Towards a Systems and Complexity Perspective of the National System of Innovation

Sibusiso Manzini

In partial fulfillment of the Master of Science (Leadership and Innovation),
Faculty of Engineering, University of KwaZulu-Natal

2009

DECLARATION

I Sibusiso Thomas Manzini declare that

(i) The research reported in this thesis, except where otherwise indicated, is my original work.
(ii) This thesis has not been submitted for any degree or examination at any other university.
(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
(iv) This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
a) their words have been re-written but the general information attributed to them has been referenced;
b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced.
(v) Where I have reproduced a publication of which I am an author, co-author or editor, I have indicated in detail which part of the publication was actually written by myself alone and have fully referenced such publications.
(vi) This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Signed: ……………………………………………………

Date: ……………………….

To

Edward Lorenz (1917 – 2008),

the “father of chaos theory”

who passed away during the compilation of this thesis.

Abstract

The national system of innovation (NSI) is well entrenched within South Africa’s policy discourse, as a conceptual framework for understanding the nature and functioning of the country’s totality of science and technology efforts. The NSI is proving to be a powerful concept in that it permits, for instance, a holistic view of how scientific activity relates to economic performance. However, the NSI is a relatively new construct in the South African context. For this reason, there is a need for a proper understanding of what constitutes the NSI, how it functions and how best to make sense of it. This study undertakes a hermeneutic exploration and assessment of the NSI as a conceptual framework for understanding the structure and performance of knowledge institutions within South Africa. To this end, the NSI concept is unbundled into its constituent elements and then subjected to a deep theoretical analysis in order to critically examine the core ideas behind the constituent terms. Drawing on the writer’s hermeneutic-phenomenological input, the study critically examines the salient features of the NSI as they find expression in various official science and technology policy documents and reports. The elements that make up South Africa’s national system of innovation are identified and their roles defined. An argument is presented as to why, collectively, these elements demonstrate system behaviour. Chaos and complexity frameworks are then employed to shape a conceptual platform to underpin this philosophical enquiry with an ultimate view to developing a robust theoretical framework of the NSI. The study demonstrates the usefulness of chaos and complexity in explaining, for example, the evolution and current organisation of the NSI. Recommendations have been made about how chaos and complexity perspectives could be applied in general and strategic management of the NSI, as well as in research.

Contents

Figures

Tables

CHAPTER 1
INTRODUCTION AND RATIONALE

1.1 Introduction

The notion of a national system of innovation was introduced into South Africa's formal public policy discourse by the White Paper on Science and Technology of 1996. In this instance, the national system of innovation is conceptualized as "a means by which a country seeks to create, acquire, diffuse and put into practice new knowledge that will help that country and its people achieve their individual and collective goals" (Department of Arts, Culture, Science and Technology, 1996). The system itself would comprise all individuals and organizations that are involved in the creation and use of knowledge for the country's social and economic benefit. The test of success of a national system of innovation is the extent to which knowledge, technologies, products and processes it produces are converted into increased wealth by industry and business, and an improvement in the quality of life of all members of the society.

The introduction of the national innovation system concept signaled a new way of thinking about science and technology in the country. Firstly, the causal relationship between scientific activity and economic performance was made more explicit. Secondly, the need to bring about increased coherence and integration in the functions and activities of the country's science and technology institutions was given a sharper focus. Thirdly, innovation – the conversion of ideas into useful products and services - was set as the ultimate prize of all scientific and technological effort. The government's role in relation to the national system of innovation comprises policy formulation and resource allocation. To further its interest in developing and promoting innovation through the national system of innovation, the government demarcates three key areas of responsibility for itself:

- To ensure that South Africa has in place a set of institutions, organizations and policies which give effect to the various functions of a national system of innovation;
- To ensure that there is a constructive set of interactions among those institutions, organizations and policies; and

- To ensure that there is in place an agreed upon set of goals and objectives which are consonant with an articulated vision of the future which is being sought. (Department of Arts, Culture, Science and Technology, 1996)

Given that this study is about how the different actors of the national system of innovation interact in order to operate as a system, it is important to understand the role of government as spelled out in the policy documents and enacted in practice. It is a matter of particular interest, looking at the three responsibilities of government outlined above, that government's coordination role is limited to ensuring that there are constructive interactions among the institutions. The study explores in some detail the nature and extent of government's role in the development and operation of the national system of innovation (NSI). More specifically though, the study explores the key drivers in the evolution of the NSI and proposes useful ways in which to explain it. It is in the interest of policy makers to ensure that the national system of innovation upon which they exercise oversight, is sufficiently well-organised to produce the benefits of science and technology. For this reason, there is a need for a proper understanding of what constitutes the NSI, how it functions and how best to make sense of it.

It has long been established that science and technology are key drivers of social and economic development of nations (Juma & Yee-Cheong, 2005; Mallick & Chaudhury, 2000). The countries that are able to master the application of scientific knowledge in such a way as to introduce new products and services into the global world economy are fast becoming the leading economies of the world. Knowledge-based economies such as those of Japan, Singapore and Finland have managed to record sustained economic growth in spite of their lack of natural resources (UNDP, 2001). A study by Sir David King presents clear evidence of a relationship between scientific output and economic wealth of nations (King, 2004).

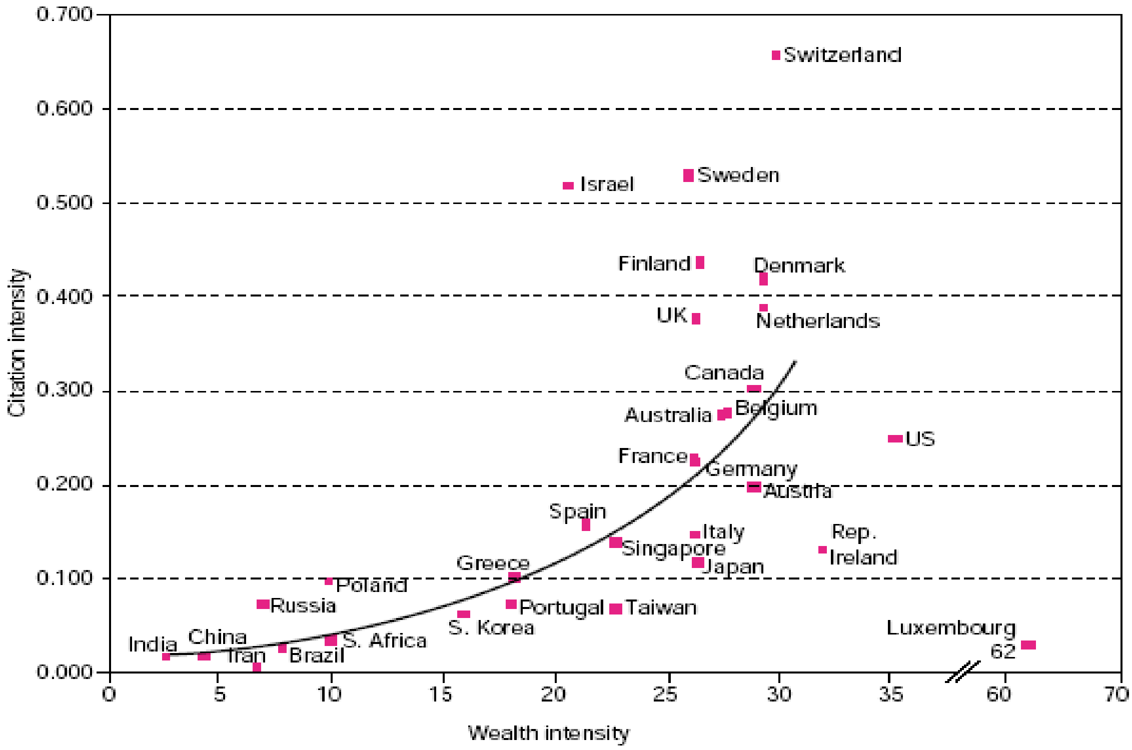

Figure 1-1: Relationship between science intensity and economic performance (King, 2004, p 313)

In the above graph, the citation intensity, as a percentage of world output, is used as a proxy for science and technology intensity. Wealth intensity is given in GDP per capita in thousands of US dollars at 1995 purchasing power parity. The graph suggests a positive correlation between the science and technology output of a country and its wealth intensity. It can thus be concluded that if a country wants to improve its economic performance it has to increase its contribution towards the global pool of knowledge. The knowledge output of a country depends on the productivity of its knowledge generating institutions such as universities, research institutions and private sector entities such as business and industry.

For a long time South Africa's economy has been largely dependent on its rich stock of mineral resources. However, a general fall of traditional commodity prices, the finite lifespan of mineral reserves and the relative high cost of value-added products, suggest that the country's economy can longer depend on its minerals and other primary products. The economy needs to further diversity, and more importantly, move towards the production of high-value products through beneficiation.

Beneficiation requires the generation of creative ideas about how a primary resource could be converted into a useful product that addresses specific needs which can be of economic value. There has to be a technical capability to carry out the value-addition processes that are required for beneficiation. There has to be a potential market for the product or service being produced and capital to support the innovation and commercialization process. There should also be a sustained pool of adequately qualified people to perform knowledge creation and sustain the country's technical capability to carry out the innovative processes. All of these functions within a country are often performed by various independent institutions that somehow interact within a country's economy. The extent to which the above requirements are in place within a country determines the capacity of that economy to succeed. The imperative of the economies of scale and the intensity of competition in the global economy are such that, within a country, all the institutions that have a stake in technological innovation have to cooperate optimally. In most countries, particularly in the weak economies of the developing world, this demands a nationwide invigoration of all its institutions and organizations.

The National System of Innovation (NSI) has in recent years gained currency as a conceptual framework to describe how institutions within a country interact to bring about a knowledge-driven economy. The NSI concept is particularly useful to policy makers in government and has thus been adopted by the Department of Science and Technology in South Africa. However, in relatively free market economies such as South Africa, knowledge creation and technological innovation functions are performed by diverse public and private institutions that enjoy varying degrees of autonomy. Under such circumstances, the cooperative behaviour of the institutions and organizations that operate within a country, towards supporting national economic ends, cannot be taken for granted. If indeed there is such cooperation among the organizations towards the development of a functional innovation system, it cannot be adequately ascribed to central planning and control. In the absence of clear evidence of central planning, we are left with a burden to explain a system that appears to have evolved from voluntary self-driven interactions and networks between a country's institutions and organizations.

This study undertakes a hermeneutic exploration of the NSI as a conceptual framework for understanding the systemic structure and performance of knowledge and economic institutions within South Africa. In the discussion below, the NSI concept is unbundled into its constituent elements and then subjected to a deep theoretical analysis in order to re-create the meaning of the term. In this exercise, studies in literature related to the NSI are used to critically examine the core ideas behind the concepts. Drawing on the writer's hermeneutic-phenomenological input, the study critically examines the salient features of the NSI as they find expression in various official documents and reports, particularly from the South African perspective. Systems and complexity frameworks are woven together to shape a conceptual platform to underpin this philosophical enquiry with an ultimate view to developing a robust theoretical framework of the NSI.

In order to maintain competitiveness, in an increasingly globalizing world economy, a country has got to transform its economy from the one that depends on simply exporting minerals and primary agricultural products to the one that is able to add value to these products. A knowledge-based economy relies on the application of knowledge in the beneficiation of primary goods and the creation and improvement of services, products and solutions. Such an economy would require, among other things, massive investments in skills development so that it could promote the application of knowledge towards technological innovation and industrial development. This transformation of the economy demands that all the institutions that have a role in knowledge-creation and technological innovation be aligned cooperatively in order to promote innovation across the whole country. These institutions form part of the National System of Innovation (NSI).

The National System of Innovation is defined in South Africa's National Research and Development Strategy as "a set of functioning institutions, organizations and policies that interact constructively in the pursuit of a common set of social and economic goals and objectives, and that use the introduction of innovations as the key promoter of change" (Government of South Africa, 2002). The organizations and institutions referred to in the definition include government departments, public science councils, government laboratories, funding agencies, universities, private research laboratories and technology-based industries. These are diverse organizations and entities, each with its own goals, policies and programmes. However, for the NSI to function, they need to be aligned into a coherent system that is geared towards achieving the shared social and economic goals of the country.

There is, however, in South Africa no piece of legislation or any other legal requirement that makes it an obligation for all these entities to cooperate. Furthermore, there is certainly no obligation or mechanism that drives these disparate entities to function as a system. In this consideration then, by what control and coordination mechanism, if any, are the various institutions, organizations and policies able to cooperate towards the achievement of shared national goals? This is the central question that is being addressed in this philosophical study.

This study argues that South Africa's economy does exhibit system features, that is, it manifests the existence and operation of inputs, processes and outputs that reflect cooperation and coherence at a national level. An extensive analysis of the major elements that make up the NSI is conducted; in order to lay bare their individual and collective roles and functions. The substance of this enquiry attempts to construct a theoretical model that can be used to explain the NSI phenomenon. It is argued in this discourse that a creative blend of systems, chaos and complexity theories provide a robust theoretical platform to make sense of the nature, evolution and functioning of the national system of innovation of South Africa.

South Africa is joining a growing list of countries that have adopted the National System of Innovation approach as a means of understanding and characterizing the organization and functioning of their emerging knowledge-based national economies. However, as is appropriate to a new concept, there is a need to create a solid theoretical base for making sense of the NSI. We need to understand, for instance, the conditions and mechanisms that bring about a situation where relatively independent institutions organize themselves creatively and responsively toward the pursuit of a common set of objectives as expected in the NSI.

In particular, the study contributes to finding plausible answers to the following critical questions:

1. Which institutions and organizations in South Africa constitute the National System of Innovation and what are their roles and functions?
2. In what ways do South African institutions that are active in knowledge production and technological innovation collectively demonstrate system behaviour?
3. How can chaos and complexity theories be applied in describing the behaviour of the national system of innovation?

The study proposes and demonstrates the usefulness of a systems, chaos and complexity perspective in describing the nature and functioning of the NSI. Before embarking on an extensive examination of a range of thinking tools to systematically address the questions listed above, it seems fitting to start by explaining in a bit more detail the need for this study.

1.2 Rationale

The Department of Science and Technology's stated mission is to "develop, coordinate and manage a national system of innovation that will bring about maximum human capital, sustainable economic growth and improved quality of life for all" (quoted from internal Department of Science and Technology marketing and branding material). Given the centrality of the notion of the "National System of Innovation" in South Africa's policy approach to national science and technology initiatives, it is imperative to understand the meaning and consequences of this conceptual approach.

The National System of Innovation is made up of organizations, institutions and policies of various sizes, functions and characteristics. There are knowledge generating institutions such as research facilities at universities and science councils. These institutions largely focus on basic and applied research in various science and technology domains. Then there are institutions that develop the knowledge into various technological applications. Further down the knowledge value chain, there are those institutions that are concerned with converting technologies into services and products for the markets. All these institutions have a stake in the innovation system. However, each has its own objectives and means of operation. Some are private institutions, others public, and some, a little of both.

Some are scarcely aware of, or involved in, the activities of others, such as small technology-based industries that operate in the so-called “second economy”. Indeed some organizations may not even be aware that they are constituents of a NSI. Yet, they are all interconnected in the NSI by the fact that they, to a lesser or greater extent, play various roles in bringing about a knowledge economy for the country’s development.

From a central planning perspective, it is important for the entities concerned to have an understanding of how the national innovation system works. The government invests heavily in the various areas of knowledge and technology creation that form part of the NSI with the intention of promoting economic growth. It would be highly important for the government and the institutions that operate under its mandate to have an understanding of how the NSI functions. This could inform its policy approaches, investment strategies and funding options.

A better understanding of how the components of the NSI interact and cooperate would be particularly important to the Department of Science and Technology, whose function includes managing and coordinating the country’s national innovation system. The knowledge about how the system responds to internal and external influences and stimuli would arm the Department with the necessary tools to “control” the system, if it can be controlled at all. If the NSI exhibits autonomous characteristics, knowledge about nature and extent of this should inform the approaches of the Department and other players toward influencing the course of the system.

The knowledge of the system dynamics of the NSI is also important for the various players within and outside the system. Some of the institutions that form the NSI are inextricably linked to one another through their various roles and relative functions. For instance, the pool of qualified research engineers in a particular discipline that may be needed by the NSI, have to be supplied by the country’s universities. The institutions concerned within the NSI should be able to send appropriate messages to signal this need to the universities. It would be important to understand the communication dynamics of the system in order to organize, mediate and propagate relevant stimuli that would bring about the required responses from the universities and other affected institutions. All this requires a fairly sophisticated understanding of how the various components of the system interact, communicate and cooperate.

Research related to the NSI is increasingly focusing on understanding the role of knowledge and technological innovation in economic development of countries and regions. The causal relationship between a nation's technological innovation output and its economic development is increasingly being understood. However, there is not much research done towards understanding the "systemness" of the national system of innovation, particularly in so far as developing a theoretical basis for explaining system behavior of the NSI.

The NSI approach towards understanding how technological innovation operates within national economic systems is relatively new. There is therefore a need to develop theoretical tools to sharpen our understanding of this conceptual framework. This study is meant to begin to fill this gap and stimulate further interest and research in this area.

1.3 Complexity and the NSI

Chaos and complexity theories have their roots in physics and mathematics. Applications of these theories have been extended to self-organizing systems or "complex adaptive systems" in biology (Baskin, 1998; Goodwin, 1997), chemistry (Lehn, 2002), business (Hock, 1996), psychology (Contractor, 1998), ecosystems (Kay & Schneider, 1994; Kay, 2000) and information systems and technology (McBride, undated; Montresor et al, 2002). The organization and functioning of an ant colony is often used to illustrate complex adaptive system behaviour (Montresor et al, 2002). A comprehensive simulation of food gathering ants is done by Guerin & Kunkle (2004) to illustrate how entropy producing systems, through various stages of organization, learn to bring about "structure formation" (p 137). In this perspective, a complex adaptive system consists of large numbers of autonomous agents that individually function in simple (and chaotic) ways but collectively produce surprisingly complex and unpredictable (yet organized) behavior. According to Kay (2000) the dynamics of complex adaptive systems are a function of positive and negative feedback loops created between the autonomous agents in the system and their environment.

Complex adaptive systems operate without any centralized coordination and are highly adaptive to changes in their environment. Montresor et. al. (2002) argue that complex adaptive systems are resilient to what they call "deviant behavior" or failures. This idea of resilience simply means that a complex adaptive system always "succeeds" in producing the outcome for which the alignment of its components is ideally suited to produce. Whether these emergent outcomes are perceived as beneficial or not is a matter of subjective evaluation of each case in point.

Thermodynamics, as a fundamental natural process, is useful in illustrating the basic elements of the behaviour of complex adaptive systems. Central in the thermodynamic model is the role of entropy (i.e. disorder) and enthalpy (i.e. order). The second law of thermodynamics defines the relationship between entropy and enthalpy in closed systems. Naturally, the condition of "closed system" often assumed in the application of the second law of thermodynamics in physics and chemistry is not useful for systems that are open to interaction with their broader environment, such as social systems. A comprehensive critique of this issue is done by Kay (2000). Building on Schrödinger's (1944) postulation of "order from disorder" and the work done by Prigogine (1955), he further elaborates on the operations of thermodynamics in open systems, which are moved away from equilibrium by exchanges of material and energy with the environment. Such systems are referred to as dissipative structures and their entropy relationships were first formulated by Denbeigh (1951) and Prigogine (1955). However, these formulations are found to be inadequate because they are limited to the immediate neighbourhood of equilibrium. To address this problem, Kay (2000) first describes the behaviour of a system away from equilibrium and then introduces the concept of "exergy" in order to reformulate the second law of thermodynamics and its application to dissipative structures. The sudden manifestation of unexpected highly ordered organization is postulated as evidence of the presence of "attractor states" that are characteristic of systems that driven away from thermodynamic equilibrium (Guerin & Kunkle, 2004). The definition of attractors in social systems, however, remains a matter of conjecture. Nevertheless, scholars such as Reason & Goodwin (1999) are convinced that strange attractors underlie the "deterministic chaos" found in systems of living organisms and societies. Wheately (1992) prefers to call the manifestation of a strange attractor in organizations a “meaning attractor” (p 136). The presence of attractor states is one of the pieces of evidence that one could look for in order to connect chaos and complexity to the national system of innovation.

Of direct relevance to this paper is the application of chaos and complexity theories in social systems. While there is an increase in the use of chaos and complexity theories to explain social systems, many scholars have recognized the need of a sound theoretical foundation which takes into account biological agents that exhibit cognitive, linguistic and autopoietic characteristics (Maturana & Varela, 1980), such as human beings. Goldspink (2000) proposes a meta-model for such social systems by drawing on systems and autopoietic theories. He constructs an ontology of this model by carefully defining, from first principles, different classes of agents, and how “systems of systems of agents” may coexist (p 8). Gershenson & Heylighen (2002) underline the importance of the role of the observer in defining the system, its components, purpose, levels and aspects of its self-organization. The importance of the role of the observer is of particular significance to this study because in delineating the National System of Innovation, the observations and data that is being employed in the study emanates from actors that are part of the system. The idea of an interpretive approach in describing self-organizing systems is underlined by McBride (undated) who argues for a qualitative study of patterns over time. He combines chaos and complexity theories to describe organizational behaviour as unstable, aperiodic, deterministic, dynamic and nonlinear (p 6-7).

An observation that is often associated with complex adaptive systems is that they are sensitive to initial conditions (Tsoukas, 1998). Consequently, chaotic systems are seen as deterministic as their endpoints could be derived from the initial conditions. I think the application of this concept in the study of social systems is of limited use given that social systems are equally sensitive to constant changes in their environment with which they are inextricably linked. Conceptually, determinism runs counter to the grain of complex adaptive social systems, whose understanding is founded on self-organizing due to “learning” by system actors through feedback mechanisms. The study will provide an opportunity to further deliberate on the meaning and implications of “initial conditions” to social systems. At this point, it is sufficient to propose that “initial conditions” are critical in so far as they are not preceded by an external influence on the system. The introduction of any external influence at any point following the “initial conditions” requires by default a recalibration of the point of interference as the new “initial conditions”.

1.4 Theoretical underpinnings

This study attempts to conjoin interpretively two grand theoretical frameworks. On one hand, it is the national system of innovation as a conceptual framework for describing the constitution and performance of knowledge and technology institutions of a country. On the other hand, it is the systems and complexity theory, as a theoretical tool to describe self-organizing behaviour of social systems. These two theoretical frameworks are both in development within different knowledge communities. In this study, an attempt is made to bring the two together in order to fashion an integrated theoretical model for understanding the national system of innovation. I am going to draw on the ideas about the application of chaos and complexity theories to social systems to try and describe why the concept of the National System of Innovation could benefit from these theory perspectives. I will do this by matching, in a single narrative, the features of the National System of Innovation and the key principles underlying systems, chaos and complexity theories. Hermeneutics is used as an interpretive framework for examining the NSI on one hand, and systems and complexity, on the other, in order to formulate an argument to support the thesis of this study, namely that systems and complexity provide useful insights into the NSI.

1.4.1 Systems theory

The relevance of systems thinking in the study of the NSI is quite conspicuous. The power of a holistic view of the various agents that make the NSI and the dynamics of their interactions is brought to bear in the narrative. Reason & Goodwin (1999) list some principles that are pertinent to systems thinking, presenting them as the six principles of complexity. These are: (1) rich interconnections, (2) iteration, (3) emergence, (4) holism, (5) fluctuations and (6) edge of chaos. This selection is by no means authoritative and could be faulted for eschewing key principles such as self-organisation. Rich interconnections, iteration, holism and fluctuations are important concepts in systems thinking and are briefly introduced here to illustrate their relevance. A comprehensive overview of the literature on systems theory is done in Chapter 3. In addressing the critical questions of this study I will employ these principles, either directly or indirectly, for reasons of expediency and parsimony. Further in the discourse, other important characteristics associated with complex adaptive behaviour such as self-organization, emergence, non-linearity, feedback and openness are brought into the discussion in order to buttress the thesis of this study.

1.4.1.1 Rich interconnections

Kauffman (1993) as quoted by Goodwin and Reason (1999) define complex systems as comprising rich patterns of interconnections between diverse components. A thorough knowledge of the properties of the components does not translate into an understanding of the whole and how it could develop. This is because complex adaptive systems are dynamic and self-organizing on the basis of continuous feedback. In this way, a complex system cannot be simply a sum of its parts.

The National System of Innovation is made up of organizations, institutions and policies of various sizes, functions and characteristics. Practically, all aspects of South African life that are related to science and technology comprise the innovation system. On one hand there are knowledge creating institutions such as research facilities at universities and science councils. There are institutions that develop the knowledge into various technological applications. Further down the so-called knowledge value chain, there are those institutions that are concerned with converting technologies into services and products for the markets. All these institutions have a stake in the innovation system. However, each has its own objectives and means of operation. Some are private institutions, others public, and some, a little of both. Some are scarcely aware of one another or of the fact that they are constituents of the NSI. Yet, they are all interconnected in the NSI by the fact that they are all important role-players in bringing about a knowledge economy for the country's development. An analysis of how all these entities interact is important for understanding how the whole unfolds.

1.4.1.2 Iteration

Iteration often involves a pattern of activity repeated within certain constraints. In the study of complex systems such iteration may result in the emergence of an unexpected result which manifests order. The order that arises is in the form of a "rich network of interacting elements" which derives from the iterative process and the consequences thereof (Reason & Goodwin, 1999). In practical terms, within the NSI, iteration may take the form of action and reflection within the elements of the system. This could involve visiting the same experience over and over again with the purpose of practical and reflective learning. The forms of learning involved would include phases of experiential, presentational, propositional, and practical learning (Reason & Goodwin, 1999).

It may not be immediately possible to argue that there is currently an iterative process going on within the NSI. However, there certainly is scope for creating cooperative inquiry groups representing the various elements of the system. Apart from instituting the iteration that could bring about emergence, such an interaction could deliver other systemic learning benefits.

1.4.1.3 Emergence

The defining characteristic of self-organizing systems is the unexpected appearance of orderly behaviour of the system from seeming total chaotic individual behaviour of its component elements. In the case of the NSI, the individual component organizations and institutions work toward achieving their own objectives, for instance, to make profit in the case of private businesses. However, from a systems perspective, the NSI exhibits measurable performance indicators which are markers of system behaviour.

The obvious challenge when it comes to the NSI is to create conditions for emergence of the goals of Department of Science and Technology (DST), such as the increase of innovation. However, this presents a dilemma, in the sense that a complex adaptive system is self-organizing: emergence cannot be programmed by an outside agent. This can be resolved in this way. The DST can be regarded as an autonomous part of the NSI, in much the same way as other components. In this way, the achievement of the goals of the NSI is no longer externally driven. Consequently, to guide the NSI toward achieving what it considers as its "goals", as a management approach, DST should seek to "change the system from within" by instituting a process of iteration described above that would culminate in the development of Wheately's (1992) "meaning attractors" within the system.

1.4.1.4 Holism

System characteristics such as those produced by the NSI are of necessity holistic performances of the system. There is no privileged part or parts of the system that can possibly possess or produce the emergent system behaviour. This serves as an illustration of self-organizing qualities of the NSI, which consists of institutions that play various but all important roles.

The NSI has a multiplicity of institutions within itself that play varied roles. The test for this enquiry is to demonstrate an integrated holistic characteristic and performance which cannot be ascribed to any number of individual components of the system. Furthermore, that holistic output should be an outcome of the interactions of the elements of the system without pre-engineering from outside. The exhibition of holism should be seen as evidence of the togetherness or "jointedness" of the members of the system.

1.4.1.5 Fluctuations

A further characteristic of complex systems is the fluctuations in the patterns of behaviour exhibited by the system. A systematic scrutiny of system behaviour of the NSI would need to be observed to establish precisely the trends of key holistic variables. At this point I could postulate that system variables would demonstrate non-convergent trends before critical moments of emergent orderly behaviour.

The first challenge for this enquiry is to identify the variables that are representative of systemic behaviour. Secondly, there has to be a means of observation or measurement that is sharp enough to reveal the trends of the fluctuations with increasing iterations. The observation should be able to make distinct the divergent and convergent behaviour which respectively demonstrate chaotic and orderly behaviour.

1.4.1.6 Edge of Chaos

Emergence within complex adaptive systems occurs within a zone that is characterized by manifestations of both chaotic and orderly conditions. This is referred to as the "edge of chaos" (Ortegon-Monroy, 1999). There is a possible application of this concept to the NSI given that the system itself consists of self-governing institutions and organizations that pursue their own individual businesses and objectives. As the evolution of the behaviour of the system is observed over time, in response to the common social and economic conditions within the country and globally, individual reactions of organisations could at some point find resonance which could precipitate some form of emergence. These would occur during conditions that exhibit both chaos and order.

1.4.2 Self-organisation

In exploring the ideas that shape this discourse, self-organisation is a pertinent point of departure. The phenomenon that is being investigated is that of the manifestation of self organization in the national system of innovation. In fact, it will be argued as this discourse unfolds that, the NSI is itself, a product of self-organisation. However, what is self-organisation?

Picture a pile of stones left in the middle of a deserted area somewhere. If, upon return to that area, you find the stones having been rearranged in some ordered fashion, to form a wall, a pyramid or some other organized form, it could be surmised that an external agent had been at work. It is on the basis of this kind of reasoning that archeological excavations all over the world, upon systematic investigation, yield evidence about the existence and nature of ancient kingdoms and cultures.

In the case of the stones, the manifestation of organization is taken as evidence of an external agent that brought about the ordered outcome. This is because stones are not regarded as autonomous agents that can bring about any effect on their own accord. In this sense, a pile of stones is deemed incapable of self-organisation.

