Knowledge Processes and their role in Innovation – a comparison of selected Chinese and Indian Practices

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(Deemed to be University under Section 3 of the UGC Act, 1956)

CERTIFICATE

The research embodied in this thesis, entitled **Knowledge Processes and their role in Innovation - a comparison of selected Chinese and Indian Practices,** was conducted by Mr.Murali Murti in the School of Natural Sciences and Engineering, National Institute of Advanced Studies, Bangalore, India, under the supervision and guidance of the undersigned. It is hereby certified that the thesis submitted is a bonafide record of research done by the candidate in fulfillment of the requirements for a doctoral degree, and that the thesis has not previously formed the basis for the award to the candidate of any other degree, diploma, associateship or fellowship or any other similar title of any other university or society.

Place : Bangalore

Date: December 6, 2019

Arun Vishwanathan
(Advisor)

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DECLARATION

I hereby declare that the work presented in this thesis, entitled **Knowledge Processes and their role in Innovation - a comparison of selected Chinese and Indian Practices,** has been carried out under the guidance of Dr. Arun Vishwanathan and has not formed the basis for the award of any other degree, diploma or fellowship previously. The particulars given in this thesis are true to the best of my knowledge and belief.

Place: Bangalore

Date: December 6. 2019

Murali Murti

Abstract

Innovation is today recognized as key to fostering economic development and building technological strengths in firms, industries and countries. While generally described in the common understanding as anything that is new and has an impact on a large scale, it is technology-driven innovation that has assumed prominence in the contemporary environment.

Academic research and study of innovation has encompassed a variety of disciplines. From these efforts, innovation has emerged as a complex phenomenon that requires a variety of factors and concepts to describe. As innovation assumes prominence in countries such as India and China, which are aiming to catch up with the more advanced countries, the factors that go to make successful innovations possible are of increasing interest.

This thesis examines the different approaches adopted in the field of innovation studies and identifies knowledge processes as key to understanding innovation. The applicability of this has been investigated through detailed research into three industry segments.

Based on the research, frameworks of innovation based on knowledge processes have been presented including a comparison of practices in selected Chinese and Indian organizations.

Frontispiece

Clockwise from top left:

*"**Knowledge**" by Murali Govindaraj,*

*"**Innovation**" by Murali Govindaraj,*

*"**Artificial Intelligence in China**" abstract graphic*

*"**First recorded symbol of Zero**"*

Bakshali manuscript 3rd century India.

Author’s Biographical Sketch

Murali Murti holds a B.Tech in Electrical Engineering from the Indian Institute of Technology, Bombay and a PGDM in Management from the Indian Institute of Management, Calcutta. As a management practitioner, he has extensive experience in the Indian Information Technology industry, working in senior positions with premier companies both in India and overseas. As an academic, he has taught MBA courses as Professor of Management at PES University, Bangalore. He has published and presented in international journals and conferences. His research interests are innovation, technology policy and development, and strategic management.

Dedication

This Thesis is dedicated to
The MINSK – 2 Computer

the very first computer installed at
The Computer Centre
Indian Institute of Technology, Bombay
Based on Diode-Transformer-Logic
on which I wrote my first computer program
and learned the meaning of innovation

Acknowledgments

This thesis would not have been thought of, conceptualized, registered for, proposed, researched, and completed without the unceasing support and selfless encouragement of more people than I can remember. If I have omitted anyone among the names below, please be assured that it was only by oversight caused by an overloaded memory.

Let me begin by acknowledging my heartfelt gratitude to my Doctoral Advisory Committee members, Dr. Arun Vishwanathan, my Supervisor, Professor S. Chandrasekhar, and Professor Lalitha Sundaresan. I could not have asked for a better DAC than mine, and I will always cherish the experience of working with you. Those who have completed a thesis know that a dissertation involves a large number of decisions, not always taken in serial order. Professor Chandra, your peerless instinct for the right decision, more than anything else, has given final shape to this thesis. Your wide range of knowledge of the subject of innovation, incisive analytical ability, and your adherence always to the highest intellectual standards inspired me to give my best to this thesis. Professor Lalitha Sundaresan, your ability to get to the heart of a problem and frame a solution in the most practical way possible, gave me invaluable inputs when I needed them most, especially in the framing of the Research questions and the Research Design in general. Arun, your faith in me and your unvarying, cool-headed support during the ups and downs that PhD students go through, were indispensable for reaching the conclusion of this long journey. I learnt more from you than I could have imagined possible on how to write a readable thesis and readable articles. Thank you for monitoring my progress over so many years and providing me motivation at just the right time in exactly the right words.

Let me now acknowledge, in the chronological sequence of my PhD journey, all those who inspired and supported me. For motivating me to think of a PhD after so many years in industry, my thanks go to Dr. Kalyani Rangarajan, former Director of the PESU Department of Management, and Dr. KNB Murthy, Vice Chancellor of PES University.

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I thank the National Institute of Advanced Studies for giving me the opportunity to register and complete my PhD. From the mandatory entrance test and interview process, the course requirements, the six-monthly reports and the Annual Colloquia, NIAS treated me as a student just the same as everyone else, despite my frequently getting mistaken for a faculty member. NIAS, thank you for an exhilarating and rejuvenating experience.

I must first thank Dr. VS Ramamurthy, former Director of NIAS, for his consistent interest in my thesis and his invaluable inputs and reviews of my material. I thank next all the faculty of the International Strategic and Security Studies Program, especially Prof. Rajaram Nagappa, Mr. S Gopal, Dr Mayilvaganan, Prof. Ramani, and Amb. Kumar.

Among the other faculty of NIAS, I thank all those whom I interacted with, which includes mostly everybody. In particular, my thanks go to Dr Dilip Ahuja, Prof. Narendra Pani, Dr Shivali Tukdeo, Prof. Carol Upadhyaya, Dr Rajesh Kasturinrangan, Dr Hippu Nathan, and many others who taught me during the first- and second-year courses, and who rejigged my mind to think like a PhD student. Of all the experiences I have had in the past eight years, it was my time as a student sitting in a class that I shall remember with the greatest joy.

A special note of thanks to Ms. JN Sandhya, who contributes more selflessly to more students than can be imagined. Always with a smile and a friendly word of advice, she kept me always on course from the administrative perspective. My thanks also to all the other administration staff in NIAS, who helped me so much with report preparation and laptop management whenever required.

When I walked into NIAS for my first day as a bonafide student, I was apprehensive about how so many young people would respond to me. I needn’t have worried. From the first moment, the student body accepted me as one of their own and enveloped me with the warmth of their friendship. I have no words to express how grateful I am to have been among their enthusiasm, energy, and never-failing humour.

Now let me come to those closest to my heart. First, my sister Meera for her heartfelt love, support and encouragement. Not a week passed without her inquiring about my progress. To my sons Chaitanya and Dhritiman, who were ever willing to critique me most bitingly, I say thank you as only a father can for never letting me compromise on standards. To our dogs Zara, Yoda and Dogtu, you are assured of a special place in heaven for lifting my spirits as only pets can.

And finally, to the one person who matters more to me than anyone else, who encouraged me with word and gesture, who, in the middle of her exacting and demanding career, took the trouble every day to send me articles about anything that could possibly be connected to my thesis, who ensured I had the most comfortable workspace as possible at home, who cheered me on every day, who lavished me with all the love from her largest of hearts, my everlasting thanks to my wife Prabha.

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Chapter 1

Introduction

1.1 <u>Background to the study</u>

The common understanding is that innovation is anything that is new and has an impact on a significant scale. There is more than ample evidence of the impact of innovation on everyday life in modern societies. Innovation has been termed “the central issue in economic prosperity” (Porter M. E., 1998) and “the act that endows resources with a new capacity to create wealth” (Drucker, 1984). Such observations reflect the recognition of the role of innovation in fostering economic development and in building technological strengths in firms, industries and countries.

The common understanding is that there exists a wide range of types of innovation – technological, financial, marketing, organizational innovations, new business models, to name only a few. All of these are seen in contemporary societies. Among the various types, as they relate to the business and economic worlds, technology-driven innovation has assumed increasing dominance in the modern world. This is an outcome of the exponential growth of technological knowledge, leading to a surfeit of technologies to choose from for problems requiring solutions (Chandrasekhar, 1996). In turn, the exponential growth in technological knowledge leads to greater interest in possible innovations amongst companies, industries, and increasingly, countries.

The common evidence available, however, reveals that innovation takes place at different intensities in different settings. Two basic questions arise from this observation. Under what conditions does innovation take place, and why are there different levels of innovation across organizations, industries and countries?

Modern academic approaches to answering these questions and understanding innovation have focused on two broad perspectives.

The first, which can be termed the macro perspective, views innovation as a black box whose external dimensions and effects can be described, and which can be studied independently. In the macro perspective, innovation has consequences and externalities that go far beyond the individuals that developed the innovation, and it is only necessary and sufficient to link these externalities and effects to broad environment and structural trends and changes, without going into the finer details of how individual innovation actually come into existence.

The second perspective, which can be termed the micro perspective, examines innovation as it takes place within the unpacked black box or black boxes, with a view to understanding how groups of people act on streams of knowledge to create innovations. The micro perspective has the objectives of analyzing processes, causal factors and innovation behaviour by individuals and organizations.

The conundrum faced by innovation researchers so far is that both these perspectives provide only post-facto analyses of innovation. Both models explain in depth what happened in the past. In contrast, in the real world, innovations in the process of happening focus on finding solutions to problems with an eye to the future. Neither the macro or micro perspectives provide insights into innovation as it happens, or insights into how approaches to developing solutions to problems present themselves to individuals and teams within organizations.

The macro approach has been associated with policy making at the level of companies, industries and countries. But policy making at these different levels in different countries has not led to better or more efficient innovation across the board. In similar vein, the micro perspectives help to explain what happened in specific cases. But companies and individuals who study these cases without reference to the external environment find themselves no closer to successfully replicating the processes by which significant innovations take place.

When innovation happens, the individuals involved are somehow able to integrate both the macro and micro perspectives within their efforts. Resolving the innovation conundrum therefore requires an integrated model that combines the macro and micro perspectives. But despite a lot of effort in trying to understand innovation, no comprehensive model that explains innovation has emerged. No broad-based model that links the macro and micro perspectives of innovation has been developed. All that can be postulated is that innovation is a complex process in which concepts such as product and technology lifecycles, overarching external trends and changes, tightly coupled informal networks of people working within diffuse organizational structures, visionary managerial leadership, knowledge transfer networks within and outside the organization, and many other factors play roles.

That innovation begins with the identification of a bottleneck of some kind that needs to be removed is evident from the analysis of past cases (Chandrasekhar, 1996). Yet it is not clear whether the impetus for the removal of such bottlenecks, and therefore the impetus for innovation, comes from the external environment or the internal structures and dynamics of the organization. No model has yet been developed that ties together all these disparate threads.

One developing contemporary view is that innovation fosters societal learning and knowledge generation (Stiglitz & Greenwald, 2014). This observation has highlighted the possible role of information and knowledge networks in the innovation process (Cohen & Levinthal, 1990). For countries aiming to catch up with the technologically advanced world, such as China and India, these insights have been of compelling interest. As China and India grow in economic and geopolitical importance, a focus on establishing effective knowledge networks as an imperative of innovation that hastens the process of catching up becomes vital (Wolf, et al., 2011).

Recent research has therefore focused on the role of knowledge as it relates to innovation in organizations. The diverse ways in which organizations, teams and individuals obtain, select and generate knowledge seem to cut across the entire innovation cycle. In the globalized and Internet-intensive world of today, access to knowledge is less of a problem than it was in the past. What seems to be significant are the processes and orientation to separate out the wheat and the chaff from both micro-environmental and macro-environmental sources., This ability to effectively leverage the critical and correct knowledge as triggers for successful innovations appears to be critical.

In this research I postulate that a focus on knowledge as related to innovation may provide insights that enable the unpacking of the innovation black box linking innovation processes to the environment outside. The primary objective of this thesis therefore became a systemic investigation into these complex knowledge processes and their role in innovation. A second objective of this thesis was to investigate how knowledge processes and their impacts differ between select Indian and Chinese organizations.

1.2 Scope of the research

When researching a field as vast as innovation, defining the scope is a *sine qua non* for meaningful results. Innovation research can be dimensioned broadly along *types of innovation, industry, geography, time period* and *aspects of innovation.* In this research, *technological innovation* has been selected as the focus, since it has the most significant impact, as is shown in the Literature Survey chapter of this thesis, on the economies of countries and the daily lives of people. Although the word "technology" itself has been defined in diverse ways, for the purposes of this thesis the definition of technology used is the one given by Emmanuel G. Mesthene as "the organization of knowledge for the achievement of practical purposes" (Mesthene, 1970). This definition is comprehensive enough to include organizational innovations in structure and strategy, in addition to the more conventional, dictionary understanding of technology as the application of scientific concepts for practical applications.

That technological innovation is seen in all industries is common understanding; however, many innovations have impacts only within their industries. Some, however, have impacts beyond the boundaries of their own industries. For this research, it was felt that it would be more meaningful to study such innovations and sectors. Therefore, the *Information Technology (IT)* industry was selected as the main field of research, since there are virtually no areas of human activity that have been left untouched by computers and IT. In the chapter on Research Design, these ideas are expanded on to explain how the selection was made of supercomputers, the software industry and small defence technology companies as sub-fields for the research. The last was chosen because the defence sector, in many ways and in different countries, has historically been the source of many significant technological innovations that have had impacts beyond their immediate application. As an example, the computer industry itself, as is shown in the chapter on supercomputers, was born out of a military requirement. A final reason to choose the IT sector as the main field was the background of this researcher, which is explained in greater detail in the Research Design chapter.

Within the broader IT field, the selection of India and China as the *geographical fields for innovation research* suggest themselves automatically, given the institutional location of this research in the National Institute of Advanced Studies (NIAS) in Bengaluru, India. For many years, NIAS has done work in comparative studies on China and India, and this research aligns well with that institutional focus. The practical conveniences of access to the field and cost of data collection round off this selection. Within these boundaries, however, research into any aspect of the Information Technology field, which is well known to be global in its spread and organization, requires constant reference to other countries, particularly the United States. This has been sought to be accomplished by data collection from secondary sources wherever necessary.

Finally, as stated above, innovation is a many-dimensional phenomenon, which has been studied from a vast number of perspectives, as the Literature Survey chapter shows. Any doctoral research necessarily concentrates on one aspect of a broader field. As stated earlier, the knowledge aspect of innovation, and more specifically knowledge processes, offered a promising field for investigation and forms the core of this research. Nevertheless, the nature of innovation is that it can result in production of *public goods* that have been theorized as contributing to a learning society (Stiglitz & Greenwald, 2014). Such a perspective is useful in a thesis that aims to study similarities and differences between two countries in innovation. This thesis therefore goes beyond the singular focus on knowledge processes to cover a larger perspective on innovation, in the literature survey, data collection and analysis, to the extent that is practically possible without losing coherence.

1.3 *Rationale for the research*

Why study innovation at all? More specifically, why study one aspect of innovation as evidenced in one sector in two countries? In one sense, the vast body of knowledge comprising innovation research that has developed since the early 20th century, numbering well into the thousands of articles and books, itself answers this question (Floricel, 2007). From this body of knowledge, two illustrative directions have been selected that provide a rationale for this research; namely, the importance of innovation in the past, and the potential for its importance in the future.

Figure 1.1 shows the changes in per capita GDP from 1960 to 2017 in four countries; China, India, Nigeria and the Congo (World Bank, 2017). In 1960, the Congo and Nigeria were more prosperous, on a per capita basis, than China or India. By 2017, the situation had changed completely. China was far ahead, and the Congo had retreated to a distant fourth. India and Nigeria had worsened on a per capita GDP basis, reckoned in current US $. With the information about China's industrialization available in the public domain, it can be hypothesized that innovation may have played a role. This illustrates the importance of innovation in the path in shaping a country's economy and the lives of its citizens, and this forms the first part of the rationale for this research.

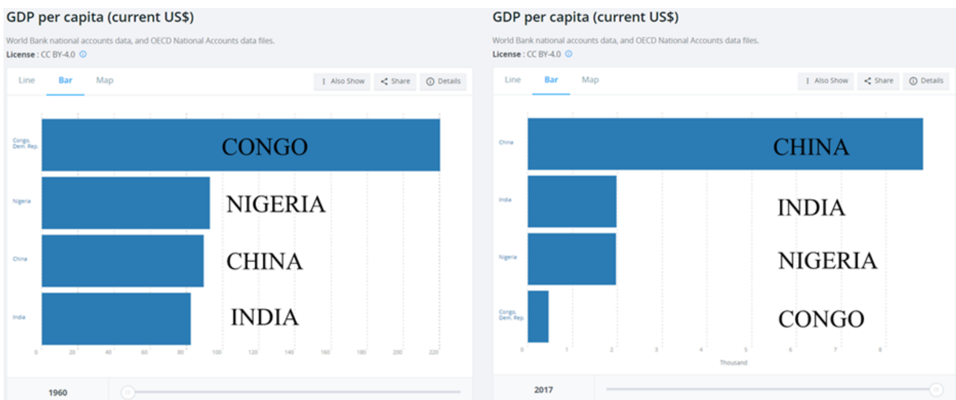


Figure 1.1 – Changes in GDP per capita in current US$ in four countries 1960-2017

As stated above, innovation begins with the identification of a problem or opportunity. It is a cliché that opportunities and problems exist in virtually infinite numbers all around us. Yet it is often not obvious what the scale of the problem or opportunity can be. Figure 1.2 illustrates the possible impact of climate change on the GDP per capita of countries around the world by 2100 (Burke, Hsiang, & Miguel, 2015). Reference to the original article reveals that, according to this forecast, the GDPs per capita of India, China and the United States are estimated to change by -92%, -42% and -36% respectively i.e. all three will suffer substantial, possibly catastrophic decreases on this metric; while the Russian Federation GDP per capita is forecasted to change by over +400% i.e. a potentially transformative rise. While this is only one of many forecasts, it does highlight the potential geopolitical consequences of climate change. In a nuclearized world, war is not as an attractive option as it was in the mid-20th century for the resolution of such massive contradictions. As an alternative, technological innovation may turn out to be the source of new strategies and new power to mitigate the effects of climate change. This hypothetical scenario illustrates the potential of innovation in the future and thus provides the second part of the rationale for this study.

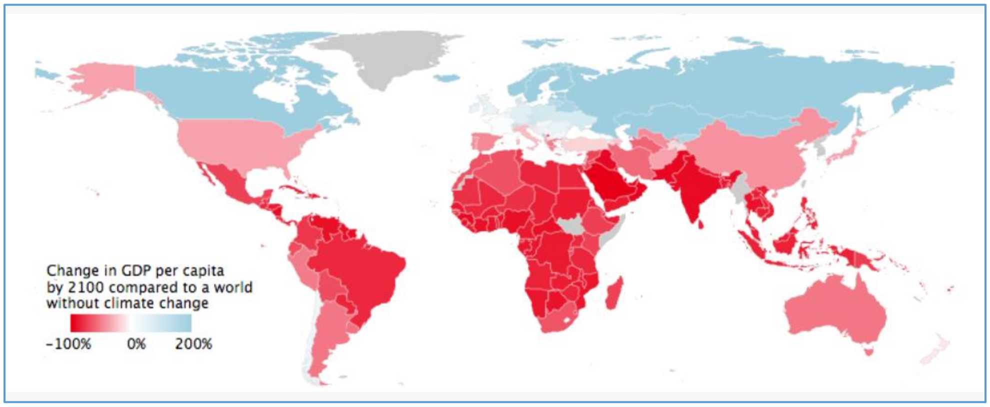


Figure 1.2 – Forecasted effect of climate change on GDP per capita by 2100

With this background, scope and rationale for this research, it is necessary now to state a central theme and assumption of this thesis. This thesis does not seek to evaluate whether one country is performing better or worse according to any set of innovation metrics. Rather, it seeks to establish a common framework within which we can understand the similarities and differences in how knowledge processes play a role in innovation in the two countries. This central theme informs the structure that has been developed for this thesis.

1.4 Structure of the thesis

The thesis is organized along classical lines i.e. a sequence of chapters detailing a linear process of study of the available literature, identification of research gaps, framing of appropriate research questions, designing an acceptably rigorous research methodology, choosing an appropriate method for analysis of data, and finally presenting the analysis and results. The structure of the thesis is shown in Figure 1.3.

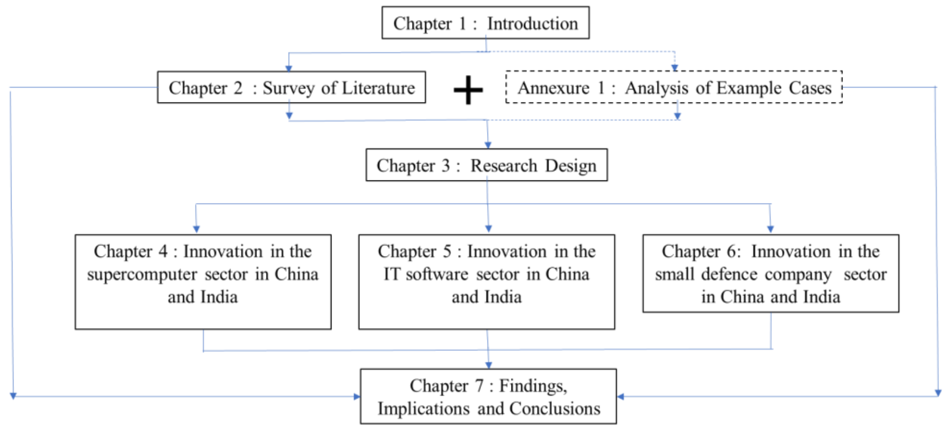


Figure 1.3 – Structure of the thesis

Chapter 2, titled "Survey of Literature" documents twelve different approaches located in the literature of innovation studies, which are termed as macro-level and micro-level studies. These cover the field of innovation studies over a period of approximately one hundred years, which can be divided into two parts, each of fifty years approximately. The first half, including the Second World War and going up to the sixties, saw approaches that considered innovation as one component of a larger rubric of human activity, for example economic activity. Thus, the attempt was to study the effects of innovation on that kind of activity. The second half, starting with the sixties, looked at innovation as an independent activity that had multidimensional consequences. Several perspectives were developed within this perspective. This led to the problem of identifying which of these many concepts and approaches – of which twelve have been documented – are the most relevant to understanding innovation in the contemporary context.

For this purpose, ten case studies available in the literature have been analyzed to identify these key concepts. Although these case studies and the analysis forms part of the Literature Survey, the analysis has been structured as Annexure I to streamline the flow of the discussion within Chapter 2. In the thesis structure diagram given in Figure 1.3, this Annexure is shown at the same level in the chapter hierarchy as Chapter 2, and *it is emphasized that the two should be read in sequence and considered together as constituting an integrated module of the thesis*.

Following the analysis developed in Chapter 2, the detailed Research Design is set out in Chapter 3. Starting with the identification of research gaps, the chapter continues to the framing of appropriate research questions, consisting of one Main and one Subsidiary Question respectively, structured around the role of knowledge processes in innovation, and the patterns of their practices in India and China. Since knowledge forms the primary theoretical focus, Chapter 3 develops a theoretical picture of knowledge concepts that provide epistemologically rigorous justification for the study of innovation framed as knowledge. With this as the starting point, the detailed design of the research project is described in twenty-one steps, some of which were executed in parallel, that start from choosing an appropriate philosophical perspective, through the selection of the appropriate research method, the definition of the specific fields of study, the optimum methods of data collection, and the processes included to insure quality of data collection and analysis. The chapter ends with a description of the expected and observed limitations to this research, and a summary of the data collected.

The next three chapters form the substantive content of this thesis and describe in detail the field investigation into the three chosen sectors. Chapter 4 covers my in-depth investigation of the supercomputer sector, Chapter 5 the software sector, and Chapter 6 the small defence technology companies sector. All three begin by providing a comprehensive overview of the sector and its technologies, including an account and analysis of historical patterns. In each case the sectoral highlights are analyzed of the two countries which are the focus of this thesis, namely, China and India, with relevant information about the United States included wherever necessary to provide perspective. From these I develop a picture of innovation patterns in the three sectors in China and India, and from the data so generated I abstract an analysis of the role of knowledge and knowledge processes. The three chapters document a total of ten case studies developed during the field investigations. In each of Chapter 4,5 and 6, I present one example of a bellwether innovation that represents the extent of impact that an innovation can have in that sector.

In Chapter 7, the final chapter titled “Findings, Implications and Conclusions”, I introduce a framework of innovation based on knowledge processes. This framework is derived from a combined analysis of the twenty case studies available – ten from the literature and ten from field research. Through this I isolate the key concepts applicable to innovation and show how knowledge processes tie them together in a coherent way at both the organization and ecosystem levels. The framework forms the detailed response to the

Main Research Question posed in this thesis. This is followed by a discussion on the patterns of selected Chinese and Indian practices in response to the Subsidiary Question. The thesis closes with a discussion of the implications of the research to the field of innovation studies in general, and then to the field of studies beyond and outside of innovation.

1.5 *Discussion*

In this Chapter, I have introduced innovation through a wide-canvas overview of its various dimensions and aspects as they relate to this thesis. This is different from the conventional approach to many a Thesis Introduction, which often begin with a definition of the key terms to be researched. In this final section of this Chapter, I turn the conventional approach around and return to the definition and meaning of innovation over the centuries to conclude the Introduction.

The word “innovation”, for much of history, was understood, ironically, as something not wholly desirable (Godin B. , 2014). From Socrates and Plato, for whom the Greek term *kainotomia*, meaning “making new”, implied change that could be harmful to the established way, till the Dark Ages, innovation, or its equivalent words, meant something both positive and negative. For a period after that, innovation was viewed as evil in the sense of threatening orthodox religious purity. It was only after the Reformation that innovation regained some of its appeal as a form of positive change. As late as the 19th century, innovation was viewed with suspicion because of a feared association with “revolution” (Godin B. , 2014). As human knowledge expanded, however, the word innovation piqued the interest of scholars, leading to the 20th century field of innovation studies.

This brief summary of the etymology of the word innovation, together with the observation that expansion of knowledge changed its definition and thus its very character, a process which is by no means complete, shows that innovation is far from a static concept. It is also clear that as the nature of innovation has become better understood, the benefits of innovation have become commensurately greater. Understanding “innovation” has been useful historically, and this fact provides an appropriate platform to now move to Chapter 2, the Survey of Literature on innovation.

Chapter 2

Survey of Literature

The field of innovation studies spans over a century and covers a vast diversity of research, as shown in the Introduction. The number of books and articles run well into the thousands. In such a huge field, it becomes incumbent to survey a representative sample and then classify the different types to aid analysis. From an extensive examination of the available literature, twelve distinct approaches and concepts that were relevant to understanding innovation were identified. These can be broadly described as those which provide a macro perspective, in which innovation is seen as a component of a larger rubric of human activity; and those which provide a micro perspective, which may also be described as a practitioner perspective, in which innovation is seen as an independent human activity. The macro perspectives were largely dominant during the first half of the 20th century, after which the micro perspectives started to make their appearance.

In the macro category, the important approaches or views are, the *economic perspective,* the *historical perspective,* the *societal perspective,* subdivided into the *social-constructivist,* the *technological determinism-based,* and the *country-level* perspectives. The *evolutionary view* is an interesting perspective that falls neither into the macro nor the micro categories. In the micro category, we can identify as critically important the *S-curve*, or *diffusion process* view, the *strategic management model,* subdivided into the *Porter five forces model* and the *resource-based view (RBV),* the *Galbraith innovation organization model,* the *Henderson taxonomy of innovations*, the *disruptive innovation perspective*, and the Stan Shih *smiling curve framework.*

The literature survey is followed by an analysis of ten case studies, which is given in detail in Annexure I. The objectives of the case study analysis were threefold; to validate the macro and micro perspectives obtained from the literature survey; to examine the extent of integration between the two; to identify any factors that were key to the innovation process or useful for further research. Combining insights from the literature survey and the case studies, it would then be possible to identify a comprehensive list of factors that describe innovation. It might also be possible to build a framework of innovation that could then be validated through fieldwork. Such an approach would be particularly useful for comparing innovation patterns between India and China.

2.1 The macro perspectives on innovation

2.1.1 The economic view

The economic perspective constitutes a macro view of innovation, one that views the phenomenon as a black box which can be described by several external dimensions and effects.

The modern study of innovation began as an economic perspective and can be traced first to Joseph Schumpeter (Schumpeter J. A., 1911). Schumpeter can be said to have provided a philosophy of innovation, rather than a specific model. He identified five basic types of innovation, namely, new products, new methods of production, new sources of supply, the exploitation of new markets, and new ways to organize business. This taxonomy covers what are now referred to as technological innovation, process innovation and organizational innovation. However, Schumpeter avoided conceptualizing a model of innovation, and instead merely emphasized the economic consequences.

Schumpeter followed up this seminal contribution to the study of innovation with an equally significant insight into the relationship between long-term economic growth and innovations in clusters of linked industries (Schumpeter J. , 1939). He showed that innovation clustering tends to occur during the troughs of long cycles (Hargroves & Smith, 2004). This thread of thought has continued to be researched throughout the 20th century, and it has been shown that clustering of innovations in linked industries is responsible for long-term economic growth (Schumpeter J. A., 1911).

The next important, again seminal, contribution to the long-wave theory of innovation was by the Russian economist Nikolai Kondratiev (sometimes spelled Kondratieff), who showed for the first time in 1935 the correspondence between long cycles of economic activity and technological development (Kondratieff & Stolper, 1935). Figure 2.1 shows the original chart as developed by Kondratiev.

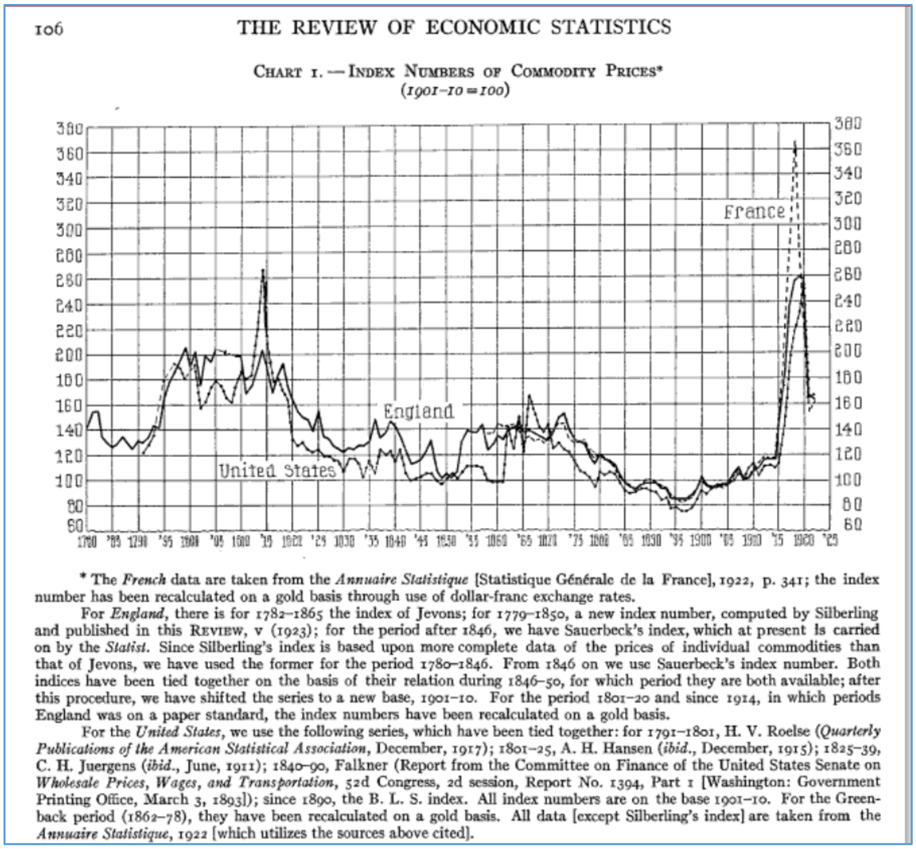


Figure 2.1 – Original Kondratiev long wave chart

Historically, it was demonstrated by Robert Ayres in 1989 that there have been five major stages, or clusters, of technological transformations (Ayres, 1990). In the first cycle, characterized by a shift in fuel from wood-based charcoal to coal, the linked iron, steam engine and coal industries created a growth spiral. Another cluster of cotton spinning, weaving and a new form of organization called the factory also created another separate spiral of growth. (1770-1800). In the second Kondriatev cycle, the two separate clusters became linked and steam power and steam engines extended to other forms of transportation such as railroads and ships. These extensions continued to fuel economic growth. (1830-1850). In the third, the rapid evolution of metallurgical and mechanical engineering, the applications of the principles of electricity to everyday life, the discovery of methods to drill and refine crude oil, the development of the internal combustion engine, and the development of electrical devices to facilitate rapid long-distance communication all contributed to the economic growth in the third Kondriatev cycle (1860-1900). The fourth was the development of synthetic materials, electronics and computers (1930-1960).

The fifth, beginning in 1980 and continuing still, is the integration of computers and communications (Ayres, 1990). By the fifth Kondriatev cycle, the economies of the more advanced countries begin to exhibit the characteristics of complex coupled open systems where clear distinctions between cause and effect begin to lose their meaning. Figure 2.2 is a reproduction of the long waves chart from the Ayres paper of 1989.

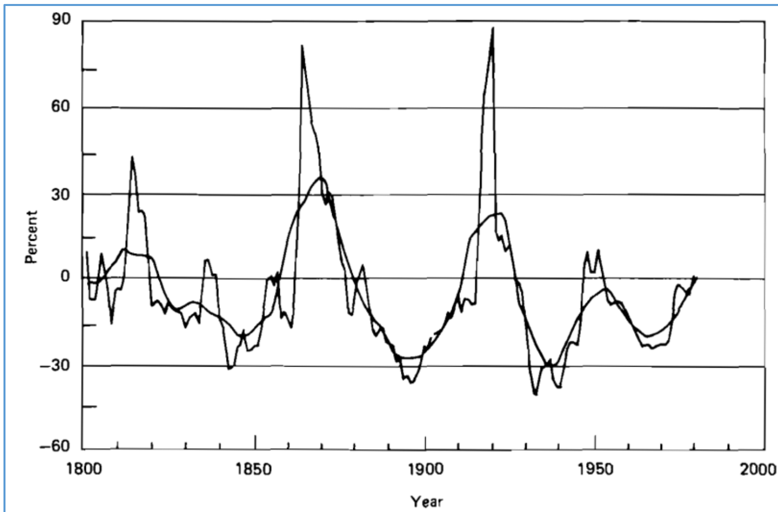


Figure 2. **US wholesale price index. (Source: N. Nakicenovic, IIASA, 1987.)**

Figure 2.2 – Original long waves chart from the 1989 Robert Ayres paper

Ayres argues that while innovation does undoubtedly occur in clusters related to long Kondriatev cycles, as historical evidence clearly suggests, the cause appears to be technological opportunity per se rather than purely economic factors. Such opportunities are created by a combination of ‘breakthroughs’ that push back the limits of existing technologies, and by the ‘convergence’ or ‘fusion’ of developments in different fields (Ayres, 1990). Ayres’s arguments are an important step in extending the economic view of innovation to an investigation of the innovation process itself and the nature and causes of technological opportunities. However, Ayres felt that the pace of innovation had slowed from 1950 to 1975 as economies grew and industries stabilized. This observation missed the innovation boom that was already well under way in the Information Technology industry.

It was Robert Solow (Solow, 1957) who first deconstructed economic growth into two causes – capital accumulation and technological progress. He showed that capital accumulation could account for only one third of the growth, and that therefore the more important drivers were technological progress and innovation. The increases in productivity that have been recorded in the subsequent fifty years have borne out the role of innovation and the creation of knowledge and its transmission as learning.

This economic view of innovation has persisted till this day, and finds its expression notably in William Baumol's characterization of economic innovation as consisting of two types; first, rent-seeking innovation, which results in greater profit or revenues to the firm through new ways of doing business, without any change in products, technology, or production methods, and second, productive innovation, which is the outcome of new technologies or new products (Baumol, 2002). Baumol gives pride of place to innovation in explaining economic growth. However, as was the case with Schumpeter, Baumol does not attempt a detailed model of innovation, but restricts himself to an analysis of the economic consequences.

Freeman and Soete (Soete & Freeman, 1997) investigated in detail the macroeconomic and microeconomic dimensions of innovation. Among the new insights they provided was the notion of diverse 'techno-economic systems', which have life cycles different from the life cycles of products in which specific technologies are embedded. Such techno-economic systems become interlinked in the modern economy (He & Maskus, 2012). Thus, externalities are generated, which in turn create barriers for innovation outside of the interlinked techno-economic systems (Graham & Senge, 1980). Such situations lead to the 'catch up' phenomenon, where firms, industries, and even countries are driven by competitive pressures to try and match the innovations that have already taken place within the interlinked techno-economic systems.

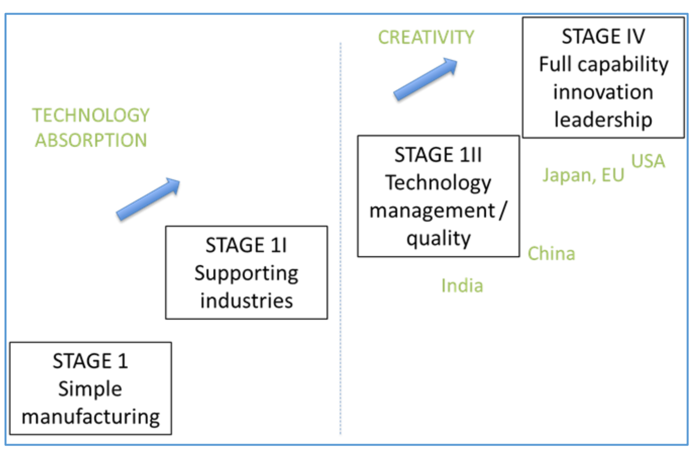


Figure 2.3 – The "catch up" staircase model

2.1.2 The historical perspective

Understanding innovation through investigating in detail historical instances of successful innovation may be said to be an attempt to link the macro and the micro descriptions (Proctor, 1998). In many instances, detailed historical records are available which make it possible to examine what happened from a variety of perspectives (Singh, 1999). In such attempts, the notion of 'artifacts' has been usefully introduced (Peck, 2011). Using historical evidence of the introduction of successful artifacts, innovation has been characterized by three aspects (Basalla, 1999). The first is diversity, highlighting the existence of a vast number of historical artifacts. The second is necessity, highlighting the human need for repeated introduction of new artifacts. The third is evolution, since historically technology seems to evolve in an organic way, giving substance to the observation that human beings seem to selectively, rather than comprehensively or randomly, choose artifacts. Other factors such as simple happenstance, business acumen and cultural constructs have also been remarked upon in the historical analysis of innovation (Pool, 1997).

2.1.3 The social-constructivist perspective

Another thread of research within the macro perspective to understand innovation in more detail was the attempt to answer a fundamental question: Does society shape technology or does technology shape society? Both views have led to approaches to understanding innovation.

A well-known example of the first view, that society shapes technology, is the 'social constructivist' approach to understanding technology, and following that, technological innovation (Bjker, Hughes, & Perach, 1987). In this approach, equal weight is sought to be given to technical, social, economic and political questions. This approach identified three requirements; the need to move away from the 'genius inventor' as the central explanatory concept, the need to move away from technological determinism, and the need to consider in an integrated, rather than a disaggregated, manner the technical, social, economic and political dimensions. The social constructivist view also represents a 'macro description' of innovation, inasmuch as it treats innovation as a "black box" without attempting to examine the processes within (Zheng, 2010).

2.1.4 The technological determinism approaches

The ‘technological determinism’ approach is an example of the second view, that technology shapes society, and posits that technology develops essentially on its own and that technology influences society rather than the other way around. In contrast, the social-constructivist and evolutionary views of technology lean towards the hypothesis that it is social and economic forces that lead to technological innovation.

The technological determinism view is associated with an oft-quoted work by Bimber, in which three approaches to technological determinism are distinguished. The first is normative determinism; which follows Habermas and posits that technology can be considered autonomous and deterministic because the norms by which it is advanced are removed from the political and ethical discourse. The second is ‘unintended consequences’ determinism, which is derived from the observations of the uncontrollability and uncertainty of the consequences of technological development. The third is the ‘nomological’ view, which claims that technological developments occur according to some naturally given logic, which is not culturally or socially determined, and that these developments force social adaptation and changes (Bimber, 1994).

Both the opposing points of view became included within the rubric of ‘science and technology studies (STS)’, which has emerged as a major field of study and has led to the concept of national innovation systems. However, these approaches all suffer from the same disadvantage of ‘macro’ descriptions of innovation, and therefore limit our understanding. It is the technological determinism view, however, which first attempted to build a bridge to the micro descriptions of innovation through technology assessment studies; and in so doing, led to a major thread of thought within the micro perspective.

It should also be noted that the technological determinism approach lends itself naturally to alignment with the evolutionary perspective, thus drawing upon the usefulness of analogy to the natural world.

2.1.5 Country level Innovation Studies

To conclude the survey of literature within the macro perspective, it should be reiterated that the potential of innovation to affect and indeed catalyze economic development and growth has been well understood over the past century (Lal, 1992).

Increasingly, therefore, innovation has become a matter of attention for governments, both from the developmental and strategic points of view (Cohen & Levinthal, 1990). A report from the RAND Corporation in 2008, for example, states in the very first sentence that "concern has grown that the United States is losing its position as a global leader in science and technology (S&T)" (Galama & Hosek, 2008). In India, too, concern has been expressed that the basic sciences are no longer attracting the best people (Anitha, 2005). The rise of China, in particular, is viewed by both the US and India as a challenge, since both India and China are viewed as "re-emerging economies" with the potential to challenge the US economically (NIAS, 2008). Governments have approached this issue from several directions, one being the concept of National Innovation Systems.

The concept of National Innovation Systems was an extension of the science and technology studies (STS) approach (Johnson, Lundvall, & Edquist, 2003). It has a historically long pedigree, going back to Friedrich List's conception of "The National System of Political Economy", which "might just as well have been called the National System of Innovation" (Freeman C. , 1995). It is, however, Beng-Ake Lundvall who is credited with first having used the term in 1992 (Freeman C. , 1995). Since then, the concept has acquired wide currency and has formed the basis for substantial research on innovation at the national level (Archibugi & Coco, 2005).

The Report of the OECD (OECD;, 1997) on "National Innovation Systems" (NIS) is the definitive guide to the concept and its applications. There have been a profusion of articles and reports examining NISs at the national level in various countries and providing comparisons between different countries. Holbrook was one of the first to use NIS concepts to analyze in detail innovation in British Columbia (Holbrook, 1997). Paterson and others (Paterson, Rob, & Mullin, 2003) showed how the NIS approach leads to more effective science and technology policies, through a comparison of the South African, Latin American and Chinese experiences. This led to the introduction of the terms "technoware, humanware, infoware and orgaware" to describe aspects of a country's NIS.

A second approach that governments have taken is to benchmark their countries against others using a variety of indicators. By 2011, the first steps had been taken towards evolving "indicators" of innovation at the national level (Archibugi, Denni, & Fillipetti, 2009). Belitz and others (Belitz e. a., 2011) give a comprehensive account of the development of an indicator for a NIS and its application to 17 industrialized countries. Despite these achievements the NIS concept also avoids building a model of the innovation process, and instead concentrates only on identifying the components and actors involved in innovation at the national level (Frenken, 2001).

The drawback of both the national innovation systems approach and the indicators approach lie in their "macro description" nature (Frenken, 2004). Both approaches tend to view innovation as akin to a chemical reaction in a test tube. If the ingredients are all present in the right proportions, hopefully a brown ring will form at the top of the solution in the test tube. But the evidence of the past century, and certainly that of the present shows that innovation seems to take place because of entirely separate factors that need to be understood through a micro view (Maclaurin, 1950).

2.1.6 The evolutionary view

Understanding innovation as a process of evolution has been a novel contribution of recent research. The evolutionary perspective bases itself on analogies that can be drawn between the way organisms and species evolve and mutate in the natural world and the way in which technologies and inventions have appeared and disappeared in the economic and business worlds (Basalla, 1999). The evolutionary view starts with the observation that, in the natural world, genes are the fundamental building block of life. Gene aggregation lead to chromosomes. Chromosomes and genes undergo transformation and change through mutation and recombination processes. The environment around them affects these changes. Combinations of chromosomes create species. Species cooperate and compete based on available resources in their environment. Natural selection filters out the best suited for survival and propagation of the species. This continuing dynamic of variation, selection and procreation ensures a continuing adaptation of genes, chromosomes and species to the changes within and without the ecosystem.

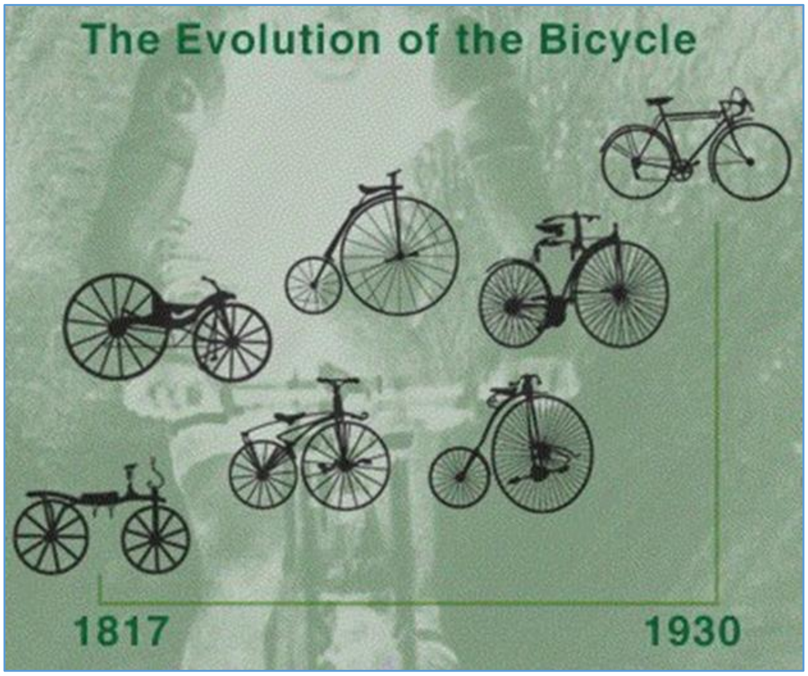


Figure 2.4 - An example of technological evolution

The bicycle is an example of the possibly evolutionary nature of technology. Though the bicycle has a fairly long history of development, the standard safety bicycle even after being developed in 1884 took a long time to stabilize – around the end of the 1890s. A large number of variants trying to solve a variety of user and technology problems characterized the period from about 1879 to 1898. The safety bicycle became the standard after that (Pinch & Bjiker, 1984). The evolutionary path shows that basic elements are redesigned and recombined to generate better performance.

In the economic and business worlds, technologies play the role of fundamental building blocks, akin to genes (Chandrasekhar, 1996). Technologies represent know-how or knowledge, and through processes of recombination and generation of new knowledge, technology domains evolve (Kleiner, 2009). The evolution of these domains is affected by the economic and socio-cultural domains around them. Technology domains lead to development of families of products and services (Kelly, 2011). These are filtered out in the economic and business worlds through the phenomenon of market selection, which plays an exactly analogous role to natural selection in the natural world. Market selection, in turn, leads to the evolution of new technologies that are better fitted to adapt in the turbulence of the economic and business environments. The evolutionary view of technology and innovation has been refined recently to bring in the concept of an ecosystem (Adomavicius, Bockstedt, Gupta, & Kaufmann, 2004) (Ebesberger, Laursen, Saarinen, & Salter, 2005).

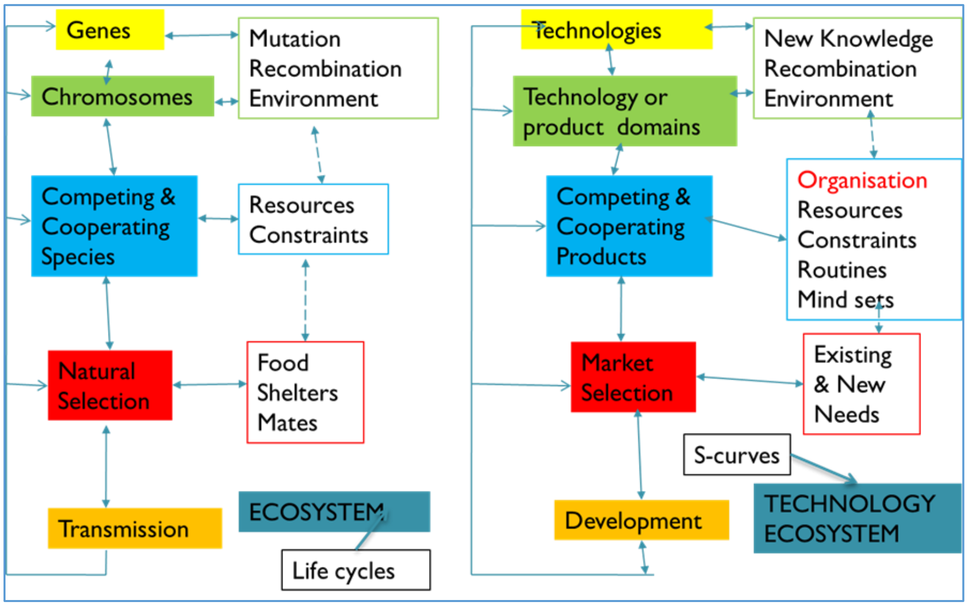


Figure 2.5 - Comparison of biological and technological evolution

While the evolutionary perspective may be properly classified as a macro view to begin with, it nevertheless offers the promise of a future integrated model by postulating processes such as recombination and generation of knowledge. The study of such processes, again, is analogous to gene level studies in molecular biology. The great strengths of the evolutionary perspective are the striking similarities of the patterns to be found in the natural world, which today are accepted as valid models of the evolution of all species on our planet. These similarities presage, perhaps, a similar comprehensive model of how technologies and innovations evolve (Chandrasekhar, 2011).

2.2 *The micro perspectives of innovation*

2.2.1 The S-curve and diffusion process view

The first step in the direction of the process view of innovation was the seminal study on the diffusion of innovations by Everett M. Rogers (Rogers, 1962). Rogers surveyed the acceptance rates of 508 different innovations and showed that all innovations diffuse in similar ways into the environment over time, and that the process of diffusion can be modeled by the S-curve or the product life cycle.

The introduction of the S-curve as central to the phenomenon of innovation was a crucial step towards its understanding. It provides the 'missing link', since it makes evident the fact that innovations occur cyclically, with fresh innovations replacing the earlier ones as existing products and their underlying technologies approach the end of their life cycles (Chandrasekhar, 1996). In the technology industry, Moore's Law is a well-known example of this phenomenon (Bowden, 2004). These initial first steps of a process view of innovation constitute a significant attempt at a micro description of innovation i.e. a 'within the black box' perspective that describes in detail the innovation process itself and in so doing, establishes causal relationships.

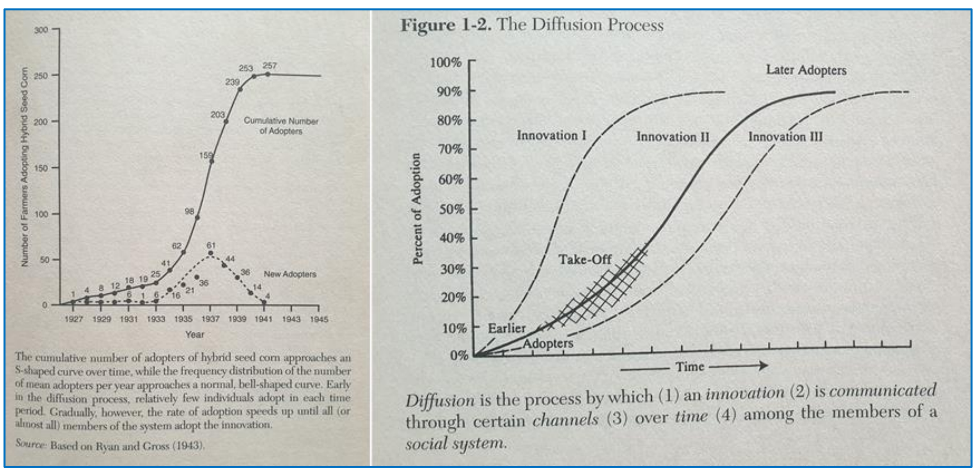


Figure 2.6 a. – Original Rogers S-curve innovation diffusion diagrams

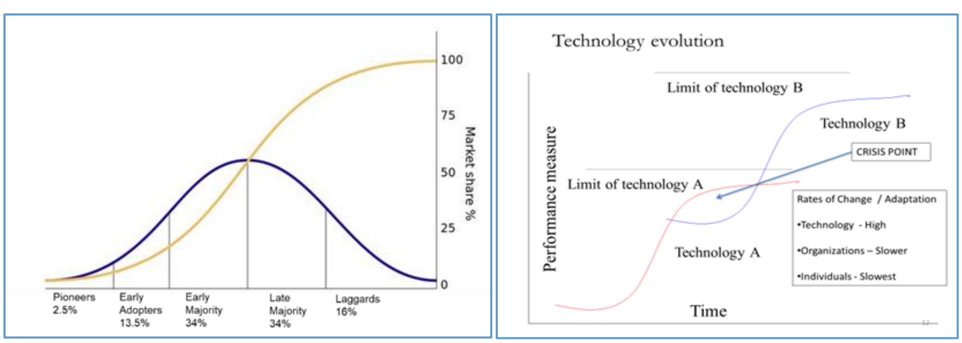


Figure 2.6 b. - The S-curve of diffusion, life cycle and innovation inflection points

The S-curve that Everett showed as representing the diffusion of innovations into the environment over time was first developed in the fields of biology and agricultural sociology. The S-curve remains one of the most highly validated models in virtually all economic and business environments, and hence is an essential component of any model of innovation.

2.2.2 The strategic management perspectives

Contemporaneously with the application of the S-curve to explain the diffusion of innovations, a different insight appeared from the field of management research. However, instead of concentrating on innovation, management researchers approached the problem of success or failure in the marketplace from the standpoint of corporate strategy. The question they wanted to answer was: How do companies decide what to do in order to do better than their competitors? How, in short, does it develop competitive advantage? Framed in this manner, the question indirectly references innovation as one of the candidate strategies, and expands the scope of innovation to include business model or process innovations in addition to technological innovations or new products.

The strategic management perspective has resulted in two broad approaches. The first is conventionally termed the structure conduct performance approach. This postulates that the decisions a company takes, and its performance are driven mainly by the structure of the industry within which it operates. This is best expressed in the Porter Five Forces Model (Porter M. E., 1980).

The five forces model postulates that the success of a competitive strategy is determined by a company’s responses of five interlinked forces in the environment, namely, intensity of competition, buyer power, supplier power, threats of new entrants, and threats of substitution. The five forces model was based on rigorous research in American companies and is usually represented in the following diagram:

Figure 2.7 – Original 1979 Porter's Five Forces diagram

The second approach is conventionally termed the Resource Based View or RBV. The RBV postulates that the success of a company's strategies is not determined by its external environment, but by its ability to effectively marshal its internal resources. For a company to survive, it must develop the requisite capabilities, termed competencies. In order to get ahead of its competitors, it needs to develop exceptional capabilities, termed distinctive competencies, in at least some areas of its operations. The continued changes it needs to make in order to capitalize on its core competencies is the basis for its business and corporate strategy. The RBV is usually represented by the following diagram:

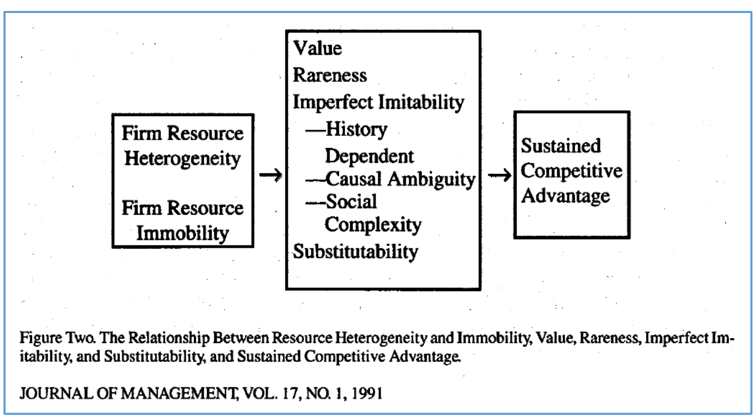


Figure 2.8 – Original 1991 Barney Resources-Based View (RBV)

Both the five forces model and the RBV are conceptually grounded in the economics of David Ricardo. In his famous analysis of what leads to a farmer's success as compared to a competitor with exactly the same acreage of land, Ricardo identifies a superior location which provides lower costs of market access, or superior seeds and soil which give him greater productivity and lower costs per unit, or a combination of both as *factors or capabilities* that provide *competitive advantage*. This analysis led Ricardo to formulate the theories of absolute advantage and comparative advantage, both of which are relevant to the macro analysis of innovation at the industry and country levels.

In David Ricardo's conceptual breakthrough lie the seeds of the link between the strategic management perspective and innovation. A company can innovate based on its perception of its external environment. Or it can innovate by building up distinctive competencies in the form of employee skills and know how. Either way, the strategic approach offers some links between a company's environment and its internal processes, and therefore between the macro and micro perspectives of innovation.

2.2.3 The Galbraith organizational model

The organizational perspective of innovation constituted the attempt to understand innovation from a causal perspective of organizational behaviour. In this effort, we may distinguish three seminal works that have defined the framework for this research approach. The first was by Jay Galbraith, who researched and then set out the roles and linkages between the members of successful innovation teams. The four key roles identified viz. *idea generators, sponsors, orchestrators and gatekeepers;* help understand the innovation process within organizations. He also conceptualized the different ways in which these four roles could combine to form an innovation process. In so doing, Galbraith defined both a linear sequential model and a network model of innovation, based on the patterns of interaction between the roles (Galbraith, 1982). The linear sequential model has since been extended to include models in which activities take place in parallel, but the concept of the roles involved remains the same.

Ideators (team)	Originators of the proposal and project
Sponsors	Provide management support to the ideator team
Orchestrators	Generally the CEO or top management – to transition organization to the new direction
Gatekeepers	Responsible for information flow, communication and coordination

Figure 2.9 - The Galbraith innovation organization model

2.2.4 The Henderson innovation taxonomy

The second key development was the taxonomy of innovations defined by Henderson (Henderson & Clark, 1990). Four types of innovation were defined, radical, modular, architectural and incremental. Based on the extent to which the functional performance of an artifact is affected by changes in its fundamental components or by the way they are combined, or whether they represented a combination of novel new technologies, innovations were grouped into categories. The grouping provides a way in which one can link the changes in the product or processes that are needed to the extent of change that is needed within the organization.

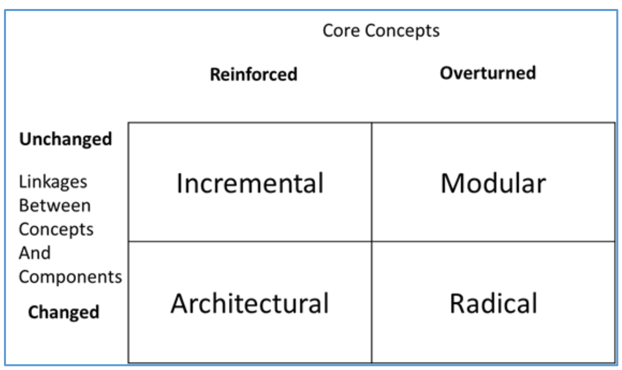


Figure 2.10 - The Henderson taxonomy of innovation types

The Henderson model was groundbreaking in that it provided an insight into the way that innovation teams approach a problem in real life. The key breakthrough provided by the Henderson model was that innovation is a ‘forward looking’ rather than a ‘backward looking’ process, i.e. innovators look for a new solution that will solve the problem and succeed in the future, rather than merely replicating something from the past.

2.2.5 Disruptive innovation model

A further major contribution to the understanding of innovation at the micro level was the typology of innovations introduced by Christensen to explain why successful companies repeatedly fail to anticipate new technologies and very often are replaced by new companies (Christensen, 2000). Innovations, according to Christensen, are of two types, the incremental and the disruptive. Incremental innovations are typical of large, stable organizations, while disruptive innovations are the defining characteristic of small, agile companies, which ultimately grow to replace the earlier leaders. Incremental innovations, as defined by Christensen, correspond to the incremental innovation category of Henderson, while disruptive innovations subsume the architectural, modular and radical forms of Henderson. It should also be noted that the Christensen typology corresponds to some extent to the Baumol division of economic innovations into the rent-seeking and productive categories respectively. To this extent, the Christensen typology is an attempt to bridge the gap between the macro and micro perspectives at the level of the individual firm (Booz & Co, 2010) (Christensen, 2006).

