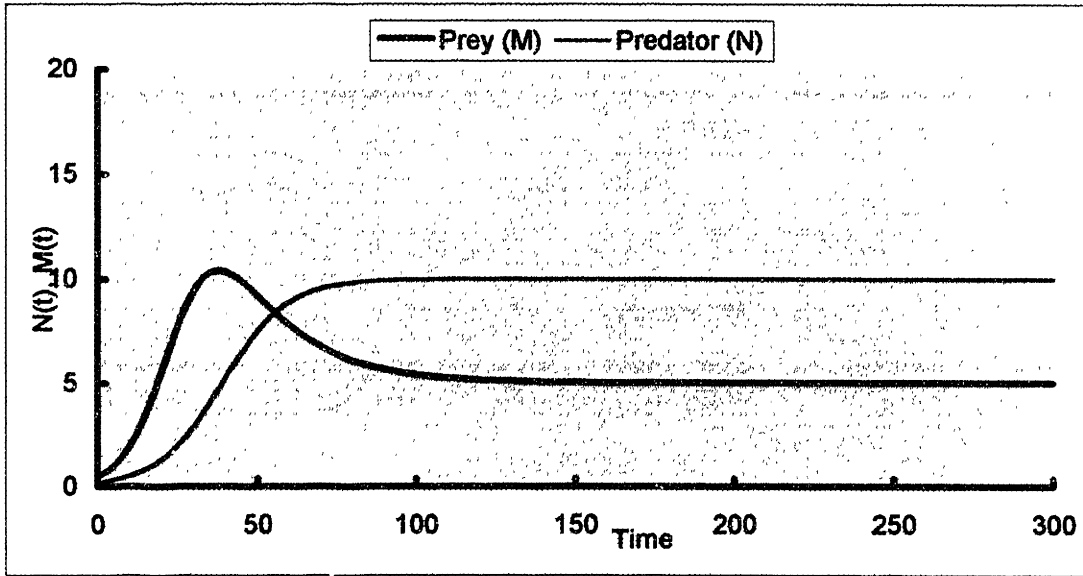
between the two cases is of course the slope of the line $dN/dt=0$. By comparing the two generic phase diagrams in Figures 5.6 and 5.26, we note the different orientation of the direction vectors in similar subregions.

As in Case 1 above, we can set $c_{nm}=0$ to emulate Farrell's case where he sets $D=0$. Figure 5.31 shows the effect and can be compared with Figure 5.27, where the initial conditions and the coefficients are the same, except for c_{nm} that has been set equal to zero in Figure 5.31. Note that the equilibrium point slides up the equilibrium line where $dN/dt=0$ as c_{nm} is decreased. The effect is a significant change in the behavior of both technologies, essentially changing the status of the eventual winner.

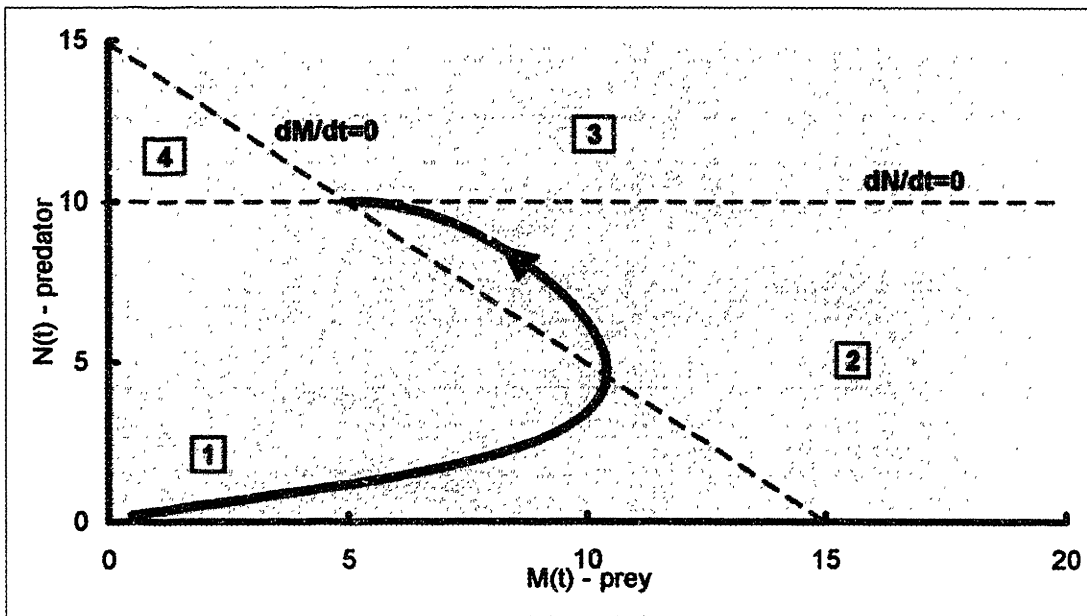
Case 4: $c_{mn} > a_m b_n / a_n$ and $c_{nm} > a_n b_m / a_m$

To illustrate this case, we select $c_{mn}=0.02$ and $c_{nm}=0.01$. Figure 5.32 shows the phase diagram with the equilibrium lines for this case as well as the signs of dM/dt and dN/dt in the various subregions. The equilibrium lines divide the region $M, N > 0$ into four subregions. Even though there is an equilibrium point in the region $M, N > 0$, we find that in this case the trajectory does not converge to a unique point as in the other three cases discussed so far. The final point of convergence is either $(M=a_n/b_m, N=0)$ or $(M=0, N=a_n/b_n)$. In this case the location of the final point of convergence is unstable and depends on the initial value of the trajectory. If the initial value is in subregion 2, the trajectory will converge to $(M=a_n/b_m, N=0)$, i.e. N dies out and M converges to its logistic limit. If the trajectory starts in subregion 4, it will converge to $(M=0, N=a_n/b_n)$, i.e. M dies out and N converges to its logistic limit. For the purpose of determining what

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0$	$N(0)=0.2$	$N^*=10$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.01$	$M(0)=0.5$	$M^*=5$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$		



(a)



(b)

Figure 5.31 Pure competition interaction (Case 3: $a_m b_n / a_n > c_{mn}$ and $a_n b_m / a_m > c_{nm}$) with $N(0)=0.2$ and $M(0)=0.5$ (a) time domain (b) phase diagram. *Defender's advantage=0.*

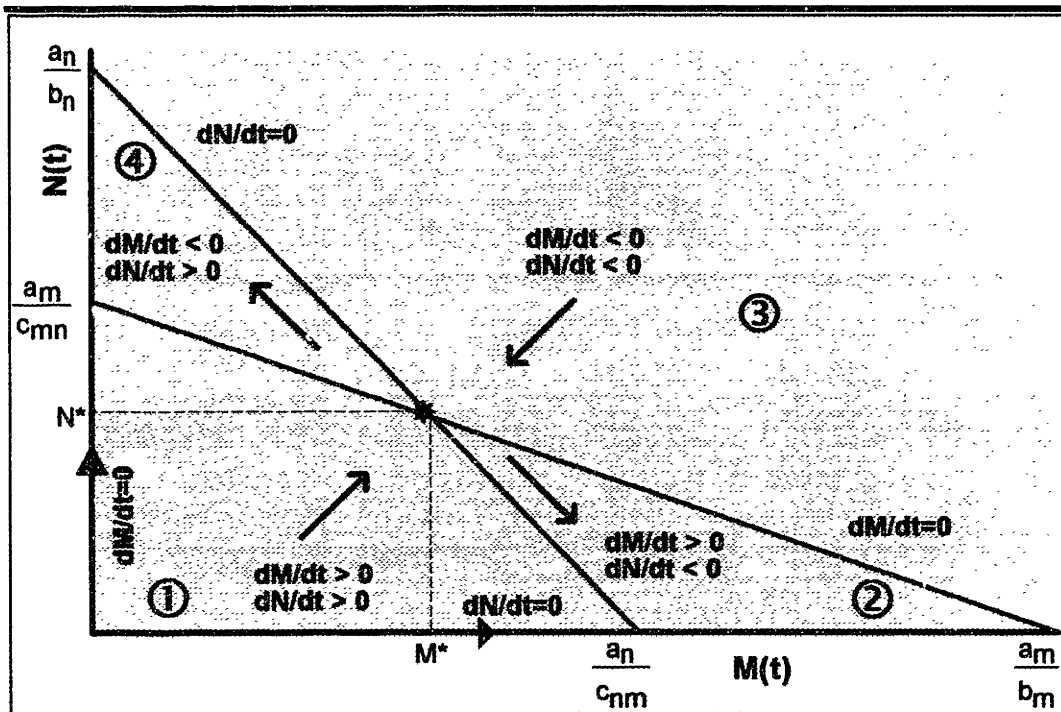
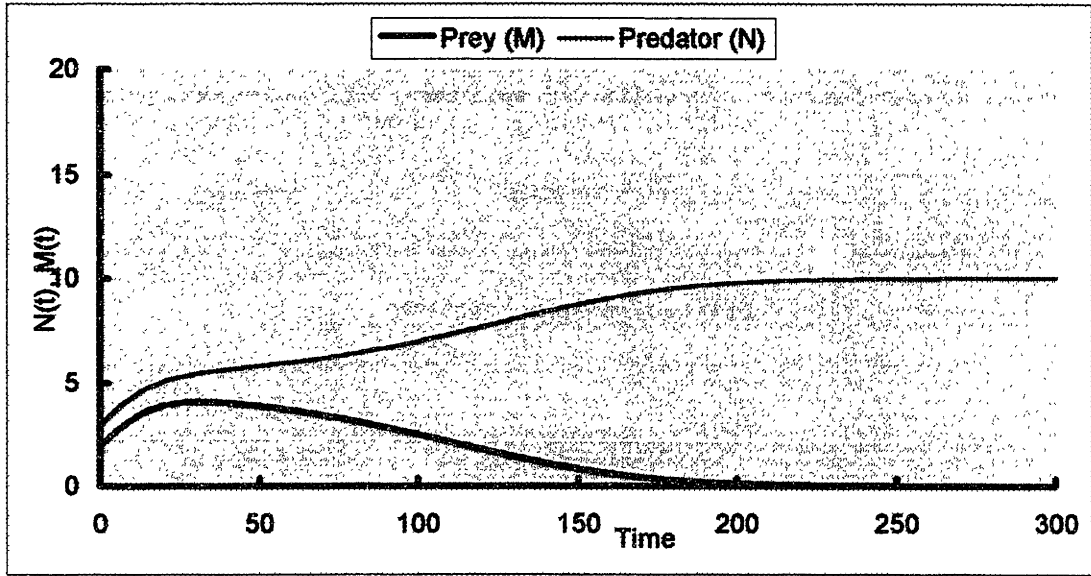


Figure 5.32 Phase diagram for pure competition system with equilibrium point in the region $M, N > 0$ (Case 4: $c_{mn} > a_m b_n/a_n$ and $c_{nm} > a_n b_m/a_m$). The trajectory terminates in the equilibrium point.

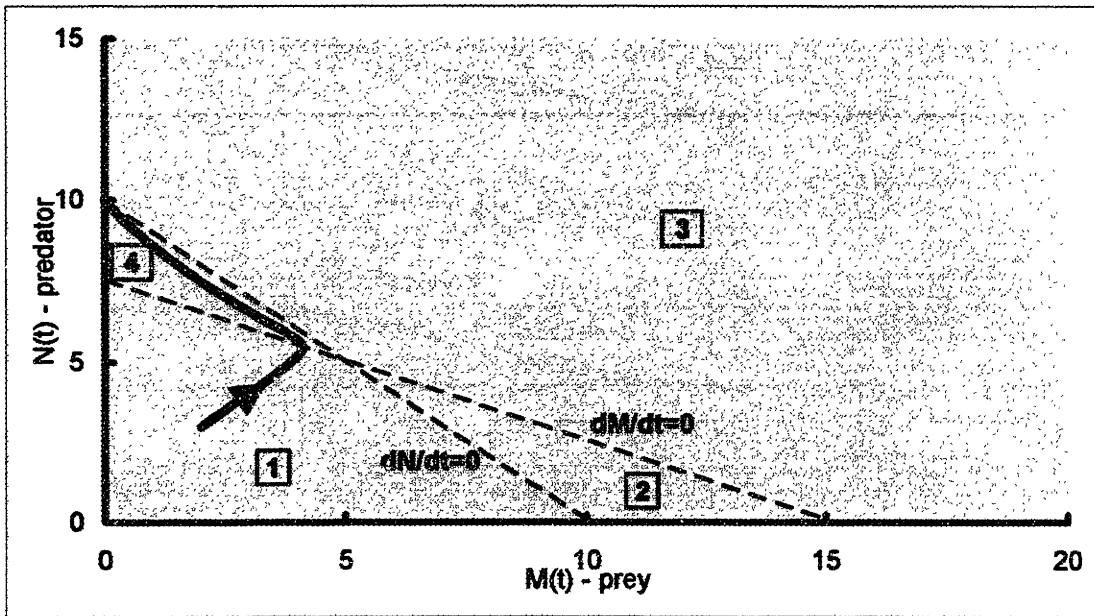
the final of convergence will be, it would seem that subregions 1 and 3 can be each be divided into two regions by a diagonal line originating at the origin and extending towards the upper right. If the trajectory originates to the right of this line, it will converge to $(M = a_m/b_m, N = 0)$, whereas it will converge to $(M = 0, N = a_n/b_n)$ if it originates to the left of the line.

Figures 5.33-5.38 show the trajectories and time domain curves for initial values in each of the four subregions. Figures 5.33 and 5.34 show how two initial points in subregion 1 that are in close proximity to one another but are apparently separated by the dividing line mentioned, will give rise to trajectories that terminate in the two different final values

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.01$	$N(0)=3$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=2$	$M^*=5$
	$a_m b_n / a_n = 0.015$		$a_m b_m / a_n = 0.0067$		



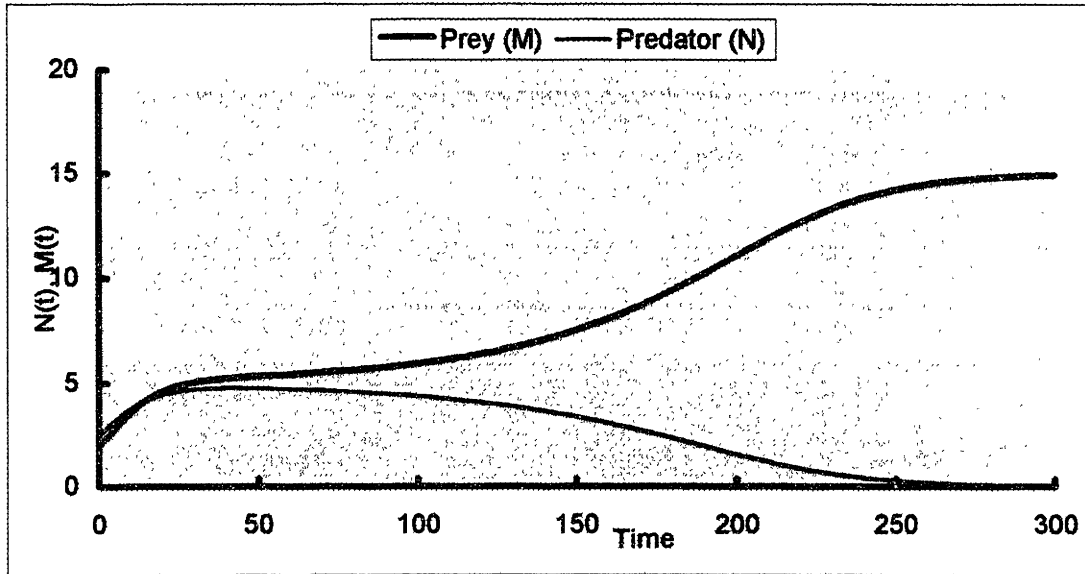
(a)



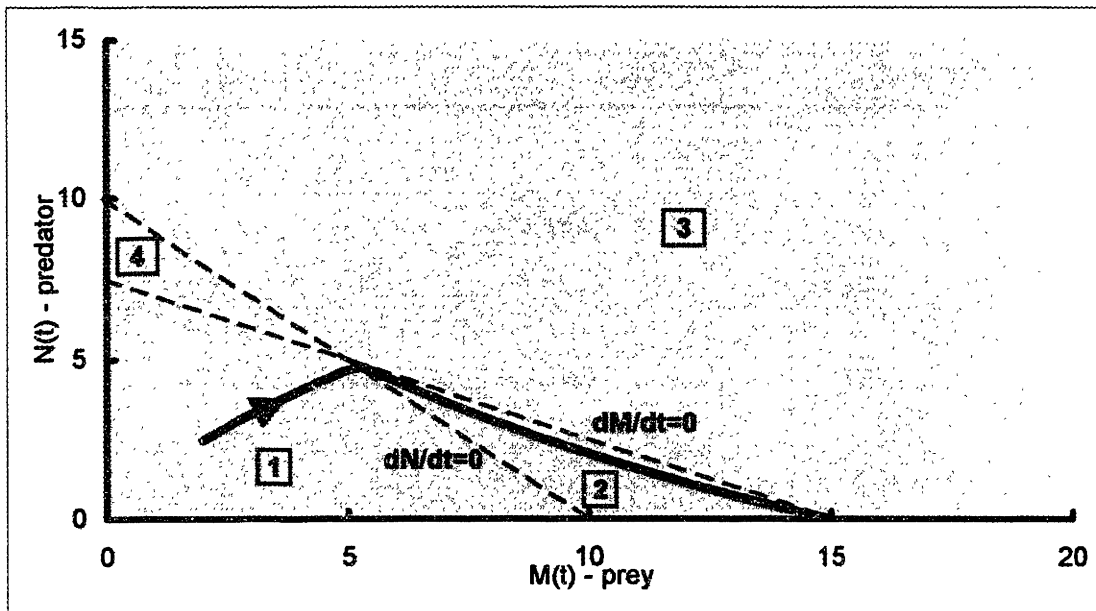
(b)

Figure 5.33 Pure competition interaction (Case 4: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=3$ and $M(0)=2$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.01$	$N(0)=2.5$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=2$	$M^*=5$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$		



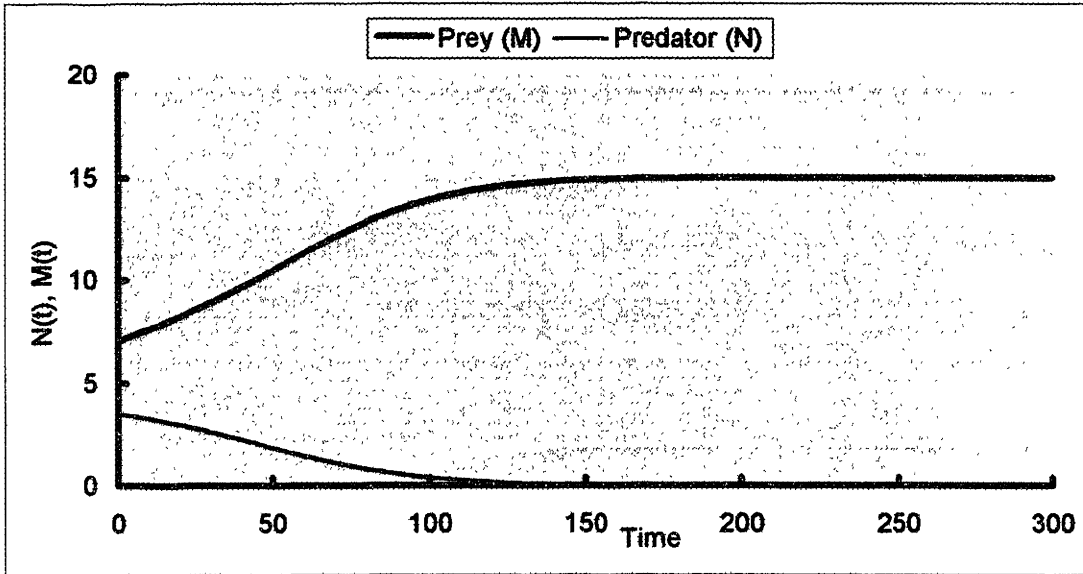
(a)