The notion of spontaneous, dynamically-produced organization is at least centuries old (Shalizi, 2001). Hints about the notion of self-organisation, although not necessary termed in this way, could be picked up from a wide variety of sources ranging from African folklore to the works of the French philosopher Rene Descartes, as illustrated in this provocative sketch he proposed:

> *"… what would happen in a new world, if God were now to create somewhere in the imaginary spaces matter sufficient to compose one, and were to agitate variously and confusedly the different parts of this matter, so that there resulted a chaos as disordered as the poets ever feigned, and after that did nothing more than lend his ordinary concurrence to nature, and allow her to act in accordance with the laws which He had established…"* (Descartes, 1637, part 5)

Clearly, the rise of order out of utter chaos was a notion not lost to Descartes, or to the many generations of philosophers and scientists that came after him. However, the term "self-organisation" took shape after World War II, particularly within the development of cybernetic and computational theories (Yovits & Cameron, 1960; Von Foerester & Zopf Jr, 1962). When it comes to the use of the term itself, Shalizi (2001) is adamant that it first appeared in a paper by W. Ross Ashby in 1947. Nevertheless, and quite wrongly, it would seem, credit for the first use of the term is often attributed to Farley and Clark (1954).

With no direct access to Ashby's writings, I have to rely on the definition of self-organisation, attributed to him by Shalizi (2001). Firstly, Ashby defined the organization of a system as the functional dependence of its future state on its present state and its current external inputs, if there are any. Ashby thus understood a system to be self-organising if it changed its own organization, rather than being changed by an external agency (Shalizi, 2001; p 6).

A consequence of this definition is that, if the state space is S and the input space is I, the organization of the system is described by the function $f: S \times I \rightarrow S_n$, *where* S_n is the new state of self-organisation. Now, the crucial question is by what mechanism does S convert to S_n? In other words, how does self-organisation occur? Ashby (1960) paraphrased by Shalizi (2001) provides the following answer to the question:

> *"Organization is invariant. It may be, however, that the function f is well-approximated by another function g in a certain region of the state space and by a different function h in another region. If*

the dynamics then drive the system from the first region to the second, we will see an ***apparent*** *change in the organization, from g to h, though the true, underlying dynamics remains the same"* (Shalizi, 2001; p 7, emphasis in the original).

While mathematically the above explanation looks elegant, it belies intuition when confronted with physical phenomena. Take for instance, an ant colony that transforms from one state of organization to another over an observed passage of time. It would take more than a conceptual leap to describe the new state as an "apparent" change or a mere manifestation of another function in a different region of the state space, as suggested by Ashby.

The application of the term self-organisation has taken different forms in various disciplines. In the physical sciences it was applied in pattern formation and spontaneous symmetry breaking (Nicolis & Prigogine, 1977) and to cooperative phenomena (Haken, 1977). An elaboration of the work done by Ilya Prigogine is given in Chapter 3 of this report. Some research suggests that self-organisation in some systems yields critical states (Bak, Tang & Weisenfield, 1987; Jensen, 1998). On the basis of the latter seminal paper, Bak (1996) goes on to make grand claims about how nature works.

The phenomenon of self-organised criticality alluded to above (Bak, Tang & Weisenfield, 1987) is typical of dynamical systems which have a critical point as an attractor. This observation which was arrived at in statistical physics is akin to the spatial and temporal scale invariance properties that define a critical point in a phase transition. Self-organised criticality provides a hint as to how the phenomenon of complexity comes about in nature. This is discussed in greater detail under the topic of complexity in Chapter 3.

In computer science, the concept of self-organisation is primarily applied to the study of the phenomenon of learning (Selfridge, 1959; Yovits & Cameron, 1960), particularly unsupervised learning (Hinton & Sejnowski, 1999), memory (Kohonen, 1984), adaptation (Holland, 1992) and emergent or distributed computation (Resnick, 1994; Crutchfield & Mitchell, 1995). Self-organisation has been observed in economics (Schelling, 1978; Krugman, 1996) and ecology (Arthur, 1990).

The relative value of the various works is highly contested, not only between disciplines, but also within. For instance, in fluid mechanics, the transition from lamellar to turbulent flow is seen as an instance of self-organisation by Klimontovich (1990); others within the same discipline (e.g. Frisch, 1995) vehemently dispute this. In plant ecology, some see the succession of plant communities as a manifestation of self-organisation while others don't (Shalizi, 2001). Although such disputes abound, they do not lend clarity to the meaning of self-organisation. Furthermore, if such disputes are commonplace in the natural sciences, more vigorous disputes may be expected in the human and social sciences, which are disciplines that have a tradition of tolerance for divergent meanings. This study, as it looks at the ecology of institutions and organizations within a national system of innovation, belongs to the latter classification and its claims would thus be subject to contestation.

1.4.3 Analytical tools

A major challenge at the heart of this study is to manage the analytical interface between conceptual paradigms. The preceding discussion has briefly introduced one front of the confrontation which involves the emerging national system of innovation and chaos and complexity. This study is an effort to employ chaos and complexity to make sense and expand understanding of the national system of innovation. On another front, there is a methodological challenge in terms of the approach or approaches towards teasing out meaning. This study is both hermeneutical and ontological in that meaning is sought in two dimensions, i.e. from texts and organizational functioning of the NSI, on one hand, and, the meaning of the core concepts that are involved in this theoretical investigation.

1.4.3.1 Hermeneutics

Hermeneutics can simply be described as "the science and art of interpretation" (Daniel, 1986; p 196). Interpretation has to do with making or bringing out the meaning of something. In this study the meaning of the NSI is being examined for the purpose of determining its essence and functioning. Systems, chaos and complexity, it is being argued, collectively form a formidable hermeneutic framework in this regard.

Hermeneutics as a systematic analytical approach to meaning-making has its roots in the interpretation of religious writings (Ihde, 1997), beginning with Judaism and Christianity as the first religions that had a heritage of sacred texts (Daniel, 1986). In religious studies, the stakes for robust interpretive frameworks are high given the quest for establishing the "truth". Through the practice of theologians over centuries, religious exegesis evolved into a system of rules and principles which brought about hermeneutics as a systematic approach to the interpretation of texts. Other disciplines that rely heavily on text interpretation, such as law, began to adopt hermeneutics as an interpretive methodology. Hermeneutical methods are used extensively in many social and human sciences. Ihde (1997) argues that this traditional form of hermeneutics was used to entrench the dichotomy between social and natural sciences. Classical hermeneutics was seen as the antithesis of positivism in the social and natural sciences binary.

As early as the 1970s, an increasing number of scholars began to argue for the application of hermeneutics in the natural sciences (Giddens, 1976; Habermas, 1984). Before this time, the application of hermeneutics was confined to the social, cultural and historical dimensions of science. As confidence grew in the power of hermeneutic analysis, scholars such as Ihde (1997) argued for "thingly hermeneutics" or "a hermeneutics of things" which is the application of hermeneutics in the natural science. This is the radical form of hermeneutics, which is no longer confined to application in the social aspects of science. This new all-conquering hermeneutics goes beyond the text, to the work - laboratory instruments and all - that led to the claims of the text. As Latour (1987) put it, "[t]he instrument, whatever its nature, is what leads you from the paper to what supports the paper, from the many resources mobilized in the texts to the many more resources mobilized to create the visual displays of the texts." The longstanding edifice of positivism in the natural sciences had already been torn down by Rouse (1987), as a culmination of efforts dating back to Heidegger (1962), Kuhn (1970), Giddens (1976), Hesse (1980), Foucault (1981) and Habermas (1984). Today Hermeneutic methodology appears to be well-entrenched in medical science (e.g. Baron, 1990; Daniel, 1986 and Leder, 1990) has extended to research areas such as anthropology (Ulin, 1992), quantum mechanics (Cushing, 1995; Heelan, 1995) and solar neutrinos (Eger, 1997), notwithstanding some strong reservations from certain quarters (e.g. Markus, 1987 and Suchting, 1995). This development echoes Karl Jaspers' assertion that all knowledge is a matter of interpretation (Jaspers, 1951). Ricoeur (1970) went further to declare that textual interpretation was the *model* for all meaningful exchange. The universal application of hermeneutics is strongly evident in the influential works of Gadamer (1975) and Heidegger (1962).

As discussed above, hermeneutics originates from the study of texts. However, the use of hermeneutical methodology has transcended the written word. Now, in the examination of subjects that are not in the form of physical texts, what constitutes the “text”?

It is possible to “read” entities and phenomena as if they were texts. Things that can be seen or perceived by other senses can “tell” us as much as texts can. The well-known saying “a picture is worth a thousand words” aptly reflects this perspective. In the hermeneutics of non-textual entities it is important to bear in mind that the subjects may not be inanimate objects that can remain immutable for centuries. In the study of the NSI, for instance, hermeneutics is practiced on a dynamic system that is constantly changing and developing.

In this study, some of the interpretation of the NSI is based on literary texts, i.e. policy documents, reports and theoretical material on the NSI. However, I will call upon experiential understanding of the NSI. This involves making explicit what is being understood, and use this to build deeper and richer meanings. This process involves taking a journey from a basic reading of a text or situation, to an interpretation of the data or phenomenon that is under study and, on this basis, building high-level theories and alternative frameworks. The interpretive process engaged in this study in not presented with any dogmatic assumptions. It has to be seen as an eclectic qualitative journey towards meaning-making. It is eclectic in the sense that there is no ideological bias against any method but a judicious use of all available data and warrants in pursuit of deeper insights. This approach is immanent in Gadamer’s hermeneutic tradition as illuminated by Engel (1991; p 141) as follows:

> *Interpretation is not to be reduced to a particular method, and even less to a scientific method; it is a practice, shared*

> *by all human beings, which can be reflective or self-conscious, but which is primarily implicit in our lives.*

The hermeneutic approach that is adopted for this study, as indicated above, provides the means to deal with the subject under discussion in a unique and penetrative way. It enables me to bring to bear my own experience in interpreting events, data and phenomena that are related to the subject under discussion. Nevertheless, a cautionary note is appropriate: as in any qualitative enquiry, in this approach biases impinge on the analytical process due to the limitations and idiosyncracies of the experiential context. Furthermore, as Dryzek (1982, p 310) put it, "[g]eneralization in social science is a chimera, as all situations are different." The spectre of a "chimera" has, as it would be observed, tamed the urge to make sweeping generalizations.

1.4.3.2 Reasoning scheme

In keeping with the interpretive stance discussed above and the conscious effort to maintain a simple yet effective flow of argument, no particular reasoning methodology is being nailed on the mast. Nevertheless, an in-depth examination of this thesis would decipher Toulmin's framework (Toulmin, 1978) as a thread that runs throughout this narrative. Hitchcock (2005) proposes criteria for good reasoning based on Toulmin's model as follows:

> *First, we must be justified in accepting the ultimate grounds on which we base our reasoning. Second, our grounds must include all the relevant justified practically obtainable information. Third, the conclusion must follow in virtue of a justified warrant. Fourth, if the warrant is not universal, we must be justified in assuming that in the particular case there are no defeaters that rule out application of the warrant. (p 375)*

It is asserted that the above criteria have been adhered to throughout this thesis. An illustration of how Toulmin's framework was applied at a broad level would serve to illuminate the point. The main **claim** that is being made in this study is that the NSI can be described in terms of systems and complexity theories. In the next three chapters, a comprehensive discussion of the entities under discussion constitutes the **data** that is being presented to buttress the argument. Chapter 5 outlines the supportive **warrants** and **backing** linking the data to the claim, in terms of the methodological guide presented by Simosi (2003).

As a conclusion to this introductory chapter of this dissertation, it is useful to recapitulate. The onset, and subsequent global dominance, of knowledge-based economies in the last century precipitated a solid rationale for the study of the role of technological innovation in social and economic development. It was demonstrated that South Africa has joined an increasing number of countries that have adopted the national system of innovation as an organizing framework for making sense of and fostering technological innovation in the country. The three critical questions for this study have been identified as a means of understanding the essence, function and exposition of South Africa's national system of innovation. An introductory treatment of systems, chaos and complexity, as pertinent theoretical frameworks to illuminate the investigation, has been done. The concept of self-organisation is given a fair amount of discussion, given its centrality in this study. In a way, prospectively at this point, it could be argued that the thesis presented for this study is that the national system of innovation manifests the phenomenon of self-organisation.

The characteristics of chaos and complexity discussed above serve merely to introduce some of the important features that are under scrutiny in this discussion. A more elaborate discussion of chaos and complexity, which are critical conceptual frameworks for this study, is done in Chapter 3 below. This section traces, in a more or less chronological order, the gradual development of systems, chaos and complexity theories, to a point where they have permeated almost every discipline of knowledge. In this elaboration, critical concepts are picked up and subjected to scrutiny as they relate to the critical questions of this study.

The application of the key features of systems, chaos and complexity to the description of the nature and performance of the NSI is done in Chapter 5. This is, however, preceded by a comprehensive delineation of the make up of South Africa's national system of innovation in Chapter 4, in response to the first critical question. A critical discussion arguing the basis for the inclusion of the elements that are deemed part of the NSI is done. This is followed by suggestions of how the interaction and cooperation of the members of the system occurs.

The immediate next chapter, namely Chapter 2, explores the unit of analysis for this study, which is the national system of innovation. The focus is given to an ontological and critical analysis of the concept itself, rather than the actual constitution of the NSI. A discussion of the actual composition of the NSI follows as an exposition of the first critical question in Chapter 4, as indicated above.

Chapter 2

An Ontological Review and Critique of the NSI Concept

2.1 Introduction

Ontology is a term that is generally applied to the examination of the nature of being and the relations involved. The term has however developed very different meanings. Here it is used to describe a phenomenological review of the national system of innovation as an entity that exists in society and economy. South Africa is largely used to contextualize the nature, behaviour and relations of the NSI. An approach that is used in the review is that of subjecting the constituent concepts of the "national system of innovation" construct into an intuitive analysis of its fundamental properties. In this way a deconstruction and reconstruction of the term is accomplished in order to tease out its salient connotative features.

2.2 Origin of the NSI concept

An effort has been made to establish the origins of the concept "national system of innovation" in literature. While there seems to be no contention on the matter of origin, there is nevertheless something of a dilemma: as far as I could determine, Christopher Freeman credits Bengt-Ake Lundvall whereas Lundvall credits Freeman for introducing the term in literature (Freeman, 2003; Johnson & Lundvall, 2003). There is however an amicable resolution to these courteous claims or rather disclaims. It appears Freeman used the term in an unpublished paper that he prepared for the Organisation for Economic Cooperation and Development (OECD) expert group on Science, Technology and Competitiveness in 1982 (Johnson & Lundvall, 2003, p 14). In this paper, the term was used particularly to emphasize the important role of government in promoting technological infrastructure.

Ten years later, in a published book, which he edited, Lundvall (1992) used the term to describe the interdependence between technical and institutional change, having undertaken extensive studies of institutions and nation states in North America and Europe. Admittedly, Lundvall's notion of the NSI concept is largely shaped by the peculiarities of the developed world context where he conducted his initial studies. The usefulness of the term in developing world contexts is a significant point for discussion. A case is yet to be made for the appropriateness or expediency of the NSI concept as a conceptual framework for understanding and shaping the behaviour of knowledge-driven institutions within a developing country. An elaborate discussion of the applicability and usefulness of the NSI concept in developing world contexts is done under a topic covering the subject below.

There is evidence from literature though which suggests that the concept "national system of innovation" may actually precede the two contributions discussed above, although the term may not have initially been constructed in the same exact words. Back in the 1800s, Friedrich List, an American economist born in Germany, published a book titled *Das Nationale System der Politischen Ökonomie,* which, translated means "The National System of Political Economy". In this book, List (1841) criticized the work of Adam Smith who advocated the view that the economy could be left to take shape in the hands of the vagaries of the individual market forces. He argues for an integrated view of national actors in the economy, including the knowledge producing institutions, the productive sectors, technology and infrastructure.

Friedrich List saw the state as the key actor in building sustained economic wellbeing for a country. He argued that the state would accomplish this by concentrating on developing its productive capacities, even at the expense of short-term gain within a generation. List put emphasis on industrial development through technological innovation as means to accomplish enduring economic wellbeing of a nation. His thinking as demonstrated in his book, dovetails with the dominant thought today on the key drivers behind the wealth of nations.

2.3 Definitions of the NSI

The NSI is a central concept in this study and thus deserves an in-depth analysis. Since the first appearance of the term in literature, as traced in the preceding discussion, the term has found widespread acceptance in scholarly publications. A survey and analysis of how the term is being used would elicit the subtle nuances that have quickly made the use of the term popular and the concept expedient as a national policy framework.

Mytelka (2003) defines the NSI as "a network of economic agents, together with the institutions and policies that influence their innovative behaviour and performance" (p 31). Mytelka goes further to characterize the innovation system as "an evolutionary system in which enterprises in interaction with each other and supported by institutions and organizations such as industry associations, R&D, innovation and productivity centres, standard setting bodies, universities and vocational training centres, information gathering and analysis services, and banking and other financing mechanisms play a key role in bringing new products, new processes and new forms of organization into economic use" (p 31).

Wangwe (2003) defines the NSI as "a set of interrelated institutions the core being those which generate, diffuse and adapt new technological knowledge. These institutions may be firms, R&D institutes, universities or government agencies. Institutions mark boundaries, which have an influence on uncertainty [sic]" (p 77).

Niosi (2002) sees the NSI as "a set of interrelated institutions; its core is made up of those institutions that produce, diffuse and adapt new technical knowledge, be they industrial firms, universities, or government agencies" (p 291).

According to Freeman (1987) the NSI is a "network of institutions in the public- and private-sectors whose activities and interactions initiate, import, modify and diffuse new technologies".

Lundvall (1992) defines the NSI as the "elements and relationships which interact in the production, diffusion and use of new, and economically useful knowledge…"

Nelson & Rosenberg (1993) see the NSI as the "set of institutions whose interactions determine the innovative performance of national firms".

Niosi et al (1993) defined the NSI as a "system of interacting private and public firms (either large or small), universities, and government agencies aiming at the production of science and technology within national borders."

Patel & Pavitt (1994) see the NSI as "national institutions, their incentive structures and their competencies, that determine the rate and direction of technological learning (or the volume and composition of change generating activities) in a country".

A contribution from Metcalfe (1995) proposes the NSI as "that set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process".

Metcalfe (1995) goes further to suggest that the NSI is "a system of interconnected institutions to create, store and transfer the knowledge, skills and artifacts which define new technologies".

An analysis and synthesis of the above definitions reveal several crucial themes in the manner in which the NSI is conceived and employed among scholars:

2.3.1 A variety of institutions

The above definitions all indicate that the NSI is composed of a range of institutions that serve a variety of functions within an economy. The institutions can be private or public, which presupposes that they may be operating with very divergent economic motives. In fact, in this consideration, some may be competitors. The organizations may be big or small. In developing countries, the small enterprises are usually constituted by the informal sector whose contribution to national innovation may not always be fully understood or accounted for. The participating institutions in the NSI may be operating at different levels. Some may be involved in knowledge production by way of basic research or directed research, such as the universities and public research organizations. Some may be involved in technological development and other activities relating to the acquisition, adaptation, generation and diffusion of technology. Some scholars include within the ambit of the NSI bodies as diverse as the standard setting institutions and the banking sector. There is a variety of another sense in the use of the term "institutions". It refers not only to organizations but also to a set of "habits, routines, rules, norms and laws, which regulate the relations between people, and shape social interaction" (Johnson, 1992; p 26). This aspect underlines the importance of system governance and the efficiency of both the written and unwritten rules of engagement that characterize the nature of interactions among system components.

2.3.2 Interactions

A theme that cuts across all the definitions of the NSI shown above is that of interactions among the members of the NSI. The use of the term "network" suggests a profile that is embedded on free-flowing communication and interlinked functionality. It conveys a sense of connectivity, as in a spider's web, where an effect on one part induces a change in other parts in the network. Therefore, system characteristics and behaviour can only be borne out of the synergistic sum of the constituents of the system. This conception underscores the importance of rich connections between the different components of the system. The role of information and communication technologies in supporting knowledge systems cannot be overemphasized. More importantly though, it is the quality of those interactions, rather than the mere physical connectivity, that is more critical. System components, in order to optimally respond to the needs of their economic environment, have to "listen" to one another so as to respond efficiently to address the social and economic needs of the society in which they operate.

2.3.3 Technological learning

Looking at the definitions above, there is a strong sense that the NSI is composed of institutions that interact is such a way as to bring about a technological *change* in the economy. Although the definitions do not explicitly state this component but it comes through in the wording used. The picture that is being created is that of organizations and institutions, each playing a role towards a process that ultimately results in something that none of the individual parts has. The process itself can be characterized as that of co-learning and co-discovery. The outcome is a change in the technological state of the economy. On one level, this change could be in a form of a completely new or improved product, manufacturing or production process. On another, perhaps not so obvious level, the change is reflected in a new order or quality of networks and interactions among the system components. In a way, with each success, the system improves becoming more adept at accomplishing even better outcomes. This may explain the "virtuous cycle" of innovation that is observed by Muchie (2003) in knowledge-based economies.

Although the NSI concept developed and propagated from studies of the developed economies such as Japan, its relevance has been recognized in thinking about policies for the developing countries. To this end, various researchers from the South have embarked on research on the NSI or incorporated its ideas in policy and planning. Arocena & Sutz (2000; p 58-59) argue that when the NSI concept is approached from the developing world perspective, there are at least four essential aspects that need to be kept in mind, namely:

- The concept originated from the countries of the North as an ex post concept, whereas for most developing countries it is an ex ante concept. This means that in the developing world, the concept was built on the evidence of empirical data while in the developing world few examples illustrate a current manifestation of the NSI.

- The NSI concept should be seen as carrying a normative element in that, when it is being used in literature, it does allude to better ways of organizing science and technology systems in an economy. As a result, a developing country has to first make an evaluation as to the approach that would most suit it, rather than copy whatever the latest policy fashion is out there.

- The concept is relational in that it emphasizes the importance of connection, i.e. cooperation between the various players within the country's NSI.

- The NSI concept can be an object of policy making. The idea behind this aspect is that, while there will always a debate about whether NSIs are created or evolve spontaneously in society, countries are able to take decide and implement specific policies with a view to influencing the shape of their science, technology and innovation.

The latter point is highly pertinent for the theme of this study in that, it hints at possible perspectives about how the NSI comes into being. As it will be shown in this study, the NSI cannot be completely planned and regulated from a central control point. Certainly, not every detail of the NSI can be plotted from a blueprint. There is enough evidence to suggest that aspects of the nature and functioning of the NSI are emergent properties that emanate from the complex interactions among the constituents of the NSI. The main purpose of this study is to apply chaos and complexity theories for the purpose of shedding light on this aspect so as to explain how the NSI evolves and functions. These ideas are elucidated in Chapter 5 of this report.

2.4 Contemporary issues on the NSI

What should be the ends of national innovation policies? There is probably less agreement on this question than is on what innovation is. Jamison (2003) describes what he characterizes as a "bifurcation" in the ways in which policy makers view the role of science and technology in society. As a result, two distinct camps have emerged, each driving its own agenda on the question of the role of research, development and innovation. There are those whose sole agenda for innovation policies is economic growth. In the other camp, there are those who pursue social and environmental wellbeing (Jamison, 2003; p 63).

While it may be tempting to immediately argue that the two ends identified above may not be necessarily mutually exclusive, the differences in the two paradigms are not trivial either. In the context of South Africa, for instance, choices about innovation policies could elicit huge dilemmas. For example, would it be appropriate for the country's innovation policy to pursue technology-driven economic growth at the expense of job creation? This question is pertinent because in the past few years, the country has experienced what has been termed "jobless growth". Consequently, government economic policies that were perceived to be behind this kind of growth, such as the Growth, Employment and Redistribution (GEAR) economic policy, which was adopted in 1996, came under immense criticism.

In developing countries that have huge social challenges, national innovation policies cannot ignore their socio-political implications. If national economic policies promote innovation-driven economic growth without considering, for instance, how income disparities, would be bridged, then those policies could be justifiably regarded as shortsighted and inappropriate. Recently, environmental considerations have begun to permeate global discourses on economic growth. The environmental effects of energy-demanding growth by countries such as China, have underscored the urgency of sound policies on sustainable growth. In South Africa, the economic growth-driven pressure on the national electricity grid, which resulted in regular blackouts that would continue for several years, highlighted the need to consider the implications of economic growth for energy demand. Thinking and policy making on technology-driven economic growth, in the context of national innovation systems have to take into account broader social issues.

How could the global discourse in innovation policy be characterized? Jamison (2003) is of the view that contemporary innovation policies are largely about producing marketable products and services. This is how he characterizes current innovation policy making:

> *"What is at issue here is not whether science and technology satisfy and particular social or human need or, for that matter, help solve any particularly pressing social, environmental or human problem; the overriding, and more or less exclusive, concern is rather whether a market can be found for new innovations, and, if so, how shares in that market can be increased for the purposes of corporate expansion and growth"* (Jamison, 2003; p 64).

There is no doubt that innovation and commercialization are almost twin-ideas in most innovation discourses. Across the world, every effort is being made to organize innovation systems in such a way as to derive maximum profits for national economies. The role of knowledge producing institutions such as universities and science councils is changing. Government policies are placing demands on these institutions to raise their own income, often through products and services derived from their knowledge output. The business of these institutions is increasingly geared towards spinning out companies in which they would hold equity or otherwise derive royalties from their patented intellectual property. The scientific research environment is shifting from a "publish or perish" culture to a "patent or perish" one. This raises questions about whether the *raisons d'être* of these institutions are still valid and whether they still receive the attention they deserve within the milieu of the new ventures.

The world food crisis that has broken onto the world stage is a case to ponder in this respect. A question that needs to be asked is, how is it that just when the world has seen a revolution in the technologies for food production, that we are witnessing a global food crisis? According to the World Bank (2008) U.S. wheat export prices rose from $375 to $440 per ton between January and March 2008, while Thai rice export prices increased from $365 to $562 per ton, over the same period. This came on the back of a whooping 181% increase in global wheat prices in the 36 months leading up to this period. What is more ominous from the same World Bank report is that the high food prices are going to persist well above the 2004 levels through 2015 for most food crops. The consequences of the high prices for countries, particularly in the developing world, are expected to be far-reaching. In this context, the hopes for realizing the noble Millennium Development Goals are dealt a grievous blow.

The above broad scenario of rising food prices in spite of improved production technologies is but one point to ponder in considering national policy options for science and innovation. Other important issues to be taken into account include environmental sustainability, ethical dimensions in genetically modified organisms, just intellectual property regimes for indigenous knowledge and many others.

In order to conduct an in-depth analysis of the NSI concept, it is useful to examine the connotative meanings of each of the words forming the term. Each of the words that make up the term, that is, “national”, “system” and “innovation” carries a significant import for the NSI as a conceptual framework. It is thus appropriate to unbundle the composite term and conduct a thorough examination of each of the constituent words that form it.

2.5 Innovation

The term “innovation” is a noun that is used to describe a process or a product of that process. In the former sense, innovation has been defined as “the creation, diffusion and use of new ideas applied in the economy”. In the latter, it is defined as “new production processes, new products, new forms of organization and new markets” (Lundvall, Muchie & Gammeltoft; 2003, p 2). In the context where new production processes and products are accomplished, it is referred to as technological innovation.

Innovation can be an incremental or radical process, as Wangwe (2003) describes:

> *"Innovation is a cumulative process gradually making use of pre-existing possibilities and components according to the principle of path dependence. However, innovations may result in radical break from the past rendering obsolete a substantial part of accumulated knowledge"* (p 77).

Technological innovation has become the hallmark of economic development in modern economies. Entrepreneurial activity brings about value in an economy through the introduction of higher value goods and services, accomplished through more efficient production processes and other input savings. The beneficiation of mineral and agricultural products, for example, can be accomplished through the application of technological innovation.

One of the consequences of innovation is what Schumpeter (1942) termed "creative destruction". When new products and services enter the market, they inevitably threaten longstanding technologies and products by introducing more cutting-edge technology and better product functionality. Creative destruction was responsible for the demise of monopolies such as Xerox in photocopying and Polaroid in instant photography.

The continuous application of innovation is the lifeblood of a growing economy. The resurgent economies of the last few decades were characterized by high levels of technological innovation. The bourgeoning rents earned from the export of high-tech products in vast markets across the globe, result in the growth of the wealth of the domestic economies. The social consequences of this economic growth for the countries concerned, namely, higher employment, better paying jobs, improved health provision and better education systems, create a positive feedback cycle that ensures sustained economic and social development.

In the context of globalization, which characterizes the current world economic status quo, not to innovate is a sure way to economic stagnation as better products from other countries are guaranteed to supplant local products, resulting in erosion of market share and income for local companies.

Lundvall, Muchie & Gammeltoft (2003) argue that developing countries that want to compete successfully in the global economy need to move rapidly into the fast growing sectors that are characterized by the use of advanced technologies. The appropriation of information and communication technologies by the countries in the Far East bears testimony to how such economies could rapidly grow. There is however a need to invest in skills development and infrastructure as a prerequisite to successful entry to such high-tech industries.

Johnson and Lundvall (2003) see innovation as "a continuous cumulative process involving not only radical and incremental innovation but also the diffusion, absorption and use of innovation" (p 15). This suggests that innovation is driven not only by rapid technological output. There is also a need to develop the capacity of an economy to absorb new innovations and technologies through a range of inter and intra organizational relationships and characteristics. Innovation capacity is therefore embedded in a system of supporting networks that include scientific research, technological development, education, product development, marketing strategies, management practices and venture finance. The "systemic embeddedness" (Mytelka, 2003) of these processes finds expression in a national system.

2.6 System

Private firms are often the drivers of innovation within an economy because the production of new products and services is what keeps them in business. Competitive advantage at the firm level is created and maintained by technological innovation in the knowledge economy. Leading companies globally, in any economic sector, rely on their ability to harness new knowledge in order to keep ahead of competitors. To this end, private companies increasingly spend more resources on research and development.

Firms however cannot maintain an innovative culture in isolation. On one hand, they need to draw on knowledge that may not be produced within their establishments. With increased specialization and integration of knowledge and technologies in products, this is certainly the case. On the other hand, firms need to be closer to their clients in order to keep in touch with their changing needs. However, the two entities are by no means the only important sets of players to maintain contact with. They also need to be in touch with their suppliers and very often with their competitors (Lundvall, Muchie & Gammeltoft, 2003). Rich interactions with all the relevant stakeholders is important for the companies to receive the feedback that they may employ in making decisions about future innovations that may be required.