2.2.6 The Smiling Curve model

A firm's value chain can be broadly categorized into three categories: the upstream(input), the downstream (output or market) and the center (Mudambi, 2008). While upstream activities comprise basic and applied research and development and intellectual property creation, downstream activities typically comprise marketing, distribution, brand management and after-sales services. Activities in the middle usually comprise manufacturing, assembly and other repetitious processes aimed at turning out standard products on a mass scale.

The founder of Acer, the well-known laptop manufacturer, Stan Shih (Shih, 1995) analyzed the computer industry value chain and argued that the value-added curve of the industry takes a *"smiling shape"* (value added is taken as equivalent to gross profit and should be more precisely termed as value capture). The smiling curve shows that while higher value is created by companies specializing in both upstream and downstream activities (located at both the left and right side of the curve), firms located in the middle add the lowest value.

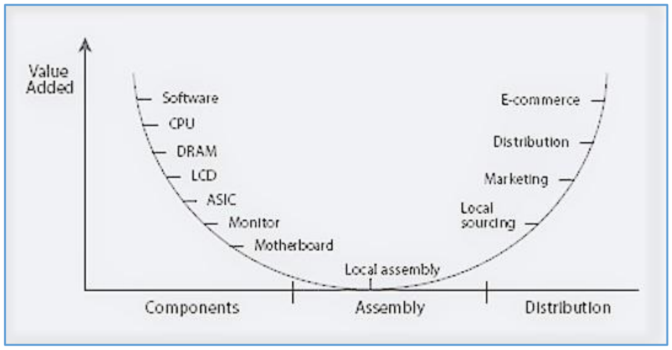


Figure 2.11 - Original Smiling Curve as drawn by Stan Shih

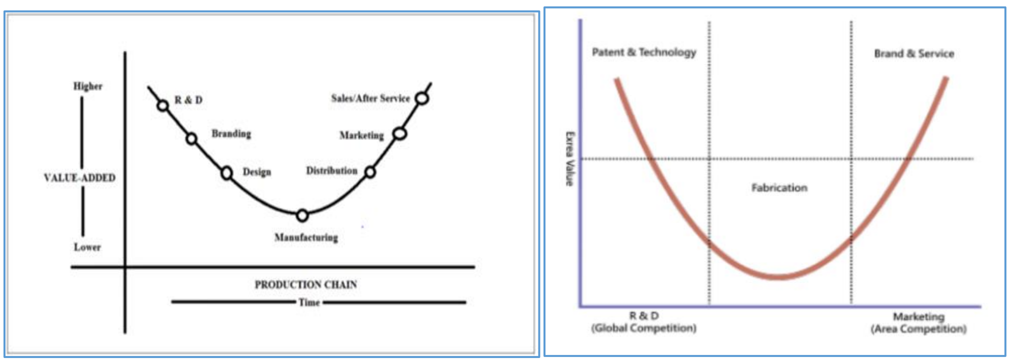


Figure 2.12 - Generalized representations of the Smiling Curve

Shih demonstrated that the two major factors driving the extent of value capture are entry barriers and accumulation of capability: the higher the entry barriers and the greater the accumulation of capabilities, the higher the value capture. For example, the establishment of a brand name business in microprocessors requires the overcoming of high entry barriers such as intellectual property and brand equity and implies high levels of investment over a long-time frame in R&D and marketing (branding), respectively. On the other hand, entry barriers and switching costs are lower for computer assemblers because it is relatively easy to build the needed capabilities. This results in rapid imitation and intense competition. Shih followed up his theory by taking steps, as the founder of Acer, to spin off its basic motherboard business, and concentrate instead on building a brand name business and thereby circumvent the low value commodity assembly problem.

Subsequent research has validated the Smiling Curve concept in the electronics industry (Shin, Dedrick, & Kraemer, 2012), as well as in other industries. The question then arises; if the higher value capture at either end of the curve the more attractive business proposition is, then why is it that all companies do not follow the same path. The answer lies in a surprising corollary discovered by researchers – that to be sustainable in the long run, higher value capture also requires substantially higher investments in infrastructure and customer relationship management. This results in Return on Investment (ROI) evening out across the Smiling Curve even though the value capture might be higher at the two ends of the curve. Additionally, the value proposition changes as the industry moves along the S-curve; what is a single value chain in the Pioneer phase breaks into two halves in the Mature when scale becomes important, similar to the two main choices offered by the Porter's Model of differentiation and cost leadership. Some companies may end up getting stuck in the middle, low value add segment. Therefore, whether a company decides to concentrate on the middle low value region or end high value segments of the Smiling Curve is as much a matter of company culture and top management choice as it is pragmatic business decision making – an important insight for innovation studies.

These concepts afforded by the Smiling Curve are important contributions to the study of innovation; and consequently, we include the Smiling Curve as a distinct practitioner approach in its own right (Zhao & Dong, 2011). Fittingly, in the context of this thesis, the concept was first stated by a Chinese individual, albeit Taiwanese.

The discussion of the Smiling Curve bookends the Survey of Literature of innovation in general. The wide and varied perspectives available for understanding innovation need to be tested against the real world to determine their applicability and effectiveness for understanding contemporary innovation. To this end, an analysis was undertaken of ten documented case studies covering a variety of innovation situations.

2.2.7 Analysis of example cases

The aims of this exercise were as follows:

i. To validate the macro and micro views of innovation as put forth in the literature survey
ii. To look for any insights as to how the two views can be integrated
iii. To identify factors useful for conducting research into innovation.

The case studies were divided into two sets – four relating to the macro view, five to the micro view, and one covering both. The four cases relating to the macro view were:

i. The change in business strategy at Apple Computers during the 1990s
ii. Development and launch of Compact Disks by Philips in the early 1980s
iii. The changes in the Indian and global watch industries consequent to the availability of digital electronic technologies in the 70s.
iv. Development of the Anti-Ship Ballistic Missile by China in the 2000s

The five cases relating to the micro view were:

i. Development of the Sony Trinitron colour television
ii. Development of the photolithography process for the manufacture of integrated circuits
iii. Development of a single-crystal alloy used in fighter aircraft jet engines by China
iv. Development of a charge-coupled-device (CCD) based remote sensing satellite equipment by ISRO in India.
v. Development of the world's first stealth aircraft by the SkunkWorks division of Lockheed.

The one case covering both perspectives was;

i. The setting up and growth of Fairchild Semiconductor, the first Silicon Valley company, in the late 50s and early 60s

Since the presentation of the analysis within this Chapter would require, for contextual clarity, the presentation of the full original cases as well, the detailed analysis of the example cases, as stated earlier, has been moved into Annexure I of this thesis. A second objective was to maintain continuity of narrative within the Chapter. It is emphasized, however, that the detailed analysis of the cases should be read together with this Chapter as one integrated module. The summary of the analysis is presented in Figure 2.13, and this becomes the starting point for the next stage of discussion in the Literature Survey.

S.N.	Case	Starting Point	S-curve stage	Henderson options	Smiling Curve option	Galbraith model strength	Outcome
1	Apple Computers	Opportunity	Incubation to Growth	Architectural / Modular/ Radical	High value capture	Medium	SUCCESS
2	Phillips Compact Disks	Opportunity	Pioneer	Radical	High value capture	High	SUCCESS
3	Indian watch industry	Opportunity	Growth	Radical / Modular / Architectural	High value capture	High & Low	SUCCESS & FAILURE
4	China ASBM	Problem	Pioneer	Radical	--	High	SUCCESS
5	Sony Trinitron	Opportunity/ Problem	Pioneer	Radical / Architectural	High value capture	High	SUCCESS
6	Photolithography process	Problem	Pioneer	Architectural	--	--	SUCCESS
7	China single crystal alloy	Problem	Mature	Modular	--	Low	FAILURE
8	ISRO CCD	Problem/ Opportunity	Pioneer	Architectural	--	High	SUCCESS
9	Lockheed SkunkWorks	Problem	Pioneer	Radical	High value capture	High	SUCCESS
10	Fairchild Semiconductor	Opportunity	Pioneer	Radical	High value capture	High	SUCCESS

Table 2.1 – Summary of analysis of example cases

This summary of the analysis of cases shows the following:

1. Innovation begins with the identification of a problem or opportunity
2. To craft an innovation, useful points of reference are:
    a. The relevant S-curve(s)
    b. The Porter framework or RBV framework or relevant Smiling Curve depending upon the stage of the product or industry S-curve
    c. The Henderson taxonomy options that provide substance to the kind of changes
    d. Smoothly functioning innovation teams organized according to a loosely or tightly coupled hybrid organizational model like the Galbraith model
    e. Leadership and resource commitment as evidenced by willingness to operate at the high value-add ends of the Smiling Curve or the differentiation or cost leadership positions of the Porter or RBV frameworks
3. For innovation to be successful, the efficiency of the innovation teams is paramount, so the strength of the Galbraith model in the organization is critical.
4. Such teams form knowledge networks for sharing of information and knowledge. To utilize the latest, or best applicable, concepts and technologies, the knowledge networks need to extend beyond the boundaries of the organization. The routines used for the creation of these formal and informal knowledge networks that cuts across traditional organizational hierarchies appears to be important
5. For teams to work together effectively, efficient exchange of information and knowledge is necessary.

6. This brings into focus the possible role of knowledge processes in innovation. Knowledge processes are therefore candidates for research into innovation.

In the above analysis, it will be observed that the Porter Five Forces Framework, the RBV perspective and the Smiling Curve are all evidenced. From a theoretical standpoint, the Smiling Curve can be considered as a special case of a combination of the Porter Five Forces framework and the RBV. However, from a practitioner perspective, the Smiling Curve is more "real", in the sense that it presents a variety of decision options for selection based on the culture of the organization and the personalities of the leadership. Chinese industry, especially in the IT sector, appear to have adopted the Smiling Curve as a strategic planning tool to a greater extent than either the Porter framework or the RBV. With his experience in industry, this researcher also finds the Smiling Curve intuitively easier to use than either the Porter or RBV frameworks; it is more "user friendly", to borrow a term from the software industry. For these reasons, in Figure 2.13, the Smiling Curve is listed with the clear understanding that it represents equally the Porter and RBV models as well.

The analysis of the ten example cases highlights the potential importance of knowledge and knowledge processes in innovation (Hargadon, 2002). Knowledge processes thus become a candidate for research into innovation, and this has been adopted in this thesis, as the title suggests. As a prelude to situating knowledge concepts within the formal research design, an overview of the available research into knowledge as related to innovation is now presented.

2.2.8 Knowledge and innovation research studies in the literature

In the real world, it has been postulated that there exist two types of knowledge, tacit and explicit. As intuitively obvious, tacit knowledge refers to knowledge that is generally embedded within the human brain and mind often through experience, while explicit knowledge refers to knowledge that is codified and recorded in some form, such as a document, a diagram or an electronic record, inter alia. The correspondence of this taxonomy to the philosophical traditions of empiricism and rationalism is clear. Extensions to this model include bringing in the concept of "reusable knowledge", i.e. knowledge widely available, shared, and circulating within an organization, going beyond the notion of tacit knowledge centered essentially on one individual (Nonaka, 1994) (Bratianu, 2009).

To understand the relationship between knowledge, both tacit and explicit, and innovation, there have again been two approaches, the macro and the micro. At the macro level, research has focused on aggregate estimates of knowledge available in a country or industry, and an examination of the nature of knowledge flows within “systems of innovation”, again in aggregate numbers (Frawley, Platesky-Shapiro, & Mathews, 1992). Giovanni Dosi identified knowledge search as a general feature of technological progress and analyzed it from a micro-economic perspective (Dosi, 1988). Chang and Chen studied systems of innovation (SI) at the national, regional and sectoral levels to map the effect of knowledge flows (Chang & Chen, 2004). It was found that there was no common model for mapping knowledge flows. Related studies in China and India concluded that access to global knowledge databases was important (Altenburg, Schmitz, & Stamm, 2008).

At the micro level, the most widely used description of knowledge has been the Nonaka model. This model postulates that exchange, generation and flows of both tacit and explicit knowledge occur through four processes (Nonaka, 1994). These are described as socialization, internalization, externalization and combination processes, and are usually represented in the following diagram, called the Nonaka model:

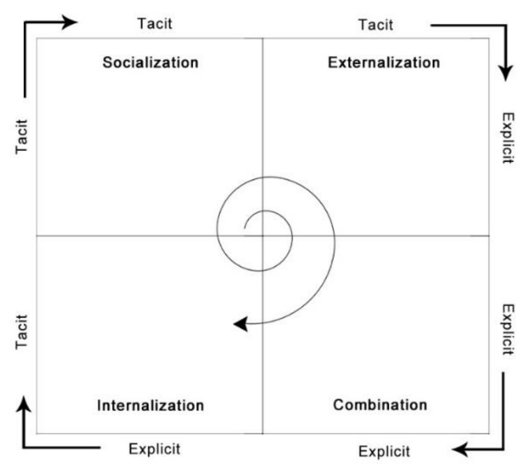


Figure 2.13 – Original 1994 Nonaka Knowledge Exchange diagram

By linking the four exchange processes to experience, dialog, refining of knowledge and creation of knowledge, Nonaka’s model captures well the nature of innovation as an outcome of knowledge processes. The different kinds of outcomes are illustrated well by Pasteur's Quadrant (Stokes, 1997).

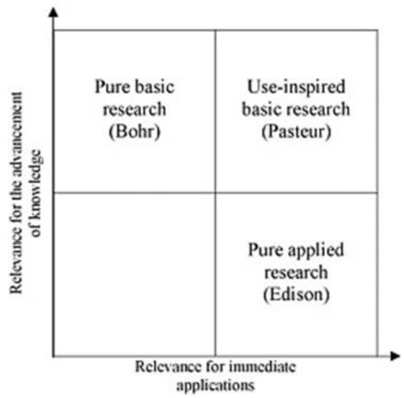


Figure 2.14 - The Pasteur Quadrant

Yet, while Nonaka's model provides a good framework for linking knowledge processes and innovation, it does not provide insights into why innovation levels should be significantly different given the greater transparency and availability of information for some time now (Gourlay, 2004). It also does not provide any link to knowledge flows in the aggregate, at a societal level, and therefore why knowledge available in the public domain, as a public good, should be utilized differently by different organizations, industries and countries (Shapiro & Varian, 1999).

We now turn to the available research literature on knowledge processes in innovation. Since this spans a wide variety, this section has been organized country-wise for convenience.

2.2.8.1 Overview of country-specific research into knowledge and innovation

United Kingdom

While research into the role of knowledge in innovation is a relatively new field, there are some studies that provide insights. Research conducted in the UK on knowledge process patterns in small and medium-sized British companies reveals that most firms access knowledge from international sources. New technologies and professional intelligence are the most frequently sourced categories of knowledge. Knowledge flows both ways – UK firms both import and export knowledge. There is a clear association in this sample between innovation and knowledge processes. Informal networks are important in the knowledge process. International knowledge exchange is vital to remaining competitive in globalized markets. Finally, even small firms need to pay increased attention to such issues as investments required for knowledge sourcing and building innovation capabilities (NESTA, 2010)

Ireland

Research conducted into knowledge processes and practices in high technology clusters in Ireland, using three case studies as the basis, reveal an insightful picture. Knowledge processes have two basic objectives. The first is to close knowledge gaps at a micro level. The second is to close equipment gaps. The efficiency of the knowledge process depends a good deal on the clarity with which a problem is defined. When such clarity exists, knowledge processes takes place at multiple levels in the firm. When the problem is not clearly defined, knowledge processes tend to take place at the individual level. In either case, organizational capacity to process knowledge effectively is built up. In all cases, there are multiple paths through which the innovations ultimately emerge (Purcell & McGrath, 2011).

China

Research conducted in China, in the three major high technology clusters located at Beijing, Shanghai-Suzou, and Shenzen-Dongguan reveals a somewhat different picture. Despite variations in ownership, industrial structure, market orientation and technological investment, firms in all regions have invariably reported internal development as the main source of core technology. Internal knowledge sources are clearly seen as more important than external knowledge access. Further, the level of technological innovation, based on the responses, was found to be negatively correlated with external orientation in both capital investment and export production. In these three clusters, a higher level of technological innovation does not co-exist with stronger production linkages and knowledge exchanges with both local firms and foreign- invested enterprises. What seem to be significant are the regional setting, the ownership, the ability to mobilize capital, corporate strategy and management interest (Lin, Wang, Zhou, Sem, & Wei, 2011) (Xu, 2011).

These three examples suggest that knowledge processes could be a significant factor in innovation. Further, the Chinese example clearly shows that the local country context has a major impact on the nature of knowledge processes and the level of innovation. Given that all three locations – the UK, Ireland, and China – show reasonable levels of technological innovations, the conclusion can be drawn that there is more than one route to innovation.

There is no similar data available for India, and it is therefore felt that research into knowledge processes in Indian organizations as related to innovation constitutes an important and useful area for investigation.

2.3 Discussion

The Literature Survey has revealed two main streams of thought, which have been termed as the macro and micro perspectives. Along these two paths, research has concentrated on the contexts of how societies get affected by innovation, or on the contexts in which practitioners operate when making innovation "happen" in teams and organizations. Innovation seems to have the property of evolving from an interesting idea to a public good that can change societies.

Consideration of these two streams of thought lead to the main insights that inform the rest of the thesis. First, knowledge, like innovation, has the empirically validated property of sometimes evolving from an interesting idea to the ability to change societies, leading to the question that perhaps there is a link between knowledge and innovation. Second, because of this property involves exchange of knowledge between individuals located within and external to teams and organizations in the real world, the knowledge processes that enable the "small to big" evolution perhaps have connections to innovation. Third, because innovation has been observed empirically to vary in intensity between organizations, industries and even countries, there are perhaps different patterns and practices of such knowledge processes to be observed and studied.

From these three insights has emerged the concept of knowledge processes which are related to innovation as a candidate focus for research in this thesis. The next chapter, on Research Design, will lay out in details how this concept is sought to be investigated in depth against the larger backdrop of innovation in the real world.

Chapter 3

Research Design

It is a truism that all research starts in a state of ambiguity, and the present thesis is no exception. More specifically, research has been hypothesized as starting with three ambiguities – research ambiguity, philosophical ambiguity and methodological ambiguity (Morais, 2019). As stated in Chapter 2, this research began with the theme of innovation as the general focus. With the completion of the Literature Review and the analysis of the ten example cases, the focus of the research acquired greater clarity. The research design was then initiated and proceeded on a systemic basis aimed at deconstructing the ambiguities iteratively to arrive at detailed decisions that describe the Research Design. In this Chapter, I lay out in detail the design path, comprised of twenty-one components (Morais, 2019), traversed iteratively and not always sequentially, that led to the design decisions that define this thesis.

3.1 Selection of Research Topics

As described in the Introduction, **"innovation"** was the major concept identified as the subject for research. This generic term was deconstructed through a detailed Literature Review and Analysis of Example Cases, from which the term **"knowledge processes"** emerged as the candidate for this research in juxtaposition with "innovation", and more specifically technological innovation, at the primary level.

At a secondary level, the theme of differences in knowledge processes patterns and practices as related to technological innovation emerged as the subsidiary candidate for the research.

3.2 Main Streams of Thought

The Literature Survey revealed that there are two main streams of thought or approaches to innovation studies. These are the **macro perspective** and the **micro perspective**. The research field had started off with a focus on the macro perspective and then had branched out into a parallel micro perspective. In recent years, attempts had begun to take shape to integrate the two approaches.

The analysis of example cases had shown that not all perspectives are equally necessary or useful for understanding specific situations. Yet it was also undeniable that all the different approaches were considered essential to understanding innovation. What seemed to be missing was a framework that allowed the linking together of the disparate threads of innovation studies.

3.3 Research Gaps Identified

Of the twelve approaches and views of innovation surveyed in the literature, six of them include innovation as part of some larger activity. The economic approach treats innovation as embedded in economic activity, and the outcomes of innovation show up embedded in economic data. The historical approach does not offer a general enough definition of innovation, situating it within a larger rubric of "artefacts", thus defining it as a form of craftsmanship. The social constructivist view suffers by situating innovation within a technical, social, cultural and economic environment, and positing that innovation is an outcome of interactions between elements of that environment in some way. The technological determinism school views technology as somehow distinct from society, without resolving the contradiction that it is humans who create technology and innovations. Country-level innovation studies situate innovation within a "national innovation system", without explaining how changes in such a structure can add to or hamper innovation (this has been explained earlier as the unstructured test tube experiment approach). The evolutionary view suffers from the same drawback as natural selection theory, which is that analysis and explanation is always post-facto and of little use to a team tasked with finding an effective solution to a problem in the present. Innovation studies using any of these approaches, therefore, ends up as an outcome of studies of the larger field.

It is when we look at innovation from the practitioner perspective that innovation emerges as a viable subject for investigation on its own merits. This is because innovation is only one in the vast diversity of practitioner activities. Of the practitioner approaches, the strategic management view considers innovation as a subset of strategy and therefore exhibits the same flaws, to a lesser extent however, as the economic, historical and other approaches discussed above. The disruptive innovation concept, though currently of great interest, is a post facto method of analysis of exceptionally successful and distinctive innovations and offers little of value to the vast numbers of innovations that are not disruptive.

In the aggregate, the analysis of the ten case studies showed that the S-curve, the Porter Model, the RBV model, the Smiling Curve, the Galbraith organizational model, and the Henderson taxonomy are all significantly relevant to innovation. For the reasons already outlined in Chapter 2, the Porter, RBV and Smiling Curve models are mirrored in each other to some extent, and again for reasons explained in Chapter 2, the Smiling Curve is taken to represent also the Porter and RBV models in this thesis. Further, they are all relevant simultaneously in a given situation. However, none of the them on its own can provide a complete framework for understanding innovation. A framework is therefore required which can simultaneously harness all these concepts in the context of innovation.

The research gaps, and their implications, thus identified are summarized as follows:

1. **There are several different definitions of innovation in the literature, arising out of the different perspectives. There is a need for a broad-based definition of innovation that can be usefully employed across perspectives.**
2. **Within the surveyed literature on innovation, four major practitioner perspectives were identified as relevant to innovation as an independent area of study. There is a need for a framework that links and integrates the practitioner perspectives in one coherent model.**
3. **Based on the analysis of real-life cases, knowledge processes were identified as an important concept that could be used for the study of innovation. A framework is required that links knowledge processes with innovation.**
4. **There has been very little research into the linkages between knowledge and innovation in India and China, creating scope for research in this area.**
5. **There has been very little research into innovation practices on a comparative basis between India and China. The present research addresses this gap within the context of (2) and (3) above.**

6. **There is a need for a framework that makes possible the linking of the micro and macro perspectives, to provide valid insights into the way similar companies handle innovation in China and India, and how these aggregate at the country level.**

3.4 Research Questions

In a field as wide and varied as innovation studies, especially when multiple research gaps are to be addressed, it is the recommendation of authorities in research design that research questions should be framed in a broad rather than narrow manner, to allow for an overarching umbrella under which a large number of concepts can be discussed (Cresswell, 2007). This guideline has been followed in this research, and accordingly the following research questions were framed based on the research gaps identified:

Major Question:

1. **What are the connections between knowledge processes and innovation?**

To answer this question, the research investigated the following two hypotheses:

H_0: (null hypothesis) There are no connections between knowledge processes and innovation.

H_1: There are connections between knowledge processes and innovation

Subsidiary Question:

2. **What are the patterns observed in selected Indian and Chinese organizations with respect to the connections between knowledge processes and innovation?**

These questions are framed broadly enough so that the first gap – absence of a sufficiently comprehensive definition of innovation – can be addressed within the context of the investigation. They are also worded to allow for a framework, rather than a model, to emerge from the investigation. Here the term “model” is used in the sense of replicability, while “framework” is used in the sense of a coherent set of concepts or ideas that can be used for analysis, the creation of a heuristic, or for the definition of a process.

3.5 Review of important concepts and definitions

As shown in the Literature Review, some work has already been done in the area of knowledge as related to innovation. For the most part, studies have concentrated on the *knowledge search* aspect as related to innovation. This focuses efforts on the mechanics of the search process while avoiding the need for a rigorous definition of knowledge, innovation and processes. In turn, the knowledge studies area has no need to include innovation in its rubric. The need for clear definitions was identified as a necessary first step in research design for this thesis.

Definition of knowledge: The nature of knowledge has engaged the attention of epistemologists since the dawn of philosophical thinking and analysis. There are two questions to be answered. The first is "what is knowledge" i.e. what is the definition of knowledge? The second question is "how do we obtain knowledge" i.e. what are the sources of knowledge?

Despite centuries of effort, however, epistemologists have been unable to agree on acceptable, accurate and precise answers to either question. The most commonly used definition, in answer to the first question, is "justified true belief", also called the tripartite definition of knowledge. To answer the second question, epistemologists accept that there are two broad traditions of discourse. These are, first, empiricism, which holds that our knowledge is primarily based on experience; and second, rationalism, which holds that our knowledge is primarily based on reason. Epistemologists have, again, been unable to agree which of these traditions holds the 'truth", or if a combination of the two is always necessary (Ichikawa, 2012).

For the purpose of understanding knowledge as it relates to innovation, it is the submission of this researcher that the definition of knowledge is less important than a consideration of the sources of knowledge acquisition and generation. Since innovation is a creative act that generated new knowhow, and therefore knowledge, from existing and already available knowledge, it is possible to postulate that a combination of the empirical and rationalist traditions is necessary always for innovation. This provides a neat philosophical underpinning to innovation research based on knowledge concepts, since it allows us to move on to the types of knowledge encountered in the real world, without getting blocked by the absence of a definition.

Definition of innovation:

Innovation can be viewed as actions based on knowledge that leads to new knowledge. Alternatively, ***innovation is a creative act that generates new knowledge from existing and already available knowledge***.

Such a description, which is self-evident and qualifies as a micro description of innovation, allows us to transcend the boundaries imposed by the different theories of innovation and the need to distinguish between artifact and non-artifact forms of innovation. From a macro perspective, at a societal level, innovations – whether in the form of publications, patents, technologies, products, processes or services - result in new knowledge available to audiences beyond consumers alone. One distinctive features of such new knowledge creation, arising out of significant innovations, is that very often such knowledge becomes a “public good” with significant externalities beyond the immediate consumers of a new product or technology (Stiglitz & Greenwald, 2014).

Knowledge as a public good, in turn, has the potential to transform industries and countries through catalyzing solutions for problems far beyond the original domain. The spinoffs from technology development for space programs continue to be examples of this phenomenon. This highlights the importance of innovation from a policy perspective both at country and organizational levels. Innovation is important for country-level policy making because of its capacity to positively affect the lives of millions of people. At the organizational level, innovation is important for policy because it underpins strategy and therefore the success of a firm. For innovation policy to be effective, good knowledge policies are important. Understanding knowledge, therefore, is both useful and desirable for researching and understanding innovation.

Definition of knowledge process: The survey of the literature has not thrown up any clear definition of the specific term *knowledge process.* The dictionary meaning of the word “process” - a series of actions or steps taken in order to achieve a particular end – has been used in this section to construct a definition of knowledge process as; *a series of actions or steps taken to enable transaction of knowledge between individuals or entities.* This definition subsumes, and is not limited by, the Nonaka taxonomy of *internalization, socialization, combination and externalization* (Nonaka, 1994).

3.6 Philosophical stance

The first five sections in this chapter constituted the theoretical basis underpinning this thesis. The first step to moving to the methodological stage are the choices comprising the *philosophical stance*. The term "stance" is used here to mean the collective set of a researcher's decisions on *philosophical assumptions*, *philosophical worldview* and *approach to inquiry* (Cresswell, 2007).

There are five philosophical assumptions that any researcher needs to take decisions on, namely, *ontology*, or the nature of reality in the specific research field, *epistemology*, or "how does the researcher know what he knows" which is taken to mean the relationship between the researcher and the "researched", *axiology*, or the role of values, *rhetoric*, or the language of research, and *method*, or the process of research.

For this thesis, the decisions that were taken were:

- Ontology: **The nature of innovation is that it is a real-world phenomenon that cannot be separated from the context in which it occurs**. As an example, innovation in Apple was different from innovation in Microsoft, to cite an instance from the example case analysis.
- Epistemology: The researcher in innovation needs to interrogate either individuals qualified as members of the Galbraith organization types, or documents authored by similarly qualified individuals. On a post-facto basis, analysis by recognized authorities or entities is acceptable. For example, the World Bank is a reliable source of country-level financial data, and the University of Tennessee for information about the global supercomputer sector.
- Axiology: The values the innovation researcher brings to the task is that of a nonjudgmental observer. As stated in the Introduction, **this thesis will make no judgmental comparisons between China and India but will rather highlight similarities and differences in innovation patterns and practices**.
- Rhetoric: The innovation researcher adopts a neutral "rapporteur rhetoric" while documenting and analyzing the data.
- Method: The innovation researcher takes a context-specific approach, prioritizes particulars before generalizations, and takes an iterative, learning-based approach to interrogating the research field.

These decisions on fundamental philosophical assumptions lead to the next step in refining the philosophical stance, namely, the selection of the appropriate *paradigm or worldview*. At the very outset, the ontological assumption in innovation studies, in the view of this researcher, that innovation cannot be separated from its context, automatically precludes a purely deconstructive “scientific” approach, such as used in medicine. In other words, innovation is not a “cell” that can be isolated from the “body” to investigate its characteristics. The “dependent/independent variable” paradigm is thus not applicable. In consequence, the decision in this thesis is to *prioritize qualitative over quantitative research*.

In qualitative inquiry, the literature lists four different world views. These are:

- *post-positivism*, which is oriented towards the scientific approach, and emphasizes reductionism and determinism
- *social constructivism*, which aims at understanding the world through subjective experiences
- *advocacy/participatory*, which emphasizes research with an action agenda
- *pragmatism*, which focuses on outcomes (the actions, situations and consequences of research) rather than the antecedent conditions. This worldview emphasizes ‘what works” and solutions to problems and is flexible regarding methodology.

Of the above, **pragmatism** is an appropriate choice for this research, and rounds off the philosophical stance.

3.7 Research strategy

As observed above, *innovation cannot be separated from its context*. This automatically *precludes the laboratory methodology of research*, typically found in the sciences, in which a sample of a phenomenon is isolated from its context and investigated independently. This also *precludes the purely quantitative methodologies* of data collection which are suited more to the laboratory environment.

This specific research investigates gaps in the understanding of the phenomenon of innovation. There are no guidelines or examples of past successful research in this area to draw upon. The area of knowledge as it relates to innovation is particularly weak in terms of guidelines for research. The research questions have therefore been framed relatively broadly to allow for the phenomenon to be explored in depth. For a real-world phenomenon such as innovation, **qualitative research methods based on a pragmatic worldview** are a suitable choice.

3.8 Methods of data collection

Within the rubric of qualitative studies, there are five general methods available for use in qualitative research (Cresswell, 2007). These are:

- *narrative research*, with a focus on exploring the life of the individual;
- *phenomenological research*, with a focus on understanding the essence of an experience;
- *grounded theory research*, with a focus on developing a theory based on data from the field;
- *ethnographic research*, with a focus on describing and interpreting a culture-sharing group;
- ***case studies research***, with a focus on developing an in-depth ***understanding of a multidimensional phenomenon within a bounded system***.

From the above, it can be observed that the **case study method** is best suited to this specific research. An additional factor supporting this choice is that the "unit of analysis" for a case study is "an event, a program, an activity involving more than one individual" (Cresswell, 2007). This is virtually identical to a textbook description of innovation in practice.

This thesis follows the contemporary perspective on case study research to emphasize that this form of qualitative research has many singular characteristics and advantages. As stated by Robert Yin, one of the most influential writers on the method, case studies offer advantages along three dimensions (Yin, 2009):

- It is an empirical enquiry that investigates a phenomenon within its real-life context
- A case study should be used when the boundary between phenomenon and context are not clear
- It is a method in which multiple sources of evidence are used.

The case study process is well described in the literature. The following diagram is an example (Huws & Dahlmann, 2007):

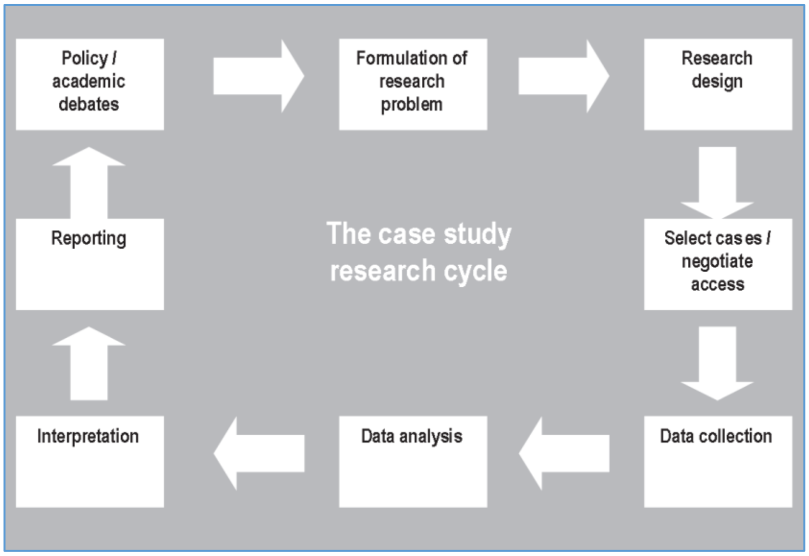


Figure 3-1 – Individual Case Study research process

Four features of case study research have been listed by Huws and Dahlmann (Huws & Dahlmann, 2007), which are readily applicable to innovation studies. Case studies are:

- *Holistic* in nature, and hold potential for bridging the quantitative and qualitative approaches
- *Based on multiple realities*
- *Heuristic, interpretative, inductive and iterative*
- *Require in-depth face to face field work*

There are three types of cases identified in the literature, namely, *exploratory, explanatory and example*. Since this thesis investigates a new concept, knowledge processes as related to innovation, the type of case most applicable is the **exploratory case study**, covering both the context and the phenomenon, given the premise that innovation cannot be separated from its context.

3.9 Data Analysis techniques

The selection of the case study as the primary method of investigation in this research leads to the next question, namely, which is the best method for analysis and derivation of conclusions (Rowley, 2012). The three considerations here are:

- *generalization*, or the ability to extend the analysis of a case study to the larger field;

- *validity*, or establishing consistency of logic and observance of data collection protocols;
- *reliability*, or repeatability of results.

For satisfying these three conditions, the two methods of deriving results are *inductive reasoning* and *deductive reasoning* (Eisenhardt & Graebner, 2007). The case study method lends itself to the use of **inductive reasoning** to arrive at analyses and results, and it is this method which will be employed in this research.

3.10 Quality criteria

According to Yin, there are four criteria to evaluate the quality of a case study (Yin, 2009). These are *internal validity, external validity, reliability, and objectivity.* These, however, have been supplemented in the literature (Lincoln & Cuba, 2002) by four alternative criteria:

- ***Credibility*** (in preference to internal validity). Credibility refers to the extent to which a research account is believable and appropriate.
- ***Transferability*** (in preference to external validity). Transferability in qualitative research is synonymous with generalizability, or external validity, in quantitative research. Transferability is established by providing readers with evidence that the research study's findings could be applicable to other contexts, situations, times, and populations.
- ***Dependability*** (in preference to reliability). Dependability in qualitative research means the stability and verifiability of data over time and over conditions.
- ***Confirmability*** (in preference to objectivity) This criterion has to do with the level of confidence that the research study's findings are based on the participants' narratives and words rather than potential researcher biases.

The case studies in this thesis will be evaluated for quality on these criteria rather than the original Lin list.

3.11 Unit of analysis

The unit of analysis for this research is ***a knowledge process as related to an innovation***. An innovation is described here as "an event, a program, an activity involving more than one individual", following the textbook.

3.12 Levels of analysis

There are three levels at which analysis will be done in this thesis, namely:

- the ***team level***, where the objective is to understand distinct knowledge processes as related to innovation at the individual and the team level, bookending the *micro perspective on innovation*
- the ***organizational level***, to understand knowledge processes at a first level of aggregation, and enable the identification of similarities and differences at an industry level
- the ***ecosystem level***, primarily at the national level, to understand knowledge processes as related to innovation at a second level of aggregation, to enable the identification of similarities and differences at a nation-state level.

3.13 Nature of data

Data collected according to the following are acceptable protocols for the case study approach according to the literature (Rowley, 2012):

- Data from qualified secondary data sources i.e. articles, books, documents
- Data from semi-structured interviews of both primary participants and third-party related individuals
- Data from case studies already available which are judged to be of adequate quality on similar parameters.

3.14 Origins of data

The origins of the data are the following:

- *Semi structured interviews*: The qualification for selecting an interviewee was conformity to one of the four Galbraith organization member types i.e. either an ideator (member of the operational innovation team), a sponsor, an orchestrator, or a gatekeeper; either at the team, organization or ecosystem level.
- *Secondary sources*: Articles, books, and other documents from authors qualified under the same Galbraith criteria as the interviewees

3.15 Research field and sample selection

For the results to be meaningful in a field as large and varied as innovation, the sample should be as representative of the population as possible. The problem is compounded by the need sometimes to select an entire sector – for researching supercomputers, an entire country is a better unit of research than any one of the myriad companies which participate in the construction of a supercomputer. At the other extreme, in the software industry, the example is frequently cited of VisiCalc, the first spreadsheet program on a microcomputer and which inspired IBM to develop the IBM PC, was written by a company with just two main employees. Conventional sample stratification based on size, geography, number of employees, and the like, is not suitable for the innovation field.

For this thesis, therefore, unusual criteria were used to define the sample. These were *evidence of innovation, presence across boundaries, practicality, and impact across the economy*. By evidence of innovation it was meant that innovation should be a feature of the sample across size of organization and over time – the real estate sector, for example, fails this test. By presence across boundaries, it was meant that the sample type should be present at the minimum in India and China, and if possible, globally. By practicality, it was meant that the sample should be easily accessible for quality field work by this researcher. By impact across the economy, it was meant that innovation in that sector would have an impact across other sectors as well.

The Information Technology sector presented itself as a suitable candidate, for reasons that are obvious. First, the innovation has been a defining characteristic of the IT sector since inception. Second, it is global in coverage with uniform technological standards that are accepted by everybody. Third, it has a large and successful presence in both China and India, with thousands of companies of sizes ranging from the very large to the very small, thus simplifying the researcher's job. Finally, IT is today pervasive across all economies; there are few aspects of organizational or personal life that remain untouched by information technology.

From the micro perspective i.e. the team and company levels, the IT industry satisfied the four criteria. However, it was also necessary to select a sample that would be representative from the macro perspective i.e. that exhibited features that could enable an aggregated understanding of knowledge processes related to innovation at an industry and national level, in addition to the company and team levels. For this reason, the sample was further iteratively subdivided into *three sizes of organization* – large, medium and small – and *three scales of innovation impact* – national, industry and company. Through this creative process, the final sample was selected as follows:

Criteria	Sector / Organization
Large size + national impact	Supercomputer sector in China and India
Medium size + industry impact	Medium-sized IT software companies in China and India
Small size + company impact	Small defence sector companies in China and India

Figure 3.2 – Research field and sample selection

Based on the sample selection, and given the premise that innovation cannot be separated from its context, the structure of the case studies was refined to two main parts:

- To establish the context, the first part of the case study would be a sector-level analysis that would provide a global overview of the sector, with in-depth sections on China and India.
- The second part would consist of detailed country-level analysis, including shorter company-specific case studies included to provide insights, through examples of specific innovations, on knowledge processes as related to innovation in China and India.

3.16 Researcher perspectives on the study

This researcher is an experienced practitioner, who has worked on many occasions in many capacities on innovation-related projects, providing him with insights into how companies innovate in the "real world". At the micro level, his experience has led to a deeply held personal value that a differentiation strategy based on innovation should be privileged, whenever possible, over a cost-based strategy when a company considers its strategic options. At the macro level, this researcher accepts Baumol's formulation of innovation as the engine of free market economy, and of Stiglitz and Greenwald's formulation of innovation as leading to a beneficial learning society (Baumol, 2002) (Stiglitz & Greenwald, 2014).

3.17 Scientific logic of the research

Entire books have been written about the scientific case for innovation (Smith, 2003). In this thesis, however, the scientific logic for this research is built on the two perspectives identified in the Literature Survey, namely, the micro and the macro.

At the micro level, the "scientific" case for innovation is well established, based on empirical evidence in abundance of new products and services contributing to the solution of problems, better quality of life and living conditions, enhanced employment opportunities, and new avenues for success for individuals and organizations. Innovations frequently lead to the introduction of new technologies, which in turn foster innovation in a self-regenerating cycle (Smith, 2003). At the macro-level, the economic case for innovation has also been well established, as shown in the Literature Survey, through the work of Solow, Baumol and Stiglitz & Greenwald (Solow, 1957) (Baumol, 2002) (Stiglitz & Greenwald, 2014).

Looking to the future, as shown in the Introduction, there are several areas of serious concern which can and should be addressed by innovation. What is lacking today is a systematic approach to innovation that mitigates the risks and increases the potential for success. It is the belief of this researcher that this research has the potential to change individuals, companies and public policies as well in a radical manner by illuminating the value of knowledge perspectives and processes.

3.18 Limitations of the research

Like all research, this thesis has certain limitations. The major limitation was accessing Chinese organizations and data. This was mitigated by accessing, to the extent possible, Chinese companies which had operations in India, or whose senior executives were visiting India. A second issue was the use of secondary data sources, which is acceptable according to case study research theory, if primary interviews were not possible. The secondary sources however needed to be selected based on the quality and relevance of the material.

Another limitation was the availability of primary information, particularly in the supercomputer sector. This was mitigated by making use of the excellent Top500 analyses that are published regularly by the University of Tennessee, which are accepted as the industry standard all over the world.

3.19 Qualifications and suitability of the researcher

My educational qualifications (a B.Tech in electrical engineering from IIT Bombay and an MBA from IIM Calcutta), my work experience of over three decades of work in the IT sector in India and abroad at all levels from trainee to topmost levels of management, cutting across all functions, and my academic bent developed through experience as faculty in an MBA school, all qualify me well for this research. I believe that this combination of attributes ensures quality of research in the three selected sectors, namely, supercomputers. IT software industry, and small defence technology companies.

3.20 Partners in this research

Although no partners have been formally associated with this research, a large informal network of individuals contributed to this research through insights and inputs, and facilitation of access for interviews and information. At the institutional level, my Advisory Committee have been more partners in this endeavor than supervisors.

3.21 Availability of time and resources for this research

The three-year time period provided by the Institutions has proved adequate for the journey from proposal to thesis.

3.22 Discussion

The twenty-one steps listed in this Chapter have provided a research design that is epistemologically rigorous and based on the past successful experience of other PhD scholars (Morais, 2019). However. the proof of any pudding lies always in the eating, so the results of the research as set out in the next three chapters will reveal whether the Introduction identified the correct themes, whether the Literature Survey covered the correct concepts, and whether the Research Design ensured a successful outcome.

Chapter 4

Innovation in the supercomputer sector in China and India

This chapter forms the first of three which are substantively based on field work in the sample sectors and organizations as specified on the Research Design. It is structured in four main sections. The first section establishes the context, in line with the Research Design (section 3.15) through an exhaustive overview of the supercomputer sector globally, from its origins in the 1960s to its present status. Included in this section are detailed expositions on the history of supercomputers, the technologies of supercomputing, the innovation framework specific to supercomputers, country-wise activities in the supercomputer sector, and the application landscape for supercomputers.

The second and third sections provide a comprehensive overview of supercomputing in China and India. Included in these sections are detailed expositions on the history of the sector in the country; major milestones achieved over the years; the current installed base of supercomputers; the ecosystem for supercomputer research technology transfer and knowledge utilization; investments in supercomputing; applications of supercomputing in the country; announced plans for the next decade; analysis of strategy followed; analysis of innovation patterns observed; and finally, the first analyses in this thesis of knowledge processes in the supercomputer sector in each country.

The fourth section is devoted entirely to analysis and inferences to be drawn with respect to the similarities and differences in innovation patterns, and similarities and differences specifically of knowledge processes in China and India.

4.1 The context – the global supercomputer sector

From an innovation perspective, the computer industry, or more properly the Information Technology (IT) industry, is commonly recognized as one of the most visible contemporary examples of the impact of innovations on a global scale. Within the IT industry, the 'supercomputer' sector has played a role since the early days of computing. The term 'supercomputer' is used interchangeably with 'high performance computing (HPC)' in the contemporary literature of computing. It refers to computer systems, consisting of hardware, software and applications software, that provide close to the best achievable sustained performance on demanding computational problems, which cannot be solved by any other means available at that time (Bell, 2015). In this sense, the very first computer was a supercomputer.

By their very definition as systems intended to address the most demanding computational problems, HPC systems have been applied to problems often of strategic importance. Well-documented uses of HPC have been, inter alia, in the fields of advanced weapons design, weather forecasting, aerodynamics, cryptography and security related communications, space research and engineering, and increasingly, in molecular dynamics simulations for medical applications. (Top500, n.d.). HPC has therefore been recognized as a strategic capability at the apex country level in many countries, including the United States, China and India (Ministry of Science and Technology of the People's Republic of China, 2016) (White House Executive Order 13702, 2015) (Cabinet Committee on Economic Affairs India, 2015).

HPC can be distinguished from the more conventional general-purpose computing (GPC) in several ways. The first and most obvious difference is that HPC is intended to solve a restricted class of problems. HPC systems, therefore, are designed for optimal performance within a relatively narrow domain as against being adaptable for a wide range of problems as GPC systems are designed to be. Second, HPC systems are specifically designed for optimal performance in scientific computation using floating point arithmetic, as against general purpose computers which are designed for acceptable performance across a variety of data types. Third, HPC systems run restricted classes of software, such as the Linux operating system and language compilers intended for scientific rather than general purpose applications. Four, the application environment of HPC is such that a system will be intensively utilized for one, or at most a small number of scientific applications, rather than extensively used for many more general applications. Five, to illustrate the differences in business focus, the number of installations of an HPC system is usually very small. Performance, rather than business scale, determines success in HPC. This has resulted in intensive competition in the HPC field to develop ever higher-performance systems year after year (Top500, n.d.).

The focus on performance in HPC systems have led to the identification of three guidelines, or 'laws' (Gustafson, 1988). The first is Moore's Law in semiconductors, which postulates that the number of transistors on a single chip doubles each year. Moore's Law is well known to apply to the general computing field also. The second law, specific to HPC, is Amdahl's Law, which relates the efficiency of parallel processing to problem solution speeds. The third is Gustafson's Law, which relates the size and complexity of a potential problem to the extent of parallelism in computing. HPC systems can therefore be said to be bounded, at any given time, by the extent to which technology has tested the boundaries of these three laws.

These differences in the HPC sector as compared to the general computing sector, and the three laws that bound system performance, make HPC technology development different in turn from GPC technology. HPC system design starts from the fundamental theoretical definition of a supercomputer: "The ideal supercomputer has an infinitely fast clock, executes a single instruction stream program operating on data stored in an infinitely large and fast, single memory" (Bell, 2015). Any HPC system design must assume at the outset a "theory of computation" i.e. the abstract mathematical model of computation that is best suited to the class of problems that is sought to be tackled. Implementation of this abstract model then involves designing algorithms that will most efficiently lead to solutions of the identified problem class. Finally, development of the processors, memory and communication hardware that are best suited to implementation of the algorithms, involves a recursively fresh application of the fundamentals of quantum physics in the design process (Karmarkar, 2015). Thus, as distinct from GPC systems, development and application of an HPC system involves the successive approximation of real-world phenomena, using both digital and analog concepts in the mathematical and quantum domains and an ever-finer degree of granularity (Karmarkar, 2015).

These distinctive characteristics of HPC systems thus provide substantial leeway for variation and creation in the design and application of HPC systems. Therefore, HPC systems are ipso facto fertile ground for innovation, and the history of HPC provides ample evidence of this phenomenon. In keeping with the overall objective of this thesis, the following sections will therefore focus on the nature, patterns and issues involved with innovation in the HPC space, starting with an overview of the history.

As a prelude, to provide a perspective on how HPC performance is measured, it is necessary to mention specific HPC-related terms and definitions. A full list of these is given in Annexure 2.

4.1.1 History of supercomputers

As stated above, the very first computer was, by definition, a supercomputer. The status of the world's first electronic computer goes to the German Z3, developed by Konrad Zuse and unveiled in 1941 in Berlin. It was truly the world's first programmable, fully automatic digital computer. It was based on 2000 electromechanical switches and its program instructions and invariant data were stored on punched film and fed in externally. It was used by the German Aircraft Research Institute for statistical analysis of wing flutter. The Z3 was however destroyed during a 1943 Allied bombardment of Berlin. With the passage of time, Konrad Zuse has been given due recognition as the inventor of the modern digital computer (Ceruzzi, 1981).

On the Allied side, the first truly successful electronic computer was designed and developed to solve one of the most challenging mathematical and logical problems of its day, namely the decrypting of the German codes transmitted via the Enigma machine during the Second World War. This first machine, which is today called Colossus I, had a single objective – the "cracking" of the German code. It utilized a unique combination of electronic and mechanical devices and equipment. It could be used for only one application. In its time, it was the only machine of its kind, although by the end of the war there were ten installations at Bletchley Park in the UK. Its entire concept and design rested on an abstract class of mathematical entities called universal Turing machines. Both the Z3 and Colossus therefore satisfied all the five characteristics of supercomputers as listed above. An interesting footnote to the history of the Colossus was that its existence was kept completely confidential till 1970, and behind this screen of secrecy it continued to be used for decrypting Russian signals till well into the 1960s (Copeland, 2010).

The next notable electronic computer to be developed was the ENIAC (Electronic Numerical Integrator And Calculator). Unveiled in 1946 at the University of Pennsylvania, it was first used for evaluating the feasibility of thermonuclear weapons, although its primary function came to be the calculation of artillery tables for the US Army (Bellis, 2017). The ENIAC was distinctive in that it was entirely electronic in its construction, using vacuum tubes to implement digital computing logic. In turn, as was only to be expected in the Cold War, the USSR also developed and deployed its first large computer, the BESM-1, in 1951.

The ENIAC, because of the publicity surrounding it, soon spawned several other computers from American private sector companies, notably International Business Machines, which introduced the IBM 701 in 1953, and described it as the first “general purpose computer”, although all the 19 machines produced went to defence-related government departments (Bellis, 2017). By the mid-1950s, the general-purpose computer, so-called because it could be reprogrammed for different applications, was firmly established on the path to transforming the world, and the trajectories of supercomputing and general-purpose computing had effectively diverged. It is in this context that we turn now to the modern, post 1960, history of the supercomputer.

The modern history of supercomputers can be divided into three eras – the Monocomputer / Gigascale era, the Multicomputer / Terascale era, and the Petascale / Exascale era. By a coincidence of historical symmetry, the Monocomputer era- from 1964 to 1995 is also usefully understood as the era where comparisons were best made in gigaflops. Similarly, the Multicomputer era – from 1993 to 2008 - featured systems whose speeds were best compared in teraflops. Finally, since the next era architectures use new and innovative quantum physics concepts, this researcher has used the term Petascale / Exascale era for the post-2008 period.

4.1.1.1 The Monocomputer / Gigascale era

The modern history of HPC can be accurately said to have been pioneered by Seymour Cray, who most observers have called the Father of Supercomputing and its first true legend. In 1964, while he was with Control Data Corporation, Cray conceptualized the design and architecture of a computer with the objective of making it the fastest ever built. This machine, the CDC 6600, defined the architectures of single processor computers for the next thirty years. It featured parallel processing, pipelining, vector processing, and the sharing of a single memory by multiple processors.

Figure 4.1 - The CDC 6600

The architecture lasted thirty years till the last of its kind, the Cray T90, which was about 64,000 times faster than the CDC 6600 and delivered a performance of 60 Gflops on the Linpack. The following table and chart depict the increase in HPC performance from 1964 to 1995 during the Monocomputer /Gigaflop era:

System	Year	Performance
CDC 6600	1964	0.001
CDC 7600	1968	0.6
CDC STAR 1000	1974	0.1
Cray 1	1976	0.2
Cray 1S	1978	0.3
CDC 205	1980	0.6
Cray XMP	1982	1
Cray 2	1985	3
Cray YMP	1987	7
Cray C90	1991	20
Cray 3	1993	30
Cray T90	1995	60

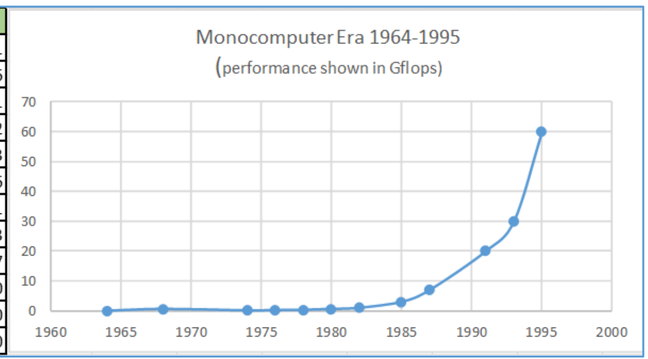


Figure 4.2 - The Monocomputer Era

In the context of this dissertation, it is noteworthy that China had indicated as early as 1972 their objective to equal the United States in supercomputer technology (Mullaney, 2016). China had already developed and deployed its first supercomputer by 1983 (OTA, 1987). The historical record shows no such equivalent statement of objective from any individual or government department in India at that time.

4.1.1.2 The Multicomputer / Terascale Era

Experiments in multicomputer architectures began during the 1970s in universities and research laboratories. (Flynn & Podvin, 1972). During the 70s and early eighties, the first few multiprocessor machines made their appearance (Wilson, 1994). Notably, China demonstrated its first multiprocessor machine, the "757" with a speed of 10 Mips, in 1983 (OTA, 1987).

By the turn of the 90s, early experiments in multicomputer architectures had demonstrated that their potential was greater than the simpler Cray monocomputer architectures. Accordingly, in 1993, the Thinking Machines CM5 multicomputer HPC was able to demonstrate a performance of 60 Gflops, two years before the Cray T90. From then on, the multicomputer architecture took over completely and has remained the norm till date.

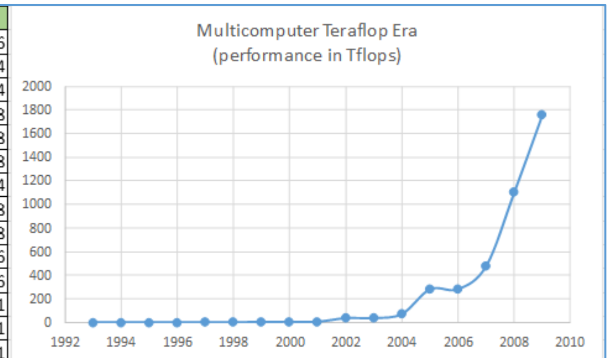
It is noteworthy that the PARAM 8000, developed by the Centre for Advanced Computing (C_DAC) in India, was an early example of a successful multicomputer architecture, and was benchmarked as the second fastest in the world in 1990.

Some of the significant milestones since 1993 have been as follows:

1. In 1993, the first Linpack benchmark set was finalized and used as a basis for comparing the performance of supercomputers.
2. In 1993, the first Top500 list, which gave the details of the top 500 highest performing supercomputer sites in the world, was compiled by a non-profit group. Since then, the Top500 lists have been released twice every year in June and December.
3. The era saw the entry of Japan into the HPC sector. From 1993 to 2008, Japanese computers were at the head of the Top500 list for 5 years in all.
4. The Accelerated Strategic Computing Initiative (ASCI), launched in the US in 1994, provided an umbrella for the US HPC community in government, academia and industry to collaborate on competing with Japan.
5. The ASCI program led to the ASCI Sandia system breaking the teraflop barrier in 1998, turning in a Linpack Rmax of 1.338 teraflops.
6. In the mid-2000s, both India and China made their entries into the Top500 lists. In June 2006, India had 8 systems listed in the Top500, while China had 19 systems.
7. In 2008, the IBM Blade Runner became the first supercomputer to break the petaflop barrier, turning in an Rmax score of 1.105 petaflops.

The table and chart below illustrate the progress in HPC performance during the Multicomputer/Terascale era:

System	Year	Performance
TM CM5	1993	0.06
Fujitsu NWT	1994	0.124
Fujitsu NWT	1995	0.124
Hitachi MC	1996	0.368
ASCI RI Sandia	1997	1.338
ASCI RI Sandia	1998	1.338
ASCI RI upg	1999	2.4
IBM SP3	2000	4.938
IBM Power 3	2001	4.938
NEC Earth Simulator	2002	36
NEC Earth Simulator	2003	36
IBM Blue Gene	2004	71
IBM Blue Gene	2005	281
IBM Blue Gene	2006	281
IBM Blue Gene	2007	478
IBM Blade Runner	2008	1,105
Cray Jaguar 6	2009	1,759



N.B. In 1990 PARAM 8000 from India clocked 5 Gflops
Second fastest in the world in 1990

Figure 4.3 - The Multicomputer / Terascale era

4.1.1.3 The Petascale era

The Petascale era represents a continuation of the Multicomputer era to the extent that the multicomputer architecture that emerged in the mid-1990s has remained the choices for all developers of HPC system. However, it also differs from the previous era in two important respects. As the limits of computation using available microprocessor technology are approached, researchers are turning once again to the fundamentals of computer science and quantum physics to find ways to break through the petascale-exascale barrier. Some of these new concepts have been reported in the latest Chinese HPC systems. The second difference is that for the first time since the dawn of the HPC era in 1964, it is China which has assumed the leadership position, displacing the United States both in the power of their machines (37.3% of total installed HPC capacity against 30.5% in the US), as well as in the total number of systems installed (167 systems against 165 US). In the Top500 lists, a Chinese supercomputer has headed the list continuously from 2011 till date in 2016. In the terminology of economic development, China is no longer “catching up”. It has successfully caught up with the United States and is now forging ahead. This astonishing development represents the culmination of a forty-year systematic process that began in the Mao era itself, well before the famous “863 Plan” for high technology capabilities, instituted under Deng Xiao Ping in 1986 (MOST, China, 2016).

However, in response, the US has instituted a new program, called the National Strategic Computing Initiative, through an Executive Order from the President (Ezell & Atkinson, 2016). The NSCI clearly states that the main objective of the program is continued US leadership in the HPC area, through exascale and beyond (White House Executive Order 13702, 2015) (Thibodeau, 2016). Given the equally comprehensive Chinese goals announced publicly for achieving exascale by 2020, it is clear that competition between the US and China will be the dominant feature of this stage of HPC evolution.

The table and chart below give the summary of the progress so far during the petascale era:

System	Year	Performance
IBM Blade Runner	2008	1.105
Cray Jaguar 6	2009	1.759
Tianhe 1 Intel	2010	2.567
Fujitsu SPARC	2011	10.51
Cray XK7 Intel	2012	16.325
Tianhe 2 Intel	2013	33.862
Tianhe 2 Intel	2014	33.862
Tianhe 2 Intel	2015	33.862
Sunway Taihu Light	2016	93

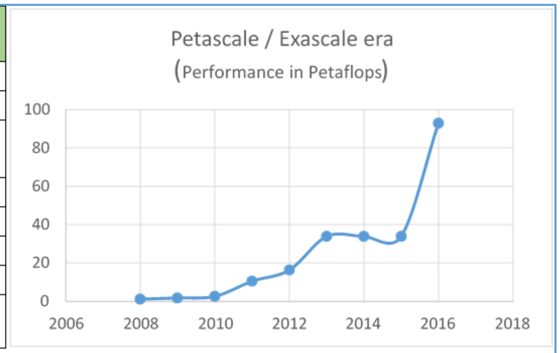


Figure 4.4 - the Petascale Era

4.1.1.4 From Petascale to Exascale – the available forecast

Four countries have announced concrete plans to break through the petascale-exascale barrier. There is considerable public information already available regarding these plans. In this section, we will summarize the initiatives of the two major competitors, namely, China and the United States, either of whom may be the first to break the exascale barrier.

1. *China:*

China has announced three parallel initiatives to achieve exascale (CAS, 2016). These are:

- An initiative at the National Research Centre for Parallel Computing Engineering and Technology (NRCPCET), which had earlier developed the Sunway TaihuLight, currently the world's fastest supercomputer (2017 data).
- A programme at the National University of Defence Technology, which had earlier developed the Tianhe series of supercomputers, culminating in the Tianhe-2, currently the world's second fastest supercomputer (2017 data)

- A third initiative at the Sugon Information Industry, which is currently ranked as Asia's #1 supercomputer company in terms of sales, and #6 in the world, holding 35% market share in China. The Sugon project will be in collaboration with its long-standing technology partner, the National Centre for Intelligent Computing Systems (NCIC).

The available reports suggest that the three projects will follow different architectural paths, although the NRCPCET and NUDT approaches appear somewhat similar. The Sugon architecture, however, is based on a radically different concept which they term as the "Silicon Cube" modular concept, and which they claim will be almost infinitely scalable. China has announced that it expects to deploy the first exascale system by 2020.