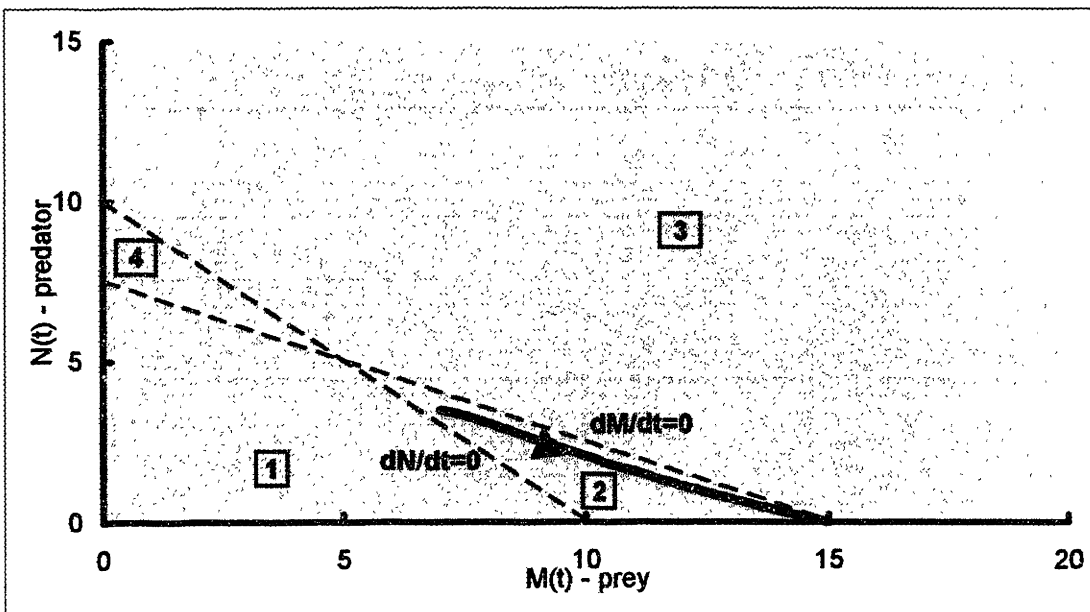
(b)

Figure 5.34 Pure competition interaction (Case 4: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=2.5$ and $M(0)=2$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.01$	$N(0)=3.5$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mm}=0.02$	$M(0)=7$	$M^*=5$
	$a_m b_n / a_n = 0.015$		$a_n b_m / a_m = 0.0067$		



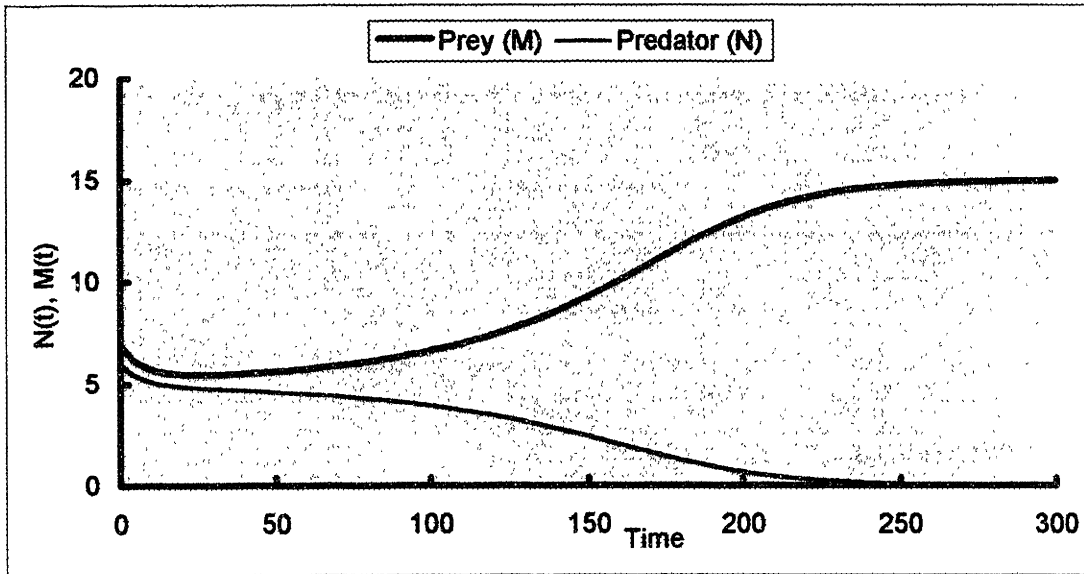
(a)



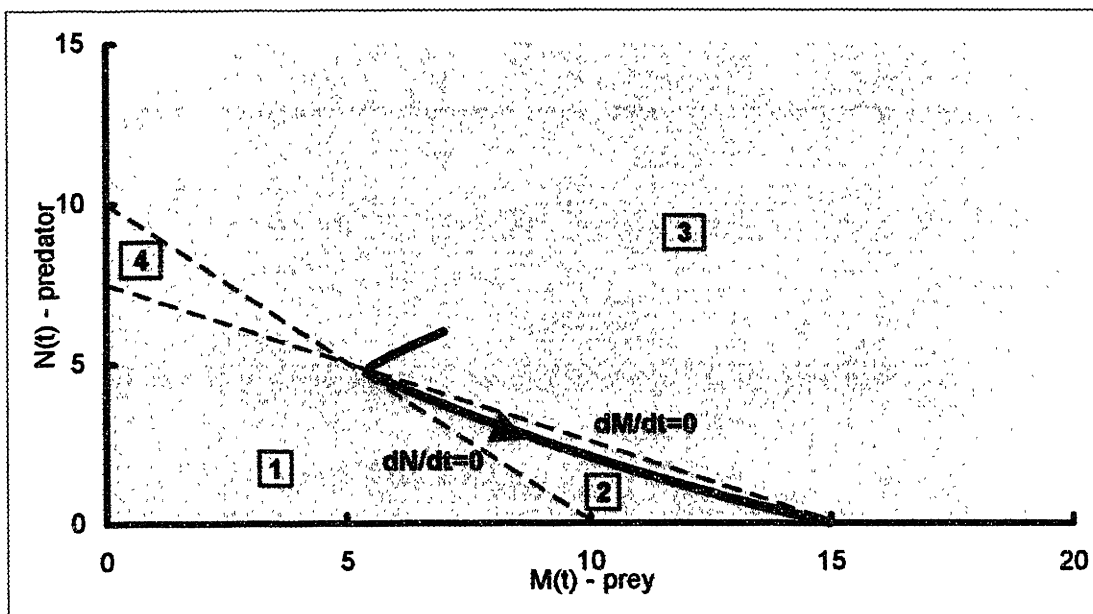
(b)

Figure 5.35 Pure competition interaction (Case 4: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=3.5$ and $M(0)=7$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.01$	$N(0)=6$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=7$	$M^*=5$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$		



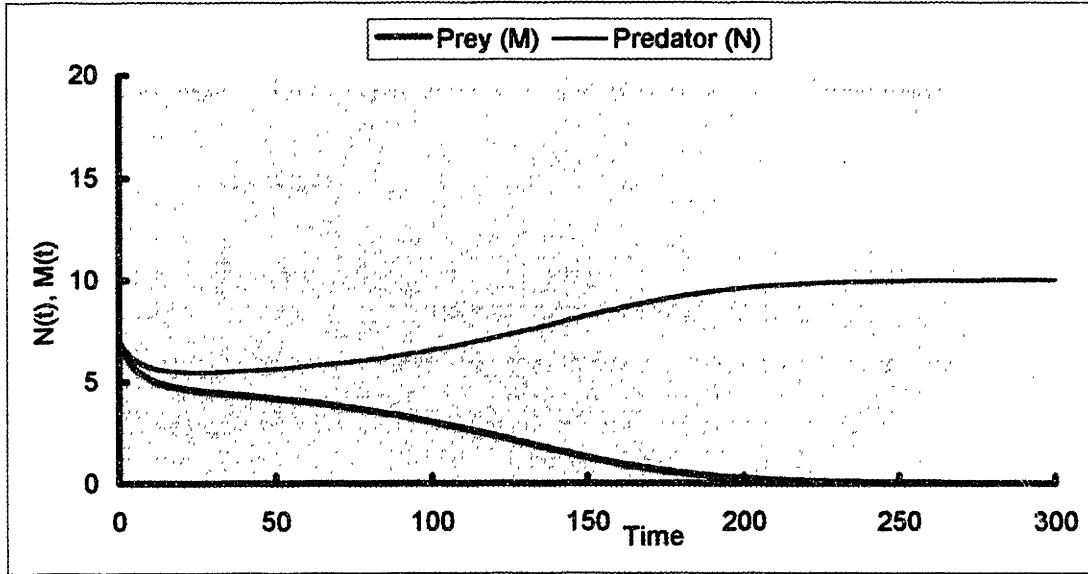
(a)



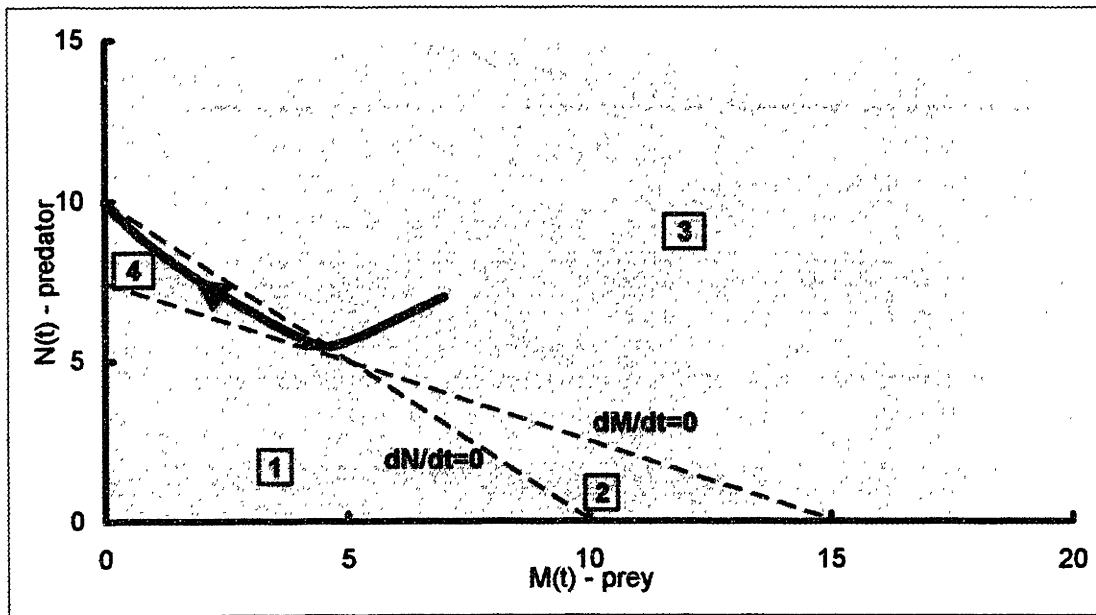
(b)

Figure 5.36 Pure competition interaction (Case 4: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=6$ and $M(0)=7$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.01$	$N(0)=7$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=7$	$M^*=5$
	$a_m b_n / a_n = 0.015$		$a_m b_n / a_n = 0.0067$		



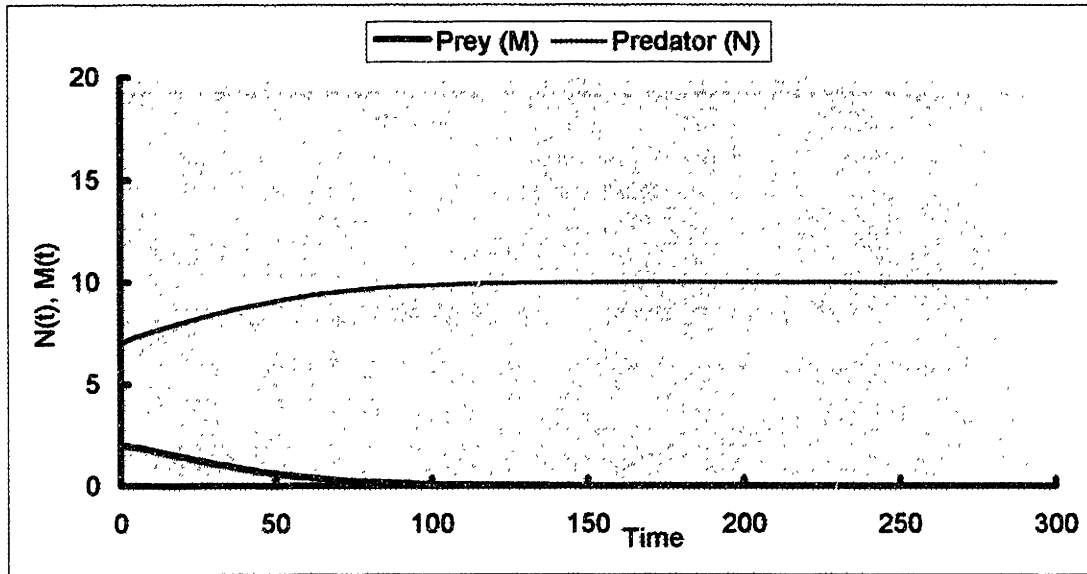
(a)



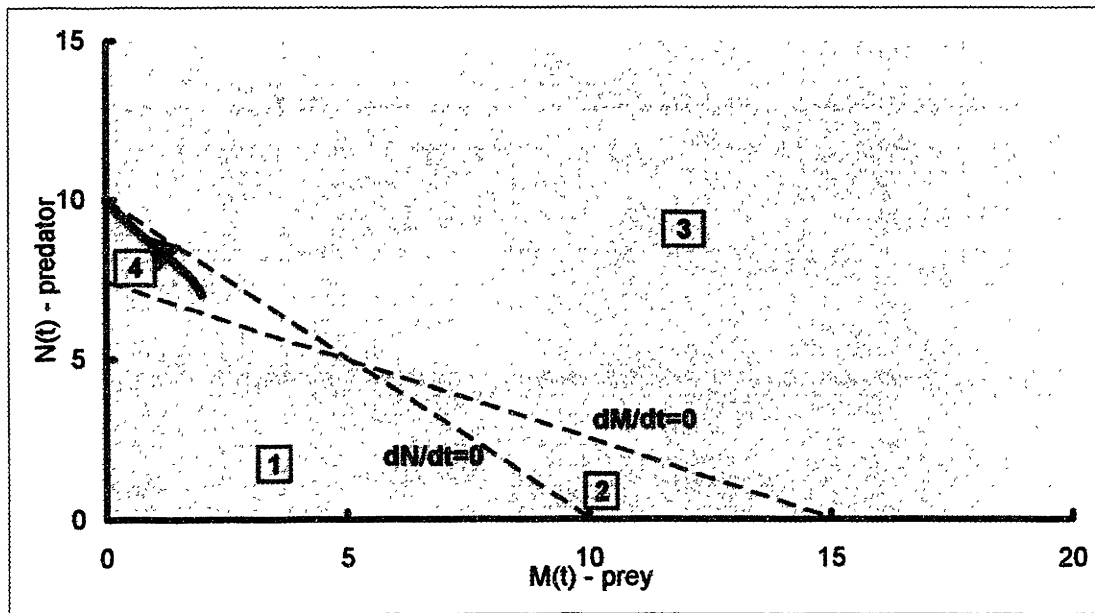
(b)

Figure 5.37 Pure competition interaction (Case 4: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=7$ and $M(0)=7$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.01$	$N(0)=7$	$N^*=5$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=2$	$M^*=5$
	$a_m b_n / a_n = 0.015$		$a_m b_m / a_m = 0.0067$		



(a)



(b)

Figure 5.38 Pure competition interaction (Case 4: $a_m b_n / a_n < c_{mn}$ and $a_n b_m / a_m < c_{nm}$) with $N(0)=7$ and $M(0)=2$ (a) time domain (b) phase diagram.

mentioned above. Similarly, Figures 5.36 and 5.37 show the same phenomenon for two initial values in close proximity to each other in subregion 3. Figures 5.35 and 5.37 show how trajectories originating in subregions 2 and 4 eventually terminate in $(M=a_m/b_m, N=0)$ and $(M=0, N=a_n/b_n)$, respectively.

Note that in this case one of the technologies eventually dies and the other converges to its limiting logistic value. The winner is determined by the *initial conditions*. Within the admittedly artificial boundaries of the model, this notion does, however, add fuel to fire in the discussion of determinism.

Modeling symbiosis with a system of differential equations

Finally we come to the third mode of interaction, viz. that of symbiosis, where each technology enhances the growth of the other. This mode can be modeled by

$$\frac{dN}{dt} = a_n N - b_n N^2 + c_{nm} NM \quad (5.44)$$

$$\frac{dM}{dt} = a_m M - b_m M^2 + c_{mn} MN \quad (5.45)$$

where all coefficients are positive. Note also the positive signs of both the competition coefficients c_{nm} and c_{mn} . The equilibrium lines on the phase diagram that indicate where $dM/dt=0$ and $dN/dt=0$ are given by

$$\frac{dN}{dt} = 0: \quad N = \frac{a_n}{b_n} + \frac{c_{nm}}{b_n} M \quad (5.46)$$

$$\frac{dM}{dt} = 0: \quad N = \frac{b_m}{c_{mn}} M - \frac{a_m}{c_{mn}} \quad (5.47)$$

As before the axes are also equilibrium lines, i.e. $dM/dt=0$ on the N -axis where $M=0$ and $dN/dt=0$ on the M -axis where $N=0$. As in the case of the modified predator-prey formulation, we again modify Pielou's solution for the case of pure competition (1969, p.59), to yield the solution for the symbiotic mode, i.e.

$$N(t+1) = \frac{\lambda_n N(t)}{1 + \beta_n N(t) - \left(\frac{c_{nm}}{b_n}\right) \beta_n M(t)} \quad (5.48)$$

where

$$\lambda_n = e^{a_n} \quad (5.49)$$

$$\beta_n = \frac{b_n(e^{a_n} - 1)}{a_n} \quad (5.50)$$

and

$$M(t+1) = \frac{\lambda_m M(t)}{1 + \beta_m M(t) - \left(\frac{c_{mn}}{b_m}\right) \beta_m N(t)} \quad (5.51)$$

where

$$\lambda_m = e^{a_m} \quad (5.52)$$

$$\beta_m = \frac{b_m(e^{a_m} - 1)}{a_m} \quad (5.53)$$

As in the case of pure competition, we should not take the nomenclature of *predator* and *prey* to literally here. The terms merely serve to identify two technologies that have a symbiotic effect on one another's growth. From the phase diagram viewpoint, there are again two cases, viz. $b_n b_m < c_{nm} c_{mn}$ and $b_n b_m > c_{nm} c_{mn}$. Figures 5.39 and 5.40 show the generic phase diagrams for the two cases. Note that in the first case there is an equilibrium point in the region $M, N > 0$ and in the second case there is not. The coordinates for the equilibrium point are given by

$$M^* = \frac{a_m b_n + a_n c_{mn}}{b_m b_n - c_{nm} c_{mn}} \quad (5.54)$$

$$N^* = \frac{a_n b_m + a_m c_{nm}}{b_m b_n - c_{nm} c_{mn}} \quad (5.55)$$

In order to illustrate the dynamics of a symbiotic relationship, consider the system

$$N(t) = N(0.1 - 0.01N + c_{nm}M) \quad (5.56)$$

$$M(t) = M(0.15 - 0.01M + c_{mn}N) \quad (5.57)$$

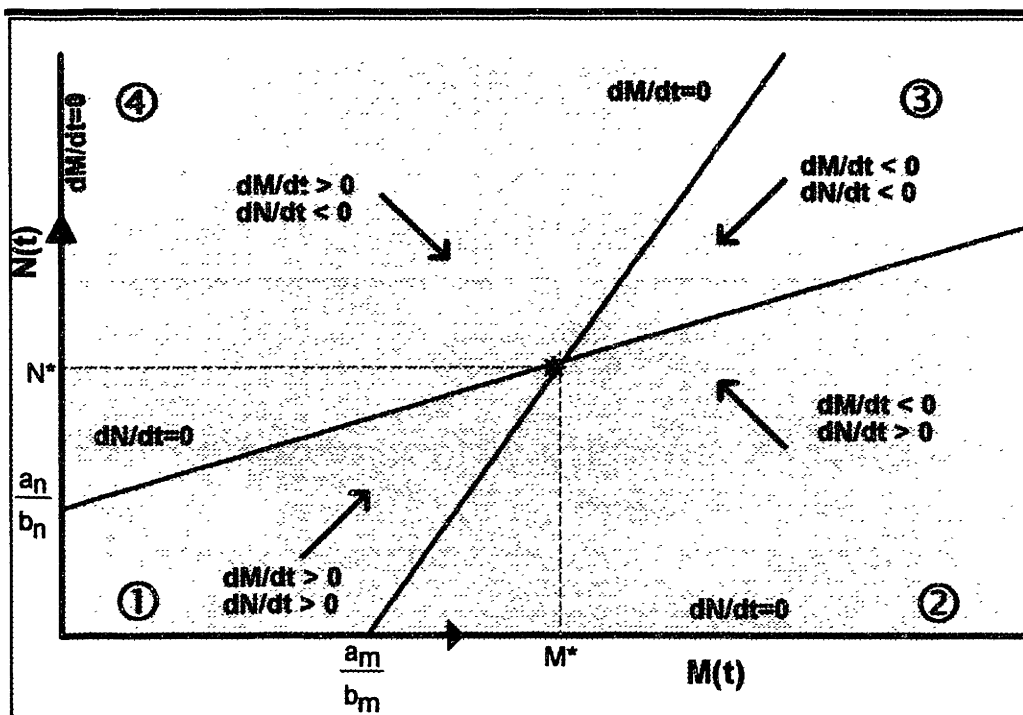


Figure 5.39 Phase diagram for the symbiotic system with an equilibrium point in the region $M, N > 0$ (Case 1: $b_n b_m > c_{nm} c_{mn}$)