In countries that are advanced in innovation, these rich interactions are an important feature of the economy. It is this connectedness of the institutions within the economy that drives innovation. In their comparative study of the innovation system of Brazil with those of European countries, Viotti & Baessa (2005, p 30) found that the interactions in the European economies was a lot more pronounced. This observation is also borne out in the study of Latin American economies done by Arocena & Sutz (2000).

To illustrate the importance of linkages that form a network which constitutes a system, most definitions of the NSI refer to "institutions". For example, Mytelka (2003) defines an innovation system as "an evolutionary system in which enterprises in interaction with each other and supported by institutions and organizations such as industry associations, R&D, innovation and productivity centres, standard setting bodies, universities an vocational training centres, information gathering and analysis services, and banking and other finance mechanisms play a key role in bringing new products, new processes and new forms of organisation into economic use" (p 31). In this definition, the term "institutions" refer to "sets of common habits routines, established practices, rules or laws that regulate the relations and interactions between individuals and groups" (Edquist & Johnson, 1997; p 7).

According to Mytelka (2003), the definition of "institutions" given above is important for five reasons:

Firstly, it makes explicit the importance of "actor competencies, habits and practices" which underpin linkages, investment and learning – the three "key elements that underlie an innovation process". Thus, the mere presence of R&D organizations within a shared geographical space, such as a country, does not in itself, presuppose a system of innovation.

Secondly, it builds awareness of the fact that habits, practices and institutions are learned behaviour patterns, circumscribed by historical and geographical peculiarities. As a consequence of this, learning and unlearning become important attributes of system actors.

Thirdly, it focuses attention on the multidirectional knowledge and information flows as the essence of an innovation system. The drivers behind and dynamics of the flow of knowledge cannot always be determined beforehand. This therefore highlights the need for a finger-on-the-pulse assessment of the system operations in order to support adaptive policy making.

Fourthly, it facilitates the inclusion of the demand-side as a core component of the innovation system. As a result, the distance between knowledge production and the market is diminished in such a way that all these components are constantly and dynamically engaged in co-shaping of the research agenda and technology demands.

Lastly, it draws attention to the roles of local actors with respect to the three key elements of the innovation process, namely, learning, linkage and investment. Particularly in developing countries, small and medium enterprises should be encouraged to fully participate in the promotion of innovation.

The importance of a joined-up network of organizations and institutions within a country is critical for the promotion of innovation. The strength of industrial economies is not solely based on the individual core-competencies of the companies but also on the strong networks that exist between them. In the developing countries, which historically do not have strong self-regulating mechanisms for building networks, the role of government becomes important in putting in place incentives, legislation, infrastructure and other mechanisms that promote the connectivity of the economy in order to build a strong system of innovation. This thought logically leads to the need for a national approach to innovation.

2.7 National

At a time when globalization has become the dominant feature of big business and trade, it may be something of a paradox that the national system of innovation has become a dominant framework among policy theorists and makers. However, while firms may be the main actors in innovation and learning, the capacity to develop the nationwide networks that are critical for technological learning resides with government. For this reason, nations remain a "legitimate unit of analysis" for describing the nature and performance of innovation efforts globally (Muchie, 2003). The improvement of product design, manufacturing processes and establishment of new product lines requires firm-level innovation. However, the supporting context of institutions, policies, infrastructure, logistics, technology, culture, communications, marketing, knowledge production, business environment, entrepreneurship, intellectual property protection and information and communication technology connectivity all provide a foundation upon which technological innovation could take place. A national perspective on innovation therefore provides a comprehensive purview for understanding the nature and assessing the performance of a country's knowledge-based production machinery. From this it could be postulated that, from a policy perspective, the promotion of innovation within a country cannot succeed if it is not driven by central players and authorities that can effect nationwide changes. For this reason, the role of government, particularly in small economies, is crucial in promoting and supporting technological innovation (Wangwe, 2003).

Government investment in R&D can be a very strategic intervention in the economic activity of a country. Knowledge is the "quintessential public good" whose use by one firm or individual would not diminish its availability to others (Amsden & Cho, 2003). In fact, the wider the circulation of knowledge within the technological networks within a country, the greater are the chances for emergent technological progress for the country as a whole. An investment in developing an innovative society that is driven by knowledge production is likely to set in place a virtuous cycle of technological success through further enhancement of the knowledge infrastructure. Unlike information, knowledge is not easily lost as it becomes embedded in the fabric of the institutional network of the innovation system.

An additional incentive and motivation for supporting endogenous investments in knowledge production and technological innovation, derives from an analysis of the investments by multinational companies in the countries in which they operate. Multinational firms invest only up to 15% of their R&D expenditure outside of their home base (Amsden & Cho, 2003). Figures vary, depending on the region, with the European multinationals investing up to 40% of R&D in other EU states. However, in latecomer countries, R&D investment by the multinationals operating within these countries remains miniscule (Patel & Vega, 1999). This is true even in instances where knowledge generation and technological innovation are required to adapt products to local market conditions.

Perhaps ironically, it could be argued that globalization may have influenced the emergence of nation-states as critical players for building the capacity for industries to compete successfully in the unfolding economic order. The importance of knowledge production and technological excellence has called upon firms to cooperate with various stakeholders in order to develop competitive advantage. These partnerships involve disparate institutions such as universities, research organizations, small and medium enterprises, large firms, government departments, funding organizations, development agencies, intellectual property organizations and others. To bring into alignment such an array of organizations requires vast institutional capacity and a supporting communication and organizational infrastructure that spans across a nation, at the very least, for most nations of the world.

National policies still dominate the context in which business and trade are conducted. Proprietary, labour and fiscal policies are still the remit of government. Bilateral and multilateral trade agreements are still brokered and serviced by nation-states. Custom policies, duties, taxes and related institutional frameworks all reside within the ambit of government. Policy and planning at the level of the nation-state therefore remains the focal point in determining the conditions for success. The nation-state therefore remains an important factor for building the capability for global competitiveness, without which firms would struggle to survive in almost all industrial sectors. This is particularly true for small countries, which require a complete mobilization of its national resources towards building innovation-based industries.

Efforts at the level of the nation-state are not by themselves sufficient (Lundvall, Muchie & Gammeltoft, 2003). Specific actions to support these efforts need to be introduced at levels both below and above that of the state. At a local level, communities, small enterprises and local innovation systems need to be invigorated and aligned with national policies. Beyond the state, particularly for weak states, complementary regional innovation networks should be pursued in order to buttress national competencies. The initiatives at the level of the European Union for promoting regional innovation capacities are a good example of supranational efforts to support national strengths. African countries would do well to embark on similar regional partnerships

2.8 NSI and developing countries

The NSI concept originated from the study of developed economies, and as such, largely describes the nature and content of economic activity that obtains in those economies. The appropriateness of the NSI concept to make sense of economic activity or as a basis for developmental policy change in developing countries needs to be tested. There are inherent conceptual dangers in applying uncritically developed economic terms to developing economies.

There is a strong view that the processes that characterize technical change in developed countries are at variance to the ones that obtain in developed ones (Viotti & Baessa, 2005). For this reason, it is important to be especially circumspect in applying the definitions and models. It could be a mistake for a developing country, for instance, to attempt to mimic the economic development in a developed country. The variables that shape the economic circumstances in the two countries could be so divergent that it would not be possible to replicate the desired evolution. It is therefore important to identify and analyse the essential differences in order to be able to understand the causes of underdevelopment and design appropriate models to stimulate systemic economic change through technical change.

One way of studying the differences is to conduct comparative studies of innovation surveys that are based on similar empirical data. Most innovation surveys that are performed in the developing countries are based on those that are carried out in European Union (EU) or Organisation for Economic Cooperation and Development (OECD) countries. The limitation to this approach is in that the national surveys conducted in various developing countries often exhibit different methodological difference. Viotti & Baessa (2005) outline some of these, as depicted in Table 2-1 below.

Country	**Methodological Basis**	**Questionnaire Reference**	**Period**	**Activities**
Argentina	Oslo Manual & Bogota Manual	CIS3 (with major adaptation)	1998-2001	Manufacturing
Brazil	Oslo Manual	CIS3 (minor adaptation)	1998-2000	Manufacturing, mining & quarrying
EU	Oslo Manual	CIS3 (minor national adaptation)	1998-2000	Manufacturing & services
Malaysia	Oslo Manual	CIS3 (minor adaptation)	2000-2001	Manufacturing
Mexico	Oslo Manual	CIS3 (minor adaptation)	1999-2000	Manufacturing
South Africa	Oslo Manual	CIS2 (major adaptation)	1998-2000	Manufacturing & services

Table 2-1: Main methodological features of innovation surveys in selected countries (adapted from Viotti & Baessa, 2005)

As shown in the table above, there are a number of variances in the national surveys that are conducted in the countries involved, ranging from methodology to economic activity surveyed and lengths of periods under consideration. It is nevertheless argued that these methodological differences allow for qualitative comparisons to be made between the countries on high-level issues that distinguish research and development activity in developing from developed countries.

The innovation profiles of developing countries suggest that they lag significantly behind in the key variables of technical change when compared to the developed countries. Key differences outlined by Viotti & Baessa (2005) include:

- Developing countries produce a much lower number of new products into their respective markets;
- Developing countries have a low incidence of simultaneous product and process innovation than developed countries
- Developing countries invested much lower in innovation than developed countries;
- Developing countries record a much lower percentage of extramural research and development activities;
- Enterprises in developing countries invest a much lower percentage of their turnover in total expenditure in innovating activities;
- The number of research and development workers in developing countries is much lower than in developed countries;
- There is much less incidence of enterprise cooperation in innovation activities in developing countries;
- There is much lower financial public support for innovation in the developing countries than in the developed countries.

The above weaknesses constrain the development of robust innovation systems within developing countries. In this way, a study of the state of development or health of an innovation system can be useful in explaining the socioeconomic status of a country and can also offer a prognosis for its future development. A well-functioning innovation system creates a virtuous cycle of development by creating and promoting positive feedback loops that further stimulate more innovation. Innovation promotion in a country creates this virtuous cycle by building institutions that create order and stable living conditions that are necessary to provide people with opportunities and incentives to engage in learning new competencies (Johnson & Lundvall, 2003).

Several researchers of innovation systems in have expressed reservations about the relevance or appropriateness of the term “innovation systems” in reference to most developing countries (Johnson & Lundvall, 2003; Muchie, 2003). Several reasons are put forward to explain the inappropriateness of the term, particularly in relation to African countries. The first has to do with the observation that innovation in these countries, in terms of the development of new products and processes, is a rare phenomenon. This is especially true for the kind of innovations that can have a bearing on global markets. The second major concern has to do with the weak linkages that exist between the organizations that are meant to be forming an innovation system of the country. Clearly, when a country's institutions are not interlinked so as to facilitate co-learning and the bridging of the gap between the producers and users of technology, there is no way that the collective would constitute a system in any meaningful sense.

At a more fundamental level, the greatest issue that disqualifies most African economies from being perceived as innovation systems, is the fact that their nation-states are weak and can hardly support an innovation system of any significance. Muchie (2003) describes the problem of weak African states as follows:

> *"During the last forty years fifty-four states have emerged in Africa. Most of these entities are fragile or weak. Such a fragmented pattern of nation building bequeathed from the post-colonial condition has proved more a hindrance than a facilitator in the pursuit of any meaningful national independent industrial and technology strategy and policy. The post-colonial state suffered from two major constraints: a) inability to manifest an agency different from those external actors who provide aid to sustain it, b) inability to govern society by breaking out of the maze of domestic conflicts, political, economic, social and cultural problems" (Muchie, 2003; p 47).*

It is reasonable to accept that weak nation-states do not augur well for strong national systems of innovation, given the requirements for strong support to institutions and their integration to operate as a system. As a remedy to this specific problem, Muchie (2003) advocates a grand idea of an "Africa-Unification Nation" (p 48), which he believes stands a better chance of creating the necessary conditions that could support an Africa-wide system of innovation.

Notwithstanding the limitations discussed above, there is consensus in that the promotion of innovation is a way to go for developing countries. Shin (1996) suggests that the developing countries that are latecomers may actually enjoy certain advantages over the developing countries in some respects. These include:

- leapfrogging directly into the use of the latest and most advanced technologies, rather than go through the older and obsolete technologies. Developing countries, for example, can move straight into the use of cellular telephony and fibre options, rather than copper-based networks that have become dated.
- enjoying the benefits of technologies developed elsewhere, without having to invest huge resources in developing them.
- taking advantage of economies of scale by moving straight into huge plant sizes, without having to experiment with risky low scale trial runs.

Notwithstanding the possible benefits of latecomers, Wangwe (2003) notes that while some countries have managed to take advantage of this status towards catching up with the frontrunners, others have failed. As a result, the group that has been left behind has actually fallen back even further. Many of the countries that are in this group are in the sub-Saharan region of the African continent.

Muchie (2003) is of the view that African countries could capitalize on technological innovation by bringing it to bear on their vast natural resource endowments in the following way:

> "*Instead of trying to manufacture products that others are already producing, Africa has vast opportunities to create new lines of production and fabricate and introduce* [sic] *new products into the world market. What it needs is a robust system of innovation that links up to the world's leading centres of innovation whilst re-articulating a distinctly African-wide national political economy of production*." (p 46)

The opportunities for implementing the above approach are abundant. Africa is rich in almost every mineral of practical use to mankind. It has unique species in a long list of cereal and other plant food varieties. Africa is home to a rich and unique biodiversity. Already in South Africa, an example of this approach has begun. Through policy and legislative interventions, minerals such as diamonds and platinum, have begun to be locally beneficiated rather than being simply exported as low-value raw materials. With proper investment in these emerging industries, there is a potential to grow these into economically meaningful industrial hubs in the future. Africa can no longer continue to play the role of supplier of cheap raw materials into the insatiable black hole of global world economy, if it wants to loosen the grip of poverty around it. In the same way as some of the oil-producing countries, such as the United Arab Emirates, the content has to begin to set a foundation for a diversified economy, through judicious investments in technological innovation.

2.9 Stages of technological development

There is a view in literature that countries evolve through particular stages of technological development. This process is sometimes referred to as “technological learning” (Wangwe, 2003). It starts with simple imitation and develops into advanced forms of creative imitation. With increased investments in the technological capabilities of the country, fully-fledged innovation ultimately takes root. This development path could be observed in the development of some of the economies of the far-East. A counter-argument against this development pathway could be made, using indigenous knowledge as an illustration. Countries whose overall innovation performance may be limited, could, nonetheless, enjoy a competitive advantage in innovations that are based on their indigenous knowledge and technologies. On the basis of these local capabilities they may possess the means to leap-frog some of the stages stated above. As a resolution to the notion of set stages of technological development, it seems reasonable to suggest that a country could conceivably be a follower in some areas of technological innovation while simultaneously a leader in others.

The countries that are late adopters of technology-based industrial development seem to exhibit at least two types of characteristics. One group can be described as “integrationist” and the other “independents” (Amsden & Cho, 2003). The integrationists take advantage of foreign direct investment in order to develop their own technological capacity. The independents commit their own national investments in order to create technologies and cutting-edge capacities. The integrationists, at the mercy of foreign investment, seem to struggle to maintain the growth of their innovation systems.

2.10 How institutions interact within a NSI

In order to determine how institutions interact within a national system of innovation, it is important to understand at a basic level the expected role of science and technology in society. In South Africa, scientific research and technological innovation have been recognized by government as essential for addressing the social and economic challenges that are facing the country. In this perspective, science and technology in South Africa is expected to address the following challenges (Department of Arts, Culture, Science and Technology, 1996):

- Promoting competitiveness and employment creation
- Enhancing quality of life
- Developing human resources
- Working towards environmental sustainability
- Promoting an information society

Looking at the above list of priorities, it is apparent that various stakeholders and role players within the country would have to be involved in achieving the stated challenges. The achievement of any of the above priorities requires a high level of alignment of policies and strategies as well as cooperation among a host of institutions and organisation at various levels of the South African society. Given the massive coordination and management challenge this alignment poses, and the number of institutions, policies and organisations, how do the institutions respond? This is a key question for this study and ideas about what happens in reality are explained in greater detail in chapter 4 of this report.

2.11 How successful is the NSI approach?

Niosi (2002) provides an in-depth assessment of the effectiveness and efficiency of the NSI approach and comes to the conclusion that NSIs are both “x-inefficient” and “x-effective”. He then proposes methods to measure the efficiency and effectiveness of the NSI. The efficiency and effectiveness indicators are summarised in the table below, adapted from Niosi (2002, p 299).

	Benchmark	**Level**
Effectiveness Indicators	Graduates as percentage of new enrolment	University
	Publications per university researcher	University
	Patents per industrial researcher	Industry
	Number of firms conducting R&D	Government policy
	Number of research universities	Government policy

Efficiency Indicators	Cost of university graduates	University
	Cost of university publications (publications/HERD)	University
	Cost of industry patents (total patents/BERD)	Industry
	Cost of government laboratories' patents	Government labs

Table 2-2: Indicators of NSI effectiveness/efficiency by Niosi (2002)

A brief examination of the above proposals by Niosi (2002) illustrates the difficulties in measuring the performance of a national system of innovation. Firstly, there will always be a difficulty in connecting a cause to a specific effect. For instance, the number of firms conducting R&D may be a function of something other than government policy. While government policy may be promoting R&D, companies may cut down R&D within a particular country because of market factors that have nothing to do with government policy.

There are systemic effects that cannot be accounted for through a mechanical measurement. Aspects of system behaviour may be manifestations of knowledge flows, communication, feedback and synergistic effects interactions between organizations and institutions within the NSI. Thus, the level indicator ascribing the effect to one or the other component of the NSI would be way off the mark. Notwithstanding the above limitations, the indicators and benchmarks shown above are widely used across the world, for example, by the OECD and the National Science Foundation of the United States of America.

2.12 Regional systems of innovation

As a postscript to the discussion on the national system of innovation, it seems appropriate to briefly touch on the notion of regional systems of innovation. A regional system of innovation is brought about when science and innovation institutions cooperate beyond the boundaries of nation-states, bringing about cooperation among several countries.

The benefits of science and technology cooperation at a regional level are demonstrated by multilateral organizations such as the European Union, which has a strong science and technology agenda. The science and technology cooperation within the EU supports and is supported by the strong national innovation systems of the member countries. Countries within developing regions, such as Africa, would have to contemplate regional cooperation, without the benefit of established national innovation systems. The rationale for regional cooperation among developing countries may be stronger than for the developed nations.

Scerri (2003) identifies several reasons for regional cooperation for countries in sub-Saharan Africa. The first is a possible creation of a regional market with the benefit of economies of scale. In the SADC region, for example, most of the 14 member states have small populations and undeveloped industrial bases. However, as a region, the area has a population of more than two hundred million, offering various economic possibilities in terms of cross-border partnerships. The second is the enhanced possibility for harnessing indigenous technology bases. The shared geographical space and socio-cultural heritage of the region presents possibilities in industries based on biological and mineral natural resources, among others. The third reason has to do with the benefits that could be derived from the free movement of financial capital, knowledge, technology and labour. A regional economic integration, which progressively permits the free flow of these drivers of knowledge-based economic growth, could promote the development of the region.

It would be naïve to assume that a regional integration of innovation systems would be without challenges. Theoretically, it is possible that regional integration could favour the relatively more advanced countries. For instance, the freedom of movement of people could induce a brain drain in smaller countries. It is therefore important for the development of a regional innovation system to be a carefully planned process so that no country ends up being a net loser in the transition.

The purpose of this chapter was to unpack the NSI concept in order to make explicit some of the issues that are of importance to this study. The origins of the concept were probed and the composite ideas that form it were dismantled, examined and again meaningfully put together. The critical role of interactions among the elements of the NSI and how they bring about technological learning was identified. The usefulness of the concept of the NSI was then evaluated in view of various contemporary issues that face developing countries, such as South Africa. The next chapter focuses on the core theoretical frameworks of this study, namely systems, chaos and complexity.

Chapter 3
Systems, Chaos and Complexity

3.1 Introduction

When any subject matter is under common examination there is usually a consensus on a method of investigation and explanation that would suffice in establishing knowledge claims in that subject. Such rules of intellectual engagement would delineate the parameters of what can be regarded as an authoritative body of knowledge of that subject and push to the periphery dissident and apocryphal views. No terrain of philosophical enquiry is stricter in protecting the boundaries of its body of knowledge and the acceptable methods of enquiry than the natural sciences. Nevertheless, from time to time, such parameters are themselves put under scrutiny and even replaced by "better" ones (Kuhn, 1961), when found to be no longer viable in advancing the cause of scientific development.

Modern scientific thought is commonly perceived as a product of the Renaissance which took place in Europe from the 1500s. From the earliest days of scientific thought the predominant approach in the advancement of scientific knowledge, technology and other fields of intellectual enquiry has been characterized by reductionism. As a prelude to the introduction of systems, chaos and complexity theories, I will discuss the effects of reductionism as a paradigm of enquiry, firstly in natural science and by extension, in social and human sciences. The brief critical discourse on reductionism, which follows below, provides a context which is being used in this study as a rationale for the introduction of systems, chaos and complexity theories to make sense of matter, events and phenomena, particularly in social systems.

3.2 Reductionism and science

In the *Rules for the Direction of the Mind*, Descartes (1628) outlines an approach to "the direction of our mind so that it may form solid and true judgments on whatever matters arise". Descartes recognized the need to establish firm rules that would govern the intellectual process for determining truth. In Rule IV he declares, "There is a need of a method for investigating the truth about things". The expectation was that the "method" would expunge superstition and other superfluous means of establishing knowledge.

Rule V seems to capture the essence of his approach:

> *"The method consists entirely in an orderly arrangement of the objects upon which we must turn our mental vision in order to discover some truth. And we shall be observing this method exactly if we reduce complex and obscure propositions step by step to simpler ones, and then, by retracing our steps, try to rise from intuition of all of the simplest ones to knowledge of all the rest." (http://smith2.sewanee.edu/texts/Ecology/OnReductionism, accessed 04/02/2008)*

It is often concluded from the above rule that Descartes proposed that the key to understanding complex propositions was to break them down into constituent simpler ones. By examining the constituent elements closely, a global picture could be deciphered. This seems to herald an approach that has been termed reductionism which has dominated scientific enquiry for centuries.

Reductionism is an approach to understanding matter and phenomena that presupposes the existence of their constituent indivisible elements; examining the properties and interactions of these constituent elements would reveal the hidden truths about the respective extensive properties of matter and phenomena. As an illustration of the central idea of reductionism, consider the following equation which describes the relationship where w comprises of constituents x, y and z:

$$w = x + y + z$$

In terms of reductionism, the properties of object or event w could be deduced completely from a summation of the properties of x, y and z. In fact, we would not even concern ourselves with w anymore, so long as we could fathom x, y and z as they would, collectively, fully explain w.

The illustration above may be an oversimplification of what constitutes reductionism. However, it approximates the definitions that have been given of reductionism, mostly, it has to be admitted, from its critics. For example, reductionism is seen as an approach to scientific investigation that proposes that:

> *"everything in reality is but one kind of thing…"* (Machan, 2008)
>
> "all real scientific puzzles boil down to a question of physics." (Gallagher & Appenzeller, 1999)
>
> *"It is all in the Schrodinger Equation"* (Lucas, 1996)

One of the consequences of reductionism has been that functional biology, for instance, is made to read much like molecular biology. As a result, phenomena that are of interest to a biologist at the level of an organism are reduced to chemical equations that describe molecular interactions which add little value in the understanding of the behaviour of the organism. Explanations of personality disorders in psychology are reduced into concerns about a deficiency in this or the other chemical in the bloodstream. Thus, in this perspective, a palliative for schizophrenia is simply pharmacological, eschewing the social conditions that may be a factor in the observed disorder. In elementary mechanics, the definition of concepts such as force, power, work and energy have been reduced to mathematical equations, of dealing a blow to the conceptual understanding of the meanings of the terms.

The proponents of reductionism could retort to this kind of criticism of their method by saying that reductionism is successful because "it works", as demonstrated in the advancement in technology as evidenced in the last two centuries. It seems reasonable to concede to the demonstrable success of reductionist-driven science and technology, provided the limitations of the reductionist worldview are spelt out as follows:

In nature, often the summation of the properties of the parts, do not measure to the properties of the whole, i.e. sometimes $w > x + y + z$. This is particularly significant in social systems, such as organizations, where human factors render an empirical determination of cause and effect futile. No amount of meticulous study of individuals could explain aggregate effects such as organizational behaviour.

Furthermore, limitations to reductionism are being observed in various scientific areas such as mathematics itself, where discontinuities that cannot be described or predicted by logical deterministic approaches manifest themselves.

3.3 Systems theory

The beginnings of the systems age can be traced back to the 1940s (Senge, 1990). Systems thinking originates from the idea of expansionism, which is a view of the world that is, in some ways, intuitively opposite to that of reductionism. Expansionism is an approach to the world that views all objects, events and experiences as parts of larger wholes. The focus of expansionism is in the bigger set of relations, i.e. the system, rather than in the constituent elements. Senge (1990, p 12) demonstrates the effect of systems thinking in practice in the development of cybernetics from preceding work done in communication, languages and symbols. Cybernetics grew from an expansionist process that progressively took account of the larger wholes in which the constituent elements belonged.

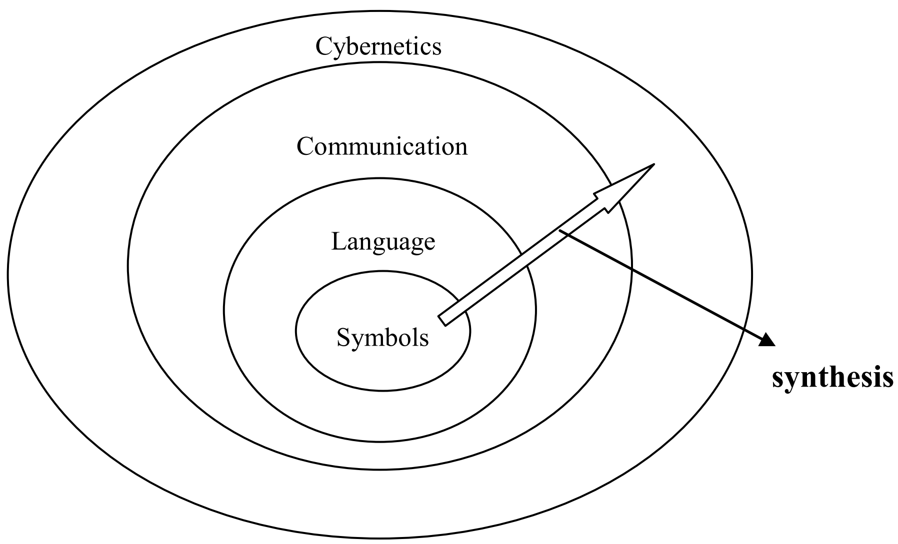

Figure 3-1: An illustration of the development of cybernetics

"Systems" as an approach to research was pioneered by Ludwig von Bertalanffy in biology from the application of cybernetics to living systems (von Bertalanffy, 1968). A systems approach to living organism could be more successful than traditional reductionist approaches to understanding the biological, behavioural and social phenomena of living organisms. Von Bertalanff saw the pertinence of a systems approach to knowledge development beyond the biological sciences, as can be seen from this quote:

> *"Concepts like those of organization, wholeness, directiveness, teleology, and differentiation are alien to conventional physics. However, they pop up everywhere in the biological, behavioural and social sciences, and are, in fact, indispensable for dealing with living organisms or social groups. Thus, a basic problem posed to modern science is a general theory of organization. General system theory is, in principle, capable of giving exact definitions for such concepts and, in suitable cases, of putting them to quantitative analysis" (von Bertalanffy, 1968).*

Senge (1990) defines a system as a set of two or more interrelated elements of any kind. A system is not an indivisible element but a whole that can be divided into parts. A system thus demonstrates the following properties (Senge, 1990):

1. The properties of each element of a system have an effect on the properties of the whole system.
2. The properties and behaviour of each element, and the way they affect the whole, depend on the properties and behaviour of at least one other element in the set. Thus, a single part cannot independently affect the whole, without a contribution from at least one other part.
3. A system cannot be subdivided into the subsystems that make it up.

A key implication of the above three properties of a system is that a system is more than the sum of its parts. Moreover, the situation of an element within a system, changes its functionality or capability. In other words, to a certain extent, the properties of a subsystem within a system, are, in one way or the other, shaped by the fact that it belongs to the system. In this sense it could be conceived that a system delineates the parameters of what its members can be. In this perspective, it would be impossible to decipher the properties of a part apart from the whole. Senge (1990) expresses this idea as follows:

> *"Viewed structurally, a system is a divisible whole; but viewed functionally it is an indivisible whole in the sense that some of its essential properties are lost when it is taken apart. The parts of a system may themselves be systems and every system may itself be a part of a larger system. For example, a state contains cities and it is part of a nation; all are systems."* (Senge, 1990; p 14)

An implication of the systems approach to this study is that, making sense of the nature, role and function of an organization such as the CSIR, can only be accomplished when the CSIR is viewed as a part of a larger system, for example, the national system of innovation of South Africa. Systems analysis operates by way of a synthetic mode of thought rather than analytic. A systems approach is more interested in putting things together than in taking them apart, in a bid to gain deep insights into their nature, function and behaviour.

As an illustration, let us apply systems thinking in criticizing the performance of the South African national system of innovation. Research institutions can defend their poor research output by bemoaning the fact that they do not get well trained scientists from the universities. The universities might argue that they are constrained by the quality of learners graduating out of the school system. The schools may in turn argue that they cannot provide quality education because the universities do not graduate appropriately qualified science teachers. This illustrates the point that, from a systems perspective, a critique of any element of a system is a futile exercise, if it is undertaken separate from a comprehensive examination of the whole to which that element belongs.

The appeal of the systems thinking approach has an even greater bearing than in biology when applied to social systems such as organizations. Social systems have rich interconnections and networks which are constantly changing. Social systems are therefore open systems, allowing ongoing exchange of matter and energy with the environment. This is different from physical systems whose description is often limited to closed systems or simulations thereof.