2. United States:

Like China, the American effort to achieve exascale consists of the development and deployment of three exascale machines, named Aurora, Frontier and El Capitan. All three are driven by the US Department of Energy's Exascale Computing Project (ECP). Aurora is to be installed at the Argonne National Laboratory, Frontier at Oak Ridge and El Capitan at Lawrence Livermore. Details are currently available only for Aurora. The first Aurora machine will be installed at the Argonne Leadership Computing Facility (ALCF). The project is currently in the final stages of design review, and the formal contract for constructing the machine is expected to be awarded in the first half of 2018 (Feldman, 2017).

Aurora will be jointly developed by Intel Corporation and Cray, utilizing the Knights Hill processor module from Intel. The DoE has announced that the architecture will be "novel", without revealing any further details. It will support the three new "pillars" of 21st century supercomputing; namely, complex simulations, very large data sets, and deep learning. Construction of Aurora is targeted to begin in 2020, with deployment in 2021.

From the foregoing, it is apparent that the "race to exascale" as it has been called (Higginbotham, 2016)is distinguished from the three previous barrier transitions (the first supercomputer, gigascale to terascale, and terascale to petascale) by the following:

- For the first time in the history of supercomputing, the United States may not be the country to break the next barrier

- There are many new architectures officially under consideration. In the previous cases, only one major architecture form was selected by all contenders.
- Power efficiency has become one of the major criteria for architecture choice
- With the entry of China into the top rung, the dominance of high-end semiconductor technologies by the US has come to an end.
- The power efficiency of the new Chinese processors used in the Sunway Taihu Light – at 6 Gflops / watt as compared to 2 Gflops/ watt in the 2015 Top500 list head – is an indication of fundamental research that Chinese scientists have successfully accomplished in the quantum physics domain, and of their success in translating this research into robust semiconductor chip design and manufacturing.
- The information relating to the "Silicon Cube" of China, and the "novel" architecture of Aurora suggest that the earlier architectures have plateaued in terms of potential. Exascale may represent the beginning of a new S-curve.
- The diversity in architectures under consideration is an indication that the limits to Moore's Law are coming slowly within sight, as fundamental research at the theoretical and experimental levels enable alternatives to emerge which had previously not been envisaged.
- Unlike the earlier eras, where complex simulations formed most of applications, the emergence of massive data analytics and deep learning / AI as important application areas for exascale suggests that the technology requirements have expanded in width as well as depth.
- Although there have been public indications by senior Indian government officials of India's intention also to build an exascale machine, there is no position paper, or any other official document published yet.

4.1.1.5 The role of government

It is significant that supercomputing in every country which has aspired to achieve some level of competence in this sector has been initiated by government. From the WW II and post-war initiatives in Germany, the UK, the US and the USSR as indicated above, to inter alia China, Japan, France and India, the first steps towards supercomputing have been taken by government initiative.

However, the first "modern" i.e. post 1960 era, the Monocomputer / Gigascale era was located entirely in the American private sector. It is remarkable that it was also dominated by a single individual, Seymour Cray (Bell, 2015). As further evidence of this "private sector model", it is a matter of historical record that when Cray set up Cray Research in 1973, the new company found ready financing from Wall Street investors.

Although there is no recorded official policy announcement to the effect, it is probable that the first serious effort by a government to encourage the HPC sector was in Japan in the early 1980s, when Osaka University became the site of the first Japanese supercomputer (Bell, 2015).

The lesson that government had a possible role to play in HPC was not lost on China, which instituted the first government-level policy to acquire competitiveness in high technologies. As mentioned earlier, China had indicated its interest in supercomputing as early as 1972, even during the turmoil of the worst stages of the Cultural Revolution in Maoist China (Mullaney, 2016). By the early eighties, China had already constructed its first supercomputer (OTA, 1987). However, the real impetus for Chinese supercomputing was provided by the famous '863 Program', as it is called today, which came into being through a personal directive from Deng Xiaoping. China has continued the 863 Program with unwavering focus since then, and the home-grown SW26010 chips which form the heart of the 93 petaflop Sunway TaihuLight System, which have superior power efficiency by a factor of three, are testimony to the astonishing success of the program.

In India, the Centre for Development of Advanced Computing (C-DAC), was established in 1988 after the US denied export of a Cray supercomputer to India. C-DAC constructed the PARAM 8000 prototype in 1990, which was benchmarked as the second fastest in the world. The PARAM 8000 was a ground-breaking example of multicomputer architecture. Except for some administrative measures during the 2000s, such as the combining of C-DAC with other institutions, the next formal Indian government policy intervention came in 2015, when the National Superconducting Mission was announced.

Recognizing the growing competition from Japan, the US government announced its first new intervention after WW II in 1997. The Accelerated Strategic Computing Initiative, known better by its acronym ASCI, produced almost immediate results. From 1997 to 1999, supercomputers constructed under the ASCI program headed the Top500 lists. Thereafter, till 2010, US HPC systems held the top position for 8 out of 10 years.

With the acceptance of the strategic importance of HPC, it has now become the norm for governments to announce specific initiatives to promote HPC within their countries. The following are the important contemporary examples:

- *China:* The expansion of the 863 program with additional investments in semiconductor manufacturing (MOST, China, 2016) (Thomas, 2015) (Ernst, 2015)
- *United States:* The National Strategic Computing Initiative was announced in July 2015, through Executive Order 13792.
- *European Union:* has announced its initiative on supercomputing through a multi-country effort by EU members in 2014 (European Commission, 2012)
- *India:* The National Superconducting Mission was announced in March 2015 (Cabinet Committee on Economic Affairs India, 2015)

4.1.2 Innovation Era Transition Points

To examine the innovation processes in HPC more closely, it useful to bring in one of the most basic concepts in innovation theory, namely the S-curve (Chandrasekhar, 2011)

As would be apparent from the three "era" charts above, each represents a modified S-curve, with a long initial "tail" and a short terminating "tail". It is at the intersection of these S-curves that innovation takes place, in the theories developed so far (Chandrasekhar, 2011). We will therefore now focus attention on the transition points.

The significance of the era transition points and their relation to innovation models and concepts become apparent when the three charts are juxtaposed in one diagram.

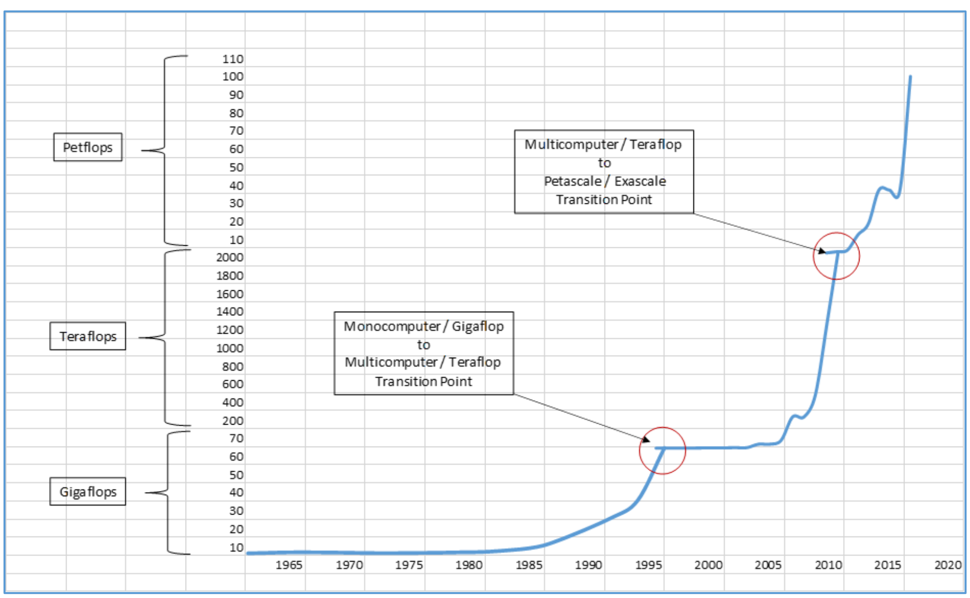


Figure 4.5 - The Supercomputer S-curves

From the history of HPC, it is apparent that innovation takes place to a very substantial degree at these innovation points. It is these innovation processes that enable the shift from one era or one generation to the next. To understand more fully how innovation happens e at each transition point, it is necessary to ask the following questions:

i. What are the components of an HPC system in respect of which innovation can take place?
ii. What are the different kinds of innovation that can take place given our understanding of the components?
iii. What is the ecosystem within which innovation takes place in the HPC sector?
iv. What are the critical factors that can be identified for successful innovation to take place in HPC?
v. What are the characteristics of the knowledge processes that operate in the context of 1-4 above?

4.1.3 The Technologies of Supercomputing

As mentioned in the Introduction, the design of an HPC system begins with a consideration of the theoretical computing model that is best suited to the solution of the class of problems to be solved. This is then followed by the design of algorithms for the solution of the problem set. Some of these algorithms may be freshly evolved, some others may be extensions of those already operational and tested. This provides the basis for evolving a theoretical architecture of the system. Following this is the "real world' implementation of the model, algorithms, and architecture in the form of hardware, systems software and application software. From the innovation perspective, therefore, computational models, architectures and algorithms are also treated as components of an HPC system (US National Research Council, 2003).

The hardware and software components in a typical high-end HPC system have been identified, in this thesis, using information available on the world's fastest supercomputer, the Sunway TaihuLight System. The following pages provide images that can be used to describe the architecture and components of the Sunway. The images are from the publicly available report on the Sunway prepared by Jack Dongarra of the Oak Ridge National Laboratory, USA (Dongarra, 2016). The Sunway is the bellwether innovation for this chapter.

To provide a brief overview of the Sunway TaihuLight supercomputer's development and installation history, it was developed by China's National Research Centre for Parallel Computer Engineering and Technology (NRCPC). The microprocessor cores contained in the SW26010 chips were designed and manufactured by the Shanghai High Performance IC Design Center. It is installed at the National Supercomputing Center at Wuxi, jointly managed by the Tsinghua University, City of Wuxi and the Jiangsu province. The Center will be a public supercomputing facility that will provide services for public users in China and across the world.

The total cost of the system is estimated at $270 million, not including maintenance and running costs. Funding was provided by the Chinese government, the City of Wuxi and the Jiangsu province.

4.1.3.1 Architecture and Physical Implementation of the Sunway TaihuLight System

The source for the diagrams and images in this section is the Top500 "Report on the Sunway TaihuLight System" by Jack Dongarra, published by the University of Tennessee (Dongarra, 2016).

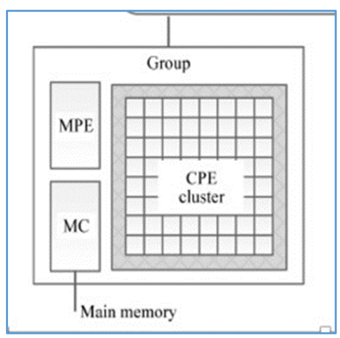


Figure 4.6 - Block diagram of a Core Group – 4 per Node

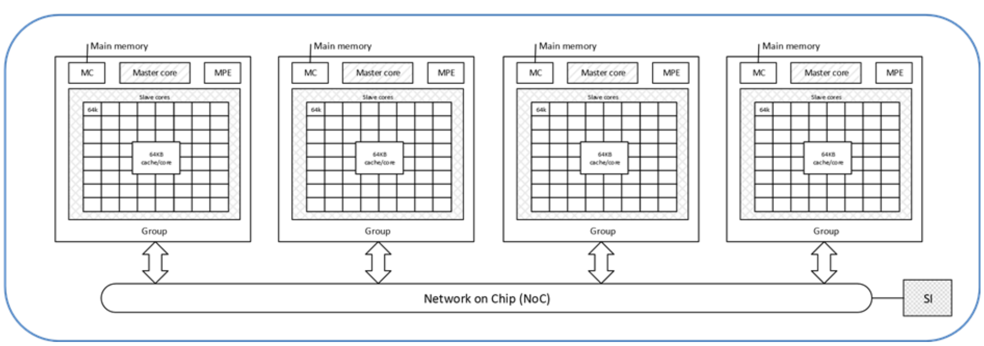


Figure 4.7 - Block Diagram of a Node with 4 core Groups

Figure 4.8 - The SW26010 (260 cores) processor that implements a Node

Figure 4.9 - Two nodes on one card

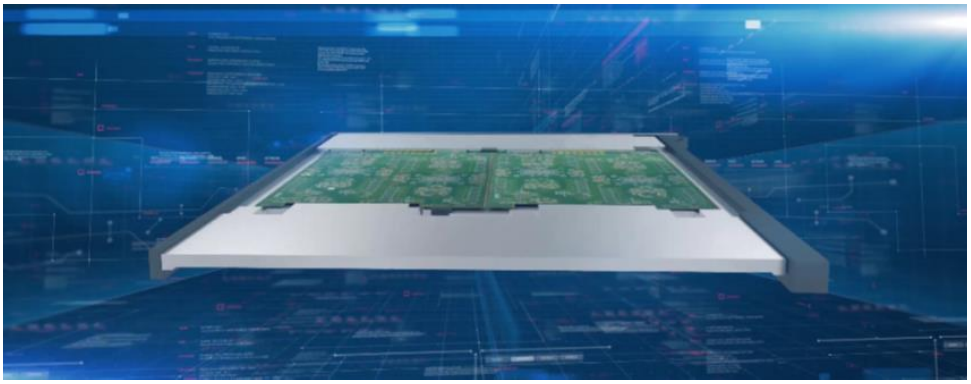


Figure 4.10 - Four cards on one board, two up and two below on the other side

Figure 4.12 - A Supernode composed of 32 boards and 256 nodes

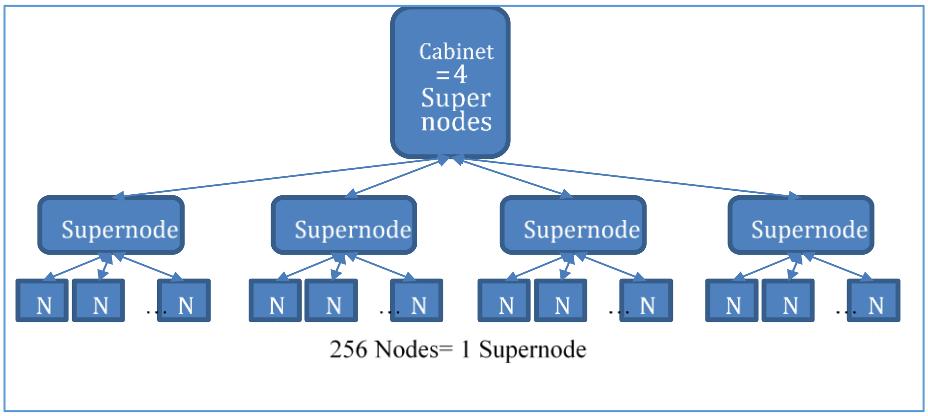


Figure 4.13 - Block diagram of cabinet composed of 4 Supernodes/1024 Nodes

Figure 4.14 - A Cabinet composed of 4 Supernodes / 1024 nodes

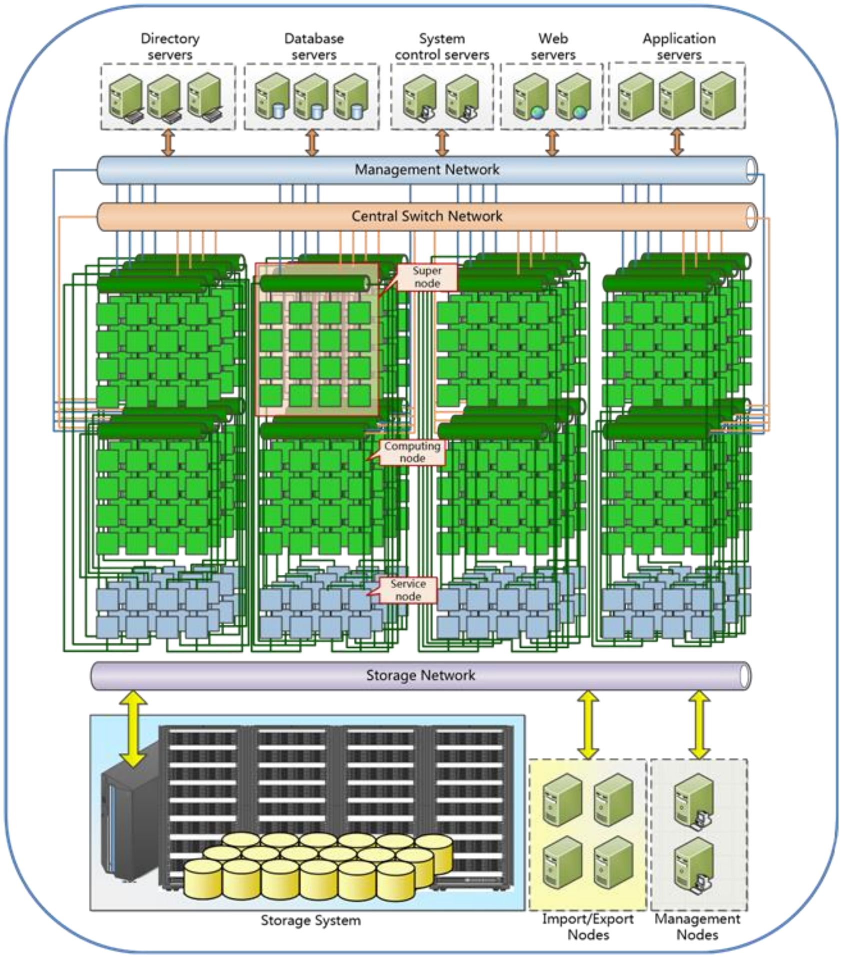


Figure 4.15 - Architecture Diagram of complete Sunway TaihuLight System

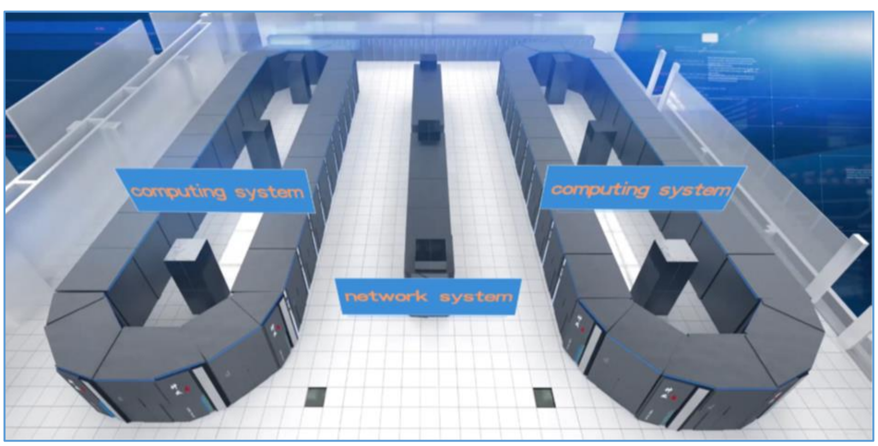


Figure 4.16 - A view of the complete Sunway TaihuLight System installation

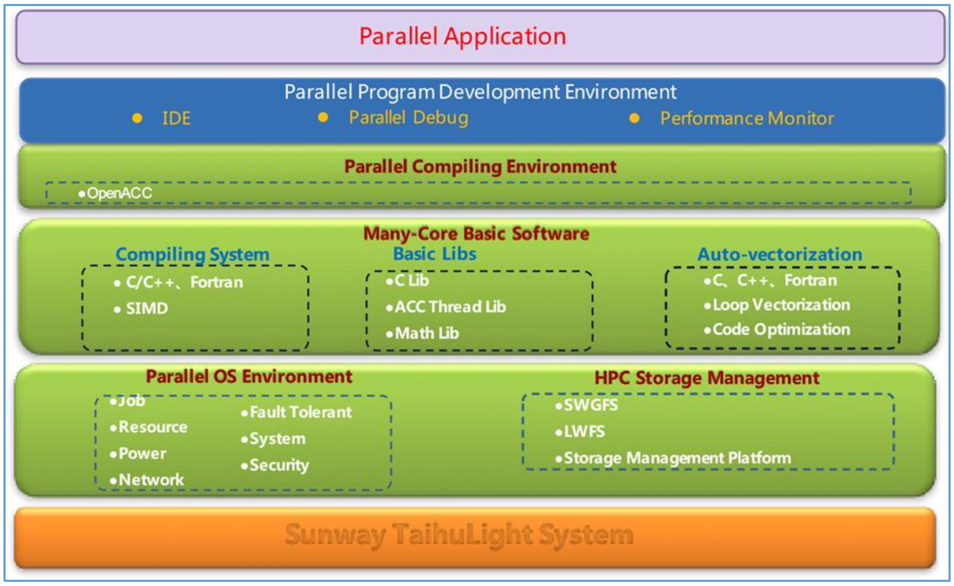


Figure 4.17 - Software Stack of the Sunway TaihuLight System

From the above available information about the Sunway, the following major components for a top-of-line HPC can be distinguished, including both hardware and software, and including the computational model, algorithms, and architecture as mentioned above:

i. Theory of computation model adopted for the design.
ii. Computational algorithms specific to the supercomputer and class of problems
iii. Architecture of the system
iv. The microprocessor chips that provide the ‘cores’ and ‘nodes’ that are combined in a multicomputer architecture to construct the supercomputer.
v. The memory chips that form the storage used by the programs and data.
vi. Interconnection hardware between cores and local memories
vii. Interconnections between nodes to form supernodes.
viii. Network hardware to interconnect supernodes and physical ‘cabinets’ housing the hardware. There are three categories of networks within the supercomputer – the management network, the central switch network, and the storage network.
ix. The server system – consisting of subsystems for directory servers, database servers, system control servers, web servers, and application servers.
x. The secondary storage systems
xi. The power supply system
xii. The cooling system for the supercomputer.

xiii. Operating system and HPC storage systems software
xiv. Many core systems software modules, including compilers, libraries and auto-vectorization modules
xv. Parallel compiling environment
xvi. Parallel program development environment
xvii. Parallel applications suites

4.1.4 Innovation Frameworks for supercomputing

The Henderson model ((Henderson & Clark, 1990) , depicted in the diagram below, provides a useful taxonomy for understanding innovation in the superconducting sector and for identifying potential areas for innovation. The model postulates four types of innovation – radical, modular, architectural and incremental, according to whether there are fundamental changes in components and / or interrelationships.

Using this model, the table in Figure 4.18 has been constructed using cited sources of information in the supercomputer sector. The green-bordered areas are considered as having potential for radical or modular innovation. In the table, the following may be observed:

i. There are considerable attempts at Radical / Modular innovation on the hardware side, particularly on the core processor aspect. This is understandable since performance improvements depend mostly on processor speeds.
ii. There are attempts at modular innovation on the interconnection and network hardware systems. This again has considerable effect on performance.
iii. On all the other components, only architectural and incremental innovations have been attempted.

Component	Radical	Modular	Architectural	Incremental
Theory of computation model	**Potential for innovation**		All	All
Algorithms			All	All
Architecture	Sunway, Fujitsu ARM	IBM, Cray, Intel	All	All
Processor chips	China, ARM, Intel, IBM	IBM, Intel	China, Japan, IBM, Intel	China, Japan, IBM, Intel
Memory chips	**Potential for innovation**		All	All
Node-memory interconnections	**Potential For innovation**	Sunway, Fujitsu ARM, IBM, Cray	All	All
Node-node interconnections		Sunway, Fujitsu ARM, IBM, Cray	All	All
Network hardware	**Potential For Innovation**		All	All
Server systems			All	All
Secondary storage			All	All
Power supply			All	All
Cooling system			All	All
OS/HPC storage systems software			All	All
Many-core systems software			All	All
Parallel compiling environment			All	All
Parallel programming environment			All	All
Parallel application suites			All	All

Figure 4.18 - Scope for HPC innovation according to the Henderson taxonomy

The following inferences may now be drawn:

i. *Radical innovation*: There is scope for radical innovation in the theory of computation, algorithms, architecture concepts, all major support systems and all major software components. Radical innovation in semiconductor technologies for processors and memories can be expected to continue. As an example, China has identified silicon photonics as a promising area for research in the post-exascale era (Singer, 2016)

ii. *Improvements in algorithms* could yield significant benefits even with existing systems.
iii. *The scope for improvements in performance is highest in the interconnection and network systems*. This is because a lot of time is lost in moving data around during a computation.
iv. *The systems software area is completely open for radical and modular innovations*. For example, a new operating system, or a new programming language suitable for specific problems, could make considerable difference to the utilization of an HPC system.
v. In the support systems such as the power system or the cooling system, *innovations could make a difference* to the performance of the hardware.

4.1.5 Innovation Ecosystem for HPC

Strategically important, expensive sectors such as HPC require an extensive ecosystem to flourish, and for innovation to take place. From the history of HPC as analyzed above, and its varying success in different countries, we may identify the following elements as comprising the HPC ecosystem:

- A community of scientists doing fundamental research in the physical and mathematical sciences, particularly in semiconductors, of competitive quality internationally.
- A community of technologists doing active research into all aspects of computer sciences.
- Companies / organizations that are successfully translating the fundamental research into design of processors, memories and their associated technologies.
- Companies / organizations that are proficient in semiconductor chip fabrication
- Companies / organizations that are successful in building and operating computing equipment across the spectrum of performance and application requirements.
- Academic and training infrastructure for the education and training of engineers and scientists specializing in HPC technologies.
- Active government support for HPC in the form of policies, missions, and programs.
- An active investment and financing community with adequate resources to invest to the levels required for HPC
- Awareness in the user community – whether in the political and bureaucratic leadership, the defence sector, the security sector, commercial sector, the medical and pharmaceutical sectors, the environment sector, etc., of the benefits of HPC and the need to treat it as a strategic resource.

- A well-networked body of HPC practitioners, drawn from the above communities, with active linkages to the global HPC community.

This list can be restated as composed of eight sectors of a nation-state; namely, the ***political leadership***, the ***bureaucracy***, the ***military***, the ***education sector***, the ***basic sciences research*** sector, the ***applied sciences research*** sector, the ***financial markets***, and the ***industrial sector***. Using this classification, a sectoral innovation ecosystem can be represented as shown in Figure 4.20.

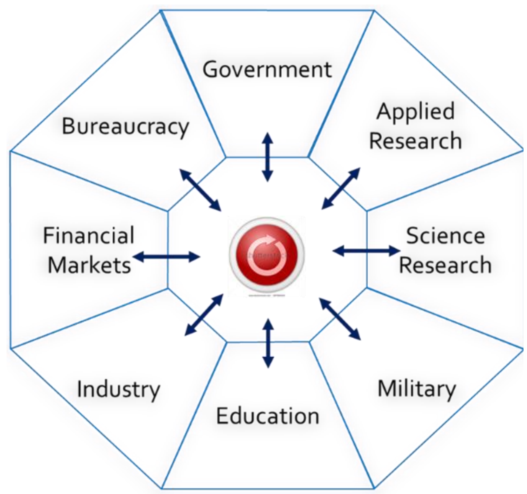


Figure 4.20 – Components of a sectoral innovation ecosystem

4.1.6 Critical factors for innovation in HPC

Given the nature of HPC, innovation in the sector is necessarily spread over a long-time horizon. A perspective to view how HPC can be catalyzed was described comprehensively in the report on "The Future of Supercomputing" prepared by the National Research Council of the US in 2003 (US National Research Council, 2003). The report proposed a model with a focus on balanced investment along two major axes:

1. *Investment in radical / innovative areas of HPC,* including, but not limited to:

    a. Broader theory of computing
    b. New Concepts from physics and mathematics
    c. New architectures
    d. New hardware approaches
    e. New algorithms

f. High end education and training to build up adequate human resources for HPC.

2. *Investment in incremental and evolutionary improvements*, such as:

a. Improvements in hardware technologies
b. Improvements in systems and application software
c. Improvements in algorithms
d. Improvement in manufacturing processes

4.1.7 Country-wise performance in the HPC sector

With the ready availability of data from the Top500 initiative, it is possible to analyze the extent of success in HPC by different countries. The two parameters used for this purpose are the *percentage of the total global number of HPC systems (N)* that are installed in a country for a given year; and, the *percentage of the total global installed HPC capacity (C)* that is available in that country. The chart is shown in Figure 4.21 and the corresponding data in Figure 4.22.

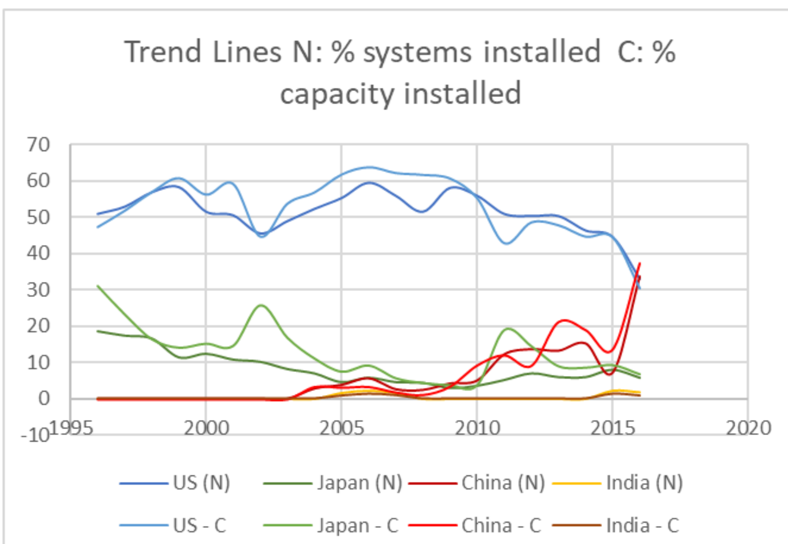


Figure 4.21 – Comparative HPC status in four countries

Year	US (N)	Japan (N)	China (N)	India (N)	US - C	Japan - C	China - C	India - C
1996	51	18.6	0	0	47.3	31.1	0	0
1997	53	17.4	0	0	51.8	23.3	0	0
1998	57	16.6	0	0	56.9	16.5	0	0
1999	58.4	11.4	0	0	60.7	14.2	0	0
2000	51.6	12.4	0	0	56.2	15.3	0	0
2001	50.6	10.8	0	0	59.1	14.7	0	0
2002	45.6	10.2	0	0	44.7	25.8	0	0
2003	49	8.2	0	0	53.7	16.9	0	0
2004	52.4	7	2.8	0	56.8	11.2	3.4	0
2005	55.4	4.6	3.8	1.6	61.7	7.6	3.2	0.8
2006	59.6	5.8	5.6	2.2	63.7	9.3	3.4	1.3
2007	56	4.6	2.6	1.6	62.1	5.8	1.9	0.9
2008	51.6	4.4	2.4	0	61.6	4.5	1.2	0
2009	58.2	3	4.2	0	60.6	3.9	3.5	0
2010	56	3.6	5	0	55.2	3.9	9.3	0
2011	51	5.2	12.2	0	42.9	19	12.1	0
2012	50.4	7	13.6	0	48.6	14.6	9.2	0
2013	50.4	6	13.2	0	47.8	9.1	21.2	0
2014	46.4	6	15.2	0	44.7	8.7	19	0
2015	44.6	8	7.2	2.2	44.5	9.4	13.7	1.3
2016	33	5.8	**33.6**	1.8	30.5	6.9	**37.3**	0.8

Figure 4.22 – Data of percentage of Top 500 installed in numbers (N) and capacity (C)

4.1.8 The Application Landscape

The term “classic trinity” has been used to describe historically important supercomputing applications. These are cryptography, the design of nuclear weapons, and weather forecasting (Mullaney, 2016). However, with the advent of petascale and exascale systems, the application landscape has evolved far beyond the classic trinity. It is now possible to analyse HPC like other industries, in terms of revenues in the different vertical market segments, categories of applications, and future directions.

It is important to appreciate that “HPC industry market”, as aggregated in revenue terms, includes equipment and services that are not necessarily for “supercomputers” alone. We may segment the market into servers, software, storage, networking, cloud-based solutions, services and miscellaneous products and services. Of these, only a percentage would go specifically into “supercomputers”. For the sake of clarity, we shall designate a supercomputer as a product that includes a server whose cost is greater than USD $1.5 million (Snell, 2017). The wealth of data is available from numerous reports of the US Congress. The global market is summarized in Figures 4.23 through 4.27.

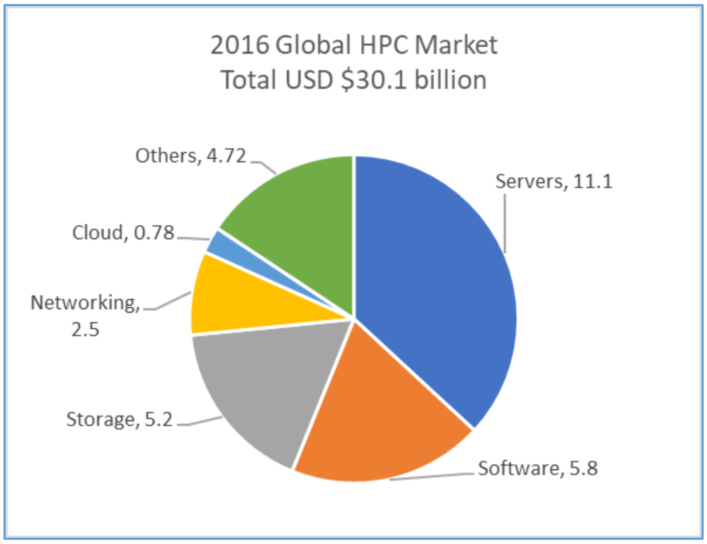


Figure 4.23 - Global HPC technology market shares

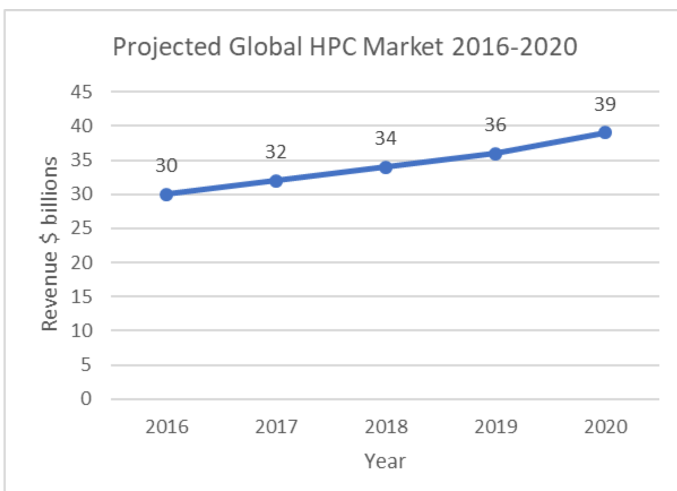


Figure 4.24 - Global HPC market growth

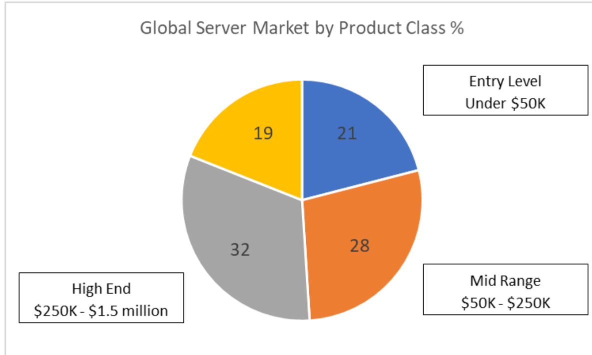


Figure 4.25 - Global server market by product class

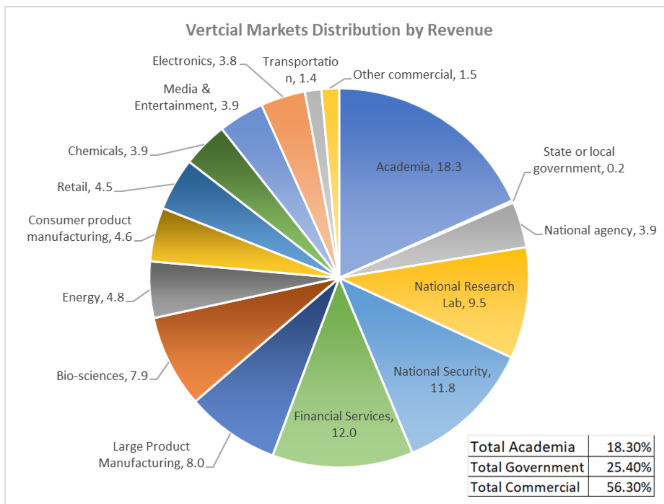


Figure 4.26 - Global vertical markets

The chart shows the increasing importance of the commercial market for HPC, which is already double of the market for government applications (Snell, 2017).

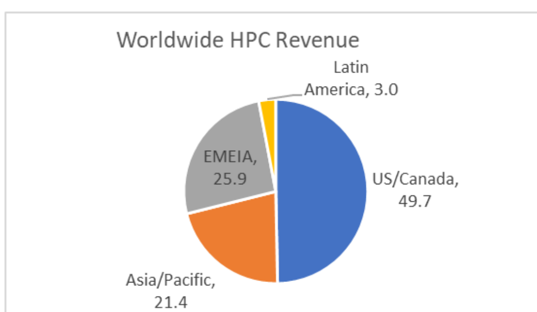


Figure 4.27 - Global markets by geography

Although China has the fastest systems and the largest number of installations, in revenue terms the US market is still five times as large (Snell, 2017).

It is remarkable that as compared to the global Information Technology software and services industry, which registered $1600 billion in 2016, the HPC industry is miniscule at $30 billion. Despite this, the perceived importance of the supercomputer segment is out of all proportion to its purely economic impact, given the national level focus outlined in sections above. This underscores the strategic significance of the sector, while at the same time highlighting the fact that this strategic significance is viewed differently by different countries.

The application landscape may also be examined from perspectives other than the purely economic dimension outlined above. First, the nature of applications has evolved together with technology. Very often, the one has driven the other. Second, not all applications are of equal importance to all countries. Third, although the range of applications in one era may not be of significance to one or more countries, emerging and future applications may well be of great interest, thus providing an incentive for such countries to invest in HPC. This opens the possibility of countries "coming from behind" to catch up with the leaders, i.e. leapfrogging an era to achieve competitive status with the leaders (Snell, 2017).

As the race to exascale intensifies, it is useful to examine the perspective in which applications are viewed . Two areas of application may be examined in this context:

- In *large product manufacturing*, it is expected that product development cycles could be cut by up to 50%. This would become possible because of the ability to simulate an entire product at various levels of decomposition under a complete range of operational environments. This is currently possible largely only through field trials and destructive testing. Companies, and indeed countries, could find it easier to enter and compete in new markets and products because of faster HPC capabilities (Joseph & Conway, 2014).

- In *energy studies*, forecasting the role of different technologies requires computational capacities which are not yet achievable. For example, to forecast the rate of renewables adoption, it is necessary at the same time to model in developments and changes in the nuclear, coal and petroleum sectors. These in turn need to be factored into simulation of demand patterns for energy in different parts of the world, and into the simulation of climate change patterns that are likely to evolve (Watson, 2015).

To conclude the discussion on the application landscape, two emergent paradigms are of interest:

- *Machine Learning and Artificial Intelligence*: This field has attracted great interest in recent years, and the US Department of Energy has formally signalled that it will form the "third pillar" of applications for exascale (Feldman, 2017).

- *Quantum Computing*: This represents a possible discontinuity and disruption of computer theories and technologies as we understand them today (Snell, 2017). Although this field has been studied from the conceptual perspective for many years, practical demonstrations of usable technologies is still over the horizon. However, it is clearly an area of strategic interest to China as well as the US. This area, again, could provide opportunities for "coming from behind" to catch up with the leaders.

With this background, we turn now to the details of the two case studies of supercomputing in China and India, with special reference to innovation patterns and knowledge processes that can be observed.

4.2 The supercomputer sector in China

4.2.1 History

The origins of Chinese computing, and with it supercomputing, go back to 1958, when a group of engineers at the Institute of Military Engineering at Harbin created the country's first vacuum tube computer. In the decade that followed, despite the turbulence caused by the Sino-Soviet split and the launch of the Great Proletarian Cultural Revolution, the country's nascent computer industry nevertheless maintained a meaningful momentum. By 1972, when an American computer delegation arrived for the first time to meet their Chinese counterparts, China had already developed the capability to build a third-generation computer, based on integrated circuits. Remarkably, the chips they had used had been manufactured in China itself (Mullaney, 2016)

The report submitted by the American team after the visit contains some revealing insights. First, they noticed the emphasis the Chinese placed on self-reliance and indigenous development; though they clarified that this was due to necessity, because of China's political isolation at that time, rather than by choice. Second, they explained the advantages of this approach principally in terms of raising a generation of competent computer scientists. Third, they highlighted their ability to set up a manufacturing infrastructure for computers even in an unforgiving environment – integrated circuits, for example, were manufactured in a repurposed glass window factory.

What struck the American team forcefully, however, was the obvious interest of the Chinese in the fastest and most powerful computers in the US at that time, the Burroughs B6700 and the CDC STAR, rather than the minicomputers which were just beginning to make their mark in the US. The team was equally struck by the use of the word "supercomputer" by the Chinese, leading to a remark in the report that "they will continue the trend towards bigger and faster computers, and perhaps they will attempt a very big step next."

The available historical record does not provide detailed information on developments in the ensuing decade, but the next reference to the computer industry in China is contained in a 1987 report of the Office of Technology Assessment of the US Congress, which is reproduced below:

Table 7.—Major Achievements in China's Computer Industry, 1977-85

1977	Development of China's first microcomputer (DJS-050).
1979	Development of HDS-9 (5 MIPS) by CAS Institute of Computer Technology.
	Development of DJS-052 microprocessor (eight bit, one chip).
1983	Development of China's first supercomputer ("Yinhe" ["Galaxy"], 100 MIPS) by the S&T University for National Defense in Changsha.
	Development of the 0520 microcomputer (IBM PC compatible) by the MEI Institute No. 6 and production by Beijing Wire Communications Factory.
	Development of the "757" 10 MIPS parallel computer by CAS Institute of Computer Technology.
	Development of a 16-bit desk-top computer (77-II) by the Lishan Microcomputer Corporation.
1984	Development of the 16-bit TQ-0671 microcomputer system by the Tianjin Computer Institute (CPI: MC 68,000).
1985	Development of NCI-AP 2701 floating point array processor by MEI North China Institute of Computer Technology.
	Development of NCI-2780 super-minicomputer (32 bit) by North China Institute of Computer Technology (Clone of DEC VAX 11/780).
	Development of 8030 computer by East China Institute of Computer Technology (compatible with IBM 370/138).
	Development of YH-X1 super-minicomputer by the S&T University for National Defense in Changsha.

SOURCE: Office of Technology Assessment, 1987.

Figure 4.28 - Early Chinese computer development

This one table alone provides a wealth of insights into China's strategies, which will be dealt with in greater detail later in this section. However, it is important to note that, by 1983, China had already developed its first supercomputer, with a speed of 100 Mips, and furthermore, had also already developed a parallel processing computer with a speed of 10 Mips. These two facts alone place China as competitively among the top five countries in computer technology by the turn of the 80s. It should be noted that this was during the turbulent aftermath of the Cultural Revolution, and in the initial stages of the launch of Deng Xiaoping's modernization drive in 1980. Remarkably, as many as seven different institutions had been cited in the list of achievements as the locations of development.

There are two further important developments that need to be highlighted in the history of Chinese supercomputing. The first is the inclusion of information and communication technologies in the very first edition of China's famed "863" program, personally approved by Deng Xiaoping, based on the postulate that "techno-nationalism" was to form a core part of China's strategy for the future, i.e. that the harnessing of technological power was crucial to strategic success of nation states in the future (Feigenbaum, 2003). This provided the policy and structural framework for development and commercialization of a wide range of technologies, including supercomputing, that has been carried through consistently into the 21st century.

The second was an initiative in 1989, to set up three supercomputing centres in China as a joint project between the State Planning Commission, the State Science and Technology Commission, and the World Bank, that included a number of protocols for joint technology development (Fan, 2001). This infrastructure provided the initial impetus for China's later impressive performance in this sector. With this background, we will now move on to summarize the important milestones achieved by China since.

It should also be noted, in the context of this thesis, that at the time the import of a Cray supercomputer into India had been blocked, the United States, through the World Bank, was participating in the development of supercomputing capabilities in China. However, the embargo on supercomputers with speeds greater than 1 Gflops applied equally to China and India.

4.2.2 Major Milestones

Covering a fifty-year period, the Chinese supercomputer effort is rich in milestones, of which the following constitutes a summary of major events:

Year	Milestone
1983	Development of China's first supercomputer "Yinhe" with a speed of 100 Mips
1983	Development of first parallel processing computer, speed 10 Mips
1986	Inclusion of supercomputers in the first 863 program
1989	Setting up first three National Supercomputing Centres jointly with World Bank
2002	DeepComp 1800 ranked #43 by speed in the world
2003	DeepComp 6800 ranked #11
2004	Dawning 4000A ranked #10
2010	Tianhe 1A ranked #1
2016	Sunway Taihu Light ranked #1 with a speed of 93 petaflops. First major supercomputer to use China-designed and manufactured processor chips.
2017	Chinese supercomputers account for more than 40% in the Top 500 list
2017	National Artificial Intelligence 2017-2030 Plan released

Figure 4.29 - Major milestones in Chinese HPC

Within this broad picture, it is instructive to list the milestones achieved by one major source for China's supercomputers; the Sugon Information Industry, manufacturers of the "Dawning" series of supercomputer that placed China at #10 in 2004 (Sugon, 2018). Sugon was set up in 1990 and has always partnered closely with the National Research Centre for Intelligent Computing Systems (NCIC) (Sugon, 2018).

While impressive, Sugon's list of milestones, shown in Figure 4.30 below, reflect the achievements of only one of the many organizations involved in China's supercomputer sector. A similar list of milestones could be drawn up for the Lenovo Group, for example, which was set up by the Chinese Academy of Sciences and which produced the original DeepComp series of supercomputers; or for organizations associated with the National University for Defence Technology (NUDT), which developed the Tianhe 1A system; or for organizations associated with the National Research Centre for Parallel Computer Engineering and Technology (NRCPC), which developed the Sunway Taihu Light.

Year	Milestone
1990	NCIC was founded
1993	Dawning 1 launched, China's first Symmetric Multiprocessing(SMP)supercomputer, ending the embargo on supercomputers with speeds
	greater than 1 Gflops.
1995	Dawning 1000, a MPP architecture supercomputer with a speed of 2.5 Gflops. Winner of the First Prize of National Science and Technology Progress by Chinese Academy of Sciences
1997	Dawning 1000 deployed at the Liaohe Oil Field, the first successful large-scale application of a Chinese supercomputer.
1998	Dawning 2000, a cluster architecture 20Gflops machine, recognized officially as a key achievement of the 863 program.
2001	Dawning 3000, achieved a speed of 403.2 Gflops
2002	Mapping of the rice genome using the Dawning 3000, recognized internationally.
2003	1000th Dawning HPC system delivered, utilized for the Shen Zhou manned space mission
2004	China becomes the third country to enter the Top 10 list. President Hu Jintao recognizes this achievement as a "symbolic independent innovation" by China.
2005	High Performance Computing Committee of China Computer Society (HPCTC) was founded with an office at Sugon.
2006	High Performance Computer Standardization Committee(HPCSC) was
2008	founded. Sugon opened Tianjin Manufacture base and HPC Application Experience Center. The 2000th Dawning HPC system was delivered
2009	Dawning 5000 launched, fastest computer in Asia and #10 in the world. China became the second country to build a 100 Tflops computer. Supported rendering and weather forecasting for the 2008 Beijing Summer Olympics. Sugon became the #1 vendor in China with a 26% market share.
2010	Dawning 5000 utilized for power dispatching in the State Grid.
2011	Dawning 6000 unveiled, speed 1.2 Petaflops, the second fastest in the world.
2014	First Sugon HPC system with indigenously manufactured Loongson chips.
2015	IPO on the Shanghai Stock Exchange.
2016	Launch of the Silicon Cube system with 3-D Torus network topology, the prototype of the Earth System Numerical Simulator, optimized for deep learning and AI.

Figure 4.30 - Sugon Industries Milestones

With regard to the future, the National Artificial Intelligence Plan released by the Chinese government in July 2017 clearly spells out the objective of achieving global leadership in AI by 2030.

4.2.3 Installed Base

The Top500 list provides information on the 500 fastest systems installed worldwide. Data on systems that fall out of this category are not available in the industry publications. In 2017, China had 202 systems installed out of the 500 listed in the Top500 list. It was evaluated at 9.2% of the global HPC market by business volume (Snell, 2017), which would include systems smaller than those listed in the Top 500.

In terms of Chinese vendors, Lenovo led with 81 systems in the top 500, followed by Sugon with 51 systems (Top500, n.d.). By market share measured by business volume, however, Sugon retains the top spot, reflecting its penetration into other lower speed and lower price segments.

The 202 systems identified in the Top500 lists are distributed as follows in the different segments:

Segment	Number
Academia	5
Research	11
Government	16
Industry	169
Classified	1

Figure 4.31 - China HPC installed base in Top500

Academia, research, classified users, and government account for 16.4% of the top 202 installations, and industry the balance 83.6%. This demonstrates the considerable penetration of HPC in Chinese industry. Of the 11 listed under research, 6 are installed at National Supercomputing Centres, 2 in centres for meteorology and atmospheric physics research, 1 each in research centres for electric power, marine sciences and computer technologies. The role of the National Supercomputing Centres is of particular interest to this thesis, since their setting up was among the first initiatives to establish supercomputing in China.

4.2.4 Ecosystem for supercomputer research, technology transfer and knowledge utilization

During the 1970s and early '80s, when the Chinese supercomputer program was still in a nascent stage, research and development took place at multiple centres. This is evidenced by data available on the Yinhe supercomputer and the 10 Mips parallel processor (OTA, 1987). Although there is no evidence of formal collaboration networks, it can at least be inferred that competition was not discouraged. With the launch of the 863 programs, however, the ecosystem for formal collaboration and knowledge exchange was put into place. The first step in this direction was the setting up of China's first three National Supercomputing Centres at the Chinese Academy of Sciences, the National University for Defence Technology, and at the Tianjin Computer Institute (Fan, 2001).

Today, the ecosystem for R&D, technology transfer and knowledge dissemination and training is well organized and has produced the results referred to in the previous sections. The principle components of this ecosystem are:

1. *Research Institutions*: Three major research centres that are operational:
    i. National Research Centre for Parallel Computer Engineering and Technology (NRCPC)
    ii. National Centre for Intelligent Computing Systems (NCIC)
    iii. National University for Defence Technology

2. *National Supercomputing Research Centres*: These are organized into the China National Grid, with the nodal centre located at the Chinese Academy of Sciences. There are 8 centres in all, located at:
    i. Supercomputer Centre at the Chinese Academy of Sciences, Beijing (SCCAS)
    ii. Guangzhou, housing the Tianhe-2, the second fastest in the world at 33 Pflops
    iii. Changsha, housing the 1.3 Pflops Tianhe-1A
    iv. Jinan, with the Sunway Blue Light at 740 Tflops
    v. Shanghai, with the Magic Cube operating at 240 Tflops
    vi. Shenzhen, with the Nebulae, in the Top 10 list.
    vii. Tianjin, with the Tianhe-1 operating at 2.5 Pflops
    viii. Wuxi, housing the Sunway TaihuLight, the fastest in the world at 93 Pflops.

3. *Commercial organizations linked to the Research Centres and the NSRCs*. These are a distinctive feature of the Chinese supercomputer sector and perform the crucial role of technology transfer, commercialization, and product diffusion. Interestingly, many of these have been promoted and are owned, at least in part, by the Research Centres (CAS, 2016). For example, the Lenovo Group, best known for its laptops and PCs, but with also a major HPC division, was promoted and is still owned partially by the Chinese Academy of Sciences. Similarly, the Sugon Information Industry was promoted and is still partially owned by the National Centre for Intelligent Computing.
4. *Universities and polytechnics*: Some of these would have their own inhouse supercomputing facilities, but all have access to the China National Grid linking the eight NRSCs.
5. *User organizations in the government, public and private sectors*. These provide the primary sources of information and knowledge about the application landscape and how it can evolve. In this category, we also include the financial community, both in markets and local communities, which

participate in investing in both organizations such as Lenovo and Sugon, as well as in the setting up of new NSRCs and the procurement of new supercomputers.

In this ecosystem, the most important role in expanding the supercomputer sector in China is played by the NSRCs, which act as the bridge between the R&D community, the manufacturing community and the user community. For example, the original statement of purpose of the Tianjin centre read as follows:

- *The completion of the national supercomputing center*, a major national scientific and technological service platform, industrial technology innovation platform human resources, training platform.
- *To establish and improve the information industry* in Tianjin Binhai New Area technological innovation system and build high-performance computing applied R&D centers.
- *The establishment of production and research cooperation mechanisms*, in order to project as a link to drive high-performance computing services, R & D and production of high-performance computers and other related information industry.

This vast Chinese ecosystem, which may be accurately termed a hybrid model, is proposed to be represented by the following diagram (in the opinion of this researcher, the Chinese supercomputing ecosystem is elegant in the simplicity and efficiency of its design):

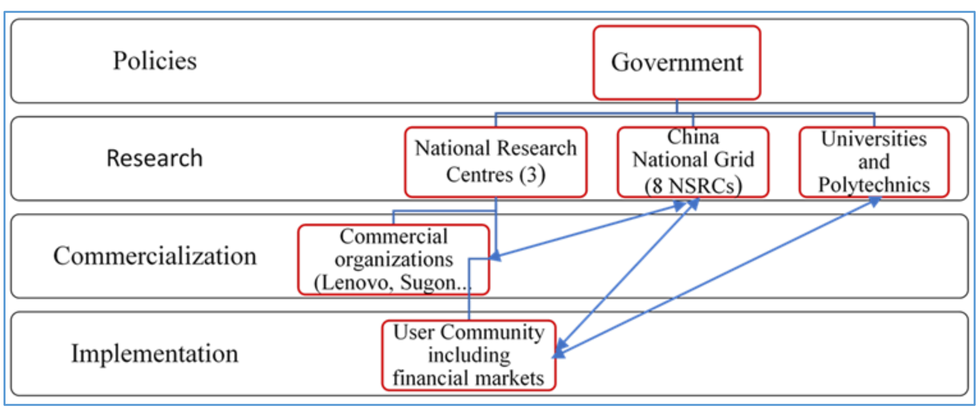


Figure 4.32 - China HPC ecosystem

Using the concept depicted in Figure 4.20, we represent the Chinese supercomputer ecosystem as fully integrated in the following diagram:

Figure 4.33 - China HPC ecosystem

4.2.5 Investments in supercomputing in China

The 863 programs clearly mandated that it was the responsibility of the State to fund initiatives contained in the program, as these were considered of strategic importance to the country as a whole. Thus, we may conclude that the initial funding of the sector was entirely to the State's account during the '80s and the '90s. Some external aid was available from time to time, such as World Bank assistance for the setting up of the first three NSRCs. Nevertheless, as the size and the scope of the sector expanded to its present scale, funding came in from outside of state sources as well.

As a starting point, we may use the percentage of China's share of the world's HPC market. With a 9.2% share of a $30.1 billion market in 2016, China spent $2.77 billion in 2016 on HPC products and services. Using simple linear interpolation over a 30-year period, Chinese investment in HPC from 1986 to 2016 is estimated at approximately $40 billion.

The sources of these funds may be divided into central government, local governments, and banks or financial companies, since it can be assumed that corporate customers fund procurement of capital equipment such as supercomputers through bank lending. A unique feature of the Chinese supercomputer sector is the participation of local governments in the funding process. A case in point is the funding pattern for the Sunway

TaihuLight. As mentioned earlier, the total cost of the system in $270 million (Dongarra, 2016), with funding provided by the following:

- Central Government - $ 90 million
- City of Wuxi - $ 90 million
- Jiangsu province - $ 90 million

This demonstrates the extent to which even local governments in China are invested in a sector which is commonly assumed to be of importance only at a central government level, or in very large corporate organizations.

The investment figures reveal an important fact about supercomputing. China's expenditure on HPC is a fraction of the spending by the US. Yet in terms of technological development, China is matching and may even outstrip the US in the near future. Therefore, investment alone is an insufficient metric to measure a country's performance in this sector. This supports the proposition that it is still possible to "come from behind to catch up" (Snell, 2017). The analysis of innovation possibilities given earlier in this chapter, in which it was demonstrated that radical innovation is possible in virtually all the 18 major component groups of a supercomputer system, further bolsters this proposition.

The Chinese government clearly buys into this perspective, as indicated by their recently announced National AI Plan, which has the objective of achieving global leadership in Artificial Intelligence by 2030, as mentioned earlier. Investments of up to $60 billion have been earmarked for this purpose, representing a quantum jump in the level of effort.

4.2.6 Applications of supercomputing in China

Given the large installed base and the volume of investment in HPC, as evidenced by China's share of the global market, it may be concluded that all the application areas covered in the section on the application landscape find presence in China. The question is the extent to which organizations can successfully and continuously leverage their investments in HPC. In other words, to what extent have supercomputer applications diffused into the Chinese economic ecosystem? To what extent have these applications been developed by the Chinese alone?

While it is difficult to obtain this level of granularity of information in the framework of a thesis such as this, what can be evidenced is the extent to which Chinese scientists and engineers are encouraged to develop newer and more optimal applications for supercomputers. One indicative measure of this is Chinese participation in the annual global competition for the Gordon Bell award.

The Gordon Bell awards are prizes instituted by the Association for Computing Machinery (ACM), for the best papers presented at the annual Supercomputing Conference series in different categories. The awards have been presented since 1987. More than one competitor may receive a prize, depending on the quality of the submission. They are intended to recognize applications of supercomputing that demonstrate:

- *evidence* of important algorithmic and/or implementation innovations
- clear improvement over the previous state-of-the-art
- *solutions* that do not depend on one-of-a-kind architectures (systems that can only be used to address a narrow range of problems, or that cannot be replicated by others)
- *performance* measurements that have been characterized in terms of scalability (strong as well as weak scaling), time to solution, efficiency (in using bottleneck resources, such as memory size or bandwidth, communications bandwidth, I/O), and/or peak performance
- *achievements* that are generalizable, in the sense that other people can learn and benefit from the innovations

Till 2014, teams from the United States dominated the competition, winning a clear majority of the prizes, with some competition from Japan from time to time (Thesigers, 2015). But in 2015 and 2016, all the prizes in all the categories went to Chinese teams. This provides evidence of three kinds:

- China is actively encouraging research into HPC applications, with the stated objective of catching up with the best.
- China is investing resources in developing human capital for supercomputer applications.
- Because of the relatively late entry to the competition, China still has a long way to go in terms of the width and range of applications for which solutions have been developed.

We may conclude from the above that, as compared to their progress on the hardware side, China is somewhat more behind the United States on the software side, both in terms of systems software, such as operating systems, language compilers and the like, and also as regards applications. Catching up on the software front with a focus on Artificial Intelligence has become the next objective for China's supercomputer sector, as evidenced in the July 2017 announcement of the National AI Plan.

4.2.7 Announced Plan for the future

China has publicly announced two plans for the future, together providing a perspective till 2030.

1. *The Exascale Plan*: As mentioned earlier, China has announced three initiatives to achieve exascale as part of the Thirteenth Five Year Plan period (Trader, 2016). These are:
    - *Tianhe-3*, to be developed by the National University for Defence Technology (NUDT), the Tianjan NSRC, and the government of the Tianjin Binhai New Area. The target date for deployment is 2020.
    - *Silicon Cube*, to be developed by the NCIC and Sugon Information Industry
    - *An unnamed exascale machine*, which will be the next of the Sunway series, to be developed by the NCRPC.

2. *The National Artificial Intelligence Plan*: In July 2017, the Chinese government formally unveiled the objectives for the National AI Plan, as follows, with a planned investment of $60 billion to achieve them:
    - Catch up with advanced global levels and application by 2020
    - Make major breakthroughs in basic theories by 2025
    - Become a global innovation centre in this field by 2030.

The above demonstrate that China has now set its sights on becoming the global leader in supercomputing by 2030 (He & Bowser, 2017). The Exascale plan is relatively incremental in its approach, appearing to build on China's past success in catching up on the hardware front. There is no indication of any breakthrough approaches based on fundamental research, such as quantum computing or photonics/ photon tunneling. This is a little surprising, given that China's main competitor, the United States, has clearly announced an attempt at a "novel" architecture for exascale. The AI Plan, on the other hand, seems designed to leverage AI in a radical attempt to overcome China's perceived lag in software and applications.

4.2.8 The Strategy Followed:

The analysis of strategies followed by China in the supercomputer sector can be logically divided into three phases, the pre-1986 phase, the 1986-2016 phase, and the post-2016 phase.

In the pre-1986 phase, as indicated earlier, China had achieved significant milestones by 1986. Among these were the development of the Yinhe 100 Mips supercomputer, the 10 Mips parallel processor, the capability to indigenously design and manufacture integrated circuits, the capacity to develop systems software, such as operating systems and language compilers, as well as application software indigenously; and to accomplish all this within an umbrella capability to acquire and absorb knowledge about the state-of-art in technology.