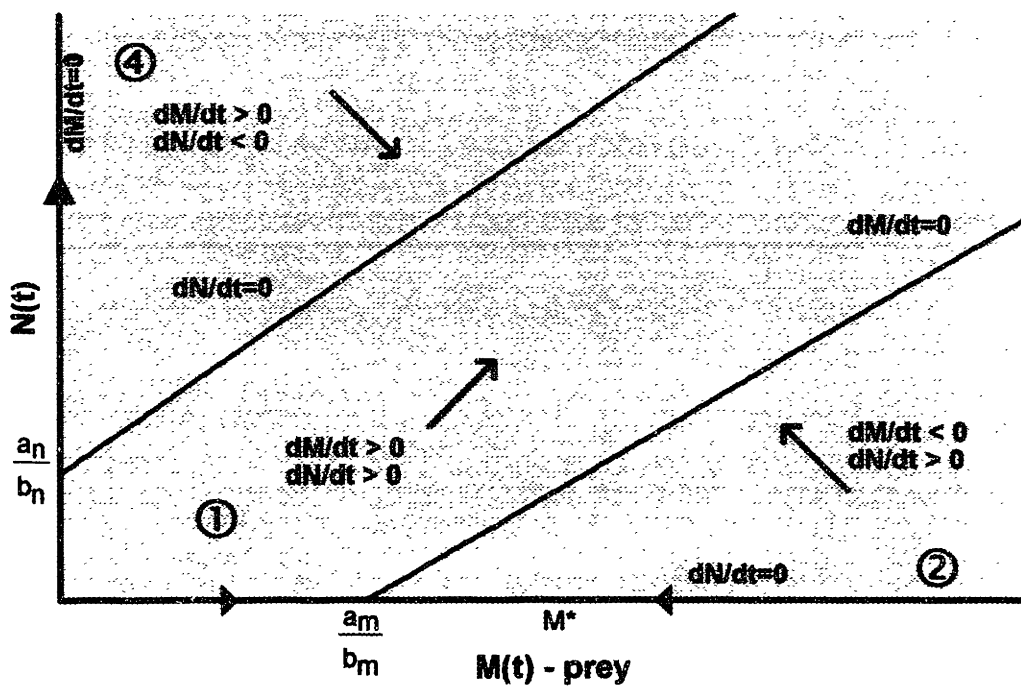


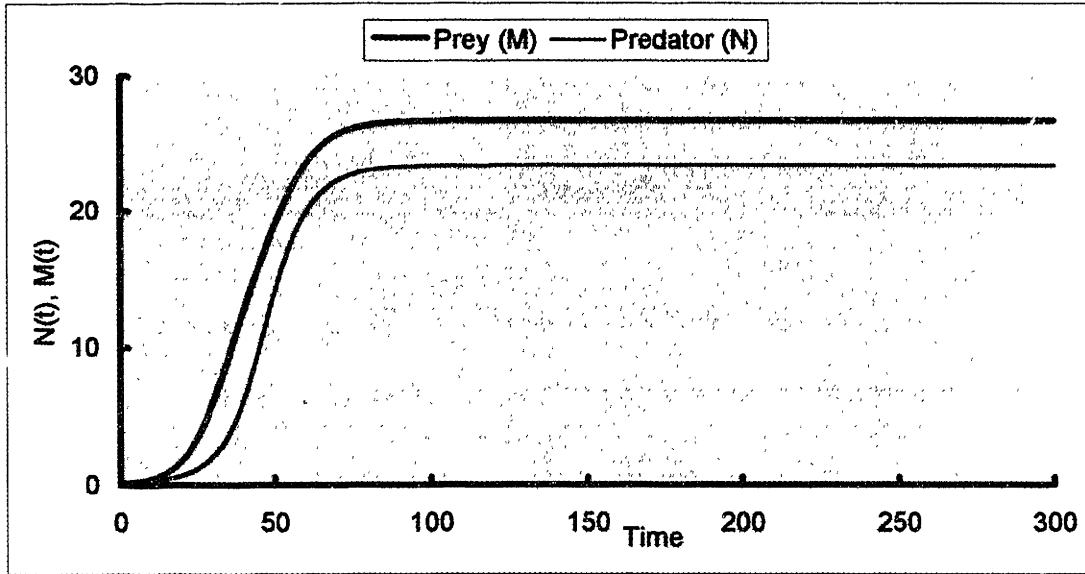
Figure 5.40 Phase diagram for the symbiotic system with no equilibrium point in the region $M, N > 0$ (Case 2: $b_n b_m < c_{nm} c_{mn}$).

Case 1: $b_n b_m > c_{nm} c_{mn}$

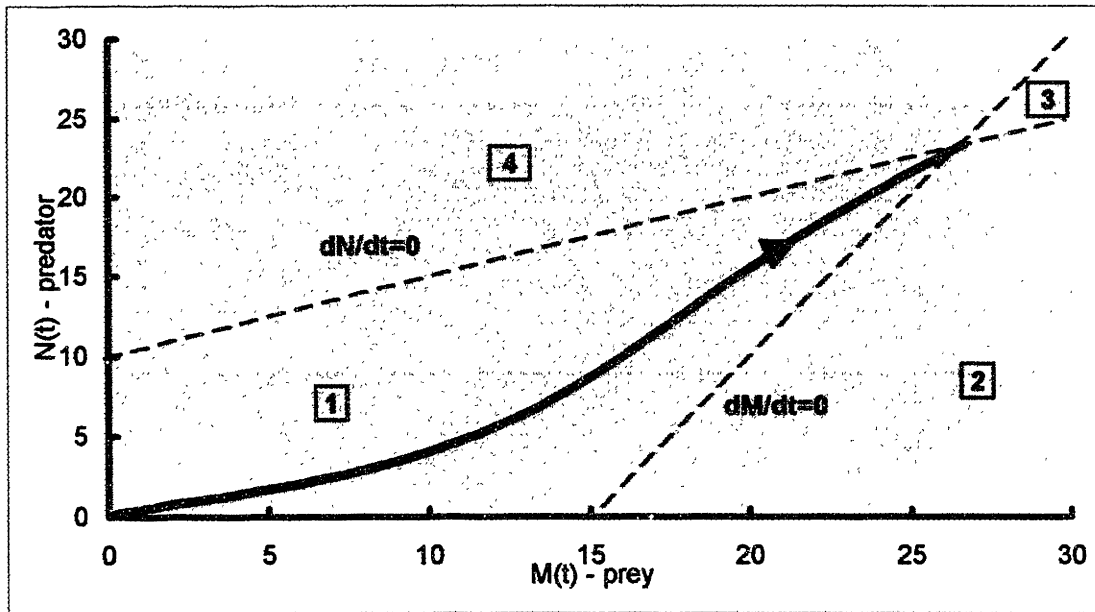
Choose $c_{mn}=c_{nm}=0.005$. Figure 5.39 shows that the equilibrium lines divide the region $M, N > 0$ into four subregions. We find that the trajectory approaches the equilibrium point when $b_n b_m > c_{nm} c_{mn}$. As before, the path of the trajectory depends strongly on the initial values of the two technologies. Figures 5.41-5.44 show trajectories as well as time domain plots for the same system but with initial values in the four subregions. Note that the trajectory can approach the equilibrium point in either a clockwise or an anti-clockwise fashion. Recall that Figure 5.8 illustrates the same system but with no interaction between the two technologies. Comparing Figure 5.8 with Figure 5.41, we see that both technologies have benefited from the symbiotic interaction. Both technologies attain a higher final value when there is a symbiotic influence and both grow towards those values faster. Figure 5.42 presents an interesting case where the mature technology is under attack from an emerging technology. Note that the initial values represent a situation where a mature technology is well established and the emerging technology begins with a very small value. As the emerging technology grows, the mature technology initially declines, but then regains a positive growth.

A very interesting phenomenon occurs when $c_{mn} c_{nm}$ approaches $b_n b_m$. It would seem that this mode can also give rise to oscillations in the mature phase of an S-curve. Recall that similar oscillations were found in one of the predator-prey cases. It is important to keep in

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=0.1$	$N^*=23.33$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.005$	$M(0)=0.1$	$M^*=26.67$
	$b_m b_n=0.0001$		$c_{mn} c_{nm}=0.000025$		



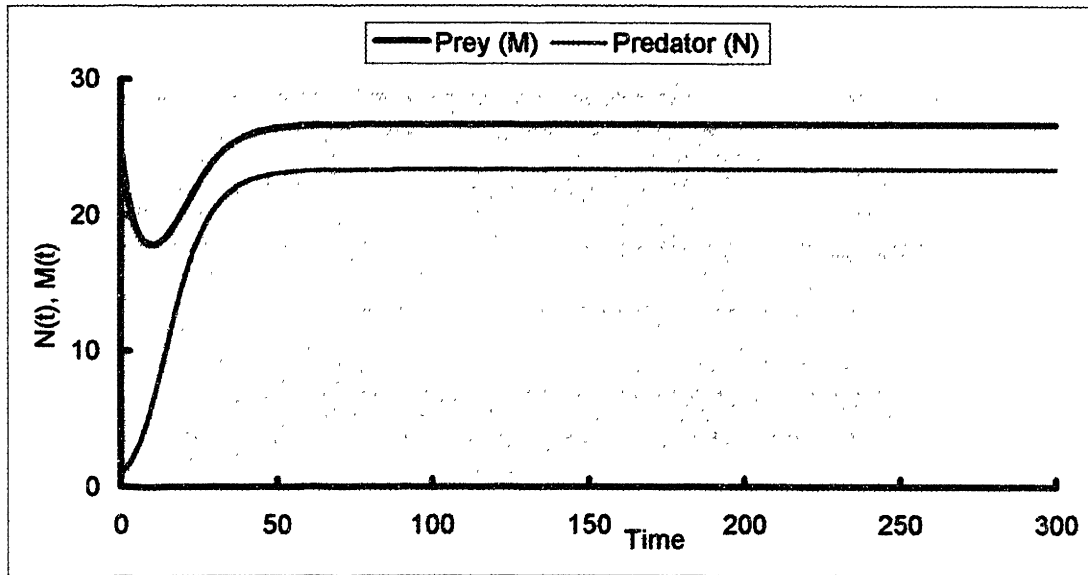
(a)



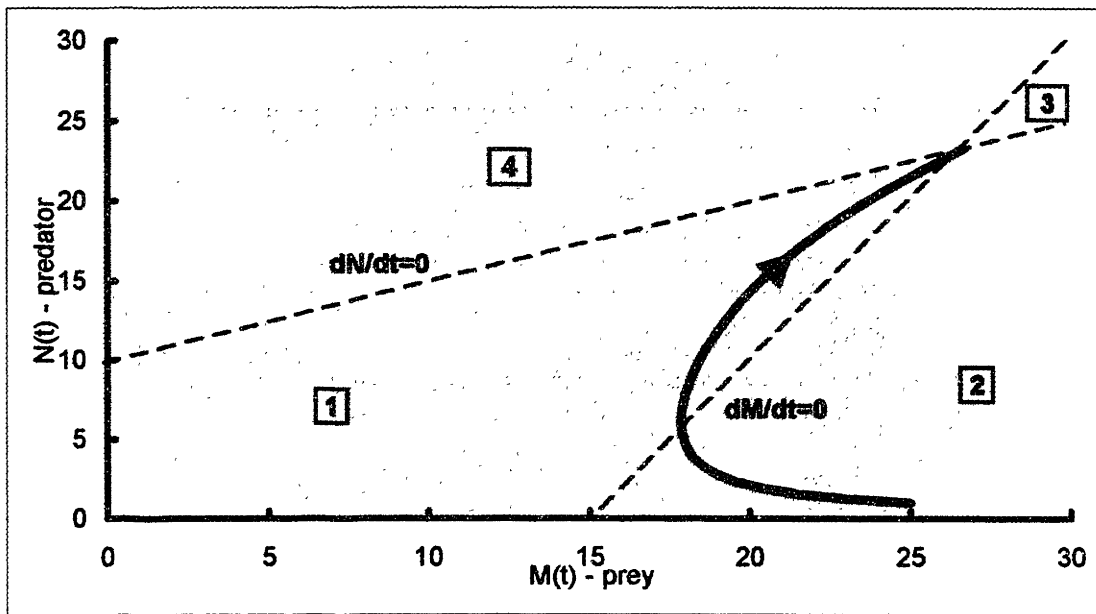
(b)

Figure 5.41 Symbiotic interaction (Case 1: $b_m b_n > c_{mn} c_{nm}$) with $N(0)=0.1$ and $M(0)=0.1$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=1$	$N^*=23.33$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.005$	$M(0)=25$	$M^*=26.67$
	$b_m b_n=0.0001$		$c_{mn} c_{nm}=0.000025$		



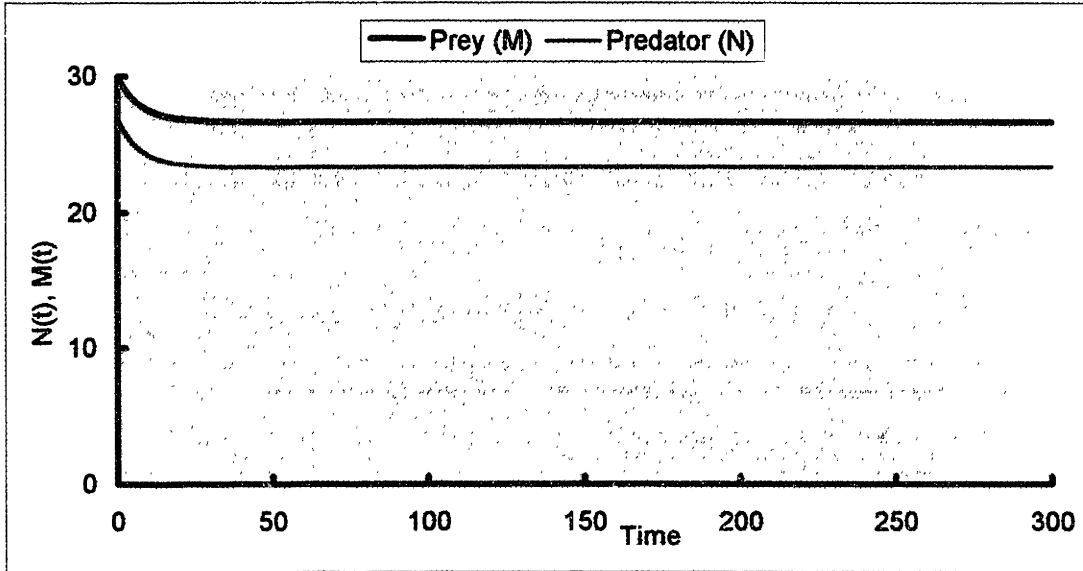
(a)



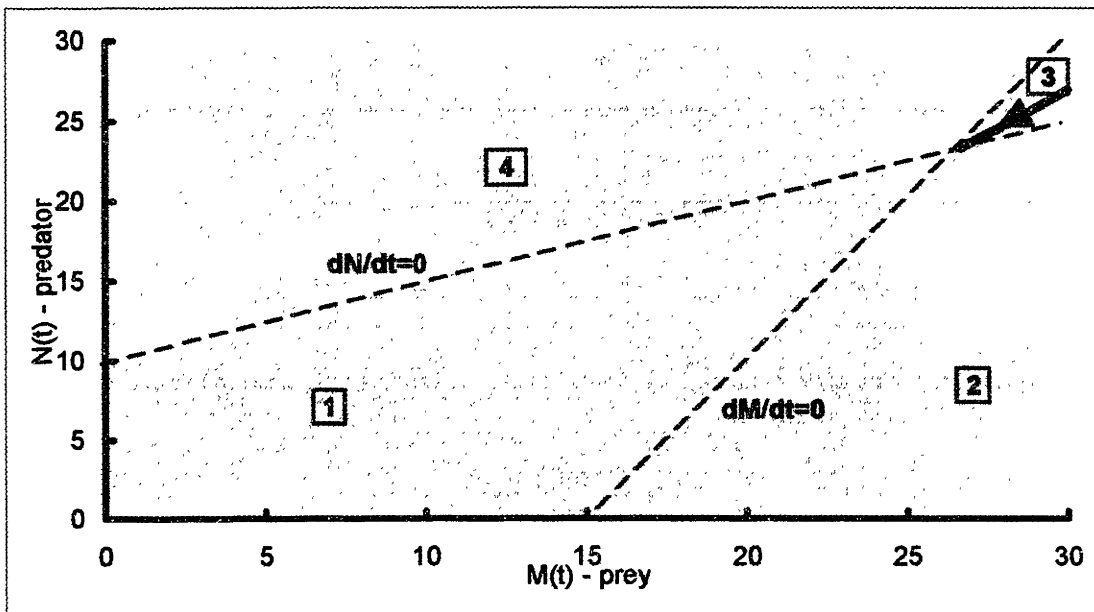
(b)

Figure 5.42 Symbiotic interaction (Case 1: $b_m b_n > c_{mn} c_{nm}$) with $N(0)=1$ and $M(0)=25$
 (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=27$	$N^*=23.33$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.005$	$M(0)=30$	$M^*=26.67$
	$b_m b_n = 0.0001$		$c_{mn} c_{nm} = 0.000025$		



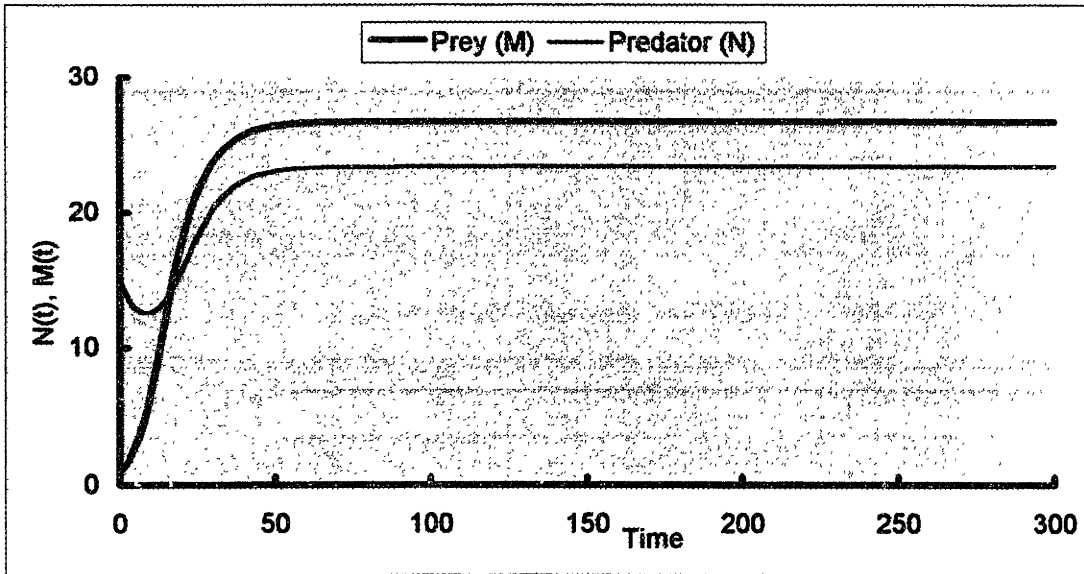
(a)