In thinking and applying the systems approach, it is important to heed the warning by Flood & Jackson (1991) that the concept is used not necessarily to refer to things in the world but as a particular way of organizing our thought about them. They elaborate this caution in the following manner:

> *"Although the early adherents of systemic thought used systems concepts to refer to situations in the world as if they were real systems, we have since learnt that this view is not satisfactory, particularly when considering social situations such as encountered in business, government and international relations. In these circumstances the "real world" is simply too complex to capture using systems models. We are better off, therefore, self-consciously using systems models as abstract structures for organizing our thoughts about problem situations."* (Flood & Jackson, 1991; p 4)

In recognition of some of the limitations of systems theory stated above, in this study the systems approach is supplemented with chaos and complexity theories. As it is argued elsewhere in this report, chaos and complexity theories are applied metaphorically as conceptual instruments to aid the theorizing process, i.e. perception and meaning making, on the national system of innovation.

3.4 Chaos and complexity

It is useful to trace the history of chaos and complexity in order to provide a logical sequence of how the fundamental ideas evolved which are going to be applied in this thesis. As we trace the history of chaos and complexity, we will see how the ideas are being assimilated in various disciplines. Such assimilation and application will serve as a pattern for the application of chaos and complexity to the subject of this enquiry, namely, the national system of innovation of South Africa.

3.4.1 History of chaos and complexity

The origins of chaos and complexity are often traced to Henri Poincaré who, already back in the late 1800s, had discovered the phenomenon of strange attractors (Ortegon-Monroy, 1999). In 1889 Poincaré entered his attempt at solving the three-body problem in celestial mechanics, as part of a worldwide competition organized to celebrate the 60th birthday of King Oscar of Sweden and Norway (Barrow-Green, 1997). Poincaré, although he could not solve the problem, was nevertheless declared a winner, given the groundbreaking effort his paper had made. As his manuscript on the problem was prepared for publication in Acta Mathematica, a serious error was discovered in the text. The research work done by Barrow-Green (1997) on the history of this episode reveals that it was when Poincaré was doing rework on his manuscript that he discovered mathematical chaos. A quotation found in his 1903 essay titled "Science and Method" indicates that he had a full grasp of *sensitivity to initial conditions*, a concept considered to be one of the hallmarks of chaos and complexity:

> *"If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment. [B]ut even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation approximately. If that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so; it may happen that **small differences in the initial conditions produce very great ones in the final phenomena**. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon."*
> (http://www-chaos.umd.edu/misc/poincare.html, accessed 9/9/2005; emphasis in the original quotation)

The critical importance of initial conditions that Poincaré alluded to was directly demonstrated in 1960 by Edward Lorenz, a meteorologist as he was performing computer simulations for weather prediction. Using a set of twelve mathematical equations, with the aid of a computer, he set to model the behaviour of the weather. As he processed the solutions that emerged from his calculations, he noticed a pattern that astounded him. Owing to a minute change in the input data, the predicted weather pattern would diverge completely from the pattern that could be intuitively expected from the input data. As a result, weather that should have happened doesn't materialize at all. On the other hand, something that ought not to have happened develops into an extreme threat (http://www.imho.com/grae/chaos/chaos.html, accessed 9/6/2005). This phenomenon of *sensitivity to initial conditions* popularly became known as the “butterfly effect” perhaps owing to the possible effect described by Ian Stewart as follows:

> *“The flapping of a single butterfly’s wing today produces a tiny change in the state of the atmosphere. Over a period of time, what the atmosphere actually does diverges from what it would have done. So, in a month’s time, a tornado that would have devastated the Indonesian coast doesn’t happen. Or maybe one that wasn’t going to happen, does”* (Stewart, 1989; page 141).

Later on Lorenz performed further simulations which, when depicted on a graph, produced a double spiral curve, which he called a Lorenz attractor. The paper published by Lorenz in 1963 of the phenomenon did not elicit much attention (Ortegon-Monroy, 1999). As a result his revolutionary discoveries remained unacknowledged by the scientific community. It was only in the 1970s that this changed, when suddenly his results were independently observed by scientists in diverse fields such as mathematics, physics, biology and chemistry. Chaos then became a growing field of research interest.

Robert May, a biologist, began to examine the patterns of behaviour of biological populations organisms that were subject to the threat of predators and limited food supply (Ortegon-Monroy, 1999). He used a simple mathematical equation to calculate the population of the species for successive years, as a function of the growth rate. As he increased the value of the growth rate, he noticed that instead of the population settling on a single value, it would jump between two separate values from one year to another. As he continued to raise the growth rate value, the split of population values increased to four different values. Further increases resulted in further splits which became more rapid. After a certain growth rate value it became impossible to predict any population value.

To demonstrate, in a simple mathematical way, the effects of feedback on the population growth, let’s consider a practical mathematical relationship that can describe a predator-prey scenario.

Suppose x_t represents a population x at a point in time t. To determine the population at a successive time $t+1$, the following question could be used:

$$x_{t+1} = ax_t(1-x_t)$$

where a represents the rate of population growth, or the number of offspring produced by each adult under normal circumstances, i.e. when there is no feedback caused by overcrowding. The factor $1-x_t$ represents the effects of overcrowding on the population, if $x=1$ is the maximum population that is possible without causing extinction.

The above equation is able to forecast successive population growths as a function of the growth rate a. For example, when $a < 1$, the population decreases to 0, which culminates into extinction, owing to a population growth below unity. When a is between 1 and 3, the population settles on a specific value, representing some steady state, which could be explained in terms of equilibrium among competing species in a given ecological setting.

Interesting behaviours of the equation begin to manifest when a moves beyond the value of 3. Initially, successive iterations of the values of a that are slightly larger than 3 produce a population value that oscillates between two figures, one high and another low. The high value corresponds to more favourable conditions permitted by a low population density whereas the low value is a consequence of an opposite set of circumstances. This phenomenon demonstrates the effects of environmental feedback on the population growth. When the value of a are increased further, the population further splits into initially 4 values that further split into 8 and then 16, etc. Meanwhile, for each successive generation, the population jumps from a high value to a low and back to a high and then low, and so on. The split of the population value is called a bifurcation. As the value of a approaches 3.57 the number of bifurcations increase more rapidly. At values of a that are above 3.57, the relation enters a domain of complete unpredictability, with no discernable pattern demonstrated in the population values produced by the equation. This is the point at which chaos is reached. A major implication of this phenomenon is that, beyond a specific point, it becomes impossible to determine the population.

The observations made by Robert May are reminiscent of the discovering made by Lorenz. The emergence of non-linearity in the population values matches the observation made by Lorenz on weather prediction. The manifestation of the doubling and redoubling cycles of values are akin to the attractors that Lorenz discovered. A graphical representation of May's population values calculated from the equation discussed above, yields increasingly complicated curves as much as the curve drawn by Lorenz. Upon closer inspection, although the curves depict unpredictable values, they still fluctuate within predictable broad parameters and exhibit a level of self-replication. The geometric depictions of chaotic systems demonstrate unpredictable yet non-random trajectories. The shape of the curve suggests that certain values are favoured while others are systematically eschewed. The preferred values are characteristic of deterministic chaos and are referred to as chaotic or strange attractors.

The term "strange attractor" was coined by David Ruelle to describe an observed tendency of systems to move toward a fixed point or to oscillate within a specific delineated cycle (Ruelle, 1980). Irrespective of the starting variables, it seems that in nature, specific broad states of what is possible are confined within set parameters. Without paying any respect to the initial conditions, systems in nature would in time converge upon the strange attractor (Gleick, 1987).

Benoit Mandelbrot has done extensive studies on the geometric depictions of deterministic chaos (Mendelson & Blumenthal, www.mathjmendl.org/chaos/, accessed 9/6/2005). The geometric illustrations of the physical reality of deterministic chaos demonstrate what is called self-similarity, i.e. repetitive reproduction of the same shapes at different scales of the same diagram. Mandelbrot coined the term "fractal" to name these shapes, and he describes them as follows:

> *"Fractals are geometrical shapes that, contrary to those of Euclid, are not regular at all. First, they are irregular all over. Secondly, they have the same degree of irregularity on all scales. A fractal object looks the same when examined from far away or nearby-it is self-similar. As you approach it, however, you find that small*

pieces of the whole, which seemed from a distance to be formless blobs, become well- defined objects whose shape is roughly that of the previously examined whole. Nature provides many examples of fractals, for example, ferns, cauliflowers and broccoli, and many other plants, because each branch and twig are very like the whole. The rules governing growth ensure that small-scale features become translated into large-scale ones."
(http://www.fortunecity.com/emachines/e11/86/mandel.html, accessed 4 April 2008.)

Fractals have played a significant role in bringing to life the phenomenon of deterministic chaos. In this way, the properties of chaos and its consequences have been made accessible to people beyond those that are engaged in abstract mathematics. Furthermore, the phenomenon of fractals has brought into close contact not only variant scientific areas but also led to joint projects between science and art. Fractal geometry, made more possible by powerful computers, displays various kaleidoscopes of images that reveal intricate forms for exploring chaotic behaviour. The Mandelbrot set is an example of a fractal that produces various forms which could reflect real-world physical shapes, such as in Figure 1 below.

Although non-random, chaotic systems are impossible to predict, for example at the interface between order and chaos. It has been proven that the mathematics that underlies this transition is similar for all systems undergoing this onset of chaos. This is often characterized by the doubling and redoubling effect discussed above, with all scaling details exhibited by fractals, identically independent of a system's precise nature. Mitchel Feigenbaum, in the 1970s, investigated the closely the bifurcation phenomenon. He demonstrated that the phenomenon was predictable at the transition between order and chaos. Feigenbaum has shown that all these phenomena prominently exhibit numbers determined by his theory, for example 4.6692016 …, for a logistic map. This number, which represents the ratio at which bifurcations occur, is called the Feigenbaum constant. This is a constant of nature whose decimal values have been accurately calculated to over a thousand, which determines the rate of the onset of chaotic patterns (http://www.rockefeller.edu/research/abstract). The practical effect of the Feigenbaum numbers has been evidenced in diverse real-life situations including irregular heartbeats at the onset of hear attacks, a dripping water faucet, fluctuating animal populations, electrical signals in circuits, lasers and various chemical reactions.

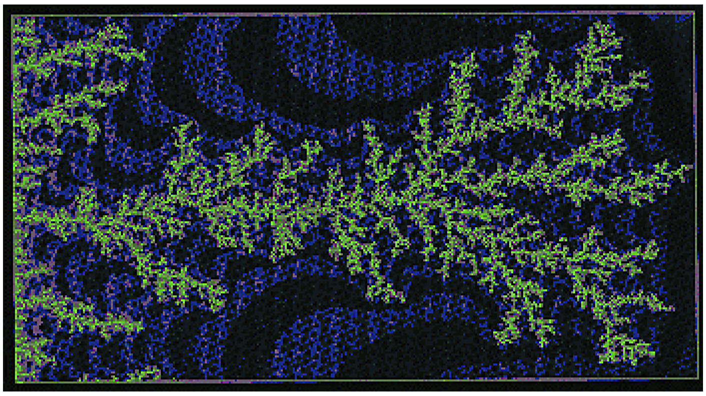

Figure 3-2: A random fractal called a "diffusion limited aggregate" produces fern-like shapes that model lightning and other natural phenomena (http://www.fortunecity.com/emachines/e11/86/mandel.html, accessed 04/04/2008)

3.4.2 Edge of chaos

An interesting concept that emerges in the study of chaos and complexity is that of the "edge of chaos" (Langton, 1990). In his research on cellular automata (CA) Langton defined a parameter (λ) as a fraction of rules in which the new state of the cell is living, depicted by a number between 0 and 1. If $\lambda = 0$, then all cells die immediately, since every rule leads to death. If $\lambda = 1$, then any cell that has at least one living neighbour will stay alive in the next generation. The key result of his research was evidence of a transition between the two values in which the system transits between order and chaos. The point of transition, i.e. the edge of chaos, is typified by a high degree of complexity. While the work of Mitchel, Hraber & Crutchfield (1993) modified earlier assumptions made by Langton, the central idea of the phenomenon of phase transitions in the space of CA still persists.

A number of studies that have since been done seem to confirm the basic idea about the existence of unique properties in systems operating at the edge of chaos. Stuart Kauffman's work on the random boolean networks (RBN) is a good example of this convergence. Kauffman (1993) developed the RBN as a stylized mode of gene interdependence, made up of N automata with two states 0 and 1, each representing a Boolean function of K variables. The study confirms a phase transition between order and chaos and the maximization of information processing ability near the point of transition.

The work done by Miramontes (1995) and Guerin & Kunkle (2004) on the behaviour of ants lends credence to the existence of the edge of chaos. What was observed in this study is that, individual ants seem to display behaviour that oscillates between bursts of activity and inactivity. With the presence of other ants in the vicinity, the activity level of the ant would change. Ant movement can either be self-induced or be activated by neighbouring ants. When there are only a few ants in the neighbourhood, individual ant activity is self-induced with no instigation from the ants in the vicinity. At high population densities, there is a sharp drop in both self-induced and neighbour-induced activations because the colony tends to maintain constant activity levels. An interesting observation is that around a critical population density, the number of neighbour-induced activations became large. This critical population density also coincides with the maximum level of entropy that is measured of the number of ants activated. It has been observed that ant colonies seem to be developed around the predicted values of population density.

Research work done by Nagel and Rasmussen (1994) suggests that traffic flows could be optimized at a critical traffic density, where the time taken by the individual driver would average between the shortest time possible for the journey and the longest as in a severe traffic jam. However, the high level of unpredictability around the critical density may dissuade the individual drivers, even though the throughput would be increased on aggregate. This is because the slightest hiccup in the traffic would result in a major delay, with a much larger impact than when the traffic jam is at its worst. This result underlines the observation that the edge of chaos presents unique opportunities and challenges.

3.4.3 Fitness landscapes

A valuable contribution into the development of complexity theory is the idea of fitness landscapes as described by Kauffman (1995). Kauffman uses the concept of fitness landscapes to explain in evolutionary biology how species change in time through gene recombination. The idea considers a landscape consisting of peaks of various heights and troughs. Each point on the landscape represents a level of fitness of a genotype due to inherited genetic properties. In order for the species to improve its fitness, it will have to leave its current point for a higher one in the landscape. This will be accomplished through genetic mutation and natural selection.

Although the idea of fitness landscapes is not new in evolutionary biology (Wright, 1932), the idea here is creatively used to depict evolution in nature as a complex adaptive process fraught with challenges and possibilities. A shift to a nearby higher peak on the fitness landscape for example, poses a danger, albeit temporary, of first going through a lower fitness peak. In an environment, as in nature, where multiple species with competing interests coexist, co-evolutionary processes shape the species to a point where they achieve a degree of collective adaptation yielding maximum average fitness (Lewin, 1992). The point between order and chaos, where species can achieve the highest level of fitness, in the context of one another, is the edge of chaos.

The concept of fitness landscape bears a lot of meaning, at least at a metaphoric level, for a social milieu of organizations, such as science and technology institutions within the context of the NSI. In particular, the struggle for survival and evolution of each organization, in the context of others in a changing environment, finds a lot of expression in the fitness landscape concept. The implications of the fitness landscape in this context are worth a dedicated study and are thus not applied in this discussion.

3.4.4 Dissipative Structures

Thermodynamics, as a fundamental natural process, is useful in illustrating the basic elements of behaviour of complex adaptive systems. Central in the thermodynamic model is the role of entropy (i.e. disorder) and enthalpy (i.e. order). The second law of thermodynamics defines the relationship between entropy and enthalpy in closed systems. Naturally, the condition of “closed system” often assumed in the application of the second law of thermodynamics in physics and chemistry is not useful for systems that are open to interaction with their broader environment, such as social systems. A comprehensive critique of this issue is done by Kay (2000). Building on Schrödinger's (1944) postulation of "order from disorder" and the work done by Prigogine & Stengers (1984), he further elaborates on the operations of thermodynamics in open systems, which are moved away from equilibrium by exchanges of material and energy with the environment. Such systems are referred to as dissipative structures and their entropy relationships were first formulated by Denbeigh (1951) and Prigogine (Prigogine & Stengers, 1984).

These formulations, however, were found to be inadequate because they are limited to the immediate neighbourhood of equilibrium. To address this problem, Kay (2000) first describes the behaviour of a system away from equilibrium and then introduces the concept of "exergy" in order to reformulate the second law of thermodynamics and its application to dissipative structures. The sudden manifestation of unexpected highly ordered organization is postulated as evidence of the presence of "attractor states" that are characteristic of systems that driven away from thermodynamic equilibrium (Guerin & Kunkle, 2004).

The precise definition of attractors in social systems, however, remains elusive, except for rich metaphoric value. Nevertheless, scholars such as Reason & Goodwin (1999) are convinced that strange attractors underlie the "deterministic chaos" found in systems of living organisms and societies. Wheately (1992) prefers to call the manifestation of a strange attractor in organizations a "meaning attractor" (p 136). At the very least, it has to be conceded that the analogical value of dissipative structures for social systems research is immense in that it demonstrates the applicability of complexity phenomena in open systems. It is in this sense that reference is made to the concept of dissipative structures in this study of the NSI.

3.4.5 Self-organized criticality

The work done by Bak, Tang & Wiesenfeld (1987) demonstrates the link between self-organisation and complexity through the observation of the phenomenon of self-organised criticality. Apart from this major discovery, the research work yielded several observations that are of major importance in understanding the origin and nature of complex behaviour.

Firstly, the study linked together three factors that have been observed to generate complexity. In the study of cellular automata, various experimental works in computational mechanics (e.g. von Neumann, 1966; Wolfram, 1986) demonstrated that complexity stemmed from systems of local interactions. As shown in the above discussion, Mandelbrot's work on fractal geometry is derived from iterative mathematical laws. In phase transitions, complex behaviour is associated with power laws. The work done by Bak, Tang and Wiesenfeld (1987) on a simple automaton exhibited all three features, namely, fractal geometry, 1/f noise and power laws as involved in critical-point phenomena.

Secondly, the study demonstrated the robustness of the conditions that lead to complexity. It was observed that variable parameters of the system could be significantly altered without affecting the emergence of critical behaviour, which strengthens the notion of self-organised criticality. In this respect, the emergence of complexity was demonstrated to be a spontaneous process generated from simple local interactions in a natural environment, rather than a phenomenon artificially produced from controlled laboratory conditions or computer simulations. The demonstration of self-organised criticality strengthens the value of chaos and complexity as useful theories for describing natural phenomena.

The foregoing discussion traces the development of chaos and complexity from various strands of scientific effort. A strong case is made of the need for these perspectives in the natural sciences as well as the social sciences. The imagery provided by the key concepts lends powerful metaphors for application in the study of the NSI. The last two chapters of this thesis demonstrate the richness of chaos and complexity in making sense the nature and dynamics of the national system of innovation of South Africa. The next chapter delves into the NSI itself, to lay out its constituents, in preparation for the deployment of chaos and complexity theories in its explication.

CHAPTER 4
SOUTH AFRICA'S SCIENCE AND TECHNOLOGY LANDSCAPE

4.1 Overview

South Africa's science and technology landscape is the subject matter and unit of analysis of this study. In the introductory chapter of this thesis, the origins of the NSI concept in relation to South Africa's science and technology territory were discussed. The NSI was defined in the National Research and Development Strategy of South Africa as "a set of functioning institutions, organizations and policies that interact constructively in the pursuit of a common set of social and economic goals and objectives, and that use the introduction of innovations as the key promoter of change" (Government of South Africa, 2002). Chapter 2 is devoted to a comprehensive discourse that fully unpacks the meaning of the terms and their connotations for a developing country such as South Africa. The purpose of this chapter is to delineate the composition of the NSI. It is a response to the first critical question of this study, which is:

Which institutions and organizations in South Africa constitute the National System of Innovation and what are their roles and functions?

It is perhaps important to start with a disclaimer: it is virtually impossible to map out a complete inventory of what the NSI comprises. This is true not only for the visible elements of the NSI such as organizations but also for the intangible, such as policies and networks. The participating organizations include both the public and private sectors; the latter incorporates the informal sector which, by its very nature, is difficult to fully account for. There are also non-governmental organizations that are active, albeit in a smaller role. It is not easy to immediately determine the relative value of contributions by the various players. However, in terms of expenditure in the 2006-2007 financial year, private business accounted for almost 56% of all R&D expenditure in the country, as shown the table below. The total expenditure on R&D for the year 2006-2007 in South Africa is R16.5 billion (DST, 2008).

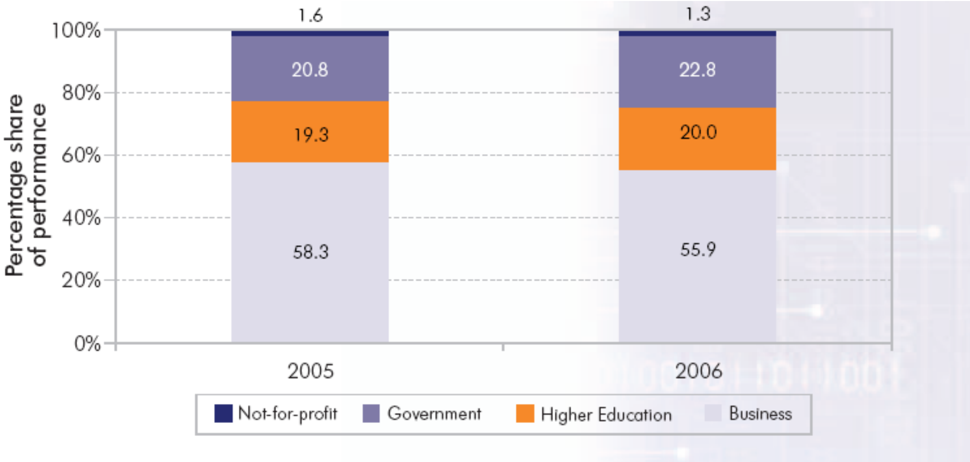

Figure 4-1: Performance of R&D by sector (DST, 2008)

South Africa's NSI comprises of the following list of interrelated and interlocking entities:

- Legislation, policies and strategies
- Advisory bodies
- Funding agencies
- Education institutions
- Research and development
- Technology transfer and innovation
- Enterprises, NGOs and civil society

4.2 Legislation, policies and strategies

Legislation, policies and strategies are documents that regulate the scope, functions and powers of the institutions and organizations that form the NSI. The acts of parliament set in place foundational aspects of science and technology, particularly where the cooperation of a cross-section of the country's government departments and society is essential. Most of the legislation has to do with establishing the key institutions, delineating their powers and functions. Some of these institutions are discussed below.

Some of the laws provide a basis for securing strategic advantages for areas of science and technology that are deemed by the country to be of national importance. The Astronomy Geographic Advantage Act, for instance, makes provision for the preservation of parts of the country that could be instrumental for providing competitive bases for hosting international astronomical observation equipment. Radio-quiet zones in the Northern Cape are examples of areas that are earmarked for the massive Square Kilometre Array Radio telescope (the SKA) which South Africa is bidding to host. More is said about the SKA in the latter part of this section which deals with major S&T initiatives.

Laws, policies and strategies are important in understanding the nature and function of a national system in that they describe ways in which organizations and institutions are meant to interact with one another. They provide also a backdrop against which the actual behaviour of the different institutions within the NSI, relative to one another, could be understood. The extent of the departures of behaviour from the formal norms may indicate a degree of self-regulation and adaptation.

The most important policy documents for South Africa's science and technology that have been produced since the new democratic order began in 1994 are the White Paper on Science and Technology, the National Research and Development Strategy and the recent Ten-year Plan for Science and Technology. These are discussed briefly below, in order to lay a foundation for a good understanding of the key issues and objectives that underpin the NSI in South Africa.

4.2.1 The White Paper on Science and Technology (1996)

The White Paper on Science and Technology was the first comprehensive policy document to be approved by parliament as a blueprint for science and technology development in post-apartheid South Africa (DACST, 1996). It followed years of discussions and extensive consultations which took place within the ruling party, government, the science and technology fraternity and the larger society at large. The notions of "innovation" and the "national system of innovation" were first introduced by the White Paper to the South African policy context, as a framework for understanding and managing the collective of the country's organizations and institutions that have a stake in scientific research and technological innovation.

The White Paper presented a strong argument for embracing technological change as a centre piece of the country's economic growth and transformation effort. The paper delineates five broad themes upon which the country would shape and pursue global competitiveness while addressing the social and economic needs of its people. These are:

- Promoting competitiveness and employment creation
- Enhancing quality of life
- Developing human resources
- Working towards environmental sustainability
- Promoting an information society

The White Paper laid a framework for organizing efforts from the part of government towards bringing about a knowledge economy. The reference to a national system signaled a strong need for science and technology institutions to contribute towards shared national ends. The White Paper remains a point of reference for science and technology policy discourse in South Africa.

4.2.2 The National Research and Development Strategy (2002)

Using the White Paper as its launch pad, the thrust of the National Research and Development Strategy (Government of South Africa, 2002) was to map out government's science and technology strategy around three areas, namely innovation, human capital and governance. The innovation pillar entailed setting up science and technology missions around key areas for South Africa's economic development. These were:

- Poverty reduction – to develop, demonstrate and diffuse technologies that have a direct impact on the quality of life;
- Key technology platforms – to support the development and growth of industries in biotechnology and information and communication technology;
- Advanced manufacturing – to build knowledge intensity that would impact on the country's various manufacturing industries;

- Resource-based industries – to take advantage of the country's rich primary resources by strengthening technological excellence to further develop industries in agriculture, fishing and forestry, mining and minerals, and energy production.

The human resources development pillar was meant to address the critical shortages of researchers in many important areas; the transformation of the demographic profile of the country's research manpower by training more black and female researchers; and strengthening the quality of researchers and research output, particularly in areas where the country enjoys clear advantages.

The governance pillar of the strategy was aimed at addressing the fragmented state of science and technology institutions. The strategy called for streamlining planning, budgeting and reporting arrangements for the country's public science institutions. This would create coherence in the research agenda and bring about administrative and resource efficiencies.

4.2.3 The Ten-Year Plan for Science and Technology (2007)

The subtitle of the ten-year plan is "Innovation Towards a Knowledge-Based Economy" (DST, 2007), which suggests the centrality of innovation in government's policy for economic transformation. The plan aims to close the gap between itself and the recognized knowledge-driven economies by focusing on long-range objectives, which are termed "grand challenges" in the plan. The four key drivers to be employed to realize these grand challenges are human capital development, knowledge generation and exploitation, knowledge infrastructure and enablers to address the innovation chasm. The grand challenges to be addressed in the ten years to 2018 are identified as follows (DST, 2007):

- "Farmer to Pharma" value chain - to strengthen the bio-economy using the nation's indigenous resources in pharmaceuticals and biotechnology.

- Space science and technology - to grow the country's capabilities in satellite technology and to harness its geographical advantages for earth observation, communications and navigation.

- Energy security – to secure safe, clean, affordable and reliable energy supply for the country's medium and long-term needs.

- Global climate change – using the country's strategic geographical location to develop a leading centre for climate change research.

- Human and social dynamics – to develop capacity to understand the complex human factors that shape responses within organizations and society.

As a response to the above policies, South Africa begun to increase its levels of investment in science and technology, from a very sharp decrease prior 1994 to a target of 1% of GDP by 2008 and 2,5% by 2018. The investment trajectory of the country's Gross Expenditure on Research and Development (GERD) in the post-apartheid period is depicted below in the table published by the Department of Science and Technology (DST, 2006).

The dip in the GERD in the years prior to 1994 can be ascribed largely to the diminished government investments that were directed to securing energy self-sufficiency and military dominance in the region. Such investments were part of a comprehensive effort by the apartheid regime at the time to forestall international isolation and economic sanctions on account of apartheid policies.

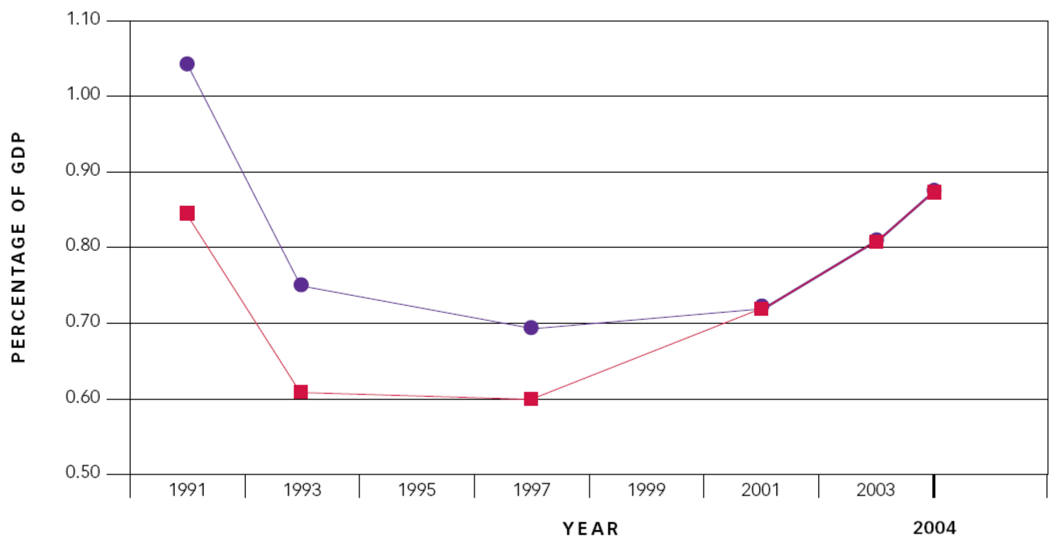

Figure 4-2: South Africa's GERD revised and unrevised, 1991 - 2004

The table above depicts two graphs, one drawn by connecting the round dots and the other connecting square dots. The latter shows GERD figures that included expenditure on military research, which was not included from 2001 figures onwards.

As mapped out in the ten-year plan, the country seems to be on course to transform into a knowledge economy through innovation.