What was remarkable about the Chinese strategy in the pre-1986 phase was the multiplicity of organizations working in the sector. As the report of the Office of Technology Assessment shows, as many as seven different institutions were simultaneously active in the sector (OTA, 1987). There appears to have been no attempt to discourage competition between these institutions, although there is no direct evidence to support this contention.

It is also noteworthy that there was an emphasis on manufacturing. It was not enough to merely understand the theory of computers; it was necessary to make machines that performed well. The reasons for this can only be speculative today. It is interesting that the initial Chinese computer effort which began in 1958 and continued till 1986, was contemporaneous with the Great Leap Forward initiative of Mao Zedong, for which the famous slogan was "Let a hundred flowers bloom" and which encouraged "mass mobilization, social levelling, attack on bureaucracy, and disdain for material obstacles" in the words of Mao himself. Although the Great Leap Forward is universally considered to have been an utter failure, and nowhere more so than in China itself, the patterns observed in the early days of China's computer industry may reflect an unexpected heritage. The strategy for the 1956-1986 period is summed up by this researcher as ***"competitive communism."***

The next 1986-2016 period was the most important for the supercomputer sector in China, and fifteen major inferences may be made from the foregoing sections:

i. *Acceptance of technology as a national priority by all stakeholders*. These we may identify as the political leadership, the military, the bureaucracy, the scientific research establishment, the applied research establishment, the education infrastructure, industry, and the financial markets. Achieving this consensus among all eight stakeholders was the signal achievement of the 863 plans.

ii. *Statement of national purpose*, as the formal manifestation of the acceptance of the strategy by the eight stakeholders.

iii. *Acceptance by all stakeholders of the goal of catching up with and equaling* all other countries in key technology areas

iv. *Acceptance of the role of both the state and the financial markets* for funding the plan. No project was to be left behind because of funding problems, even if low in value.

v. *Constructing a Hybrid Model for implementing the plan*. This has been described earlier in this chapter in the diagram of the ecosystem for R&D, technology transfer and knowledge dissemination. The tightly coupled hybrid model proved itself by the track record of success achieved.

vi. *Acceptance of the role of both the public and private sectors in implementing* the plan.

vii. *Encouragement of competition between institutions*. This represented recognition of the strengths of the pre-1986 approach.

viii. *Encouragement of both basic and applied research within the same institution*. The Chinese Academy of Sciences is a good example of this approach, which came to be called the "one academy two systems" approach, which served the purpose of addressing the entire R&D and manufacturing life cycle.

ix. *Encouragement of innovation, including radical innovation* at all stages and levels. This was a formally stated policy.

x. *Encouragement of incubation of commercial organizations* by research institutions. Both Lenovo and Sugon represent successful outcomes of this strategy.

xi. *Encouragement for building knowledge networks*. At this highest level this was an attribute of the hybrid model itself. Chinese scientists and engineers were given a lot of freedom to interact widely with the outside world, through participation in conferences, joint working groups with other countries, exchange visits and the like. All this contributed to the strengthening of knowledge networks, and specifically to intensive knowledge acquisition, absorption and dissemination.

xii. *Encouragement of the entry of companies into the entire commercial value chain*, from productionisation of prototypes, to manufacturing, marketing and customer support in a competitive international environment.

xiii. *Encouragement of collaboration with other countries and organizations* if considered necessary. Thus, Intel chips were used in some Chinese supercomputers even as indigenous development of processors was under way in China.

xiv. *Flexibility and decentralization of policies at the local level*. Thus, Lenovo could take its own decisions independent of other institutions.

xv. *Continuity in the broad streams of policy* to ensure stability and discourage short-term thinking.

The 863 Plan and the Hybrid Model both represent radical innovations in their own right. This researcher sums up the supercomputer strategy in the 1986-2016 period as "***competitive Chinese capitalism***"; although Deng Xiaoping had initially termed the overall approach as "*socialism with Chinese characteristics*."

Although presently still early in the post-2016 phase, the following may be discerned as the Chinese strategy for the next 15 years:

- *Leadership* will replace "catching up" and "parity" as the national objectives for the sector.
- The *Hybrid Model* will continue, since it has proved itself.
- *Levels of investment* will be significantly ramped up.

4.2.9 Innovation patterns

We may examine the patterns of innovation to be observed in China in the supercomputer sector at two levels. The first is at the level of the national infrastructure, based on the information available about the infrastructure. The second is at the purely technological level, based on the information available of the technological features of operational Chinese supercomputers.

To address first innovation patterns at the national level, it is pertinent to recall Baumol's seminal work on the role of innovation in the modern economy (Baumol, 2002). Baumol identified five major characteristics of successful innovation-based economies. Although Baumol's work has been criticized for too much focus on model building and not enough analysis on "history and fortuitous circumstances" (Field, 2003), it nevertheless provides a useful framework for investigating industry ecosystems. In this context, the extent to which the Chinese supercomputer ecosystem satisfies all the five Baumol criteria is remarkable. This has been summarized below using Baumol's five criteria this as follows:

i. *Oligopolistic competition*: China, to an extent greater than any other country except the United States, has built competition into the design of its ecosystem. From the earliest days, there have been multiple institutions working on supercomputers. Even in the exascale plan, there are three competing research institutions. Competition is also encouraged between commercial enterprises, as the record shows.

ii. *Routinization of innovation activities*: The role of the NRCs and the NSRCs, and their close coupling with commercial enterprises, institutionalizes this aspect.

iii. *Productive entrepreneurship*: From the Mao era onwards, China has strongly emphasized the development and manufacture of products as opposed to profit seeking through trading.

iv. *The rule of law*: Although details of this are somewhat limited, it appears that the rule of law is strong enough in China, at least as far as the supercomputer sector is concerned, to satisfy major global players such as Intel and Hewlett-Packard.

v. *Technology selling and trading*: Chinese participation in the international technology market is strongly evident. For example, the Tianhe-1 used Intel processors, while Lenovo provides HPC solution services globally.

Within this framework, the unique feature of the Chinese ecosystem is the close relationship, including partial ownership, between the government-owned research organizations and market-driven commercial companies. Using the Henderson taxonomy, we may conclude that the Chinese supercomputer ecosystem is a radical innovation.

To address next innovation at the technological level in China, we have referenced publicly available information on the Sunway TaihuLight, the NCIC Silicon Cube, and the application expertise evidenced by recent Chinese domination of the Gordon Bell awards. Using these, the Henderson taxonomy table developed earlier in the chapter has been extended to summarize the level and patterns of Chinese technological innovation. This is shown in Figure 4.34.

Component	Radical	Modular	Architectural	Incremental
Theory of computation model	***Potential for innovation***		√	√
Algorithms			√	√
Architecture	Silicon Cube	Sunway, Tianhe	√	√
Processor chips	***Potential for innovation***		√	√
		China SW2600		
		series		
Memory chips	***Potential for innovation***		√	√
Node-memory interconnections	***Potential for innovation***	√	√	√
Node-node interconnections		√	√	√
Network hardware			√	√
Server systems			√	√
Secondary storage	***Potential***		√	√
Power supply			√	√
Cooling system	***For***		√	√
OS/HPC storage systems software			√	√
Many-core systems software			√	√
Parallel compiling environment	***Innovation***		√	√
Parallel programming environment			√	√
Parallel application suites			√	√

Figure 4.34 – Innovation patterns in Chinese supercomputing

This table reveals that the Chinese have acquired considerable mastery over all the components of supercomputer systems at the modular, architectural and incremental levels. It is only recently that some evidence has become available of attempts at radical technological innovation as well, in the increased focus on quantum computing and AI, for example. Thus, the Chinese may be said to have focused more on catching up at the industry level, rather than risking radical technological innovations based on fundamental scientific or computational theory breakthroughs, that would have enabled them to "catch up by coming from behind".

The aversion to risk that is evidenced in the chart above is supported by the history of the Chinese academy of Sciences in the late nineties. Following the "one academy two systems" directive, the Academy was forced to bifurcate its activities into basic and applied research. The quality of research suffered as a consequence, and the Academy even faced the danger of being shut down due to funding constraints and the perceived lack of returns (Cong, 2015). The Academy responded by expanding rather than downsizing its activities, by setting up new institutions that depended to a larger extent on private investment, and which ae required to compete with other institutions in the nature of their work (Cong, 2015).

4.2.10 Knowledge processes in the Chinese supercomputer sector

We turn now to the questions central to this thesis. How has China used knowledge to formulate and achieve their goals in the supercomputer sector? How has knowledge contributed to innovation in the supercomputer sector in China? What patterns and processes can be inferred in this context? As in the previous section, we will address these questions at two levels – at the ecosystem level, and at the technological level.

To consider the first two of the above three questions at the ecosystem level, the history of the 863 plan provides compelling evidence of the importance that the Chinese attached to knowledge and the degree to which such knowledge had been absorbed and internalized. For example, the four technocrats who made the successful appeal to Deng Xiaoping to accord technological capability the highest priority as a national strategy, drew directly from the dictum of Marshal Nie, the former head of the nuclear weapons program, in many details such the importance of state funding, organizational structures and the like (Feigenbaum, 2003). Similarly, the four leaders were already part of a close-knit professional network, and thus understood the value of knowledge exchange. Finally, they had a deep appreciation of the importance of intermediate management structures, as this excerpt reveals:

> "In their final form, the strategic weapons programs were not merely showcases of the regime's achievements. They were also evidence of the success of the intermediate management institutions that the program's PLA patrons had attached to the push and persuaded China's senior political leaders to endorse in guarantee" (Feigenbaum, 2003)

These intermediate management structures required adherence by the political leadership to four specific aspects of leadership (Feigenbaum, 2003), as follows:

i. *Continuous engagement by the political leadership with experts* on a direct, regular, and in great details basis on both technical and policy issues.
ii. *Guarantees of the primacy of technical solutions* by the political leadership
iii. *Institutionalization of routines* making technical assessment and continuous leadership-expert contact possible
iv. *Commitment of resources* to the targets specified by the experts

The Chinese strategy in supercomputing was deeply informed by the national-security heritage of the 863 programs, as outlined above. Since the perspective of national security requires a nation to consider its position in relation to other countries, the same principle would apply to the supercomputer plan as well, i.e. that the success of the program would be measured in relation to the achievement of other countries, and not on a stand-alone basis. Thus, monitoring the status, details and growth of supercomputer sectors in other countries became an imperative, i.e. *knowledge search and acquisition became a continuous imperative*. Following such monitoring, appropriate changes would need to be made if required in China's own activities and plans, resulting in *absorption of new knowledge, fresh knowledge generation* by Chinese scientists and engineers in response, and *dissemination of such fresh knowledge* to ensure that planned changes were in fact implemented. In the light of the foregoing, the results achieved by the Chinese supercomputer sector during the past three decades therefore provide compellingly positive answers to the first two questions.

The importance attached to knowledge by the leaders of the 863 program shows most clearly in the design of the ecosystem for the supercomputer sector, specifically in the importance attached to competition. Assessing progress though competitive benchmarks is a common enough approach. But the Chinese leaders drew lessons from their earlier military experience, that not only was knowledge about the enemy important, but perhaps knowledge of successes and failures within their own military was equally as important (Feigenbaum, 2003). Thus, it became desirable to institutionalize internal competition as a strategy to achieve success. The radically innovative design of the supercomputer ecosystem reflects the absorption of past military knowledge by the Chinese technocratic leadership.

With this background, we may now turn to the third question, viz. what can be inferred about knowledge processes at the Chinese supercomputer ecosystem level? From the foregoing, we can infer the following:

i. Importance of continuous knowledge acquisition from the external and internal environments. In terms of knowledge processes, this may be termed continuous ***knowledge search***.

ii. Importance of choice of useful and relevant knowledge. In process terms, this may be termed as ***knowledge selection***, based on specific parameters. Given the military background to the Chinese strategy, the parameters for selection of knowledge may be inferred to be *competitive value* and *innovation value*.

iii. Importance of deep assimilation of knowledge at all appropriate levels. In process terms, we may term this ***knowledge absorption***.

iv. Importance of response to new competitive inputs. This requires new strategies, tactics and actions, whether in technologies or operations, and this may be termed ***knowledge generation***.

v. Importance of dissemination of information about the response. We may term this ***knowledge dissemination***.

Of these five identified knowledge processes of search, selection, absorption, generation and dissemination, ***innovation clearly is an alternate name for the knowledge generation process***. But for innovation to not only happen, but successfully happen in a competitive context, it is necessary to ensure that the right knowledge is continuously available. Therefore, *the selection process acquires paramount importance*, and in the Chinese case as remarked above, the criteria for selection can be inferred to be competitive value and innovation value. The success of the Chinese supercomputer program can be inferred to also mean a continuous sensitivity to what is happening elsewhere, both within China and outside, as a benchmark to work with. We may once again emphasize that this focus on competitive performance is rooted in the Chinese military-based national security view of technology as one of the critical weapons from a security perspective.

With the foregoing, we may now move on from the macro to the micro perspective and consider the same three questions in the perspective of technological innovation in supercomputers. To again take up the first two questions, viz. the importance of knowledge and the use of knowledge at the technology level specifically in Chinese supercomputing, it should be observed that the following has been established in this chapter. First, that China has historically measured its performance in supercomputing by its presence in the Top 500 list and the performance of its teams in the Gordon Bell awards. Second, their announced future plans, specifically in exascale and AI, show that the same strategy will continue, having been judged as successful. Thus, the same competitive perspective that we observed at the ecosystem level may also be inferred at the technology development level. Knowledge of competition can therefore be inferred as paramount in Chinese technology development, and therefore availability of knowledge specifically with competitive value and innovation value is critical to Chinese supercomputer development.

The third question therefore gets answered with the same set of five processes that can be identified as working at the technology development level as well, namely, knowledge search, knowledge selection with the specific parameters of competitive value and innovation value, knowledge absorption, knowledge generation and knowledge dissemination.

That knowledge processes appear uniform at both macro and micro levels, albeit in the specific case of Chinese supercomputing, offers interesting insights into the nature of innovation in general. First, for innovation to be considered at all, a problem must be judged as having no readily available solution, therefore requiring a fresh approach. Second, solutions must be evolved using scientific concepts and technologies which are judged to be useful. Third, the choice of concepts and technologies to be used depend on the selection criteria, and therefore different organizations and entities may evolve different solutions to the same problem. Fourth, the choice of solution will also determine the nature of the outcome. To come back to supercomputing, to stay ahead, even the leader must monitor what the others are accomplishing.

With the foregoing analysis, we can now refer back to the Research Design and the Main Research Question of this thesis, with its associated two hypotheses H_0 and H_1. ***The case study of supercomputing in China has revealed clearly that there are indeed connections between knowledge processes and innovation, thus invalidating the null hypothesis H_0.*** We can now confidently proceed to investigate in greater detail hypothesis H_1, namely, the connections between knowledge processes and innovation. Importantly, we can also now proceed to investigate the Subsidiary Research Question, namely, the patterns and practices, similarities and differences, in knowledge processes as related to innovation in selected Chinese and Indian organizations. This conclusion provides the appropriate springboard to investigate next the supercomputer sector in India.

4.3 The supercomputer sector in India

4.3.1 History

After India became independent in 1947, the push to acquire capabilities in science and technology came from the very highest levels of the Indian state. Jawaharlal Nehru, a strong believer in the power of science and technology, introduced and obtained assent from Parliament for the Scientific Policy Resolution in 1958, which sought to foster research in all its forms, "pure, applied and educational", in order to meet the requirements of "the country in science and education, agriculture and industry, and defence" (Rajaraman, 2012). The first indigenous Indian computer, using vacuum tube technology still current at that time, was developed and commissioned in 1962 by a group of scientists at the Tata Institute for Fundamental Research and was given the name TIFRAC. It is relevant to note that TIFRAC was used by scientists in India's atomic energy program (Rajaraman, 2012). However, recognizing that technology was advancing faster than it could keep up, TIFR opted to import India's first large computer, a CDC-3600, in 1963. With one of the fastest computers in the world at that time, the TIFR CDC-3600 can be termed India's first supercomputer installation.

However, it was only after the military setback with China in 1962 that the importance of computers was recognized, albeit under the larger rubric of electronics. The head of the Indian atomic energy program, Dr Homi Bhabha, was appointed the Chairman of the first committee to define a national-level policy for electronics and computers. During the deliberations, different points of views were expressed. For example, Dr Vikram Sarabhai, one of the founder leaders of India's space program, felt that "this field of computers is far more fundamental, of wider significance than any other field of electronics", and opined that the country should attempt to build capabilities across the entire spectrum, from research to manufacture. Others, for example Prof. V. Rajaraman, felt that "any strategy should take into account the genius and resources of the country. We do not have a large enough internal market to justify the chronological development of components first, circuits next and then complete systems. We should start in the reverse order and design systems first and import the components." (Rajaraman, 2012).

The Bhabha Committee report was the first step to what is now called the Indian Information Technology industry today. It is however clear that during the 1960s, the importance of a strong indigenous technological and manufacturing base in computers, arising from the possibilities offered by computers for countries such as India, was strongly accepted and received a degree of support and encouragement at the highest levels which was absent anywhere except in the Western world and the USSR. In terms of relevance of the policy history since then to the supercomputer sector, it is sufficient to state that in the decades that followed the Bhabha Committee report, the Indian policy regime underwent a number of twists and turns. Instead of a manufacturing base, by 1995 a highly liberalized, market-driven software industry emerged in preference to hardware (Parthasarathy, 2004) (Rajaraman, 2012) (Swaminathan, 2014). Not till 2012, through the National Policy on Electronics, was there a renewed policy intervention to boost design and manufacture of semiconductor components and chips (Swaminathan, 2014). The only reference to supercomputers, till 1988, was in their categorization as very large computers that were eligible for import (Rajaraman, 2012).

To locate the trajectory followed by the Indian supercomputer sector specifically within this larger canvas, we may list the important milestones in its evolution. Included in the chronology below are some critical policy decisions. Figure 4.35 depicts the milestones over a sixty-year period.

4.3.2 Major Milestones

Year	Milestone
1963	Installation of the CDC-3600/160-A at TIFR
1963	Bhabha Committee constituted
1966	Bhabha Committee report submitted
1970	Department of Electronics established
1971	Electronics Commission instituted
1972	BESM-6 from USSR installed at Bhabha Atomic Research Centre
1972	National Centre for Software Development and Computing Techniques (NCSDCT) set up in TIFR (later renamed National Centre for Software Technology)
1973	Electronics Commission decision to prioritize software over hardware
1973	Rejection of proposals from Fairchild, TI and Sony to set up semiconductor manufacturing facilities in India
1984	Supercomputing Education and Research Centre set up at IISc.
1984	Government initiates search for a joint venture partner for HPC
1985	Orders placed for Cray YMP supercomputers for SERC and Indian Meteorological Department
1987	CDC and Honeywell-Bull shortlisted for joint venture decision
1988	US government disallows export of Cray YMPs to India
1988	Centre for Development of Advanced Computing (C-DAC) set up in Pune
1989	SERC implements a network of computers centred around a CDC Cyber992 as alternative to the Cray
1991	PARAM supercomputer using transputers for parallel processing successfully demonstrated at C-DAC, rated at 5 Gflops, second fastest in the world
2007	PARAM PADMA launched, ranked 171 in the Top500 list
2007	TATA EKA demonstrated. First private sector supercomputer, rated at 172 Teraflops, ranked #4 in the world
2012	National Policy on Electronics announced
2013	SAGA-220, developed inhouse by ISRO, commissioned, with a speed of 220 Tflops
2013	PARAM YUVA-II, unveiled, speed 524 Tflops, first Indian supercomputer to cross 500 Tflops, ranked #62 in the world
2015	National Supercomputing Mission announced
2018	PRATYUSH supercomputing facility, based on Cray systems, inaugurated in Pune, providing 4 Petaflops capacity

Figure 4.35 - Milestones in Indian HPC

The chronology of milestones shows that although the policy regime followed an erratic path, technological innovation still took place to a certain degree. We may conclude from this that India is still evolving in the supercomputer sector. To understand this evolution and what it is composed of, we will examine in greater detail, based on field research, the following:

i. The PARAM series of supercomputers
ii. The Tata Eka supercomputer
iii. The differences in policy regime formulation between the Electronics Commission decision to de-emphasize hardware and the 2012 National Policy on Electronics.
iv. The National Mission for Supercomputing 2015

4.3.2.1 The PARAM series of supercomputers:

The genesis of the PARAM supercomputer project lay in the decision of the United States to embargo the export of US-manufactured computers with speeds of 1 Gflops or higher. This affected the contracts that had been awarded earlier by the Indian government for two Cray XMP supercomputers for the Indian Meteorological Department and the Indian Institute of Science. In 1988, the US formally conveyed its rejection of an export license to India. Sensing that this was likely to happen, alternatives were already planned and worked on in India. The National Aeronautical Laboratory (NAL) developed a high-speed computer called FLOSOLVER, but which was custom-tailored only for aircraft design. Similarly, the Department of Atomic Energy (DAE) and the Defence R&D Organization (DRDO) both developed similar specialized machines called ANUPAM and ANURAG respectively. But none of these could be considered an alternative to the Cray. There were also no steps taken to try and combine the work of these three organizations.

The decision was then taken to set up the Centre for Development of Advanced Computing, or C-DAC as it came to be called. The new organization was tasked to operate in “mission mode” to produce a supercomputer that could substitute for the banned Cray at the IMD. A second, more long-term reason for setting up C-DAC was that technology was judged to be changing very fast and India needed to keep up. As part of this effort, Dr Vijay Bhatkar was appointed Director of C-DAC and a budget of Rs 30 crores sanctioned for the effort with a target of three years for completion. A three-person team consisting of Secretary for the Department of Electronics Mr. KPP Nambiar, Dr Bhatkar, and Dr Gulshan Rai visited China to assess the best path forward. In the team’s assessment, China’s capabilities were roughly the same as India (Interview 1, 2016).

The C-DAC, and specifically Dr Bhatkar, took a bold decision to pick the still-new distributed memory MIMD (Multiple Instruction Multiple Data) parallel processing architecture, using very small processors called transputers (transistorized computers) that had been designed specifically for parallel processing and had shown great promise during the 1980s. The prototype machine was called PARAM 8000 (for PARAllel Machine), which also means “highest” or “best” in Sanskrit. It utilized 64 T-800 Inmos transputers in the first prototype, and in the second prototype the number of processors was increased to 256., It also included one Intel i860 floating point accelerator for every four transputers. The PARAM was benchmarked in Zurich at 5 Gigaflops and adjudged the second fastest in the world in 1991 (Interview 1, 2016). A photograph and architecture diagram of the PARAM are given in Figure 4.36.

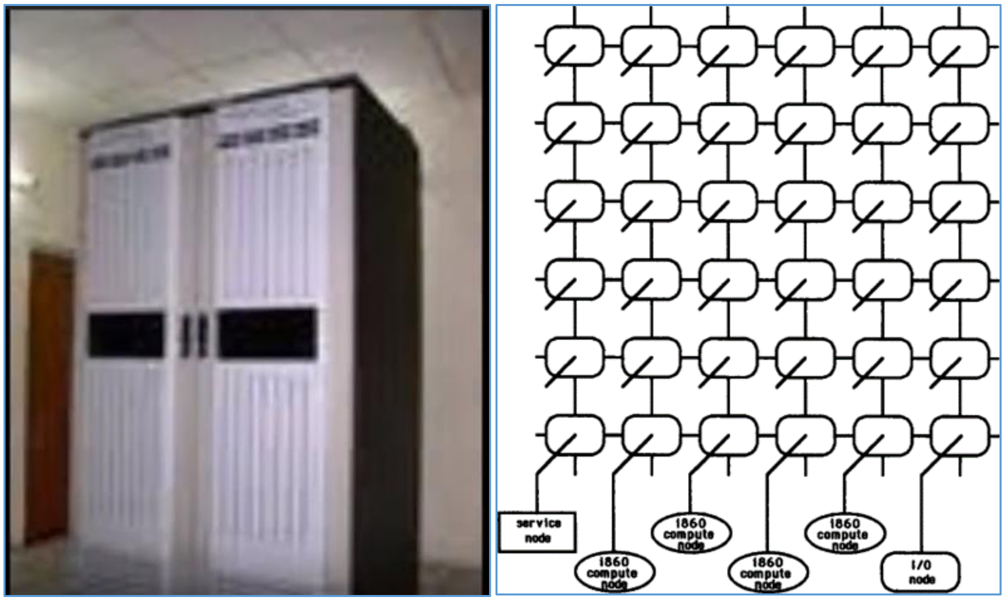


Figure 4.36 - PARAM – India's first supercomputer

By the mid-90s, as the pace of miniaturization accelerated according to Moore's law, transputers soon gave way to more powerful and versatile processors for floating point arithmetic and scientific work, such as the RISC processors from IBM and the SPARC from Sun Microsystems. Accordingly, C-DAC abandoned transputers as a technology in favour of newer and better options but retained the parallel processor approach which had become standard in the world by then. Over a period of twenty years, till the mid-2010s, C-DAC rolled out 13 variants of PARAM, the latest in 2016, the PARAM Ishan, being clocked at 300 teraflops. An earlier machine, the PARAM YUVA II launched in 2013, was the first Indian machine to exceed 500 teraflops (Interview 1, 2016) (Interview 3, August 2017). C-DAC continued the approach of using off the shelf processor chips from international vendors, but made no attempt to design and develop their own (Interview 8, 2017).

Although it may appear than C-DAC lags far behind the rest of the world, especially China, it should be observed that the 100 petaflop barrier was crossed internationally for the first time in 2004, and the 500 teraflop barrier exceeded in 2007. In comparison, the PARAM series crossed both barriers simultaneously with the PARAM YUVA II in 2013. Thus, the PARAM series can be assessed as having been generally 5-10 years behind the state of art in supercomputing over the past twenty years. In terms of user requirements, the PARAM series has been adjudged by testimonials as adequate for the jobs they were intended for. This illustrates another fact about supercomputing; that it is not the maximum speed available which is alone the true determinant of the impact of supercomputers, but also the extent and intensity of user applications (Interview 3, August 2017). As on date, 52 PARAMs have been installed, with 12 in overseas markets including Russia, Germany, Canada, Singapore, and Central Asian and South East Asian countries.

4.3.2.2 The Tata Eka supercomputer

Figure 4.37 - The Tata Eka

The Tata Eka was the first and only foray by the Indian private sector into supercomputing. The venture had its genesis in the attempt by the Indian government to convince Indian scientists and engineers of Indian origin resident overseas to return and work in India. In 2005, Dr Narendra Karmarkar, the noted Indian mathematician best known for his “Karmarkar algorithm” used for optimizing solutions to various classes of problems, agreed to return from the US. He proposed that he work on supercomputers, since his optimization algorithm could be used for evolving a superior design (Interview 5, 2017). Accordingly, he joined the Tata Institute of Fundamental Research in Mumbai and started work on a supercomputer design project, for which the initial funding came from Mr. NR Narayana Murthy, the then Chairman of Infosys Technologies Limited (Ramachandran, 2006). The Chairman of the TIFR Council at that time was Mr. Ratan Tata, the head of the Tata Group.

Dr Karmarkar asked for project funding of the order of Rs 400 crores, which TIFR concluded was beyond its capacity. According to TIFR, there was also not a sufficiently detailed project proposal. Dr Karmarkar therefore expressed his desire to resign from the project at TIFR. The Tata Group stepped in with an offer to complete the project in the private sector under the aegis of the Tata Group. A new company was set up for this purpose, called Computation Research Laboratories, to be headed by Dr Karmarkar and Dr Sherlekar of Tata Consultancy Services, who was earlier his undergraduate batchmate in IIT Bombay. The new company set as its objective the development of the world's first petaflop machine, based on Dr Karmarkar's proposal for an innovative approach (Interview 5, 2017) (Interview 6, 2017).

In June 2007, Dr Karmarkar resigned from the project, citing "differences over business model and commitment to delivery plan" (TNN, 2007). In addition, a proposal to acquire a Taiwanese component manufacturer had been mooted by Dr Karmarkar, which had been turned down by the Tata management oversight committee. Dr Karmarkar felt that such quick and bold steps were necessary to win the race to the first petaflop machine, while the Tata board felt there was inadequate business justification (Interview 5, 2017).

Despite the departure of its lead technology manager, CRL succeeded completing the project in November 2007. Although the 1 petaflop target was not reached, the Eka nevertheless clocked a speed of 117 Tflops, making it the fourth fastest supercomputer in the world at the time. The Tata group described the result as a "team effort", but nevertheless acknowledged the contribution of Dr Karmarkar particularly in optimizing the architecture (TNN, 2007). Dr Karmarkar described the optimization done on the architecture as based on "advanced projective geometry" (Interview 5, 2017).

The Eka has been subsequently upgraded to 14,352 cores using off the shelf Intel QuadCore Xeon processors. In 2011, the Eka was ranked #58 in the world with a speed of 172 teraflops.

Since then, Dr Karmarkar has claimed to have developed a completely radical architecture using quantum tunneling, which according to him can be implemented using available semiconductor fabrication technologies. His proposal has however not found any financial backers either in the public or private sector till date (Interview 5, 2017).

4.3.2.3 Differences in policy making from 1972 Electronics Commission to NPE 2012

The decision in 1972 by the Electronics Commission to prioritize software over hardware, which led to rejection of proposals for semiconductor design and manufacture in India, has been described as "the single decision that can be held largely accountable for India missing the microchip revolution of the 1980s; a revolution which propelled Hong Kong, Singapore, Taiwan, Korea, and later China, to leadership positions in the world" (Swaminathan, 2014).

Since substantial portions of the record from those days remains classified, it has not been possible to exhaustively research the deliberations that went into the decision. However, it is possible to conclude from field interviews with individuals who interacted with the Electronics Commission in 1972 that there was no wide-ranging process of consultation with other stakeholders in government, military or industry. The decision appears to have been taken based on discussions within the Electronics Commission alone (Interview 2, 2017). In retrospect, it can also be concluded that after the 1972 China conflict, the Indian armed forces developed a degree of mistrust of civilian decision-making competencies, including in technology, and negotiated a greater degree of autonomy and budgets for their technology procurements, a mistrust and pattern that persists to this day (Cohen & Dasgupta, 2010) (Sardeshpande, 2014). This may have had a bearing on the fateful Electronics Commission decision.

In contrast, the National Policy on Electronics, the NPE 2012, was preceded by reports from no less than four different committees with members drawn from different sectors of industry and government (MCIT/DEIT, 2012). These were the Ajai Choudhary Committee, headed by the eponymous Chairman of HCL Infosystems, the Sam Pitroda Committee headed by the then Chairman of the Knowledge Commission, the V Krishnamurthy Committee headed by the then Chairman of the National Competitiveness Council, and the consulting firm Frost and Sullivan (Swaminathan, 2014). All the four committees were broadly in agreement on the policies to be enacted to address the three major challenges facing Indian electronics; namely, one, to create a self-sustaining manufacturing base; two, to develop the electronics system design and manufacturing (ESDM) sector to globally competitive levels; and three, to acquire and sustain national expertise in research, development, and commercial-scale production of high technology products and services (Swaminathan, 2014). All these three challenges have been addressed in the NPE 2012 (Frost&Sullivan, 2014).

Notable in regard to the new policy is the degree of alignment of the various stakeholders that has been achieved (IBEF, 2009). This demonstrates that an Indian ecosystem in high technology electronics, which would include supercomputers, has started to form. It is particularly interesting that the defence establishment has also moved to align itself with new policy initiatives such as NPE 2012; a development that has been linked to the demonstrated success of the nuclear weapons program, the DRDO program, particularly the Agni series of ballistic missiles, the acclaimed success of the civilian space program of the Indian Space Research Organization, and perhaps most important, the downstream and upstream technologies in chip design and manufacture that have accrued from the Tejas light combat aircraft program (Swaminathan, 2014). The successes of the Tejas programme goes to support the contention that advanced projects contribute more than just another weapons system from a strategic perspective., It shows that the crucial domestic design and development capability is achieving maturity (Viswanathan, 2016).

4.3.2.4 National Supercomputing Mission 2015

The genesis of the NSM 2015 lay in discussions within the Planning Commission in 2010 on how to respond to the increasing success of China in the supercomputer sector during the first decade of the 2000s (Interview 4, 2016). This led to a meeting convened on December 13, 2010 by Prof. N. Balakrishnan of the Indian Institute of Science to discuss the strategy going forward. Twenty-eight scientists and engineers drawn from academia, government and the private sector participated in the meeting. This meeting was followed by several others, after which a report with recommendations was made to the Scientific Advisory Committee to the Prime Minister (Interview 1, 2016). The broad recommendations were (ET Bureau, 2011):

i. To initiate a national-level plan that would require an investment of 5-6000 crores
ii. The plan would operate in a national mission mode
iii. The duration of the mission would be five years
iv. The objective would be to install and network around 50-100 supercomputers on a national grid, on a scale never-before attempted

v. The grid would place unprecedented computing power in the hands of academia, government and industry
vi. Access to the widest possible user base would ensure commercial viability of the project
vii. Included in the project would be investments to develop home-grown supercomputers of varying speeds
viii. The private sector would be involved in a big way
ix. The project would be the largest ever undertaken outside the realms of defence, atomic energy and space.
x. To start with, development would use off the shelf chips, but over time, expertise in chip design would be built up

The announcement and launch of the mission took several more years, but finally in March 2015, the National Supercomputing Mission was announced by the Prime Minister's office (Cabinet Committee on Economic Affairs India, 2015). The Mission conforms broadly to the recommendations made earlier, and proposes the following:

i. Setting up a National Supercomputing Grid consisting of 73 supercomputers
ii. Linking this with the National Knowledge Network that is under implementation to network Indian research institutions
iii. An investment of Rs 4500 crores (approximately $ 700 million) for this purpose
iv. It would envisage designing and manufacturing supercomputers in India under the Make in India program of the government
v. The implementation agencies would be the Department of Science and Technology (DST), the Department of Electronics and Information Technology (DOEIT), and the Indian Institute of Science, Bangalore.

Since this is the first major government policy in India on supercomputers after the setting up of C-DAC, which was not really a policy but a project with an initially limited objective of developing a supercomputer that could substitute for the Cray YMP, it is not possible to develop a detailed comparison. But the following observations may be made:

i. The technology capabilities gap appears to be 5-10 years as compared to China. *It is therefore possible for India to "come from behind to catch up", even if only a limited extent*.
ii. Compared to the 202 machines that China has in the Top 500 list, India had only four in 2017. Therefore, *the installation base can be concluded to be the major gap and a greater problem to solve than the technology gap.*

iii. Within the 202, China has as many as 169 in in industry, whereas India has zero. The usage gap is even wider than the installation gap.

iv. The formulation of the NSM displayed the same broad-based approach as with the NPE 2012, showing that *a supercomputing ecosystem is beginning to form in India*.

In the light of the above, the NSM 2015 can be assessed as a mature approach by a maturing ecosystem, with priority given to expanding the utilization of supercomputer resources by scientific research and industry. The strategic and economic benefits of supercomputing usage on a wide scale, while attempting to catch up with the state of art in technology, and simultaneously limiting investment to reasonable levels, are sensible objectives for India to set herself as she resumes the path to competitive supercomputing.

4.3.3 Installed base

The installed base of supercomputers in India is rather small. As noted in the section above about the PARAM series, the number of PARAMs installed in India was approximately 40. The Top 500 list for India adds another 10 approximately, including the latest acquisitions. Use of HPC-class servers on a restricted basis in large corporate organizations in the telecom, ecommerce, automotive, pharmaceutical and energy sectors is likely, but there are no specific statistics available. Even an optimistic estimate, however, would place the total number of HPC systems, including sub-Top 500 class, at less than 100.

4.3.4 Ecosystem for supercomputer research, technology transfer and knowledge utilization

To address this topic, we will divide the history of supercomputing in India into three periods; pre-1988, 1988-2008, and finally 2008- the present.

In the pre-1988 period, the ecosystem could be described as non-existent, since the term supercomputer was only one entry in the list of computers that were eligible for import. In other words, it was left to a user organization to decide completely on its own if a supercomputer was required; and then build up the justifications that would enable the organization to navigate its proposal through the labyrinthine pathways of the licensing and financing procedures of the government.

In 1988, following the US ban on the export of a Cray YMP, and the realization that supercomputers could form an important strategic resource, an ecosystem took shape in the form of one organization, namely C-DAC. C-DAC combined research, development, manufacture, marketing, and customer support within itself. The form of ecosystem in the 1988-2008 period can be described as a singular ecosystem, with some linkages to the bureaucracy as the only other stakeholder in play. Academia, other research institutions, and companies in the public and private sectors remained in the role of customers. There was little or no collaboration with potential competition, as the case of the Tata Eka showed.

It is in the post-2008 period that the outlines of a national ecosystem can be discerned, although it is still in the process of evolving. The process of consultation that led to the NPE 2012 and the NSM 2015 brought all the major stakeholders into at least policy alignment, although how collaboration among them in terms of results cannot yet be evaluated. We may represent this evolving country ecosystem in the following diagram, with the dotted lines indicating evolution still in progress:

Figure 4.38 - The Indian HPC ecosystem

It is reiterated again that multiple capability points for development of supercomputers existed in India, namely, C-DAC, NAL, DAE, DRDO, ISRO, the private sector like Tatas, as well as academic institutions such as IISc and the IITs. However, no cohesive strategy evolved to combine these capabilities in some way and establish a manufacturing base.

4.3.5 Investment in supercomputing

With the low installed base, as detailed above, India's investment in supercomputing has been very low. It is in NSM 2015 that there is substantial investment for the first time, which has been budgeted at Rs 4500 crores or $ 700 million. Even if the private sector chips in substantially to invest in supercomputing products and services, it is difficult to see how this investment can exceed $ 1 billion by 2020.

4.3.6 Applications of supercomputing

Due to the absence of investment from industry in supercomputing, except perhaps in unrecorded sporadic cases, applications of supercomputing have remained within the academic, research and classified domains. While no information on classified applications is available, by definition, we may assume these include two of the classic trinity; namely, nuclear weapons design and cryptography.

C-DAC lists the following as applications of the PARAM range:

- Computational Atmospheric Science
- Computational Fluid Dynamics
- Computational Biology
- Computational Structural Mechanics
- Bioinformatics
- Computer aided engineering
- Seismic data processing

There has been no attempt by any organization or persons in India to compete for the Gordon Bell awards.

4.3.7 Announced plans for the next decade

Beyond the NSM 2015, there have been no announced plans for the next decade, or till 2030, as other countries have done.

4.3.8 Analysis of strategy followed

We may usefully look at strategies followed in terms of the same three time frames as were defined above for the analysis of the ecosystem; namely pre-1988, 1988-2008, and post-2008.

In the pre-1988 period, there was no recognition in policy statements of supercomputers as anything other than a special class of computers. This period was therefore characterized by an absence of strategy for supercomputing. Coupled with the decision of the Electronics Commission in 1972 to de-emphasize hardware manufacture in favour of software, one inference which may be drawn was that there was no recognition or acceptance of technology, and specifically high-performance computing, as a strategic resource to be developed and grown indigenously. In this respect, the strategy treated HPC as a means to a strategic end, specifically for advanced weapons design, including nuclear weapons, and aerospace, rather than as an end in itself.

In the 1988-2008 period, there was greater recognition of the strategic role of technology. It should however be noted that this recognition was a reaction to the American embargo, rather than a realization arrived at within the Indian strategic ecosystem. The perspective with which HPC was viewed clearly suggests such an approach. The initial objective set for C-DAC was to develop one supercomputer as an alternative to the Cray YMP that had been embargoed. Once that objective had been attained, although there were statements to the effect that India should develop HPC capability, the record shows that there was no further policy or strategic interest in the sector. There was no realization that this could be the first step to developing useful strategy alternatives at a national level (Anderson, 2010). It was left to C-DAC to define their own strategies and priorities and try and win support and funding for their plans.

Before we move on to the analysis of the post-2008 period, it is important to note a consistent thread that ran through Indian policy making from 1960 to 2000 that even stretched to a few years beyond 2000. This was that *in order to solve a problem or address an objective, a specific organization should be set up and assigned the task.* Thus, ECIL was assigned the task of developing and manufacturing computers during the 1970s. Similarly, C-DAC was set up to develop a supercomputer. Nowhere in this approach was there any recognition of the benefits of competition. This researcher proposes to term this approach as “***Indian monopoly socialism”***.

In the post-2008, the strategies outlined for supercomputing in India show increasing sophistication as the ecosystem evolved. There is first the involvement of all stakeholders in the policy making process. Second, the involvement of both the public and private sectors suggest that there is some recognition of the benefits of competition. the entry of the Tata Group and the Tata Eka revived the moribund PARAM program. Although it is too early to reach any definitive conclusions, the new strategy seems to reflect the American way of doing things. It appears that there will be a division of roles between policy and core infrastructure for the government and implementation for a predominantly private industry. We may term such an approach as “***competitive capitalism”.***

In the entire history of Indian supercomputing, what stands out is the lack of clear objectives for the sector. What, exactly, is the sector supposed to achieve? Is it supposed to equal China in all respects, or only in some, and if so, how specifically? If China is not a benchmark, are there any other metrics by which the performance of the sector can be measured? Behind all this, there is the fundamental question which Indian policy makers continue to avoid: Are science and technology by themselves seen as national capabilities, and strategic resources for India; or are they only the outcomes of the applications of science and technology to address specific capabilities such as strategic weapons and therefore need not be treated specially (Chandrasekhar & Basvarajappa, 2001).

4.3.9 Innovation Patterns

We may analyze innovation patterns in Indian supercomputing at both the ecosystem and technology levels. At the ecosystem level, we can immediately conclude that in the pre-2008 period there was no innovation at all since there was virtually no policy. Even after 2008, the NSM can be termed at best an approach that supported incremental innovation in the priority given to building basic supercomputing architecture.

At the technology level, however, the picture is different. From the perspective of technological innovation, it is noteworthy that Indian scientists and engineers were able to evolve two examples of innovation, one radical and the other modular. We may analyze them as follows:

We can apply the Henderson taxonomy to determine if the PARAM represented an innovation, and if so of what type. Clearly, the use of transputers to construct the processing unit of the PARAM supercomputer can be characterized as both a modular and an architectural innovation, as compared to what was conventional in computing in the 1980s. Furthermore, since this was the first major parallel processing implementation in a supercomputer that recorded significant performance – successfully ranking at #2 worldwide in 1991 – we may ***characterize the PARAM as a radical innovation***.

The Eka architecture was based on the use of 1800 standard Intel microprocessors, using an innovative near circular layout as compared to more conventional parallel linear aisle configuration. Thus, the CRL team was able to build a machine that required less area and therefore lower interconnection lengths over an Intel Infiniband network. In addition, the Eka was the first machine in the world to use optical fibre cables to interconnect the servers and processors (Raj, 2012). Based on this analysis, and applying the Henderson taxonomy, we may ***characterize the Eka as a successful modular innovation***, based on its ranking at #4 in the world.

In the light of the above, the willingness of Indian scientists and engineers to "think out of the box", as it were, is in surprising contrast to the innate caution and conservatism observed in Indian policy making. That the country was not able to effectively leverage these strengths is evidence of significant shortcomings in the ecosystem, which are only recently being addressed.

4.3.10 Knowledge processes in the Indian supercomputer sector

As with the analysis of supercomputing in China, we will analyse knowledge processes at two levels – the ecosystem and the technological. Again, as in the section on China, we shall attempt to answer the following questions: How has India used knowledge to formulate and achieve their goals in the supercomputer sector? How has knowledge contributed to innovation in the supercomputer sector in India? What patterns and processes can be inferred in this context?

At the ecosystem level, we will again look at these questions in the framework of two time-periods; the first pre-2000 and the second post-2000. In the pre-2000 period, it is necessary to note first that till the late 90s, there was no significant technological success that had been achieved in any strategic technology area, excepting the civilian space program under ISRO. Thus, in the 1970s for example, there was no available network of individuals with any credible record of success in the strategic arena. It should be recalled in this context that the Indian nuclear weapons program was kept under wraps till 1998. There was therefore no proven knowledge of management of large strategic projects. In the absence of such credible knowledge, policy makers took ad hoc decisions on many occasions. In term of process, we should also observe that there was no systematic attempt to acquire, select and absorb knowledge at the ecosystem level, through joint programs with other countries to determine how other countries were doing and evolving the best way forward. The ecosystem knowledge base remained underdeveloped. In consequence, there was little or no new knowledge generation and dissemination at the ecosystem level. This was exacerbated by the lack of competition under the Indian monopoly socialism strategic approach.

In the post-2000 period, the situation had changed radically. By 2008, in the space of a single decade, a track record had been established of successful large strategic projects – in the defence sector, the nuclear weapons program, the missile program, the Tejas program, and several other large DRDO projects such as the Arjun battle tank, and so on. In the space sector, ISRO had proven itself repeatedly as comparable to the state of art anywhere in the world. In software, the Indian private sector had proved itself capable of competing effectively on a global stage in business terms through building and managing huge organizations. All these contributed to the changed perceptions that have informed policy making which has become increasingly sophisticated since then. In process terms, much more knowledge has been searched for, acquired, selected and absorbed than before; and as an outcome, new knowledge in the form of new policies has been generated and disseminated. At the ecosystem level in India, therefore, we may note *the same five processes that had been inferred in the Chinese case – search, selection, absorption, generation and dissemination*.

We now focus in particular, on the *selection process*, as in the analysis of the Chinese situation. As there, the criteria for selection or rejection will be a function of the objectives which have been set. Unlike in the case of China however, where the drive is to equal and if possible, overtake the US, the objectives in India are relatively vague. Therefore, the main selection criteria would appear to be *"adequacy value"*. The question seems to revolve around the issue as to whether a technology or a strategy is adequate to accomplish the task, rather than whether the technology or strategy is on par with the best in the world.:

Turning now to the technology level, we may observe that the situation is quite different. The evidence of innovation in the PARAM and Eka supercomputers show clearly that the technological objectives which the development team set for itself was to be the best, in both cases. To an extent, these objectives were achieved. Therefore, the knowledge processes which would have been at work were:

- a comprehensive *search* for knowledge defining the state of art;
- knowledge *selection* with criteria to isolate the best or most promising,
- *absorption* of the knowledge needed by the team;
- *generation* of new knowledge to meet the stated objectives;
- finally, the *dissemination* of the newly generated knowledge in preparation for the next stage of development.

The difference between the ecosystem pattern, where adequacy is the primary objective used as a selection criterion, and the technological pattern, where *competitive performance* is the primary objective and selection criterion, yields interesting insights into what has happened in the past in the Indian supercomputer sector. The adequacy objective, especially in the early days with minimum or zero competitive objectives at the sector level, has had the effect of slowly strangling initiatives that aim at radical or modular technological innovation, through lack of administrative and financial support or simple neglect. Both the PARAM and Eka experiences provide evidence of this. Second, the persistence of the adequacy pattern at the ecosystem level in NSM 2015 has had the effect of excluding, at the very beginning itself, initiatives for possible radical innovation in the future, as the fate of Dr Karmarkar's proposal shows. To put it recursively, adequacy may be adequate in the short term, but it is not optimal in the long.

4.4 Analysis and inferences

In this section, we will focus on summarizing the important findings in the foregoing, and then focus specifically on some aspects of the knowledge processes that could be observed in operation in the Chinese and Indian supercomputer sectors.

The history of supercomputing shows that it has been accepted as a sector of strategic importance by all major countries. Consequently, the growth of the sector has been driven by government initiatives in every case. By its very nature, supercomputing lends itself to continuous innovation across the entire Henderson innovation matrix, i.e. every new development throws up further opportunities for radical, modular, architectural and incremental innovation. This has led to successive technology S-curves, which have spawned three eras in supercomputing, with the fourth, the exascale era, around the corner. In fifty years, the industry has grown to $ 30 billion in revenue, with the US accounting for nearly half. China is growing at the fastest rate but still only has a 10% market share.

From the application perspective, supercomputing was originally utilized for what has come to be called the "classic trinity" of nuclear weapons design, cryptography, and climate studies. In fifty years, the number of applications has morphed into the thousands, despite the complex mathematics at the heart of every application. The number of applications is accelerating with the availability of so-called "big data" and the quickening rate of developments in the artificial intelligence space. All this has put tremendous pressure on governments to define policies, allocate resources, and build capacities for the medium and long term, and the response has been commensurate in all countries, including India, where the National Supercomputing Mission was launched in 2015.

Supercomputing has spawned an additional special node in the ecosystem that provides industry research reports. The Top500 organization, which works on a non-profit basis, benchmarks and ranks by performance the top 500 supercomputers globally. In 2017, China was the clear leader, occupying the top spot in terms of both speeds, at 93 petaflops, and the number of installations in the top 500, at 202.

China recognized very early the importance of technology as a strategic asset and instituted its famous 863 programs to develop capabilities in a wide range of technologies. In supercomputing, China set itself the clear goal of first equaling and then overtaking the US. This has resulted in technological innovation across the spectrum taking place in China since the 1990s.Technologically, China appears to have pulled even with the US., However in terms of market size, still lags the US by a factor of five. China hopes to become the global leader by 2030 through investing $ 60 billion in artificial intelligence-based technologies.

In contrast to China, India has followed a more erratic path, which has only recently started to acquire definite direction. Despite this Indian engineers and scientists have shown an impressive willingness to attempt radical and modular innovations. The present Indian strategy appears to be less to compete and more to reach a certain critical mass, which has been dimensioned in the National Supercomputing Mission 2015 as a nationwide network of 70 high-speed supercomputers. For this effort India has allocated a budget of Rs 4500 crores or $700 million.

Our analysis shows that it is possible to identify two models. The first model is of innovation as a knowledge process which results in new knowledge based on first, the knowledge of a problem or opportunity, and then the generation of new knowledge based on the outcomes of other innovations and knowledge of concepts and technologies available for utilization in solutions. The second is of innovation as a process that consists of five knowledge processes, namely, search for knowledge, selection of acquired knowledge based on specific parameters, absorption of this selected knowledge into the system, generation of new knowledge based on the available knowledge base, and finally the dissemination of the newly generated knowledge. Both models are informed by the strategies adopted in their sectoral or organizational environments. These models allow us to compare Chinese and Indian supercomputing from the perspective of knowledge processes.

In the case of China, since achieving parity with the US and then overtaking it are the superordinate objectives of their strategy, the knowledge processes operate in consonance with the strategy. Therefore, the problem is identified as the development of the fastest supercomputer by China. Consequently, the choice of technologies to be used for solving the problem are the latest available and ideally developed indigenously by China. The objectives of any fresh innovation would be to exceed the outcomes of previous innovations in the field., This would require a careful scrutiny of the outcomes data set to ensure that the right knowledge is available. In terms of the five knowledge processes identified, the selection process criteria would be competitive value and innovation value., The search, absorption, generation and dissemination processes would also operate in such a way as to complement the selection criteria. We can say that the Chinese emphasis on competitive value and innovation value of knowledge implies that they use a ***ranking-based methodology*** for selection of knowledge items. At the ecosystem level, this also ensures that enough investment and administrative support is made available for the objectives to be met.

The Indian strategy, in contrast, appears to achieve a critical mass of 70 supercomputers in a national network, and thus can be described as the aspiration to reach a minimum level rather than the top level. In terms of knowledge processes, this implies that India uses a ***percentile-based methodology*** for selection rather than a ranking-based methodology for selection. This percentile-based, satisficing approach directly affects both the innovation and knowledge process models. Thus, the identified problem is how to develop a machine that meets minimum rather than maximum performance objectives. This would affect the choice of technologies to be selected as well as the previous outcomes against which the innovation is judged.

The advantages of a ranking-based methodology are there for all to see in the performance of the Chinese supercomputing sector. The advantage of a percentile-based methodology, on the other hand, is principally that it results in much lower levels of investment i.e. adequate bang from very little buck. The disadvantage of percentile-based strategies is that the bar can get driven quite low, to the extent of stifling or shutting out possible radical innovations, and more seriously, affecting the quality of capabilities that are built up. These may have serious strategic consequences later.

To expand on this, the adoption of a percentile-based methodology means that India is willing to make to do with a lower standard of manpower than China,., To give a micro-level example of how this affects knowledge processes, this means that available management know-how on the issues and solutions to managing the maverick "mad scientists", who are often found in cutting-edge R&D departments, is simply not searched for or absorbed, as both the C-DAC and Tata Eka instances illustrate.

More seriously, the Indian NSM 2015, though impressive at first glance, does not seem to factor in the huge disparity in investment levels – China's $50 billion against

India's $1 billion. When the investment ratio is 50:1, and when it is public knowledge that China intends to invest at least another $ 60 billion by 2030, India needs to find ways to catalyze the radical and modular innovations that her scientists and engineers have shown they are capable of. Unfortunately, the percentile-based approaches operating at the ecosystem level work in the opposite direction.

4.5 Discussion

This chapter represents the first formal research output of this thesis. Drawing upon the research design for this thesis, the chapter investigates the research sample and field using the case study method. That investigation has been documented as a comprehensive case study of supercomputing in this chapter. As required by the research design, the broader case study of supercomputing is structured in three parts, comprising the global supercomputer sector, the supercomputer sector in China, and the supercomputer sector in India. It also encompasses within it, as required by the research design, several shorter cases which provide data for the investigation of knowledge processes as related to innovation.

To assess the quality of this case study, the criteria set out in the research design can now be applied. The quality criteria listed were *credibility, transferability, dependability, and confirmability.* The credibility of this chapter's content is established by noting the reliance on both explicit quantitative data, such as records of performance in terms of speed, and explicit qualitative data, such as citations, quotations from available documents, and interviewee statements. This researcher has taken care to record interviewee statements in neutral "reportage" processed from the raw interview notes, rather than repetition of original sentences and phrases. Transferability has been established by structuring the chapter such that it could be used as a template for investigation of the supercomputer sector in other countries. Dependability has been ensured by the extensive use of explicit knowledge in the form of citations to books, articles and other records, both independently in the chapter and as supporting evidence for interviewee statements. Confirmability has been established by reliance on the written record and processed interviewee statements; at no point do the researcher's opinions intervene.

In terms of advancing the thesis objectives of answering the Main and Subsidiary Research Questions, this chapter has successfully invalidated the null hypothesis, thus clearing the way for an in-depth investigation of knowledge processes as related to innovation in the Chinese and Indian contexts. A conceptual framework of knowledge processes has emerged, based on inductive reasoning from the data in the chapter. In the next chapter, this conceptual framework will be applied to data relating to the Information Technology software field, to test whether the framework is valid in that context also; thus setting up the basis for generalization of the framework, and for refining and expanding the inferences relating to innovation that can be drawn from its application.

Chapter 5

Innovation in the Information Technology software sector in China and India

Unlike the supercomputer sector, which has historically been driven by government requirements in most countries, including China and India, and which typically focuses first on the strategic aspects and then on the commercial, the Information Technology (IT) software sector has had a different provenance and follows a different paradigm. By common understanding, the IT software sector has historically been market-driven and therefore characterized by a global outlook from its very inception. The differences in environment provide a good context in which to investigate whether the conceptual model of knowledge processes as related to innovation, as derived in the previous chapter on supercomputers, would apply to the IT software sector as well.

5.1 The context – the global software industry

The term "information technology" was first coined by Leavitt and Whisler in a prescient Harvard Business Review article in 1958 (Leavitt & Whisler, 1958). According to the authors, the new, emerging, "information technology' had three distinctive attributes. One, it used digital computers to perform high speed calculations on large masses of data. Two, it applied mathematical and logical techniques to "program" solutions for decision-making problems. Three, it would, in the future, facilitate the simulation of higher order thinking through computer programs. Sixty years later, in the 21st century, with computing devices ubiquitous in all areas of life and with the spread of Artificial Intelligence-based applications, it is apparent that all three of the authors' predictions have come to fruition.

In contemporary parlance, the term "information technology' has become shortened to the acronym IT, and more recently, to the single word "tech". Information Technology is generally accepted as comprising hardware, or the electronics performing the computing task; software, or the programs written to direct the hardware; and applications, the domain of problems to which IT is sought to be applied for solutions. The distinction between software and applications is drawn to distinguish between general purpose programs that provide a common user interface for developing solutions to problems, usually referred to as systems software; and programs that assist in the solution to specific problems, usually referred to as application software. In the common understanding, therefore, the IT industry is understood as products and services that comprise either hardware, software, or applications; or products and services that combine all three in some purposive way.

These distinctions in terminology have acquired importance principally because of the gargantuan size of the IT industry. Within this general description, each of the three components has acquired independent status as industries; there is thus a hardware industry, a software industry and an applications industry, all global in spread (Campbell-Kelly, 2004). In 2016, the global IT industry was estimated at $2.5 trillion; of this, the global hardware industry was estimated at $900 billion and the global IT software and services industries at $ 1.6 trillion (Standard & Poors, 2017). Within this global spread, different countries have emerged as specializing in different sectors of the industry. For example, Taiwan and South Korea have specialized in semiconductor manufacturing, while India has emerged as a global hub for software.

It is common knowledge, and the common understanding, that innovation has been the hallmark of the IT industry. This fact automatically provides a larger context for the research in this thesis. Within this larger context, the IT software industry has also been characterized by continuous innovation since the 1950s. The industry data shows that both India and China have enjoyed considerable success in this sector since the 1980s. The IT software sector therefore provides a compelling field for research into innovation in these two countries.

In keeping with the overall objective of this thesis, the following sections will therefore focus on the nature, patterns and issues involved with innovation in the IT industry space, with a focus on software, starting with an overview of the history of the industry. This chapter on innovation in the IT software sector will be divided into the same four major sections as in the chapter on supercomputers i.e. an overview of the global industry, the IT sector in India, the IT sector in China, an analysis of knowledge processes as related to innovation in this industry, and ending with a discussion that summarizes the chapter and leads into the next. As in the previous chapter, one case study of a major, large scale success will be included.

5.1.1 History of software and the software industry

As with much in the IT industry, as is now the common understanding, the concept of a computer program was itself a radical innovation in the Henderson taxonomy, since it represented a completely new way of solving problems. In the early days of computing, programming was simply one of the many new activities that were needed for the solution of a problem. Over the decades, the landscape of programming has expanded to such a vast extent in scope and depth that it is now recognized as a new science, namely computer science. The application of the principles of computer science to problem solving has resulted in an immense body of computer programs, collectively referred to as software.

The term "software" was first used with specific reference to computing in 1958 by the mathematician John W Tukey (Tukey, 1958), when he wrote:

> "Today the 'software' comprising the carefully planned interpretive routines, compilers, and other aspects of automative programming are at least as important to the modern electronic calculator as its 'hardware' of tubes, transistors, wires, tapes and the like".

Listed in this description are two examples of innovation that had already taken place in software, namely, "interpretive routines" (commonly called interpreters today), and "compilers", both of which are programs that first enable writing programs using alphabets and numerals found in natural languages, and then convert them into machine-executable electronic signals. We may therefore date the origin of software as a separate domain of activity, and with it, its origin as a separate industry, to approximately the mid-1950s. The industry has grown enormously since then and is now over $900 billion in revenues globally (OECD, 2006) (OECD, 2017). To this should be added the global industry for IT services, which developed contemporaneously with programming, and which is in the same category of size measured by global revenues (Campbell-Kelly, 1995).

The defining characteristic of software programming, till recently, was that it was purely a labour-intensive activity, although dependent on innovations in hardware to trigger fresh thinking. Labour was the only major resource required, albeit of a highly skilled variety. The availability of this skilled labour in different parts of the world has thus influenced the emergence of clusters where the software industry has become concentrated. Labour as the major resource determined the evolution of software into a separate industry. Originally an intrinsic part of a computer system, the similarities between software programs running on different computer systems led to an exploration of the potential for "portability" of computer programs from one hardware to another. Such portability had obvious benefits in terms of cost and scale.

From the perspective of innovation, the sixty-year technological history of the global software industry can be divided into six eras of approximately a decade each:

i. 1960-1970: Software as programs proprietary to a computer, not separate from hardware
ii. 1970-1980: Software as program products and services portable across specific computer hardware
iii. 1980-1990: Software as products and services in an independent sector within the Information Technology industry.1990-2000: Software as a component of networked IT solutions at the enterprise and local network level
iv. 2000-2010: Software as a component of globally available Internet-based IT solutions, products and services
v. 2010 –: Software as an intelligent Internet-based resource available to individuals and enterprises.

1950-1970:

During this first era, software was treated as an indivisible part of a computer system and thus had no separate business identity of its own. Based on a rule of thumb of the cost of software as 15% of the total cost of a computer system (Campbell-Kelly, 1995), the revenue growth of the software "industry" during this period is shown in Figure 5.1. Nevertheless, this era witnessed the setting up of the first few companies devoted to software development and services alone. The first such "software company" is generally agreed to be Systems Development Corporation, which was set up in 1956. Computer Sciences Corporation (CSC) came into existence in 1959 and still exists today as global major. In India, Tata Consultancy Services was set up in 1968, the pioneer and still the largest company in the Indian IT industry.