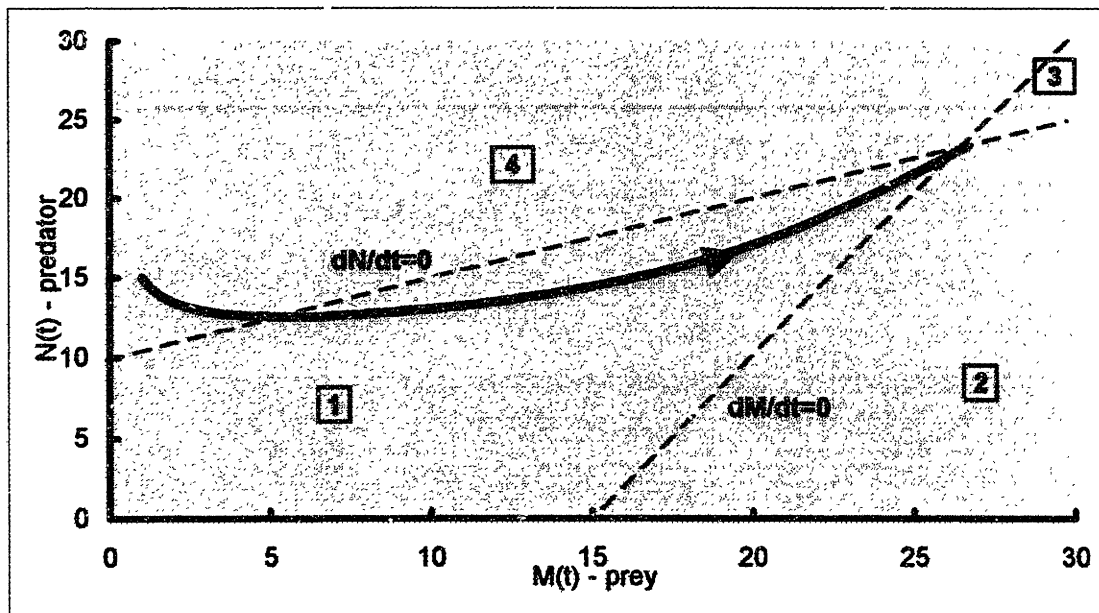
(b)

Figure 5.43 Symbiotic interaction (Case 1: $b_m b_n > c_{mn} c_{nm}$) with $N(0)=27$ and $M(0)=30$ (a) time domain (b) phase diagram.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.005$	$N(0)=15$	$N^*=23.33$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.005$	$M(0)=1$	$M^*=26.67$
	$b_m b_n = 0.0001$		$c_{mn} c_{nm} = 0.000025$		



(a)



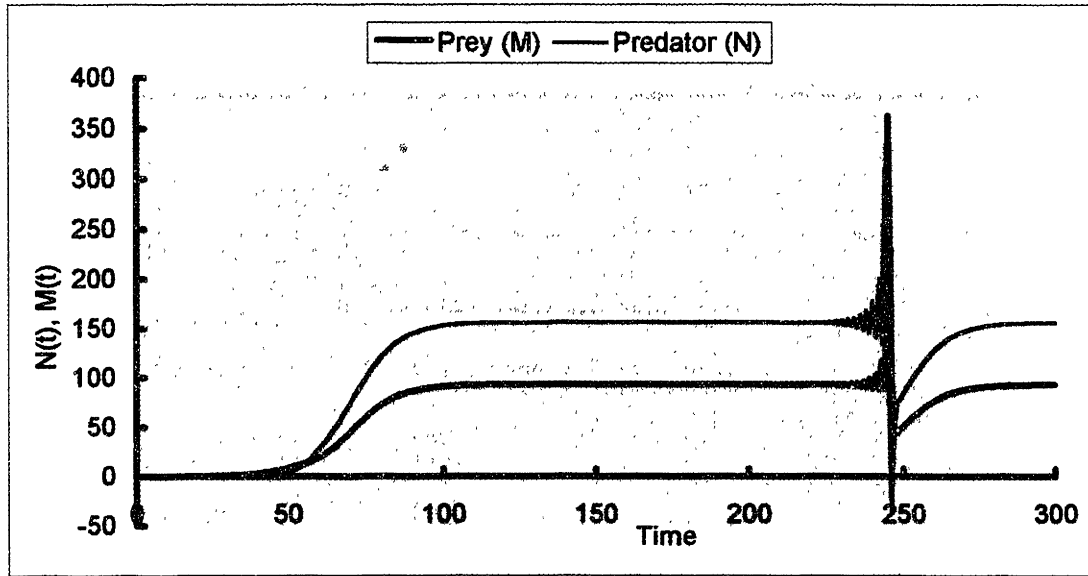
(b)

Figure 5.44 Symbiotic interaction (Case 1: $b_m b_n > c_{mn} c_{nm}$) with $N(0)=15$ and $M(0)=1$
 (a) time domain (b) phase diagram.

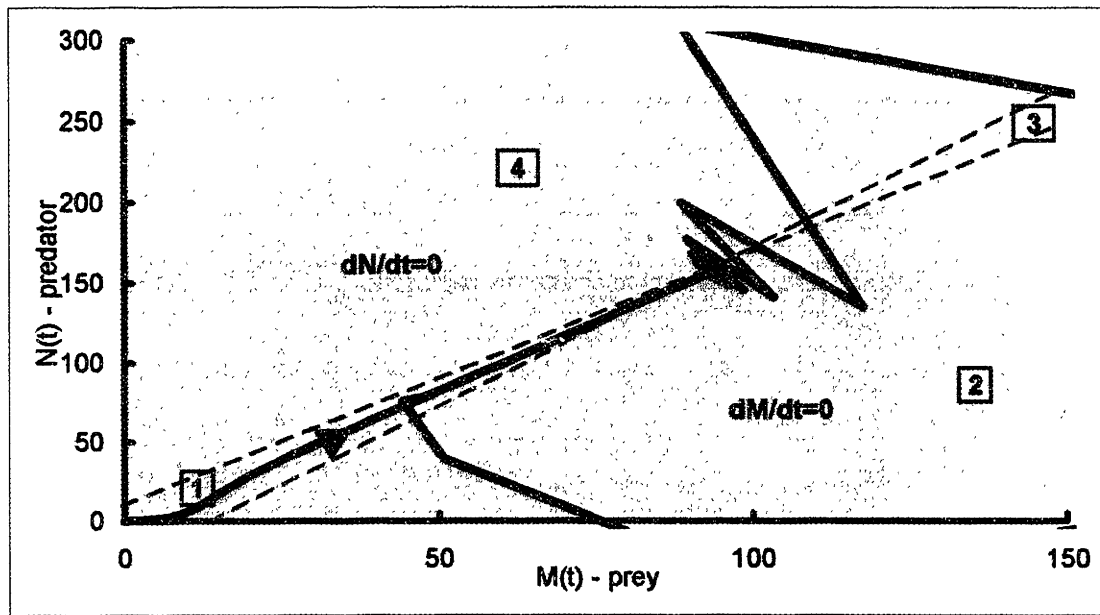
mind, though, that the fact that this type of oscillations was not observed in any of the other cases or the pure competition mode does not imply that they cannot occur there, since numerical examples have been used to illustrate the dynamics of the various modes rather than rigorous mathematical proofs.

Consider now the phase diagram in Figure 5.39. As expected, a trajectory that initiates in subregion 1 will grow towards the equilibrium point. However, rather than terminate at the equilibrium point, the trajectory seems to overshoot and breaks into an oscillatory pattern. A cursory inspection of the oscillatory pattern reminds one of a chaos-like state. Figure 5.45(a) shows the time plots and phase diagram when $c_{mn}=0.005$ and $c_{nm}=0.0157$, yielding values of $b_n b_m=0.0001$ and $c_{nm}c_{mn}=0.000079$. Both technologies live fairly uneventful lives, following regular growth along S-curves until approximately $t=240$ when they both break into the chaos-like oscillatory pattern. By examining the time domain plot in Figure 5.45(b) one might wonder what gives rise to the sudden burst of oscillations in the mature phase after the two technologies coexisted for a long time during which both followed normal logistic growth. An examination of the associated phase diagram in Figure 5.45, however, reveals that the time when the oscillations start, corresponds with the time when the trajectory in the phase diagram reaches the equilibrium point. There is thus nothing mystical about the time when the oscillations start. If the coefficients are known, the phase diagram can be constructed and subsequently the

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.0157$	$N(0)=0.01$	$N^*=156$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.005$	$M(0)=0.01$	$M^*=93$
	$b_m b_n = 0.0001$		$c_{mn} c_{nm} = 0.000079$		



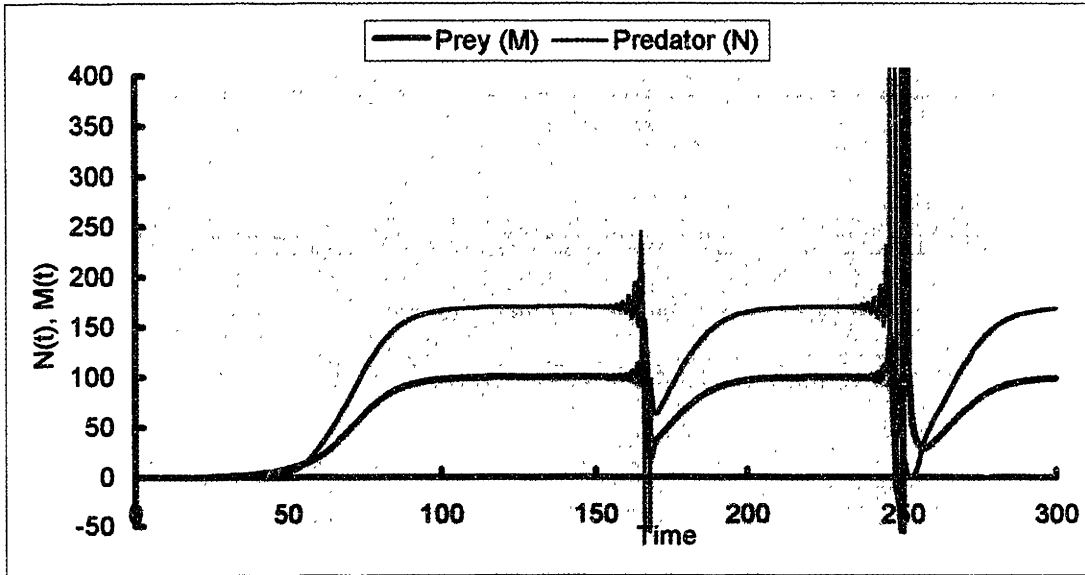
(a)



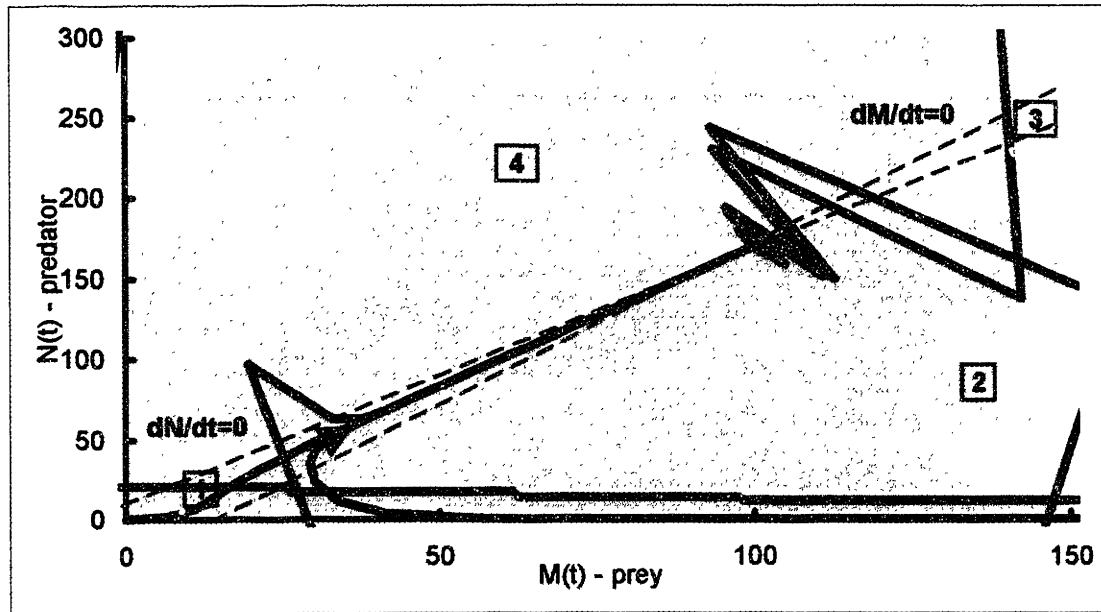
(b)

Figure 5.45 Symbiotic interaction (Case 1: $b_m b_n > c_{mn} c_{nm}$) with $N(0)=0.01$ and $M(0)=0.01$ (a) time domain (b) phase diagram. Note the chaotic oscillations.

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.016$	$N(0)=0.01$	$N^*=170$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.005$	$M(0)=0.01$	$M^*=100$
	$b_m b_n = 0.0001$		$c_{mn} c_{nm} = 0.00008$		



(a)



(b)

Figure 5.46 Symbiotic interaction (Case 1: $b_m b_n > c_{mn} c_{nm}$) with $N(0)=0.01$ and $M(0)=0.01$ (a) time domain (b) phase diagram. Note the chaotic oscillations.

time when the oscillations will commence can be predicted. Figure 5.46 shows the case where $c_{mn}=0.005$ and $c_{nm}=0.0160$ (with $c_{nm}c_{mn}=0.000080$). Increasing $c_{nm}c_{mn}$ ever so slightly thus gives rise to a more pronounced oscillatory behavior.

One may well ask if the oscillatory behavior can be explained by looking at the phase diagram. Note that the phase diagram in Figure 5.39 resembles that of Case 3 in the pure competition mode (Figure 5.26) in the sense that there is an equilibrium point and that the direction vectors in each of the subregions point at the equilibrium point. There are, however, some differences, the important one being that in Figure 5.39 both equilibrium lines have positive slopes, whereas in Figure 5.26 they have negative slopes. Cursory simulations of Case 3 in the pure competition mode have so far failed to exhibit the same oscillatory behavior, with all attempts resulting in the trajectory terminating in the equilibrium point. It should be stressed again that, given the nature of this investigation, this does not prove that it cannot happen there.

No doubt the fact that we use an iterative difference model to calculate the progression of the phase trajectory plays a major role in the onset of the oscillations. Each new value is a function of the previous value, with finite differences between samples. Although it has not been verified analytically in this thesis, one can postulate that the direction vectors in subregions 2 and 4 in the vicinity of the equilibrium point are large. Keeping in mind the scale on which Figure 5.45 is plotted, one nevertheless finds that subregion 3 spans a

narrow angle at the equilibrium point. If the trajectory thus overshoots the equilibrium point somewhat due to the finite increments in which it must advance, the trajectory will find itself in either subregion 2 or 4. The direction vectors in those regions (which we postulate are large) will send the trajectory in the opposite direction (for example from subregion 2 to 4 or from subregion 4 to 2). The incremental difference nature of the model will enforce the amplification of the oscillations. Note that in this example, the oscillations eventually drive the trajectory into the regions where $N < 0$ or $M < 0$. In a real situation, negative population values are not feasible and hence the model breaks down.

From the viewpoint of understanding the dynamics of the interaction, however, it is important to take note of this oscillatory behavior and the conditions under which it can occur. The behavior that results when $c_{nm}c_{mn}$ approaches $b_n b_m$ would seem to resemble chaos. Although we give no formal proof in this thesis that the oscillatory behavior observed in the predator-prey and symbiotic modes are chaotic, the behavior is very characteristic of chaos and suggests that it may indeed be the case. In order to distinguish the oscillations that we have generated here from other types of oscillations, we shall hence take liberty of referring to them as “chaotic oscillations”. A more thorough investigation of the nature of these oscillations may prove to be a worthwhile endeavor. This issue is taken up again in Chapter 6.

The chaotic oscillations observed here are a far cry from those shown in Figure 2.2. Recall that we postulated there that the oscillatory behavior in the mature phase of plywood's S-curve may have been induced by the emergence of waferboard/OSB. Note that the two technologies simulated in Figure 5.13, 5.14, 5.45 and 5.46 break into oscillations simultaneously — something that plywood and waferboard in Figure 2.2 do not do. Keep in mind, however, that the system shown here is purely to illustrate the concept, and that the possibility that the plywood/waferboard case cannot be modeled with this model should not be dismissed out of hand without further investigation of the behavioral characteristics of the model. The coefficients a and b in this example were randomly chosen with c adjusted to illustrate the case. It should also be kept in mind that the simulated results were generated with a difference equation and the time increments in the model hence plays an important role in the behavior, particularly when a chaotic situation occurs. Note that the model also sometimes yields negative values for N and M , something that cannot occur if N and M represent the real sales of the technologies for example, where we assume $M, N > 0$. Additional study that is beyond the scope of this thesis, is required to investigate the chaotic nature that is observed in this mode.

Nevertheless, the results obtained here and in the predator-prey mode do indicate that, in principle, one can expect oscillatory behavior in the mature phase of S-curves *under certain circumstances* when two technologies have symbiotic or predator-prey relationships. From the nature of the Pearl equation and the results in Figure 5.8 we know

that in the absence of another technology, oscillatory behavior does not occur and hence we can infer that (within the realms of the difference model), the chaos-like behavior is caused by the symbiotic or predator-prey interaction among the technologies. The onset of chaos depends very strongly on the relative strengths of the coefficients.

Case 2: $b_n b_m > c_{nm} c_{mn}$

The generic phase diagram for this case is shown in Figure 5.40. Simulations of this case yielded phase diagrams and time domain plots for both technologies that are completely unstable and do not resemble logistic growth or S-curves at all. Hence we leave the further study of this case for another time.

Modeling generic competition between a number of technologies

The model that has been developed in this chapter can easily be extended to account for more than two technologies competing in the same market niche. Consider N technologies that are competing in the same market niche¹⁷, and let $T_i(t)$ represent technology i with ($2 \leq i \leq N$). The differential equation for $T_i(t)$ can be expressed as

$$\frac{dT_i}{dt} = a_i T_i + \sum_{j=1}^N s_{ij} c_{ij} T_i T_j \quad (5.58)$$

where all coefficients are positive and $s_{ii} c_{ii} = -b_i$. Furthermore, $s_{ij} = 1$ if technology j has a positive influence on technology i 's growth, whereas $s_{ij} = -1$ if technology j has a negative

¹⁷ Note that in this case N is an integer that represents the *number* of technologies, rather than in previous paragraphs where it represented the growth curve of a particular technology.

influence on technology i 's growth. Marchetti (1987, p.391), Hannan and Freeman (1989, p.102) and Modis (1992, p.229) have suggested similar sets of equations. However, they seem to refer only to the case of pure competition (and not the multiple modes as we do in this thesis) and they do not offer solutions for the equations.

Given the experience we now have with adapting Pielou's solution, we find that the difference form solution for $T_i(t)$ can be found by extending Pielou's solution (1969, p.59) to the general case, i.e.

$$T_i(t+1) = \frac{e^{a_i} T_i(t)}{1 - \sum_{j=1}^J \frac{s_{ij} c_{ij} (e^{a_i} - 1)}{a_i} T_j(t)} \quad (5.59)$$

This formulation can be used to model the interaction of any finite number of technologies where the interaction among any pair can either be pure competition, predator-prey or symbiosis. Although it is difficult to visualize, one can of course also extend the trajectory to an N -dimensional phase diagram.

Applying of the model

The mathematical model presented in this chapter is developed as a supporting tool for the multi-mode framework for technological interaction that was developed in Chapter 3. Obviously the model in its present form is far from perfect. It does, however, have the potential of being a useful managerial aid when used in conjunction with the multi-mode framework. In principle, the model can be used to simulate technological interaction and

evaluate strategies. In effect this implies determining strategies to manipulate the trajectory on the phase diagram. In order to do so, more knowledge will have to be gained about the behavior of the model and particularly which external forces influence the coefficients.