4.3 Advisory bodies

4.3.1 National Advisory Council on Innovation (NACI)

(Information accessed from http://www.naci.org.za, 03/08/2008)

NACI is a council that is appointed by the Minister of Science and Technology in order to advice him/her, and by extension the cabinet, on the role and contribution of science, technology and innovation in the achievement of national objectives. In this perspective, the key national objectives in question are given as follows:

- improve and sustain the quality of life of all South Africans;
- develop human resources for science and technology;
- build the economy; and
- strengthen the country’s competitiveness in the international sphere.

The council currently consists of 22 members from various backgrounds, who bring into the body a range of expertise and experience in science and innovation. In terms of the NACI Act, which determines its role and function, the advisory role of the council should focus on the following arrears:

- Coordination and stimulation of the NSI
- Promotion of cooperation within the NSI
- Structuring, governance and coordination of the S&T system
- Revision of the innovation policy
- Strategies for the promotion of all aspects of technological innovation

- Identification of R&D priorities
- Funding of the S&T system

The council executes its function through various subcommittees and advisory committees, as shown in the structure below. An executive committee meets every month to dispose of matters as indicated by the council. A small secretariat provides day-to-day support to the council, carry out studies and reviews that are necessary to formulate advice. The diagram below indicates how the various structures of the National Council on Innovation relate.

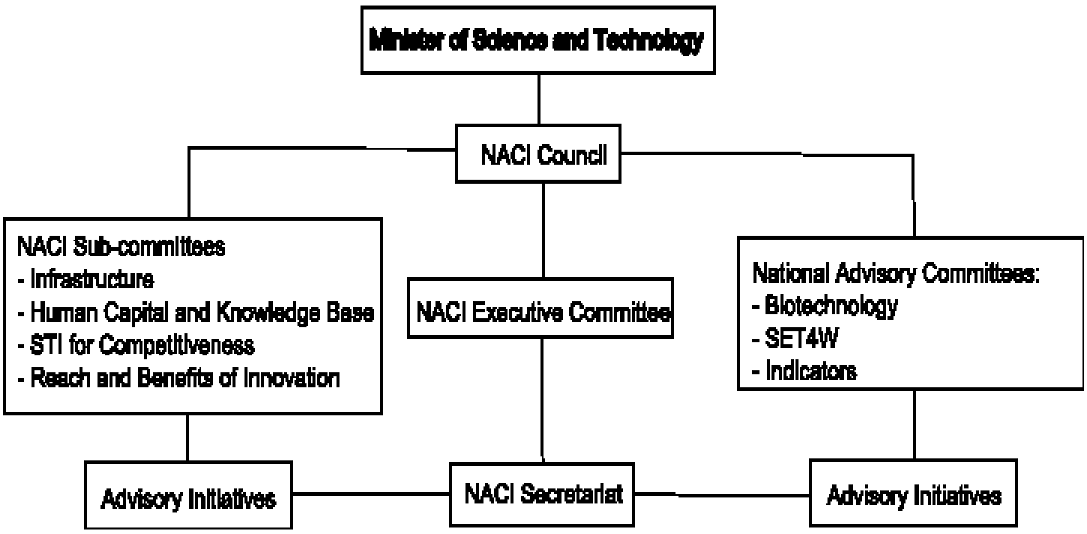

Figure 4-3: NACI structure, accessed from NACI website (http://www.naci.org.za, 03/08/2008)

The committees identified in the above structure suggest that the various areas of focus of NACI's efforts to provide advice on the key science and technology challenges affecting the country. The council's business plan for 2008 indicates plans to formulate a study on energy, suggesting a response to the energy crisis facing the country at this time.

4.3.2 Academy of Science of South Africa

(Information accessed from http://www.assaf.co.za/, 03/08/2008)

The Academy of Science of South Africa (ASSAf) was inaugurated in May 1996. It was formed in response to the need for an academy of science consonant with the dawn of democracy in South Africa. In response to the development needs of the country, ASSAf is activist in its mission of using science for the benefit of society, with a mandate encompassing all fields of scientific enquiry in a seamless way, and including in its ranks the full diversity of South Africa's distinguished scientists.

The Parliament of South Africa passed the Academy of Science of South Africa Act, Act 67 of 2001, which came into force on 15 May 2002. ASSAf is thus the official national Academy of Science of South Africa, recognised by Government and representing South Africa in the international community of science academies. In terms of the Act, the objectives of ASSAf are:

- to promote common ground in scientific thinking across all disciplines, for example the physical, mathematical, life, human, social and economic sciences;
- to encourage and promote innovative and independent scientific thinking;
- to promote the optimum development of the intellectual capacity of all people;
- to provide effective advice and facilitate appropriate action in relation to the collective needs, opportunities and challenges of all South Africans; and
- to link South Africa with scientific communities at the highest levels, in particular within Africa, and further afield (http://www.assaf.co.za/about.html, 03/08/2008).

4.3.3 South African Academy of Engineering (SAAE)
(Information accessed from http://www.saae.co.za/, 02/08/2008)

The South African Academy of Engineering is a non-profit, independent institution whose objective is to promote excellence in the science and application of engineering for the benefit of all members of the public in South Africa. The Academy comprises over 100 South Africa's most eminent engineers of all disciplines and related professionals with proven ability and achievement.

Given the recent formation of SAAE, its activities are still limited. According to the website of the SAAE (www. http://www.saae.co.za, accessed 2 August 2008), the activities that are being developed include:

- Providing a forum for discussions of issues relevant to the formulation of public policies for engineering based activities.
- Organising projects, symposia, meetings and discussions to make best possible use of the multi-professional expertise of the fellows in support of national goals.
- Promoting the innovative application of engineering in South Africa to improve the quality of life of its people.
- Promoting the recruitment, education, training and development of engineering and technical persons from previously disadvantaged groups to increase the technological base of the nation.
- Enhancing excellence and innovation in South African industry by participating in the Annual Technology Top 100 Presidents Awards for export achievement.
- Establishing and maintaining relations with overseas Engineering Academies and the International Council for Engineering and Technological Sciences.

The election of members to the Academy is by invitation only. A maximum of 20 new fellows may be elected annually who have made exceptional contributions to engineering. They are elected by their peers for personal achievement of exceptional merit and distinction. Fellows are distinguished by their title "Fellow of the South African Academy of Engineering" and accordingly use the letters FSAAE next to their names.

4.4 Funding agencies

4.4.1 National Research Foundation (NRF)

(Information accessed from http://www.nrf.ac.za/, 04/08/2008)

The NRF is the main public funding agency for science and technology in South Africa. The role of the NRF is to support and promote research through funding, human resource development and the provision of the necessary research facilities, in order to facilitate the creation of knowledge, innovation and development in all fields of the natural, social, human sciences and technology. The NRF was established in 1999 by an act of parliament as an agency for promoting and supporting basic and applied research as well as innovation. The NRF directs public resources towards academic research, human resource development and supporting South Africa’s national research facilities.

The mandate of the NRF includes the advancement of research in all fields of humanities, social and natural sciences, engineering, technology and indigenous knowledge. It also fosters international partnerships locally and internationally. The NRF also provides information on research as well as strategic advice.

The NRF's facility called the Research and Innovation Support and Advancement (RISA) is responsible for the promotion and support of research and research capacity in the fields of knowledge and technology through:

- investing in knowledge production and promoting basic and applied research, technology development and innovation;
- increasing research capacity and advancing equity;
- investing in research infrastructure; and
- facilitating strategic partnerships and knowledge networks.

The research that is supported by RISA contributes to addressing South Africa's development challenges. Grant funding is prioritised around the following nine focus areas:

- Unlocking the future: advancing and strengthening strategic knowledge;
- Distinct South African research opportunities;
- Conservation and management of ecosystems and biodiversity;
- Economic growth and international competitiveness;
- Education and the challenges for change;
- Indigenous knowledge systems (IKS);
- Information and Communications Technology (ICT) and the information society in South Africa;
- Socio-political impact of globalisation: the challenge for South Africa; and
- Sustainable livelihoods: the eradication of poverty.

The two main support mechanisms employed by the NRF in disbursing funding under the RISA programme, are as follows:

- Student support through block grants to institutions and two complementary types of postgraduate student support i.e. free-standing scholarships and fellowships awarded directly to postgraduate students for studies locally and abroad; and grantholder-linked bursaries granted to researchers within their NRF support package and may be awarded to students selected by the NRF grantholder.

- The Department of Labour, in conjunction with the Departments of Education and of Science and Technology, is responsible for ensuring training in scarce skills, both in Higher Education and other training institutions. The Department of Labour allocates resources from the National Skills Fund (NSF) to the NRF for bursaries and scholarships. The NRF created the Scarce Skills Fund to promote and support students that study at postgraduate levels in areas where skills are scarce and to postgraduate students with disabilities.

The NRF is also responsible for managing a number of national research facilities. A list and brief description of each facility is given below (http://www.nrf.ac.za/profile/, accessed 04/08/2008).

4.4.1.1 South African Astronomical Observatory (SAAO)

The SAAO is the national centre for optical and infrared astronomy in South Africa. Its primary function is to conduct research in astronomy and astrophysics in southern Africa. As the premier optical/infrared astronomy facility in Africa, SAAO also plays a leading role in the promotion of astronomy on the continent. Through devising a vastly superior spherical aberration corrector, and a variety of other innovations, SAAO has contributed to making the Southern African Large Telescope (SALT).

4.4.1.2 SALT Foundation (Pty) Ltd (SALT)

Completed in 2005, SALT is the largest single optical telescope in the southern hemisphere with hexagonal mirror array 11 metres across. SALT will generate a vastly increased data flow compared to the current set of telescopes and instruments in Sutherland. While it may be similar to the Hobby-Eberly Telescope (HET) in Texas, SALT is a redesigned optical system that uses more mirror array. It is able to record distant stars, galaxies and quasars a billion times too faint to be seen with the naked eye. Funding for SALT came from international partners including South Africa, the United States, Germany, Poland, the United Kingdom and New Zealand.

4.4.1.3 Hartebeesthoek Radio Astronomy Observatory (HartRAO)

HartRAO is the national research facility responsible for research and training in radio astronomy and space geodesy in South Africa. The 26 metre diameter radio telescope is available for research either as a single, independent instrument or in global networks of radio telescopes, using the technique of a very long baseline interferometer (VLBI). HartRAO is one of only five permanent fundamental space geodesy stations worldwide and participates in geodetic VLBI through the International VLBI Service, in satellite laser ranging (through the International Laser Ranging Service) and in the Global Positioning System (GPS) (through the International GPS Service). The data is available to the international community.

4.4.1.4 Hermanus Magnetic Observatory (HMO)

The HMO functions as part of the worldwide network of magnetic observatories. Its core function is to monitor and model variations of the Earth's magnetic field. It is primarily the HMO's scientific achievements, critical location, and unique facilities that make it indispensable in the global network of magnetic observatories. The density of geomagnetic recording stations in Africa is significantly less than in other continental landmasses. The continuous recording stations operated by the HMO are the only operational sources of ground-based geomagnetic field data south of the equator in Africa. The HMO is one of only four geomagnetic observatories whose data is used by the World Data Centre for Geomagnetism in Kyoto, Japan, for measuring geomagnetic storm intensity.

4.4.1.5 South African Institute for Aquatic Biodiversity (SAIAB)

The SAIAB is an interactive hub focused on serving the nation by generating, disseminating and applying knowledge to understanding and solving problems on the conservation and wise use of African fish and aquatic biodiversity. SAIAB cares for and develops the National Fish Collection; generates knowledge through research on aquatic biodiversity and the fundamental processes and conservation of aquatic biodiversity in Africa; and trains and educates knowledge workers in aquatic biodiversity. It addresses national and international issues in aquatic biodiversity through the priorities set by national and international funding agencies. SAIABs new offsite wet collection facility will house the National Fish Collection.

4.4.1.6 South African Environmental Observatory Network (SAEON)

The purpose of the SAEON is to generate and archive reliable long-term information relevant to the sustainable management of natural resources and habitat over a range of eco-regions and land uses. These include pristine (wild) landscape, partially pristine (managed) landscape, agriculturally (rural) transformed landscape and urban transformed landscape. SAEON establishes innovative research platforms and information-management systems for long term multidisciplinary, multi-institutional and participatory ecosystem studies with strong regional and global linkages. These research platforms are coordinated as nodes, with the first one – the Ndlovu Node – established during 2004 in Phalaborwa. The second node is one for the coastal-inshore zone and was established in 2006 in Grahamstown. The SAEON Fynbos Node, the Marine-Offshore Node, the Arid Lands Node and the Grasslands/Forests/Wetlands Mosaic Node are expected to be launched during 2006/07. SAEON also runs an innovative education outreach programme which focuses on educators, learners and post-graduate students.

4.4.1.7 iThemba Laboratory for Accelerator Based Sciences

iThemba LABS (Laboratory for Accelerator Based Sciences) is a multidisciplinary research centre and provides facilities for:

- basic and applied research using particle beams
- particle radiotherapy for the treatment of cancer and other life-threatening lesions
- the supply of accelerator-produced radioactive isotopes for nuclear medicine and research.

iThemba LABS brings together people working in medical, biological and physical sciences who are interested in using accelerated particle beams, by providing opportunities for research and postgraduate training in these separate disciplines, and also by stimulating mutual interest in the inter-disciplinary areas.

4.4.1.8 South African Agency for Science and Technology Advancement (SAASTA)

SAASTA aims to be the leading science advancement agency communicating the value and impact of science and technology in a dynamic knowledge economy, and simultaneously building the science, engineering and technology human resource base. The agency is the NRF's official vehicle for facilitating the promotion of SET in society. SET education, through pre-tertiary, tertiary and lifelong learning initiatives, provides the base for creating the required human capital for South Africa's SET endeavours. SAASTA's contribution to the NRF vision is to grow the pool of quality learners today who will become the scientists and innovators of tomorrow.

4.4.1.9 National Zoological Gardens (NZG)

The NZG was declared a national research facility in April 2004 and has since been engaged in a strategic reorientation process to align with, and make a contribution to, the core missions and strategic priorities of the NRF. The NZG, popularly known as the Pretoria Zoo, is undergoing radical transformation from being a traditional zoological garden, to being a national facility for and an active participant in terrestrial biodiversity research. It has the potential to offer South Africa, Africa and the international community at large the infrastructure required to conduct world-class and knowledge-generating research. The NZG houses one of the largest animal collections in the world, and operates three breeding centres covering an area of over 6 000 hectares. The NZG is well placed as an education platform, receiving close to 600 000 visitors a year, comprising learners, educators and the general public.

4.4.2 Water Research Commission (WRC)

(Information accessed from http://www.wrc.org.za/, accessed 11/08/2008)

Following a period of sever drought, the Water Research Commission was established in 1971. This demonstrated the need for knowledge generation on water resources, given that South Africa is one of the countries that have limited supply in this regard. The establishment of the WRC was meant to focus research efforts and increase funding available for water research and development. The WRC would provide strategic leadership in order to direct funding to the priority areas of research for the country.

The WRC was established in terms of the Water Research Act (Act No 34 of 1971), following a period of serious water shortage in South Africa in the early 1970s. It was deemed to be of national importance to generate new knowledge and to promote the country's water research purposefully, owing to the view held that water would be one of South Africa's most limiting factors in the 21st century. In 1971 when the WRC was founded, research and development in water was limited to a few institutions with insufficient funding. There was no research co-ordination in this sector and some key research fields were completely neglected. Furthermore, there was no overall strategic direction or leadership that would provide for the identification of priority areas or appropriate technology transfer. The WRC was established to address all these issues.

South Africa is still under threat of insufficient water supplies, while water quality and availability issues are becoming more acute. However, the country is much better prepared to deal with this problem owing to the WRC's meaningful contribution to the development of the capacity of the water sector, the broadening of the country's water-centred R&D base, and the WRC's continued commitment to direct and fund research on critical issues.

In the future it is envisaged that South Africa's water problems may intensify due to increase in demand owing to population increases, among other demands. Issues such as water for all, quality of life, and a sustainable environment are an essential part of the country's national priorities and require considerable attention. Furthermore, the implementation of the National Water Act of 1998 and other national water strategies places considerable demand on water management and calls for research support. The leadership role of South Africa among nations in southern Africa and in the rest of the continent, especially with regard to water resource and water supply and sanitation issues, poses new challenges and requires new initiatives which are within the mandate of the WRC.

Bearing this in mind, the mandate of the WRC includes:

- Promoting co-ordination, co-operation and communication in the area of water research and development
- Establishing water research needs and priorities
- Stimulating and funding water research according to priority
- Promoting effective transfer of information and technology
- Enhancing knowledge and capacity-building within the water sector.

The essence of the strategy of WRC is, therefore, to be continuously relevant and effective in supporting both the creation of knowledge through R&D funding and the transfer and dissemination of the created knowledge. An appropriate, sustainable knowledge base that is effective in its ability to absorb new knowledge is a prerequisite for effective knowledge dissemination. The WRC, therefore, aims to develop and support a water-related knowledge base in South Africa which is both representative and sustainable, with all the necessary competencies and capacity vested in the corps of experts and practitioners within academia, science councils, other research organisations and government organisations (central, provincial and local) which serve the water sector.

The WRC provides the country with applied knowledge and water-related innovation, by continuously translating needs into research ideas and, in turn, transferring research results and disseminating knowledge and new technology-based products and processes to end-users. By supporting water-related innovation and its commercialisation, where applicable, the WRC seeks to provide further benefit for the country.

In summary, the strategic direction of the WRC is focused on:

- An integrated approach to meeting South Africa's societal and water-sector R&D needs
- Provision of integrated solutions to invariably complex, inter-disciplinary problems
- Ongoing strategic identification of needs (short, medium and long-term needs, both explicit and implicit)
- Investment in knowledge creation, transfer and dissemination (http://wrc.org.za, 11/08/2008).

4.4.3 Technology and Human Resources for Industry Programme (THRIP) (Information accessed from http://www.nrf.ac.za/thrip/, 11/08/2008)

THRIP is an initiative aimed at supporting South Africa's industry through supporting research and technology development as well as enhancing the quality and quantity of appropriately skilled people. THRIPS operates by bringing together researchers, academics and industry in funding partnerships that are designed to improve the quality of their products, services and people. THRIP challenges companies to match government funding for innovative research and development in South Africa.

Managed by the National Research Foundation (NRF) on behalf of the Department of Trade and Industry (the dti), THRIP gives local industry the means to obtain specific responses to its technology needs, by unleashing the potential of our students, researchers, and science and technology experts. THRIP's objectives and priorities ensure that projects not only result in competitive, world-class technologies, but that they also support the growth and transformation of the South African society.

THRIP focuses on projects that specifically promote and facilitate scientific research, technology development and technology diffusion, or any combination of these. All projects funded by THRIP must include human resource development, but the choice of technological focus is left to the industrial participants and their partners.

The industry and the dti share the costs – and therefore the risk – of developing commercial technology on a R2 to R1 basis (industry: the dti). The dti's support may be doubled if a project supports certain THRIP priorities.

Funding takes place in the following ways:

- Firms and THRIP invest jointly in research projects where project leaders are on the academic staff of South African Higher Education Institutions (HEIs).
- THRIP matches investment by industry in projects where researchers/experts from Science, Engineering and Technology Institutions (SETIs) serve as project leaders and students are trained through the projects.

Technology Innovation Promotion through the Transfer Of People (TIPTOP) schemes promote the mobility of researchers and students between the industrial participants, HEIs, and SETIs involved in joint projects. Four TIPTOP schemes are available. These are:

- The exchange of researchers and technology managers between HEIs, SETIs and industry.
- The placement of SET graduates in firms, while they are working towards a higher degree on a joint research project.
- The placement of SET graduates in small, medium and micro enterprises (SMMEs).
- The placement of SET skilled company employees within HEIs or SETIs.

THRIP aims include the following:

- To provide South African industry with the means to obtain specific responses to its technology needs.
- To produce a flow of highly-skilled researchers and technology managers who understand research, technology development and the diffusion of technology from the viewpoints of both industry and academia.
- To provide a new and enhanced educational experience within the context of technology development and/or diffusion, through participation by students in collaborative projects.

THRIP objectives:

- To increase the number and quality of people with appropriate skills in the development and management of technology for industry.
- To promote increased interaction among researchers and technology managers in industry, higher education and SETIs, with the aim of developing skills for the commercial exploitation of science and technology. This should involve, in particular, promoting the mobility of trained people among these sectors.
- To stimulate industry and government to increase their investment in research and technology development, technology diffusion and the promotion of innovation.
- To promote increased collaboration between large and small enterprises, Higher Education Institutions and Science, Engineering and Technology Institutions, by conducting research and development activities leading to technology transfer and product or process development.
- To promote large (thematic) collaborative research and development projects in the dti priority areas.

THRIP priorities:

The dti's financial support for a project may be doubled, if it supports any of the following THRIP priorities:

- To support an increase in the number of black and female students who intend to pursue technological and engineering careers.

- To promote technological know-how within the Small, Medium and Micro Enterprise (SMME) sector, through the deployment of skills vested in HEIs and SETIs.
- To facilitate and support multi-firm projects in which firms, including at least one SMME, collaborate and share in the project outcomes.
- To facilitate and support the enhancement of the competitiveness of black owned enterprises (BEEs) through technology and human resource development. (THRIP, http://www.nrf.ac.za/thrip/, accessed 11/08/2008)

4.4.4 Innovation Fund

(Information accessed from http://www.innovationfund.ac.za, 02/08/2008)

The Innovation Fund (IF) is mandated to promote technological innovation through investing in novel South African technology development and commercialisation. The funding instruments that are managed by the Innovation Fund are listed as follows

4.4.4.1 Research and Development

Technology Advancement Programme (TAP): invests in research and development from proof-of-idea/science to proof-of-concept, and is open to publicly funded institutions (including higher education institutions and science councils), small and medium sized businesses, and any consortia consisting of these.

Missions in Technology Programme (MiTech): a public-private partnership programme for the development of technology platforms, typically with large industry players, which are driven by industries and will lead to multiple products and services. Large businesses wishing to partner must provide 50% of the required investment in cash.

4.4.4.2 Commercialisation

Seed Fund: Invests in early commercialisation/start-up activities to take a technology that is at proof-of-concept / prototype to the market. The R&D funding stage instruments also make provision for early commercialisation planning activities, to ensure an executable business plan exists when the prototype technology is delivered.

4.4.4.3 IP Support

Patent Support Fund for SMEs: In response to the dearth of patenting activity amongst South African companies, this instrument is open to SMEs, to assist in absorbing the cost of protecting their intellectual property through patent registration, at any stage of the patenting process.

Patent Support Fund-Technopreneur: This fund supports the filing of at least a South African provisional patent application in respect of technological inventions by individuals, so-called techno-entrepreneurs, where such inventions have commercial merit and a prototype can be developed in under twelve months.

Patent Support Fund for Research Institutions: Provides subsidy to publicly funded institutions (higher education institutions and science councils) for costs incurred in filing and prosecuting patent applications, and maintaining patents.

Patent Incentive Scheme: A scheme to encourage patent protection through cash incentives to inventors in publicly funded institutions (higher education institutions and science councils) who obtain patents for their inventions.

The R&D as well as commercialisation stage funding instruments mentioned above also cater for expenses associated with intellectual property protection and management, as appropriate. (http://www.innovationfund.ac.za, 02/08/2008):

4.4.5 Tshumisano Trust

(Information accessed from http://www.tshumisano.co.za, 11/08/2008):

Tshumisano Trust is an implementation agency set up by the Department of Science and Technology for the purpose of supporting the Technology Stations Programme (TSP). The Trust provides technical and financial support to Technology Stations, which are based at the country's universities of technology. The Technology Stations in turn offer technical support to existing small and medium enterprises (SMEs) by providing technology solutions, advice and training.

The services to SMEs are provided by technical experts with the requisite skills and expertise. The experts range from professors, lecturers, postgraduate students and external consultants. In this way, the initiative contributes towards enriching research and development work within the host institutions as well as solving technology based problems experienced by the SMEs.

The Tshumisano Trust manages and co-ordinates the technology stations programme with its technology stations as competent service providers to SME's and thus to relieve the DST from the direct implementation management. A Project Management Unit (PMU) at the trust manages the activities of the Tshumisano technology stations programme. Its main functions are (http://www.tshumisano.co.za, 11/08/2008):

- Dialogue with all stakeholders to clarify goals and expectations.
- Strategic guidance and co-ordination for the achievement of the programme objectives, taking into consideration cross cutting issues e.g. Black Economic Empowerment (BEE) and gender empowerment.
- Comprehensive strategic and financial management of the TSP on behalf of the DST or any other stakeholder or donor(s) i.e. receiving grants and donations, allocation of funds to Universities of Technology, managing funds for major projects, major equipment and special initiatives and awarding respective financing to the Technology Stations upon motivated requests.
- Advocacy for the TSP concept in the University of Technology community and facilitation of a enabling environment for the commercial operation of Stations.
- Marketing and establishment of strategic partnerships and linkages as well as fund raising of the TSP with the SME community and with other relevant government support programmes as well as private sector partnerships.
- Development and facilitation of strategies for sustainability.
- Development and provision of generic tools, services and information for all Stations.

Tshumisano provides technical and financial support to Technology Stations, which are based at Universities of Technology/Technikons. Technology Station Programme (TSP) was developed by Department of Science and Technology (DST) to strengthen and accelerate interaction between Technikons/Universities of Technology (UoT) and SME's. The UoT hosts the Technology Stations by providing a sound institutional, organizational and legal framework. (http://www.tshumisano.co.za, 11/08/2008):

4.4.6 Seda Technology Programme (stp)
(Information accessed from http://www.seda.org.za/ accessed 11/08/2008)

The Seda Technology Programme (originally the Godisa Trust), a special initiative of the national Department of Trade and Industry, is responsible for technology transfer and business incubation. The mission of the organisation to contribute to South Africa's economic development through the creation and support of technology business centres, which include incubators and technology demonstration centres. These centres provide a variety of business support services and office infrastructure to small enterprises. The stp provides support to SMEs in five areas, namely:

- Establishment of technology business centres
- Advising on appropriate business models to be adopted
- Development on appropriate business models to be adopted
- Advisory and consultancy services
- Technology transfer and diffusion

4.4.7 Biotechnology Regional Innovation Centres (BRICS)

The Department of Science and Technology set up the BRICS in selected regions of the country in order to stimulate biotechnology research. To date four BRICS have been set up, namely LIFELab, Cape Biotech, BioPAD and PlantBio. The BRICS focus on research and development that is relevant to the economy of the region in which they are situated. According to DST's Annual Report for 2006-2007 (DST, 2007b), the BRICS have financially supported a combined total of more than 100 innovative projects in various areas of biotechnology, disbursed in excess of R500 million, created 38 companies and more than 400 jobs. Some of the areas of activity of the BRICS include:

- Anti-HIV microbicides – technologies that enhance women's ability to deal with the threat of infection;
- Gene discovery, including from deep mines (a feature of SA's gold mine industry);
- Improvement of cattle breeds (Bonsmara) – application of new technologies to strengthen South Africa's agriculture;
- Bio-treatment of acid mine drainage – the Rhodes BioSURE Process that uses a unique cocktail of bacteria to neutralise the pH of mine drainage using human sewage
- as a carbon source;
- Drug delivery – both a platform for rate modulated drug delivery designs, and target-specific drug delivery;
- Biological control products – treatments for pests affecting commercial agriculture;
- Bioleaching – use of microbes to leach metals from their ores; and
- High throughput sequencing – Inqaba Biotech – the first African company to offer a service of this nature. (DST, 2007b)

4.5 Science councils

South Africa has got a number of national science councils that have been established to carry out research and development in a variety of disciplines. A brief description of some of them, as obtained from their respective websites, follows.

4.5.1 Agricultural Research Council (ARC) (http://www.arc.agric.za/, accessed 22/09/2008)

The ARC was established by the Agricultural Research Act 86 of 1990 (as amended) and is the main agricultural research institution in South Africa. In terms of the Act, the objectives of the ARC as "conducting of research, development & technology transfer in order to:

- Promote agriculture & industry;
- Contribute to better quality of life;
- Facilitate/ensure natural resource conservation"

Ten research institutes within the council, carry out this function, whose activities are grouped under five divisions: (1) grain and industrial crops, (2) horticulture, (3) livestock, (4) natural resources and engineering, and (5) sustainable rural livelihoods. The ARC is also responsible for maintaining national assets and undertaking programmes or rendering services that are required from time to time by the Department of Agriculture (DoA) and other stakeholders. The ARC reports to the DoA as its line function political authority. (http://www.arc.agric.za/, accessed 22/09/2008).

4.5.2 Council for Geoscience (CGS)

(Source of information http://www.geoscience.org.za/, accessed 22/09/2008)

The Council for Geoscience (CGS) is the legal successor to the Geological Survey of South Africa, which was formed in 1912 by the amalgamation of 3 former Surveys, the oldest of which - the Geological Commission of the Cape of Good Hope - was founded in 1895. The Geoscience Act, Act 100 of 1993, established the CGS in its present form. Today, the Council provides earth-science information and services to improve the management of natural resources and the environment, boasting excellent facilities and expertise.

The work of the Council for Geoscience focuses on the following areas:

- Geoscience mapping
- Water resource assessment and protecction
- Minerals development
- The environment and chemical geohazards
- Engineering geoscience and physical geohazards
- Education and information

(http://www.geoscience.org.za/, accessed 22/09/2008)

4.5.3 Council for Scientific and Industrial Research (CSIR)

(Source of information http://www.csir.co.za/, accessed 22/09/2008)

The CSIR was established in 1945 through an act of parliament. The CSIR is the biggest single science institution in South Africa and is one of the leading science and technology research, development and implementation organisations in Africa. The CSIR's main site is in Pretoria, Gauteng Province, while it is represented in other provinces of South Africa through regional offices. In terms of its mandate, the CSIR transfers the knowledge generated through research activities by means of technology and skilled people. The broad knowledge domains involved are biosciences; the built environment; defence, peace, safety and security; materials science and manufacturing; and natural resources and the environment.