Year	Total Computer Sales	Software 15%
1950	214	32.1
1956	743	111.45
1960	1500	225
1965	3000	450
1970	7196	1079.4

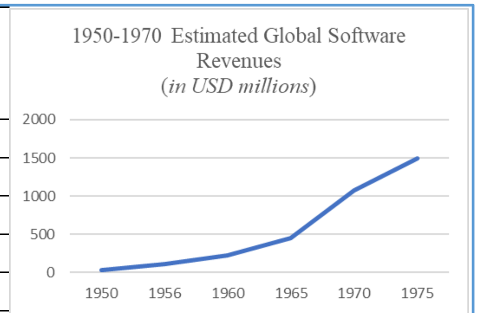


Figure 5.1 – Growth in the software industry 1950-1970

Many of the most important and fundamental instances of innovation in the software industry made their appearance during the early days of computing. Examples are the introduction of assemblers, interpreters and compilers which made possible the so-called high-level programming languages such as FORTRAN, COBOL and Algol, enabling programmers to write code in a manner analogous to natural languages and thus achieve much higher levels of productivity. Possibly the most important innovation event of this era was the development of an "operating system" for the first time on the IBM System 360 series of computers, offering a comprehensive user interface for all computer operations, and which has remained the conceptual model for all subsequent operating systems such as UNIX, Linux, Apple iOS, MS-DOS, Windows, and so on.

1970-1979:

In 1969, IBM announced the "unbundling" of software, meaning that customers could now buy software products and services independent of the hardware. This decision, described as "the crucial inflexion point in the development of the software products industry" (Yates, 1995), is generally accepted as signifying the birth of the software industry. This immediately led to the emergence of many companies specializing in IBM-related software alone. This is reflected in the rapid growth of the industry during this decade.

Concomitant with the growth of the "mainframe software" industry, the burgeoning minicomputer industry witnessed the most significant software technological innovations since the 1950s. These were the development of the 'C' language and the UNIX operating system. The 'C' language was intended as a general-purpose language, suitable for all applications, that could be compiled and run on any computer. It therefore provided true portability of software programs for the first time. Since UNIX itself was written in C, marking the first time that an operating system was written in a machine-independent language, UNIX itself became the first truly portable operating system. UNIX can be termed a revolutionary innovation, truly radical in the Henderson taxonomy. UNIX and C enabled the software industry to develop completely free of dependence on any hardware manufacturer. Figure 5.2 shows the growth of the industry during this period

Year	Revenue
1970	2.5
1971	3
1972	3.6
1973	4.3
1974	5.1
1975	6.5
1976	7.7
1977	10
1978	12
1979	15

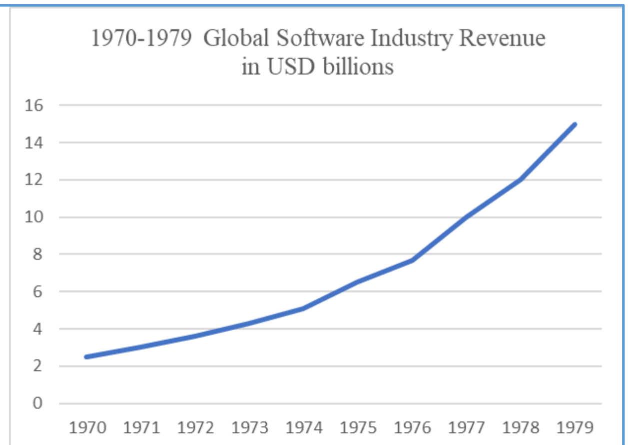


Figure 5.2 – Global software revenue 1970-1979

1980-1989:

This decade saw the industry assume the form with which the world is familiar today, namely, a large global agglomeration of companies of all sizes from small to giant, serving all possible sectors of IT usage, from government and industry to education, the home and the individuals of all ages. This became possible mainly because of the introduction of the personal computer first by Apple and then by IBM. The PC made possible the availability of computing power on an individual's desktop, with software catering to an individual's specific needs that could be purchased or licensed as and when required. At the enterprise level, this decade also witnessed the rise of companies such as Oracle and SAP, who today dominate the enterprise software market.

It is during this decade that we can say the Information Technology industry became the driver of the world economy, both in terms of the its own business potential and its impact on the economic productivity of all other sectors. In India, the software sector started to take shape with a host of companies working in software services as well as products coming into existence.

Figure 5.3 shows the growth of the global software industry during this period. Towards the end of the decade, a new paradigm emerged in computer programming, called object-oriented programming, which made possible for the first time the reusability of individual software modules, leading again to a quantum jump in programming productivity.

Year	Revenue
1980	18
1981	21
1982	23.5
1983	28.2
1984	35.25
1985	40.7
1986	45
1987	53.85
1988	68.05
1989	70

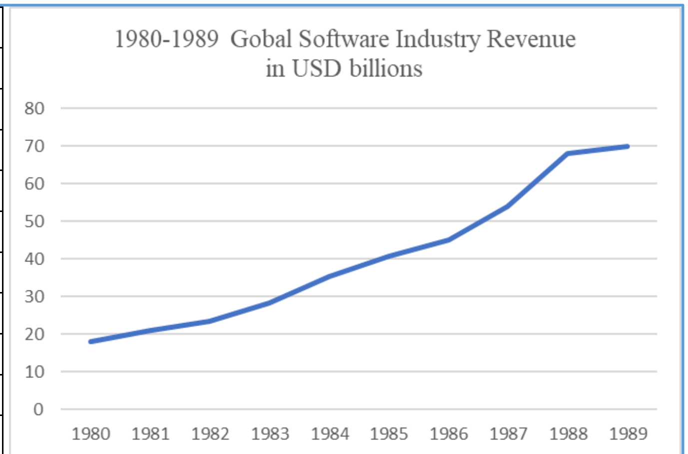


Figure 5.3 - Growth in software industry 1980-1989

1990-1999:

During the 80s, telecom equipment was increasingly embedded with microprocessors, memories, disks and other computing equipment, including of course software. With the PC increasingly ubiquitous in enterprises and homes, it was a logical step forward to try and network all these different machines. The term "convergence of computer and communications technologies" first began to be heard around the start of the decade of the 90s, leading to the concept of the "information superhighway" (Resnick, 1994), which was quickly superseded by the Internet (Leiner, et al., 1997). Nevertheless, the 90s saw enterprises achieve networking through high speed corporate Local Area Networks(LANs) and Wide Area Networks (WANs), with communications across geographies enabled by satellite-based telecommunications. Figure 5.4 shows the growth of the industry in perhaps its most explosive phase.

In this process, individuals too became increasingly interlinked through networks. Such was the impact that by the mid-1990s, the Internet and the World Wide Web had come into existence. This grand fusion of computing and communications has transformed the world beyond the imaginations of the 20th century. ***The Internet is beyond question the greatest innovation of the IT industry***.

Year	Revenue
1990	75
1991	80
1992	87
1993	96
1994	107
1995	120
1996	132
1997	145
1998	160
1999	175

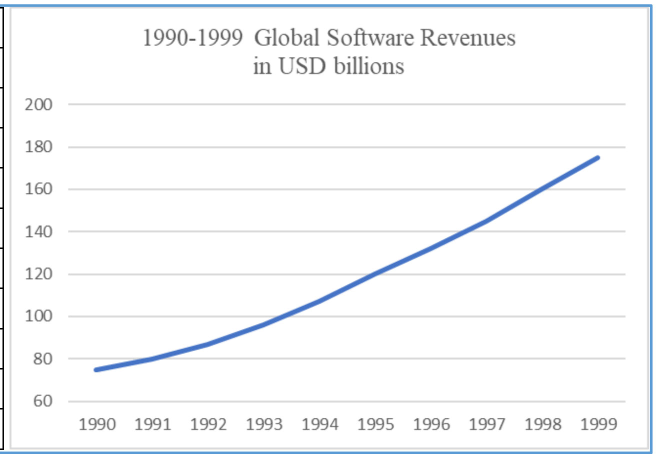


Figure 5.4 - Growth in software industry 1990-1999

2000-2009

The so-called "dotcom boom" of 2000 and its rapid meltdown in 2001 acted as a correction to the overheated growth of the IT industry globally. Companies with the capacity to innovate in emerging market niches and with robust business models were able to pull ahead and increasingly define the industry. During this decade, innovation in the software industry was driven almost entirely by Silicon Valley, and by 2010 Google, Amazon, Facebook and many other similar companies had reconfigured the industry in just 10 years. Figure 5.5 depicts the industry performance during this phase, with a correction during the 2008 global financial crisis.

Year	Revenue
2000	180
2001	175
2002	175
2003	195
2004	210
2005	220
2006	275
2007	330
2008	385
2009	370

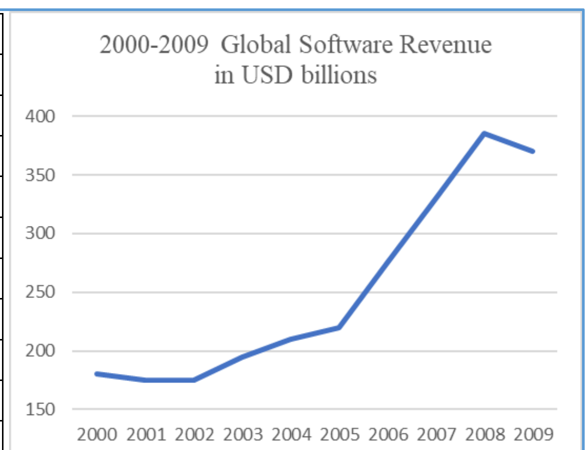


Figure 5.6: Global software industry revenues 2000-2010

The distinction between personal and enterprise computing started to blur during this decade (Castells, 2014). The growth of the industry continued to be fueled by innovation. All software became oriented to the Internet. Enterprise IT transformed from report generation to real time business process management across geographical boundaries. Personal computing, which earlier consisted essentially of word processing, spreadsheets and PowerPoint presentations, became centred around collaborative communications over the Internet. The decade once again saw the dominance of Silicon Valley in IT innovation, with the venture capital industry continuing to grow.

2010-2018

The second decade of the 21st century has seen Leavitt and Whisler's 1958 prediction come finally to pass, with the increased application of Artificial Intelligence (AI) and machine learning concepts to software and IT in general. *More remarkable, however, is the gradual fading out of the use of the word "computer" in everyday discourse.* One cause of this has been the growth of mobile computing, , enabling handheld devices that can be operated by laymen with many orders of magnitude higher processing power than the IBM System/360s that were used by NASA to send astronauts to the moon. *Thus, the word "device", which can connote everything from a phone to laptop to a deskside PC, has entered general usage*. This in turn had led to the term Internet of Things or IoTs, denoting the linking to the Internet of not just human beings using computing devices, but entire systems of machinery with built-in AI capabilities; the best-known example of these being the so-called autonomous self-driving automobile. Figure 5.6 shows the growth of the global industry during this period:

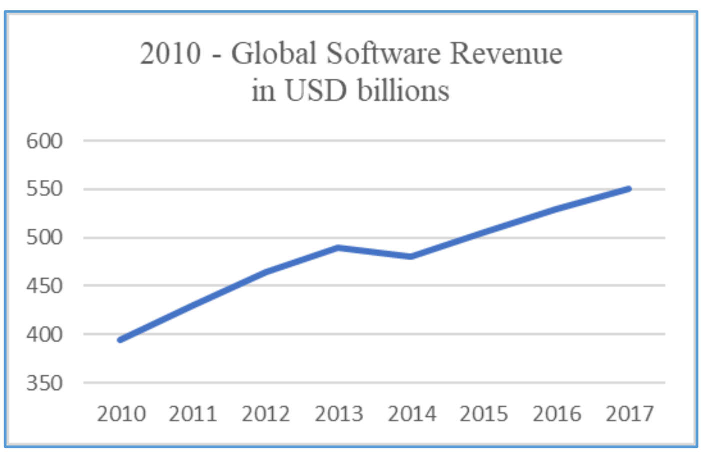


Figure 5.6 - Global Software Industry Revenues 2010-2017

5.1.2 The technologies of software

The software industry has been widely researched over the years. A number of taxonomies have been developed to describe the industry and its technologies. Of these, this researcher has selected two for the purpose of this thesis. These are:

1. *The Global Industry Classification Standard (GICS)* published by Morgan Stanley Capital International (MSCI). In the GICS list, software is classified into two categories – application software and systems software - as shown in Figure 5.7 (MSCI, 2018).

4510130	**Software**	**45103010**	**Application Software**
			Companies engaged in developing and producing software designed for specialized applictions in the business and consumer markets. Includes enterprise and technical software, as well as cloud based software.Excludes companies classified in the Interactive Home Entertainment Sub-Industry. Also excludes companies developing and producing systems or database managment software classified in the Systems Software Sub-Industry
		45103020	**Systems Software**
			Companies engaged in developing and producing systems software and database management software.

Figure 5.7 – GICS classification of software

2. The expanded *Association for Computing Machinery (ACM) taxonomy* developed by Lethbridge and Forward, which categorizes software into 154 distinct types expanded from different categories (Lethbridge & Forward, 2008). The authors condense these at a higher level as shown in Figure 5.8. Even at this higher level of categorization, this taxonomy yields 21 different categories of software. Using the Henderson taxonomy of four innovation types, there are therefore 84 different possible innovation categories possible in software. At an industry level, these 84 different types aggregate into S-curve transition points that broadly characterize industry changes over the years.

A. Data-dominant software	B. Systems Software
A.con Consumer-oriented software	B.os Operating systems
A.bus Business-oriented software	B.net Networking / Communications
A.des Design and engineering software	B.dev Device / Peripheral drivers
A.inf Information display and transaction entry	B.ut Support utilities
	B.mid Middleware and system components
	B.bp Software Backplanes (e.g. Eclipse)
	B.svr. Servers
	B.mal Malware
C. Control-dominant software	**D. Computation-dominant software**
C.hw. Hardware control	D.or. Operations research
C.em. Embedded software	D.im. Information management and manipulation
C.rt. Real time control software	D.art. Artistic creativity
C.pc. Process control software (i.e. air traffic control, industrial process, nuclear plants)	D.sci Scientific software
	D.ai Artificial intelligence

Figure 5.8 – ACM Taxonomy of software

It is only in the US that innovation has been exhibited across all 21 areas. In both China and India, the successes so far have been in data-dominant software, control-dominant software and computation-dominant software. In the key fundamental and strategic area of software, the United States reigns supreme, despite thousands of Indian-origin and Chinese-origin engineers working on precisely those areas in US corporations.

As evidenced by the CEOs of Microsoft and Google, Indian engineers have in many cases outclassed their American counterparts. There are many similar examples of Chinese-origin engineers succeeding in the industry. The conundrum is why an ecosystem comparable to, or similar, to the US has not developed yet either in India or China after more than half a century.

5.1.3 Innovation transition points in the software industry

We may now combine the above into a single chart to identify the S-curve transition points which locate the major innovations. The seven commonly accepted major innovation events, which subsume both technological and business model innovations, are shown as located in time in Figure 5.9.

Year	Innovation events
1969	IBM unbundles software
1976	The 'C' programming language and the Unix operating system are developed
1982	Microsoft launches MS-DOS
1988	Local are networks (LANs) and object-oriented programming (OOP) are developed
1998	The Internet and the World Wide Web become pervasive
2006	Cloud based computing evolves
2015	Artificial Intelligence (AI) based applications become significant

Figure 5.9 – Major events driving innovation in the software industry

We now map these significant innovation events onto the global revenue graph of the software industry (OECD, 2017). This is shown in Figure 5.10.

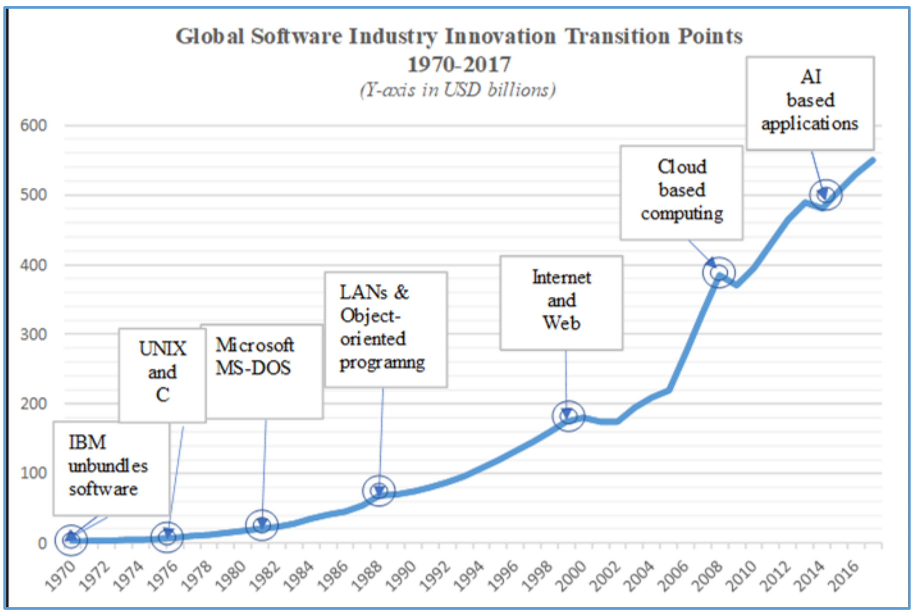


Figure 5.10 - Software S-curve transition points

Figure 5.10 shows that the growth, in revenue terms, of the industry appears to follow the historical innovation transition points, thus *validating the common understanding that the software industry runs on the innovation engine.* This observation allows us to link innovation in software technology and the software industry with the availability of venture capital, an important source of finance due to the special nature of the industry.

As remarked earlier, software by its very nature is labour-intensive. The output of this labour-based work is a software program that falls into a continuum between two extremes i.e. the program can be general-purpose or custom-tailored for one specific application. The organized work of software programming, in teams or indeed organizations, leads to two different business models depending on which extreme a company chooses to work:

1. *The product development model*: This is characterized by high initial levels of R&D, leading to a prototype or early versions that allow testing for acceptance in the market. If accepted, the product sells well in the market, generates profits and earns returns over time for the company, thus creating shareholder value and brand salience. This is a capital-intensive model, requiring infusions of large amounts in the initial stages. Companies such as Microsoft, Oracle, SAP, Google, Facebook all typify this model. Technological innovation is the critical capability of successful companies following this model.

2. *The software services model*: The takes advantage of the labour-intensive nature of software development, which lends itself to high margins based on expertise or low manpower costs or both. Companies such as Accenture and Cap Gemini earn high margins through providing high levels of technological expertise in the IT consulting businesses. Similarly, Indian IT companies, typified by Tata Consultancy Services or Infosys Technologies, have been extremely successful in using labour arbitrage i.e. charging international rates for offshore software development engineers who are paid at lower Indian salaries. The success of this model depends on building financial strengths through high profits and capitalizing these through the stock market. This model does not require technological innovation but does require entrepreneurial energy and managerial competence.

Both models require infusion of funds at the early stages before a critical mass, so to speak, is reached and the company can then expand on its own steam. This early stage investment is the domain of the venture capital industry. The history of the venture capital industry shows a marked preference for the capital-intensive model, since it leads to quicker and higher returns. We can therefore postulate that the venture capital industry has a clear interest in technological innovation in the IT sector. We will now examine the history of the VC industry to assess the accuracy of this postulate.

5.1.4 Venture capital and innovation framework in IT.

To appreciate the role that venture capital plays in the software industry, it is necessary to first describe the funding cycle, or the typical stages of funding, that a software company can go through from start-up to listing on stock exchanges. The diagram prepared by Kmuehmel is accepted and reproduced generally in industry and research publications as an accurate representation (Kmuehmel, 2015). It is reproduced in Figure 5.11.

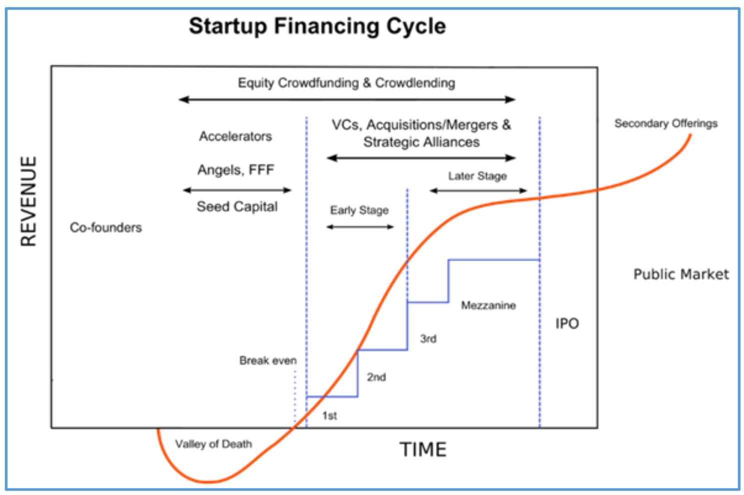


Figure 5.11 – The funding cycle in the IT software industry

This diagram requires some explanation. It plots revenue earned by the company against time, as the company, hypothetically, grows from an idea to listing on stock exchanges through an Initial Public Offering. During this process, funding for the company takes place through the following stages:

1. *During the R&D stage*: This corresponds to the Introductory stage in a typical S-curve. Funding during this stage is usually obtained from either "own sources", "friends and family", or "angel investors. These act as "accelerators" for the company, enabling it to grow through the stages of developing a prototype, testing it in the marketplace, and achieving enough sales to reach the break-even point. To the extent that innovations take place

during this phase, it is pertinent to notice that the accelerators fund the innovation process.

2. *During the growth phase*: This corresponds to the Growth stage in a typical S-curve. Funding during this stage comes from the Venture Capital (VC) and Private Equity (PE) industries. The objective of funding during this stage is to fund the commercialization of the product or technology and build the company to successful maturity. It is pertinent to note that neither VCs nor PEs fund the innovation process. What they do is to finance innovations that they judge as having potential for success, for further growth and financial returns for their investments. Thus, by extrapolation, we can postulate that the extent of VC and early stage PE funding is an indication of the intensity of innovation in an industry or country.

The value of venture capital as a measure of innovation intensity is particularly significant from the perspective of knowledge processes. This emerges from analyzing the typical decision process by which a VC fund takes a decision to invest in a technology, product, or company. A typical decision process is shown in Figures 5.12, in which a VC firm quantified the risk and return probability from a potential target investment, to come to a determination that that the investment was indeed worthwhile, even though the initial assessment was that there was only a 1% probability of the target company achieving mass market leadership status. (Kauffmann Fellows, 2012).

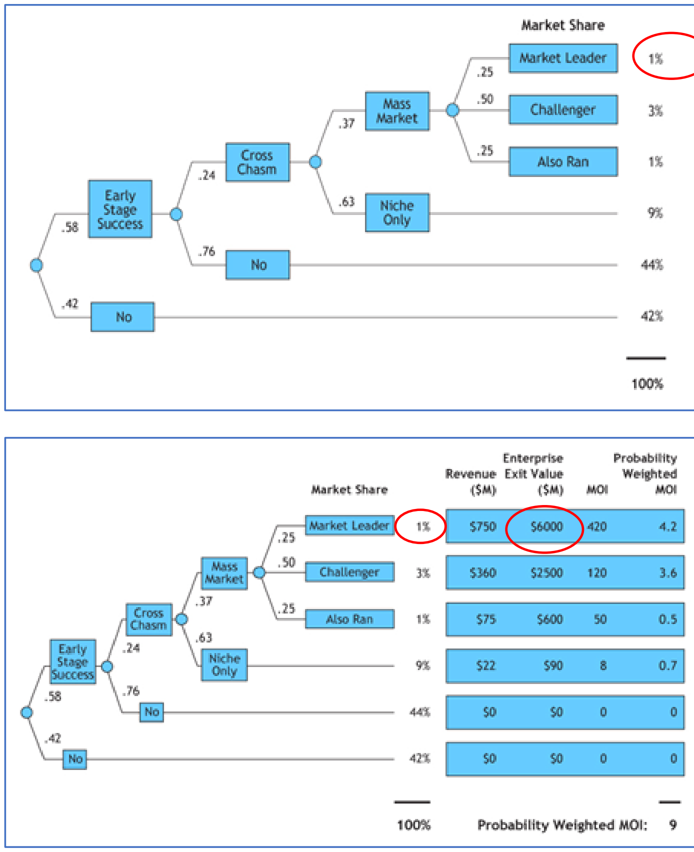


Figure 5.12 - Initial and Final Assessment of a VC opportunity

The decision process portrayed in Figure 12 reveals the following:

1. The criteria for which information was collected were:
   a. Capacity for early stage success
   b. Capacity to reach a critical mass ("crossing the chasm"0
   c. Likelihood of remaining a niche player
   d. Potential for reaching the mass market, in which case, what was the likelihood becoming a mass market leader, challenger, or an "also-ran"
2. The outcomes which were quantified were:
   a. Probable revenues
   b. Probable Enterprise Value at exit
   c. Probability Weighted Multiplier Of Investment (PWMOI)

From the above, it may be inferred that the VC firm:

1. ***Searched for knowledge*** about 1a. to 1d. above
2. ***Selected relevant knowledge*** from the larger mass searched for based on the VC's own accumulated knowledge base and competencies in the industry

3. ***Absorbed and internalized*** the selected knowledge
4. ***Generated*** probable outcomes based on past knowledge available
5. ***Disseminated*** the generated knowledge in a form suitable for decision making.

This case study of a VC process shows that a venture fund follows a rigorously defined set of knowledge processes to arrive at a decision. Of significance is the emphasis placed on ascertaining whether the target under consideration has, first, early stage potential i.e. enough innovation content to ensure successful entry in the market; and second, whether it can “cross the chasm” i.e. whether the innovation content can enable the target to acquire a sufficient critical mass to fuel its further growth. We may therefore conclude from this case study that the first test of acceptance by a VC is innovation content. We may therefore abstract from this to conclude, therefore, that ***VC investment in an ecosystem is a measure of the extent to which VC knowledge processes evaluate the innovation content available in the ecosystem.***

We will conclude the general discussion of the global IT software industry with a description of the global industry ecosystem. As in the case of the supercomputer sector, any industry ecosystem can in general be described by eight components. It is a matter of common knowledge that the global software industry is relatively free of linkages with governments, bureaucracies or militaries. Since software is a labour-intensive activity, there is a strong linkage to the Education component, particularly as regards technical manpower. There is also a strong linkage to the venture capital and financial markets. The role of applied research and scientific research is relatively less as compared to manufacturing or process-oriented industries, because of the lack of need for research into materials or manufacturing processes. It should also be noted that there are many other complementary assets that need to be present for the software industry to grow; for example, semiconductor manufacturing, a robust telecom infrastructure, other hardware technology industries such as disk storage, optical technologies for displays, and so on. These provide some indications of why the software industry has flowered most in the United States.

We depict the industry ecosystem in the following diagram, following the supercomputers case:

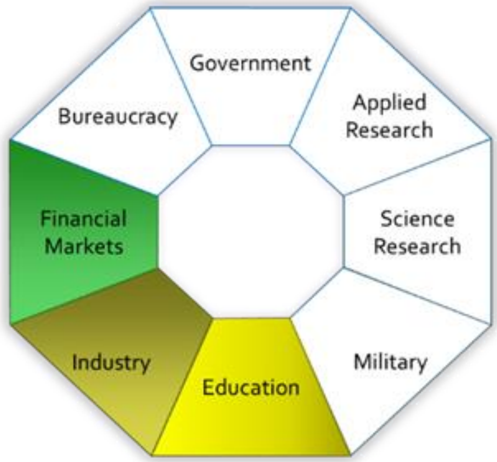


Figure 5.13 – Generalized global IT software ecosystem

The strong linkage between the industry and education sectors can be seen by comparing the total size of the trained manpower force in the US, China and India. This is depicted in Figure 5.14.

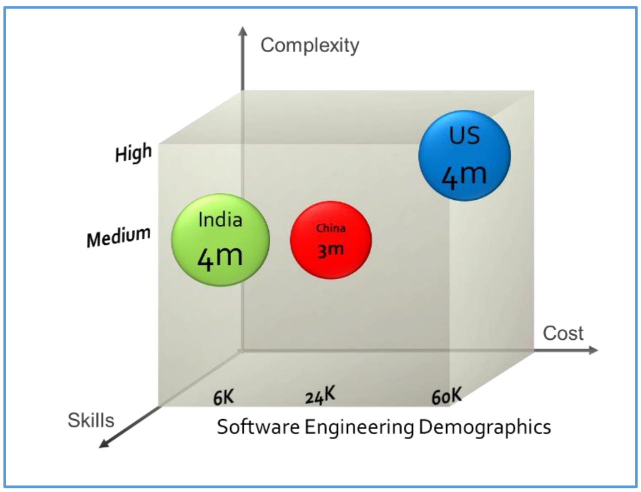


Figure 5.14 – Software manpower characteristics in the US, China and India

At a macro level, both India and China now have manpower strength of the same order as the US. However, the US has manpower which is more skilled at a higher level of complexity than either China or India. In terms of cost, the US remains the highest at $60,000/- per annum average, while costs in India and China are 10% and 40% of the US average (NASSCOM, 2015).

We next investigate the extent of linkages between the financial markets and the industry with specific reference to the innovation scenario. We introduce for this purpose the term “unicorn”, coined by the industry and now in wide usage, representing a startup which has achieved a market valuation of at least $1 billion (Hars, 2015). We combine this with the number of “VC destinations”, as evidenced by deal volume, to arrive at the comparative analysis depicted in Figure 5.15.

2016-17 Data (USD)	Global	India	China
IT Software and Services	1600 bn	150 / 9.4%	300 bn / 18.8%
Systems software and products	900 bn	Very low	Very low
IT services	700 bn	150bn	300 bn
Market Share		21%	42%
Venture capital deal flow	80 bn	5	7
VC fund share		6%	6%
No. of cities in top 20 VC destinations	20	2	2

Figure 5.15 – Global, Chinese and Indian VC picture

The growth in the number of “unicorns” in the three countries is depicted below in Figure 5.16.

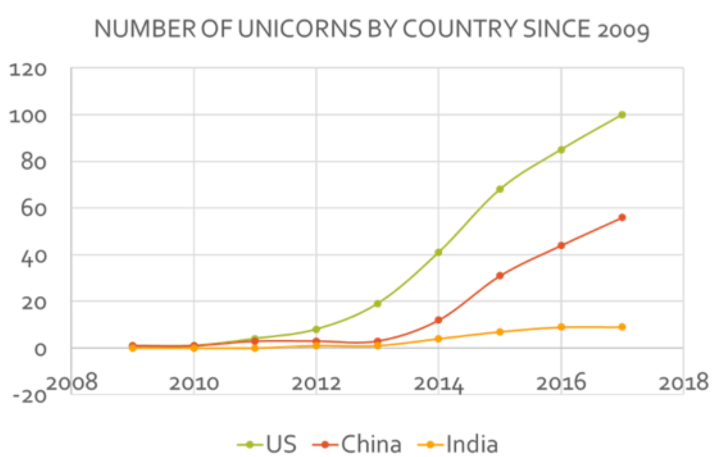


Figure 5.16 – Growth in number of unicorns in three countries

We will use these conclusions to next describe and analyze the contemporary situation of the software industries in India and China. Again, the structure will follow generally that used in the chapter on the supercomputer sector.

5.2 *The IT software industry in India*

5.2.1 History

The history of the Indian IT software industry can be usefully broken up into ten distinct phases, covering the fifty years during which the industry has grown to over $150 billion in revenues (Heeks, 2016).

Early stage entrepreneurship: It is noteworthy that the Indian IT software industry came into existence first in a startup mode in the private sector, despite the prevailing socialist political-economic environment and despite the presence in India of International Business Machines (IBM) from the US and International Computers Limited (ICL) from the UK. The industry can trace its origin to a seminal event – the setting up in 1968 of a division of Tata Sons, then the largest Indian private sector group, to provide computer usage consultancy and management information reporting services to the other companies in the Tata group. This new division was christened Tata Consultancy Services and was headed by FC Kohli, who can rightfully claim to be the father of the industry. TCS drew heavily for manpower from the Indian Institute of Technology, Bombay, during its early years. Competition emerged in 1975 in the form of Patni Computer Systems, started by Ashok Patni, a young graduate of IIT Bombay. The following year, Dr Lalit Kanodia, a graduate of MIT, established Datamatics Ltd in Bombay. All three companies provided much the same mixture of manpower and data processing services. The practice of overseas staff augmentation, or body shopping as it is popularly called, began during this phase.

Systems software R&D: With the exit of IBM from India in 1977, domestic computer manufacture received a boost. From the Government side, the Electronic Corporation of India (ECIL) moved actively into the manufacture of 16-bit minicomputers patterned on the DEC PDP-11. In the private sector, four small companies quickly emerged – DCM Data Products from the DCM group, ORG Systems from the Sarabhai group, Wipro Infosystems from the Wipro group, and HCL, which was the first true “Silicon Valley model” Indian startup. The manufacture of computers required the availability of operating systems, language compilers and associated software products, and in the five years from 1977-1982, a considerable body of expertise came into existence in India. The quality of this expertise can be gauged from the fact that engineers from all these companies soon started receiving lucrative offers from established majors such as Intel and IBM, and more importantly, from young companies such as Microsoft and Apple. For example, RV Rao, who was the systems software head in HCL, was recruited by Microsoft in 1981 and rose to become the chief architect of the Microsoft Windows operating system which dominates in PCs today.

Products and services: As observed earlier in this chapter, the 1980-1989 period saw the proliferation of a host of small companies which developed and marketed software products such as spreadsheets, word processors, database management systems and the like. This had a profound effect on companies in India, and very quickly a few Indian product companies were established. Notable among these were Wipro Systems, an ambitious attempt to compete with products directly in the US market and Softek Limited with a suite of products that gained acceptance in the Indian market. The computer manufacturers viz ECIL, HCL, DCM and ORG also developed their own products, which were competitive in terms of specs with equivalent US products, but significantly failed to recognize the global market potential. There was therefore no meaningful investment in international business development or attempts to look for venture capital funding.

During this period, CMC (Computer Maintenance Corporation of India), which was the company set up by the government to take over the assets and operations of IBM after its exit in 1977, emerged as a leader in software solutions in India. CMC quickly ratcheted up important successes, including the Passenger Reservations System for Indian Railways, and banking computerization at the branch and regional office levels.

Pilot offshore development centres: In 1986, the innovation that would become the business model for the industry for the next three decades was introduced by Texas Instruments. Using a satellite communication link, TI set up India’s first offshore software centre in Bangalore, that developed software in close electronic collaboration with the headquarters in Houston. The TI experiment proved the viability of a services-oriented business model based on labour arbitrage, or lower costs of manpower that could still deliver acceptable quality. In 1989, this model, called the Offshore Development Centre (ODC), was replicated by Nortel, and thereafter by every Indian software company ever since (Rajaraman, 2012). We will term this Milestone #1 in the industry.

Shutdown of the products businesses: The business success of the "services-oriented companies" as compared to the "product-oriented companies" convinced Indian industry that the product space was less attractive than services, and by 1990, virtually the entire product development efforts by Indian companies had shut down. We will term this Milestone #2 in the industry.

The companies that remained steadily successful during this entire tumultuous period were TCS and Patni, and from the early 1980s onwards, similar "me too" business model companies started to establish themselves. The most significant among these was Infosys Technologies, which was set up by a team that broke away from Patni. By 1990, the Indian industry was composed almost entirely of small services companies that derived a large part of their revenues from body shopping. In 1990, total revenues had crossed Rs 100 crores and the industry association NASSCOM – National Association of Software and Services Companies – was set up.

Proving the Offshore Development Centre model: From 1990 to 1995, the industry grew fivefold to Rs 500 crores in total revenues. This was fueled almost entirely by the adoption of the TI / Nortel model by Indian industry. The most visible instance of this was a major outsourcing effort by General Electric, who farmed out business to four Indian companies – TCS, Infosys, Wipro and Patni – with high volumes but lower margins. NASSCOM played an important role by aligning the industry on a common marketing platforming, which highlighted well qualified English-speaking manpower, reliable telecom / satellite links, reasonable cost, good quality of delivery, and 24-hour operation due to the time zone difference, leading to almost double the productivity.

Figure 5.17 depicts the performance for the two years 1998 and 1999. By the end of the decade, the Indian software industry had shifted completely to the ODC model, driven by increasingly fast global communications over the Internet and the proven financial upsides of labour arbitrage, with exports to the US dominating the industry. The domestic sector contributed less than 40% to the industry size. We will term this Milestone #3 in the industry.

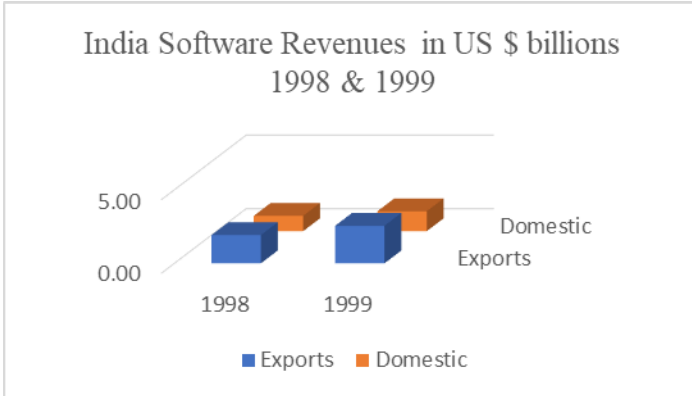


Figure 5.17 - Industry performance in India for 1998 and 1999

The Y2K opportunity: Labelled the "crisis that never was", the so-called Y2K problem – which threatened to crash systems all over the world due to the inability to adapt to a year change beyond 19xx – was nevertheless seized on by Indian industry as a one-time business opportunity. While it added no technological depth, the Y2K boom trebled the industry's revenues to over Rs 1500 crore in the five-year period. This was also the period when stock market began to take serious notice of the software industry as a possible vehicle for wealth, and IPOs started to take place at increasing frequencies. This may be termed Milestone #4 in the industry (Dossani, 2004).

Post dot com crash (2000-2010) Business Process Outsourcing, Remote Infrastructure Management and Wealth Creation

While the US software industry was struggling with the aftermath of the dot com crash of 2000-2001, Indian industry continued to expand steadily using the same tested business model of offshoring over a communications link. Application areas meanwhile diversified from pure software to business process outsourcing (call centres and customer support) and remote IT infrastructure management.

The IT software industry, growing at 30%-50% per annum, achieved celebrity status with a string of high-profile IPOs such as Infosys, HCL Technologies, TCS and many others. On the Bombay Stock Exchange, the IT industry quickly became associated with the highest returns. Success in these endeavours propelled the industry to the New York Stock Exchange and NASDAQ. In the process, the industry started to demonstrate its potential for enormous wealth creation, which took place on a scale unprecedented in Indian history, with many "dollar millionaires" making their appearance practically overnight. For example, the Wipro Chairman, Azim Premji, was briefly the second richest individual in the world, and the number of Indian IT billionaires crossed into double figures. Internationally, the so-called "Brand India" became strongly associated with Indian software skills, and the city of Bangalore acquired the status of an international destination for global software companies.

The industry continued to be highly export-oriented, with the offshore outsourcing model adopted by virtually all companies. The domestic market for software, in contrast, did not fare so well as measured in revenue terms. Figure 5.18 depicts the performance of the Indian IT industry during the first decade of the twenty-first century.

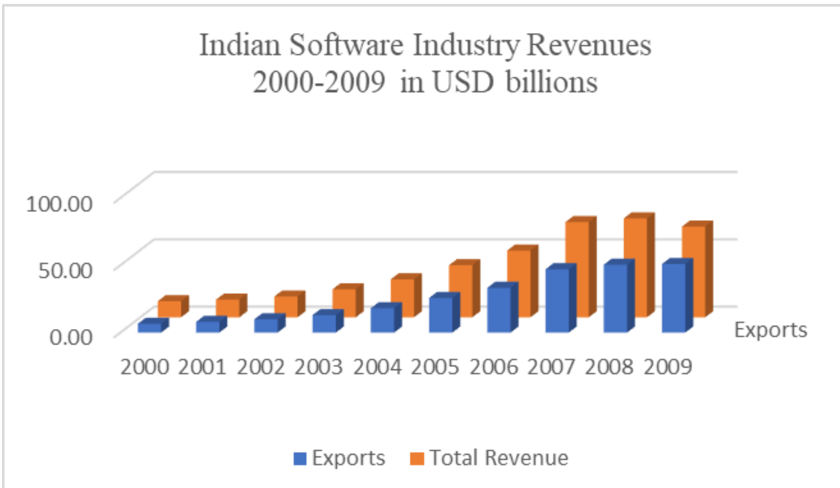


Figure 5.18 - Indian software industry 2000-2009

Despite its impressive financial performance and growing managerial maturity, strengthened by an increasing internationalization of its manpower base, the Indian IT industry did not produce any innovations comparable to those from Silicon Valley during this decade. There was a continued reliance on the already proven blended onsite-offshore services model, and a continued inability to produce successful products that could be marketed either in large volumes or at high prices. This will be termed Milestone #5.

Transition to a new cycle: The period 2010-2015 saw changes in leadership across the board in the industry, as a new generation of leaders took over from the original entrepreneurs in companies such as Infosys, Wipro and HCL. But this sparked no new wave of innovation. For all practical purposes, Indian industry continued to resemble, in terms of its business model, the companies of the 1990s.

The growth rate of the Indian software industry slowed down noticeably during this first half of this decade, coming down to less than 20% from the rates of more than 30% during 2000-2010. The same companies that dominated earlier continued with no new competition coming in. What did expand greatly in India were the applications markets, such as e-commerce, online banking, payment gateways and the like. Again, innovations that were observed were mainly incremental or at most architectural, and primarily in business models. No new technology emerged from the $ 150 billion Indian IT industry. Figure 5.19 depicts this situation.

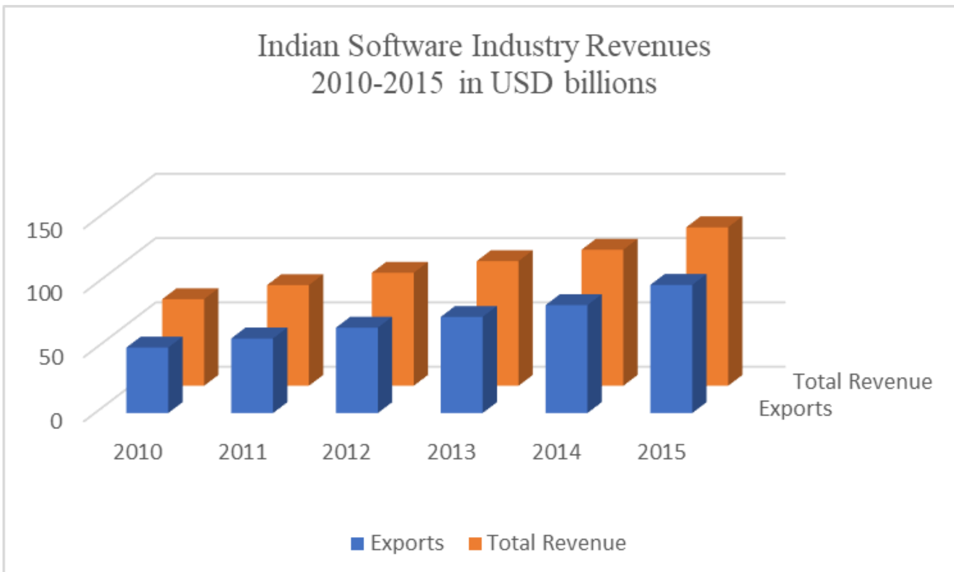


Figure 5.19 - Indian IT software revenues 2010-2015

Artificial Intelligence and the future: With AI and machine learning become priorities and a concern for industries in all sectors globally from 2015 onwards, the Indian IT industry has to now face up the possibility of a significant proportion of their workforce, especially in the BPO and other low-technology domains, getting replaced by AI-driven entities.

5.2.2 Major Milestones

Figure 5.20 depicts the major milestones listed in the section above with reference to the industry performance (Heeks, 2016).

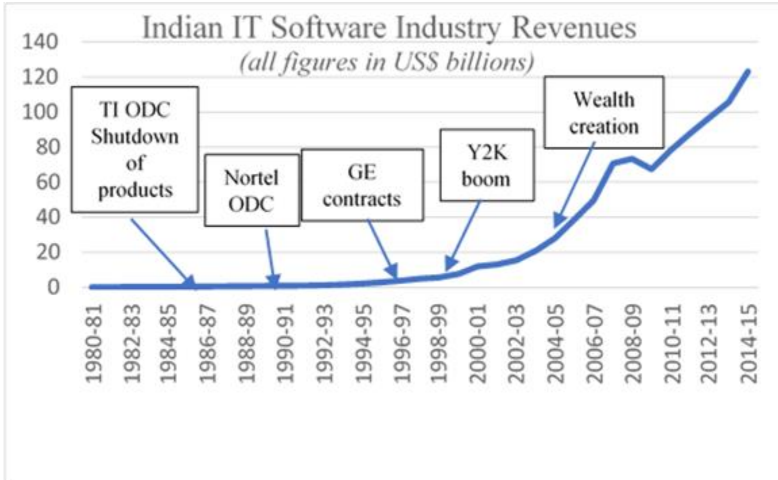


Figure 5.20 – Milestones and industry revenues

The Indian IT industry is significantly different from the global industry in terms of the relative absence of S-curve transition points. This bears out the earlier description of the industry as one in which essentially the same business model carried through for over two decades.

5.2.3 Venture capital and the software industry in India

The strength of the linkage between the industry and the financial markets can be assessed by comparing the extent of VC fund penetration into the industry as compared to the global level over a 10-year time frame. This is shown in Figure 5.21.

As compared to a global average of VC funding as a percentage of revenue of 8.34%, the Indian average is 1.46%, or slightly less than one-fifth the global number. This clearly reflects the weak link between the industry and the VC markets. As discussed earlier, the VC industry is oriented strongly to innovation, so the low VC penetration into the Indian software industry reflects the perceived low level of innovation.

Year	Global revenue	Global VC funding	Ratio	India revenue	India VC funding	Ratio
2005	220.00	20.17	9.17	38.67	0.65	1.68
2006	275.00	26.48	9.63	49.58	0.72	1.45
2007	330.00	30.97	9.38	70.70	0.93	1.32
2008	385.00	29.29	7.61	73.40	1.10	1.50
2009	370.00	21.56	5.83	67.34	0.88	1.31
2010	395.00	25.92	6.56	78.26	0.95	1.21
2011	430.00	36.27	8.43	87.84	1.43	1.62
2012	465.00	32.64	7.02	96.90	1.14	1.17
2013	490.00	36.07	7.36	105.72	1.53	1.45
2014	480.00	59.37	12.37	123.22	2.40	1.94
Average VC Funding vs Revenue Ratio						
			8.34			***1.46***

Figure 5.21 – Comparative VC penetration into Indian software industry

5.2.4 Indian software industry ecosystem

Following the approach in the chapter on supercomputers, we may now describe the ecosystem for the Indian IT software industry.

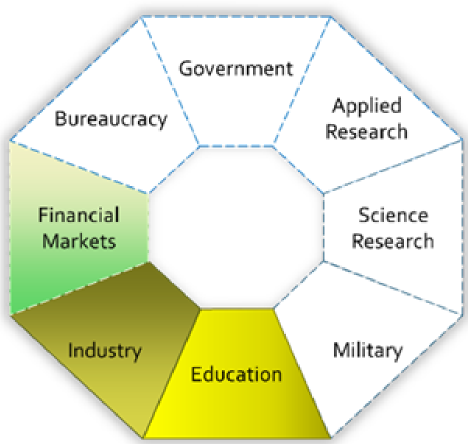


Figure 5.22 – Indian software industry ecosystem

This ecosystem diagram shows that the coupling between the education and industry sectors is high, as evidenced by the size of the manpower force in India of approximately 4 million (NASSCOM, 2018).

The weak link, discussed above, between the Indian industry and the VC markets leads to a dotted line in the ecosystem diagram. This weakness of linkage reflects in the relatively slower growth in the number of “unicorns” in India as compared to China and the US.

5.2.5 Innovation patterns and strategies observed

As already observed, the extent of VC penetration into Indian IT software companies is low at 1.46%. It is also interesting that the total market capitalization of the top 10 IT companies on the National Stock Exchange stood at approximately $20 billion in July 2018, compared to an annual revenue of over $ 150 billion of the industry, a ratio of 13%. In contrast the total market capitalization of Microsoft, the world’s richest company, has a market capitalization to revenue ratio of close to 10:1, with at least three other companies – Apple, Amazon and Alphabet – in similar territory.

This asymmetry acquires significance because of the global character of the IT software industry. With virtually no cross-border barriers or tariffs, all countries have access, for all practical purposes, to any product anywhere in the world. Thus, all countries and the companies located in them are in open competition for an unrestricted global market. Therefore, the countries with strong ecosystems for innovation have an obvious advantage, and this is reflected in the continuing dominance of the US in the software arena.

The relatively weak link between the financial markets and Indian industry reflects in the patterns of innovation that we can observe. With a workforce of over 4 million, Indian industry has been unable to produce a Google, a Facebook, or a Dropbox, let alone a Microsoft or Oracle.

To investigate this situation, we present the following four case studies, covering the period from 1980 to 2015. Since the objective of thesis is to understand knowledge processes as related to innovation in a balanced way, and not to evaluate the percentage of successes or failures, two of the case studies represent successes and two failures. The four case studies also represent a balance between the product and services models, including one named company (TCS) as an example of overarching success similar to the Sunway TaihuLight in supercomputing. TCS is the bellwether for this chapter.

5.2.5.1 Case Study 1 (during the early 1980s)

Company A had entered the minicomputer market in India following the exit of IBM and new policies designed to encourage indigenous manufacture. The first product, based on an 8-bit microprocessor and running a proprietary operating system and BASIC language interpreter modified for commercial applications, was a success in the market and established Company A as the leader in the nascent private sector industry. Based on this, the company made plans to develop and market a 16-bit minicomputer, again with a proprietary CPU based on PDP-11 architecture, a proprietary operating system and a suite of application software.

The customer requirement, however, had meanwhile evolved to a desire for real time transaction processing from video display terminals connected to a powerful central computer. This put Company A's new minicomputer at a disadvantage, since it lacked the necessary processing power and memory capacity. Therefore, the R&D of Company A looked for an innovative solution.

The final decision was a radically new architecture till then unseen in India, consisting of a network of computers, shown in Figure 5.23.

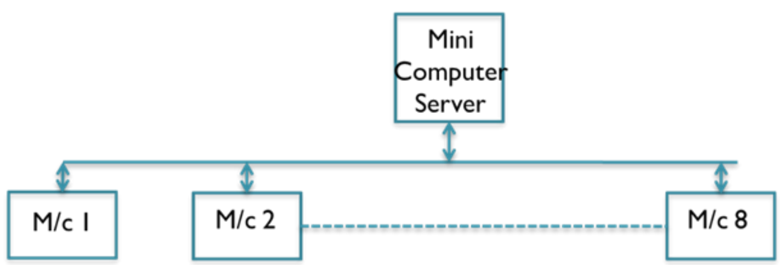


Figure 5.23 – Networked architecture circa 1980

The software problem that arose, however, was also unprecedented: How to organize data and files on the server? Whatever the solution, the directive from the management was clear - the end result should be a clear product USP (unique selling proposition) for the company.

The solution was devised through stages. In the first stage, technology alternatives were sourced from the IIT Delhi library. In the second stage, the sourced material was discussed with the R&D. In the third stage, a technology selection decision was taken. The IBM System R specification – describing a concept which was termed a relational data base management system (RDBMS) - contained in an article in the IBM Systems Journal, was recommended and then selected as the basis for development. Although IBM was in the process of developing an RDBMS of its own based on the new specification, the project was still under wraps. The Company A team would therefore be venturing into uncharted territory. The decision taken, an R&D team was assigned to study the spec and develop an implementation plan.

Over a period of two years, the project was successfully completed, and prototypes and test versions delivered to customers. This was one of the only three minicomputer RDBMSes available in the world in the early 1980s – the other two being from Ingres and Oracle Corporation respectively! The architecture in Figure 5.23 was also the first implementation of a computer network as a solution anywhere in India.

At this point, during the early 1980s, Company A made two fundamental strategic errors. First, the new RDBMS software was bundled with the hardware and marketed as part of the product, instead of as an independent and portable software product. Second, the networking expertise developed by Company A was not marketed as an independent service to organizations using different types of hardware, thus missing out on the revenue potential of a new services business line.

The consequences of these errors became apparent ten years later, during the 1990s. Oracle Corporation had by then become the global leader in database software products, with a turnover in billions. The concept of computer networking had been adopted by Sun Microsystems as a basic philosophy, and Sun had become the world's network computing leader. Both Oracle and Sun played stellar roles in the evolution of the Internet, in which Company A could have been one of the pioneers if different decisions had been taken. By then, Company A had long abandoned its R&D efforts and had adopted instead the same blended onshore/offshore services business model as TCS and Infosys. From a risk-taking and somewhat inefficient leader, Company A had changed into a risk-averse but efficient follower.

However, the availability of funding for such R&D projects also played a critical part in the different paths traversed by Company A and Oracle Corp. Company A had access to no external funding whatsoever, except for working capital from banks. Oracle, in comparison, was bankrolled in its early years by a very large contract for the development of database software from the US intelligence community.

5.2.5.2 Case Study 2 (mid 1990s)

Company B was an Indian IT education major, the largest in the country. Started during the early 1980s, the company had developed a highly successful business model that consisted of the following:

- An inhouse R&D for courseware development taking into account as many emerging technologies as possible, with the objective of providing “state of art cutting edge” education to its students.
- A distributed delivery model consisting of education centres located all over India, some operated by the company and the rest on a franchisee model
- Stable cashflow via collection of fees 100% in advance from the students.
- A well-staffed and equipped training centre for faculty development
- Placement services

The major constraint the company was working under was the Indian government regulation that “degrees” could only be awarded by a “university”. To qualify as a University, an organization had to conform to a multiplicity of stringent criteria administered by the University Grants Commission (UGC). The company had not been able to obtain university status due to the distributed nature of its operations and was therefore compelled to award only “diplomas”. Diplomas did not receive recognition as equivalent to a degree from either prospective employers, overseas universities or from the perspective of societal status. This was despite the higher quality of courseware and faculty as compared to most universities.

The emergence of the Internet offered a new opportunity to the company. It now appeared possible to deliver its courses online, using innovative faculty and evaluation methods. Company B initiated a project to develop technology that would implement the online education concept. To offset the costs of development, Company B kept open the option to license, or even sell, its technology platform to other interested companies. The end result was a sophisticated online education platform that anticipated successfully many features which characterized later Learning Management Systems (LMS). However, Company’ B’s own marketing efforts were not very successful in attracting students in the

Indian market. The decision was then taken to try and recover the costs of the project via an outright sale of the technology.

An American private university, which had already started its own online courses, evinced interest in the technology, and a deal was struck to sell the technology and the IPR. In less than a decade, the American private university was the largest in the world for online education in specific areas of specialization and went on to a successful IPO.

5.2.5.3 Case Study 3 - Tata Consultancy Services (TCS) in the mid 2000s

As mentioned in the first part of this section, Tata Consultancy Services (TCS) was the first Indian software company, coming into existence in 1968. Over the years, TCS has remained consistently the largest in terms of revenues and has provided the inspiration for practically every Indian software company that followed. During its trajectory of growth, TCS has experimented with all the various software development models, from pure services in onsite mode where it began, to pure product development. The dominant paradigm it has settled into has been the *"blended onsite + offshore global delivery model"*, in which a mix of teams located in different countries work collaboratively over the Internet. As mentioned earlier, this model, first implemented by Texas Instruments in 1986, represents the most successful innovation so far in the Indian software industry, and has been responsible for India acquiring the stature it has as a major software power. The TCS global delivery model is depicted in Figure 5.24 below.

TCS has a publicly stated policy and structure for encouraging innovation, shown in a diagram in Figure 5.25. Although no internationally successful products, compared to the top US instances, have been launched as yet under the TCS brand, TCS has developed as an innovation partner for many international organizations. In the India, TCS is well known for many large-scale customized implementations in pan-Indian Government and commercial organizations. For instance, TCS runs, on a systems integration basis, the entire passport issue and verification system for the Ministry of External Affairs, with TCS contracted staff working in the various regional passport offices, with MEA officers performing the supervisory role.

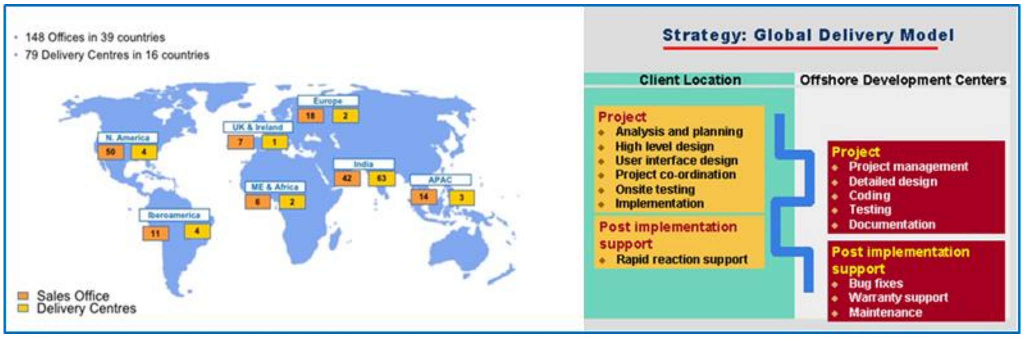


Figure 5.24 – TCS global delivery model

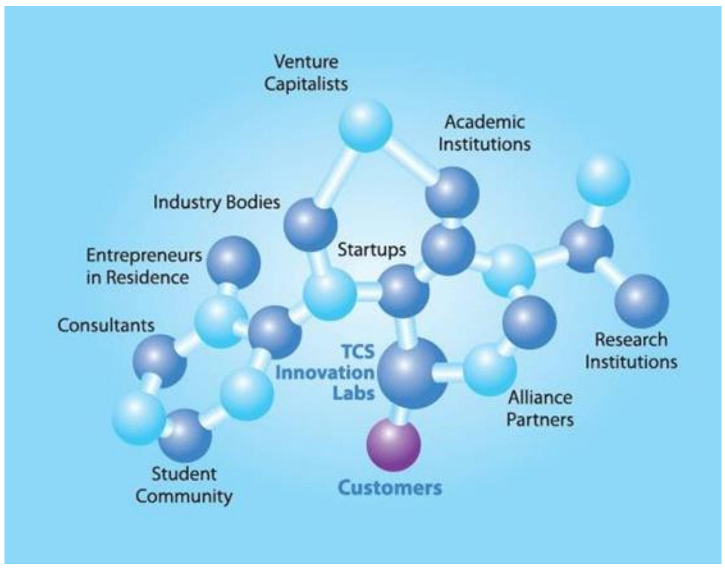


Figure 5.25 – TCS Innovation structure

5.2.5.4 Case Study 4 (1995 - mid 2010s)

Company D was set up in Pune during the mid-1990s by an entrepreneurial team consisting of two brothers. The elder brother was running his own small business of computer repairs and found that his customers had begun to increasingly ask for help with virus attacks. Sensing an opportunity in this, he convinced his younger brother, who had just then graduated with a degree in computer science, to write an antivirus package that could run on PCs and cost less than the then available antivirus brands from US and European vendors. The computer repair business would provide the funding and infrastructure. As the development team was very small – just the younger brother and a classmate – the running costs were minimal.

The company soon found that they were gaining acceptance from their customers, because of the level of personalized service they were able to offer. Many of their customers were located in small towns on the outskirts of Pune. The customers, who very often had low levels of computer literacy limited to using email, a word processor and a spreadsheet at most, now had an alternative to going to a Pune computer sales outlet or to a vendor office to obtain an antivirus package. Instead, one of the two brothers from Company D would personally come by, install the package, collect the payment and take care of training the customer on its usage.

Over the years, the company stuck to its policy of investing very little in marketing and branding as the international vendors were wont to do. Instead they remained steadfast to their "personal selling" philosophy. As their the company sales grew, they extended their strategy of concentrating on the smaller towns and outskirts of Pune to developing a network of retailers, who then followed the same personalized approach as Company D. By the end of the 2000s, the company had in place over 5000 distributors. Their growth had gone almost unnoticed because of their very low marketing profile, but their reputation was spreading by word of mouth. By 2011, Company D had crossed Rs 150 crores in annual revenues and had remained profitable throughout.

In 2012, Company D received Rs 60 crores in equity from a major venture capital fund. They were able to employ more people, and by 2016 the employee strength increased beyond 500, of which over 100 were in R&D. *In 2016, Company D launched a successful IPO, in which its valuation was assessed at over Rs 1500 crores*.

Company D is an example of an Indian software product company which has achieved success of the kind that Silicon Valley is famous for.

5.2.6 Analysis of Innovation-related Knowledge Processes in India

As discussed, the process of venture capital investments bears some relation to the perceived innovation level. It was also discussed that the venture capital investment decision process was based on rigorous analysis of the available knowledge, and involved the five knowledge processes defined as search, select, internalize, generate and disseminate. Our data also showed that of venture capital investments as a percentage of industry revenue was 14.41% in the US and 1.3% in India.