As was pointed out in previous sections in the chapter, there are still many aspects of the model that need to be tended to before it can be practically implemented. Determining in which of the three modes the interaction is occurring — and if it is predator-prey mode, which is the predator and which the prey — is obviously not a trivial exercise. An even more complicated task will be the actual estimation of the coefficients, especially since the coefficients will probably change with time. The logistic coefficients a and b may change their magnitude as a function of time, whereas the competition coefficients c may change magnitude and sign, the latter action indicating that a change in the mode of interaction has occurred. In addition the coefficients c couple a set of non-linear differential equations. There are also some underlying implicit assumptions, in particular that it is possible to track the growth (or diffusion) of the technologies as a function of time. In order to influence the trajectory by manipulating the coefficients, one would also need to know what the real world influences are that determine the values of the coefficients. The discussions in a previous chapter on the factors that influence the rate of diffusion give some indication of the complexities involved in this process. When dealing with two or more technologies, the coupling between the various technologies will no doubt

complicate the process of determining the coefficients. All of the above is of course under the grand assumption that the model accurately describes the behavior of the system in the first place.

Keeping in mind that the model is intended to be used in conjunction with the multi-mode framework, research will have to be done to verify both. Research challenges with regard to the framework itself were discussed in Chapter 3. A similar effort is required with regard to the mathematical model described in this chapter. Having gained some insights into the dynamics of the various interaction modes in this chapter, we know that the nature of the interaction among the competing technologies can differ significantly depending on the particular mode, as well as on the ratios of the coefficients and the initial values of the technologies at the time they start to interact. From a managerial perspective, however, it is reasonable to assume that one would not as a rule want to be involved in the mathematical intricacies of the model, the estimation of coefficients or the determination of potential functions. One of the thrusts of future research should thus be to distill the mathematics of the model to useful managerial guidelines, particularly with regard to the formulation of attack and defense strategies.

Notwithstanding the difficulties mentioned above, one should not dismiss a potentially useful model just because there are still some major issues to resolve or because all the details have not been worked out. Instead the approach we take here is a positive one,

namely to recognize the concept of the multi-mode framework as being potentially useful in the management of technology. Based on this premise we then use the mathematical model that supports the framework to explore the characteristics of the various modes of interaction as well as some of the possible applications — assuming that the problems can be overcome. Should the model prove to be useful, market forces will probably dictate that the difficulties mentioned above, as well as others that are not foreseen now, will be addressed research-wise.

Countering the seemingly inevitable demise of a mature technology

In order to illustrate the type of application in which the model can be used, particularly in aiding the plotting of strategies for defense and attack, let us thus now proceed to investigate a hypothetical case study. It is important to keep in mind that this case study is in no way intended to be a prescriptive managerial strategy, nor does it pretend to simulate any real situation. The express purpose of this section is to extend the theoretical work that has been done in this chapter to a hypothetical application, thereby hopefully providing impetus to stimulate further research.

Within the realms of the multi-mode framework, the process of *setting a strategy* comprises of an attempt to manage the growth patterns of the various technologies. It is useful to think of the growth of a technology as being influenced by three sets of factors, some of which may be interrelated. The three sets of factors are:

- Factors that enhance the growth of a technology, independent of the influence of other technologies. These factors determine the logistic coefficients a_n and a_m .
- Factors that inhibit the growth of a technology, independent of the influence of other technologies. These factors determine the logistic coefficients b_n and b_m .
- Factors that relate the influence that one technology has on another's growth, whether it be positive or negative. These factors determine the competition coefficients c_{nm} and c_{mn} . It was pointed out previously that more research is required to determine the factors that influence these coefficients, particularly as they pertain to the various interaction modes.

From the viewpoint of the model, the strategy setting process thus entails determining what the path of the technology trajectory *seems to be*, determining what the desired path *should be* and then attempting to influence the coefficients to finesse the trajectory in the desired way. From the viewpoint of the mathematical model, strategy formulation implies an attempt to manipulate the coefficients of the system, thereby influencing the path of the trajectory. The coefficients are to be manipulated by acting upon the factors that, in turn, influence them. It would be reasonable to assume that as a first recourse, one is typically in a better position to influence and manipulate your own coefficients, rather than those of the opponent, although the latter course is certainly not inconceivable.

The concept of a technology trajectory in the phase plane seems like a potentially useful way of graphically illustrating the interaction between technologies. If one is able to determine which one of the three modes the interaction is in at any given time, one should be able to anticipate the trend of the technology trajectory. In addition to indicating trends that can be expected, estimating the final destination of the trajectory is also a useful exercise. As we have seen, several of the interaction modes can lead to the ultimate extinction of one of the technologies. Recalling the previous discussion of mortality indicators, one can certainly envision that the managers of a mature technology facing extinction will want to know if there are signals indicating this possibility. The trend of the technology trajectory can be interpreted as a signal that conditions are ripe for the ultimate demise of a technology. From the mature technology's viewpoint, recognition that this may be the case can evoke a whole spectrum of defensive actions as was referred to in Chapter 3.

Once the trajectory's path is estimated, there is of course no reason to necessarily accept it as a *fait accompli*. Management's role and responsibility, in fact, is to take appropriate action when precursor signals indicate the onset of an unfavorable turn of events. One of the defense strategies may be to try to save the mature technology from extinction and even retaliate against the emerging technology. From the emerging technology's viewpoint, on the other hand, there are certainly cases where the emerging technology's strategy will be to benefit from the mature technology as long as it can and hence the aim

will be to let it live whilst it enhances the growth of the emerging technology, rather than attempting to go all out for its immediate demise.

In order to illustrate the concept, consider now the case where a mature technology is under attack by an emerging technology. Let us assume that there is a predator-prey interaction where the emerging technology (predator) benefits from the growth of the mature technology (prey) but the emerging technology has an inhibiting effect on the mature technology's growth. Let us further assume that the interaction corresponds to Case 2 of the modified predator-prey model, i.e. $c_{mn} > a_m b_n / a_n$. The phase diagram is shown in Figure 5.7. Consistent with the assumptions of our conceptual exploration of the model, we are not concerned here with the mechanism whereby it can be determined what the mode of interaction is or what the coefficients are, but just assume that it can be done. From Figure 5.7 we know that if the situation persists, the defending mature technology (M) will die out and the emerging technology (N) will stabilize at a_n / b_n . As a defensive measure, the managers of the mature technology may want to formulate a strategy to save M .

Consider the case depicted in Figure 5.15 as an example to illustrate the scenario. If we assume for the moment that we know that a predator-prey interaction will be sustained (for some external reason), then from the knowledge of predator-prey interactions that we have gained so far we know that the best that the mature technology's managers can do is

to try and manipulate the coefficients to bring about Case 1 of the predator-prey mode, i.e. they have to effect a change within the predator-prey interaction from Case 2 to Case 1. Figure 5.6 shows the phase diagram of Case 1 (where $c_{mn} < a_m b_n / a_n$). Note that rather than die out, the mature technology stabilizes at the value dictated by the coordinates of the equilibrium point (M^*), as does the emerging technology (N^*). In the long run and under the assumption of constant coefficients, the two technologies thus co-exist at the equilibrium levels. In reality such a long run co-existence is not realistic, but it is a goal to guide the formulation of the defense strategy for the present attack.

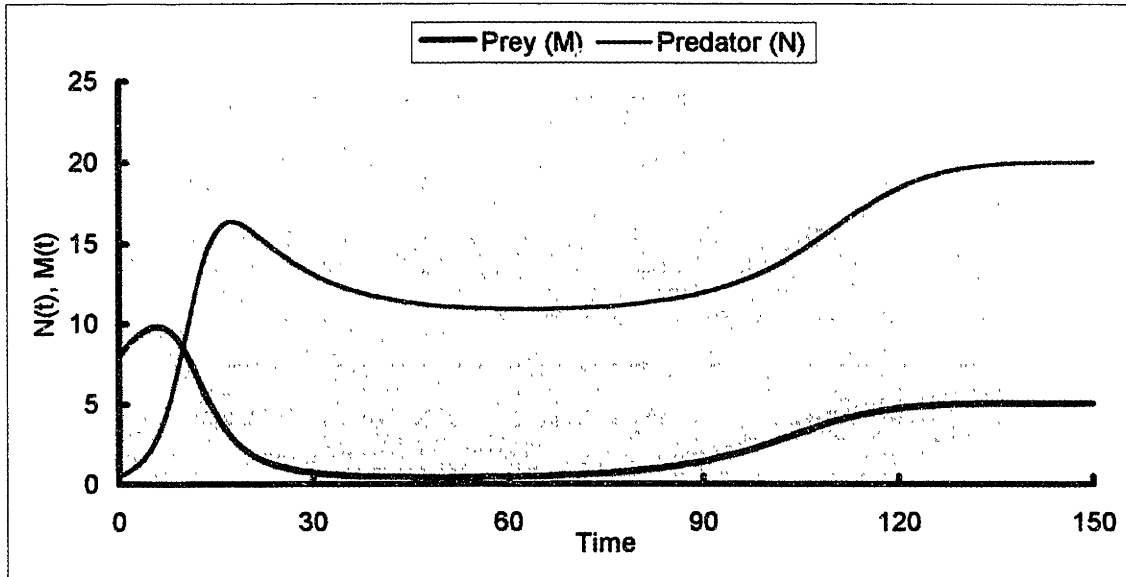
Without the benefit of an understanding of the dynamics of the system, one can intuitively argue that in order for the mature technology to defend itself against the emerging technology, the inhibiting effect of the emerging technology on the mature technology's growth must be curbed. In terms of the model, this implies that c_{mn} must be reduced. The validity of such an intuitive action is supported by the model. The question that cannot be answered intuitively, however, is by how much c_{mn} should be reduced? Having had some insight into the dynamics of the model, we know that the answer is imbedded in the ratios of the coefficients. In order to save M from extinction, it is necessary to try to influence the coefficients from a situation where $c_{mn} > a_m b_n / a_n$ to one where $c_{mn} < a_m b_n / a_n$ (given that a predator-prey mode is sustained). In some cases it may also be easier to try to adjust ratios rather than absolute values. For example, it may (again for some external reason) be easier, cheaper or more cost-effective to adjust the ratio $a_m b_n / a_n$ by adjusting the interplay

among the three coefficients rather than attempting to adjust only one. Understanding what the benchmark for c_{mn} is (namely $a_m b_n / a_n$), gives one the flexibility of response to decide which of the coefficients are the most appropriate targets for manipulation and what to aim for.

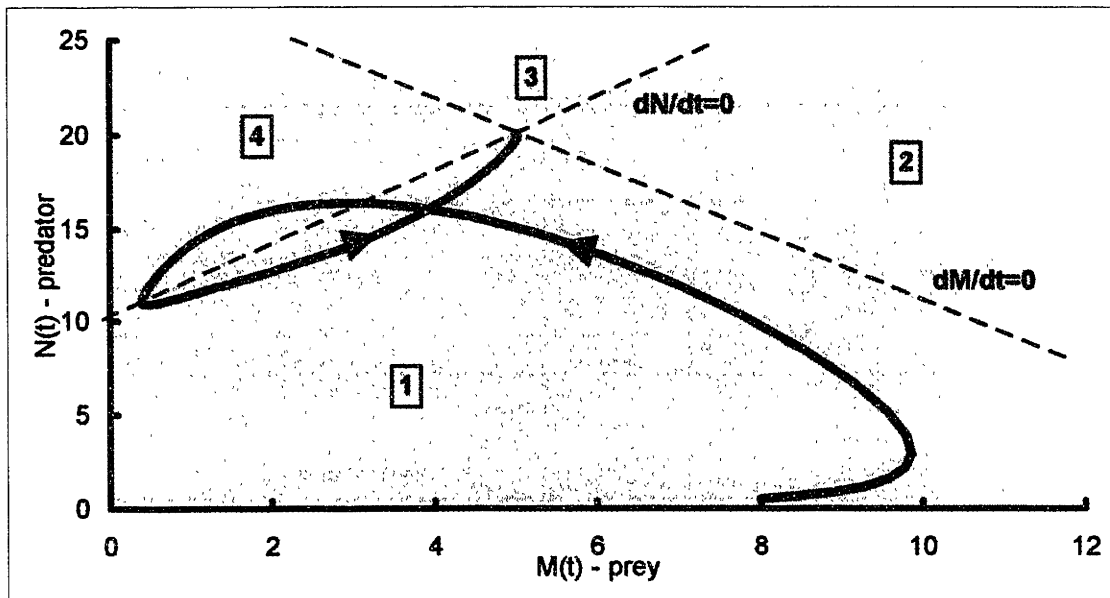
Let us now return to the case depicted in Figure 5.15 and investigate the effect of an attempt to reduce the factors that result in the emerging technology inhibiting the mature technology's growth, i.e. an attempt to reduce c_{mn} . Figure 5.47 shows the case where c_{mn} is assumed to have a value of 0.02 from time $t=0$ until $t=10$. At that time the managers of the mature technology realize the danger that the emerging technology poses and devise a defensive strategy to try to reduce c_{mn} . Assume that they succeed and subsequently reduce c_{mn} from 0.02 starting at time $t=10$ to 0.005 at time $t=100$. It is further assumed that c_{mn} retains the value of 0.005 from $t=100$ onward. Note that the final value of c_{mn} (0.005) is below the critical level needed for survival ($a_m b_n / a_n = 0.02$). By comparing the graphs in Figure 5.47 with those in Figure 5.15, it is evident that the strategy is successful in saving the mature technology from extinction. The effect of reducing the inhibiting effect of the emerging technology on the mature technology's growth clearly enables the mature technology to regain some growth, and finally settling at the coordinates of the new equilibrium point. From the phase diagram we see that even though the measures start taking effect at $t=10$, the actual turn-around point is disturbingly close to the intercept of the equilibrium line $dN/dt=0$ with the N -axis. Had the trajectory

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=0.5$	$N^*=20$
Prey	$a_m=0.15$	$b_m=0.01$	$c_{mn}=0.02; 0.005$	$M(0)=8$	$M^*=5$

c_{mn} changes from 0.02 at $t=10$ to 0.005 at $t=100$



(a)



(b)

Figure 5.47 Saving a mature technology by reducing c_{mn} (from 0.02 at $t=10$ to 0.005 at $t=100$). Compare with Figure 5.15.

actually reached the axis, the mature technology would have died without the possibility of resuscitation. Since we have not adjusted the benefit that the emerging technology gains from the mature technology, we can expect that the mature technology's revived growth should also benefit the emerging technology. Clearly this is the case. The emerging technology seems to emulate the mature technology's revived growth, settling at a final value that is greater than the logistic saturation level (a_n/b_n) that would have resulted if the mature technology had died completely. Such is the nature of predator-prey interaction.

Rather than attempting to reduce c_{mn} , however, circumstances may dictate that a more appropriate strategy for the defenders of the mature technology may be to try to increase a_m , i.e. to strengthen the factors that stimulate the mature technology's inherent growth. The aim of this strategy would be to raise the level of $a_m b_n/a_n$ above that of c_{mn} . Recall that the phenomenon where a mature technology acquires a new lease on life when attacked by an emerging technology is known as the *sailing ship effect* and was described in Chapter 3. Figure 5.48 illustrates this phenomenon where a single technology is competing against the market as described by the Pearl equation and is depicted in Figure 4.1, except that a is now increased from 0.15 to 0.2 at time $t=75$. Figure 5.49 shows the predator-prey interaction depicted in Figure 5.17, but where a_m is increased from 0.15 to 0.3 at time $t=10$, resulting in an $a_m b_n/a_n$ -ratio that is larger than c_{mn} and hence sufficient to save M . In this case we assume that the increase is instantaneous. The

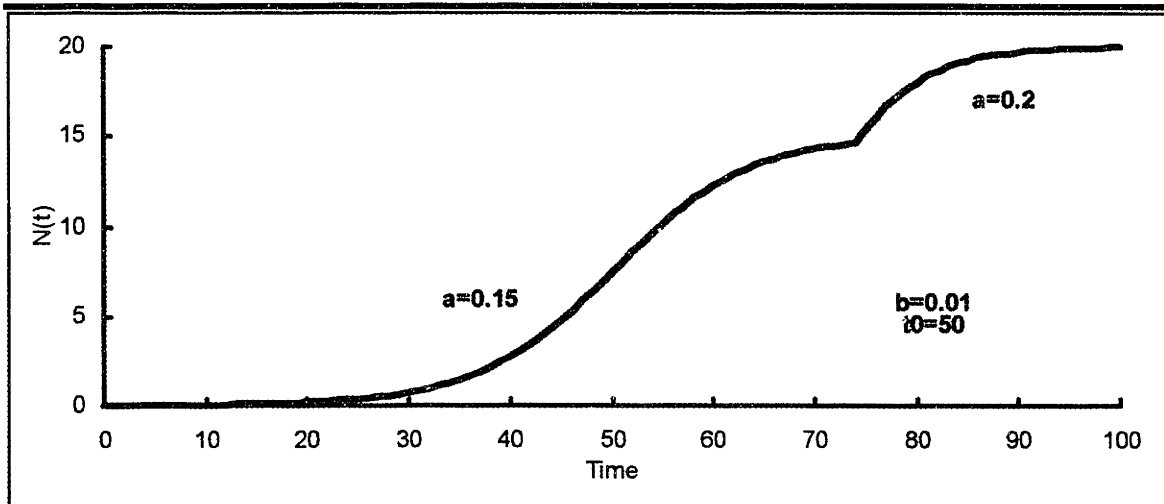
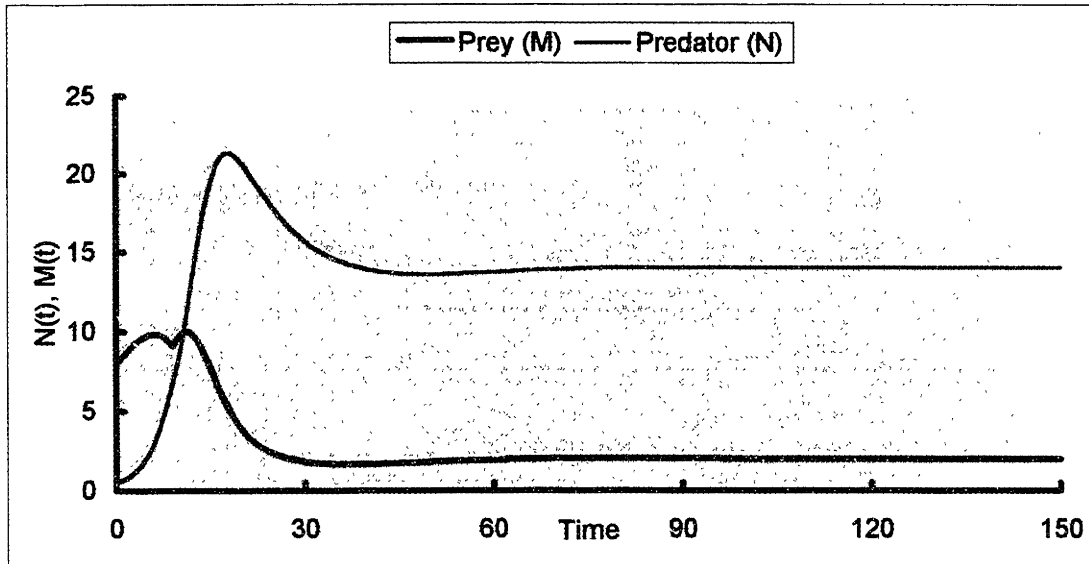


Figure 5.48 S-curve with “sailing ship” effect (a changes from 0.15 to 0.2 at $t=75$). Compare with Figure 4.1.