The CSIR is also developing capacity in emerging research areas, which are new areas of science that could be unique to local circumstances or successful internationally and need to be established for local competitiveness. Currently these include nanotechnology, synthetic biology and mobile autonomous intelligent systems. The CSIR houses specialist facilities of strategic importance for African science. These include information and communications technologies; laser technology; and space-related technology. Further important units within the CSIR include R&D outcomes and consulting and analytical services.

The CSIR, like other science councils, is funded through an annual grant from Parliament, through the Department of Science and Technology (DST), which accounts for close to 40% of its total income. The remainder of its income is generated from research contracts with government departments at national, provincial and municipal levels, the private sector and research funding agencies in South Africa and abroad. Additional income is derived from royalties, licences and dividends from IP management and commercial companies created by the CSIR. The parliamentary grant is focused on the knowledge base and facilities in the CSIR to ensure these stay at the leading edge of technological development. It is invested in developing new areas of expertise, undertaking 'pre-competitive' research too risky for the private sector to fund and for training young researchers. The CSIR's shareholder is the South African Parliament, held in proxy by the Minister of Science and Technology.
(http://www.csir.co.za/, accessed 22/09/2008)

4.5.4 Human Sciences Research Council (HSRC)

(Source of information http://www.hsrc.ac.za/, accessed 22/09/2008)

The Human Sciences Research Council (HSRC) is a statutory body, established in 1968. The HSRC conducts large-scale, policy-relevant, social-scientific projects for public-sector users, non-governmental organisations and international development agencies, in partnership with researchers globally, especifically in Africa. The HSRC aligns its research activities and structures to South Africa's national development priorities such as poverty reduction through economic development, skills enhancement, job creation, the elimination of discrimination and inequalities, and effective service delivery.

Since August 2005, the HSRC began to focus on bridging the gap between research, policy and action; thus increasing the impact of research. This effort involves collaborations with key stakeholders such as government, other research organisations, multinational agencies, universities, non-government organisations and donor organisations. Some of the main areas of research activity currently are the following:

- Centre for Service Delivery
- Child, Youth, Family and Social Development
- Democracy and Governance
- Education, Science and Skills Development
- Social Aspects of HIV/AIDS and Health

(http://www.hsrc.ac.za/, accessed 22/09/2008)

4.5.5 Medical Research Council (MRC)

(Source of information http://www.mrc.ac.za/, accessed 22/09/2008).

The Medical Research Council of South Africa was established by section 2 of the South African Medical Research Council Act. 1969 (Act No. 19 of 1969). In terms of this Act, the objects of the MRC are, through research, development and technology transfer, to promote the improvement of the health and the quality of life of the population of the Republic and to perform such other functions as may be assigned to the MRC by or under this Act. To fulfil its mandate, the MRC performs the following functions, among others:

- undertakes research on behalf of the government or any person or institution, or support such research financially;
- operates and maintains national research facilities that are assigned to it;
- promotes co-operation between South Africa and other countries with regard to research, development and technology transfer;

- establishes and controls research laboratories and other facilities in those fields of research which the Board may from time to time approve;
- make grants-
- to universities, technikons, colleges, museums and scientific institutions in aid of research by their staff and to establish channels for the exchange and supplementation of knowledge and expertise. (http://www.mrc.ac.za/, accessed 22/09/2008).

4.5.6 Mintek

(Source of information http://www.mintek.co.za/, accessed 22/09/2008)

Mintek, South Africa's national mineral research organisation, is one of the world's leading technology organisations specialising in mineral processing, extractive metallurgy and related areas. Mintek works closely with industry and other R&D institutions to provide service test work, process development and optimisation, consulting and innovative products to clients world-wide. Mintek is an autonomous statutory organisation which reports to the Minister of Minerals and Energy. About 35 per cent of the annual budget of R290 million is funded by the parliamentary grant, with the balance provided by contract R&D, sales of products and services, technology licensing agreements, and joint-venture private sector companies. Mintek has about 500 permanent staff members, over half of whom are scientists, engineers and other technical R&D specialists.

Mintek's activities include:

- providing essential services (information, consulting and experimental);
- increasing the competitiveness of industry by developing appropriate technology to cut costs and improve recoveries;
- developing "breakthrough" process technologies and novel uses for metals and their products;
- marketing its commercial products and technologies to industry;
- establishing strategic partnerships and joint ventures;
- participating in regional development initiatives and Southern African Development Community activities and projects;
- maintaining and expanding international scientific links; and,

- developing the human resources potential of the region through educational and training activities.

Mintek has a complete range of process development services, from preliminary bench-scale investigations to large-scale piloting and integrated flowsheet development in support of bankable feasibility studies. Engineering design, plant construction and commissioning are carried out in conjunction with partners across the world. Mintek's comprehensive laboratory and piloting facilities for sample preparation, milling, flotation, physical separation, smelting, leaching, pressure leaching, and metal recovery and purification are supported by internationally accredited analytical laboratory and mineralogical services. (http://www.mintek.co.za/, accessed 22/09/2008)

4.5.7 Standards South Africa (Stanza)

(Source of information http://www.stansa.co.za/, accessed 22/09/2008)

Stanza was established in terms of the Standards Act, 1945 (Act No. 24 of 1945) and continues to operate in terms of the latest edition of the Standards Act, 1993 (Act No. 29 of 1993) as the national institution for the promotion and maintenance of standardization and quality in connection with commodities and the rendering of services including:

- publishes national standards which it prepares through a consensus process in technical committees
- provides information on national standards of all countries as well as international standards
- tests and certifies products and services to standards
- develops technical regulations (compulsory specifications) based on national standards, monitors and enforces compliance with such technical regulations
- monitors and enforces legal metrology legislation
- promotes design excellence
- provides training on aspects of standardization.

Stanza recently aligned its activities with seven different industry sectors, each housing the whole range of services pertinent to a particular industry. The seven industry sectors are:

- Chemicals
- Electrotechnical
- Food and Health
- Mechanical and Materials
- Mining and Minerals
- Services
- Transportation

(http://www.stansa.co.za/, accessed 22/09/2008)

4.5.8 National Health Laboratory Service (NHLS)

(Source of information http://www.nhls.ac.za/, accessed 22/09/2008).

The NHLS is an amalgamation of public health laboratory services which started in June 1999, aiming at uniting the fragmented public health laboratory services, avoiding duplication of services resulting in wastage and cost-inefficiency and, most importantly, creating a world-class health laboratory service accessible to all South Africans in all corners of the country. The main institutions to be brought under the NHLS are:

4.5.8.1 *South African Institute for Medical Research (SAIMR)*

The SAIMR was established in 1912 by an agreement between the Chamber of Mines and the Union Government of South Africa. Its primary task was to carry out research, and, in particular, to try to reduce the high death rate from pneumonia and other diseases prevalent in mineworkers on the Witwatersrand. The SAIMR was also permitted to carry out diagnostic work and charge for this service and to sell vaccines it produced. The work was done on a non-profit basis, the surplus earned going towards the development of the organisation. In the national interest, the SAIMR expanded its functions far wider, to include research into all the diseases that posed health problems in South Africa, such as pneumonia, diarrhoeal diseases, meningitis, malaria, poliomyelitis, tuberculosis, cancer, heart and genetic diseases and AIDS, and established for itself a worldwide reputation for excellence.

4.5.8.2 *National Institute for Virology (NIV)*

The NIV was established in 1976 when the government took over the laboratories of the Poliomyelitis Research Foundation. The NIV was the national virology reference centre in the country and had several reference laboratories accredited by the World Health organization, the only biosafety level-four laboratory in Africa. This is the highest safety status accorded to a laboratory and it provides the environment for scientists to work with highly contagious and dangerous bio-hazardous materials and pathogenic organisms such as viruses causing Congo fever, Lassa fever and Ebola fever.

4.5.8.3 *National Centre for Occupational Health (NCOH)*

The NCOH was established as the Pneumoconiosis Research Unit of the former SAIMR in the 1950's. It was subsequently transferred to the Council for Scientific and Industrial Research (CSIR), thereafter to the Medical Research Council (MRC) and in 1979 became a part of the then Ministry of Health. The centre has the capacity to investigate occupational diseases and laboratories for occupational environment analysis. It serves as the occupational medicine department for the University of Witwatersrand and was internally restructured in 1997 to accommodate a changing occupational health environment.

4.5.8.4 *University Pathology Laboratories*

The pathology departments and laboratories of the medical schools of the universities of the Witwatersrand, Pretoria, Cape Town, Limpopo, Stellenbosch, Free State, Walter Sisulu and KwaZulu-Natal are involved in teaching, research, training and the provision of diagnostic services to the hospitals in which they teach their students.

4.5.8.5 *Provincial Departments of Health*

These include laboratories set up by the various provinces particularly in the rural areas.

The NHLS forms a national network of integrated pathology laboratories throughout the country that utilise common laboratory management systems and transport networks to facilitate transport of specimens, referral of tests to reference laboratories and delivery of results. Approximately 265 laboratories are included in the NHLS, employing about 6,500 people. Their activities comprise diagnostic laboratory services, research, teaching and training, and production of sera for anti-snake venom, reagents and media. All laboratories provide laboratory diagnostic services to the national Department of Health, provincial hospitals, local authorities and medical practitioners.

Research conducted by the NHLS covers a wide spectrum of activities in all pathology disciplines. Grants in support of research are made by the SA Medical Research Council, the Cancer Association of South Africa, the SA Sugar Association, Poliomyelitis Research Foundation, pharmaceutical companies, private donors and a number of overseas institutions, among others. A large part of the research programme is financed by the NHLS itself from the earnings of its laboratory services. (http://www.nhls.ac.za/, accessed 22/09/2008).

4.5.9 The Africa Institute of South Africa (AISA)

(Information obtained from http://www.ai.org.za/, accessed 22/09/2008).

The Africa Institute of South Africa is an independent research organisation and think-tank, focussing on Africa in its research, publications and resource library. The Institute has built a solid reputation over 40 years, combining in-depth analysis and research with topicality and policy relevance.

AISA's mandate gives it full responsibility to conduct research on African affairs; the institute covers all topics in contemporary Africa, ranging from politics, socio-economics and issues of development. AISA also houses one of the most impressive libraries for documentation on African affairs in the world. AISA's researchers include some of the foremost thinkers on contemporary African affairs in the world and their research output is of a magnificent standard. (http://www.ai.org.za/, accessed 22/09/2008).

4.6 Tertiary education institutions

South Africa has 23 public universities, following a process of mergers and incorporations of its universities and technikons. The technikons are now referred to as universities of technology. The amount of investment in research and development that is contributed by the universities is 20% of the total for the country

(DST, 2005). The types of research that are conducted by the universities are mainly basic and applied research, as reflected in the table below. Owing to historical reasons, the bulk of research output is concentrated in a few of these universities. In addition to the 23 public universities, there are several foreign and private universities that are also active in the country, contributing to training and research.

	Amount	
Type of research	R 000	%
Basic research	1 049 330	41,4
Applied research	979 626	38,7
Experimental research	505 014	19,9
Total	**2 533 971**	100,0

Table 4-1: Types of research performed by higher education institutions (DST, 2005)

4.7 Answer to the 2nd critical question

The foregoing discussion provides an extensive review of the capacity of the NSI, in terms of the large array of institutions and organizations that constitute it. A question that has to be addressed has to do with the extent of cooperation and connectivity of all the component entities. This is the substance of the second critical question for this study, which is:

In what ways do South African institutions that are active in knowledge production and technological innovation collectively demonstrate system behaviour?

The next section is devoted to providing an answer to this critical question. Further elucidation of this question is done in the next two chapters, where the discussion is taken up in the context of chaos and complexity. See subsections on interconnectedness, self-organisation and emergence. Here, only a beginning is made to address the question.

4.7.1 System behaviour and performance of the NSI

To conclude this section which maps out the institutions and organizations that make up South Africa's NSI, it is useful to provide an indication of the performance of the innovation system as a whole. For this purpose, a few performance indicators will be used based on the National R&D Surveys conducted by the Centre for Science, Technology and Innovation Indicators (CeSTII) of the HSRC. Two aspects are important in this analysis. Firstly, the indicators will illustrate the level of success the NSI has achieved towards attaining national objectives. Secondly, indicators will provide a hint about the extent to which the institutions and organizations within the NSI are cooperating towards the attainment of national goals.

4.7.2 Funding of R&D in South Africa

The funding of R&D in South Africa can be a complete study on its own. For the purpose of this study, it is to sufficient to provide a broad synopsis of the salient features. The figures discussed here are provided by CeSTII of the HSRC on behalf the Department of Science and Technology. The latest figures available are for the 2006-2007 R&D survey. The funding for science and technology in South Africa has seen an earnest rise since the publication of the White Paper in 1996 as can be seen in the figure below. South Africa spent more than R16.5 billion on R&D in during the financial year 2006-2007 which represents 0.95% of GDP.

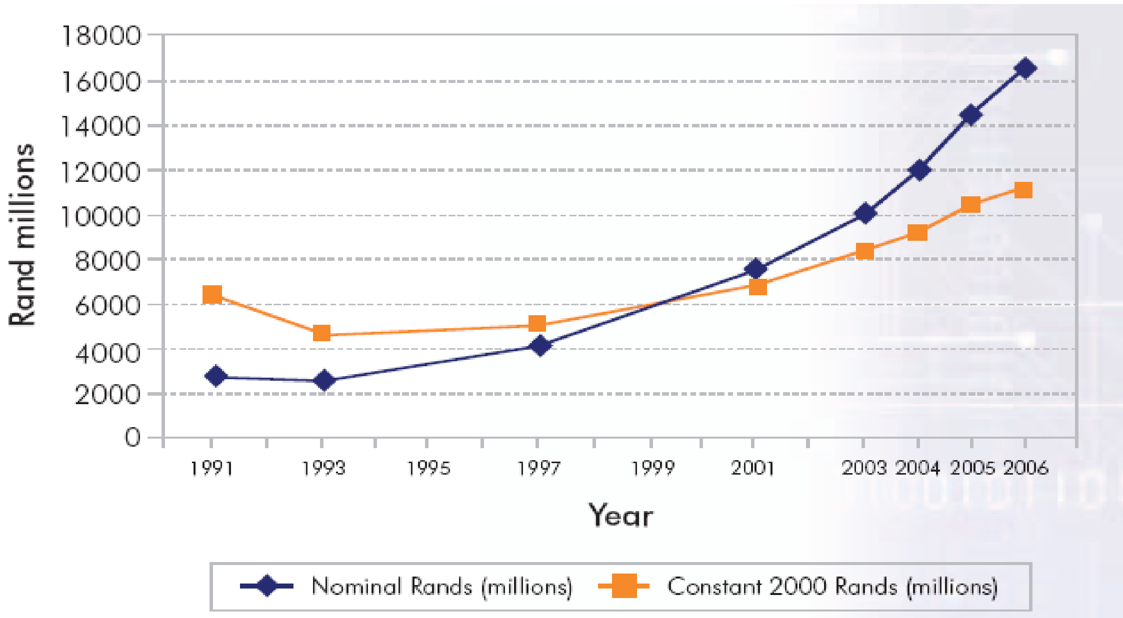

Figure 4-4: South Africa's gross expenditure on R&D (DST, 2008)

In terms of percentage of GDP, the figures translate into the following graph:

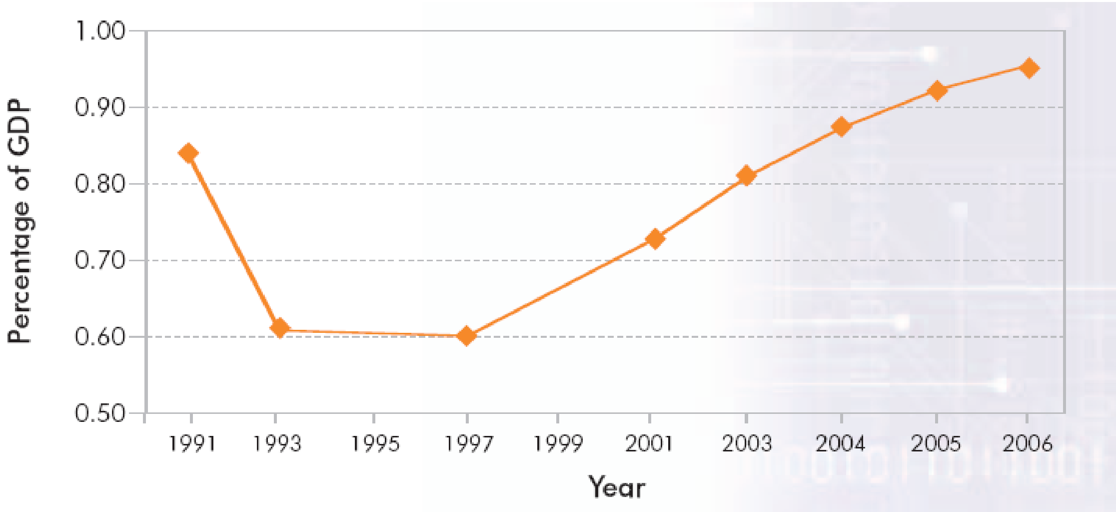

Figure 4-5: South Africa's R&D expenditure as percentage of GDP

The graphs suggests that the country is on course to achieve a 1% level of expenditure by the year 2008, which had been set as a target by DST.

The private sector continues to be the main contributor of R&D funding in South Africa, which is an anomaly for a developing country. The figures indicate that in 2006, the private sector contributed almost 56% of all funding for R&D, as indicated in the graph below:

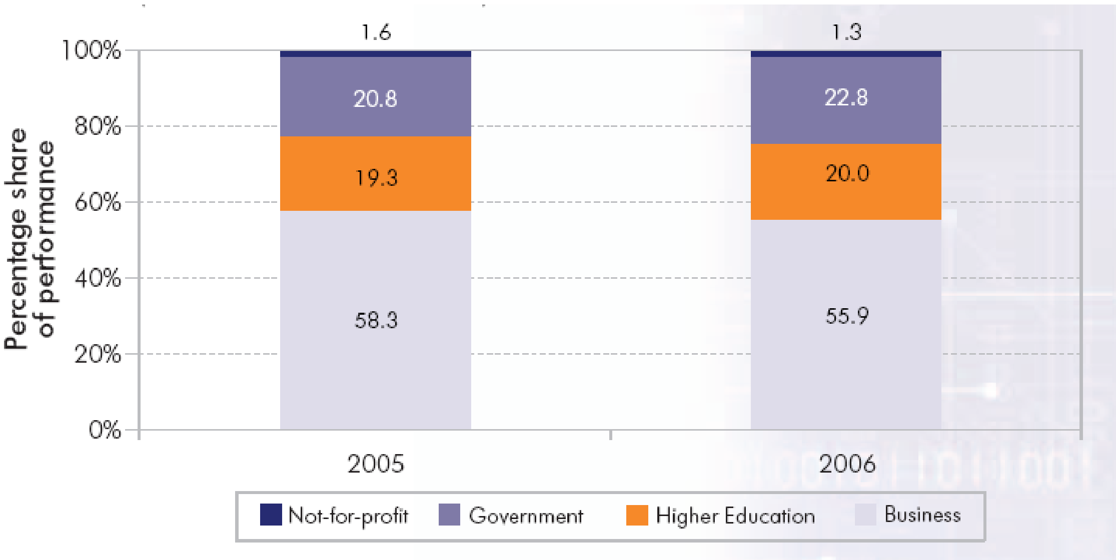

Figure 4-6: Performance of R&D by sector (DST, 2008)

For a country that has only recently begun to mobilize its national resources towards technological innovation, South Africa's efforts suggest that its policies and programmes are on course to accomplish its ambitious goals as set out in the White Paper and the National R&D Strategy. There are continuing challenges, such as the relatively small human resource base, that continues to record slow growth. The new Human Capital Development Plan and the Ten-year Innovation Plan address this and other challenges. The country appears to have the necessary institutional capacity to stimulate growth in science and technology and a full development of a knowledge economy.

The performance of the NSI suggests a level of coordination among the institutions and organizations. The growth in R&D expenditure by the private sectors may indicate that the private sector, even though it is not under the jurisdiction of government, is somewhat responsive to system movements that promote increased investment. This is a very positive trend because it reflects the reality of the leading knowledge economies, where private business contributes the bulk of R&D resources.

Such responsiveness on all the components of the NSI is illustrative of the level of development of system behaviour. This demonstrates that the parts work together in achieving their own business objectives as well as the national objectives of the society they operate in. The introduction of new policies and performance goals by the public sector elements of the NSI appear to induce a positive feedback from the side of industry. It is demonstrated in the next chapter, in the analysis of expenditure on R&D by each sector, that there is great deal of cooperation among the various sectors of the NSI. This is a symbiosis that is critical for the health of the system. To this end, changes in policy that are effected by one part of the system have an influence across all other parts. Changes, both positive and negative, that affect one part of the system, reverberate across all the linked components. All these elements confirm that the various institutions and organizations that have a stake in R&D in South Africa collectively exhibit system behaviour.

The next two chapters will provide further evidence of system behaviour of the components of the R&D institutions of the country. However, in this discussion, theories of chaos and complexity are being applied to explain some of the emergent phenomena and increased self-organisation.

CHAPTER 5

THE NSI AS A NON-LINEAR COMPLEX ADAPTIVE SYSTEM

5.1 Overview

In the last chapter, the elements that make up South Africa's national system of innovation were identified and their roles defined. Furthermore, an argument was presented as to why, collectively, these elements demonstrate system behaviour. In this chapter, an argument is presented for a chaos and complexity perspective on the national system of innovation. In the opening chapter of this thesis, the properties of chaos and complexity were identified and described. These properties are being used below to anchor an argument that the NSI's behaviour could be described on the basis of chaos and complexity.

A thesis that is being put forward in this study posits that the national system of innovation has demonstrated characteristics that suggest that it has the capacity to self-organise. What is being presented in this chapter is the evidence of that self-organisation. It has been demonstrated in the preceding chapters that self-organisation is a concept that straddles physical, mathematical and social sciences. It is accepted that there is no universal formal definition of what constitutes self-organisation (Shalizi, 2001). This is true for the "exact" sciences as much as it is for social and human sciences. How then are we going to demonstrate self-organisation for the subject under discussion in this enquiry?

To answer this question, we will embark on an intuitive exercise, based on observations from the performance data of the national system of innovation. For the purposes of this discussion, self-organisation would be sufficiently demonstrated if the elements of the NSI discussed in the last chapter collectively exhibit unitary behaviour without prior external programming.

5.2 Interconnectedness

The South African national system of innovation is made up of a set of interrelated institutions that create, diffuse and adapt new technical knowledge such as the universities, science councils, government laboratories, government, private business and non-governmental organizations. The results of the latest (2004-5) R&D survey depicted in the table below show the amount of expenditure on R&D by each sector and the relevant source of funding for each case. The reason for the table in this discussion is to demonstrate the extent of interconnectedness among the elements that form the national system of innovation. The expenditure figures shown in the table are used as a proxy for demonstrating the extent of cooperation that happens in actual terms around R&D activities.

	Business enterprise		Government		Higher education		Not-for-profit		Science councils		Total	
Source of funds	Amount		Amount		Amount		Amount		Amount		Amount	
	R 000	%	R 000	%	R 000	%	R 000	%	R 000	%	R 000	%
Own funds	4 295 002	63,5	308 487	59,9	11 07 695	43,71	50 617	25,5	190 521	9,5	5 952 322	49,6
Government	481 519	7,1	129 685	25,2	170 616	6,73	37 892	19,1	1 096 818	54,9	1 916 530	16,0
Other local business	371 362	5,5	2 666	0,5	364 041	14,37	18 411	9,3	293 030	14,7	1 049 510	8,7
Higher education	N/A	N/A	274	0,1	N/A	N/A	586	0,3	1 438	0,1	2 298	0,0
Other South African sources	410 168	6,1	16 454	3,2	156 640	6,18	19 481	9,8	159 956	8,0	762 699	6,4
Foreign	1 208 310	17,9	57 765	11,2	303 002	11,96	71 281	36,0	254 287	12,7	1 894 645	15,8
Agency funding (e.g. NRF, MRC, ARC etc.)	N/A	N/A	N/A	N/A	402 925	15,90	N/A	N/A	N/A	N/A	402 925	3,4
Science councils	N/A	N/A	N/A	N/A	29 052	1,15	N/A	N/A	N/A	N/A	29 052	0,2
Total	**6 766 361**	**100,0**	**515 331**	**100,0**	**2 533 971**	**100,00**	**198 268**	**100,0**	**1 996 050**	**100,0**	**12 009 981**	**100,0**

* N/A entered where specific source of funds was not asked of the relevant sector

Table 5-1: 2004-2005 R&D expenditure by sources of funding (DST, 2005)

An immediate observation that can be made from the table is that every sector receives funding for R&D from almost every other sector. The universities raise most of their funds for R&D from other sources, with only 43,71% derived from own sources. This is completely true for the higher education sector. As it may be expected, the business sector, because of it being profit-oriented, has fewer funding partners for R&D. Nevertheless, more than a third of business funding for R&D comes from other sources within South Africa’s NSI.

The significance of these funding levels for a new NSI is in that they signify the extent of collaborations in research activities. These collaborations may be in the form of joint research projects, contract R&D arrangements or institutional funding obligations. The general conclusion that could be drawn is that the various sectors, i.e. institutions and organization within South Africa’s NSI have a high degree of interconnectedness. This means that the various sectors work with one another and thus dynamically influence each other in a complex web of relationships and networks.

5.3 Complementarities

The table below (Table 5-2) shows R&D expenditure by socioeconomic objective of the various sectors during the financial year 2004-2005. The top three of four percentage expenditures for each sector is largely different to the rest of the sectors. However, looking at the total column, a fairly even distribution of expenditure covers the whole spectrum of economic objectives. This observation suggests, even though each sector has its own bias, in terms of priority R&D investment, overall a high degree of complementarities among the sectors ensures that all the important areas for the country are covered. This point is amplified by the nature of contribution made by the not-for-profit sector. Even though the overall contribution of this sector to the total R&D expenditure of the country, at a little above 1%, could be considered miniscule, the contribution is by no means insignificant, in the areas where this investment is made. In social development and community services, for an example, the not-for-profit sector outspends, in real terms, both business and government by far.

The main message behind the observation of these complementarities in expenditure is that the performance of South Africa's NSI is depended on the contributions of all the individual contributors put together. A true picture of what constitutes the NSI and how it performs cannot be put together based on only some of the sectors. Even a small component in terms of size, as exemplified by the not-for-profit sector, is crucial in developing a holistic view of the NSI. This further demonstrates the "systemness" of the country's national system of innovation.

	Business enterprise		Government		Higher education		Not-for-profit		Science councils		Total	
	Amount		Amount		Amount		Amount		Amount		Amount	
Socioeconomic objective	R 000s	%	R 000s	%	R 000s	%	R 000s	%	R 000s	%	R 000s	%
Division 1: Defence	**718 491**	**10,6**	**237**	**0,0**	**2 069**	**0,1**	**1 441**	**0,7**	**160 864**	**8,1**	**883 101**	**7,4**
Defence	718 491	10,6	237	0,0	2 069	0,1	1 441	0,7	160 864	8,1	883 101	7,4
Division 2: Economic development	**4 895 638**	**72,4**	**245 493**	**47,6**	**735 329**	**29,0**	**56 356**	**28,4**	**1 057 410**	**53,0**	**6 990 226**	**58,2**
Economic development unclassified	0	0,0	0	0,0	102 936	4,1	0	0,0	0	0,0	102 936	0,9
Plant production and plant primary products	209 583	3,1	57 072	11,1	60 922	2,4	942	0,5	198 256	9,9	526 775	4,4
Animal production and animal primary products	38 024	0,6	57 955	11,2	72 192	2,8	13 647	6,9	118 171	5,9	299 990	2,5
Mineral resources (excluding energy)	711 661	10,5	0	0,0	15 898	0,6	0	0,0	251 953	12,6	979 512	8,2
Energy resources	301 603	4,5	0	0,0	16 709	0,7	490	0,2	16 916	0,8	335 717	2,8
Energy supply	292 545	4,3	0	0,0	31 871	1,3	1 164	0,6	542	0,0	326 122	2,7
Manufacturing	1 115 221	16,5	0	0,0	102 001	4,0	0	0,0	138 792	7,0	1 356 014	11,3
Construction	365 271	5,4	620	0,1	26 956	1,1	0	0,0	61 761	3,1	454 608	3,8
Transport	363 545	5,4	3 140	0,6	14 347	0,6	0	0,0	41 935	2,1	422 968	3,5
Information and communication services	588 233	8,7	6 068	1,2	50 745	2,0	0	0,0	22 090	1,1	667 136	5,6
Commercial services	718 856	10,6	815	0,2	41 588	1,6	2 994	1,5	2 086	0,1	766 339	6,4
Economic framework	11 280	0,2	35 748	6,9	93 107	3,7	33 695	17,0	50 045	2,5	223 875	1,9
Natural resources	179 816	2,7	84 076	16,3	106 057	4,2	3 425	1,7	154 861	7,8	528 236	4,4
Division 3: Society	**911 606**	**13,5**	**189 241**	**36,7**	**722 819**	**28,5**	**125 674**	**63,4**	**324 973**	**16,3**	**2 274 312**	**18,9**
Society unclassified	0	0,0	0	0,0	102 936	4,1	0	0,0	0	0,0	102 936	0,9
Health	873 468	12,9	76 373	14,8	328 251	13,0	23 471	11,8	203 178	10,2	1 504 741	12,5
Education and training	20 087	0,3	94 694	18,4	132 616	5,2	66 400	33,5	68 755	3,4	382 553	3,2
Social development and community services	18 050	0,3	18 174	3,5	159 016	6,3	35 803	18,1	53 040	2,7	284 082	2,4
Division 4: Environment	**145 034**	**2,1**	**48 560**	**9,4**	**226 063**	**8,9**	**10 632**	**5,4**	**144 737**	**7,3**	**575 026**	**4,8**
Environment unclassified	0	0,0	0	0,0	34 312	1,4	0	0,0	0	0,0	34 312	0,3
Environmental knowledge	32 776	0,5	37 663	7,3	94 667	3,7	4 641	2,3	87 752	4,4	257 500	2,1
Environmental aspects of development	70 069	1,0	5 252	1,0	40 122	1,6	5 704	2,9	20 436	1,0	141 583	1,2
Environmental and other aspects	42 188	0,6	5 645	1,1	56 963	2,2	286	0,1	36 549	1,8	141 631	1,2
Division 5: Advancement of knowledge	**95 593**	**1,4**	**31 800**	**6,2**	**847 691**	**33,5**	**4 165**	**2,1**	**308 067**	**15,4**	**1 287 316**	**10,7**
Advancement of knowledge unclassified	0	0,0	0	0,0	102 936	4,1	0	0,0	0	0,0	102 936	0,9
Natural sciences, technologies and engineering	92 497	1,4	22 797	4,4	427 087	16,9	0	0,0	246 359	12,3	788 740	6,6
Social sciences and humanities	3 096	0,0	9 002	1,7	317 668	12,5	4 165	2,1	61 708	3,1	395 640	3,3
Total	6 766 361	100,0	515 331	100,0	2 533 971	100,0	198 268	100,0	1 996 050	100,0	12 009 981	100,0

Table 5-2: R&D expenditure by socioeconomic objective (DST, 2005)

A further point to be made from the above data has to do with the degree of openness of the NSI to outside influences. 15,8% of R&D funding is derived from foreign sources. The participation of external partners is healthy for South Africa. It creates opportunities for benchmarking and learning from more advanced innovations. An open system facilitates an exchange between the NSI and the external environment. Such an exchange permits the NSI to assume the character of dissipative structures which undergo self-organisation far from thermodynamic equilibrium (Prigogine, 1955; Prigogine & Stengers, 1984).