Given that software is still largely a labour-intensive activity, in spite of the current focus on AI to improve productivity, and that that both the US and India employ approximately 5 million software personnel, it can be inferred that the *average per employee VC investment in India is 10% approximately that of the US*. It can be further inferred that innovation-directed R&D – the focus area of the VC community – is under-invested in India as compared to the US. Given that VC funding is a critical step in the early stages of IT technology S-curves, it can be concluded that there is a likelihood of fewer innovations achieving success in the marketplace than in the US.

However, in this regard, the data from the outcomes of the four case studies given above presents a mixed picture. For example, in the case of the RDBMS developed by Company A at the same time as Oracle, Oracle received funding from the US government which enabled it to "cross the chasm" into mainstream operations. Company A was not so fortunate. The same was the case of Company B, although by the '90s the economy had opened up to external investment. TCS, however, was able to successfully navigate the funding problem, helped to a large extent by the funding always available from its parent group, but still entered the IPO market almost a decade after Infosys. In the case of Company D, however, the VC ecosystem worked very similarly as it does in the US, enabling Company D to reach the Holy Grail of the software industry – a successful IPO. Company D's strategies are well represented on a Smiling Curve.

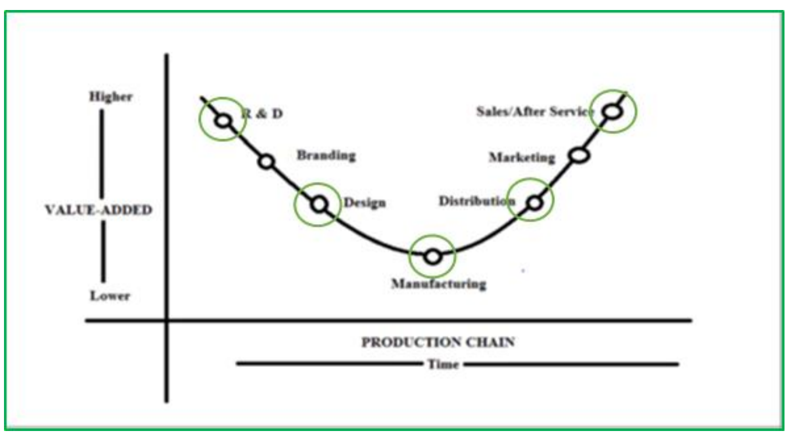


Figure 5.26 – Company D strategies in the Smiling Curve framework

The outcomes of all the four cases demonstrate some weaknesses at the ecosystem level in India, which may however be slowly dissolving. Government, financial markets, research, education and industry are not yet working in a tightly coupled manner. This has resulted in lower VC investment levels, as the VC community assesses the attractiveness of India as a business destination to be less than the US, due to the ecosystem weaknesses. Nevertheless, instances of success, as evidenced by Company D have become more common.

The case study of TCS demonstrates the extent of benefits that can accrue when companies and the ecosystem are tightly networked. Figure 5.25 shows the extent of TCS's networking within five of the eight components of an industry ecosystem, namely, *industry, financial markets, the education sector, the applied research and scientific research components*. In the public domain, TCS is also well known as networking closely with the remaining three, namely, *the government, the bureaucracy and the military*. The success of TCS is evidence of the benefits of close coupling between organizations and ecosystems.

From the knowledge processes perspective, Cases 1-4 demonstrate that effective knowledge processes operate at the individual, team and organization levels, since innovations reach the point of commercialization, but are sometimes unable to proceed further successfully due to lack of ecosystem support either in the form of adequate investment or effective Government policies. These ecosystem weaknesses reflect the lack of effective knowledge processes at the policy level. The components of the ecosystem still work in relative isolation of each other. The two success stories of TCS and Company D demonstrate, however, that these gaps may be closing.

Although India has often been termed a "software superpower" and Bangalore as India's Silicon Valley, the number of unicorns rising in China should be of competitive interest. With that perspective, we turn now to examining the Chinese IT software industry.

5.3 The IT software industry in China

5.3.1 History

The Chinese software industry has evolved on paths very different from India. The reasons for this are not far to seek. First, the availability of only a small number of English speakers till recently limited the scope for interaction with the world of technology outside China. Second, China was cut off from the rest of the world till the early 1980s, when Deng Xiaoping's early reforms opened up China to a limited extent to what was happening in the rest of the world. Even so, the emphasis in Chinese policy, especially after the first 863 program, was on manufacturing rather than services. Third, the attractiveness of China as a captive market for the Chinese software industry as compared to the competitive export market outside rendered the industry somewhat inward looking till the turn of the century. This is reflected in the availability of meaningful industry data only after the year 2000. Fourth, the much bigger role played by the Chinese state in the industry as compared to India. Fifth, the greater availability of capital and other forms of financing, including from government, in China.

Very limited information is available about the Chinese software industry during the 1960-1980 period. However, we may observe that the Chinese had acquired sufficient software capability to write their own operating systems, language compilers and application software for specific Chinese hardware, such as their first supercomputer and minicomputer, during this period.

Thenceforth, we may divide the history of the Chinese software industry into the following stages:

1980-1990: When Deng Xiaoping led the opening up of China to the world, the extent of the gap in the software arena came as a revelation to the Chinese leadership. To cope with this, the Chinese decided to follow the time-honoured "***nalai zhuyi"*** principle, often loosely translated as "take whatever-ism", but in the context of technology can be more accurately termed reverse engineering. In regard to software, *nalai zhuyi* – or *nalai-ism* (Jui, 2010) - took the form of borrowing or buying foreign products, translating them into Chinese, and then reengineering then using available Chinese IT technologies.

The process of *"nalai-ism"* was spearheaded by a number of Chinese universities and research institutions, who became the pioneers and the catalysts for the commercialization and industrialization of the Chinese software industry, following a process consisting of opening up, borrowing, and learning (Jui, 2010).

In 1984, the Chinese Software Association was formed, and for this reason 1984 is considered an important milestone in the development of the industry (Jui, 2010). From that year, the Chinese software industry can be said to have come into existence as an independent industry rather than as a part of the hardware-dominated computer industry. Following this, the industry expanded rapidly, with a number of state-owned enterprises and well as privately owned entrepreneurial ventures quickly getting established. Among the state-owned enterprises China National Software & Service Company and the China Computer Systems Integration Company are two well-known entities. Among the private companies established at that time Kingsoft, UFIDA Software and the Neusoft Group can be identified as players.

The rapid expansion of the industry and the new industry-friendly policies attracted the attention of global software majors, who sensed the immense potential of the Chinese market. Starting with marketing offices, they moved fast to establish development centres. By 1995, for example, Microsoft, Oracle and SAP had all established R&D centres in China. It should be noted that this happened about five years before they established centres in India.

One important reason for global majors to establish offices in China, especially Microsoft, was to maintain a degree of oversight over the problem of piracy. In the pre-Internet days, software was distributed on CDs, and thus easily amenable to large scale copying at a fraction of the cost of the original. Consequently, there was a great shortage of reliable data on the actual size of the Chinese market in terms of the number of customers or installations, rather than reported revenue figures. In this thesis, therefore, no data will be presented for Chinese industry performance during the 1980-2000 period (Carlson, Gallagher, Lieberthal, & Manion, 2010).

This led to lobbying from industry majors, among others, for an invitation to China to join the WTO.

2000-2018: The admission of China into the WTO was the next major milestone in the growth of the Chinese software industry. It automatically meant two things – one, China had to abide by the rules of the WTO regarding IPRs; and two, China had to start reporting accurate industry figures (OECD, 2016) (OECD, 2017).

From 2000 to 2018, the Chinese Information Technology industry, including software as a component, grew at an extremely rapid pace reaching almost $700 billion in 2017 (OECD, 2017). However, exports in 2017 were less than 10% at $54 billion.

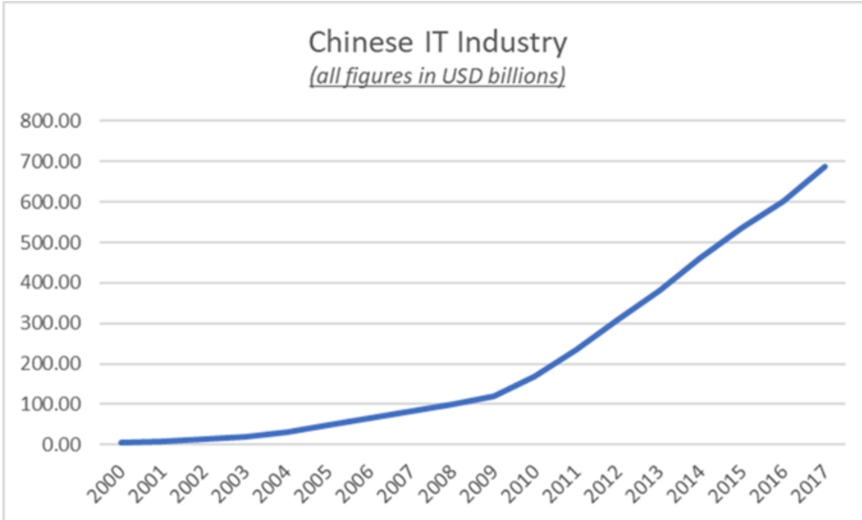


Figure 5.27 – Chinese IT industry revenues

Figure 5.27 shows the steady growth trajectory of the Chinese Information Technology industry. It also reflects some of the continuing and frustrating opacity of Chinese data. Due to many companies producing both hardware and software, often bundled together as solutions, the reporting from China continues to be in terms of Information Technology products and services rather than clear demarcations between hardware and software. The industry literature does not identify any major milestones along the way, comparable for example of TI's satellite communication-based offshore development center in India in 1986. We move therefore to examining the relationship, if any, between venture capital and industry growth in China.

5.3.2 Venture capital and the software industry in China

New project VC investment in China rose from $ 3 billion in 2007 to $29.36 billion in 2017. As with the case of India, the extent of VC investment penetration, as measured as a percentage of total revenue, offers insights. This is depicted in Figure 5.28. At 3,41%, the Chinese VC penetration is about 30% that of the global figure of 9.49% for the 10 years from 2007 to 2017 (Prequin, 2018). This shows also that Chinese VC penetration is approximately double that of India for similar, although not identical, 10-year periods.

Year	Global revenue	Global VC funding	Ratio	China revenue	China VC funding	Ratio
2007	330	30.97	9.38	83.75	3.08	3.68
2008	385	29.29	7.61	101.25	4.23	4.18
2009	370	21.56	5.83	121.25	2.71	2.24
2010	395	25.92	6.56	169.75	5.24	3.09
2011	430	36.27	8.43	235.63	12.62	5.36
2012	465	32.64	7.02	310.00	7.19	2.32
2013	490	36.07	7.36	382.25	6.36	1.66
2014	480	59.37	12.37	462.75	16.75	3.62
2015	505	76.77	15.20	535.50	19.90	3.72
2016	530	61.36	11.58	602.88	20.19	3.35
2017	550	71.94	13.08	688.75	29.36	4.26
AVERAGE VC FUNDNG AS % REVENUE						
			9.49			***3.41***

Figure 5.28 – Venture capital penetration in Chinese IT industry

5.3.3 China's software industry ecosystem

The ecosystem in China has been influenced by important Government interventions. For example, Shang-Ling Jui, the SAP Laboratories head in China, writes

> "Meanwhile the macroeconomic environment is also improving. The Chinese government has gradually begun realizing the vital role the software industry is playing in the economic development of the country and regards it as a strategic industry affecting China's international competitiveness. In the 20 years, the Chinese government has introduced a series of policies in order to facilitate the development of the software industry." (Jui, 2010)

And again:

> "..we can conclude that every few years the Chinese government issues new policies or guidelines to promote the growth of the software industry"

Jui lists the following specific policy events:

i. In 1986, the Report on Establishing and Developing the National Software Industry
ii. In 1991, the Outline of the Ten-Year Plan, which made a specific reference to the software industry
iii. In 1992, the Regulations on the Protection of Computer Software in China

iv. In 1997, the institutionalization of the annual Software Exposition

v. In 2000, "Document 18", which published the Policies for Encouraging the Software and Integrated Circuit Industries.

vi. In 2002, "Document 47" which laid out the Guidelines on Supporting the Software Industry.

vii. In 2006, the Eleventh Five Year Plan for the "Scientific Development of the Information Industry and Middle and Long-Term Programming by 2020", covering in detail every aspect of the software industry including every possible type of technology.

Jui concludes:

> "Like the author, every insider in the software sector who has observed or experienced its growth in China in recent years will have the keen feeling that the government is strengthening its support for the software industry and that the macro-environment is becoming more favourable. This trend continues. In this increasingly favourable environment, Chinese branches of multinational giants as well as local software enterprises are becoming increasingly more confident and are ready for a much brighter future." (Jui, 2010)

The Chinese software industry ecosystem is represented in Figure 5.29.

Figure 5.29 – Chinese software industry ecosystem

The Chinese industry ecosystem is tightly coupled, with all the stakeholders in close coordination with each other. With a manpower strength of approximately 4 million, and a rapidly growing VC sector, the Chinese industry is poised to drive ever higher. This ecosystem is an example of the "hybrid model", which is a characteristic of Chinese success in almost every field.

We turn now to a case study of a major Chinese software entity, to examine how innovation takes place in the software industry in China.

5.3.3.1 Case Study: SAP Laboratories China

(This case study is based entirely on the book *“Innovation in China: The Chinese Software Industry” by Shang-Ling Jui*, who has headed SAP Laboratories China now for over 20 years. It offers a unique account from a bona fide qualified insider on every aspect of innovation that is sought to be researched in this thesis. From the research perspective, the book can be viewed a documented exercise in participant observation).

Founded in the 1970s in Germany, SAP is well known as the world’s largest provider of Enterprise Resource Planning (ERP) software systems. As the name implies, ERP systems are suites of programs that link together all data and information relating to enterprise’s operations. ERP systems allow organizations to function more efficiently and with greater flexibility, thus allowing them to respond rapidly and compete effectively in changing environments.

As a company founded in Germany that possessed a product which could be deployed anywhere in the world, it was natural for SAP to establish organization structures that could address the markets in different countries. These structures were tailored to the skills available in a country; thus, it was decided that the United States, India and China offered potential for more than only sales of SAP products. This decision led to the setting up of R&D centres, later called “SAP Labs”, in each country, which were development centres that would work in close coordination with SAP R&D headquarters in Germany. Over the decades, Canada, Israel, Hungary and Bulgaria were added to the list of countries with SAP Labs.

The setting up of the SAP R&D centre in China began in 1995, and in 2002 it was officially titled as SAP Labs. Its growth can be broadly divided into three phases. In the first phase, beginning 1995, SAP Labs China executed projects for SAP HQ on an outsourcing basis. The work consisted mainly of coding and product localization work, with the specs and design remaining within the purview of HQ. This led to SAP Labs China acquiring a good base of skills and competencies. In the second phase, starting 2002, the China entity was given ownership and control over some products, although these were initially only China-centric, with overall responsibility still resting with HQ in Germany.

In the third phase, still ongoing, they became responsible for the complete innovation value chain for some products. Shang-Ling Jui refers to this as the "transition from Made-in-China to Innovated-in-China" (Jui, 2010)

The second phase has been described in some detail by Jui. Recognizing that China was a fertile market for solutions aimed at small to medium-sized enterprises, SAP China was given the task of defining the spec and design for two specific new products, both to be based on and derived from the flagship R3 product, called the SAP All-in-One and SAP Business One products. They were also offered the opportunity to take ownership of the development process. To meet this challenge, China Labs set up a development unit which they called the Collaborative Business Solution Center, which acted as a central warehouse for all information from potential customers at one end to the testing and delivery teams at the other. This won high praise from HQ, and enabled China Labs to propose even higher degrees of autonomy and participation in fundamental innovation processes. Consequently, China Labs plays an important role in the development of SAP's next generation of products, called SAP Business-By-Design.

The movement from being an average outsourcing center to an innovation hub that serves the global SAP ecosystem took about 15 years in all.

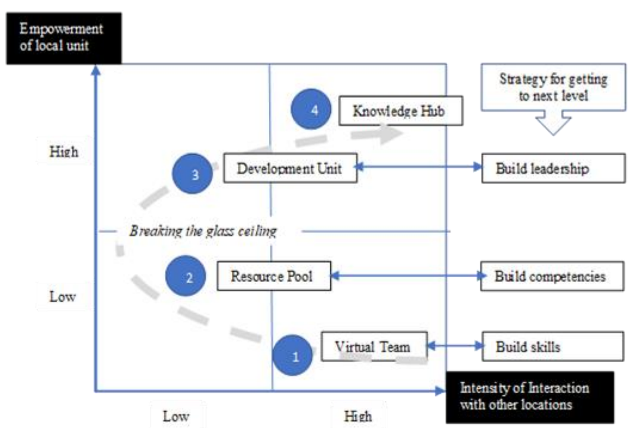


Figure 5.30 - SAP Labs China evolution to knowledge hub

Figure 5.30 shows the transition path followed by SAP Labs China (Jui, 2010). The stages 1 through 4 show how the focus shifts, from outward looking to inward looking and then outward looking again. The "glass ceiling" barrier between low-level and high-level work is also highlighted.

However, the most significant insight provided by Jui is his location of SAP Labs China within the software innovation model Jui calls the "Industry Smiling Curve", as depicted in Figure 5.31.

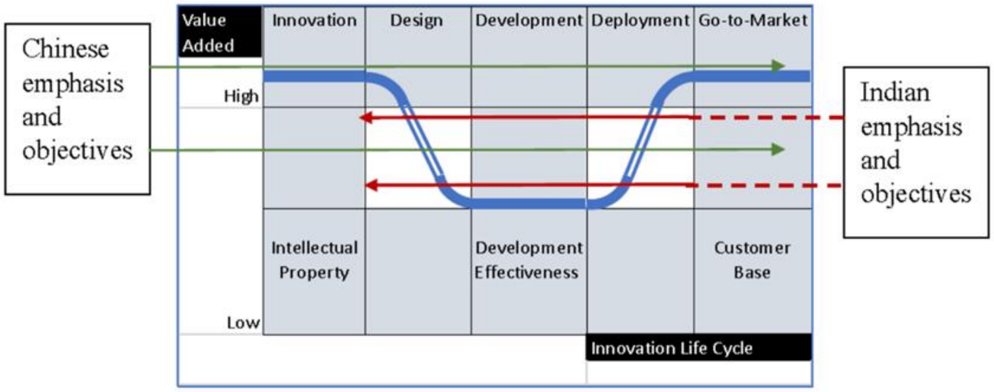


Figure 5.31 – Evaluation of Chinese & Indian Smiling Curves by Shang-ling Jui

Jui claims that SAP Labs China covers the entire value chain, or life cycle, from creative conceptualization, which he identifies as the Innovation and the source of intellectual property, through the design, development, deployment and go-to-market phases.

Jui also critiques the Indian model and claims that the Indian industry has not made sufficient attempts to enter the creative conceptualization and go-to-market phases. According to him, the Indian industry has preferred to limit themselves generally to the Design, Development and Deployment phases. The comparison is depicted in Figure 5.31 above.

Jui attributes the success of SAP China Labs in achieving this status as due first to the nature of leadership that has evolved, namely, one which has as its objective competing on an equal basis on the innovation benchmark, rather than only financial benchmarks which he claims are the hallmark of the Indian IT industry. From the very beginning, his objective as the unit head was to perform on the same level as his counterparts at SAP HQ. Second, the collaborative environment built up within his unit – called SAP Inspire – encourages the sharing of knowledge and information in order to spark innovative thinking.

This has led to the setting up of the "Innovation Club", which is dedicated to the promotion of positive interaction between SAP China Labs and the entire ecosystem. The "entire ecosystem" is described as not only only SAP offices and employees, customers and partners, but also CEO's, CIOs, experts and other representatives from government, academia, other research labs, and a wide variety of other industries and companies of all sizes. The Innovation Club currently has more than 50 members.

Although Shang-Ling Jui is the head of SAP Labs China, he is also consciously a part of China's governing elite, a fact which he refers to on multiple occasions in his book. From his book, it is apparent that he sees his role as going beyond what is routinely expected from the head of a business unit, to include active inputs to policymakers. Thus, his book states on the very first page:

> "The core idea of this book is that China's software industry should and can possess its own complete innovation value chain. The global software industry is now stepping into a new era of globalization, resulting in a new wave of value redistribution throughout the world. This represents an excellent development opportunity for the Chinese software industry. Against such a backdrop, China's software industry should make most of its advantage facing the global industry and build a complete innovation value chain for the industry, so as to eventually switch from "Made in China" to "Innovated in China". I do believe that China possesses all the domestic and international prerequisites to accomplish such a historic transformation."

5.3.4 Analysis of knowledge processes in China

The Chinese software industry is becoming increasingly global, as evidenced by the increasing level of venture capital and private equity investments, from both Chinese and overseas sources. It is significant that the number of "unicorns" that have emerged in China is growing at a rate faster than India.

The SAP China Labs case study shows that the Chinese are capable of mastering the entire innovation value chain in a highly competitive environment. It also demonstrates that the governing elite of the industry, which includes policy makers as well as industry heads, has set as its major objective the "catching up" of its industry with the US.

From the knowledge processes perspective, in which the VC industry has been shown earlier to exhibit the five basic processes, we may conclude that the SAP case study and the rising number of unicorns demonstrate that all the five knowledge processes of search, select, absorb, generate and disseminate operate at high intensities in the Chinese software industry. We may further conclude that this intensity of operation of knowledge processes is not confined only to the companies and the commercial sector, but also to the government and allied stakeholders as well as the research and education sectors. This has led to the emergence of a "tightly coupled" ecosystem, which is another example of China's successful evolution of a Hybrid Model, with close collaboration and alignment between the public and private sectors.

Finally, the third parameter – the extent of VC penetration as measured by the ratio of investments to revenue – is also significant. With a VC penetration of about one-third of the US, the rate at which Chinese innovation is increasing, as indicated by the number of unicorns, is impressive. Recent Chinese policy pronouncements of an emphasis on AI – the tune of $60 billion – show that China is serious about catching up with, and if possible, exceeding them, the United States through a strategy of concentrating on emerging technology areas.

5.4 Similarities and differences in China and India of knowledge processes

For a researcher of innovation, the software industry offers especially fertile ground for investigation. First, the science is truly global, unrelated to any specifics of material properties or their variations, for example. Second, by an accident of history, the industry evolved during the economic globalization cycle which began in the early 1960s, and thus became accessible to all countries and people at approximately the same time. Third, the consequence of globalization was a common business model that evolved and was adopted across countries; namely, first angel capital that funds innovation, then venture capital that funds growth, and then finally the entry into the stock market leading to maturity and wealth generation. There are virtually no barriers, for example, to VC firms operating equally freely in the US, China or India. This permits researchers to use a common set of parameters to compare countries.

To develop this discussion by comparing knowledge processes related to innovation in the software industries of China and India, we will use two frameworks. The first is the extent of venture capital penetration in the industry, as measured by VC investments as a percentage of industry revenue. Our justification for this is that the VC decision process, as demonstrated earlier in this chapter, is contingent on the rigorous application of the five knowledge processes of *search, select, absorb, generate and* *disseminate* to every potential client. *The VC industry, in this sense, is the custodian within the software industry of the knowledge processes that describe innovation*. Thus, aggregate VC penetration allows us to measure innovation at the industry level. The second framework is the Smiling Curve model of software innovation at the organizational team level, which describes the process as consisting of five serial phases of creative conceptualization, where the real innovation takes place, design development, deployment and finally go-to-market. During each of these phases, the five knowledge processes of search, select, absorb, generate and disseminate come into play. The Smiling Curve model allows us to analyze knowledge processes at the organizational and team levels.

At the aggregate or macro level, we have demonstrated that global VC investments as a percentage of global industry revenue averaged 8.34% for the period 2005-2015 and 9.49 for the period 2007-2017, or approximately 9.00% for the 12-year period. During the 2005-2015 period, VC investments as a percentage of the Indian industry revenue was 1.46%, and for China during the period 2007-2017 was 3.41%. Thus, the VC penetration in India was 16% of the global figure, while in China it was 38%. We may conclude from this that the VC industry, which as mentioned before is global in character and focused on innovation, views China as over twice as attractive to invest in as India. Therefore, we may conclude that China displays double the innovation intensity in software as India, as viewed through the VC lens. This implies further that knowledge processes as related to innovation operate at a higher level of effectiveness in China than they do in India.

To understand how and why knowledge processes operate differently in China and India, we must move to the organizational and team levels. To accomplish this, we will combine three elements of the foregoing discussion, namely first the Smiling Curve framework, second the Knowledge Processes framework, and finally the country -specific case studies. The combined analysis is presented in the table shown in Figure 5.30, in which KP1 to KP 5 represent the five knowledge processes of search, select, absorb, generate and disseminate.

Country Case	Creative Conceptualization					Design					Development					Deployment					Go-to-Market				
	KP1	KP2	KP3	KP4	KP5	KP1	KP2	KP3	KP4	KP5	KP1	KP2	KP3	KP4	KP5	KP1	KP2	KP3	KP4	KP5	KP1	KP2	KP3	KP4	KP5
China SAP	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
India Case 1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	×	×	×	×	×	×	×	×	×	×
India Case 2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	×	×	×	×	×
India Case 3 - TCS	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
India Case 4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√

Figure 5.32 – Consolidated view of knowledge processes in five case studies

Let us now analyze each case in detail using this perspective.

1. *SAP China Labs* has clearly executed all the five KPs effectively over the entire Smiling Curve. Therefore, we can assert that *two processes specifically have been executed well, namely the Select process and the Generate process*. This means that China Labs selected:

   - the appropriate product areas in which to conceptualize creatively
   - the right design approaches
   - the right development strategy and teams
   - the right mode of deployment
   - the right go-to-market strategy

In addition, China Labs were able to successfully innovate in each segment of the Smiling Curve. We can conclude from this that a contributing factor was the *clarity of objectives provided by the leadership team*, namely, that SAP Labs China should aim to *compete on a completely equal basis on the innovation dimension.*

2. *India Case 1* related to a new opportunity arising from a new concept of a relational database. The Indian company did not succeed in capitalizing on this opportunity, but in the US their contemporaries like Oracle and Ingres did, going onto to become multibillion-dollar corporations. *All three companies successfully innovated across the creative conceptualization, design, and development stages of the Smiling Curve*. *The difference was in the Deployment and Go-to-market stages*. While the American companies chose to deploy their product across a variety of platforms, the Indian company chose only their proprietary platform. The Select criteria were different, leading to a fatal constraint on the Indian attempt. As regards the Go-to-Market stage, we can

conclude that the Indian company selected the wrong marketing strategy, while US companies selected the correct one, and that therefore the *Select KP was executed with different parameters by the three companies*. India Case 1 also exposes the *weaknesses during the 1980s in the industry ecosystem*, specifically in the relationships between the government, the financial markets and industry

3. *India Case 2* related to the potential of the Internet for education delivery using an online platform. Once again, the same patterns as observed in India Case 1 are to be found here. The failure of the Indian company was in the Go-to-Market strategy, which is precisely where the US company succeeded, thus highlighting again the *importance of the correct Select criteria* while executing knowledge processes.
4. *TCS,* like SAP Labs China, represents successful implementation of all five knowledge processes across the entire Smiling Curve. The history of TCs shows a consistent ability to correctly *Select* the options that work best both strategically and tactically. As the company which pioneered the body shopping model, including the processes to handle immigration in the US and European countries, make payments to engineers overseas under a restrictive currency regime, and in many other ways, TCS has been particularly adept in *process innovation* i.e. the *Generate* knowledge process.
5. *Indian Case 4* presents identical features to SAP Labs. The company was small and agile and had correctly selected the right strategies across the entire Smiling Curve. Company D has clearly executed all the five KPs effectively over the entire Smiling Curve. Therefore, we can assert that *two processes specifically have been executed well, namely the Select process and the Generate process*. This means that Company D selected:
   - the appropriate product areas in which to conceptualize creatively
   - the right design approaches
   - the right development strategy and teams
   - the right mode of deployment
   - the right go-to-market strategy

These five cases illustrate two important findings.

One, the industry ecosystem has a significant effect on the ability of companies to innovate. When all stakeholders are coupled reasonably well, success has followed in both countries. Whereas the Chinese government has made it publicly clear their commitment to supporting the software industry, the Indian ecosystem is still evolving, and still has several exposed fault lines as evidenced by two of the four Indian cases, although Company D and TCS present heartening evidence that the evolution may be proceeding well.

Two, within the ecosystem, the Select knowledge process has been demonstrated to be the most critical for innovation success. The choices made by companies and teams can lead to vastly different outcomes from virtually identical starting points. This was evidenced most dramatically in the India Case 2, where a difference in go-to-market outlook – with the Indian company looking at return on investments, while the US counterpart eyed the global market – turned out to be the difference between success and failure.

We may use these observations to highlight the importance of a fundamental of innovation theory and research, namely, the S-curve. Innovation always takes place in relation to S-curves, specifically in the intersection between two of them. Knowledge processes allow companies and teams to become aware of where the opportunities lie and where they are located on an S-curve. Effectively executing the Select KP leads a company to innovation success. But for success to occur, the ecosystem in turn needs to be proactively alert to opportunities on industry S-curves and encouraging of innovation by companies. China's hybrid model seems to be oriented to encouraging innovation, and this empowers the industry to set its objectives higher to industry leadership rather than only financial success.

What has succeeded in India is the "blended onsite+offshore" model first innovated by Texas Instruments and then adopted by virtually every Indian IT company of note, like TCS has shown. India caught that particular S-curve at exactly the right time, contemporaneously with the birth of the Internet. This has led to huge financial success, with the industry crossing $ 150 billion in revenue and generating unprecedented wealth in India. But this only reinforces Shang-Ling Jui's observation that the Indian industry has been content to work largely in the design/development/deployment phases of the Smiling Curve, where the value added is less, but the financial rewards are still high enough to be attractive to the stock market. However, the Indian industry's close links with the US, due to the presence of the large Indian diaspora in that country, particularly in Silicon Valley, has also led to the "startup plus VC" culture diffusing into India.

These observations become magnified when we recall that India, in many ways, started at a more advantageous position as compared to China. India had three great comparative advantages – widespread knowledge of the English knowledge, an established educational infrastructure, and a growing and cooperative Indian diaspora in the US and Europe. Where China seems to have performed better is in the clear objective of catching up with the US across the entire value chain.

A second area where China has been advantaged is in the ready availability of finance in the introduction and growth stages of the S-curve, as remarked upon by Jui. This reflects the strength of the Chinese Hybrid Model, which enforces a greater degree of collaboration between all stakeholders including government policy makers. In contrast, three of the four Indian companies in the cases above identified lack of finance as one of the principal reasons for the failure of their innovation. This lacuna may however be mitigated as the industry grows in size and global presence. We should conclude from this that the Indian ecosystem needs to evolve to a more tightly coupled level.

To round off this discussion of how India and China compare in the knowledge processes perspective as applied to the software industry, we observe that both countries are now behind only the United States in software. We can also observe that the number of unicorns is growing in both countries. In the light of this, both countries can be said to be competing fiercely in the global market, and by all indications will be able to improve their relative performances. Clearly the differences in the software sector are not as stark as in the case of the supercomputer sector.

5.5 *Discussion*

This chapter follows the Research Design and the previous chapter in constructing a comprehensive case study on the IT software industry in three parts; the global software industry, the software industry in India and the software industry in China. It conforms to the Design by incorporating several shorter case studies of innovations in the software sector in the two countries.

Before moving on to a discussion of the outcomes of this chapter, it is necessary to apply the quality criteria set out in the Research Design to the content, as was done in the previous chapter. To recap, the criteria are credibility, transferability, dependability and confirmability. In this chapter, as in the previous, credibility is established by reliance on explicit knowledge in the form of books, articles and other forms of documentation prepared by recognized authorities in the field. For example, I have quoted extensively from Shang-ling Jui, the head of SAP China Labs who is also, as mentioned earlier, an important member of the Chinese governing elite. Transferability has been established, as before, by a chapter structure which can be applied to any other major country. Dependability is established by reliance on authoritative sources for all economic and financial data; given the importance of such data to the analysis of the software industry, NASSCOM and OECD reports have provided much of the data for the Indian and Chinese industries respectively. Finally, confirmability has been established, as in the previous chapter, by reference to explicit records and the use of the "reportage" style in the shorter case studies.

The software industry in China and India, indeed globally, is different from the supercomputer industry din the reduced role of government and the greater role of market forces. The conceptual framework of five knowledge processes has been applied to the venture capital decision mechanism and case studies in this chapter, and found to be valid, thus strengthening the case for generalization of the framework. The additional insight gained is that the framework is this valid in market driven environments as well. More significantly, this chapter highlights the importance of a strong ecosystem even in market-driven industries. This is especially so for small companies, as the four Indian case studies illustrate.

The next chapter, on small defence technology companies, will examine specifically the issues faced by smaller companies in managing innovation and growth. This selection is based on the common understanding that Information Technology is pervasive in the defence sector. The sector is often referred to as a "public good', justifying thereby the duty of citizens to support it financially through taxation. All over the world, the defence sector has historically provided opportunities for small companies to start and flourish. It can be hypothesized, therefore, that the defence sector may offer insights into how an ecosystem can be supportive and empowering for innovation in small companies. Small companies are also representative of a very important characteristic of innovation that has been demonstrated in the Literature Survey and these two chapters; that innovation takes place in small groups and small teams that network with each other through knowledge processes. The next chapter, therefore, will concentrate on how ecosystems need to develop in the modern world to empower small companies capable of innovation.

Chapter 6

The small defence technology companies sector

The chapters on supercomputers and the software industry established a conceptual framework of knowledge processes as related to innovation and brought into the discussion the impact of the ecosystem on innovation patterns. This chapter will build on these insights by examining technological innovation in one of the oldest ecosystems historically, the defence sector. The reason for the choice of the defence sector as the context for this chapter are threefold; first, the sector has been associated with and has been the source of well-known innovations; second, the defence sector has been the springboard for many small companies to achieve their early successes on the road to scaling up; and third, Information Technology is pervasive in all 21st century defence systems. Thus, the choice of defence as a context is not a departure from the Information Technology focus of the field research; it is rather an opportunity to examine the role of a typically well-defined ecosystem in fostering innovation in small companies and small teams. In some important ways also, as this Chapter will show, the defence sector has become one of the many domains of critical Information Technology applications.

6.1 The context – technology and innovation for defence

From the dawn of history, technology has been associated with wars and warfare. It has been remarked that "technology, more than any other force, shapes warfare (not war); and conversely war (not warfare) shapes technology" (Roland, 2009). As a result, technological innovation with the aim of shaping warfare has been in evidence throughout history. In ancient Greece, third order equations were stated to be useful for calculating ballistic trajectories, an example of what we would today call scientific research. Similarly, Dionysius I, ruler of Syracuse, recruited skilled people to work on new weapons of war, which today we would call applied research or research and development (Roland, 2009). Closer to today, the "Mysore" rockets designed and produced in the kingdom of Tipu Sultan became the model for the 19th century Congreve rocket, the first mass produced battlefield rocket of the modern age. In the twentieth century, technology assumed strategic significance in all domains of national security. In the 21st century, there are visible signs of technology even displacing human beings in many national security situations.

This chapter begins with two assumptions: first, it is unnecessary to restate the history of technology in national defence since it is common knowledge in every sense, and second, nation-states evolve integrated ecosystems within which technological innovation takes place continuously in the service of national security. Empirical evidence for the validity of both assumptions is readily available in the domain of common knowledge. We may, therefore, take it as a given that all nation states, or at the minimum those confident enough of pursuing independent strategies, have developed ecosystems that conform to the model we have already described in the previous chapters on supercomputers and software. Figure 6.1 below reproduces the basic ecosystem model, consisting of eight elements, all of which feed the innovation process.

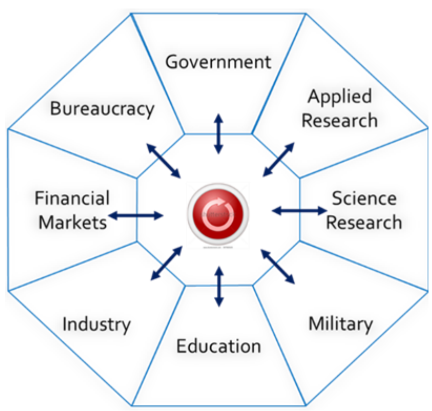


Figure 6.1 – General diagram of a sector ecosystem

This depiction of a defence ecosystem allows for the participation of the government and private sectors in varying degrees. At one extreme, all eight elements can be completely under government control, as was the case in the erstwhile USSR or China prior to the liberalization drive initiated by Deng Xiaoping. At the other extreme, the private sector would be responsible completely for the financial markets, industry, education and perhaps a significant part of the scientific and applied research elements. In most countries in the 21st century, including India and China, the defence ecosystem would allow for coupling with varying degrees of strength between the government and private sectors within the eight elements.

Among the innovations which have emerged from a modern defence context, the development of the stealth fighter aircraft at the Lockheed SkunkWorks during the 1970s, which was examined in some detail in the example cases analysis in Chapter 2, is often cited as an exemplar of the spectacular results that innovation can achieve (Lockheed Martin, 2010). Although its parent organization, Lockheed-Martin, is an extremely large corporation, the SkunkWorks team that worked on the stealth project was small and traditionally received adequate and not extravagant funding. These factors afford some relevance and some lessons for the issues faced by small companies.

Since the objective of this chapter is to examine the role of the ecosystem in fostering innovation in small companies, we will use the SkunkWorks stealth fighter development as the bellwether for this chapter, and as the *first reference point* to evaluate case studies from the Indian and Chinese small defence companies sector.

To understand policy issues related to SMEs in general, and to evaluate to what extent Chinese and Indian policy initiatives address these issues specifically in the defence sector, we will draw upon the extensive body of literature available to construct a summary of major issues that SME's face. This will be used as the *second reference point* for evaluating the nature of the interactions between SMEs and the defence ecosystems in China and India, specifically with regard to innovation.

6.1.1 First context reference point - the SkunkWorks stealth fighter project.

The outlines of the project, excluding the classified aspects, are available widely in the public domain. To summarize, in 1975 the US Air Force came to a determination that the Soviet surface-to-air-missiles (SAM) batteries, which were radar-guided and radar-controlled, posed a threat that needed to be countered by an aircraft which could somehow evade radar. Five companies were awarded contracts of one million dollars each to develop a proof-of-concept, but Lockheed was included in addition at the last moment and decided to take on the project at their own cost within SkunkWorks.

Starting from a theoretical paper written by a Russian mathematician Pyotr Ufimtsev, which related to the mathematics of diffraction and had nothing to do with weapons systems, the SkunkWorks team worked out that an aircraft surface consisting of hundreds of triangular or rectangular plates with sharp edges, arranged like an extremely large three-dimensional jigsaw puzzle, could be constructed in a way that would present a reliably low radar reflection. Converting this to a static model for the proof of concept required first writing a software program on a Cray supercomputer, which Lockheed later patented. This was the first time anywhere that the design of an aircraft started with a computer simulation, proving an indication of the extent to which Information Technology would become pervasive in defence.

In 1976, just one year later, the USAF awarded the manufacturing contract to Lockheed based on the successful proof of concept. The production-version aircraft, given nomenclature as the F-117, received Initial Operational Clearance ten years later in 1986, and flew the first combat sortie during Operation Desert Storm in 1991.

For the purposes of this chapter, we will look at two aspects of the stealth project; one, what it tells us about the nature of knowledge processes during the project; and two, the guidelines under which the SkunkWorks project team operated, particularly in reference to its processes for interaction with its parent organization, the military, and the bureaucracy, or in other words, the ecosystem.

6.1.1.1 Knowledge processes

This case presents features illustrating how knowledge processes operate iteratively, and how even small teams need to interact with the entire ecosystem. We first propose a hypothetical deconstruction of how the project proceeded, as in Figure 6.2.

From Figure 6.2, it can be inferred that the five knowledge processes framework conceptualized in Chapter 4 is validated by at least two of the known steps in the stealth project, as evidenced in the public record (Lockheed Martin, 2010); namely, the ***selection*** of the Ufimtsev paper and the ***selection*** of the Cray supercomputer as the computational platform. From the public record, again, we can see that the ***Generate*** knowledge process that has been proposed as the “innovation process” in our framework, is a viable description of the ten-foot stealth fighter proof-of-concept, christened the “Hopeless Diamond”.

SkunkWork stealth aircraft project analysis by Knowledge Processes			
Full Team	**Manufacturing Team**	**Computational Team**	**Knowledge Process Objective**
Search			for possible approaches to avoiding radar detection by an aircraft
Select			**a candidate approach; in this case the paper "Method of Edge Waves in the Physical Theory of Diffraction" by Pyotr Ufimtsev**
Absorb			the contents of the paper (within the team)
Generate			a proof of concept model through a two-stage process
		Search	for an appropriate computing platform for the simulation program
		Select	**based on some parameters (a Cray supercomputer in this case)**
		Absorb	and train staff on the programing environment of the Cray
		Generate	**and test the simulation program**
		Disseminate	the results to the rest of the team responsible for constructing the proof of concept
	Absorb		and convert into a manufacturable format the results of the simulation (itself another iteration of the knowledge processes)
	Generate		**i.e. construct a proof-of-concept model "Hopeless Diamond"**
	Disseminate		this to an internal test team
Disseminate			**the model to the external testing team from the USAF**

Figure 6.2 – Hypothetical Analysis by Knowledge Processes of the stealth project

The Hopeless Diamond was generated completely based on the results of the Cray simulation program and is shown in Figure 6.3. This experimental application of the knowledge processes framework to the stealth fighter project, resulting in the validation of the Select and Generate concepts, adds justification for generalization of the framework.

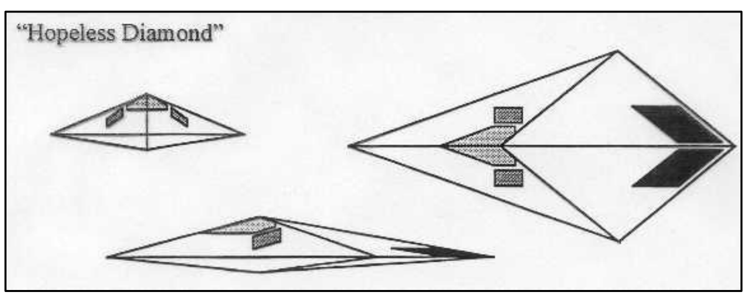
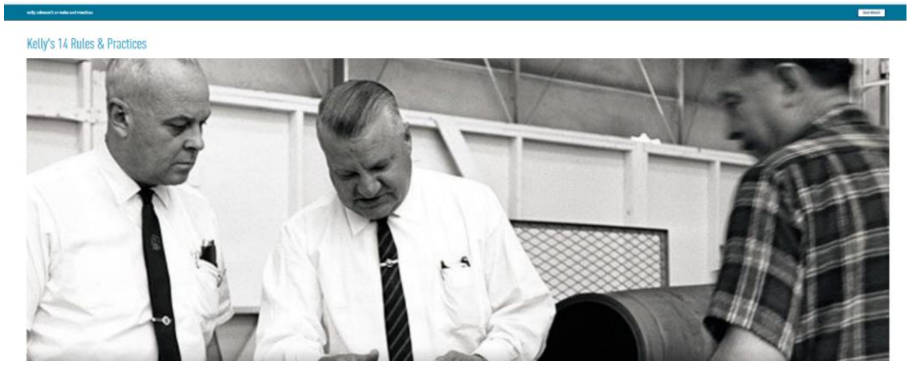


Figure 6.3 – The generated conceptual shape of the proof of concept

6.1.1.2 Processes for interaction with organizational and external ecosystems

The stealth project was only one of the many projects that SkunkWorks had undertaken after it was first set up in 1943. In the decades that followed, SkunkWorks succeeded in putting in place a *simple, flexible and effective* “way of working” that consistently produced innovative solutions to difficult problems. This became documented as “Kelly’s 14 rules and practices”, named after Kelly Johnson, the former head of the SkunkWorks unit, and reproduced in Figure 6.2.



1	The Skunk Works® manager must be delegated practically complete control of his program in all aspects. He should report to a division president or higher.
2	Strong but small project offices must be provided both by the military and industry.
3	The number of people having any connection with the project must be restricted in an almost vicious manner. Use a small number of good people (10% to 25% compared to the so-called normal systems).
4	A very simple drawing and drawing release system with great flexibility for making changes must be provided.
5	There must be a minimum number of reports required, but important work must be recorded thoroughly.
6	There must be a monthly cost review covering not only what has been spent and committed but also projected costs to the conclusion of the program.
7	The contractor must be delegated and must assume more than normal responsibility to get good vendor bids for subcontract on the project. Commercial bid procedures are very often better than military ones.
8	The inspection system as currently used by the Skunk Works, which has been approved by both the Air Force and Navy, meets the intent of existing military requirements and should be used on new projects. Push more basic inspection responsibility back to subcontractors and vendors. Don't duplicate so much inspection.
9	The contractor must be delegated the authority to test his final product in flight. He can and must test it in the initial stages. If he doesn't, he rapidly loses his competency to design other vehicles.
10	The specifications applying to the hardware must be agreed to well in advance of contracting. The Skunk Works practice of having a specification section stating clearly which important military specification items will not knowingly be complied with and reasons therefore is highly recommended.
11	Funding a program must be timely so that the contractor doesn't have to keep running to the bank to support government projects.
12	There must be mutual trust between the military project organization and the contractor, the very close cooperation and liaison on a day-to-day basis. This cuts down misunderstanding and correspondence to an absolute minimum.
13	Access by outsiders to the project and its personnel must be strictly controlled by appropriate security measures.
14	Because only a few people will be used in engineering and most other areas, ways must be provided to reward good performance by pay not based on the number of personnel supervised.

Figure 6.4 – Kelly’s 14 rules and practices

One of the key principles followed was the emphasis on small, highly skilled teams, that worked on low budgets but with a high degree of independence. This allowed them to interact whenever required directly with key stakeholders, thus cutting out a lot of red tape. Kelly's 14 Rules also became the inspiration for Steve Jobs in his way of working at Apple (Lockheed Martin, 2010).

From these 14 rules and practices, we can abstract a framework for the processes of interaction of SkunkWorks with the eight components of the external ecosystem, as shown in Figure 6.5.

Rules	Interactions with
1& 2	Military, Industry, (company)
3	Industry, Education, Applied Research, Scientific Research
4	Military and (company)
5	Military, Bureaucracy, (company)
6	Military, Bureaucracy, (company)
7	Military, Bureaucracy, (company)
8	Military, Bureaucracy, (company)
9	Military, Bureaucracy, (company)
10	Military, Bureaucracy, (company)
11	Financial markets, Military, Bureaucracy, (company)
12	Government, Bureaucracy, Military, (company)
13	Military, Bureaucracy, (company)
14	(company)

Figure 6.5 – Processes for interaction with eight components of ecosystem

"Kelly's 14 rules and practices" shows that even small teams in the defence domain need to interact with all eight components of the ecosystem to achieve repeatable successes. The converse should also be stated, namely, that the success of the SkunkWorks stealth fighter project shows that a responsive ecosystem can play an empowering role in innovation. It is this second aspect that will be investigated in greater detail in this section.

The SkunkWorks stealth project presents a microcosm of the interactions of a highly successful small innovation project team with the organizational and external ecosystems. It thus forms one suitable reference point for understanding how small defence companies in China and India function, and the similarities and differences with the SkunkWorks template and between the two countries.

6.1.2 Second context reference point - General challenges facing SMEs internationally.

Innovation challenges in small and medium enterprises (SMEs) has been extensively studied and researched intensively (Hung, Tu, & Whittington, 2008). Understanding these challenges provides useful peer-reviewed input on the special challenges that SMEs face in the defence sector. In recent years, many authors have consolidated such findings into more comprehensive lists. From the literature, a summary list of twenty challenges commonly faced by SMEs internationally has been selected based on sources cited and consolidated lists prepared by Alqahtani (Alqahtani, 2016), Bozkurt & Kalkan (Bozkurt & Kalkan, 2014), and Cordeiro & Vieira (Cordeiro & Vieira, 2012), and is shown in Figure 6.6.

Author(s)	**Description**
Piatier (1984)	Lack of government support as an important barrier to innovation in European countries
Silva, Leitao & Raposo,	Lack of financing channels
Vieira (2007)	Lack of skilled employees
	Lack of marketing information and high technology
	Organizational rigidity
Tiwari and Buse (2007)	Low budgets
	Difficulty in recruting adequate human resurces
	Bureaucracy
	Poor cooperation between enterprises
Madrid - Gujjaro	Incomplete government policies and regualtions
Garcia and Auken (2009)	Uncertain economic environment
	Lack of high qualiy human resources
Demirbas (2010)	Lack of state policies to support technology and R&D
	High cost of innovation
	Lack of appropriate approaches for raising funds
	Lack of qualified personnel
Kamalalian, Rashki	Excessive business risks
and Arbabi	Insufficient economic resources
	Unavailability of funds
	Costs associated with innovation

Figure 6.6 – Common barriers to innovation faced by SMEs

Using the eight-component framework for an industry ecosystem developed in this thesis, the distribution of SME innovation barriers according to ecosystem component is shown in Figure 6.7. Next to it is depicted the distribution of interactions by SkunkWorks, again according to ecosystem component. This provides a perspective on which barriers policymakers should concentrate on mitigating, if the SkunkWorks ideal of repeatable successful innovation is to be emulated. In the charts below, data pertaining to three components, namely Education, Applied Research and Scientific Research have been combined into one called Trained Human Resources.

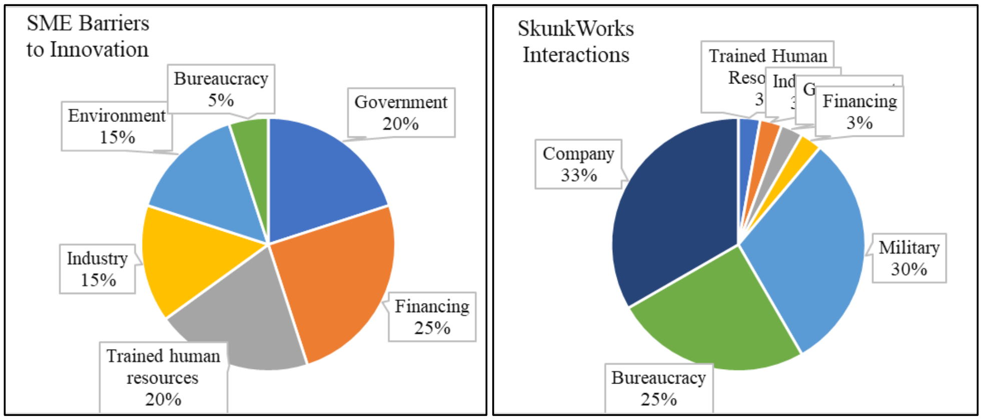


Figure 6.7 – SME Innovation Challenges & SkunkWorks ecosystem interactions

Figure 6.7 shows that SkunkWorks interactions with the government, industry, financing, and trained human resources components is *low, amounting to 12% of process focus*. In simple terms, SkunkWorks can concentrate on its work with the military and bureaucracy, taking into account its internal company policies, without having to worry too much about availability of financing, availability of trained manpower, interaction with the rest of the industry, or government policies. In contrast, the same four components amount to *80% of the challenges in general for SMEs internationally*, giving a clear indication of where policymakers should focus in order to empower innovation in SMEs for defence.

The next two sections set out some details on steps taken in China and India to respond to these challenges through policy initiatives. The country sections in this Chapter will differ in structure from the previous chapters on supercomputers and the software industry, for the following reasons. First as mentioned in the Background, the existence of an ecosystem that effectively meets the strategic and security requirements of a modern nation-state can be assumed. Second, the ecosystem is very large and complex, rendering a detailed analysis of the ecosystem structure of questionable value for the limited purposes of analyzing innovation in small companies. In the next two sections, on small defence companies in China and India, the structure will consist of four parts; a short case study of a small company, details of recent policy initiatives regarding innovation in defence, and an analysis of the possible impact of these initiatives. The chapter will round off with an analysis of knowledge processes at the ecosystem and organizational levels in the SME defence sectors in China and India.

6.2 Small defence companies in China

In the four decades since economic liberalization was initiated in China, small companies that operate as subcontractors to the Chinese military have emerged in sizable numbers. With Information Technology considered increasingly critical for the security of the Chinese state, the role of small companies has assumed increasing importance. As one observer writes, “China’s next-generation bomber, for example, is unlikely to be developed by a small start-up in Changsha. China’s next great cyber tool, on the other hand, might very well be.” (Sheldon & McReynolds, 2015).

In the larger context of encouraging innovation, China has instituted major policies at a frequency of approximately a decade. After the start of economic reform in the early 1980s, the first major policy steps regarding science and technology were the 863 programs, already referred to in Chapter 4 on supercomputers. During the 1990s, two important documents were issued regarding its R&D policies, the 1995 Decision on Accelerating Scientific and Technology Progress and the 1999 Decision on Strengthening Technological Innovation and Developing High-Technology and Realizing Industrialization. In 2006, the 15 -year Medium-to-Long-term Plan for the Development of Science and Technology, or MLP, as it came to be called, was instituted. In 2015, several initiatives specifically for the defence sector, termed as Civil-Military-Integration policies, were announced (Orr & Thomas, 2014).

To understand how SMEs in China have fared under these policy umbrellas, and the extent to which innovation has been empowered, this section starts with a short case study of a typical Chinese SME.

6.2.1 Case Study of a small/medium-sized company (SME)

(This case study is drawn from interviews with an exhibitor at the 16th China Products Exhibition held in Mumbai, India on November 22-24, 2018).

Company A is a small company located in Shenzen prefecture in China. Founded in 2003, it has a registered capital of US$ 100,000. It had reached a turnover of $ 20 million by 2015. The employee strength is 55.

Company A is engaged mainly in the development and manufacture of sensors and monitoring instruments for industrial processes. Its products are used in the military, automotive, civil engineering and automotive process monitoring

The company is strongly oriented towards R&D. It has its own R&D center, the expenditure on which is 8-10% of revenue. It keeps up with the latest trends in sensor and monitoring technologies and has a history of patenting its innovations. It collaborates with overseas companies on international projects and updates its understanding of technologies in the process. It was successfully ISO 9001 certified for its manufacturing processes in 2008.

Company A has been successful in establishing long-term partnerships with universities and research institutions. The National University of Defence Technology, Qinghua University, Chinese Academy of Engineering Physics and the "202" Department of Weapons Industry (government), are among its active collaborations.

Company A's business records show that it launched an average of 10 new products every year from 2008 to 2014. It registered an average of 8 patents per year during that period. These propelled its sales forward at an average of 15% per annum. ***According to the management, its strength is collaborative partnerships, which help its innovation performance. The roadblocks, on the other hand, arise from capital shortages, intellectual property disputes and shortage of skilled manpower***.

A significant aspect of Company A's operations is proactive collaboration with customers and suppliers in addition to research institutions and universities. As one manager put it, the conventional relationships with suppliers are no longer adequate for companies in the 21st century. Company A has therefore consciously embraced the "open collaborative innovation paradigm" and cite improvements in the bottom line as evidence of the usefulness of such an approach. That said, there have been no radical innovations, as per the Henderson taxonomy, which have emerged from Company A. Their innovations have been generally incremental or architectural. The occasional modular innovation – of a series of sensors which QSYC manufactured for a European client – has been the result of reengineering rather than original innovation.

6.2.2 SME innovation policy initiatives in the Chinese defence sector

During the 1980s, the Chinese government took the first of many major policy initiatives to promote science, technology, and R&D with the objective of catching up with and then overtaking the major powers, especially the United States. Collectively, these initiatives have come to be known as the 863 programs and are extensively documented and studies in the literature (Liu, Serger, Tagscherer, & Chang, 2017). These initiatives were primarily top-down in approach, and it widely accepted that the programs have been successful to a considerable extent (DIA, 2018). It is not the objective of this thesis chapter to retrace the ground already covered by other researchers, but instead to reference a few indicators of China's approach to small companies and innovation in them (Booz & Co, 2012).

Among these were the extraordinary step of permitting researchers in many of the main science and technology research institutes to promote and incubate companies under the banner of their institutions. For example, in the Chinese Academy of Sciences alone, dozens of small companies set up in this fashion were able to flower over the years, including in the supercomputer sector as indicated in Chapter 4. But the major focus of the policies at that time were on the large-ticket projects that could accelerate the catch-up process (Kim & Mah, 2009).

This process was stepped up in the 1995 reforms, which concentrated on high level economic incentives. Among these, the key policies were tax incentives, establishment of science parks, and increasing its financial support for R&D activities (Herrnstadt, 2008). In 1999, these measures were augmented with a further slate of incentives, including a partial tax deduction for R&D expenditures; a tax exemption for all income from the transfer or development of new technologies; a preferential 6% value-added tax rate for software products developed and produced in China; complete VAT exemption and subsidised credit for high-tech exports; and the listing of new high-technology companies on the Shanghai and Shenzhen stock exchanges, and, at the same time, to encourage infusion of advanced technology through FDI (Greeven, 2006). The Chinese government explicitly stated its objectives as building an innovation-based economy by nurturing indigenous innovation capability; developing an enterprise-centred technology innovation system and promoting the innovation capabilities of Chinese firms; and making a great leap forward in targeted strategic areas of technological development and basic research (Kim & Mah, 2009).

In January 2006, China announced its now well-known MLP, or the "Medium- to-Long-Term Plan for the Development of Science and Technology". The objective of the MLP was primarily for China to become an "innovation-oriented society" by the year 2020, and to develop "indigenous innovation capabilities (*zizhu chuangxin*)" (Booz & Co, 2012). The MLP called for investment of 2.5% of its GDP in R&D by 2020, and limit its dependence on imported technology to no more than 30% (Cao, Suttmeier, & Simon, 2006).

In 2015, the encouragement of small, innovation-oriented firms in the defence sector in China became one of the pillars of the overarching Chinese policy called Civil-Military-Integration, or CMI as it is usually called (Zhang & Luo, 2013). CMI, is a phrase used to emphasize the importance of dual use technologies, policies and organizations for military benefit. The Chinese equivalent is "*Yujin Yumin*", which translates approximately as "locating military potential in civilian capabilities" (DIA, 2018), and was first highlighted by Deng Xiaoping in the mid-1980s. This was underscored in 2017 by President Xi Jinping, who urged "great attention to the development of strategic, cutting edge technologies", thus highlighting the importance of innovation as a central component of Chinese national strategy (DIA, 2018).

CMI has been projected not only as a key enabler of the PLA's military-technological modernisation, but more importantly, as a strategy for China's long-term sustainable growth, efficiency and productivity gains, as well as for mitigating internal socio-economic and environmental challenges. At the same time, China's CMI places strategic importance on acquisition of dual-use technologies, resources, and knowledge from foreign sources in selected priority areas. China is continuously benchmarking emerging technologies and similar high-tech defence-related R&D programmes in the United States, Russia, India, Japan, Israel and other countries. This strategy has been called 'indigenous innovation', and aims to circumvent the costs of research, overcome international political constraints and technological disadvantages, and 'leapfrog' China's defence industry by leveraging the creativity of other nations, making CMI the principal pathway for China's long-term strategic competitiveness (DIA, 2018). Recent Chinese policy pronouncements have shed some clarity on how this is sought to be accomplished.

In 2015, in a major policy measure designed to attract private investment in its defence sector, China initiated "mixed-ownership reform" (MOR) referred to a "Hungai" in Chinese (Yang, 2017). MOR proposes to "securitize" China's defence assets in to induce competitive performance and thereby attract investment. Among the steps that have been taken so far are:

1. Declassification of over 3000 dual-use technology patents
2. Release of 2346 other patents to the public
3. Opening of more defence projects to private contractors

Among the other steps envisaged under MOR are the integration of defence research institutes into the private sector (SSN, 2017). The key problem in this is the reclassification of sectors into core business involving state secrets, the public welfare business relating to the national economy and people's livelihood, and the commercial business participating in the market competition.

However, this measure ran into problems of implementation because of "lack of supporting policies" (SSN, 2017), specifically as regards taxation policies and the redeployment of personnel. The "people problem" was especially significant as many state secrets were held in the form of know-how by employees of research institutes, who might face problems in redeployment into industry. In addition, the definition of "property" also had to be suitably changed to accommodate all situations, as returns on property values was not a consideration when the research institution was set up originally.

Finally, while the Chinese government considers private investment infusion essential for the transformation of the industry, the process is made difficult by the poor financial performance of many state-owned enterprises (Shanghai ICC, 2016). Figure 6.6 gives a sample of the performance problems involved.

China Defence Companies Performance 2016-17			
Company	**Domain**	**Debt / Asset Ratio**	**Return on Equity ROE**
China Electronics Technology Corporation	Informatics	33%	10%
China Shipbuilding Industry Corporation	Naval ships, carriers		1.73%
China Shipbuilding Power Corp.	Ship equipment		6.05%
Aviation Industry Corporation (14 subsidiaries)	Aircraft	>50% debt	<10%
CSSC Science & Technology Ltd	Shipbuilding	63.92%	5.12%
COMEC	Shipbuilding	77.50%	1.47%
China CSSC Holdings	Shipbuilding	67.88%	0.20%

Figure 6.6 – China Defence Companies Performance 2016-17

Such poor, indeed abysmal, performance makes it very difficult for private investors to consider seriously investing in Chinese defence companies, even though the investment community accepts that timelines for returns from defence are much longer than traditional civilian sectors. There are three additional problems which investors face:

i. China’s defence industry only accepts RMB funds, effectively limiting the scope for foreign direct investment
ii. Lack of information and transparency, leading to rampant insider trading
iii. The industry is still commanded by the “plan”, which force the investors to operate within constraints which are absent in other sectors.