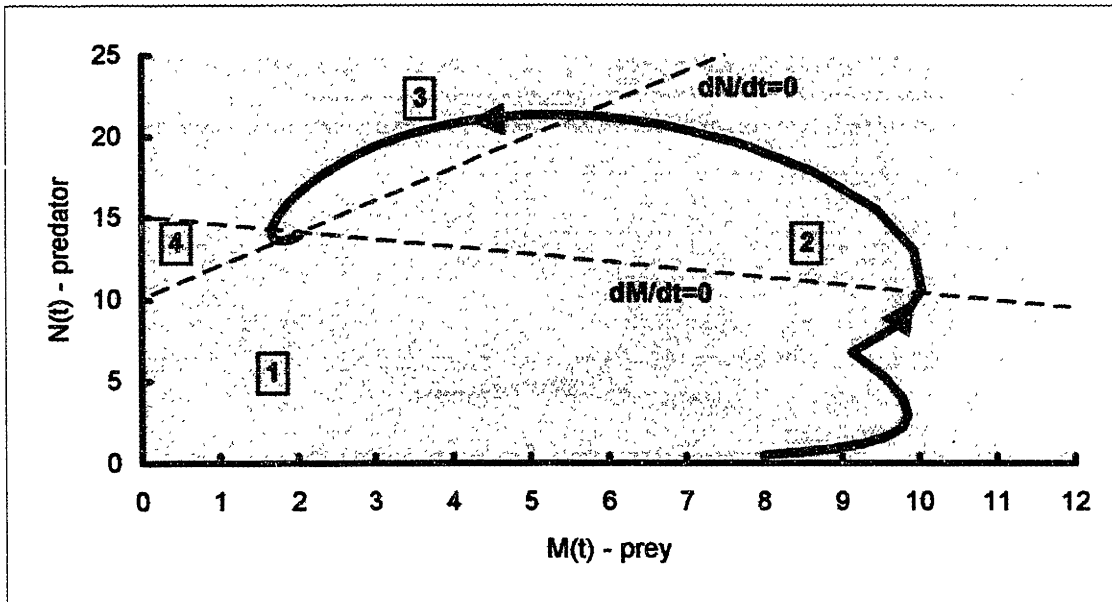
same discontinuous growth exhibited by the Pearl S-curve in Figure 5.48 is detected in Figure 5.49 for the mature technology (prey) with a corresponding discontinuous change in the path of the technology trajectory on the phase diagram. Note that the equilibrium point has now shifted into the region $M > 0$, so that both the mature technology and the emerging technology settle at the final values corresponding to the coordinates of the new equilibrium point on the phase diagram. By comparing Figures 5.49 and 5.15 it is also evident that even though M has been saved, the emerging technology has again also benefited by the increase in M 's increased growth.

From an intuitive viewpoint one might, however, just as well have argued that factors that decrease the internal inhibiting effect of the mature technology, i.e. decreasing b_m , will also save the mature technology from extinction. Faced between a choice of concentrating on the factors that decrease b_m versus those that influence the ratios discussed in the

Predator	$a_n=0.1$	$b_n=0.01$	$c_{nm}=0.02$	$N(0)=0.5$
Prey	$a_m=0.15;0.3$	$b_m=0.01$	$c_{mn}=0.02$	$M(0)=8$
	a_m changes from 0.15 to 0.3 at $t=10$			



(a)



(b)

Figure 5.49 Saving a mature technology by increasing a_m (from 0.15 to 0.3 at $t=10$). Compare with Figure 5.15.

previous paragraphs, a company may decide to base its strategy on the factors that influence b_m . From Eq (5.16) and Figure 5.6 we know that the slope of the line $dM/dt=0$ is given by $-b_m/c_{mn}$. Figure 5.50 shows how the equilibrium line $dM/dt=0$ shifts as c_{mn} is increased from zero. Once the equilibrium point has shifted into the region $M < 0$, the trajectory will terminate in the point $(M=0, N=a_n/b_n)$. Decreasing b_m may then delay the demise of the mature technology, but it will not prevent it. From Figure 5.50 it is evident that changing b_m in this case will only pivot the line $dM/dt=0$ around the equilibrium point M^{**} (which is now in the region $M < 0$), but will not move the equilibrium point back into the region $M > 0$ — a necessary condition for the mature technology to be sustained at a

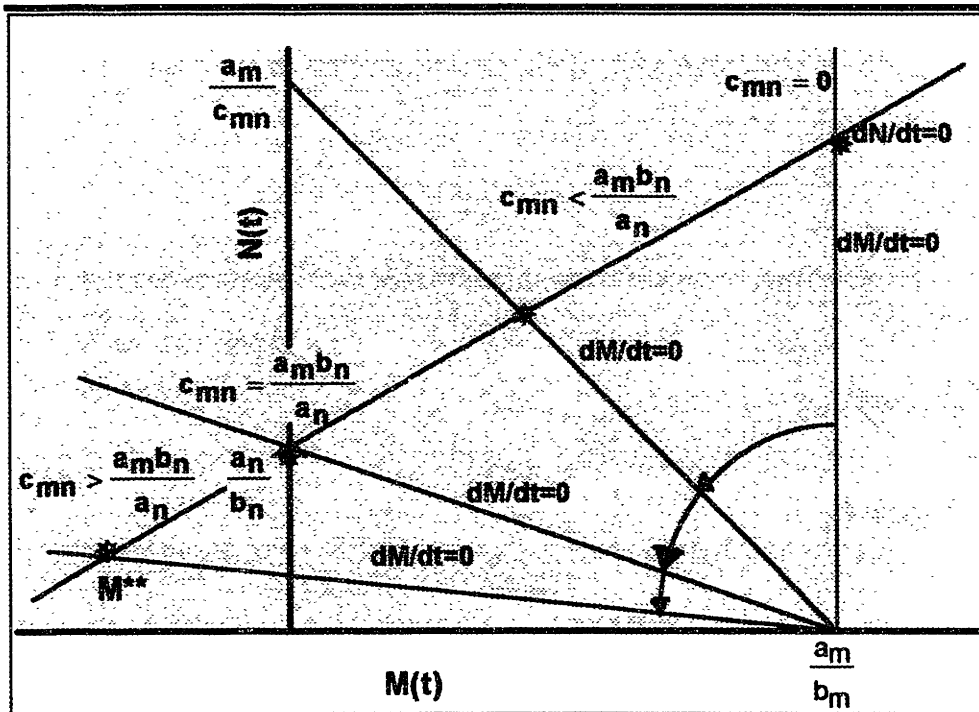


Figure 5.50 Phase diagram for the symbiotic system, showing the effect of increasing c_{mn} .

finite level. Similarly, an attempt to influence the degree by which the emerging technology benefits from the mature technology's presence (i.e. decrease c_{nm}) will slow down the mature technology's demise, but not prevent it.

If the management of the mature technology decides to base their strategy on the manipulation of factors that influence c_{mn} or $a_m b_n / a_m$, there is a chance to save the mature technology. On the other hand if they concentrate of factors that influence the other coefficients in the system, the outcome may not be so successful. From this hypothetical example we see that an intuitive strategy will not necessarily yield the required outcome. On the other hand, the multi-mode framework together with the mathematical model structures the problem in a way that allows one to determine which factors to concentrate on in order to achieve a desired effect. It also suggests an indication of the level of effort required.

THE DEATH KNELLS OF MATURE TECHNOLOGIES

*“Solemn prophecy... is obviously a futile proceeding,
except in so far as it makes our descendants laugh”*

J.B. Priestley

Oscillations in the mature phase of growth curves

We now return to address the original motivation of this study, viz. to investigate whether the oscillations that are sometimes observed in the mature phase of some technologies' S-curves are indications that those technologies are under attack by emerging technologies. Modis states “... At the extremities of the substitution process deviations from the logistic growth pattern have been observed. As the substitution approaches completion — above 90% — the trajectory pattern breaks into random fluctuations” (1993, p.161). Marchetti comments that “... these logistics or quasilogistics can become oscillatory when approaching saturation (a possible solution of Volterra equations often appearing in ecological contexts)” (1983, p.22). Referring to the oscillations in the mature phase of plywood's S-curve, Montrey and Utterback state “... We venture to hypothesize that the type of variance in production of a commodity, such as shown for plywood in recent years... is a clear sign of the vulnerability of that product to an emerging substitution such as the one depicted for waferboard OSB. The

same pattern appears in charts of sales of several other commodities such as aluminum” (1990, p.34). These quotations support the notion that the appearance of oscillations in the mature phase of some technologies’ S-curves is a recognized phenomenon. Montrey and Utterback, however, go further and lay the seed for the hypothesis that such oscillations may actually indicate the emergence of a new technology attacking the old.

As we have shown in the Chapter 4, there is strong empirical evidence that the diffusion of a technology over time displays a smooth growth pattern (often adhering to an underlying S-shaped curve). However, the actual data points very often exhibit erratic behavior in the sense that they deviate from the smooth curve. Although some of these deviations can be ascribed to measurement error, many of them cannot, and therefore must be ascribed to other influences. The deviations often exhibit a clear oscillatory behavior and it is to these oscillations that we now turn our attention. In analogy to the question as to what determines the rate of diffusion of a technology addressed earlier, one can also ask what causes the oscillatory behavior of growth curves.

Before we investigate possible causes and explanations for the oscillations, let us first consider the evidence. Three cases are shown briefly by way of introduction, but they will be discussed in more detail later. Figure 6.1 shows the diffusion of plywood and waferboard/OSB as discussed by Montrey and Utterback (1990)¹⁸. Figure 6.2 shows the number of new automobile registrations in Japan as reported by Marchetti (1983, p.15),

¹⁸ Figure 6.1 is the same as Figure 2.1, except that the data for residential fixed investment has been added.

Figure 6.3 shows the annual production of three minerals (copper, zinc and coal) in the US, also as reported by Marchetti (1983, p.22).

Since *external factors* such as those described in a previous section have such an important influence on the rate of diffusion, is it reasonable to assert that they or other external factors will also cause or influence the oscillations? Girifalco points out that erratic behavior from the smooth curve can be attributed to changes in the business, political and social environments or to the specific differing characteristics of the adopters (1991). Davies has shown that the growth curve exhibits oscillatory behavior due to the fact that the industry (niche) is expanding or contracting (1979, p.83). Several authors have, however, commented on fluctuations that some growth curves develop as they enter the mature phase (Montrey and Utterback, 1990, p.34; Marchetti, 1983, p.22; Modis and Debecker, 1992, p.116; and Modis, 1992, p.199). Note how the curves in Figures 6.1 to 6.3 grow smoothly (with minor oscillations in the case of plywood), but then break into more pronounced oscillations in the mature phase. The question that arises is whether these oscillations are brought about by the emergence of a challenging new technology. If so, is this a necessary, sufficient and unique condition for the oscillations? Obviously if one can show that the oscillations are triggered by the emergence of a new technology (and *only* by the emergence of a new technology), it will be an extremely powerful and useful indicator with profound implications, as was discussed in Chapter 2.

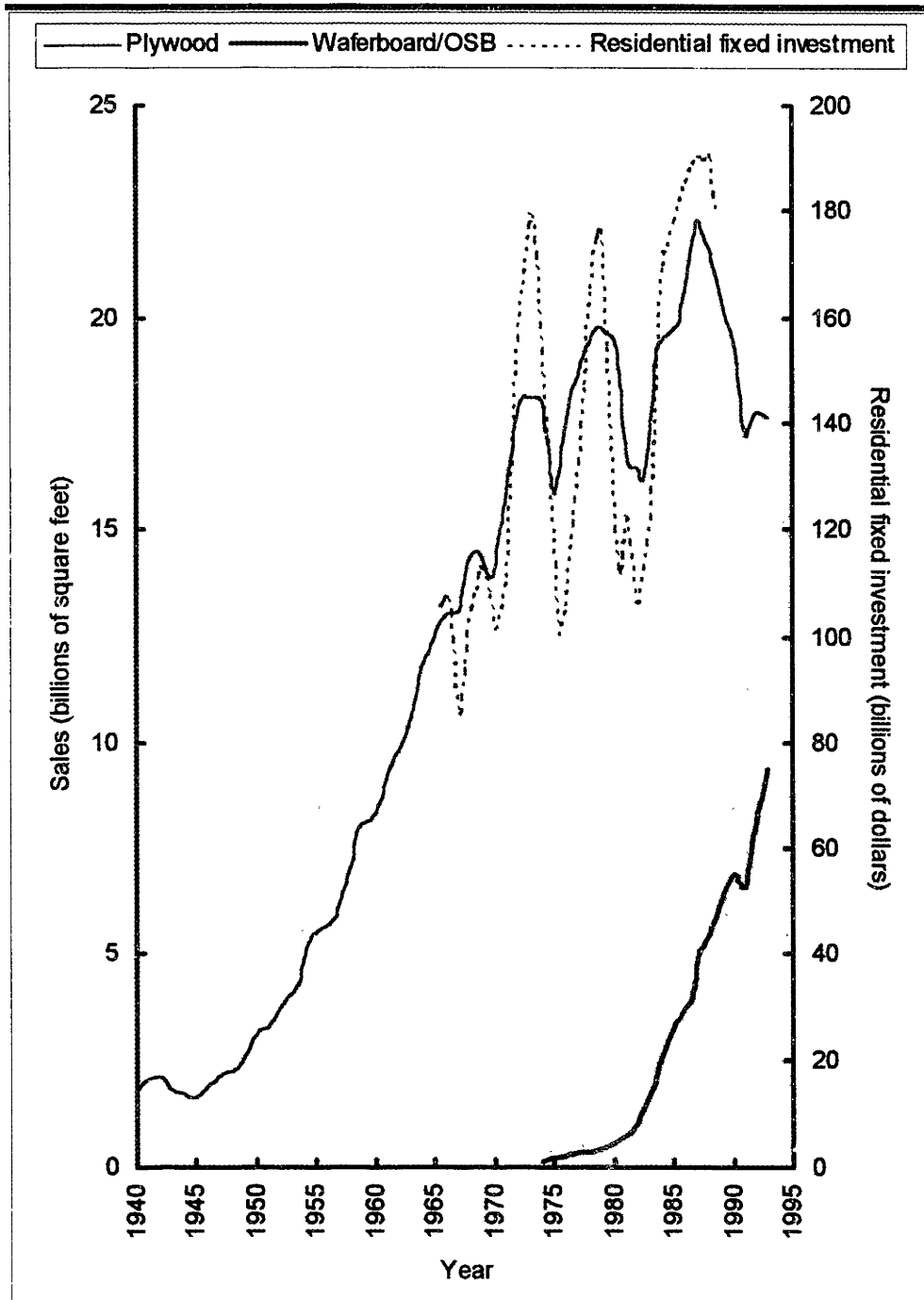


Figure 6.1 Sales of plywood and OSB/waferboard in the US (after Montrey and Utterback, 1990; and RISI, 1993) and residential fixed investment (after Gordon, 1990).

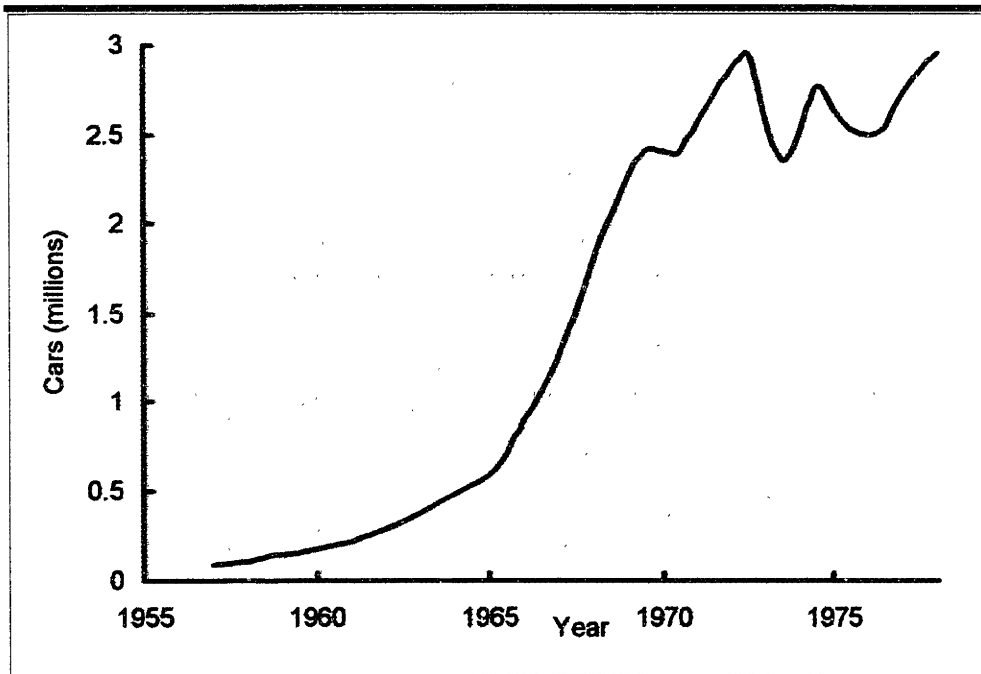


Figure 6.2 New car registrations in Japan (after Marchetti, 1983).

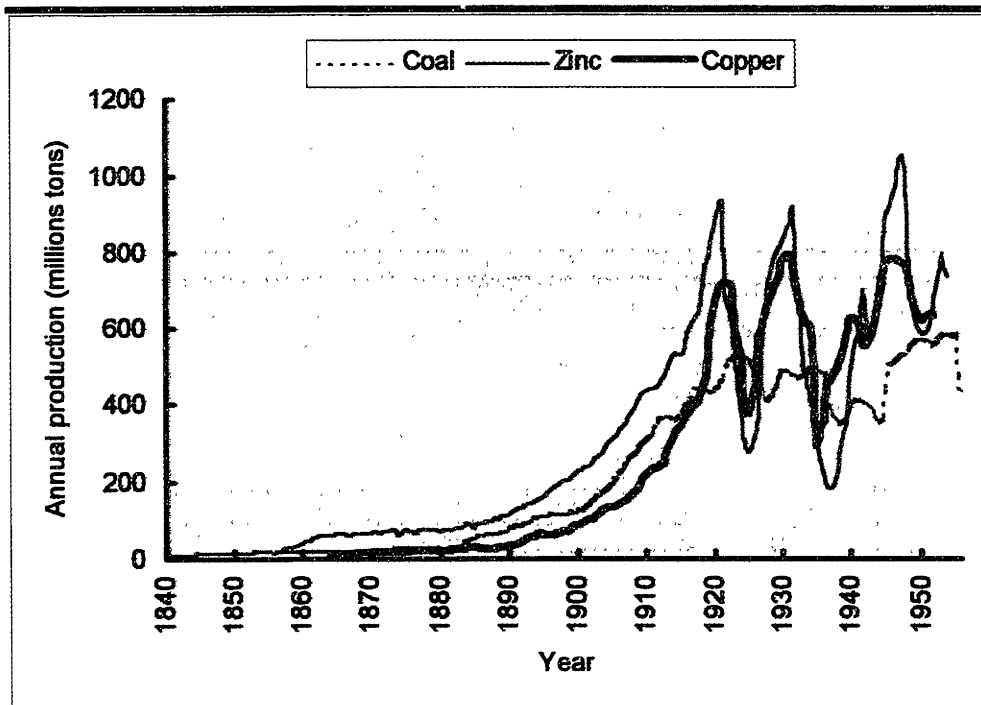


Figure 6.3 Annual production of three minerals in the US (after Marchetti, 1983).

Diffusion of plywood and waferboard/OSB

Montrey and Utterback investigated the diffusion of plywood and waferboard/OSB in the light frame construction industry (Montrey, 1982; and Montrey and Utterback, 1990). After World War II and particularly since the 1950s, plywood became the dominant structural panel in the industry, having gradually displaced lumber as the preferred sheathing material for floor, wall and roof construction. However, since the late 1960s several developments led to the appearance of new unveneered panels (notably waferboard and OSB) that started challenging plywood's dominance, viz.

- ✻ *Technology related developments.* There were process advancements for the manufacture of particle-based panels.
- ✻ *Raw material developments.* The prices of plywood were increasing fast due in part to the depletion of timber supplies suitable for the manufacture of plywood. On the other hand, new timber supplies suitable for unveneered panels were being exploited at lower costs.
- ✻ *Market developments.* The remaining raw material supply for plywood had been declining in quality.
- ✻ *Political developments.* There had been some changes in building codes that made the unveneered panels more acceptable.

The new unveneered structural panels were mainly waferboard, COM-PLY and oriented strand board (OSB). Waferboard was first produced in Canada in 1966 and then spread to

the US. COM-PLY was first marketed in 1976, but had not been proven to be a very successful product and has almost disappeared as a serious competitor. OSB has been commercially produced since 1981 and has been very successful. It has proven to be superior to waferboard and in some respects also to plywood. All three of the plywood substitutes are marketed as structural sheathing commodities. Montrey and Utterback concluded that plywood was and would continue to be at a severe cost disadvantage with regard to the newer panels, and that there was no doubt that plywood was under attack from the newer panels. Using a Fisher-Pry model they predicted the substitution of unveneered panels for plywood.