5.4 Self-organisation

The architecture of the national system of innovation of South Africa never had a blueprint. It evolved throughout the history of the republic, shaped by the forces of human interest and need, within an ever-changing milieu of the rich and unique tapestry of cultures, languages, geography, climate, biodiversity, politics, economy and the ingenuity of the people of the land.

The country's history of research and technological innovation activities may be as old as the history of humankind. Archaeological evidence suggests that symbolic thought, the very essence of humanity, emerged uniquely in this part of the world, as early as 70 000 years ago (Henshilwood et al, 2002). Evidence of organized scientific activity is amply demonstrated in the kingdom of Mapungubwe, on the northern part of the country, where paleontological findings unearthed, among other things, gold artefacts, which suggest the existence of advanced gold extraction and other advanced technologies, about a thousand years ago. In more recent history, the search and utilization of knowledge can be deciphered from the histories of all the tribes and kingdoms that dotted the expanse of the country, before the arrival of colonial settlers, about three and half centuries ago. The first research institutions as well as institutions of higher learning, in the modern European sense, were founded during the colonial period.

The evolution of the innovation system, as depicted in the last chapter, followed no pattern whatsoever. Institutions grew, sometimes as offshoots of departments within earlier institutions. South Africa's biggest research council, the CSIR was founded in October 1945, following a dramatic demonstration of the power of science and technology during World War II. Most of the science councils started as small units within the CSIR decades later. The country's main funding agency, the NRF (initially called the Foundation for Research and Development) also had a similar origin. The government department that is responsible for science and technology (i.e. DST) is one of the latest science and technology institutions to be formed, in 2002.

Similarly, the scientific legislations, strategy documents and policies often proceeded decades of self-directed practice and organization by the R&D institutions. The White Paper for Science and Technology, the first guiding national document of this nature for regulating science and technology was published in 1996. The first national R&D strategy of the country only came in 2002. This demonstrates the extent to which the country's science and technology institutions and organizations interacted and adapted, largely by themselves, without evidence of any external control and direction. Even today, the question of the size and shape of the national system of innovation remains an open question.

The apparent lack of order and central planning in the evolution of the country's national system of innovation is evidenced in the governance of the system that took shape until about 2004. The CSIR used to report to the Department of Trade and Industry while it received the bulk of its public funding from DST. Similar anomalies existed with other institutions, which defied simple planning logic. The geographic distribution of higher education institutions indicates also a lack of prior centralized planning. Some of the provinces in the country are without a single university while others boast several, sometimes a stone's throw away from each other. The various mandates of the respective science councils also indicate lack of central planning in their lack of uniformity. Some science councils, such as the CSIR carry out research whereas others, such as the Medical Research Council, largely commission and fund research work.

Now, given this background, what were the drivers that shaped the country's science and technology landscape? On what basis did institutions and organizations shape the research and technological agenda of the country? What moved institutions to interact and cooperate and how were the rules of engagement shaped, in the absence of a distinguishable central authority?

The answers to the above questions are as intractable as the content and extent of the NSI itself. The only explanation that is being proffered for the evolution of the NSI is that institutions and organizations underwent self-organisation.

5.5 Emergence

Emergence is a property of complex systems that is closely related to self-organisation. Often self-organising systems bring about emergent properties. However, emergence without self-organisation is conceivable. So is self-organisations without emergence but that would require a great deal of imagination to conceive. Before looking at some examples, let's explore the notion of emergence in some detail.

Emergence is a term that is used to describe the manifestation of a property of a system that cannot be identified or explained from the properties of any of the components that make up the system. In essence, therefore, emergent properties of a system derive from the interactions of lower level entities that make up the system while they remain unobservable at the level of the entities themselves. Thermodynamic properties of a substance, for instance, are emergent properties (Shalizi, 2001) given that such properties (e.g. temperature, pressure and entropy) cannot be ascribed to the individual molecules that make up the substance. Colour is a property of a substance (made manifest by selective absorption or reflection of light) that originates from the arrangement of the particles that make up the substance but not distinguishable in the individual particles themselves. An example at a social or organizational level is that of a swing in an election, where upon the declaration of the result, a discernable change of electoral opinion could be seen from one side to another of the contesting parties. An individual vote that is cast could not be characterized as a swing though.

A proposition that is being made here is that the ordered pattern of the NSI demonstrates emergence. It has been shown in the discussion above that the formation of the NSI evolved from the interactions of its constituent institutions and organizations. Over and above that, an observation is made that an emergent higher level property of the system is an ordered pattern, with a logical hierarchical structure. This ordered pattern of South Africa's NSI is depicted in Figure 5-1 below.

The national system of innovation of South Africa may have begun as a cluster of individual institutions dotted around the country, each carrying out its own function, with little intended alignment with other organizations or institutions. However, as the system evolved, through self-organisation, the different institutions began to interact and align into functional categories. Over time, the different institutions carved niches that began to define more precisely their place within the NSI, in relation to one another. Consequently, as the system is perceived in its entirety, a logical pattern of functional categories, as depicted in the diagram above, emerged.

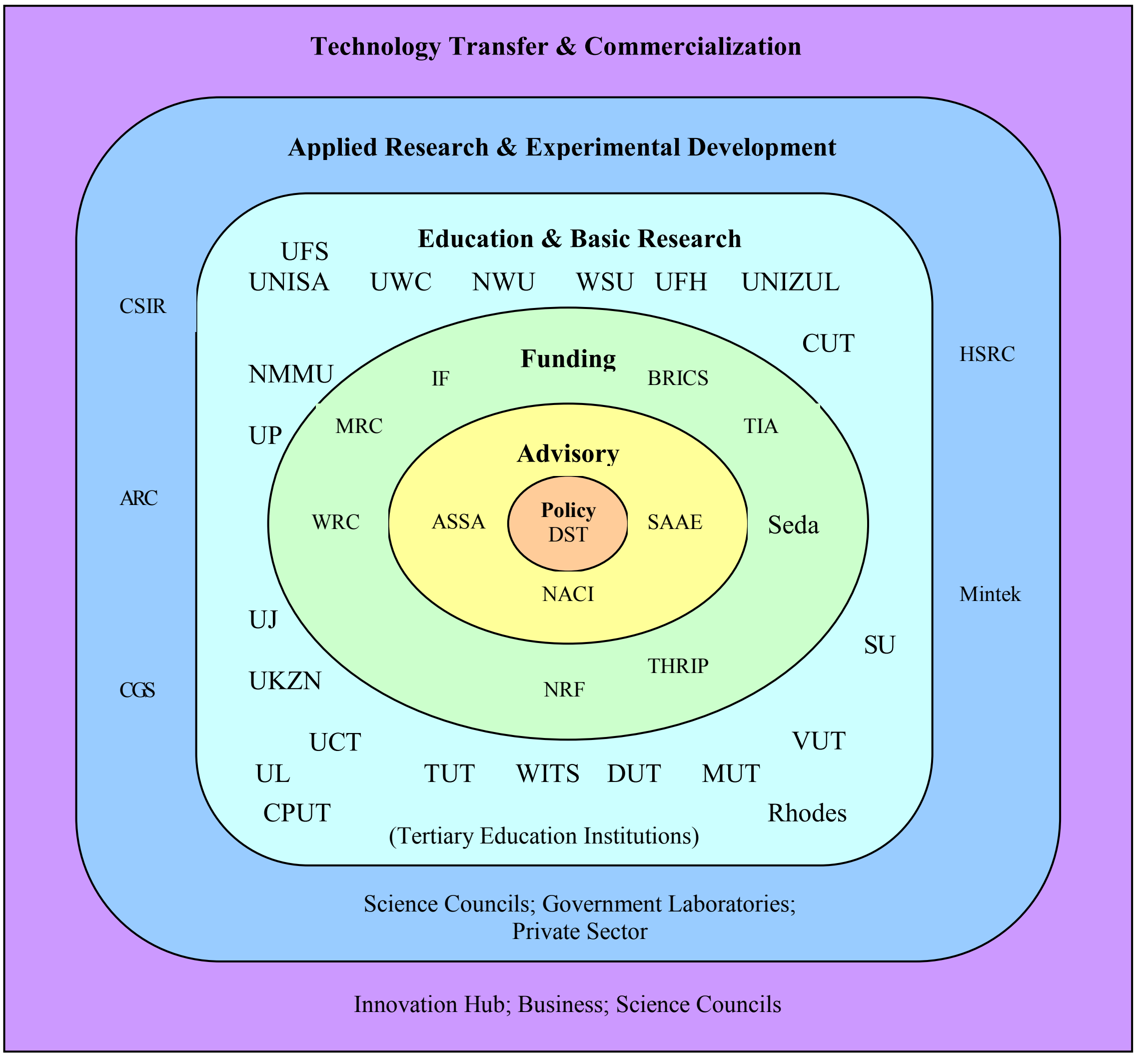

Figure 5-1: Functional Mapping of South Africa's National System of Innovation

In terms of the emergent functions, the Department of Science and Technology (DST), in consultation with other government departments, is largely responsible for policy formulation. It is important to note that the DST, as a relatively recent feature of the NSI, cannot be credited for organizing the R&D landscape in this fashion. The evolution of the institutions and their functions occurred over a period of decades. Furthermore, most of the organizations in the NSI, owe their existence not to DST but to various mandates, such as acts of parliament, as is the case with the science councils. Over the passage of time, advisory councils such as the National Advisory Council on Innovation (NACI), the Academy of Science of South Africa (ASSAf) and the South African Association of Engineers (SAAE) began to align themselves around the policy centre. Again, the alignment of these advisory bodies, which predate DST, did not come about by design or decree. Their current roles were forged out of a prolonged process of organisation and re-organisation of the NSI.

Similarly, the funding agencies increasingly became the instruments by which to drive national science and technology policies. In this manner, as if by gravitational pull of the centre, they began to serve a shared agenda of the NSI, DST and other government departments. The funding agencies, such as the National Research Foundation (NRF), the Water Research Commission (WRC), the Innovation Fund (IF) and the Technology and Human Resources for Industry Programme (THRIP), are positioned at the boundary between research and innovation performing institutions and policy and advice bodies. With their hands on the public research purse strings, they could be regarded as the gatekeepers of what gets to be done and by whom.

It is important to emphasize that the list of institutions and organizations depicted in Figure 5-1 is by no means comprehensive. Furthermore, the boundaries that are shown between functions are illustrative rather than absolute. For instance, the science councils, although shown as conducting applied research and experimental development, also do conduct basic research. Other overlaps also exist.

It is important to explain the role and function of the environment. The edge of the outer square box in the diagram marks the boundary between the NSI and its outer environment. The environment consists of all entities that are not part of the system. This includes the social, economic, political, environmental, technological and legal milieu in which the NSI is embedded. The boundary is permeable thus allowing both the NSI and the environment to influence and impact one another. By definition, the environment is constituted by “those things with which the agent interacts but over which it can exercise no direct control” (Goldspink, 2000). In the case of the NSI, as discussed in the introduction, there are expectations that it will positively impact the social and economic conditions of the country.

The emergence of the ordered functional pattern of the NSI is a phenomenon that governs non-linear self-organising systems. Conceptually, the growth of the NSI is initially characterized by an increase in the number of institutions and interactions between them, albeit in a somewhat disorderly fashion. At this point, in terms of a thermodynamic model, it could be said that the entropy of the system increases. However, it seems as the entropy increases, at some point certain constraints begin to come into play, limiting the amount of disorder and thus bring about order and structure. This is seen in the NSI in the manifestation of specialization in the operations of the institutions and the emergence of alignment in their functions.

This process seems to mimic the course of self-organisation and emergence observed by Guerin & Kunkle (2004) of the Santa Fe Institute in the context of an agent-based model of ant colony food foraging. Their experiment demonstrated that:

(1) Constraints can be constructed from entropy-producing processes in the of *boostrapping phase* self-organising systems.
(2) Positive feedback loops are critical in the *structure formation phase.*
(3) Constraints tend to decay. The continued presence of far-from equilibrium boundary conditions are required to reinforce constraints in the *maintenance phase.* (Guerin & Kunkle, 2004; p 134).

The above claims can be applied to the NSI to explain the mechanism by which constraints in the behaviour of the individual organizations is introduced and sustained. The precise mapping of the different phases, that is, when and how the agents within the NSI learned the constraints and structure of their environment could be an interesting area of further investigation. The interaction of the NSI with the broader environment renders the non-equilibrium thermodynamics model appropriate in developing insights into the NSI as a self-organising system. The NSI can thus be potentially described in terms of the dissipative structures first described by Prigogine (1955).

Chapter 6
Synthesis, Recommendations and Conclusions

6.1 Synthesis

South Africa has declared its intention to join countries all over the world that are planning and positioning their internal productive resources in order to compete successfully in a global knowledge economy. The growing importance of knowledge, as opposed to the traditional factors of production, is changing the nature of economic exchange everywhere in the world. The organisations that are able to master the production of knowledge and its conversion to tradable goods and services are topping the charts of economic growth and success. At the level of nation-states, the countries that have effective knowledge production systems record higher and more sustainable levels of economic growth. This observation is borne out by successive Human Development Reports of the United Nations Development Programme and the World Development Reports of the World Bank.

A knowledge economy is an economy in which the creation of knowledge and its application in the production of goods and services provide the basis for wealth creation and socio-economic development. In a knowledge economy, knowledge does not only join labour and capital as a factor of economic production; it is the most crucial component. In the knowledge economy, knowledge is important not for its own sake but in so far as it is applied in creating new products or services, improving production efficiencies or developing completely new production pathways. When knowledge is applied in these economically meaningful ways it is referred to as technological innovation.

The national system of innovation is a new theoretical construct in science and technology policy studies. Although the concept evolved largely from developing world economy contexts, it seems to offer useful insights into the form, character and operations of science and technology systems in the developing world. This is especially true for South Africa, a country that has evolved a sophisticated national system of organizations, institutions and policies for creating and harnessing the power of knowledge for social and economic value. South Africa has fully embraced the NSI as a framework for analysis, management and evaluation of the totality of its research and innovation efforts. This study is a contribution to the further development of the NSI as a robust framework for understanding the national science and technology systems.

A comprehensive survey and critical analysis of the growing body of literature on national systems of innovation reveal several insights on the subject. The value of a national perspective on organizing science and technology initiatives became apparent in the need for productive systems to compete globally. The important role of the quality and quantity of interactions between the different elements of a NSI has been emphasized. The need to take account of the key issues facing the economy and people of a country has been underlined. In this respect, in the case of South Africa, the innovation imperative should consider pertinent issues such as unemployment, energy efficiency and environmental sustainability as key issues or run the risk of being branded as irrelevant.

Systems, chaos and complexity are theoretical frameworks that have been presented extensively in this study as appropriate conceptual tools for making sense of South Africa's national system of innovation. Chapter 3 provides a comprehensive critical survey of these theories, starting with systems theory. On this platform, chaos and complexity was discussed, drawing insights and applications from both the natural and human sciences. Key concepts such as sensitivity to initial conditions, self-organisation, emergence, dissipative structures, edge of chaos and self-organised criticality were emphasized as well as their relevance to the NSI concept. Chapter 4 presents a comprehensive examination of the institutions and organizations that make up South Africa's national system of innovation. The survey covered legislation, strategies and policies, advisory bodies, funding agencies and R&D performing organizations. A brief discussion of the performance of the system was done to demonstrate the system character of the NSI. Chapter 5 laid down various illustrations to show that the NSI is a non-linear complex adaptive system. Examples featured the rich-interactions among the elements of the NSI, the manner in which the system evolved through self-organisation and the logical pattern it has evolved into, as a demonstration of emergence.

6.2 Recommendations

6.2.1 The NSI as a policy matter

The chaos and complexity theoretical frameworks offer new ways of thinking about the national system of innovation. This has practical value for policy makers, such as the government departments that are concerned with science and technology as well as researchers and the multitude of stakeholders within the NSI. While chaos and complexity theories were conceived as tools for manipulating non-linear empirical data in mathematical and natural sciences, there is no reason why they should not be of equal if not more benefit to the understanding of social systems (Brown, 1995). Social systems and organizational networks are fraught with non-linearity as they comprise members that demonstrate adaptive behaviour. Moreover, traditional reductionist approaches have proven to be of limited usefulness in shedding light on the self-organising, non-linear and emergent properties of social systems (Mathews, White & Long, 1999). The intention here is to organize some of the insights emanating from chaos and complexity in order to formulate thinking tools for application in studying systems of innovation.

6.2.1.1 Increased rates and variables of change

Studies into the economic role of technological innovation have become more complicated by the radical increase in the number of variables that can impact the final result. Knowledge explosion, owing to the developments in information and communication technologies is just one factor to consider in explaining the escalation in the rates of change in social systems. Change has become so embedded in the fabric of organizational dynamics such that the approaches that are based on strategic choice to management cannot offer useful insights. Chaos and complexity offers the intellectual levers that could be used to make sense of these changes. Furthermore, chaos and complexity provide practitioners and planners with the intellectual tools to deal with the spectre of unpredictability presented by some cases (Cartwright, 1991) when it comes to global results. With the vicissitudes of environmental factors, even emanating from events across the globe, organizations have become ongoing hives of instability and chaotic behaviour. Big organizations, such as the ones involved in the national system of innovation experience "shifts in organizational policy, crisis behavior [sic], negotiation processes, downsizing, organizational decline, product discontinuations, voluntary employee turnover, management succession, among others" (Mathew, White & Long 1999, p 450). In such an unpredictable organizational climate, chaos and complexity theories may provide the right mental tools to decipher the key drivers of change and prepare the organisation for whatever emergent futures that may play out.

6.2.1.2 Dynamic non-linear relationships

The national system of innovation contains many entities that are linked in a non-linear fashion and possess non-recursive self-referential elements. As it has been amply demonstrated in the preceding chapter, these elements continuously interact, and over time, evolve dynamically to produce emergent properties. Chaos and complexity theories provide the means to understand the dynamics of these interactions and changes. These theories are most suited for this purpose because they evolved out of the quest to make sense of dynamic non-linear complex behaviour, albeit in the physical and natural systems. Nevertheless, the processes that drive chaotic and complex behaviour are also present in innovation systems. Hence, it has been found to be appropriate in this study to employ these theoretical frameworks. These observations by Mathews, White & Long (1999) are fitting for the national system of innovation:

> *"Instability and unpredictability appear to be inherent to the social world and cause and effect relationships often seem to be inextricably intertwined. To the extent that the complexity sciences can help to explain, explicate, and illustrate dynamic processes in natural and physical systems, they offer the potential for a better understanding of similar processes occurring in social systems."* (Mathews, White & Long, 1999; p 451).

There is no doubt that the national system of innovation is replete with instability and unpredictability. Causes and effects are often indistinct and not linearly ordered. Chaos and complexity theories have proved to be useful in the natural sciences to explain these phenomena. They are presented here as useful templates for describing these features for the NSI.

6.2.2 Management of the NSI

The notion of a linear national system of innovation, whose operations could be prescribed and commanded on the basis of simple cause-and-effect laws, is a fallacy. We have seen in the last chapter that South Africa' NSI simply does not function in this way. We have demonstrated that from its evolution to the way its components function and interact, the NSI demonstrates qualities that manifest chaos and complexity behaviour. These properties are inimical of methods that operate on the basis of "reductionism, linear causality, objective reality, observer outside the observation, determinism, discrete entities, monological research methods, either/or thinking, hierarchy, prediction, patriarchy, yang dominance, logic, equilibrium, stability, global control, behavior [sic] specified from top down, results orientation, specialist, focus on directives, and numerous others" (Dent 1999; Axley & McMahon, 2008).

If the NSI cannot be managed and governed on the basis of the traditional methods, the question is how should it be managed then? In order to address this question in a systematic fashion, we need to consider in turn the key management functions that are pertinent to the national system of innovation of South Africa. That having been said, there is nevertheless a need to put to the test the notion of "management", as it relates to the NSI.

The Department of Science and Technology (DST) sees its mission as that of managing the national system of innovation. In this perspective DST will be regarded as the institution that is responsible for the overall management of the NSI. Government departments are generally responsible for developing policies and strategies, providing budgets and monitor the implementation of the programmes under their respective portfolios. A government department that is responsible for water provision, for instance, would set targets on the amount of work to be done to deliver clean water to communities who need it. The necessary planning required to create the necessary infrastructure is done and a whole range of activities are set in motion so that the water provision projects deliver the intended results. In this perspective, it is possible to see the management role of government department in driving various national agendas. However, when it comes to science and technology, the comparisons largely fall apart.

Firstly, the products of science and technology do not lend themselves to simple quantification, especially before they are realised. Unlike the number of water taps or dams, the development of new knowledge in a discipline is a function of inaccessible inputs, constraints, conditions and a host of incidentals. For instance, a major scientific breakthrough that has the potential to create completely new industries could emanate from serendipitous circumstances. In fact, not only is it impossible to forecast the number of scientific papers, technology packages, patents and technology demonstrators that could be produced in the country over a given period; it is impossible to state with certainty the disciplines in which they would come from. This is because knowledge production cannot be accurately subjected to set calendars.

The knowledge enterprise is also prone to the vicissitudes on the international front of science and technology. New knowledge must be subjected to international benchmarks and validation. Peer review panels subject new knowledge claims to rigorous expert examination. Patents are normally filed with international offices that have a global purview of activity across vast domains. A plethora of mechanisms and bureaucratic procedures regulate the administration of the applications that are received across the globe. Decisions on the commercialisation of technological products could depend on assessments of potential international supply and demand rather than the inherent properties of the products involved. The discovery of biological agents, including drugs and medicines, could be subject to international quality, safety and efficacy testing. Chemical and nuclear products could similarly come under the scrutiny of international watchdogs charged with investigating their compliance to international conventions and treaties.

At a functional level, a bureaucrat working in a South African government office, say at the national office of the Department of Science and Technology in Pretoria, cannot be in a position to orchestrate the responses of the various institutions that relate to the portfolio of his or her interest. Firstly, some stakeholders within the NSI are not legally bound to do the bidding of the government. The first category of these entities would be the private companies that conduct research and development. The research agenda of private companies, who, of necessity, are profit-driven, is driven by the business decisions of that enterprise, at the sole discretion of the company and its shareholders. This has a lot of bearing for a country like South Africa where the majority of scientific research is conducted by the private sector. In order to bring the considerable weight of the private sector to accomplish social goals through scientific research and technological development, the government would have to adopt very creative ways to make it attractive. The public-funded universities in South Africa enjoy a high degree of autonomy when it comes to their academic programmes, especially in relation to research. Again here, the government, or any other entity of authority within the national system of innovation, has no legal basis to demand adherence to centrally contrived research programmes.

At face value, one could expect the government to have more leverage with the science councils that are partly funded out of the parliamentary grant. However, upon closer examination, the situation may not be that clear cut. Consider, as an example, the mandate of the CSIR, the country's largest science council that reports to the Department of Science and Technology, as given by the Scientific Research Council Act, Act No. 46 of 1988:

> *"The objects of the CSIR are, through directed and particularly multi-disciplinary research and technological innovation, to foster, in the national interest and in fields which* ***in its opinion*** *should receive preference, industrial and scientific development, either by itself or In [sic] co-operation with principals from the private or public sectors, and thereby to contribute to the improvement of the quality of life of the people of the Republic, and to perform any other functions that may be assigned to the CSIR by or under this Act."* (Government of South Africa, 1990; emphasis added)

So, as it can clearly be seen in the above mandate of the CSIR, the areas of research and development that should receive priority cannot be dictated from above to the research councils. The Act extends to the research council the right to exercise its own opinion in the matter. The government, or any other authority, cannot, on the basis of the act, decree to the research institutions as to what should constitute priority. Now, if control cannot be exercised on the constituent elements of the NSI that perform research and development, there is even lesser leverage on technology transfer and commercialisation, where a complex of economic, social and political considerations dominate decision making.

We have seen in the last chapter that the national system of innovation is sensitive to initial conditions. This was identified as one of the tell-tale signs of complex adaptive systems. A single transaction in the New York Stock exchange, for example, could initiate a domino effect that could wreak havoc with the national economy of South Africa. Many examples of such a phenomenon that have occurred in the past include things such as currency speculations which have sent the value of the Rand tumbling. The value of the currency could change decisions on whether to invest in export-driven industries. In this way, a small apparently innocuous transaction, halfway across the world, could have far-reaching consequences for a whole system of institutions and organisations, leading to a possible complete collapse of industries or massive scale-down of business operations. Such is the fickleness of the NSI, which therefore renders it almost impossible to predict. Nevertheless, all this does not suggest that there is no point in engaging in a deliberate systematic management approach of the NSI. However, it should be borne in mind that the traditional management approaches may not be appropriate for a view of the NSI as complex adaptive system.

All in all, when dealing with the NSI, management approaches should contend with a system that:

- is built around processes and outcomes that cannot be subjected to strict control and timetables;
- has a fuzzy boundary, with some of its constituents potentially opting in or out at any given moment;
- does not have a designated central point of command and authority;
- consists of a multiplicity of stakeholders that have disparate, and sometimes conflicting roles, functions and interests;
- is highly prone to external, especially international, influences; and
- has, at most, a limited obligation to adhere to a central authority.

Looking at typical management functions that are applicable to nationwide entities, how could these be adapted to suit the complexity principle underlying the national system of innovation?

6.2.2.1 Planning

The plans of the Department of Science and Technology, for example, should focus more on regulating the department's own role within the NSI as an entity that is most suited to providing an enabling environment for scientific research and technological innovation to take place. The DST should take cognizance of its role vis-à-vis that of other government departments that have an interest and a stake in science and technology. Plans, while based on a holistic view of the socio-economic interest of the country, should take cognizance of the various individual interests and disparate capacities of the constituent elements of the NSI. Central plans should provide a clear view of what is considered to be of common priority but be open to all possible kinds of emergence that could emanate from the interplay of the constituent policies, processes and stakeholders. Plans should be sensitive to the inexact timeframes of research and technology development activities. Generally, "planning as learning" (de Geus, 1988) should be the fundamental approach. Scenario planning tools (van der Heijden, 1996), to explore various plausible futures of how the national science and technology landscape could be turn out, should form part of the planning regiment.

6.2.2.2 Organizing

Centralized organizing efforts of the Department of Science and Technology should operate on the principle of stimulus-response rather than command and control. Funding allocations, for instance, should take various forms such as ring-fenced funding, competitive funding, cooperative funding, contract research and development funds as well as baseline funds for supporting infrastructure and other overheads. The value of cooperative funding takes into account the inevitable web of interactions and networks that are being formed among the elements of the NSI. Means to optimize these co-dependencies should be implemented. A high degree of flexibility should be a feature of the medium term expenditure framework in order to provide capacity to respond to emergent priorities. Policies and strategies should not be prescriptive but rather ambitious, aspirational and open to interpretation.

6.2.2.3 Directing

An approach of openness when it comes to directing is important. The responsible government department, bearing in mind its limited formal and practical control over the system, should listen as much as it much as it talks to the system. This will allow it to be influenced by the real-world dynamics of the system and thus continually shape and modify its role and influence. The government department should appreciate its role more as that of a cooperating agent than that of a command centre. Monitoring and evaluation mechanisms should co-evolve with the changing dynamics of the system. This is a response to an inherent quality of the NSI as a dynamic system consisting of elements that continually influence one another. Furthermore, a flexible approach towards the system will anticipate emergent system properties that cannot be ascribed to individual elements or planned outcomes. A holistic view of the performance of the entire national system of innovation should be taken, even when zooming on a particular problem area. This is because the NSI, as a system, is a function of the interactions of all its constituent parts. Piecemeal approaches to performance monitoring will inevitably rob management of an emergent holistic view that emanates from dynamic sub-system interactions.

6.2.3 Strategic management of the NSI

The national system of innovation has so much bearing for the country's social and economic wellbeing. Therefore strategic management of the NSI is of utmost important for the country. Experiences of the past few years suggest that strategy making in South African public institutions has been dominated by rational and analytical approaches. South Africans are familiar to the importance attached to the cabinet *legotlas*, which are meetings of cabinet ministers and their top officials, often held in a secluded bush lodge somewhere. During these meetings the strategic planning decisions are made for the country. Very often, there would be select advisory committees and think-tanks, comprising experts from South Africa and beyond, to advise government on matters of strategy in different areas. Notwithstanding the efforts to engage ordinary people, through for instance *imbizos* (i.e. community meetings with political leaders), there is a general understanding that the formulation of strategy is a responsibility of people in powerful positions.

Such a culture of strategic management is referred to as strategic choice (Caves, 1984, Child, 1972, Moore 2001, Porter 1980).