For principally these reasons, Chinese financial analysts have signalled that it will be very difficult for China to build a “military industrial complex” comparable to the US unless basic structural reforms aimed at removing state monopolies are undertaken. Given the current geopolitics between China and the US, this is unlikely any time soon (Yang, 2017).

6.2.3 Potential impact of Chinese CMI initiatives

For the purposes of this chapter, despite the forty-year history of Chinese R&D policies outlined above, we will concentrate on the decade 2010-2019 as the focus for discussion. The discussion will be from two perspectives; first, an evaluation through the available literature of the outcomes of the earlier policies and the status as of 2010, and second an evaluation, to the extent possible, of the streamlining of the innovation framework for small companies, and whether it is approaching SkunkWork levels of simplicity, flexibility, and efficiency.

By 2010, many of the initiatives from the 1980s and 1990s had borne fruit dramatically as China's GDP expanded at virtually double digits for twenty years, and China had moved to the status of a "middle income country" (Booz & Co, 2012). Well known instances were the development of high-speed railways, the huge expansion in infrastructure across the country, and the startling quick transformation of China into a global manufacturing hub. However, both to casual observers and academic researchers, it was apparent that a high proportion of the advanced technological growth, as opposed to low-tech manufacturing, continued to be located in big-ticket projects rather than in innovation from small companies. This was leading China into the so-called "middle income trap" i.e. to advance from a from a middle-income country to a high-income country, in the catch-up paradigm for large countries such as China and India, requires moving forward from factor inputs and institutional development to fostering innovation, particularly in the SME sector (Liu, Serger, Tagscherer, & Chang, 2017).

This status in development, baselined effectively at 2010, is shown in the Figures 6.7 and 6.8, sourced from the referenced paper by Liu, Serger, Tagsherer and Chang.

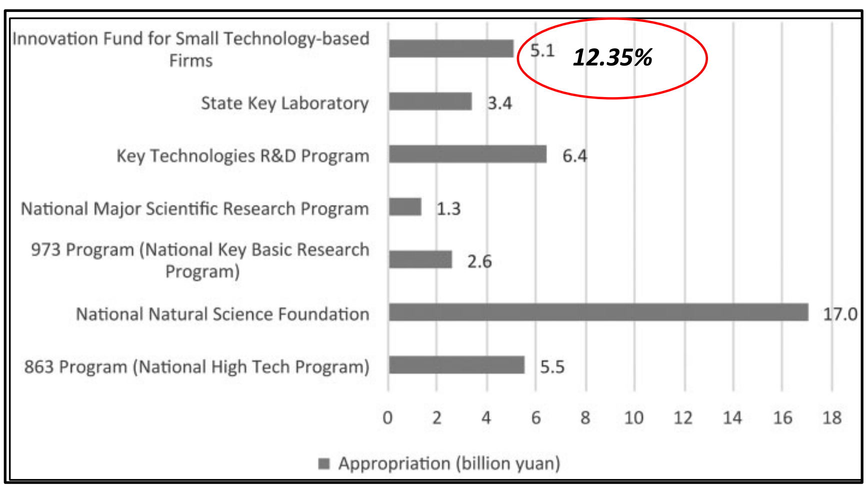


Figure 6.7 – R&D funding for SMEs in 2010

Table 1. Shares of government funds for S&T activities in high technology industry, 2004–8					
	Number of enterprises in high tech industry	Gov. funds as share of total S&T funds (in per cent)	Number of state-related enterprises in high tech industry	Gov. funds as share of total S&T funds (state-related), (in per cent)	Gov. funds to state-related enterprises as share of total Gov. S&T funds to high tech industry (in per cent)
2004	17898	5.2	2856	10.7	79.3
2005	17527	5.3	2179	11	79
2006	19161	5.3	1960	10.4	83
2007	21517	6.9	1817	20.4	75.8
2008	25817	8.4	1743	23.4	76.7

Figure 6.8 – Government funding for S&T 2004-2008

The data in Figure 6.7 shows that R&D spending for SMEs was 12.35%. More revealing, perhaps, is the data in Figure 6.8. During this period the number of SOEs in high-technologies reduced by 40% in absolute numbers and declined from 16% to 7% as a percentage of the total number of high-technology enterprises, even as the total number of such enterprises increased by over 40%. Despite this, the share of government S&T funding that went to State Owned Enterprises (SOEs) remained in the range of approximately 75-80%. This clearly showed that China remained, in 2010, a top-down, big project-oriented nation.

This analysis provides us a perspective to understand the CMI initiatives of 2015. At the macro level, to move to a high-income status as a country, China needs its SOEs to perform at the same levels of efficiency as the private sector, not just in China but on international benchmarks as well. At the same time, it needs to foster innovation by encouraging R&D in SMEs (Zhang, Zhinhua-Zheng, Mako, & Seward, 2009). The solution that has been adopted as policy is to focus on the defence sector and try and achieve these objectives in three ways; by financially reengineering defence SOEs and research institutions through divestment of unproductive assets including land, by encouraging private sector investment in defence SOEs, and by encouraging dual-use technologies through sharing of patents for civilian applications. This is an admirably innovative approach to encouraging broad-based innovation in SMEs (Chen, 2017). The question is whether these initiatives will succeed in meeting expectations.

As indicated above, the response from the private investment community has unfortunately been less than enthusiastic. Constraints such as investment only in RMB, the abysmal financial performance of defence SOEs, the lack of effective policies for managing organizational change, the continued opaqueness of government data, and the pervasive corruption; all these are red flags to any private investor. Without outside investment, China will find it difficult to make the transition to the high-income status she aspires to.

The literature also offers broadly similar opinions. For instance, Liu, Serger, Tagsherer and Chang offer the following comments:

> "One of the main findings is that of a visible evolution of China's innovation system, based partially on a changing view at the top echelons of government on innovation but revealing also a

> significant degree of policy learning within the government as well as recognition of realities and changes in innovation dynamics. While the change in the premise of innovation policy is impressive, we have also shown that moving from an investment-driven to a truly innovation-driven model for development requires far-reaching changes in institutions, policies, financing, steering mechanisms, views, and culture. Some of these are likely to happen 'on their own' as the Chinese innovation system matures, others will require further changes in government policy in order for them to happen."

In a similar vein, Abrami, Kirby and McFarlan, writing in the Harvard Business Review in 2014 (Abrami, Kirby, & McFarlan, 2014), concluded:

> "Certainly, China has shown innovation through creative adaptation in recent decades, and it now has the capacity to do much more. But can China lead? Will the Chinese state have the wisdom to lighten up and the patience to allow the full emergence of what Schumpeter called the true spirit of entrepreneurship? On this we have our doubts.
>
> The problem, we think, is not the innovative or intellectual capacity of the Chinese people, which is boundless, but the political world in which their schools, universities, and businesses need to operate, which is very much bounded."

We return now to the two points of reference stated in the first part of this chapter, namely, the SkunkWorks innovation model and the general challenges faced by SMEs and attempt to situate the Chinese SME sector within those two perspectives.

As indicated in Figure 6.7, there are four ecosystem interaction areas where policymakers need to concentrate to empower SMEs to innovate effectively. These are, streamlining interaction with government, making available trained manpower, enhancing industry collaboration, and most important, ensure adequate financing. These were also the stated concerns of Company A in the case study above.

On the first metric, government interaction, the Chinese resistance to change is palpable from the reports in the literature, as quoted above. Conditioned by decades of top-down driven authority, China's government and bureaucratic culture will not easily adapt to a reduction in direct power. The second and third areas of manpower and industry collaboration have been addressed effectively by the Chinese state, as evidenced by the high output of publications and patents.

On the financing metric, the picture is opaque, due to lack of data which has been stated earlier as a limitation of this study. Some basic observations can however be made. To begin with, the financing perspective for an SME is quite simple. A small company needs equity and debt for growth. For innovation, working capital debt is more important, which may require dealing with banks or approaching the company's investors and "selling" them an idea instead of a product or a service. To mitigate such issues, the United States has a highly effective and well-established system of proactively funding technology proof-of-concepts on a competitive bid basis and then awarding much larger manufacturing contracts to the winner. This kind of limited funding at the proof of concept stage, without having to approach banks or its own investors, is exactly what an innovative SME needs to showcase its capabilities. It also limits government financial risk. The F-117 is a standout example of the efficiency of this system; the USAF obtained a stealth aircraft fleet in just 10 years from POC (proof of concept) to IOC (initial operational clearance), for a total POC outlay of as low as $ 5 million distributed among five competitive bidders in 1975. Whether the Chinese system has become as adaptable and agile on the financing and procurement dimensions as the US military cannot be evaluated at this time by this researcher, due to the limitations of access to information as described in the Research Design.

We turn now to the Indian case, to assess the similarities and differences to the Chinese situation.

6.3 Small defence companies in India

The defence industry ecosystem in India bears the clear imprint of the historical pedigree that was born under the East India Company and then became institutionalized under the British Crown (Chaudhari, 1978). In its imperial worldview, India was one of the many subject countries under the Empire (Rivett-Carnac, 1890). Consequently, any activities related to armaments development and manufacture were restricted in scope and kept under the strict control of the imperial Indian government. This perspective, of the government controlling everything, persisted beyond 1947, in many respects even to the present day.

Post-Independence, the structure put in place by the new Indian government continued to be influenced by the past pattern of complete governmental control, but with a new twist. Responding to the need for high-technology R&D and manufacturing in the post WW II scenarios, organizations such as Defence Research and Development Organization (DRDO), Hindustan Aeronautics Limited, and Bharat Electronics Limited were set up (Nayan, 2012). The Ordnance Factory Board (OFB) continued to be responsible for the manufacture of all types of gun and artillery, and later of tanks. In this structure for defence R&D and manufacturing, the Indian government followed the same template as in other sectors, namely, one organization for every specialization in a sector (Nath, 2007). Competition between multiple government and public sector organizations, which was encouraged by China and to some extent even by the USSR in the "socialist" bloc, was absent in the Indian paradigm. In this respect, the defence sector also became a domain of *"monopoly socialism"*, to use the term coined by this researcher in Chapter 4 on supercomputers.

The 1962 conflict with China was a watershed moment for the Indian armed forces (Cohen & Dasgupta, 2010). Till then, they had accepted the principle of self-reliance, or indigenous sourcing, to the maximum extent possible. Following the 1962 setback, the armed forces demanded and obtained the right to procure equipment based on a competitive bidding basis inclusive of foreign vendors, on the principle of the "best equipment available within budget". This immediately acted as a dampener on indigenous efforts, with the armed forces openly expressing their preference on many occasions for equipment from overseas vendors. From the mid-sixties to the present day, it is possible to draw a straight line from the early imports of the MiG-21 in 1963, for example, to the present situation where India is the world's largest arms importer.

Till the economic liberalization policies of 1991, the alternative to imports continued to be overwhelmingly the public sector. There was only limited presence that was achieved by the private sector. Recognizing, however, the rapid strides in technology internationally and the burgeoning success of many private technology companies during the 1990s, particularly in software, the private sector started to receive more attention from the Ministry of Defence. In 2006, there was a new version of the Defence Procurement Procedure (DPP) that was unveiled, including for the first time an ambitious offsets policy designed to improve the level of technological capability in both the public and private sectors. Since then, there have been a number of policy initiatives designed to be more inclusive of the private sector, particularly SMEs. In 2018, innovation in defence was announced formally as a major objective (MOD, 2018).

To assess the impact of these policies, from an innovation perspective, on small defence technology companies in India, a case study is presented first, as in the section on China.

6.3.1 Case Study of an SME in the Indian defence sector

(Company B is based in Bangalore and has been extensively interviewed by the researcher.)

Company B specializes in the manufacture of real time control systems for the defence, maritime, space and industrial sectors. It was set up almost 30 years ago and has gone through several restructurings and rejigs.

The company is an important partner of the Indian nuclear submarine program, and also does work for the Indian space program. The Founder-Managing Director is a respected engineer with a PhD in engineering. The company has always succeeded in attracting top level technical staff because of the nature of the work, but their tenure in the company has also always been low because of salary levels.

The company has a business model with an R&D-based approach, involving:

- Study of the technical problem
- Designing an innovative solution
- Proposing the solution to the department concerned
- Obtaining the contract and implementing the solution

The high quality of the work done and track record over the years assures the company of contracts on a practically single tender basis. By the very nature of its business, the company works in the defence sector in a project to project mode.

Despite an excellent track record, the company has often struggled financially, for the following reasons:

1. The procurement procedures of the Indian Ministry of Defence mandate a project contract award of every project, including repeats, through a separate tender procedure.

2. Revenue flow is therefore not assured or regular.
3. The business model of designing innovative solutions and then proposing them requires the company to invest initially from its own funds.
4. Raising funds from banks is difficult because of procedures requiring collateral and other similar factors.
5. Raising funds from other financial institutions, including venture and private equity funds, is difficult because of ignorance of the defence sector within the investment community, and because the returns from other sectors are often judged to be higher.
6. So far there has been no IPO for a defence company in the Indian stock market. Consequently, the capital market is closed off as a source of funds for the moment.
7. Government has no structure or policies to financially support such innovation-oriented companies, although there are recently some encouraging signs.
8. This has implications in terms of the quality of engineers who can be employed.
9. Similarly, it becomes difficult for the company to set up infrastructure that would meet international standards.
10. Increasing requirements for certification and standards from the Indian military is a cause of concern from the financial perspective.
11. Money gets locked up in the form of bank guarantees, acting as a brake on efficient working capital management.
12. Payments from the Ministry of Defence are frequently delayed, exacerbating working capital issues.

The working capital finance problem is represented in the following diagram:

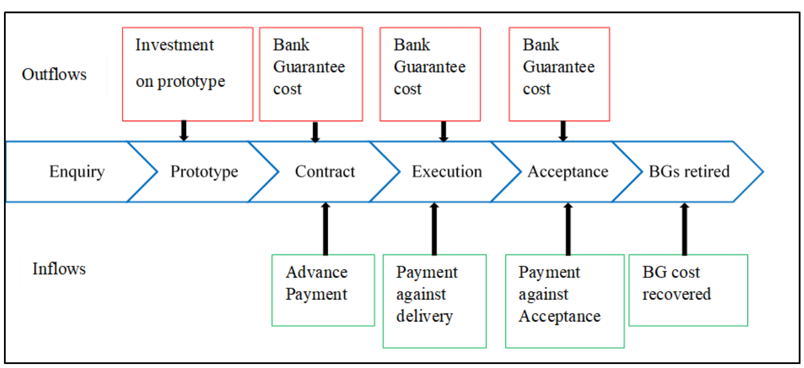


Figure 6.9 – Company B working capital inflows and outflows

Figure 6.9 shows why companies like Company B are always facing a cash crunch. The operating cycle is very long, typically 360 days from enquiry to final retirement of the bank guarantees. There are four stages of investment required by the company, for which the funds come either from a bank or from the investors as a loan. Justifying speculative expenditure at the enquiry and prototype stages to bankers and investors, for example, is always a problem for the management. Invariably, the bankers and investors attempt to push the business risk back to the company. Added to this are the interest and other establishment costs, which can be quite high in India due to high interest rates. This leads to a situation where companies such as this make healthy gross margins on projects, in the range of 30-50%, but are unable to convert this to a meaningful level of profits to enable growth through contracting for larger projects. Company B finds itself "always running to the bank for money to support government projects", in the language of Kelly's 14 rules from SkunkWorks.

Thus, any project whose execution extends to more than a year is beyond the scope of Company B, leaving it stuck in a stagnant situation from a business perspective, but highly prized by the armed forces, principally the Navy, for the quality of its technology and innovativeness of solutions.

Recently, the company has managed some financial infusion from a small boutique private equity fund. The PE fund is planning a strategy of acquiring another 2-3 companies in the defence sector and consolidating them under one banner. The fund has indicated it may then attempt the first IPO in India of a company specializing in defence technologies.

6.3.2 SME innovation policy initiatives in the Indian defence sector

The Indian government R&D organizations and public sector units in the defence sector have acquired considerable technological expertise in the seventy years since Independence, even if there were no obvious breakthrough innovations compared to those achieved in other countries. China's Anti-Ship Ballistic Missile (ASBM) system, analyzed earlier as an example case in the Literature Survey, is a good instance of a very large-scale innovation unmatched even by the US. However, the Indian record is also good in many respects, with the Integrated Missile Development Program (IMDP), which is DRDO's flagship program, holding pride of place.

Nevertheless, for the reasons mentioned, India has become the world's largest arms importer, with competition only from Saudi Arabia occasionally. The growth trajectory of imports is cause for concern for a country as large as India, from the strategic as well as economic perspectives. These concerns are the drivers of recent policy initiatives aimed at restoring a degree of self-reliance and encouraging innovation. Figure 6.10 shows India's arms imports from 1960 to 2017 (World Bank, 2018).

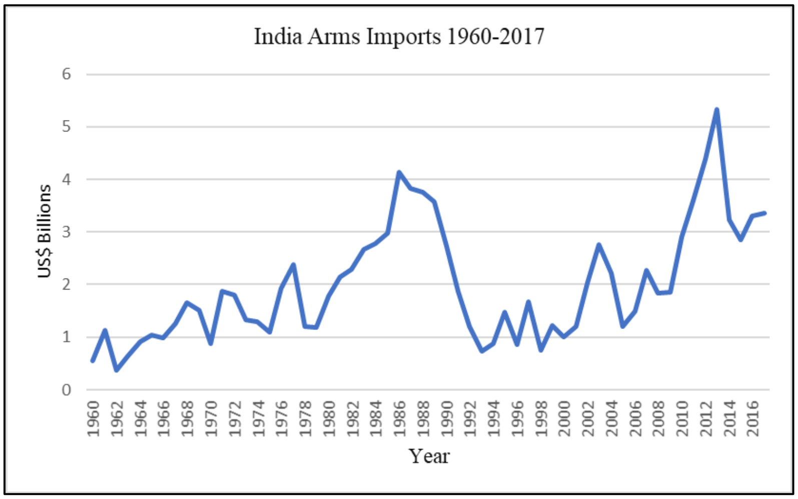


Figure 6.10 – India's arms imports 1960-2017 in US$ billions

The Government of India undertook two major steps between 2016 and 2018 to reduce imports, encourage technology transfers and indigenous manufacture, and empower innovation especially in SMEs (DDP, 2018). These were:

1. *Liberalization of the investment regime*, comprising the following:
   i. Foreign direct investment (FDI) up to 100% allowed
   ii. Investment up to 49% allowed by the automatic route; above that to 100% will require permission to be given on a case by case basis

   For all defence companies with foreign investment, licenses for operation will be required as before.
2. *Encouragement of innovation in defence technologies*:

   This is an unprecedented initiative by the Indian government in the defence sector. The plan is titled "Innovations for Defence Excellence (iDex)" and is to be implemented by two organizations, namely, the Defence Innovation Organization (DIO), and the Defence Innovation Fund (DIF) (MOD, 2018).

iDex is patterned on the concept of "Corporate Venture Capital" whereby large corporate organizations seek to engage with small startups and innovators to improve their own products and services. The Corporate VC model works though a smaller, more agile setup affiliated to the parent organization and utilizing funds set aside specifically for that purpose.

The stated objectives of iDex are to:

i. Facilitate development of innovative technologies for the defence and aerospace sectors
ii. Create a culture of engagement with startups and MSMEs to encourage co-creation of technologies
iii. Empower a culture of co-innovation and co-creation within the defence and aerospace sectors

The DIO and DIF will be jointly responsible for the implementation of this ambitious concept. The major modus operandi for implementation will be the creation of Independent Defence Innovation Hubs (clusters) at various locations in the country, which will hopefully develop into innovation ecosystems very quickly. Figure 6.11 (sourced from the Ministry website) depicts the structure and roles of various components and organizations comprising the iDex plan.

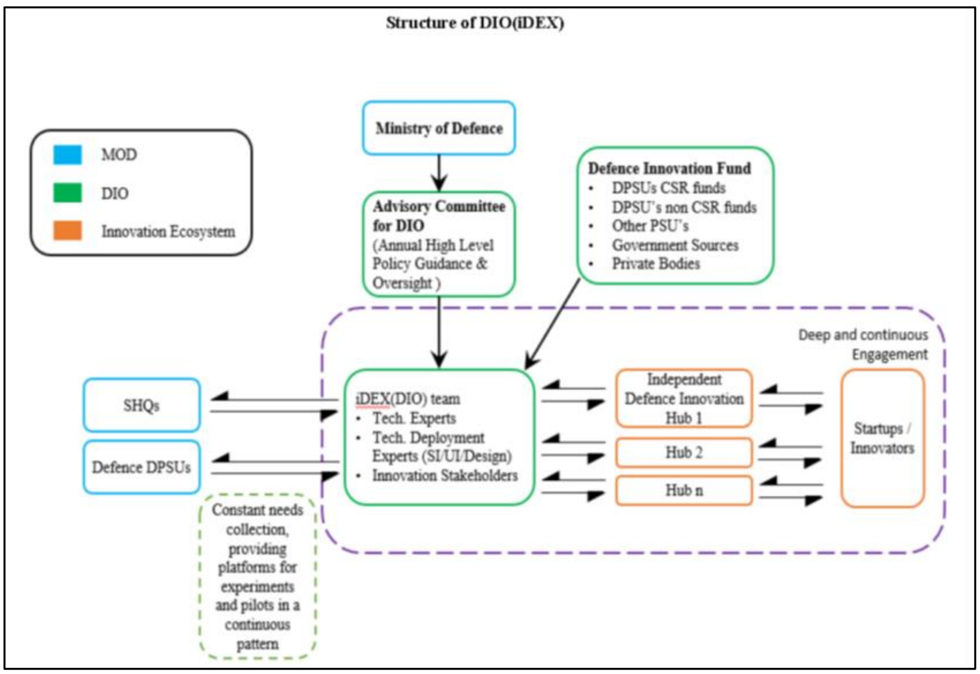


Figure 6.11 : Structure of Indian DIO (iDex)

6.3.3 Potential impact of Indian defence policy initiatives

Liberalization of the investment regime

As stated by the government, the objective of the first of the two policy initiatives listed above, namely, the changes in FDI regulations for defence-related companies, is to reduce the import bill by providing incentives for foreign vendors to manufacture in India rather than restricting themselves to sales and support. In the process, the decrease till 2013 in the index of self-reliance, which measures the indigenous content of equipment, is sought to be reversed (Behera, 2013). This objective is aligned with the "Make-in-India" policy framework which has been announced by the government. The goal of Make-in-India is broadly to increase self-sufficiency and thereby spur economic development.

However, analysts have pointed out that the new FDI policy also aims to mitigate two other challenges. First, the Indian defence budget has been shrinking as a percentage of GDP. Second, of this budget, the proportion of personnel costs has been rising sharply, forcing compromises in weapons procurement and deployment. Both of these challenges are sought to be mitigated by increasing FDI flows into defence (Pant & Das, 2019). As recently with the case of China, however, implementation might present challenges.

The issue of foreign vendors participating in a joint venture format has already thrown up some vexing issues (Pant & Das, 2019). For instance, can a vendor who is a joint venture partner in one area participate intenders in another area as an overseas supplier? Can an overseas supplier participate in different JVs with different equity percentages? The policy does not address these issues explicitly. A second question is: If a joint venture is to be privileged over an overseas supplier, how is competitiveness to be ensured i.e. how can it be ensured that the best equipment is supplied by the JV? The policy ambiguity in these and a host of other areas will take some time to be ironed out.

Perhaps the biggest issue left unresolved is the efficiency and performance of the government research institutions and the defence PSUs. While China has clearly set itself the objective of bringing the research institutions, SOEs and the private sector to the same benchmarks of efficiency and performance, the Indian government is silent on the issue. Without clarity on these aspects, it seems questionable if the Make-in-India defence policy can meet the stated goals (Pande, 2019).

In summary, the policy appears to have been rolled out without the kind of stakeholder inputs that characterized the 2012 National Policy on Electronics, analyzed in Chapter 4 on supercomputers. As instances of this, the objectives of the Draft Defence Production Policy 2018 are stated inter alia as; achieving self-reliance by 2025, making India one of the largest producers and exporters of defence material, and making India a leader in cyberspace and AI technologies (Pande, 2019). All three objectives seem untenable.

The Innovations for Defence Excellence (iDEX) plan

To evaluate this initiative, we return to the two frameworks in the beginning of this chapter and depicted in Figure 6.7, namely the SkunkWorks Kelly's 14 rules and the twenty SME challenges globally, as placed in the context of the eight elements of an industry ecosystem.

To provide a simple, flexible, and efficient environment within which innovation can take place effectively and repeatedly, as in SkunkWorks, the four most important areas that need to be addressed are *financing, provision of trained human resources, industry collaboration, and government policies*. This will enable SMEs and innovation teams in defence to concentrate on the three other elements, namely, streamlined and close interactions with the military, the bureaucracy and their own corporate environment, if part of a larger group. In concept, the iDEX framework addresses all these elements and concerns well. The details of the plan make for an interesting analysis at both the micro and the macro levels. To begin with the micro level first, we can analyze the potential impact of the iDEX plan as below.

Financing: The Defence Innovation Fund (DIF), which is a part of iDEX, has the role of providing equity finance on a venture capital basis to SMEs. Conceptualized on the lines of a corporate venture fund, the DIF can sidestep the pitfalls of both the defence tender procedures and the inability of Indian banks, under the existing regulatory regime, to provide working capital without collateral or a robust order book. By providing funding in the form of equity, the DIF can participate both in the day-to-day operations as well as valuation-based exit strategies. In case of short-term working capital requirements, the DIF has enough of a corpus to issue short-term debt as well.

Interface with the Applied Research and Scientific Research components of the ecosystem. The iDEX(DIO) team, shown in a green bordered box in Figure 6.11, and consisting of "technical experts, technology deployment experts, and innovation stakeholders", has the depth to perform this role.

Interface with the Bureaucracy and the Military. These are the two primary customers of any SME under the iDEX umbrella, and the iDEX team is clearly positioned to perform this "business relationship management" role, with inputs if required from the Advisory Committee for DIO, if necessary.

Education sector interface and provision of trained human resources. Here again, the iDEX(DIO) team can act as the interface to universities, technology institutes, research institutes, as well as the corporate sector in general, to help steer the right people to an SME if required. The team can also provide inputs for implementation of effective HR policies and the like.

Government policy interface. This would be the principal responsibility of the Advisory Committee.

Industry collaboration. This is the most interesting part of the iDEX plan. By physically locating SMEs within "Innovation Hubs" in different parts of the country, shown in the orange bordered boxes in Figure 6.11, the plan acts as a catalyst of the creation of a local ecosystem for collaboration between SMEs.

The iDEX plan thus provides for effective interaction and knowledge exchange with all eight elements of an industry ecosystem. At the micro level, the essence of the iDEX/DIO/DIF plan is to *remove the task of coordination and engagement with the ecosystem and outsource it to the iDEX team and Advisory Committee*. This should leave the SMEs free to concentrate on the work of innovation.

At the macro level as well, the IDEX plan has an interesting feature not seen before in Indian defence policies. As shown in Figure 6.11, the corpus of the DIF fund will be drawn from the CSR (corporate social responsibility) obligations of defence PSUs as well as non-CSR funding from them, as well as funding from non-Defence PSUs, Government sources and the private sector. The inclusion of all these stakeholders in the Fund structure, as "limited partners" in the argot of the investment community, will ensure that uniform benchmarks emerge over time to evaluate the performance of the SMEs as well as the Fund.

In time, the same benchmarks should diffuse into the PSU world as well as the private sector. Thus, the iDEX plan is conceptualized to achieve the same objectives as China, namely, uniform performance standards in public and private sectors, but with a bottom-up approach instead of top-down.

Among the new policies announced for the defence sector in India, the iDEX plan seems the most carefully conceptualized, with the potential to bring the operations of defence SMEs closer to the SkunkWorks ideal in process terms. This observation provides a platform to discuss next what we can infer from the preceding sections about knowledge processes in the Chinese and Indian defence sectors.

6.4 Analysis of Knowledge Processes in the Chinese and Indian defence SME sectors.

We begin this section by analyzing how knowledge processes, as related to innovation, operate at the small company level. For this purpose, we go back to the discussion of innovation in the Literature Survey. Innovation is a process that takes place to solve an identified problem or capitalize on an identified opportunity. Any team or organization has the option of trying an innovation that is either radical, modular, architectural or incremental, which are the Henderson taxonomy options, based on their assessment of the desired position of the product, technology or company on the relevant S-curve. An additional input to decide on which approach to take is provided by the "Smiling Curve", which includes in concept the Porter and RBV frameworks. In this section, we will use the Smiling Curve as the basis for examining how the "Select" process operates in small companies such as Company A and Company B above. The Smiling Curve is reproduced below in Figure 6.12 (Shin, Dedrick, & Kraemer, 2012).

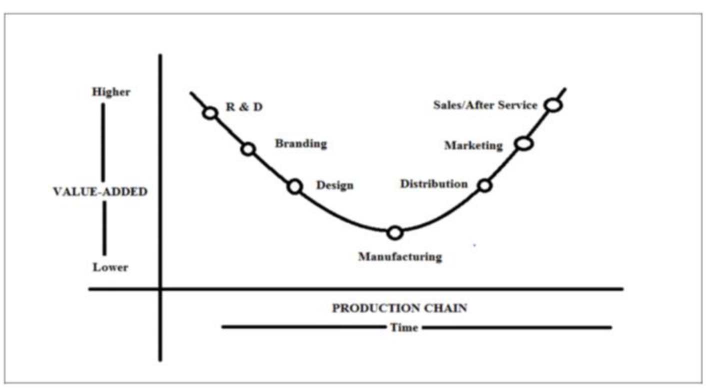


Figure 6.12: General Smiling Curve

Based on the case studies of Company A and Company B, we now analyze how the five knowledge processes operate with respect to the Smiling Curve options. This is shown in Figure 6.13.

Knowledge Process	Company A	Company B
Search	R&D, Branding, Design, Manufacturing, Distribution, Marketing, After Sales Service	R&D, Branding, Design, Manufacturing, Distribution, Marketing, After Sales Service
Select	Design, Manufacturing, Distribution, After Sales Service	Design, Manufacturing, Distribution, After Sales Service
Absorb	Design, Manufacturing, Distribution, After Sales Service	Design, Manufacturing, Distribution, After Sales Service
Generate	Design, Manufacturing, Distribution, After Sales Service	Design, Manufacturing, Distribution, After Sales Service
Disseminate	Design, Manufacturing, Distribution, After Sales Service	Design, Manufacturing, Distribution, After Sales Service

Figure 6.13: Operation of Knowledge Processes w.r.t Smiling Curve

Both Company A and Company B effectively "select out" opportunities for doing work in the high value areas of R&D and Branding. The reason, stated by themselves, is access to finance. In the absence of funding mechanisms for long gestation R&D, which is typical of the defence sector, both Company A and Company B, though adequately staffed with technical manpower, are unable to compete with larger companies, even if they have more innovative solutions. This observation brings our analysis to the ecosystem level.

As before, the role of knowledge processes on innovation in the Chinese and Indian defence SME ecosystems can be discussed at two levels, the macro and the micro. At the macro level can be included the CMI initiatives in China and the FDI liberalization policies in India. At the micro level can be discussed the patent release policies and encouragement of dual-use technologies in China, the iDEX plan in India, and how these can be enablers for SME innovation. In this section, the focus will be on the Select and Generate knowledge processes at the two levels.

At the macro level in the Chinese case, it appears that the Select process operated to identify policies which could act as enablers for China's push to move from a middle-income society to a high-income society. China's middle-income society can be said to be organized in silos such as government, military, bureaucracy, public and private sectors, and the like. A high-income society, on the other hand is characterized by blurring of lines between silos and innovation-intensive industries that are highly integrated into the rest of the nation-state. In this hypothesis, we can say that the Select parameters were "economic development", "integration", and "innovations", and the output of the Select process can be hypothesized as "uniform performance standards", "dual use technologies", "asset utilization efficiencies", and the like. Following the filtering of objectives through the Select process came the creative act of policy creation, resulting in the CMI initiatives discussed earlier. It is noteworthy that, in comparison to the supercomputer sector, the CMI policies are less directly competitive to the United States, and more inward-looking. The Chinese objective seems to be to go beyond the "military industrial complex" paradigm, which by its very terminology implies a closed subsystem with a limited number of industrial players, to a "military industrial economy" paradigm, which is open and welcoming of greater and greater numbers of new industrial players, as England was at the start of the 19th century, when she was beginning to appreciate and consolidate the power of her Empire (Satia, 2018).

At the micro level, however, the Chinese picture is more opaque. As discussed earlier, the response of the private investment community, both Chinese and international, to invitations to invest in Chinese SOEs has been underwhelming. Similarly, it is unclear if the move to make available around 3000 technology patents, held earlier in SOEs and research institutes, to the private sector has had any positive impacts at all. It appears that, unlike at the macro level, Chinese policymakers were rather less clear about which parameters, so to speak, to assign to the Select process at the micro level. The outcome, however, is reasonably clear; the financial markets and industry components of the Chinese defence ecosystem are not yet fully integrated with the other five. Using this inference, we can evaluate the Chinese defence industry ecosystem as *"partially integrated and evolving" and* render it as shown in Figure 6.14.

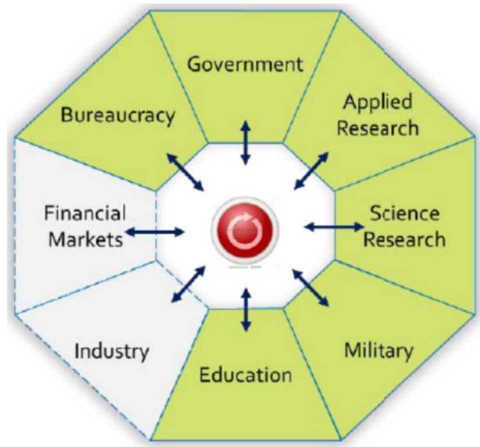


Figure 6.14 – Chinese defence industry ecosystem

At the macro level in the Indian case, the Select criteria can be seen to be different; we can hypothesize that the parameters were "reduction of imports" and "self-sufficiency". It can be noted that the policy announcements focused on the economic aspects and not the technological. As outcomes, we can further hypothesize that "foreign direct investment", "technology transfers", "joint ventures" and the like would have been the outputs. Following the filtering through the Select process would come the creative act of policy formulation, which resulted in the liberalized foreign investment regime announcement. It can be easily seen that "PSU performance improvement" or "DRDO performance improvement" would not have figured as Select criteria, given the nature of the final policy announcement. In this light, we can infer that the Indian defence sector ecosystem is still fragmented and characterized by silos, both in organizations and in policy perspectives. We may characterize the Indian defence ecosystem at the macro level as *"fragmented"*.

In contrast to the Chinese case, at the micro level the Indian picture is very clear. The Select criteria can be hypothesized easily as "innovation" and "MSMEs". The output of the Select process can again be hypothesized as "Silicon Valley model", "venture capital", "clusters" and the like. From this came the creative act of policy formulation resulting in the iDEX plan comprised of the DIO and the DIF and the implementation strategy. As discussed above, the iDEX plan addresses all eight components of an ecosystem. At the micro level, we can characterize the ecosystem as *"integrating*. However, since it is still "fragmented" at the macro level, it is appropriate to describe the Indian defence ecosystem as simply *"evolving"* and render it a shown in Figure 6.13.

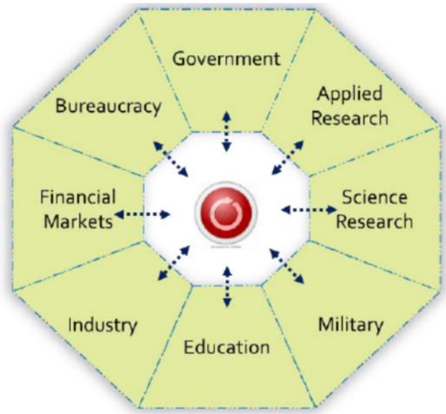


Figure 6.15 – Indian defence industry ecosystem

6.5 Discussion

This chapter completes the formal research portion of this thesis. In structure, it has departed somewhat from the previous two chapters. No description or deconstruction of the larger strategic and security ecosystem of each country has been attempted, as such an exercise would require a separate thesis and is not relevant to the narrower perspective of this thesis, which is to look at knowledge processes in the context of innovation. Consequently, the industry is not analyzed to the same depth as the previous chapters. Unlike the previous chapters, which had included companies of all sizes in their ambits, this chapter focuses on small companies. In the chapter on supercomputers, the bellwether innovation was analyzed in depth to explore and illustrate the applicability of each of the concepts identified in the Literature survey. In the chapter on software, the bellwether innovation was presented as an example of how innovative organizations can evolve. In this chapter, the bellwether innovation is analyzed in some depth and used as a point of reference to understand how innovation can actually "happen efficiently" in small companies and small teams.

As in the previous two chapters, it is appropriate to apply the designated quality criteria to this chapter. As before, all four criteria, namely, credibility, transferability, dependability and confirmability have been ensured by reliance on authoritative documented sources. As before, in the case studies, the style of presentation is neutral “reportage”, with the researchers’ opinions absent. In addition, two reference points, both based on articles and documents in the public record, have been used for analysis of processes at the micro level. This, it is believed, has added to the depth of the analysis.

In this chapter, the five knowledge processes conceptual framework developed in the previous two chapters has been assumed as providing a validated response to the Main Research Hypothesis H_1, namely, that there exist connections between knowledge processes and innovation. It has therefore been applied directly five times in this chapter, first for the analysis of the SkunkWorks stealth fighter project, then twice for the analysis of the business decisions of Company A and Company B, and finally twice for the analysis of ecosystem behavior at the macro and micro levels. The analysis has revealed clear differences in the way knowledge processes at the ecosystem level could work in China and India and the way they impact innovations in small companies. These differences in patterns give some indication of possible response to the Subsidiary Research Question, namely, what are the practices and patterns to be observed in the connections between knowledge processes and innovation in selected Chinese and Indian companies.

The three formal research chapters provide material to construct a more detailed response to the Main and Subsidiary Research Questions, to discuss their implications of the research conducted, and suggest some conclusions and directions for future research. All these are the subject of the next and final chapter, in which the findings generated thus far will be analyzed to move the thesis to its implications and conclusions, to which we now turn.

Chapter 7

Findings, Implications and Conclusions

The first three chapters of this thesis, namely, the Introduction, Survey of Literature and the Research Design, established the theoretical foundation for this research. The next three chapters, on the supercomputer sector, the software sector, and small technology companies in the defence sector, provided empirical data obtained in keeping with the guidelines set out in the Research Design. This brings the thesis to a stage where the detailed findings, their implications, and the conclusions that can be drawn from this research can be discussed.

7.1 Key Findings

Innovation can be viewed as actions based on knowledge that leads to new knowledge. Alternatively, ***innovation is a creative act that generates new knowledge from existing and already available knowledge***. This definition is epistemologically rigorous and allows the inclusion of both artifact and no-artifact manifestations of the processes of innovation. This definition also subsumes the range of possible impacts of new knowledge, from a random act of creativity to systematically creating a public good, allowing the term "invention" to be included within the continuum of innovation.

Innovation cannot be separated from its context. This was established through the Survey of Literature and the Analysis of Example Cases (in Annexure 1). This phenomenologically valid attribute of innovation leads to the inference that, for innovation to be understood, its context also needs to be understood. This inference informs the Research Design and the structure of Chapters 4,5 and 6.

Innovation begins with the identification of a problem, a bottleneck, or an opportunity. This observation was validated through the Literature Survey and the example cases, and empirically through the field research in the three sectors.

Innovation proceeds if the prognosis of possible outcomes is positive. This observation, again, was validated through the Literature Survey, the example cases, and empirical field research.

Innovation draws on a constantly evolving pool of concepts and technologies to find solutions. This observation again was validated in the same manner as the previous two findings. The nature of technological evolution appears similar in many ways to the natural selection mechanism in biological evolution. Because of this constant evolution, new opportunities, problems and bottlenecks will be constantly thrown up, and thus *innovation is and has been part of the natural order always*.

Innovation takes place through different kinds of steps or processes. Validated again through the Literature Survey, the example cases and the empirical research, this finding leads to a response to the Main Research Question. These steps can be iterative and involve feedback loops within formal and informal knowledge networks of people.

Innovation takes place within ecosystems, which can be defined at different levels. This finding was inferred from the empirical research documented in Chapter 4 on the supercomputer sector. At the country level, the ecosystem was shown to consist of eight components; government, bureaucracy, military, financial markets, industry, education sector, applied research and scientific research.

Since innovation is new knowledge crafted from existing knowledge, and since innovation is a process, there are connections between knowledge processes and innovation. This hypothesis, stated earlier in Chapter 3 on the Research Design as Hypothesis H_1 of the Main Research Question, was validated through empirical research documented in Chapter 4 on supercomputers. Consequently, the null hypothesis H_0, stated in the Research Design, as "there are no connections between knowledge processes and innovation", stands invalidated.

Five types of knowledge processes were identified through this research – Search, Select, Absorb, Generate and Disseminate. This finding was inferred from a detailed analysis of the data documented in Chapter 4 on supercomputers. This is a partial finding in response to the Main Question, which was stated as "What are the connections between knowledge processes and innovation?", the full response to which will form part of the material for the next few sections of this chapter.

Knowledge processes operate at all levels at which ecosystems are defined. This finding was inferred from the empirical research documented in Chapters 4,5 and 6.

During the innovation process, implicit and explicit references to various theoretical frameworks can be discerned. This is evidenced through the empirical research documented in Chapters 4, 5 and 6. The most important frameworks referenced, implicitly or explicitly, are the S-curve, the Henderson taxonomy, the Galbraith innovation organizational model, the Porter five forces framework, the Resources-Based-View (RBV) framework, and the Smiling Curve. The last three are closely interrelated, and as already stated in the previous chapters, the Smiling Curve will be used as a framework of reference with the clear understanding in this thesis that such references also include the Porter and RBV frameworks.

Different patterns can be discerned in the practice of knowledge processes in different environments. This was validated by the empirical research documented in Chapters 4, 5 and 6. This finding forms a partial response to the Subsidiary Research Question, that had been framed as "*What are the patterns observed in selected Indian and Chinese organizations with respect to the connections between knowledge processes and innovation?"*, the full response to which will form part of the material in the next few sections of this chapter.

Differences in patterns of the practices of knowledge processes are discernable both at the organizational and ecosystem levels. This finding is similar to, and is an extension of, the previous finding.

The "Select" knowledge process has a significant effect on the differences in patterns and practices both at the organizational and ecosystem levels. This is an important finding that provides insight into the different ways organizations, industries and indeed countries approach innovation.

The extent of integration and coupling between different components of an ecosystem has a significant effect on the patterns of knowledge processes at all levels. This is an important finding that provides insights into the differences in patterns and practices observed between Chinese and Indian organizations.

We will now expand these findings to provide a more comprehensive response to the Main and Subsidiary Research Questions, through building detailed frameworks to understand the nature and role of knowledge processes and networks in innovation at the organizational and ecosystem levels.

7.2 *The nature and role of knowledge processes in innovation*

The Literature Survey in the first chapter of this thesis showed how the study of innovation had gradually progressed during the 20th century from viewing it first as an economic phenomenon, then a societal phenomenon, until it was also recognized as worthy of investigation from the perspective of practitioners. Among the practitioner perspectives, the four most important perspectives were identified as the S-curve, the Henderson taxonomy, the Galbraith organizational model, and finally the Smiling Curve (which subsumes the Porter and RBV models). To tie together these disparate perspectives, it was shown that, starting from first principles, the concept of knowledge offered a rigorous framework for analysing innovation, based on the epistemologically rigorous definition of innovation as new knowledge generated by application of existing knowledge to a new problem or opportunity.

In this thesis, we have analyzed a total of twenty case studies, comprised as depicted in Figure 7.1

Chapter	Number of cases	Details
Literature Survey	10	Example cases
Supercomputers	3	Sunway TaihuLight (bellwether), Indian PARAM series and Tata Eka
IT software industry	5	India - TCS (bellewether) +3, China SAP Labs China
Defence SMEs	2(+1 example)	China Company A, India Company B, (SkunkWorks stealth as bellwether)

Figure 7.1 – Summary of case studies in thesis

The twenty case studies will next be analyzed through three different lenses, first through the lens of the S-Curve stage at which the innovation took place, then the lens of Henderson taxonomy option which was adopted, and finally the lens of the Smiling Curve segments which the organization chose to invest in. Of the 20 case studies, we have evaluated 14 as successes, 2 as partial successes and 4 as failures.

Case	Outcome	S-Curve Stage			
		Pioneers	Growth	Mature	Decline
Apple in the 1990s	Success	√	√		
Philips Compact Disks	Success	√			
Indian watch industry	Success		√		
China ASBM	Success	√			
Sony Trinitron	Success	√	√		
Photolithography process	Success	√			
China single alloy turbine blade	Failure			√	
ISRO charge coupled device	Success	√			
Lockheed stealth prototype	Success	√			
Fairchild Semiconductor	Success	√			
Sunway TaihuLight	Success		√	√	
PARAM supercomputers India	Success	√		√	
Tata Eka India	Failure		√		
Indian IT industry - Company A	Failure	√			
Indian IT industry - Company B	Failure	√			
Indian IT industry - TCS	Success	√	√	√	
Indian IT industry - Company D	Success		√	√	
SAP Labs China	Success		√	√	
India defence SME - Company A	Partial success		√	√	
China defence SME - Company B	Partial success		√	√	

Figure 7.2 - Case studies through the S-curve lens

As shown in Figure 7.2, the successful innovations were all either in the Pioneer or the Growth stage of the S-curve, although some of them were also borderline in the Mature stage and have been shown as such. However, three of the Failure cases were also in the Pioneer stage. We may therefore conclude that the S-curve alone is insufficient from the perspective of focus of knowledge processes.

Case	Outcome	Henderson Model Type			
		Radical	Modular	Architectural	Incremental
Apple in the 1990s	Success	√	√	√	
Philips Compact Disks	Success	√		√	
Indian watch industry	Success	√	√	√	√
China ASBM	Success	√	√	√	√
Sony Trinitron	Success	√	√	√	
Photolithography process	Success			√	
China single alloy turbine blade	Failure		√	√	√
ISRO charge coupled device	Success			√	
Lockheed stealth prototype	Success	√	√	√	√
Fairchild Semiconductor	Success	√	√	√	√
Sunway TaihuLight	Success		√		√
PARAM supercomputers India	Success	√		√	
Tata Eka India	Failure		√	√	
Indian IT industry - Company A	Failure	√	√	√	
Indian IT industry - Company B	Failure		√	√	
Indian IT industry - TCS	Success		√	√	√
Indian IT industry - Company D	Success		√	√	
SAP Labs China	Success		√	√	
India defence SME - Company A	Partial success		√	√	
China defence SME - Company B	Partial success		√	√	

Figure 7.3 - Case studies through the Henderson taxonomy lens

Figure 7.3 shows that successful innovations, as well as failures, can take place across the spectrum of Henderson options. We may conclude that the Henderson taxonomy alone is insufficient from the perspective of focus for knowledge processes.

Case	Outcome	Smiling Curve Segment		
		Components	Manufacturing	Distribution
Apple in the 1990s	Success	√	√	√
Philips Compact Disks	Success	√	√	√
Indian watch industry	Success		√	√
China ASBM	Success	√	√	√
Sony Trinitron	Success	√	√	√
Photolithography process	Success	√	√	√
China single alloy turbine blade	Failure	√		
ISRO charge coupled device	Success	√	√	√
Lockheed stealth prototype	Success	√	√	√
Fairchild Semiconductor	Success	√	√	√
Sunway TaihuLight	Success	√	√	√
PARAM supercomputers India	Success	√	√	√
Tata Eka India	Failure	√	√	
Indian IT industry - Company A	Failure	√	√	
Indian IT industry - Company B	Failure	√		
Indian IT industry - TCS	Success	√	√	√
Indian IT industry - Company D	Success	√	√	√
SAP Labs China	Success	√	√	√
India defence SME - Company A	Partial success	√	√	√
China defence SME - Company B	Partial success	√	√	√

Figure 7.4: case studies through the Smiling Curve lens

Figure 7.4 shows us that success is always associated with a focus on the Distribution segment of the Smiling Curve and failure often the consequence of lack of management commitment to the full cycle. For example, it should be noted that the Indian IT Company A case shows an innovation failure, despite a Components & Manufacturing position on the Smiling Curve. In other words, innovations are successful when the organization commits fully to ensuring the success of an innovation in the marketplace through provision of finance, people and material resources. Figure 7.4 also shows that the organization must be willing to invest either in the Components segment i.e. in R&D, or in Manufacturing, or both; in addition to back the innovation teams with investments in the Distribution segment, as evidenced by the success of Company D.

The data in Figure 7.4 highlights the role of the right kind of organizational resources as indicated by the Galbraith organizational model, described earlier in the Literature Survey (Galbraith, 1982). An organization wishing to be successful in innovation needs to empower the four Galbraith people types viz. Ideators, Sponsors, Orchestrators and Gatekeepers. The Ideators are responsible for inputs on Components vs

Manufacturing vs Distribution choices; the Sponsors are responsible for promoting the best alternative; the Orchestrators (always the top management) are responsible for ensuring organizational support in terms of people, infrastructure, material and money; while the Gatekeepers paly the crucial role of communication and knowledge flow within the knowledge networks within and outside the organization. The Gatekeepers, clearly, are responsible for effectively implementing the knowledge processes.

This brings into focus the role of knowledge processes, which is the central intent of this thesis. To examine this further, we will start with a consolidated picture of the 20 case studies including all the three lenses of the S-curve, the Henderson taxonomy, and the Smiling Curve.

Case	Outcome	S-Curve Position	Henderson Option	Smiling Curve Segment		
				Components	Manufacturing	Distribution
Apple in the 1990s	Success	Incubation-growth	Radical / Modular / Architectural	√	√	√
Philips Compact Disks	Success	Pioneer	Radical	√	√	√
Indian watch industry	Success	Growth	Radical / Modular / Architectural		√	√
China ASBM	Success	Pioneer	Radical	√	√	√
Sony Trinitron	Success	Pioneer	Radical / Architectural	√	√	√
Photolithography process	Success	Pioneer	Architectural	√	√	√
China single alloy turbine blade	Failure	Mature	Modular	√		
ISRO charge coupled device	Success	Pioneer	Architectural	√	√	√
Lockheed stealth prototype	Success	Pioneer	Radical	√	√	√
Fairchild Semiconductor	Success	Pioneer	Radical	√	√	√
Sunway TaihuLight	Success	Growth	Modular+Arch.	√	√	√
PARAM supercomputers India	Success	Growth	Modular+Arch.	√	√	√
Tata Eka India	Failure	Growth	Modular+Arch.	√	√	
Indian IT industry - Company A	Failure	Pioneer	Radical + Arch.	√	√	
Indian IT industry - Company B	Failure	Growth	Radical + Arch.	√		
Indian IT industry - TCS	Success	Gowth + Mature	Modular+Arch.	√	√	√
Indian IT industry - Company D	Success	Growth	Modular + Arch.	√	√	√
SAP Labs China	Success	Growth	Modular+Arch.	√	√	√
India defence SME - Company A	Partial success	Growth	Modular+Arch.	√	√	√
China defence SME - Company B	Partial success	Growth	Modular+Arch.	√	√	√

Figure 7.5 - Consolidated view of case studies

From the perspective of knowledge processes, the four Galbraith people types should try and ensure the following, if an innovation is to be reasonably certain of success based on the case study data:

- S-curve transition points and bottlenecks are ideal situations for innovation.
- Innovation can take place anywhere on the S-curve, but for new entrants the Pioneer/Growth positions are preferable, since both ends of the Smiling Curve can be covered for a “win-win” for both R&D and marketing. In the Mature phase, the tensions between the two ends of the Smiling Curve can lead to a win-lose situation.

- For the Pioneer/Growth phases, all three options i.e. Radical/Modular/Architectural are suitable. For the Mature phase, the options are Radical and Architectural for success.
- To the extent possible, the Distribution segment together with either the Component or the Manufacturing segment, or both, of the Smiling Curve should obtain organizational commitment and support.

Again, the data from the case studies in Figure 7.4 shows that it is indeed possible to satisfy this complex set of requirements and accomplish successful economies. As stated repeatedly in this thesis, the entire field of innovation studies centres around proposing frameworks that attempt to explain, wholly or in part, how innovations are successfully accomplished while satisfying the above set of requirements. We represent this as shown in Figure 7.6.

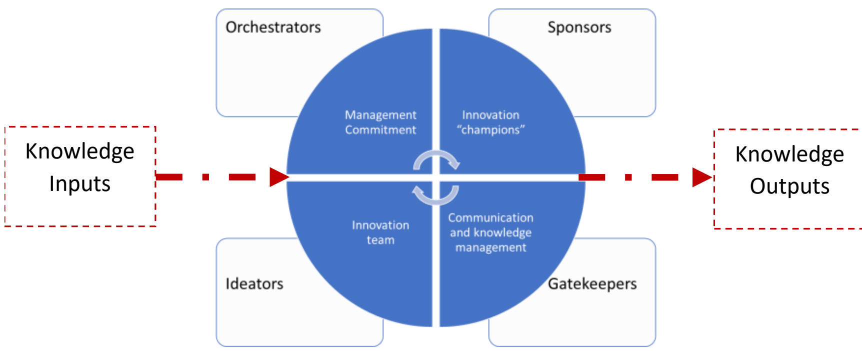


Figure 7. - Galbraith Model and Knowledge Processing

We will now attempt to contribute to this body of research by proposing a knowledge processes-based framework of innovation. For this purpose, we draw reference to the chapter on supercomputing, where we posed the three basic questions:

1. How have China and India used knowledge to formulate and achieve their goals in the supercomputer sector?
2. How has knowledge contributed to the supercomputer sector in China and India?
3. What patterns and processes can be inferred in this context?

We approached these questions at two levels – the macro, or ecosystem, level; and the micro, or organizational, level. Based on the data obtained from field research, we were able to identify two frameworks. The first framework was innovation as a knowledge process which results in new knowledge based on derived from, first, knowledge of a problem or opportunity; second, knowledge of past outcomes and benefits; and third, knowledge of available concepts and technologies to craft the innovation. The second framework was of innovation as a process consisting of five knowledge processes, namely, search, select, absorb, generate and disseminate; with the generation process constituting the crafting of the innovation.

We will now expand these assertions to develop a detailed knowledge processes-based framework of innovation. The framework will be developed at two levels – the organization and the ecosystem. Since this new framework will reference the S-curve, the Henderson taxonomy, the Smiling Curve and the Galbraith organizational model, it is appropriate to describe it as ***a framework of frameworks***.

7.2.1 A knowledge processes-based framework of innovation

We start with the definition, already stated, of any innovation as new knowledge generated by drawing on the existing body of knowledge to solve a new problem or leverage a new opportunity to yield beneficial outcomes. In other words, innovations involve the processing of knowledge to generate new knowledge. This is represented in Figure 7.7, which will be termed the Basic Knowledge Processes-Based Framework of Innovation.

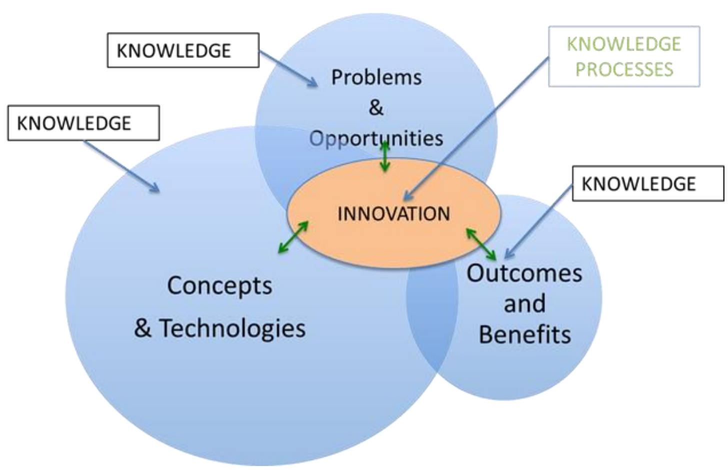


Figure 7.7 - Basic Knowledge Processes-Based Framework of Innovation

As was in the chapters on supercomputers, the software industries, and defence sector SMEs in China and India, the umbrella term "knowledge processes" resolves itself into five distinct knowledge processes. These are:

The *Search* process – in which an organization, team or person, conducts an intuitive, systematic, or unstructured search of the environment for knowledge which is relevant to the problem, opportunity, or innovation. *This process is implicit, sometimes systematic, and continuous in all organizations.*

The *Select* process – in which all knowledge acquired through the Search process is evaluated and filtered according to a set of parameters. In broad terms, the Select process would highlight knowledge relevant, for example, to the relevant S-curves, the Henderson choices available, and the Smiling Curve options, as indicated in Figures 7.2 to 7.5. *This process is also implicit, sometimes systematic, and continuous in all organizations.*

The *Absorb* process – in which knowledge filtered through by the Select process would be systematically inculcated into the innovation team. For example, tacit knowledge might be transmitted through training workshops, explicit knowledge through distribution of documents or the creation of collaborative databases, etc.

The *Generate* process – representing the actual crafting and accomplishment of the innovation.

The *Disseminate* process – by which the details of the innovation would become known. Within the organization, this might take the form of detailed documentation and manuals; in the outside world, it might take the form of an introduction of a new product, service, or technical journal articles in the case of innovative new concepts.

We represent this as the Five Knowledge Processes Framework in Figure 7.8.

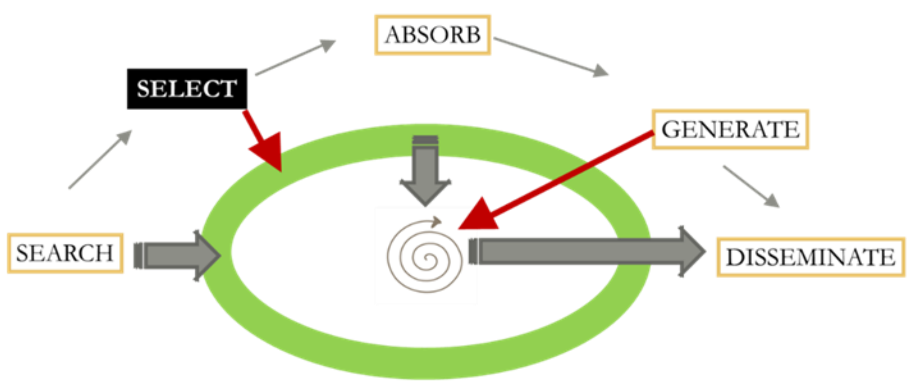


Figure 7.8 - Five Knowledge Processes Framework

Adding to these two frameworks the insights gained through the field research, we will now describe the detailed steps that the frameworks hypothesize an innovation goes through.

7.2.2 How Innovations are crafted and accomplished – a view through the lens of a combination of the two knowledge frameworks.

Step 1: Identification of the problem / opportunity

As stated above, innovation begins with the identification of a problem or opportunity. This will be based on knowledge acquired from the industry ecosystem surrounding the organization, through either a systematic search or a random input which is considered important, as shown in Figure 7.9 and Figure 7.10. In the Galbraith organizational model, this activity would be carried out by the Orchestrators and/or the Ideators, representing respectively the top management and innovators at various levels and positions in the system usually at lower levels in the hierarchy. Often ideators maybe from R&D or sales or marketing. In smaller organizations it is often easy to link ideators, sponsors and orchestrators. As organizations grow in complexity and size and functions this issue becomes much more difficult to manage. The routine versus non-routine dilemma and switching from one mode to another require new modes of working that are difficult to structure. The values, beliefs and culture within the organization and the ecosystem in which it operates also matters a great deal.