Figure 6.1 shows the sales of plywood and waferboard/OSB in the US in billions of square feet, calculated on a 3/8" basis (after Montrey and Utterback, 1990; additional data from RISI, 1993). Waferboard and OSB have been grouped together as a category of unveneered panels competing with plywood. The sharp upturn in the curve for the unveneered panels in the early 1980s corresponds with the introduction of OSB. Note how the plywood sales generally follows an S-curve and has a relatively uneventful life until approximately 1970 when the sales curve starts oscillating. The fact that these oscillations correspond with the emergence of the unveneered panels prompts the question whether the emergence of the unveneered panels triggered the oscillations in the plywood's S-curve. If so, it would lend credibility to the hypothesis that oscillations in the

mature phase of a technology's diffusion curve indicate that it is under attack from an emerging technology.

In their article, Montrey and Utterback ascribe the oscillations in plywood's curve throughout the 1970s to the "... erratic nature of the overall wood products economy during that decade. The steep drop in the mid-1970s coincides with the nation's recession during that period, during which housing construction sank to very low levels". In order to test this statement, we now compare residential fixed investment trends in the US with plywood's S-curve. The assumption is that, since the light frame construction industry is a major contributor to the residential fixed investment and this industry is one of plywood's main markets, an examination of the correlation between time series data for residential fixed investment and plywood sales would be a good indicator to test the hypothesis that oscillations in the curve for plywood are coupled to macroeconomic business cycles. Data for residential fixed investment was obtained from Gordon (1990, p.581) and is also shown in Figure 6.1. The correlation between the market swings in the curve for residential fixed investment and plywood sales is remarkable and provides strong evidence that the sales of plywood and particularly the oscillations in the S-curve, are indeed coupled to business cycles.

Note, however, the interesting phenomenon that occurs in the plywood sales in the vicinity of 1985. Even though the residential fixed investment curve keeps climbing, there seems

to be a hiccup in plywood's curve in the sense that the plywood sales do not track the residential fixed investment for a while, but then seems to catch up again. It is tempting to speculate on the cause for this deviation in the plywood sales. One hypothesis might be that the demand for structured panels was being taken up by the unveneered panels rather than by plywood. Figure 6.4 shows how the unveneered panels gained market share versus plywood, lending support the hypothesis above¹⁹. If this is the case, why does plywood then recover, as indicated by the plywood curve that resumes growth after the hiccup? A possible explanation might be that the demand for unveneered structured panels was greater than the capacity and that the slack was being taken up by plywood. If this conjecture is true, it would lend some credibility to the hypothesis that oscillations in the S-curve can be a signal that the mature technology is under attack by an emerging technology.

Table 6.1 shows the capacity and domestic demand (in billions of square feet) as well as demand/capacity ratios of plywood and OSB in the US for the period 1981 to 1989 (RISI, 1993). If we now focus on the period 1983-1987 which corresponds with the period when the trends in plywood sales seemed to lag the trend in residential fixed investment cycle as shown in Figure 6.1, we note the industry demand/capacity ratio increased from 0.80 to

¹⁹ Figure 6.4 was obtained by calculating market share from the values in Figure 6.1, assuming that plywood and waferboard/OSB make up the total market.

Table 6.1 Capacity and domestic demand (billions of sq. ft) and demand/capacity ratios for plywood and OSB in the US for the period 1980 to 1989 (3/8" basis) (RISI, 1993).

		1981	1982	1983	1984	1985	1986	1987	1988	1989
Plywd	Cpty	22.14	22.19	23.12	23.95	24.53	25.44	26.24	25.87	25.09
	Dmd	15.79	14.93	18.30	20.20	20.20	21.73	21.79	21.62	20.52
	D/C	0.74	0.69	0.82	0.86	0.84	0.87	0.84	0.86	0.86
OSB	Cpty	.52	.95	1.8	2.42	3.25	3.9	4.54	5.19	5.55
	Dmd	0.59	0.75	1.47	2.65	3.35	4.36	4.94	5.47	6.26
	D/C	0.48	0.49	0.58	0.79	0.76	0.93	0.90	0.88	0.9
Total	Cpty	22.66	23.14	24.92	26.38	27.77	29.34	30.78	31.07	30.64
	Dmd	16.39	15.67	19.77	22.85	23.56	26.09	26.73	27.09	26.77
	D/C	0.74	0.68	0.80	0.85	0.83	0.88	0.87	0.88	0.89

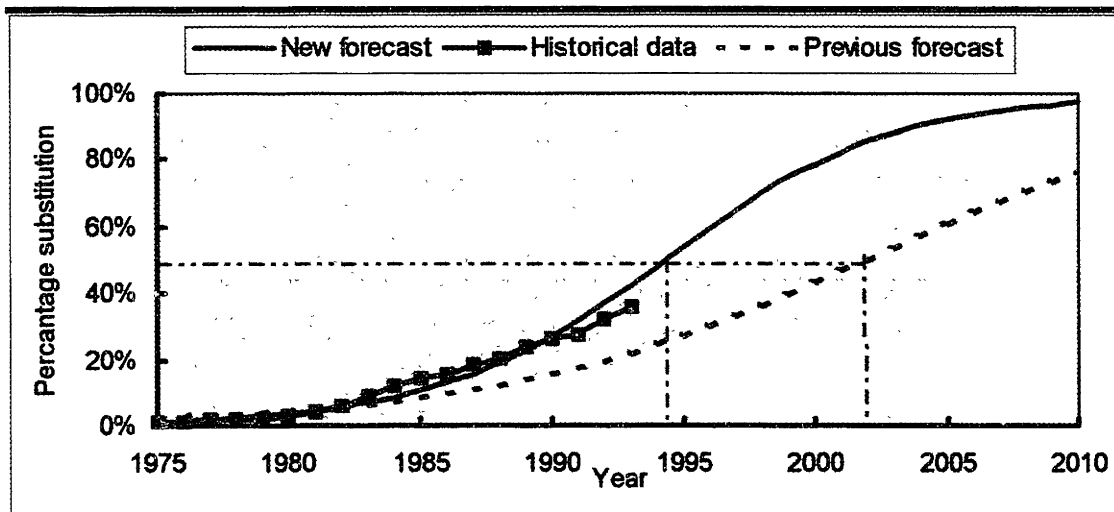


Figure 6.4 Market share of OSB/waferboard *vis-à-vis* plywood in the US. Historical data was obtained from Montrey and Utterback (1990) and RISI (1993). The new forecast refers to the forecast made in this thesis, whereas the previous forecast refers to the forecast made by Montrey and Utterback (1990).

0.87 (with a high of 0.88 in 1986), i.e. 8.8%. The demand/capacity ratio for plywood increased from 0.82 to 0.84 (with a high of 0.87 in 1986), i.e. 2.4%. However, the demand/capacity ratio for OSB increased from 0.58 to 0.90 (with a high of 0.93 in 1986), i.e. 55%. There is thus evidence of a much steeper increase in the demand/supply ratio for OSB than for plywood. This may indeed indicate that OSB supply could not meet demand and hence unfulfilled orders were filled by plywood. Note that even though capacity was still larger than demand, there might have been regional factors, for example, that caused short term shortages in OSB. This explanation of interaction between plywood and OSB/waferboard can account for the deviation in the plywood curve around 1985, and if so lend support to the larger hypothesis that the oscillations in a mature technology's curve may be caused by an attacking emerging technology. The question remains, however, why plywood's S-curve did not track the null in the residential fixed investment curve in the late sixties before the emergence of the unveneered panels. Investigating this issue may be a fruitful avenue of continuing the research in this fascinating case.

Just as one tree does not make a forest, one hiccup in a curve does not constitute an oscillatory pattern. What does emerge here, however, is some evidence that oscillations in the S-curve of a mature technology can be used as signals that it is under attack from an emerging technology. However, as the data on the residential fixed investment shows, the oscillations can also be caused by other factors that may mask or interfere with the signals that are related to the effects of the emerging technology. Interpreting the signal

thus entails more than just observing an oscillatory pattern. As this example shows, external influences like the general economic climate and business cycles can play a significant role. Taking into account measurement errors and other sources of fluctuations and oscillations mentioned, together with effects caused by business cycles, it is evident that a certain amount of signal processing will have to be done on an S-curve to extract potential signals from emerging technologies.

The issue of demand and capacity (supply) raises an interesting point that was pointed out by professor John Sterman (1994). He remarked that in an industrial setting one often finds that orders lead deliveries in time, which in turn lead the construction of capacity. These time lags can have important implications on the stability of the system. If, for some reason the orders started dropping and an overcapacity results, the system can become unstable. Such a situation can also possibly lead to oscillations in the mature phase of the S-curve. Prof. Sterman suggested that system dynamics can be used to model this phenomenon. Even though such a model is not within the scope of this thesis, it is definitely a constructive suggestion and one that should be followed up.

Having spent some effort investigating technological substitution and diffusion in the course of this study, the temptation of attempting to make a forecast was too great to resist (the warnings on making forecasts in Chapter 4 notwithstanding and in retrospect probably against the author's better judgment). As an academic exercise then if you will,

the substitution data of OSB/waferboard for plywood for the period 1976 to 1993 was applied in a Fisher-Pry model similar to the original one described by Montrey and Utterback. In making the forecast, it was assumed that plywood and OSB address the same market segments and that they account for the total market between them. This assumption is a rough approximation, since Montrey and Utterback state that there are mutually exclusive market segments for both plywood and OSB (1990, p.28). Furthermore, there is evidence that steel may soon invade the light frame construction market. If this happens, the assumptions above break down completely. On the other hand, an entry by steel will bring an interesting dimension to the case.

The parameters for the forecast were determined with the software accompanying Porter *et al.*'s book (1991). It was found that $t_0=1994.32$ and $\alpha=0.1148$, resulting in the substitution equation

$$f(t) = \frac{1}{1 + e^{0.229672(1994.32-t)}} \quad (6.1)$$

The result of this forecast is shown in Figure 6.4 together with the historical data. According to this forecast, the substitution should be 50% completed in the second quarter of 1994. Note that the parameters of this forecast are different from that of

Montrey and Utterback's original forecast²⁰, which is also shown in Figure 6.4. However, the new forecast has had the benefit of several more years of historical data.

Modeling the oscillations

One of the motivations for developing the multi-mode framework for technological interaction and the supporting mathematical model was an attempt to gain additional insight into the interaction among technologies, such as the battle between plywood and unveneered panels, and to construct a tool whereby the competition can be simulated. The oscillatory behavior that is sometimes detected in the mature phase of some technologies' S-curves was a particular focus in this regard, especially when accompanied by the emergence of a new technology.

The logic for developing the framework was discussed in Chapter 3, where examples were given of interactions among specific technologies that represent the various modes. The mathematical model that was developed to support the framework is based on the Lotka-Volterra equations. This approach has been chosen because it is very synergistic with the multi-mode framework and because of encouraging evidence in the literature that supported the applicability of the use of a Lotka-Volterra system in this case. Recall that in the section on multi-technology competition in Chapter 4, several references that

²⁰ Montrey and Utterback calculated t_0 to be 2002 and 2α to be 0.1422 (1990, p. 31).

indicate that Lotka-Volterra equations can be used to model oscillatory behavior in S-curves, were mentioned. In Chapter 5 it was shown that the predator-prey interaction that is mentioned in some of the references can indeed lead to oscillatory behavior (such as that shown in Figure 5.1), but it was concluded, however that, that type of oscillations is not the same as the oscillations in the mature phase of a technology's S-curve.

It was hoped that the model developed in Chapter 5 would yield a solution where the S-curve of the mature technology breaks into an oscillatory pattern in the mature phase at the same time at which the S-curve of the emerging technology experiences exponential growth (as is characteristic of the early phase of logistic growth), since this is the situation with the plywood/OSB case. The investigation of the model carried out *so far* has not, however, yielded such a solution. Keep in mind, though, that characteristics of the model were investigated by selecting arbitrary coefficients and empirically observing the behavior of the model. Although such an approach is useful when investigating an entirely new model in order to “develop a feel” for how it behaves, a more rigorous mathematical analysis of the model is required to determine all possible solutions. It would thus be premature to rule out any interesting solutions that the model may yield (such as the one mentioned above) before a more intensive mathematical shake-down of the model has been done.

The model did, however, yield oscillatory solutions in the mature phase of S-curves in two cases, viz. one of the predator-prey cases and one of the symbiotic cases. Recall, however, that the oscillations were echoed in both technologies rather than having oscillations in the curve for one technology while the other had exponential growth. It was mentioned in Chapter 5 that these oscillations exhibited chaos-like characteristics. This leads us to a discussion of *chaos* and its relevance to the issue at hand.

A chaos formulation

Referring to the oscillatory behavior of in the mature phase of some technologies' S-curves, Modis comments that "... These deviations have been explained in terms of states of chaos, which are encountered when the logistic function is put in discrete form, which becomes essential in order to analyze data via computer programs which employ iterative techniques, but it can also be justified theoretically because populations are discrete quantities after all" (1993, p.161). In another article Modis and Debecker make the comment that "... The annual rate of a population growth into a new niche had often been seen to follow a logistic pattern that brakes into fluctuations of random character and sizable amplitude just before reaching the ceiling" (1992, p.116). They then proceed to try to explain the oscillatory behavior of the growth curves with chaos theory. Although one can certainly level some criticism against Modis and Debecker's paper, it does suggest a justification for an investigation into the possibility that the oscillations in the growth curves may have chaotic characteristics. Before launching into a critique of Modis and Debecker's article, a brief discussion of chaos theory is in order to put the discussion into perspective.

As is frequently the case with a new, fast growing discipline in science, proponents and observers have difficulty in agreeing on an all encompassing definition, often relying on the “I’ll know it when I see it” approach. However, the phrase “stochastic behavior in a deterministic system” captures the gist of what chaos theory is about — it is the name given to a set of bounded oscillations that never reproduce identically. Non-linear dynamic systems can exhibit several different kinds of behavior, viz. stable behavior that converges to an equilibrium value, oscillatory behavior in a stable limit cycle, unstable and exploding behavior and chaotic but bounded behavior (Gordon and Greenspan, 1988, p.1). A system in a chaotic state will exhibit seemingly random oscillations that are bounded in amplitude. The oscillations appear random because there does not appear to be a distinguishable pattern. However, the amplitude of every cycle depends on the amplitude of the previous cycle in a deterministic way. This determinism in chaotic systems is an important point to recognize. Mathematically chaos theory is embodied in “... the ability of even simple equations to generate motions so complex, so sensitive to measurement, that it appears random” (Stewart, 1989). Simple non-linear deterministic equations have an uncanny ability to self-generate irregular and seemingly disorderly outputs (Mullin, 1993). Even though the resulting behavior seems to be unstable, chaos theory shows that it is actually a *deterministic chaos*.

Peitgen and Richter have shown that chaos can be modeled mathematically by casting a growth law in discrete form, thereby transforming it from a differential equation into a difference equation (1986). They have shown that, since the increments are now finite rather than continuous, a function that increases towards a limit (for example a growth curve that approaches its limit) will not be able to approach the limit in a smooth fashion.

It will typically overshoot, fall back and so on, in the process oscillating or “hunting” along an average value. Depending on the parameters describing the process, the oscillations will either subside (i.e. the amplitude converges), develop a pattern of regularity (with regard to amplitude, shape and frequency) or fall into a chaotic state where the shape, amplitude and frequency of the oscillations appear to be random. Such systems are typically very sensitive to initial conditions and the influence of external influences. Recall that the model described in Chapter 5 was also very dependent on initial conditions.

Modis and Debecker were not the first to realize the potential of chaotic behavior in describing the dynamics of technological change. Over the last couple of years several articles have been published to show the relevance of chaotic behavior and the associated use of fractals to growth models of technologies and technological forecasting (see for example Gordon and Greenspan, 1988; Bhargava *et al.*, 1990; Gordon, 1990; Gordon, 1991; Gordon, 1992). The conclusion that Bhargava *et al.* come to is telling of the sentiment of many of the papers, viz. “... the importance of the logistic equation in describing economic and social behavior is undeniable. However, one must be prepared for the greater richness of the behavior of the solutions, particularly for large values of the nonlinearity parameter λ ” (Bhargava *et al.*, 1990, p.38). The logistic equation they refer to is the discrete difference equation form of Eq (4.19) that leads to chaotic and oscillatory behavior when λ becomes large.

According to the narrative in Modis and Debecker’s article (1992), they happened upon the chaotic behavior whilst searching for ways in which to speed up algorithms to generate

S-curves. By discretizing the calculation, they not only succeeded in generating the S-curves, but also fluctuations in both the initial and mature phases of the curve. Recognizing that the fluctuations were akin to the oscillations that are often observed on growth curves, they investigated the appropriateness of a chaos explanation for the phenomenon. They proceeded by investigating the effect by changing the nature of parameters in the discrete representation of the S-curve, notably introducing complex values for α in Eq (4.19), a parameter that is normally taken to be real.

Modis and Debecker's simulations yielded systems with seemingly chaotic behavior. Their claim is that chaos theory can account for the S-shaped growth curve, the type of fluctuations exhibited in Figures 6.1-6.3, as well as similar fluctuations often observed in the early growth phases of a technology. They also suggest that chaotic behavior exists in the transitional period when one S-curve is replaced by another, i.e. when the mature phase of one growth curve is blended into the early phase of the next curve, as shown in Figure 6.5. This figure shows the annual production on bituminous coal in the US as reported by Modis (1992, p.201).²¹ It is interesting to note that Modis and Debecker does not refer to the growth of waferboard/OSB as possibly having an influence on the oscillatory behavior in the growth curve of plywood in Figure 6.1.²² It would seem that they have not considered the possibility that there can be a causal relationship between the appearance of the oscillations and the emergence of a new technology that attacks the mature one. In another publication, Modis refers to Montrey and Utterback's explanations for the fluctuations in the growth curve of plywood by saying that "... From 1970 onward

²¹ Note that the data in Figure 6.5 is an extension of that in Figure 6.3.

²² In Montrey and Utterback's original article (1990) the growth curves for plywood and waferboard/OSB were given in two separate graphs, though, and not in the same graph as in Figure 6.1.

a pattern of significant (plus or minus 20 percent) instability appeared, which Montrey and Utterback tried to explain one by one in terms of socioeconomic arguments. Given a pattern one can always correlate other phenomena to it. This type of pattern, however, could have been predicted a priori by chaos formulations” (1992, p.199). The arguments presented earlier in this chapter speak for themselves.

Modis and Debecker’s statements that “... One could reasonably expect that an upcoming growth phase in a new market niche will be heralded by precursors and, once installed, will proceed at an accelerated rhythm in the beginning” and “...A well-established S-curve will point to the time when chaotic oscillations should be expected; it is when the ceiling is being approached. In contrast, an entrenched chaos will reveal nothing about when the next growth phase will start” (1992, p.119), deserve some comment. The notion of precursors that indicate a new growth phase is noteworthy and lends support to the hypothesis that oscillatory behavior in the mature phase of technology’s growth may indicate the rise of an emerging technology. Drawing upon the inherent determinism in chaotic systems, Modis and Debecker seem to imply, however, that there is a certain inevitability in the onset of the chaotic oscillations. Gordon alludes to the same notion when he says of chaotic oscillations generated by a simulation of sales as a function of time, “... An analyst would understandably, wonder about the causes for the market swings. What caused them? ... In fact, no externalities were responsible; all of the complex behavior of this curve results from within the system.... To search for externalities responsible for the market performance would be misplaced effort, for in this

example, all of the chaotic behavior comes from internal sources” (1992, p.2). The implied determinism in Gordon’s statements is an arguable point and touches on the issues that were discussed in the section on determinism in Chapter 3. Recall from the discussion in Chapter 5 that there is actually nothing sinister or mysterious about the onset of oscillations. By examining the trajectory on the phase diagram one can pinpoint the time at which the oscillations will start. There are certainly many growth curves of technologies that do not exhibit oscillations in the mature phase, but the argument can be made that the dynamics of those systems (as embodied in the coefficients of the non-linear differential equations describing the systems) are not chaotic. It is possible, however, that certain growth systems do exhibit chaotic behavior *at some times in their lives*, in which case the outbreak of the oscillations could be ascribed to the chaotic nature of the system.