Strategic choice, as an approach to strategy formulation and management, harbours several assumptions. One is that strategy formulation must be separated from strategy implementation. The separation is often made manifest in giving the two responsibilities to two different groups of people, at different times and sometimes at different places, as depicted in the table below.

	Strategy Formulation	**Strategy Implementation**
Who does it?	Top management	Lower level employees
When?	Beginning of the year	Throughout the year
Where?	Away from workplace	At the workplace
Importance level	Special	Mundane

Table 6-1: Strategic management assumptions of the Strategic Choice paradigm

The underlying presumption in strategic choice is that reality can be forecast with appreciable levels of certainty and thus appropriate strategies could be orchestrated by rational means in order to bring about particular effects. Of necessity in this perspective, the formulation of the strategy must precede implementation, as an attempt at implementation without a well-thought out strategy as a blueprint, is tantamount to groping in the dark. A wrong strategy is a recipe for disaster. Hence, strategy formulation is a solemn exercise that is carried out by a select group of especially gifted individuals. Practically, in order to devote wholly their faculties to this special task, the top management team has to retreat away from the workplace in order to free their minds of the mundane demands of day to day work.

The discussion in the last chapter about the national system of innovation as a non-linear complex adaptive system, does not sit well with the picture of strategic choice painted above. The dynamic interplay within the elements of the NSI and the ever-present influence of the environment predispose the NSI to turbulence. “As a result cause and effect relationships may be distant in time and space, rendering forecasting and optimization difficult. In taking a systems view and a complexity perspective, complex systems produce emergent outcomes. Such outcomes are not within the control of any single actor or group of actors" (Bodhanya, 2005, p 3). There must therefore be a different approach to strategic management of the NSI than the currently dominant strategic choice approach.

Learning approaches to strategic management have been proposed (Mintzberg et al, 1998, Rajagopalan & Spreitzer, 1996). The key idea within the learning approach is that the emergent dynamic reality of non-linear complex adaptive systems, such as in the NSI, can be learnt and adapted to. This is opposed to the perspective of strategic choice that claims the capacity to know and control reality. The learning perspective suggests that if the learning is done faster than the change of the environment, the better strategic decisions could be made. As Bodhanya (2005) correctly observes, the learning approach does not adequately address strategy as an emergent phenomenon of complex systems. The Achilles heel of the learning approaches lies in that they, as much as strategic choice, are also based on an objective reality and a desire to control it.

Bodhanya (2005) describes an approach called strategic enactment, as a viable alternative to strategic choice approaches. The principal ideas that embed strategic enactment include that:

- Strategy is enacted through organizational interactions rather than designed as in strategic management;
- Strategy formation and implementation are integrated as a single gestalt rather than the formulation-implementation dichotomy found in strategic choice;
- Strategy is as a result of emergent processes at all organizational levels and thus challenges the privileged status implied in strategic choice;
- Strategy proceeds from cooperation with the environment, instead of emphasizing the boundary between the environment and the system;
- Strategy enactment is an inclusive, pluralistic and egalitarian outcome;
- Strategy is embedded in practice thus privileging the experience and input of the low-level employees;
- Strategy assumes a polyphonic organization (Rodriguez, 2004) which harkens the voices of the marginalized.

Strategic enactment offers real benefits for the national system of innovation. Firstly, it will take account and advantage of the large variety of experiences and expertise embedded within the institutions and organizations that form part of the NSI. Secondly, it will facilitate an approach towards inclusivity in matters of strategy. Thirdly, it will de-emphasize and thus limit the over-reliance on expert advice, thus fostering an investment in internal capacity for strategic input. Fourthly, it will acknowledge tacit knowledge which is often embedded in the day-to-day practices of ordinary people within the system. Fifthly, it will enable strategy to take account of emergence, a prime feature of the NSI. Sixthly, it will do away with the separation between strategy formulation and implementation, resulting in continuous organizational learning. Lastly, it will obliterate the unnecessary differentiation between thinking and strategy, resulting in the combination of these processes into a single integrated dynamic thinking-action whole.

6.2.4 Researching the NSI

As part of discussion on the implications of the chaos and complexity perspective of the national system of innovation of South Africa, it seems necessary to look into what it means for research into the NSI itself. The study of science and technology policies is a new phenomenon, especially employing the NSI perspective. On the other hand, the application of chaos and complexity theories to social phenomena is a recent research phenomenon. It is therefore pertinent to build philosophical frameworks that could be used for future enquiry in these disciplines.

Chaos and complexity theories provide very useful conceptual frameworks for research into non-linear systems that have a multiplicity of interacting agents such as systems of innovation. Most research activities in natural and social sciences often take the form of either induction or deduction. Induction is essentially a search for patterns in empirical data. In social sciences this approach is deployed in the analysis of data from opinion surveys, interviews, observation journals and quantitative data. The idea is to identify from a mass of amorphous empirical data preponderant themes that could be used to construct meaning. Deduction, on the other hand, is more or less a reverse process to induction. Deduction uses a set of established general principles in order to prove or disprove specific instances. Both induction and deduction are of limited advantage in complex systems that comprise a multiplicity of interacting agents that are governed by non-linear rules.

6.3 Conclusions

South Africa's national system of innovation comprises a variety of public and private institutions and organizations. Most of the organizations have a high level of dependence. These organizations perform a range of functions that are related to research and technological innovation. Their activities range from basic and applied research, experimental development, technology transfer and commercialization. These organizations include universities, science councils, private businesses, government laboratories and the not-for-profit organizations. All these institutions operate within a context that is influenced by policy and legal institutional frameworks and various funding instruments.

The national system of innovation of South Africa is characterized by a high level of coordination, interdependence and complementarity among the institutions and organizations which comprise it. There is a significant amount of convergence in the funding levels across the various sectors, indicating a shared objective of increasing investment in R&D. The cross-funding among the different sectors suggests a high degree of interdependence and collaboration. Each sector appears to need the support of the capacity of other sectors in order to achieve its R&D objectives. The complementarities among the various elements of the NSI are evident in the manner in which the different sectors appear to carve their investment niches in the different R&D fields. A true picture of the nature and performance of the NSI is incomplete without taking into account the contributions of all the participating components, however small.

Chaos and complexity theories offer valuable perspectives in the understanding the national system of innovation of South Africa. Several illustrations are discussed above that demonstrate that the NSI operates like a non-linear complex adaptive system. The evidence of this behaviour is reflected in the rich-interactions among the elements of the NSI, the evolution of the NSI itself through self-organisation and the emergence of the highly-ordered logical pattern it has developed into over time, without evidence of external control. The chaos and complexity perspective of the

NSI offers valuable conceptual tools for policy makers and those tasked with the oversight of the system. Recommendations have been made about how these could be applied in general and strategic management of the NSI as well as in research.

References

Amsden, A.H. & Cho, H. 2003. Differences in National R&D Systems between Early and Late Industrialisers. In: M. Muchie, P. Gammeltoft & B. Lundvall (eds.), *Putting Africa First: The Making of African Innovation Systems* (pp. 141-153). Aalborg: Aalborg University Press.

Arocena, R. and Sutz, J. 2000. Looking at National Systems of Innovation from the South. *Industry and Innovation*, 7(1): 55-75.

Arthur, W. 1990. *The Green Machine: Ecology and the Balance of Nature*. Oxford: Basil Blackwell.

Ashby, W.R. 1960. *Design for a Brain: The Origins of Adaptive Behavior*. London: Chapman and Hall.

Axelrod, R. 1997. Advancing the Art of Simulation in the Social Sciences in: Rosario Conte, Rainer Hegselmann and Pietro Terna (eds.), *Simulating Social Phenomena*, pp. 21-40. Berlin: Springer.

Axley, S.R. & McMahon, T.R. 2006. Complexity: A Frontier for Management Education. *Journal Of Management Education*, 30(2): 295-315

Bak, P. 1996. *How Nature Works: The Science of Self-Organized Criticality*. New York: Copernicus.

Bak, P., Tang, C. & Weisenfield, K. 1987. An explanation of 1/f noise. *Physical Review Letters*, 59:381-384.

Barrow-Green, J. 1997. *Poincaré and the Three Body Problem*. Rhode Island: American Mathematical Society.

Baskin, K. 1998. *Corporate DNA: Learning from Life*. Boston: Butterworth Heinemann.

Begun, J.W. 1994. Chaos and Complexity: Frontiers of Organisation Science. *Journal of Management Inquiry,* 3(4):329-335.

Bodhanya, S. 2005. Strategy Making: Traversing Complexity and Turbulence. Paper presented at 7th *International Conference on Foresight Management in Corporations and Public Organisations – New Visions for Sustainability*, Helsinki, Finland, June 2005.

Brown, C. 1995. *Chaos and Catastrophe Theories*. Thousand Oaks: Sage Publications.

Cartwright, T.J. 1991. Planning and Chaos Theory. *APA Journal*, 57(1):44-56.

Caves, R.E. 1984. Industrial Organisation, Corporate Strategy and Structure: A Survey. *Journal of Economic Literature*, 18(1): 64-92.

Child, J. 1972. Organisational Structure, Environment and Performance: The Role of Strategic Choice. *Sociology*, 6: 1-22.

Contractor, N.S. 1998. *Self-organizing System Research in the Social Sciences: Reconciling the metaphors and the models*. Urbana-Champaign: University of Illinois.

Crutchfield, J.P. & Mitchell, M. 1995. The Evolution of Emergent Computation. *Proceedings of the National Academy of Sciences*, 92:10 742-10 746.

de Geuss, A. 1998. Planning as Learning. *Havard Business Review*, March-April.

Denbeigh, K. G. 1951. *The Thermodynamics of the Steady State*. London: Methuen Ltd.

Dent, E. (1999). Complexity science: A worldview shift. *Emergence*, *1*(4), 5-19.

Department of Arts, Culture, Science and Technology (DACST). 1996. *White Paper on Science and Technology: Preparing for the 21st Century*. Pretoria: DACST.

Department of Science and Technology (DST). 2006. *National Survey of Research and Experimental Development 2003-2004*. Pretoria: DST.

Department of Science and Technology (DST). 2007a. Annual Report 2006/07. Pretoria: DST.

Department of Science and Technology (DST). 2007b. *National Survey of Research and Experimental Development 2004/2005*. Commissioned Survey conducted by the Centre for Science, Technology and Innovation Indicators of the HSRC.

Department of Science and Technology (DST). 2008. *National Survey of Research and Experimental Development 2006-2007*. Pretoria: DST.

Descartes, R. 1628. Rules for the Direction of the Mind. http://smith2.sewanee.edu/texts/Ecology/OnReductionism, accessed 04/02/2008.

Descartes, R. 1637. Discourse on the Method of rightly conducting one's reason and seeking the truth in the sciences. In: *Descartes 1985*, 1:111-151.

Descartes, R. 1954. Rules for the Direction of the Mind. In: *Descartes Philosophical Writings*. Translated by Elizabeth Anscombe and Peter Thomas Geach. Thomas Nelson and Sons Ltd. London. p. 153-180

Edquist, C. and Johnson, B. 1997. Institutions and Organizations in Systems of Innovation. In: C. Edquist (ed.), *Systems of Innovation: Technologies, Institutions and Organizations*. London: Pinter Publishers.

Farley, B.G. & Clark, W.A. 1954. Simulation of Self-Organizing Systems by Digital Computer. *Transactions of the Institute of Radio Engineers, Professional Group on Information Theory* (PGIT) 4: 76-84.

Flood, R.L. & Jackson, M.C. 1991. *Creative Problem Solving: Total Systems Intervention*. Wiley: New York.

Freeman, C. 1987. *Technology Policy and Economic Performance*. London: Pinter Publishers.

Freeman, C. 2003. Preface. In: M. Muchie, P. Gammeltoft & B. Lundvall (eds.), *Putting Africa First: The Making of African Innovation Systems*. Aalborg: Aalborg University Pres.

Frisch, U. 1995. *Turbulence: The Legacy of A.N. Kolmogorov*. Cambridge, England: Cambridge University Press.

Ghallagher, R. & Appenzeller, T. 1999. Beyond Reductionism. *Science*, vol. 284, no. 5411, p. 79.

Gleick, J. 1987. *Chaos: Making a New Science*. New York: Viking Penguin.

Goldspink, C. 2000. Modelling Social Systems as Complex: Towards a social simulation meta-model. *Journal of Artificial Societies and Social Simulation*, 3(2): 1-23.

Goodwin, B. 1997 (1994). *How the Leopard Changed its Spots: The Evolution of Complexity*. London: Phoenix.

Government of South Africa. 2002. *South Africa's National Research and Development Strategy*. Pretoria: Government of South Africa.

Government of South Africa. 1990. *Scientific Council Research Act: Act No. 46 of 1988*, as amended by Scientific Research Act, No. 71 of 1990. Pretoria: Government of South Africa.

Gregerson, H. & Sailer, L. 1993. Chaos theory and its implications for social science research. *Human Relations*, 46(7): 777-802.

Guerin, S. & Kunkle, D. 2004. Emergence of Constraint in Self-organizing Systems. *Nonlinear Dynamics, Psychology, and Life Sciences*, 8(2): 131-146.

Haken, H. 1977. *Synergetics: An introduction: Nonequilibrium Phase Transitions and Self-Organization in Physics, Chemistry and Biology*. Berlin: Springer-Verlag.

Henshilwood, C.S.; d'Errico, F.; Yates, R.; Jacobs, Z.; Tribolo, C.; Duller, G.A.T.; Mercier, N.; Sealy, J.C.; Valladas, H.; Watts, I. &Wintle, A.G. 2002. Emergence of Modern Human Behavior: Middle Stone Age Engravings from South Africa. *Science*, 295: 1278-1280.

Hinton, G. & Sejnowski, T. J. (eds.). 1999. Unsupervised Learning: Foundations of Neural Computation. In: *Computational Neuroscience*. Cambridge, Massuchusetts: MIT Press.

Hock, D.W. 1996. *The Chaordic Organization: Out of Control and into Order, 21st Century learning Initiative*. Washington DC: 21st Century Learning Initiative.

Holland, J.H. 1992. *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. Cambridge, Massachusetts: MIT Press.

Jamison, A. 2003. What is Innovation Policy All About? In: M. Muchie, P. Gammeltoft & B. Lundvall (eds.), *Putting Africa First: The Making of African Innovation Systems* (pp. 63-72). Aalborg: Aalborg University Press.

Jensen, H.J. 1998. Self-Organized Criticality: Emergent Complex Behavior in Physical and Biological Systems, vol 10 of *Cambridge Lecture Notes in Physics*. Cambridge, England: Cambridge University Press.

Johnson, B. 1992. Institutional Learning. In: Lundvall, B. (ed.), *National Systems of Innovations*. London: Printer.

Johnson, J.L. & Burton, B.K. 1994. *Chaos and Complexity Theory for Management: Caveat Emptor*. Journal of Management Enquiry, 3(4): 320-328.

Johnson, B. & Lundvall, B. 2003. National Systems of Innovation and Economic Development. In: M. Muchie, P. Gammeltoft & B. Lundvall (eds.), *Putting Africa First: The Making of African Innovation Systems* (pp.13-28). Aalborg: Aalborg University Press.

Juma, C. & Yee-Cheong, L. 2005. *Innovation: Applying Knowledge in Development*. London: Earthscan.

Kauffman, S. 1993. *The Origins of Order: Self-organization and selection in evolution*. New York: Oxford University Press.

Kauffman, S.A. 1995. *At Home in the Universe: The search for laws of self-organisation and complexity*. Oxford: Oxford University Press.

Kay, J. & Schneider, E.D. 1994. Embracing Complexity: The Challenge of the Ecosystem Approach. *Alternatives*, 20(3): 32-38

Kay, J.J. (2000). Ecosystems as Self-organizing Holarchic Open Systems: Narratives and the Second Law of Thermodynamics. In: S. E. Jorgensen & F. Muller (eds), *Handbook of Ecosystem Theories and Management*, CRC Press-Lewis Publishers: 135-160

King, D.A. 2004. The Scientific Impact of Nations. *Nature*, 430:311-316.

Klimontovich, Y.L. 1990. *Turbulent Motion and the Structure of Chaos: A New Approach to the Statistical Theory of Open Systems*. Dordrecht: Kluwer Academic.

Kohonen, T. 1984. *Self-Organizing Maps and Associative Memory*. Berlin: Springer-Verlag.

Krugman, P.R. 1996. *The Self-Organizing Economy*. Oxford: Blackwell.

Kuhn, T. 1961. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press.

Langton, C.G. 1990. Computation at the Edge of Chaos: phase transitions and emergent computation. *Physica D* 42:12-37.

Lehn, J. 2002. Toward Self-Organization and Complex Matter. *Science*, 295: 2400-2403.

Lewin, R. 1992. *Complexity*. New York: Macmillan.

List, F. 1841. *The National System of Political Economy* (translated from German). London: Longmans, Green and Co.

Lucas, J.R. 1996. The Unity of Science without Reductionism. *Acta Analytica*, 15: 89-95.

Lundvall, B. (ed.). 1992. *National Innovation Systems: Towards a Theory of Innovation and Interactive Learning*. London: Pinter Publishers.

Lundvall, B., & Muchie, M. & Gammeltoft, P. (eds.). 2003. *Putting Africa First: The Making of African Innovation Systems* (pp. 1-10). Aalborg: Aalborg University Press.

Machan, T.R. 2008. *Reduction, Science and Reason*. Science and Reason. http://rebirthofreason.com/Articles/Machan/Rectionism,_Science_and_Reason.shtml, accessed 04/02/2008.

Mallick, D.N. & Chaudhury, A. 2000. Technology Management Education in MBA Programs: a comparative study of knowledge and skill requirements. *Journal of Engineering and Technology Management*, 17: 153-173.

Mathews, K.M., White, M.C. & Long, R.G. 1999. Why Study the Complexity Sciences in the Social Sciences? *Human Relations*, 52(4): 439-462.

Maturana, H. & Varela, F. 1980. *Autopoiesis and Cognition*. Dordrecht, Holland: D. Reidel.

McBride, N. undated. Chaos Theory and Information Systems. *Chaos, Complexity and Information Systems*. www.cse.dmu.ac.uk/~nkm/CHAOS.html, accessed 01/11/02.

Mendelson, J. & Blumenthal, E. Chaos Theory and Fractals. Accessed from http://www.mathjmendl.org/chaos/, 9/6/2005.

Metcalfe, J.S. 1995. The Economic Foundations of Technology Policy: Equilibrium and Evolutionary Perspectives. In: P. Stoneman (ed.), *Handbook of Economics of Innovation and Technological Change*. Oxford: Blackwell.

Mintzberg, H., Ahlstrand, B. & Lampel, J. 1998. *Strategy Safari: The Complete Guide through the Wilds of Strategic Management*. London: FT Prentice Hall.

Miramontes,

Mitchell, M., Hraber, P.T. & Crutchfield, J.P. 1993. Revisiting the Edge of Chaos: Evolving cellular automata to perform computations. *Complex Systems*, 7:89-130.

Montresor, A., Meling, H. & Babaoglu, O. 2002. Towards Adaptive, Resilient and Self-Organizing Peer-to-Peer Systems. In: *Proceedings of the International Workshop on Peer-to-Peer Computing* (co-located with Networking 2002), Pisa, Italy, May 2002.

Moore, J.I. 2001. *Writers on Strategy and Strategic Management: Theory and Practice at Enterprise, Corporate, Business and Functional Levels, 2nd edition*. London: Penguin.

Muchie, M. 2003. Re-thinking Africa's Development through the National Innovation System. In: M. Muchie, P. Gammeltoft & B. Lundvall (eds.), *Putting Africa First: The Making of African Innovation Systems* (pp. 43-61). Aalborg: Aalborg University Press.

Mytelka, L.K. 2003. The Dynamics of Catching Up: The Relevance of an Innovation System Approach in Africa. In: M. Muchie, P. Gammeltoft & B. Lundvall (eds.), *Putting Africa First: The Making of African Innovation Systems* (pp. 29-42). Aalborg: Aalborg University Press.

Nagel, K. & Rasmussen, S. 1994. Traffic at the edge of Chaos. In: R.A. Brooks and P. Maes, (eds.), *Artificial Live IV: Proceedings of the 4th International Workshop on the Synthesis and Simulation of Living Systems*. Cambridge: MIT Press

Nelson, R.R. & Rosenberg, N. 1993. Technical Innovation and National Systems. In: R.R. Nelson (ed.), *National Innovation Systems*. New York: Oxford University Press.

Nicolis, G. & Prigogine, I. 1977. *Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuations*. New York: John Wiley.

Niosi, J. 2002. National Systems of Innovations are “x-efficient” (and x-effective): Why some are slow learners. *Research Policy*, 31:291-302.

Niosi, J., Saviotti, P.P., Bellon, B. & Crow, M. 1993. National Systems of Innovations: In Search of a Workable Concept. *Technology in Society*, 15: 207-227.

Ortegon-Monroy, M. C. 1999. *Chaos & Complexity Theory: A Review of its Status, Perspectives and Implications for Management*. Kingston: University of Lincolnshire & Humberside.

Patel, P. & Pavitt, K. 1994. The Nature and Economic Importance of National Innovation Systems. *STI Review*, 14:9-32.

Patel, P. & Vega, M. 1999. Patterns of Internationalisation of Corporate Technology: Location vs Home Country Advantages. *Research Policy*, 28:145-155.

Poincaré, H. 1903. *Science and Method*. (http://www-chaos.umd.edu/misc/pincare.html accessed 09/09/2005).

Porter, M.E. 1980. *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. New York: The Free Press.

Prigogine, I. 1955. *Thermodynamics of Irreversible Processes*. New York: John Wiley.

Prigogine, I. & Stengers, I. 1984. Order *out of Chaos: Man’s New Dialogue with Nature*. New York: Bantam Books.

Rajagopalan, N. & Spreitzer, G.M. 1996. Towards a theory of strategic change: A multilens perspective and integrative framework. *Academy of Management Review*, 22(1): 48-79.

Reason, P. & Goodwin, B. 1999. *Toward a Science of Qualities in Organizations: Lessons from Complexity Theory and Postmordern Biology*. Bath: Centre for Action Research in Professional Practice, University of Bath.

Republic of South Africa. 1988. *The Scientific Research Council Act*. Act No. 46 of 1988.

Resnick, M. 1994. *Turtles, Termites and Traffic Jams: Explorations in Massively Parallel Microworlds*. Cambridge, Massachusetts: MIT Press.

Rodrigues, R. 2004. Overcoming Organisational Silence: Leveraging Polyphony as a Means for Positive Change., e-motionalizing Management. In: *The Challenge for Globalizing Organizations, 2004 Annual Conference*, Midwest Academy of Management, 29 April – 1 May 2004.

Ruelle, D. 1980. Strange Attractors. *Mathamatical Intelligencer* 2:126-137.

Scerrie, M. 2003. The Prospects for Regional Innovation System(s) Within Sub-Saharan Africa. In: M. Muchie, P. Gammeltoft & B. Lundvall (eds.), *Putting Africa First: The Making of African Innovation Systems* (pp. 171-183). Aalborg: Aalborg University Press.

Schelling, T.C. 1978. *Micromotives and Macrobehavior*. New York: W.W. Norton.

Schumpeter, J.A. 1942. *Capitalism, Socialism and Democracy*. New York: Harper.

Schrodinger, E. 1944. *What is Life?* Cambridge: Cambridge University Press.

Selfridge, O.G. 1959. Pandemonium: A Paradigm for Learning. In: The Mechanisation of Thought Processes, D.V. Blake and A.M. Uttley, eds., vol. 10, *National Laboratory Symposia,* pp. 511-529. London: Her Majesty's Stationery Office.

Senge, P.M. 1990. *The Fifth Discipline: The Art and Practice of the Learning Organisation*. New York: Doubleday.

Shalizi, C.R. 2001. *Causal Architecture, Complexity and Self-organisation in Time Series and Cellular Automata*. Doctoral Thesis, unpublished. Santa Fe: Santa Fe Institute.

Shin, J. 1996. *The Economics of Late-comers: Catching up, Technology Transfer and Institutions in Germany, Japan and South Korea*. London: Routledge.

Stewart, I. 1989. *Does God Play Dice? The Mathematics of Chaos*. Harmondsworth, Middlesex: Penguin Books.

Tsoukas, H. 1998. Chaos, Complexity and Organization Theory. *Organization*, 5: 291-313.

United Nations Development Programme. 2001. *Human Development Report*. New York: UNDP.

van der Heijden, K. 1996. *Scenarios: The Art of Strategic Conversation*. Chichester: John Wiley.

Viotti, E.B. & Baessa, A. 2005. Innovation in Developing Versus Developed Economies: Some evidences from a comparison of the innovation surveys of

Brazil and selected European countries. In: *Proceedings of Globelics 2005 Africa – Innovation systems promoting economic growth, social cohesion and good governance*, Tshwane University of Technology, Tshwane (Pretoria), South Africa, 31 October – 4 November 2005.

von Bertanlanffy, L. 1968. *General System Theory: Foundations, Developments, Applications*. New York: Braziller.

von Foerester, H. & Zopf, G.W. (eds.). 1962. Principles of Self-Organization. In: *Transactions of the University of Illinois Symposium on Self-Organization*, Robert Allerton Park, 8-9 June 1961. New York: Pergamon Press.

von Neumann. J. 1966. *Theory of Self-Reproducing Automata*. Urbana: University of Illinois Press. Edited and completed by Arthur W. Burks.

Wallace, A. 1990. *The Green Machine: Ecology and the Balance of Nature*. Oxford: Basil Blackwell.

Wangwe, S.M. 2003. African Systems of Innovation: Towards an Interpretation of the Development Experience. In: M. Muchie, P. Gammeltoft & B. Lundvall (eds.), *Putting Africa First: The Making of African Innovation Systems* (pp. 75-91). Aalborg: Aalborg University Press.

Wheatley, M.J. 1992. *Leadership and the New Science: Learning about organization from an orderly universe*. San Francisco: Berrett-Koehler.

Wolfram, S. 1986. Random Sequence Generation by Cellular Automata. *Advances in Applied Mathematics*, 7:123-169

World Bank. 2008. *Rising food prices: Policy options and World Bank response. A discussion document for a Development Committee meeting*. New York: World Bank.

Wright, S. 1932. The Roles of Mutation, Inbreeding, Crossbreeding and Selection in Evolution. In: *International Proceedings of the 6th International Congress on Genetics*, D.F. Jones (ed.), vol. 1: 356-366.

Yovits, M.C. & Cameron, S. (eds.). 1960. Self-Organizing Systems. In: *Proceedings of an Interdisciplinary Conference, 5-6 May 1959, vol. 2 of International Tracts in Computer Science and Technology and their Application*. Oxford: Pergamon Press.

Dryzek, J. 1982. Policy Analysis as a Hermeneutic Activity. *Policy Sciences*, 14: 309-329.

Eger, M. 1997. Achievements of the Hermeneutic-Phenomenological Approach to Natural Sciences. *Man and World*, 30: 343-367.

Rouse, J. 1987. *Knowledge and Power*. Ithaca: Cornell University Press.

Latour, B. 1987. *Science in Action*. Cambridge, Massachusetts: Harvard University Press.

Kuhn, T.S. 1970 [1962]. *The Structure of Scientific Revolutions*, 2nd ed. Chicago: University of Chicago Press.

Heidegger, M. 1962 [1927]. *Being and Time*. (Trans. J. MacQuarrie & E. Robinson from the 7th edition of *Zein und Zeit*). San Francisco: Harper.

Habermas, J. 1984 [1981]. *The Theory of Communicative Action*, vol. 1 (Trans. T. McCarthy). Boston: Beacon Press.

Giddens, A. 1976. *New Rules of Sociological Method*. New York: Basic Books.

Baron, R.J. 1990. Medical Hermeneutics: Where is the "Text" we are Interpreting? *Theoretical Medicine*, 11: 25-28.

Suchting, W.A. 1995. Much Ado about Nothing: Science and Hermeneutics. *Science & Education*, 4: 161-171.

Simosi, M. 2003. Using Toulmin's Framework for the Analysis of Everyday Argumentation: Some Methodological Considerations. *Argumentation*, 17: 185-202.

Daniel, S.L. 1986. The Patient as a Text: A Model of Clinical Hermeneutics. *Theoretical Medicine*, 7: 195-210.

Ihde, D. 1997. Thingly Hermeneutics/Technoconstructions. *Man and World*, 30: 369-381.

Hitchcock, D. 2005. Good Reasoning on the Toulmin Model. *Argumentation*, 19: 373-391.

Toulmin, S.E. 1978. *An Introduction to Reasoning*. New York: Macmillan.

Markus, G. 1987. Why is there no Hermeneutics of Natural Sciences? Some Preliminary Theses. *Science in Context*, 1 (1): 5-51.

Cushing, J.T. 1995. Hermeneutics, Underdetermination and Quantum Mechanics. *Science & Education*, 4: 137-146.

Heelan, P.A. 1995. Quantum Mechanics and the Social Sciences: after Hermeneutics. *Science & Education*, 4: 127-136.

Ulin, R.C. 1992. Beyond Explanation and Understanding: Anthropology and Hermeneutics. *Dialectical Anthropology*, 17: 253-269.

Engel, P. 1991. Interpretation without Hermeneutics: a Plea against Ecumenism. *Topoi*, 10: 137-146.

Hesse, M. 1980. *Revolutions and Reconstructions in the Philosophy of Science*. Brighton: Harvester Press.

Gadamer, H-G. 1975 [1960]. *Truth and Method*. (Trans. G. Barden & J. Cumming from the 2nd [1965] ed. New York: Crossroads.

Foucault, M. 1981. Questions of Method: an Interview with Michel Foucault. *Ideology and Consciousness*, 8: 3-14.

Jaspers, K. 1951. *Way to Wisdom: An Introduction to Philosophy*. (Trans. R. Manheim). London: Victor Gollanez Ltd.

Ricoeur, P. 1970. *Freud and Philosophy: An Essay on Interpretation*. (Trans. D. Savage). New Haven: Yale University Press.

Leder, D. 1990. Clinical Interpretation: The Hermeneutics of Medicine. *Theoretical Medicine*, 11: 9-24.