Taking the view that the system can be modeled with a model such as the one in Chapter 5, for example, one can argue that the coefficients will in general *not* be constant. As was discussed before, external forces can influence the coefficients and change their values with time. It is then entirely conceivable that a chaotic solution may result if the coefficients change relative to one another to support such a solution. In making this statement, we implicitly assume (as was postulated in Chapter 5) that the coefficients will generally be time dependent. In a previous section we have argued that, from the viewpoint of explaining the oscillations with Lotka-Volterra equations, external circumstances *do* seem to influence the oscillations (not withstanding Gordon’s

comments). The issue boils down to the question whether the growth curve that a particular technology exhibits is genetically encoded into the technology (similar to the growth of some animate or organic objects, for example). If technological diffusion and substitution are social phenomena, one would think that there is no predetermined inevitability in the growth of technology. The diffusion pattern and particularly the rate of diffusion, are determined by various external factors, although we certainly acknowledge that the inherent characteristics of the innovation or technology can influence these factors. We must also not exclude the possibility that from a modeling viewpoint, the growth of a particular technology may be described by different models along its growth path, as suggested by Tingyan (1990), for example. It is quite feasible that the growth may be described by the general Lotka-Volterra equations as suggested by Bhargava, where the coefficients of the equations change with time as they are acted upon by external forces (1989). Depending on the relationship between the coefficients, the system may then exhibit smooth growth, oscillatory or even chaotic behavior in various phases of the growth cycle. Even though some technological growth patterns may exhibit chaotic oscillations, the question that should be asked is "What drove the system to chaos?"(Gordon, 1992, p.2).

Given the evidence in the literature and the chaos-like oscillations that were generated in some cases by the model in Chapter 5, further research into the applications of chaos theory to technological competition may lead to interesting and useful results.

Cars and minerals

We now return to the other examples where oscillations have been detected in the growth curves of mature technology as shown in Figures 6.2 and 6.3. There is no obvious evidence in these figures that the mature technologies are threatened by emerging technologies, and hence the examples serve more to illustrate the phenomenon of oscillations in the growth curves than attacks by emerging technologies.

With regard to the number of new automobile registrations in Japan shown in Figure 6.2, Modis comments that "... These fluctuations do not necessarily have an impact on the total number of automobiles in use. As mentioned earlier, the car niche in Japan, like that of most Western countries, is saturated. New car registrations mainly represent replacements. During hard times people tend to hold on to their cars. New car registrations dropped significantly in the United States during World War II, but the number of cars in use — the fundamental need — did not deviate from the S-shaped curve course it had been following" (1992, p.198). Marchetti comments that "... the car industry is then at the mercy of the whimsical replacement markets. The practice of subsuming one's neighbor will be the only mechanism to continue healthy growth" (1983, p.11). It will also be interesting to map the number of new car registrations with an index showing "hard times" in Japan analogous to the residential fixed investment index that was used in the case of plywood versus OSB/waferboard. If Modis' contention is correct, it will imply that the fluctuations in the curve for new car registrations are caused by factors other than

an emerging attacker. This would not mean that an emerging technology cannot *also* contribute to oscillations in a mature technology's S-curve, but certainly that it is not necessarily the only contributor.

Note that in the case of the minerals shown in Figure 6.3 there does not seem to be an obvious emerging technology that causes the oscillations by attacking the mature technologies, although a deeper search may reveal such a possibility. Marchetti does not make any comments on the coal, copper and zinc productions shown in Figure 6.2 other than to note that "... these logistics or quasi-logistics can become oscillatory when approaching saturation (a possible solution of the Volterra equations often appearing in ecological context. However, I was very curious and examined in detail the last six years... It appears here, too, that the overshooting can be interpreted as a change in maximum level perception of approach, the functional relationship being held" (1983, p.22). Even though he does not make an explicit reference to another technology attacking the minerals, his comment regarding the Lotka-Volterra equations is interesting. The mere existence of such equations (plural) implies that there are at least two technologies in the system. His comment on the overshoot, however, is congruent with the notion of a process of "hunting" along an average value as was discussed in the section on chaos. Recall also that in the section on growth rates and population densities in Chapter 3, it was stated that nature regulates the growth of a herd of antelope by way of the growth rates to the natural saturation level of the grazing. As the population of the

herd approaches the saturation level, the growth rate decreases as is typical of logistic growth. Marchetti seems to imply that in the case of the minerals he examined, the market is not such a perfect regulator as nature, and therefore some overshoot and subsequent oscillations result as the market hunts for the saturation level. If this is the case, it points to another case where the oscillations are not triggered by an attack from an emerging technology.

Finally we consider the production of bituminous coal in the US as reported by Modis and shown in Figure 6.5 (1992, p.201). The way Modis presents the scenario, there are two S-curves for coal production, the first stretching from 1850 to approximately 1950 and the second starting around 1930. The second S-curve almost has the characteristics of sailing ship effect-type growth spurt in coal production. Following his earlier arguments on chaos, Modis contends that the oscillations in the curve may be characteristic of the turmoil caused by transitions. It is interesting to take note of his comment. There may, however, also be other explanations. For example, there may not be two S-curves as he suggested, but instead the entire curve may be part of one larger S-curve. Again, however, there is no obvious evidence of an attacking technology threatening coal.

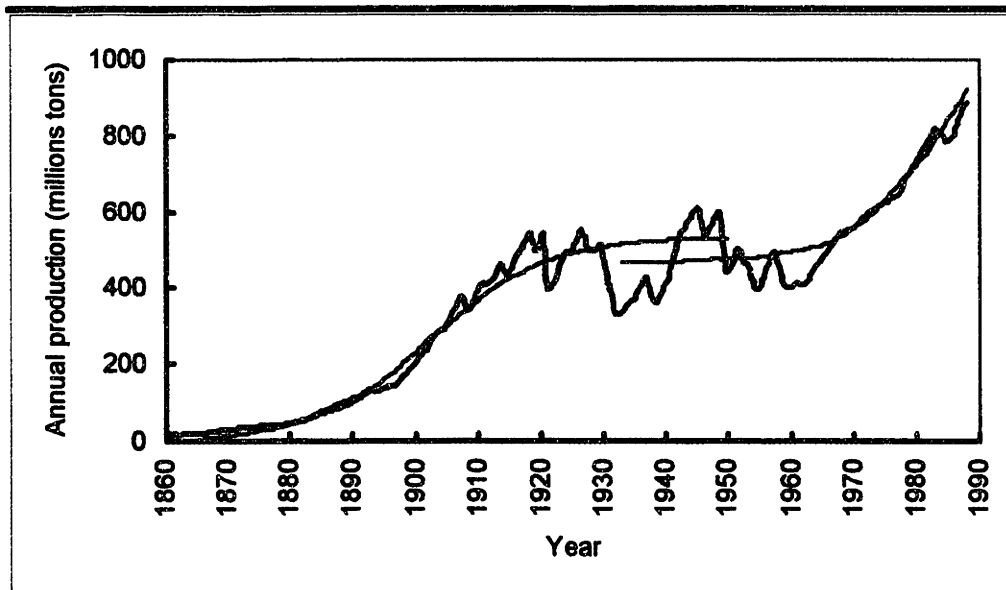


Figure 6.5 Annual production of bituminous coal in the US (After Modis, 1990).

Conclusions

We started this chapter by showing examples where oscillations occurred in the growth curves of technologies as they entered the mature phase. Montrey and Utterback suggested that such oscillations may be an indication that the mature technology is under attack from an emerging technology. In the case of plywood versus OSB/waferboard, it would seem that the oscillations were mainly caused by swings in the business cycle, but there is evidence that the emerging technology may also have an influence on the oscillations. One can infer, however, that the emerging technology is definitely not the sole source of the oscillations and may in fact not even be the major source. In the other cases examined there is no obvious evidence of emerging technologies attacking the

mature technology, although other explanations have been advanced. In attempting to draw conclusions from the empirical evidence presented, one should keep in mind the intricacies that were discussed in the section on units of analysis in Chapter 5. It may be that the choice of variable itself may have an influence on the nature of the oscillations.

Judging by the evidence presented in this chapter, there is not conclusive evidence that the oscillations that are sometimes observed in the mature phases of some technologies' growth curves are caused solely by the emergence of a new technology attacking the mature technology. It is certainly conceded, however, that an emerging technology can *also* contribute to the oscillations. Given the fact that the accurate and reliable mortality indicators can have profound managerial implications and that the surface has only been scratched in this chapter with regard to death knells of mature industries, further pursuit of this topic is certainly to be recommended. One avenue of research may be the application of signal processing techniques to "extract" potential signals from emerging technologies.

CONCLUSIONS AND RECOMMENDATIONS

*"Wisdom consists not so much in knowing what
to do in the ultimate, as what to do next"*

Herbert Hoover

The original motivation for this study was to investigate the hypothesis that the oscillations which are sometimes observed in the mature phase of technologies' S-curves are triggered by emerging technologies that are attacking the mature technologies. In an effort to understand the competition among technologies, an investigation into the more fundamental aspects of technological interaction was launched. It was found that focusing on the reciprocal effects that two technologies have on one another's *growth rate* as a measure of technological competition was well suited to the aims of the investigation. However it soon became clear that the notion of competition must be extended to the broader one of interaction. This was necessary in order to unify into a single framework interactions where two or more technologies enhance one another's growth rates (symbiosis), inhibit one another's growth rate (pure competition) as well as the case where one technology enhances the other's growth rate whilst the second inhibit the first's growth rate (predator-prey interaction).

The concept of a *multi-mode framework for technological interaction* was proposed. In this framework the effect that one technology has on another's growth rate offers itself as a powerful way of investigating the mechanisms whereby technologies interact. In Chapter 3 examples were given of technological interactions that correspond to all three the modes, and we concluded that the modes do indeed exist. The symbiotic and predator-prey modes seem to have been neglected in the literature dealing with technological innovation, however, and hence there seems to be ample research opportunities in investigating the characteristics of these modes. Not only are the different modes interesting within themselves, but the notion that the interaction among technologies will shift from one mode to another opens up another avenue of research.

In order to simulate the proposed multi-mode framework, a mathematical model was developed and presented in Chapter 5. The model is based on the well-known Lotka-Volterra equations, but differs from analogous ecological models in the way the predator-prey mode functions. Other than in the ecological case where the predator feeds off the prey and hence, strictly speaking *do not* vie for the same resources, in this case the model has been modified to reflect the fact that both technologies *do* vie for the same resources (typically research funds or the customer's orders). Closed form solutions were developed for all the cases in each of the modes and simulated results were presented. It was shown that the model can be applied to any finite number of interacting technologies. In the general case the coefficients can be time-dependent, reflecting the ability to handle

transitions from one mode to another. Even though the model is unproven at this time, it is based on well founded motivations. Not only does it account for the main thrusts of the multi-mode framework, but mathematically it is based on the same well-known ecological formulations that gave rise to the Fisher-Pry formulation.

The preliminary simulations that were performed with the model as part the development process in this thesis did nevertheless show a few interesting aspects of the interaction among technologies. The concept of a trajectory on a phase plane proved to be a very interesting and useful way of presenting the interaction among technologies. Strategies for attack and defense can be plotted on the “battleground” of the phase diagram, where the aim is to manipulate the path of the trajectory. The coefficients of the mathematical model can be brought into play as tangible (and quantifiable) targets for manipulation.

It was not possible to model the oscillatory behavior that was observed in the plywood/OSB case, i.e. where the mature technology exhibits oscillations in the mature phase of the S-curve at the same time at which the emerging technology exhibits the exponential growth that is characteristic of the early phase of an S-curve. At this point, the possibility that such behavior can be simulated with the model cannot be excluded, however. On the other hand, the model did yield oscillatory behavior in two modes, viz. predator-prey and symbiosis. In these cases both technologies oscillated at the same time (as opposed to one exhibiting exponential growth when the other oscillated). The

possibility of similar oscillations in the pure competition mode cannot be excluded at this stage. Although it has not been proven from a mathematical viewpoint yet, the oscillations that were observed seem to exhibit chaotic characteristics. This in itself is an interesting development. There have been several references in the recent literature that suggest that the oscillatory behavior in mature technologies' growth curves is a chaos phenomenon. As far as can be ascertained, the results in the thesis are the first to suggest that even though the oscillations may be chaotic in nature, the possibility exists that they are triggered by an emerging technology.

In addition, it has been shown that the so-called "catch-up" effect in S-curves can also be generated by the model. It has been observed that technologies' whose growth had been delayed for some artificial reasons have exhibited super growth and overshoot of their S-curves in the mature phase. The research in this thesis suggests that an alternative explanation for the overshoot may be the symbiotic or predator-prey interaction with another technology.

Much remains to be done with regard to both the framework and the mathematical model. The main thrust should be a verification of the framework and the model with real case studies, with particular attention being paid to the symbiotic and predator-prey interactions as well as the transitions between the modes. A technique to estimate the coefficients in the model needs to be developed. Given that the model contains a set of

non-linear differential equations with (in general) time-dependent coefficients, this will no doubt be a daunting task. One of the research thrusts should also be to distill the mathematics into ready useable managerial guidelines. Once the behavioral dynamics of the framework, supported by the mathematical model, are understood, managerial strategies for the individual modes as well as the transitions between the modes should be developed.

We can conclude, however, that the multi-mode framework and the associated simulation model, hold the potential of having very useful managerial applications, once they have been verified and tested in the field and appropriate managerial strategies have been developed for the individual modes as well as the transitions. The framework provides a setting for managers to map the interaction status of their technologies with both current and potential competitors and complementary products.

It was found that the oscillatory behavior of S-curves could be interpreted within the broader setting of *mortality indicators*. The search for emerging technologies is a complex task with no easy answers and few obvious clues. Often one finds that innovations originate in unrelated fields and attacks come from unsuspected directions. Hence one of the major problems in the search for emerging technologies is to identify the disciplines or areas where new technologies may emerge. By drawing attention to mature technologies that are under attack, mortality indicators can be a powerful tool to aid in the search. In

addition, the ability to identify indicators that mature technologies are under attack can be of tremendous value to the managers of the mature technology and give them the opportunity to formulate a timely response.

The case study of the attack of waferboard/OSB on plywood showed that the emergence of a new technology can contribute to the oscillatory behavior in the mature phase of a technology's growth curve. However, it was shown that there are also other factors that can contribute. In the plywood/OSB case it was shown that the macroeconomic business cycles mapped remarkably well onto the oscillations in plywood's S-curve and hence there is a strong suggestion that such business cycles can also contribute to the oscillations. Nevertheless, the concept of mortality indicators remains a powerful one and should be researched further, particularly the notion of oscillatory behavior in S-curves. Appropriate signal processing techniques may, for example, be able to extract the oscillatory contributions from emerging technologies that are buried in larger seasonal oscillations that dominate the total oscillatory pattern.

Several references in the literature suggest that the oscillations in the S-curve may be chaotic in nature. The research in this thesis indicates that it may indeed be the case. However, some of the references seem to suggest that the oscillations resemble chaos not only in the nature of the amplitudes and frequencies of the oscillations, but also in the predeterminedness that is sometimes assumed of chaos. Technological diffusion is a social

process rather than one ruled by the laws of nature, and as such we contend here that the diffusion trajectories of the technologies are *not* predetermined. In the thesis it was shown that, given the right combination of coefficients, the system can exhibit oscillations that are chaotic in nature. However, this should not be interpreted in the sense that the technology's fate is predetermined or that the oscillations occur "all of a sudden" and "for no obvious reason". In this thesis we accept the notion that the diffusion of technology (as reflected in its S-shaped growth curve) is influenced in part by external forces that can sometimes be stochastic in nature and that these external forces act upon time dependent coefficients in the differential equations describing the system. It then follows that it is possible that a combination of coefficients may result that drive the system into a state of chaotic fluctuations during a particular time period, just as the system may exhibit stable and smooth behavior at other times. It was also shown that the onset of the seemingly chaotic oscillations can be predicted in time by tracking the trajectory on the phase diagram and hence there is nothing mysterious about the timing of the oscillations — it is merely a result of the interplay between time dependent coefficients in a non-linear system. The notion of applying chaos theory to technological diffusion does, however, offer interesting research opportunities and should be pursued further.

The multi-mode framework presented in this thesis and the accompanying mathematical model proposes a setting within which to examine and analyze various modes of interaction among technologies. Some examples were given to show that the different

modes exist and that the interaction among specific technologies will, in general, shift from one mode to another with time. It was mentioned previously that a significant research effort lies ahead with regard to investigating the various modes and the shifts between them empirically, and then to formulate and test appropriate managerial strategies. At this point we can, however, point out a few typical conclusions from the evidence that has been gathered so far as well as the simulations that were performed with the (as yet) untested model. The aim is to illustrate the type of managerial guidelines and strategies that can result from an extension of this research.

First of all, managers should be aware that the interaction among technologies can occur in different modes, all of which require different strategies. One has become used to the idea that interaction is mostly of a competitive nature, no doubt due in part the influence of seminal books such the one by Foster (1986). However, as was shown in this thesis, symbiotic and predator-prey modes can and do also occur. Not only will strategies that are well suited to deal with a case of pure competition be suboptimal and even flawed when one is engaged in one of the other modes, but one has to be constantly sensitized to possible changes in the mode of interaction and adopt strategies accordingly. A further important observation to keep in mind is that the initial conditions have a significant influence on the path of the technology trajectory. In other words, the absolute level of maturity of the interacting technologies (and hence also the relative maturity between them) *at the time they start to interact*, plays a large part in the nature of the interaction.

One should thus be wary of a “generic” strategy for any of the modes. Strategies should account explicitly for the maturity of the various technologies. Recall that in some of the pure competition cases, the final destination of the trajectory on the phase diagram was unstable, i.e. a stronger standing in one of the technology’s strength at the onset of interaction can be a significant competitive advantage for that technology. This issue can have implications on the timing of the attack.

In several of the cases (notably in the predator-prey mode) an overshoot phenomenon was observed. An unsuspecting manager of technology may not be aware of this phenomenon and the fact that it may be occurring to his/her technology, assuming instead that the technology is on a regular logistic curve while it is fact in the overshoot phase. Such an assumption can easily lead to serious misjudgments. The estimation of the limiting value will certainly be in error. This in turn can lead to the commitment of extensive resources (such as adding additional capacity) during this phase under the mistaken believe that the curve is rising monotonically as regular S-curves do, rather than overshoot and decline to a lower final level. The question arises as to how one would know if the S-curve is experiencing overshoot rather than regular logistic growth? One of the characteristics of the predator-prey mode is that the predator benefits from the growth of the prey. Hence as both grow, the prey’s growth stimulates the predator’s growth to the point that the overshoot occurs in the predator’s growth curve. However, the super growth of the predator stunts the prey’s growth, which in turn reduces the predator’s super growth to

normal logistic growth. We noticed in many of the predator-prey simulations where the predator exhibited overshoot, that the prey's curve had already turned and was declining before the predator's growth reached a peak. Recognizing this phenomenon in the other technology's growth can thus possibly indicate that your own technology is experiencing overshoot rather than normal logistic growth. Prey technologies should also realize that anything they do to better their own position will also benefit the other technology, whereas predator technologies should realize that they can only benefit from prey technologies when the latter are growing. Too much predator aggression can lead to the untimely decline in the prey and hence also in its ability to help the predator's growth.

Given the perspective of the phase diagram as a map of the battlefield, we have seen that there are many strategies that a defending technology can deploy. Within the context of the model, we postulate that some strategies will boost the inherent growth of a technology, some will be aimed to decrease the factors that limit a technology's growth, whereas other factors will influence that nature of the interaction among technologies. It is important to realize that these factors all have different influences on the interaction. Concentration on some may be more effective than others, depending on the situation. We found, for example, that there is an asymmetry between the benefit that a predator gets from a prey and the damage that the predator does to the prey. Furthermore, the effects of the various factors are often related in ratios, leading one to the notion of developing an

understanding of the level of required to influence the interaction among the technologies relative to some of the other influences.

The benefits of symbiotic interaction were illustrated. These effects are closely related to the notion of complementary products. One should thus be aware of the benefits to be derived from such interactions, and exploit them when possible. The danger always exists, however, that symbiosis can turn to competition, leading us back to the fact that a constant watch should be kept on the mode of interaction.

In conclusion, one can say that the multi-mode framework together with the mathematical model provides a richer setting within which to take a broader view of the mechanisms of technological interaction than mere competition. There seems to be many practical managerial applications that can be developed from this approach, some of which were alluded to here. The challenge remains to build on the work that was presented in this thesis.

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