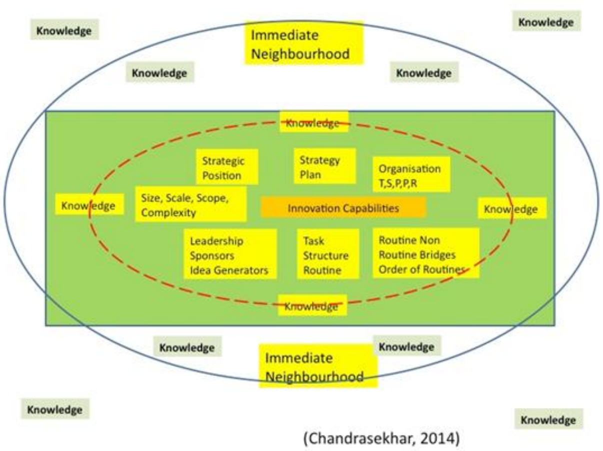


Figure 7.9: The nature of environmental scanning

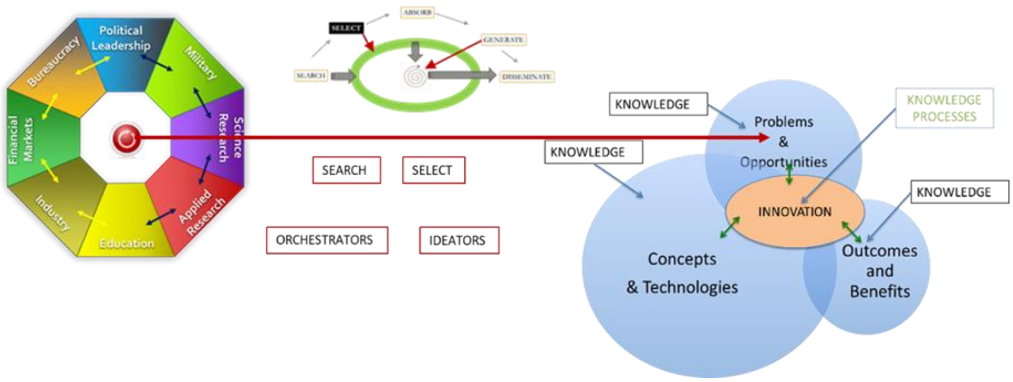


Figure 7.10: Problem Identification

Step 2: Evaluation of outcomes and benefits:

Once the problem or opportunity has been identified, it becomes necessary to evaluate, based on ecosystem search and select, whether there are any beneficial outcomes, possible through an innovation to address the problem / opportunity. This is a task that would fall to all four of the Galbraith model types.

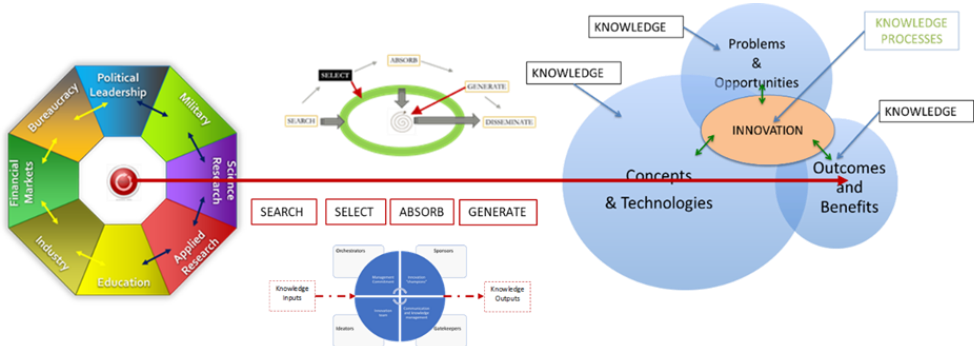


Figure 7.11 - Evaluation of outcomes and benefits

Step 3: Selection of candidate concepts and technologies to build an innovative solution

At this stage, the full Galbraith configuration would still be involved, since the selection of a technology as the basis for development of a solution would involve top management decisions.

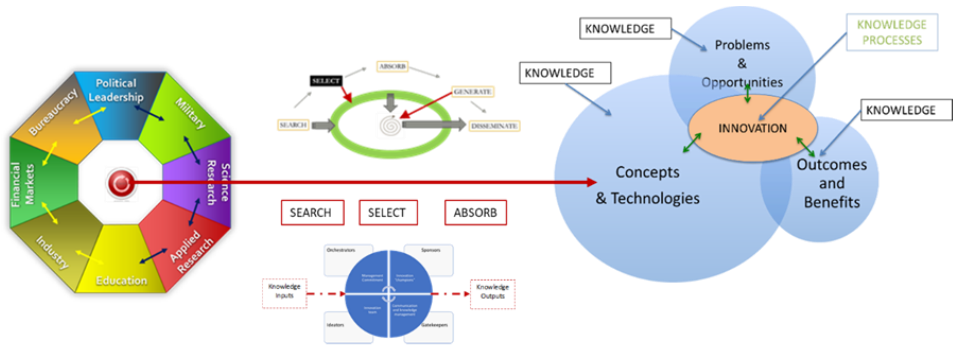


Figure 7.12 - Selection of candidate concepts/technologies for innovation

Step 4: Final dimensioned innovation decision

This is represented in Figure 7.13.

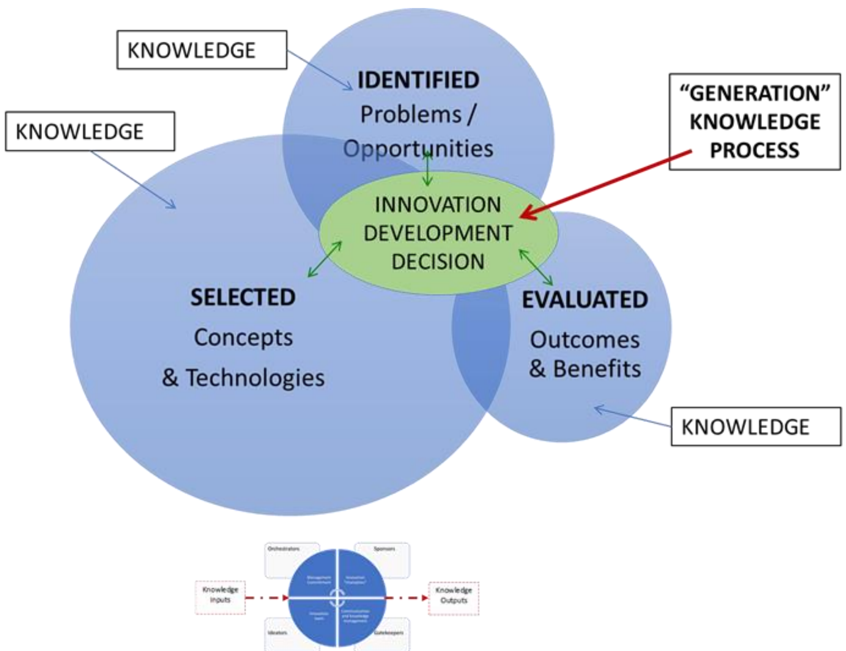


Figure 7.13 - Innovation development decision

Step 5: Selection of S-curve positioning

Once the decision to go ahead has been taken, the S-curve of choice and the positioning thereon is the first critical development decision. There are always four choices:

- On the Pioneer stage of an emerging S-curve. This provides the benefits of first mover advantage, disruption of the industry, and returns on radical technology selections, but also comes with the risk of high investment, possible failures, and perhaps superior competition. Apple is a company, for example, which consistently favours this positioning.

- On the Growth stage of an existing S-curve. This is a favoured option for many companies, since it enables them to follow the leader and build upon that success, thereby reducing the R&D and marketing investments required to create the Pioneer market. The disadvantages are that the leader may already have pulled away by the time the decision is taken. Microsoft's consistent failure to succeed in the mobile devices space reflects this conundrum.
- On the Mature stage of the S-curve. This is a viable option for many consumer product / mass market companies, with innovations taking place in the manufacturing and Distribution segments of the Smiling Curve. Innovations under this positioning will tend to be less technological in nature and more in business models or marketing.
- On the Decline stage of the S-curve. There are definite niches which can be captured in this, which are sometimes attractive to specialist companies. In the software industry for example, there is a well-known consistent demand for the maintenance of legacy applications built on old technologies. The Y2K opportunity is a classic example of this, which was remunerative enough to build financial stability into a large part of the Indian IT industry.

This stage determines the complementary assets that may be required to give the innovation a fair chance, a decision that can be taken using a combination of the Porter, RBV and Smiling Curve frameworks. In a radical or disruptive mode, depending on the availability of substitutes, resolution of the complementary assets issue may be simpler. Figure 7.14 depicts this step.

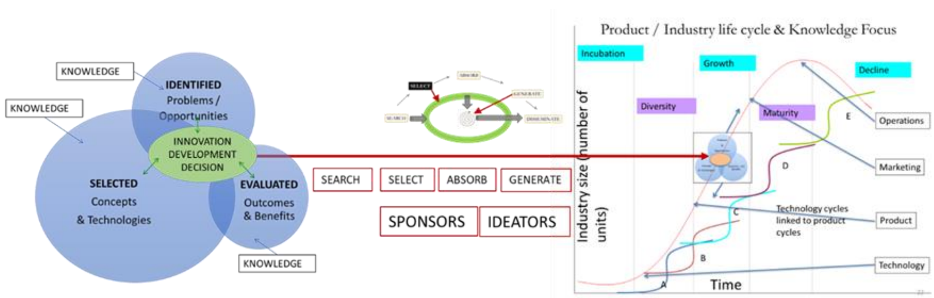


Figure 7.14 - Positioning innovation on an S-curve

<u>Step 6</u>: Selection of Smiling Curve segment

At every stage on an S-curve, an organization has multiple Smiling Curve options to pick from. These are inter alia any one of the Components, Manufacturing or

Distribution options, or any two of them, or all three. The decision would depend on the ability of top management to back their support for an innovation project with money, infrastructure, people and material resources. Step 6 is often taken simultaneously with Step 7 but is shown separately in Figure 7.15. Once again, because of investment decisions required to be arrived at, the full Galbraith model organizational configuration would be involved.

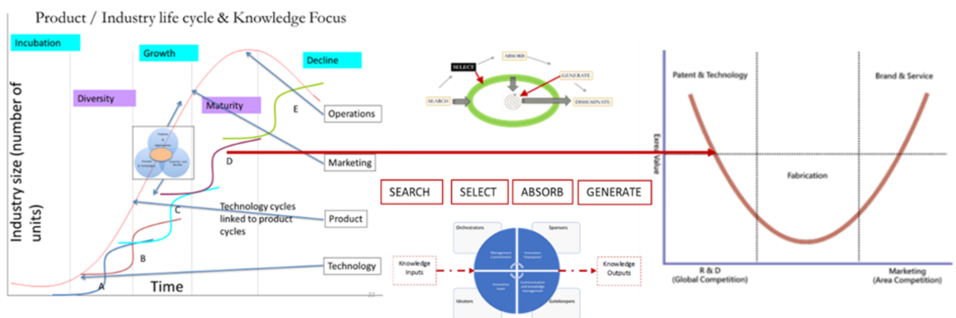


Figure 7.15 - Smiling Curve segment(s) decision

Step 7: Selection of Henderson innovation types

This step is essentially identical to Step 6, but involving decisions on whether radical, modular, architectural or incremental innovations should be attempted per the Henderson taxonomy. Again, since investment decisions, branding decisions, and the like are required to be arrived at, the full Galbraith model organizational configuration will be involved. Step 7, however, may require multiple iterations to ensure that the projected innovation performs as projected.

Figure 7.16 - Henderson taxonomy type decision

Step 8: Crafting of the innovation and its handing over to operations

In this step, which we describe as a Generate and Disseminate in terms of the five knowledge processes, the three Galbraith team members involved are the Ideators, Gatekeepers and Sponsors. Figure 7.17 depicts this step.

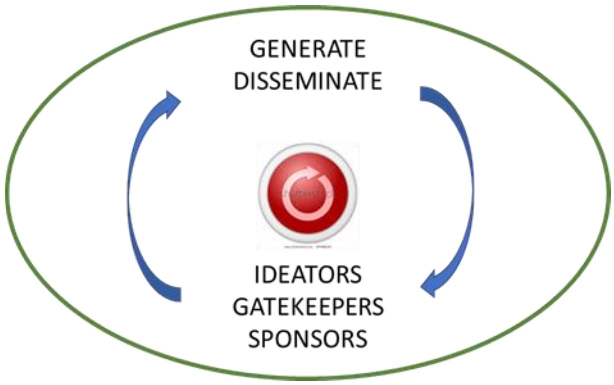


Figure 7.17: Crafting of the innovation and its transfer to operations

Step 9: Release of the innovation into the ecosystem and its diffusion over time.

If the project is executed successfully, the innovation – be it a product, service, technology, or a concept – is launched and released into the ecosystem, where it will diffuse according to its own S-curve and life cycle. Figure 7.18 depicts this process.

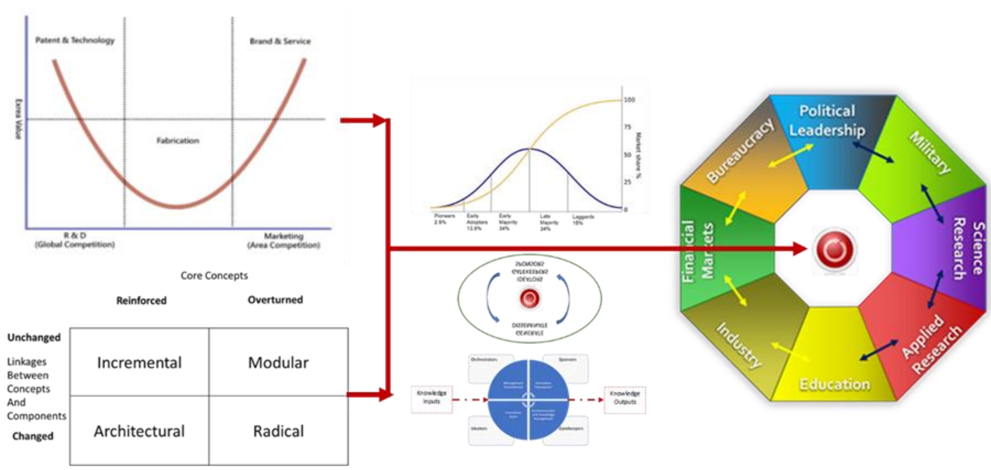


Figure 7.18 - Launch and diffusion of innovation into the ecosystem

7.2.2.1 Evaluation of the organizational level model

We will now examine in more detail the specific actions performed by the Galbraith organizational configuration members. First with reference to their participation in the eight steps outlined above, Figure 7.19 depicts the involvement of each type of Galbraith participant.

Galbraith participant	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Total
Orchestrators	√	√	√	√		√	√		√	***7***
Sponsors		√	√	√	√	√	√	√	√	***8***
Gatekeepers		√	√	√	√	√	√	√	√	***8***
Ideators	√	√	√	√	√	√	√	√	√	***9***

Figure 7.19 - Galbraith participants in each of steps 1-9

Next, Figure 7.20 depicts the number of times each Galbraith participant performs each of the five basic knowledge processes of Search, Select, Absorb, Generate and Disseminate, during the nine steps.

Galbraith participant	Search	Select	Absorb	Generate	Disseminate
Orchestrators	5	5	4	4	1
Sponsors	5	5	5	6	2
Gatekeepers	5	5	5	6	2
Ideators	6	6	5	6	2

Figure 7.20 - Galbraith participants in the five knowledge processes

Figures 7.19 and 7.20 bring out the importance of very tightly coupled innovation teams, structured on the Galbraith model. All the members are involved to virtually the same extent in all the nine steps and the five knowledge processes. In other words, an awareness of the importance of knowledge and how it can be systematically managed for innovation is critical for success.

We can conclude from this observation that failure of an innovation project, if it can be traced to specific steps, can be linked in some ways to a breakdown in the close coupling between team members and consequently inadequate attention to the importance of knowledge processes.

With this observation, we now review the field research projects from China and India described in the previous chapters. This is depicted in Figure 7.21.

CASES	Outcome	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Summary
CHINA											
Sunway Taihu Light	Success	√	√	√	√	√	√	√	√	√	All steps executed
SAP Labs China	Success	√	√	√	√	√	√	√	√	√	All steps executed
China Defence Company B	Partial Success	√	√	√	√	√	√	√	√	√	All steps executed
INDIA											
PARAM series	Success	√	√	√	√	√	√	√	√	√	All steps executed
Tata Eka	Failure	√	√	√	√	√	--	√	√	√	Failure in Step 6 - Smiling Curve options
IT Company A	Failure	√	√	√	√	√	--	√	√	√	Failure in Step 6 - Smiling Curve options
IT Company B	Failure	√	√	√	√	√	--	√	√	√	Failure in Step 6 - Smiling Curve options
TCS	Success	√	√	√	√	√	√	√	√	√	All steps executed
IT Company D	Success	√	√	√	√	√	√	√	√	√	All steps executed
Defence Company A	Partial Success	√	√	√	√	√	√	√	√	√	All steps executed

Figure 7.21: Causes of success / failure in field research cases

As already stated in the Research Design, in no way does this reflect any generic differences between Chinese and Indian organizations. Such a conclusion would be gratuitously unscientific and intellectually unacceptable.

However, there are some observations that can be made. All the successes, whether in China or India, reflect close coordination between the organization concerned and the external ecosystem in which it is immersed. This is most obvious in the case of the two defence SMEs in China and India, which depend a good deal on support from their respective ecosystems. Similarly, the successes in the supercomputer sector in both countries – the Sunway in China and the PARAM in India – came in fact from the so-called “public sector”.

In China, the sole “private sector” case featured in this thesis – that of SAP Labs China – is a success and is acknowledged by the orchestrator to have benefited from ecosystem support. The failures, which in this case are all Indian, are all located in the private sector. Therefore, it cannot be concluded that either the public or the private sector is any more, or less, efficient when it comes to innovation. Given the above picture, however, it now becomes necessary to build a framework of innovation at the ecosystem level.

7.2.3 The role of knowledge processes at the ecosystem level

Both the Basic Knowledge Processes-based Innovation Framework, shown earlier in Figure 7.7, and the Five Knowledge Processes Framework, shown earlier in Figure 7.8, can be utilized for building the ecosystem level model, since they are generic to innovation. But the lack of an equivalent to the Galbraith innovation organization structure is the major difference to be incorporated.

At the ecosystem levels – which we have described as consisting of the eight entities of government, bureaucracy, military, scientific research, applied research, education, industry, and the financial markets – the Galbraith structure deconstructs itself through the division of labour principle and distributes itself across the eight entities. The equivalents need to be described to gain an understanding of how knowledge processes relating to innovation operate at the ecosystem level.

We define the following as the ecosystem equivalents:

1. Policymakers (government / bureaucracy / military) equivalent to Orchestrators
2. Resource Providers (bureaucracy / military / financial markets / education) equivalent to Sponsors
3. Implementers (industry / scientific research / applied research) equivalent to Ideators.
4. Coordinators (government / financial markets) equivalent to Gatekeepers.

Figure 7.22 represents this correspondence.

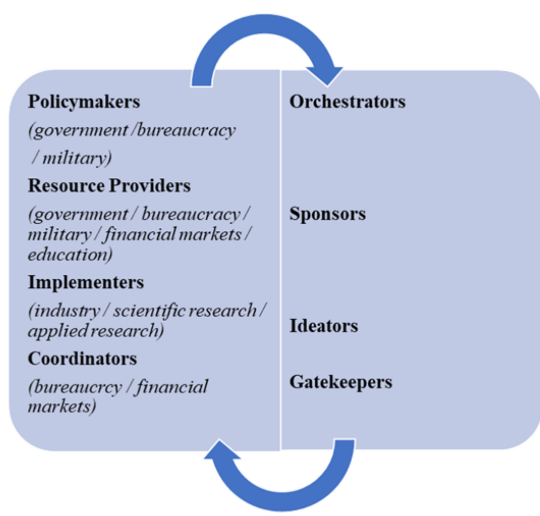


Figure 7.22 Ecosystem equivalents of Galbraith entities

Given the distributed nature of the Galbraith equivalents, the role of the ecosystem become limited to two objectives - first, to identify problems and opportunities that are important from the national strategy perspective; and second, to institute policies, streamline procedures, and provide resource support for the Implementers (companies / research institutes) to perform the task of innovation and diffuse them successfully with the involvement of financial markets.

Step 1: Identifying problems and opportunities in the ecosystem

The task of identifying problems and opportunities starts with the scanning of the environment or the opportunities that arise from the ecosystem, as shown in Figure 7.9 earlier. At the ecosystem level, this first step is similar to Figure 7.9, with the difference that it is carried out by a much larger number of entities and individuals. Figure 7.23 depicts this step

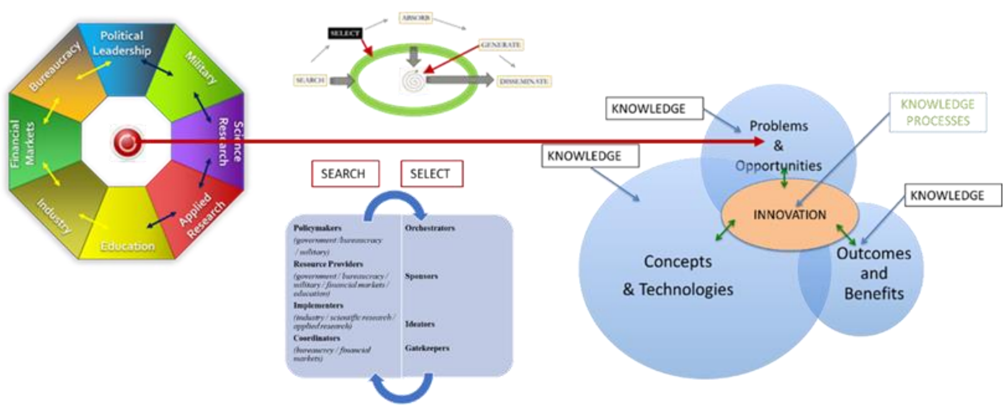


Figure 7.23 - Problem / opportunity identification at ecosystem level

Step 2: Instituting supportive policies, procedures and resources

The second objective – instituting supportive policies, procedures and resources – is met through the mirror image process of problem / opportunity identification. In this step, the inputs are the outcomes and benefits observed in the environment, including outside of the country. Figure 7.24 depicts this.

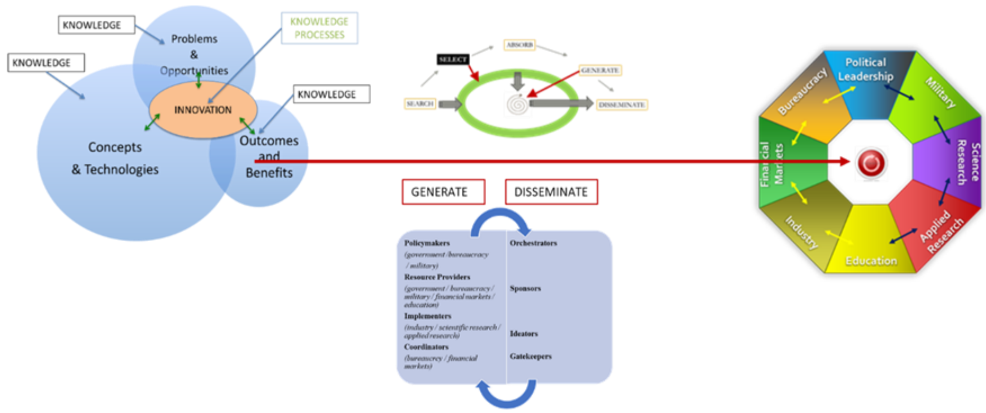


Figure 7.24 - Instituting supportive policies, procedures and resources

We represent the knowledge network formed by the individuals in this ecosystem in Figure 7.25, with 28 generic paths of knowledge exchange in the network, composed of three parts – knowledge exchange within organization members, knowledge exchange between policymakers and others in the ecosystem leadership, and between members of the organization and the ecosystem leadership. The total number of interactions would be much higher, depending on the number of individuals in the ecosystem.

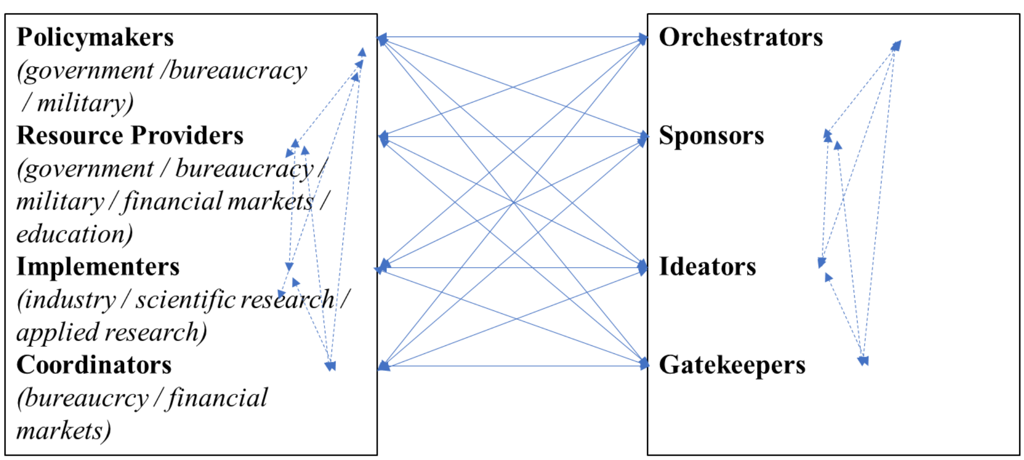


Figure 7.26 – Knowledge Network and Exchange at ecosystem level

7.2.3.1 Evaluation of the ecosystem level framework:

This may be tested through a review of case studies. We return to the 10 field research cases and evaluate in which cases the ecosystem contributed to success, or where support from the ecosystem could be construed as a cause of failure. This is shown in Figure 7.27.

CASES	Outcome	Summary	Ecosystem support
CHINA			
Sunway Taihu Light	Success	All steps executed	Positive
SAP Labs China	Success	All steps executed	Positive
China Defence Company B	Partial Success	All steps executed	Positive
INDIA			
PARAM series	Success	All steps executed	Positive
Tata Eka	Failure	Failure in Step 6 - Smiling Curve options	Absent
IT Company A	Failure	Failure in Step 6 - Smiling Curve options	Absent
IT Company B	Failure	Failure in Step 6 - Smiling Curve options	Absent
TCS	Success	All steps executed	Positive
IT Company D	Success	All steps executed	Positive
Defence Company A	Partial Success	All steps executed	Positive

Figure 7.27 - Effect of ecosystem support

This demonstrates clearly the impact of the ecosystem on the success and failure of innovations, and the necessity for a high intensity of knowledge interchange between individual companies and the ecosystem. This brings us to the next section of this chapter, an analysis of ecosystem characteristics as illustrated by selected cases in China and India.

This also concludes the full response to the Main Research Question, namely, the connections between knowledge processes and innovation. We move next to the full response to the Subsidiary Research Question, namely, the patterns of connections between knowledge processes and innovation in selected Chinese and Indian organizations.

7.3 The patterns of innovation-related knowledge processes in Chinese and Indian organizations and ecosystems

The field research documented in Chapters 4, 5 and 6 has shown that there are variations in the practices of knowledge processes across organizations in one sector, across organizations in different sectors, and across sector ecosystems in different countries. It was also shown that the key differentiators were the Select knowledge process, and the criteria used during "Selection". Accordingly, this section will illustrate similarities and differences between selected Chinese and Indian organizations by starting at the organizational level and aggregating to the ecosystem level.

7.3.1 Similarities and differences in the supercomputer sector

Knowledge practices were found to vary primarily in the way the Select process worked. In organizations, this was resulted in coverage of different segments of the three innovation frameworks, namely, the S-curve, the Henderson taxonomy and the Smiling Curve. These patterns can be inferred from the case studies on the Sunway TaihuLight, the PARAM series and the Tata Eka. At the organizational and team level, the three cases all illustrate the attempting of radical and modular innovations, the use of emerging technologies, and the framing of projects around high value-add R&D. There are indications, therefore, that the capability exists in both Chinese and Indian companies for innovation across all the segments of the three frameworks, that can be called upon if decided by the ecosystem leadership. Figure 7.28 depicts this picture.

Supercomputer Sector Select Knowledge Process - Organizational level						
S-curve		**Pioneer**	**Growth**	**Mature**	**Decline**	
	China					
	India					
Henderson taxonomy		**Radical**	**Modular**	**Architectural**	**Incremental**	
	China					
	India					
Smiling Curve		**R&D**	**Design**	**Assembly**	**Sales**	**Branding**
	China					
	India					

Figure 7.28 – Similarities and differences at the organizational level in supercomputers

At the ecosystem level, the picture that emerges in different. The data in Chapter 4 on the level of investments, the number of systems deployed, the capacity installed, and the range of applications show that the Chinese and Indian ecosystem leadership show different patterns of empowering innovation. Figure 7.29 gives a hypothetical illustration of the practice of the Select process at the ecosystem level across the same three frameworks.

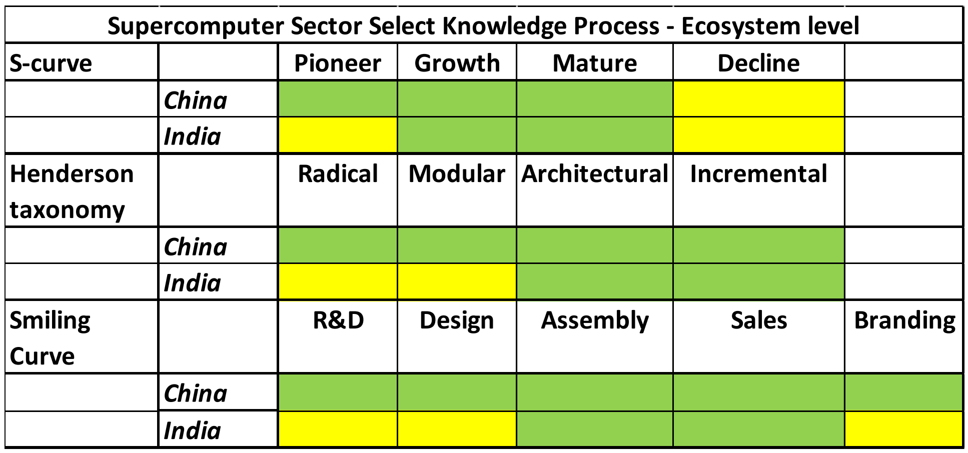


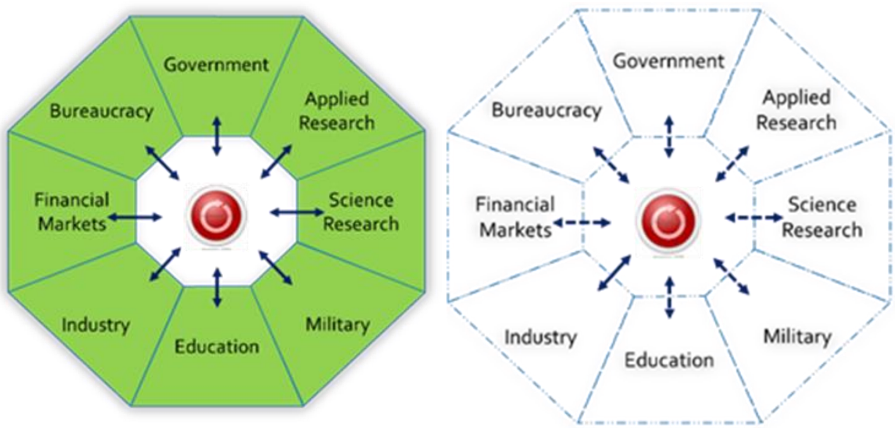
Figure 7.29 – Similarities and differences at the ecosystem level in supercomputers

The higher integration and the extent of coupling in China between the ecosystem level and the supercomputer organizations level described in Chapter 4, as compared to India, comes out in Figure 7.29. These similarities and differences can be hypothesized as due to the different criteria for the Select process at the ecosystem level. These criteria have been inferred from policy and progress statements by the Chinese and Indian ecosystem leaderships as cited in Chapter 4. This is shown in Figure 7.30.

Supercomputing	**Knowledge Selection Criteria at ecosystem level**	**Outcomes**
China	***Ranking-based for optimality:*** ▪ Strategic positioning ▪ Competitive value ▪ Innovation value	▪ *Key objective – competitive performance* ▪ Strategically advantageous ▪ Lower capital productivity ▪ Development → Usage
India	***Percentile-based for satisficability:*** ▪ Adequacy value ▪ Capital efficiency ▪ Capacity creation	▪ *Key objective – effective usage* ▪ Strategically less advantageous ▪ Higher capital productivity ▪ Usage → Development

Figure 7.30 – Similarities / differences in Select process criteria in supercomputers

These similarities and differences in turn can hypothesized as consequences of the differences in structure of the two country ecosystems, which are restated in Figure 7.31 from Chapter 4. As stated earlier, the ecosystem in China is more integrated than is the case with India.



China India

Figure 7.31 – Supercomputer ecosystems in China and India

7.3.2 Similarities and differences in the software sector

The software sector was evaluated in Chapter 5 as very different from the supercomputer sector. The major difference is the extent of integration with the global software industry, which requires conformity to global standards established elsewhere. The analysis showed that the industries in both China and India conformed largely to the global model, with venture capital playing an increasingly major role.

At the organizational level, the pattern observes was largely similar in both countries. The major difference is the Indian industry's record of successfully conducting business in the Decline stage of the S-curve, through legacy applications maintenance and technology upgradation projects. A second difference, based on the rising number of unicorns in both countries, is the greater Chinese willingness to enter the very latest technology areas in a big way – in Artificial Intelligence, principally, in which a national level plan has been developed. The practice of the Select process has been hypothesized in Figure 7.32 based on the analysis in Chapter 4.

Software Sector Select Knowledge Process - Organizational level					
S-curve		Pioneer	Growth	Mature	Decline
	China				
	India				
Henderson taxonomy		Radical	Modular	Architectural	Incremental
	China				
	India				
Smiling Curve		Concept	Design	Development	Depoyment	Go-to-market
	China					
	India					

Figure 7.32 – Similarities and differences at the organizational level in software

At the ecosystem level, the principal difference is the announced Chinese government focus on Artificial Intelligence, a technology area where the country hopes to achieve leadership by 2030. In India, the government and bureaucracy have historically left the industry alone to fashion its own trajectory, preferring instead to stimulate its growth through economic incentives such as tax holidays and special economic zone status to export-oriented companies. Figure 7.33 hypothesizes the practice of the Select process at the ecosystem level in the software sector.

Software Sector Select Knowledge Process - Ecosystem level						
S-curve		Pioneer	Growth	Mature	Decline	
	China					
	India					
Henderson taxonomy		Radical	Modular	Architectural	Incremental	
	China					
	India					
Smiling Curve		Concept	Design	Development	Depoyment	Go-to-market
	China					
	India					

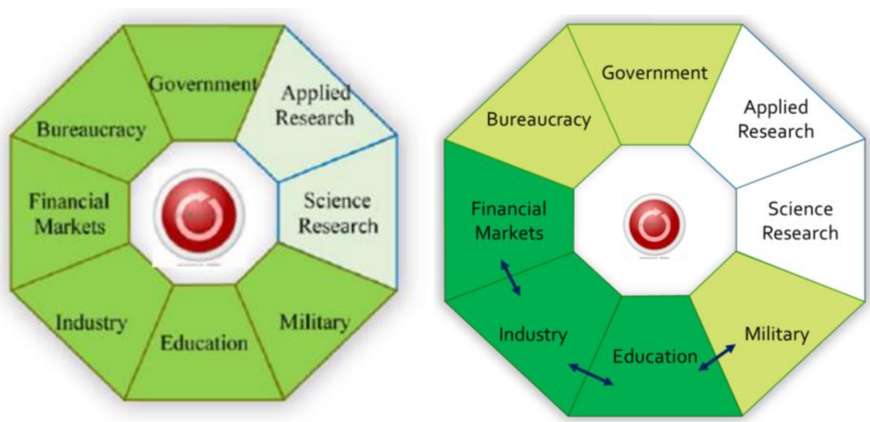
Figure 7.33 – Similarities and differences at the ecosystem level in software

The differences in emphasis in the two ecosystems can be hypothesized as reflecting the Select process criteria at the ecosystem level, as shown in Figure 7.34. The important difference, from Chinese policy pronouncements cited in Chapter 4, is the objective, in addition industry growth, of "catching up", particularly with the US, and exceeding them at least in the Artificial Intelligence area. In India, the emphasis remains on maintaining industry growth, as it has since the 1990s. The software sector is also seen as major source of employment.

Software	Knowledge Selection Criteria at ecosystem level	Outcomes
China	***Growth-based*** for: Strategic positioning Economic value Innovation orientation	*Key objective – catching up* Leadership in new technologies Employment and productivity Global competitiveness
India	***Growth-based*** for: Economic value Employment generation Innovation orientation	*Key objective – maintaining growth* Exports and domestic growth Social mobility Capacity utilization

Figure 7.35 – Similarities / differences in Select process criteria in software

In contrast to the supercomputer sector, the differences in the software ecosystems of the two countries are less pronounced, as shown in Figure 7.36. In both countries, the applied research and scientific research components are still underdeveloped as compared to the US. The Indian software industry ecosystem mirrors the global industry, with relatively weak links to the government, bureaucracy and the military.



China India

Figure 7.36 - Software ecosystems in China and India

7.3.3 Similarities and differences in the SME defence sector in China and India

As discussed in Chapter 6, China and India have shown a fundamental difference in the defence sector. China follows a top-down approach, having clearly stated, from the topmost levels, that "civil-military-integration" is a cornerstone of the strategy for transitioning to a high-income society. In the SME sector, this has meant an attempt to encourage innovation in the development of dual-use technologies. The Indian approach for defence SME's is bottom-up and venture capital driven, with the objective of creating successful innovation clusters that will hopefully help in reducing defence imports and increasing domestic manufacturing. The differences in objective may be termed as 'economic transformation" versus "economic impact".

As shown by the two cases (Company A and Company B) featured in Chapter 6, both Chinese and Indian defence SMEs show virtually identical characteristics at this time. Both employ well-qualified technocrats as entrepreneurs, with aspirations to innovation across the entire value chain. Ecosystem constraints, principally in finance, block them from realizing their ambitions. Figure 7.37 hypothesizes the Select knowledge process practice at the organizational level.

SME Defence Sector Select Knowledge Process - organizational level						
S-curve		**Pioneer**	**Growth**	**Mature**	**Decline**	
	China					
	India					
Henderson taxonomy		**Radical**	**Modular**	**Architectural**	**Incremental**	
	China					
	India					
Smiling Curve		**R&D**	**Design**	**Assembly**	**Sales**	**Branding**
	China					
	India					

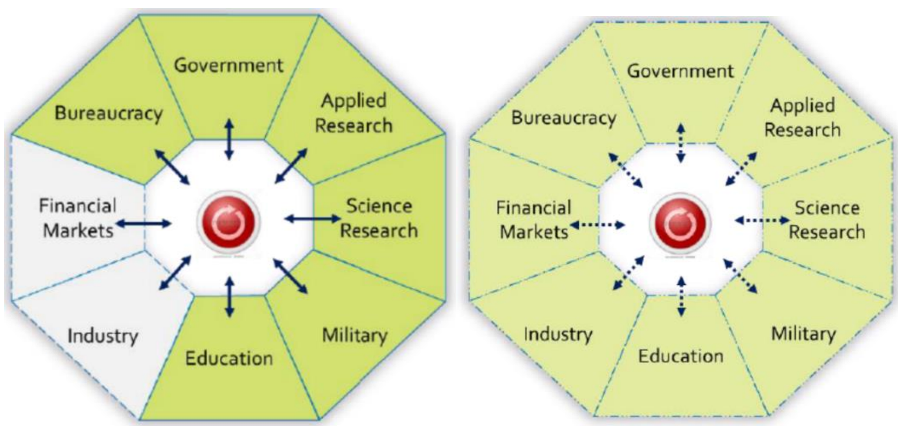
Figure 7.37 – Similarities and differences at defence SME organizational levels

At the ecosystem level, the differences in strategy show up more clearly. However, since the important policy changes described in Chapter 6 are still very fresh, there is not enough information presently to fully hypothesize the practice of knowledge processes at the SME ecosystem level in the two countries. What can be attempted is an understanding of emerging Select criteria, and this is hypothesized in Figure 7.38.

Defence SME	Knowledge Selection Criteria at ecosystem level	Outcomes
China	***Economic transformation*** Economic growth Integration of public and private sectors Innovation orientation	*Middle income to High Income nation* Uniform performance standards Efficient asset utilization Dual use technologies
India	***Economic impact*** Import reduction Manufacturing increases Self sufficiency	*Reduced dependence on overseas sources* FDI Increases Joint ventures Import substitution

Figure 7.38 – Similarities / differences in Select criteria in defence SMEs

Finally, the differences in the two ecosystems can be hypothesized as shown in Figure 7.39.



China India

Figure 7.39 – Similarities / differences in defence SME ecosystems

As discussed in Chapter 6, the Chinese defence SME ecosystem is integrated well except for the financial markets and industry components. The Indian ecosystem, on the other hand is still at a nascent stage but evolving uniformly across all eight components.

7.3.3.1 The context for the Select knowledge process in China and India

As mentioned in Section 7.2.1 above, the Select process is implicit, sometimes systematic, and continuous in all organizations. To understand something of the context in which this practice occurs, we will now combine the Select criteria from the hypothesized list in the three sectors as outlined above. This is shown in Figure 7.401. Similarly, we will combine the Select outcomes in Figure 7.41. The sets of terms thus listed provide an insight into the practice of the Select process in the two countries.

China	India
Ranking-based	Percentile-based
Strategic positioning	Adequacy value
Competitive value	Capital efficiency
Innovation value	Capacity creation
Growth-based	Growth-based
Strategic positioning	Economic value
Economic value	Employment generation
Innovation orientation	Innovation orientation
Economic transformation	Economic impact
Economic growth	Import reduction
Integration of public and private sectors	Manufacturing increases
Innovation orientation	Self sufficiency

Figure 7.40 – Context for Select criteria in China and India

China	India
Competitive performance	Effective usage
Strategically advantageous	Strategically less advantageous
Lower capital productivity	Higher capital productivity
Development → Usage	Usage → Development
Catching up	Maintaining growth
Leadership in new technologies	Exports and domestic growth
Employment and productivity	Social mobility
Global competitiveness	Capacity utilization
Middle income to High Income nation	Reduced dependence on overseas sources
Uniform performance standards	FDI Increases
Efficient asset utilization	Joint ventures
Dual use technologies	Import substitution

Figure 7.41 – Context for desired outcomes from innovation

The above sets of terms provide a flavor of the different criteria and objectives with which individuals, teams, organizations, and industries would process knowledge on the path to innovation. These terms establish the context for the practices of knowledge processes in China and India; and highlight the similarities and differences that are always in play in the minds of all individuals in the knowledge networks that comprise the innovation ecosystems.

7.3.4 Definition of a knowledge practice

We can be abstract the consolidated picture presented in Figures 7.41 and 7.42 to define a new term ***"knowledge practice"***. A knowledge practice represents a meta-aggregation of knowledge processes from a given sector that define the range of ways that knowledge processes are found to work in that sector. Put more simply, knowledge practices are the generally understood framework of approaches that inform the knowledge decisions of innovation practitioners in a sector. Knowledge practices populate the perspectives of practitioners during the process of crafting innovations. Conceptually, this can be represented as in Figure 7.42.

Figure 7.42 – Knowledge Practices as aggregations of knowledge processes

This definition of a knowledge practice brings us to the conceptual boundary of this research, whose objective was to examine patterns and practices of knowledge processes in selected sectors. Going beyond the boundaries of knowledge practices will be a fitting subject to discuss in the implications and conclusions to this research.

It thus enables us to conclude the detailed response to the Subsidiary Research Question, viz. "what are the patterns to be observed in the connections in knowledge processes and innovations in selected organizations in China and India. The conceptual definition of a knowledge practice also concludes the section on Findings. It provides a fitting basis to move to the considerations of the Implications and Conclusions of this research.

7.4 *Implications of the research*

This study has evolved a knowledge processes framework for innovation, consisting essentially of five types of knowledge processes and nine steps describing how these processes can be used for innovation. To the extent that this researcher has been able to determine, these frameworks are ***a new addition to the body of knowledge on innovation,*** enabling an integrated view of innovation from the team to the ecosystem. The knowledge process frameworks are *conceptually autonomous*, untied to any technology or industry, and *practitioner oriented.* The frameworks constitute a new methodology, described as the nine-step method, ***can therefore be deployed in environments other than the three sectors researched in this thesis***. These observations frame the discussion on the implications of the study that will now be attempted.

This study was bounded by four concepts; innovation, knowledge, processes and practices. The previous section concluded the analysis and the findings within the bounds of these four concepts. At the same time, the *context* of the study required that the research go far beyond the four concepts to discover the effect of environments and ecosystems. We will now use the additional contextual data to discuss some of the implications of this study.

Although innovation occurs in teams networked within organizations, and sometimes with other teams in other organization, the process of innovation is affected by several other actors. In Chapter 4 on supercomputers, we saw that the Chinese political leadership, bureaucracy and military played major roles in shaping the sector. In Chapter 5 on software, we found that the global software and venture capital industry largely shape the structure and performance of the Indian and Chinese sector. In Chapter 6, the role of government and bureaucracy is perhaps the strongest among the three sectors studied in this research. While some roles of these actors have been included in the ecosystem concept developed in this research, the breadth of responsibility of these actors goes much further, and frequently leads to the "top down approach" that has been seen in this study. On the other hand, the process of innovations, particularly successful ones, percolates upwards, in a "bottom up approach", to influence major actors to sometimes significant extents; the example of the SkunkWorks stealth fighter prototype is perhaps the best instance of this.

To understand the impact of a study such as this, therefore, it might be necessary to go beyond the boundaries of the study. One way of framing this is to hypothesize that processes and practices, as depicted in Figure 7.42, might have an effect on another layer above them, a layer populated by the actors in an ecosystem in perhaps a broader way than as evidenced in processes. We propose to call this layer a ***paradigm*** and depict it as in Figure 7.43 and say that it evolves from knowledge processes and practices. Just as this study researched the relationship between processes and practices, so too it might be useful to *extend this research and study the relationship between practices and paradigms*. This researcher suggests this is the *first implication* of this research

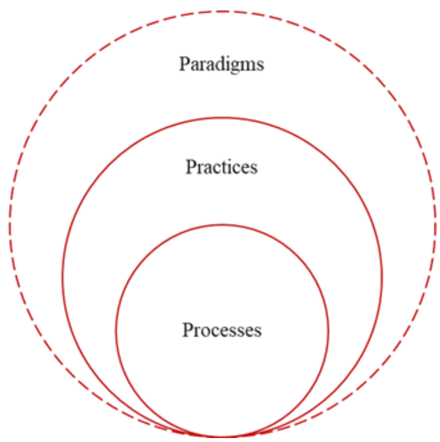


Figure 7.43 – Conceptual paradigm evolved from knowledge processes

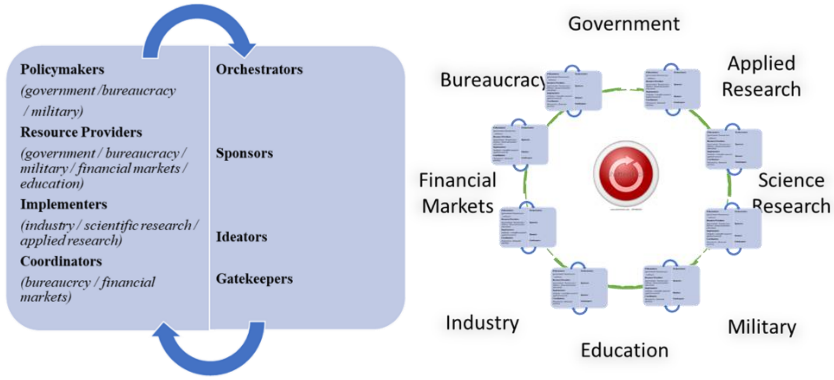
The question that arises is; is there any justification for such an idea? There are some analogies in modern history which would seem to support such a claim. Two of these analogies will be briefly discussed, software engineering and statistical quality control.

Software engineering, as it is called today, began as an individual activity called programming that required extremely specialized technical knowledge. Till the 1970s, programming was considered an art; the book "The Art of Computer Programing" by Donald Knuth, first released in the 1970s, is still considered the all-time classic in the field. Such an art required skilled manpower, and by the 1980s, the shortage of such skilled manpower had become serious enough for the term "software crisis" to start being used. Then, during the 1980s, the first attempts surfaced to try and treat programming as a *process*, which came to be called software development, that could be dimensioned and measured. By the end of the 1980s, it was generally accepted that software development was no longer an art but a process. In the 1990s, this idea was extended further, and standards came into effect to ensure reliable quality from processes, such as the ISO and

CMM (capability maturity model) standards. During the 1990s, the term "software development process" was again replaced by "*software development practices*" in the professional lexicon, and the term *best practices* became the paradigm to which software engineers were trained to conform to. In India, the organizational paradigm which has evolved from such best practices has diffused from the software industry into the many other sectors of the economy.

Statistical quality control (SQC) was first developed in a meaningful way during the 1920s by Walter Shewhart, and found widespread application in US manufacturing during WW II, but it was the statistician W. Edwards Deming who brought it into international prominence with his work with Japanese industry after the war. Till then, Japanese industry had largely viewed quality as due to the competence of the worker and had never heard of a control chart. Unsurprisingly, Japan had acquired a reputation for turning out low quality products. Deming started to train Japanese industry on "Statistical Product Quality Administration", and preached that SQC would lead to better design of products to improve service, higher level of uniform product quality, improvement of product testing in the workplace and in research centers, and greater sales through side [global] markets. Deming has been credited as major inspiration for Japan's post-war industrial boom, which rode to a large extent on high-quality products, and the Japanese management and manufacturing paradigms have been widely adopted internationally.

History is replete with many such examples, of the movement from art to craft to skill to process to practice to paradigm. To return to the SQC instance, it is interesting that SQC has been critiqued as unsuitable for measuring and controlling knowledge-intensive processes such as R&D. It is the submission of this researcher that the knowledge processes framework might make a small contribution specifically to process improvement in knowledge-intensive areas such as R&D and innovation. This submission, which is an extension of the paradigm concept is based on the hypothesis that any new paradigm will create a new network of practitioners, who will influence and participate in the knowledge exchange that will bring about transformation. The history of software engineering and SQC broadly supports this view. Figure 7.44 represents a new knowledge network of this type.



<u>Figure 7.44 - Conceptual knowledge network at paradigm level</u>

For a country like India, the findings of the research and their extension to the implication of a paradigm concept, can lead to ***three straightforward ways*** in which innovation can move from an art or a craft, or perhaps an unstructured process, to a system of practices which will lead to new paradigms with the ***potential to transform organizations, industries and the country*** in unusual ways. These three methods are very similar to the creation of the ISO and CMM paradigms in the software industry. These are:

1. Diffusion of the concepts and methodologies incorporated in the knowledge processes frameworks into individual organizations hopeful of doing innovative work; through articles, books, seminars, and training courses. This will create networks of individuals for knowledge exchange at the organizational level.
2. Diffusion of the concepts and methodologies into the ecosystem, again through the same methods of seminars and training courses and the like. This will create networks of individuals at the ecosystem level for knowledge exchange, linked to the knowledge networks.
3. Diffusion of success stories of innovation accomplished using the knowledge process methodologies into the knowledge network, accelerating the creation of new paradigms.

In this chapter, an extension to the Galbraith model was evolved to include ecosystem-level participants, through examining the relationship between processes and practices. In a similar manner, this researcher suggests that this study might be usefully extended to research *the relationship between paradigms and knowledge networks*, and how such relationships can lead to transformations in countries such as India. This could be termed a *second implication* of this research.

An example of such an extension to this research is the recent work on the concept of *comprehensive national power* (CNP), which seeks to explore how a country's power can be defined and how the different facets of a nation-state come together to create a country's comprehensive national power. This researcher suggests that this present study could contribute to this by extending the concept of paradigm. Just as practices aggregate upward to form a paradigm, so too might paradigms aggregate together to create power. This concept is shown in Figure 7.45, and a recent depiction of CNP in Figure 7.46.

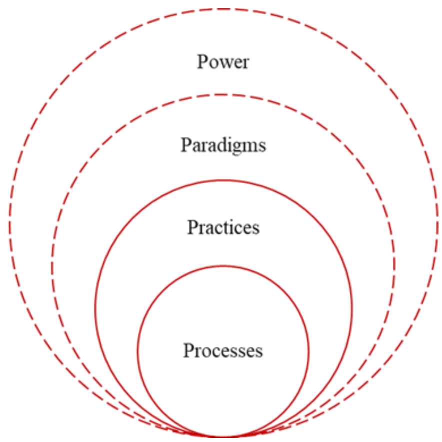


Figure 7.45 – Concept of power as aggregation of paradigms

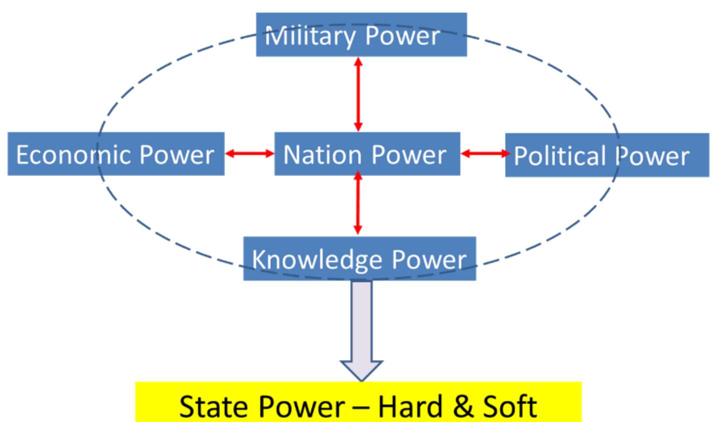


Figure 7.46 – Concept of Comprehensive National Power (CNP)

The concept of CNP has profound implications for countries such as India (Chandrasekhar S. , 2019). Recent analyses and reports have shown that China has succeeded in building up a formidable CNP level through institution of Hybrid Models across all sectors. This has been accomplished in barely four decades since the early 1980s and the institution of reforms by Deng Xiaoping (Silberglitt, Anton, Howell, & Wong, 2006). From the international relations perspective, the concept of CNP and how knowledge paradigms integrate to deliver CNP, and how such perspectives can be used to effect substantial changes in a country's international stance, could be a useful subject for research.

Central to this discussion of the implications of this research is the idea of knowledge as the key to transformation. This research has limited itself to the methods and fields documented in the Research Design, and from the research, a new way of viewing innovation has evolved. Other forms of research centred around knowledge concepts, using different methodologies and addressing different fields, or extending the present research, could also lead to new insights and paradigms. This is the *third implication* of this research, and this provides an appropriate premise to lead to the Conclusions of this thesis.

7.5 Conclusions

The Chinese general Lao Tzu famously said that "a journey of a thousand miles begins with a single step". This research began with the simple observation that what is commonly called innovation is evident all around us, and yet is evidently not the same in different countries. What has followed in this thesis is a journey, if not of a thousand miles then surely down many different paths of research,

To trace this journey, we return first to the Introduction. The rationale for this research was stated as the importance of innovation in the past and the potential of innovation in the future. The Survey of Literature showed that innovation studies had developed over the past century along two perspectives; one, the macro perspective in which innovation was studied as subsumed within another activity, such as economic activity, and two, the micro or practitioner perspective in which innovation is viewed as an independent activity worthy of study. The major research gap that was identified was the role of knowledge and knowledge processes in innovation. This led to the formulation of the research objective as the role of knowledge processes in innovation, and the research questions as the investigation of the connections between knowledge processes and innovation, and then the patterns and practices in selected Chinese and Indian organizations of knowledge processes as related to innovation.

The case study method was selected as part of the detailed Research Design, and the field was decided as the Information Technology industry in three sectors, supercomputers, software and small defence technology companies. Since innovation cannot be separated from its context, the case studies needed to include an exhaustive investigation into the context of innovation in each sector, including in China and India separately. Quality standards based on accepted research norms were adopted to evaluate the results of the research.

The findings of the research revealed extensive connections between knowledge processes and innovation, and differing patterns and practices in China and India that were significant enough to draw inferences. From the research, a conceptual structure for an industry ecosystem was evolved. Based on the findings, a detailed set of frameworks for the role of knowledge processes in innovation was presented. Based on these frameworks, a comprehensive analysis of the similarities and differences between China and India of knowledge process practices was presented. Following this, the implications of this research were discussed, and the inference drawn that this study offers considerable scope for extension into other fields as well.

The conclusions that can be drawn from this exercise can be summed up as follows. There are three new contributions made by this research to the field of innovation studies. First, the notion of innovation as new knowledge creatively generated from existing knowledge is a new definition and an important contribution to the theory of innovation. Second, the notion of knowledge processes links the idea of innovation to the concrete actions of individuals at all levels from practitioners within a team or an organization, to policymakers at the top levels of industry ecosystem. Third, knowledge processes relating to innovation at the practitioner level aggregate into knowledge practices at the organization and ecosystem levels. All three of these contributions constitute the substantive new contribution of this research to the body of knowledge on innovation.

For India specifically, which finds itself in a catch-up mode like China, this researcher offers three ways in which this study can help. First, the innovation methodology developed in this study can be used to systematize and improve the process of research and development. Second, the diffusion of these methodologies across organizations and industries creates new practices, which in turn lead to new paradigms. Third the use of these methodologies is suggested by this researcher to start early in tackling future problems such as the impact of climate change on per capita GDP of a country, which was one of the rationales for this study stated in the Introduction.

At the same time, this researcher would like to state clearly the limitations of this study. As doctoral research, this thesis concentrates on only a small part of a much larger domain. Limitations of access to organizations, people and data, particularly on the Chinese aspect, was a major constraint in the study. This thesis cannot claim to be a comprehensive study of innovation since it focused only on one aspect, that of knowledge. Much more can be done and much more comprehensively; for examples, in-depth studies using these concepts of specific sectors in India, a comprehensive study of innovation in China alone, and so on. On the positive side, this research attests to the validity of the case method in conducting research in fields such as innovation. It produces quality, as the discussion at the end of each of the substantive chapters showed, and it is the belief of this researcher that this study adds to the increasing acceptance of the case method in fields other than management research.

To end this thesis on a philosophical note, as befits a doctoral dissertation, it may be useful to discuss the very notion of knowledge in society and human existence. Recent advances in paleoanthropology have indicated that the faculty of problem solving, when it evolved in the brains of human beings, enabled our species to evolve in turn at rates leading to its dominant position on Earth today. Central to problem solving is accurate knowledge, and problem solving itself is a form of knowledge processing and knowledge generation. Knowledge thus permeates every instant of our existence at both the conscious and subconscious levels, and the way we process, and craft knowledge distinguishes us as individuals different from every other individual. To come to this realization and conduct research on how human beings process knowledge has been for this researcher the most humbling of experiences and the most human of privileges.

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Appendix 1

Analysis of Example Cases

The researcher's analysis of the ten cases is briefly summarized as follows:

1. ***Apple Computers (1990)***: The case covers the critical changes in business strategy at Apple Computer around 1990. Till then, Apple had been an industry innovator developing and designing high performance Personal Computers. All its technologies and products were developed under its own roof. Its internally developed Graphics User Interface and very customer friendly software and operating systems differentiated its PCs from its competitors. By 1990, with the IBM PC and Microsoft taking the world by storm Apple lost much of its performance edge. Apple was forced to reconsider its most basic strategies and cultural values since the large user base of the IBM Microsoft Intel standard made it difficult for Apple to compete. As the case relates, the company, under the leadership of John Sculley, decided to let go many of the traditional 'Apple' ways of doing things and embrace strategies that incorporated features such as partnering for R&D, co-opetition with IBM, their main competitor, setting up joint ventures for manufacturing outside of the US, and in general aiming to be the industry leader while simultaneously aiming to be the industry innovator. Apple's inability to straddle a low-cost product along with a high performance large scale product brings to the fore the problems and dilemmas that companies face in industries with significant network effects.

In the Apple case, we can discern evidence of:

- the importance of the industry evolution as seen through S-curves; Apple stated explicitly it wanted to be both an industry leader (which meant a low-cost position) as well as an industry innovator which meant high R&D and investment in both hardware and software. This made its position difficult to defend as compared to other players in the PC Industry ecosystem who specialized in one or the other and partnered with each other to produce the product.

- As per the Porter framework Apple was forced to move from a differentiator (innovator) into a position of cost leadership. Unable to do so, it got stuck in the middle.
- The Smiling Curve; by partnering with IBM, Apple hoped to reduce their costs of R&D and branding, this increasing their ROI at the two high value ends of the curve. Just as in the Porter framework it was unable to do either well and got stuck in the middle of the smiling curve.
- The Henderson taxonomy; Apple continued its focus on innovating in modular technologies albeit in partnership with IBM
- To a limited extent the Galbraith model; the top management power struggles were evidence of loose rather than tight coupling in the team.

2. ***Philips – launch of Compact Discs***: This case covers the strategies and decisions taken by Philips in the early 1980s to ensure the success of its CD technology. Philips was the world leader in recording on a surface using lasers. They wanted to ensure that Philips achieved the dominant position in the world market. As the case relates, Philips understood that dominating the standards process was the key to achieving this objective. This meant establishing relationships and sharing technologies with their potential competitors, while simultaneously ensuring that Philips investments in development, manufacturing, and marketing took place at levels that would prevent the competitors from gaining threatening market shares. The Philips case is similar in many respects to the Apple case, in particular the issue of a dominant standard evolving over time, and thus the need for the seeming contradictory strategies of cooperation with rivals in developing standards while simultaneously competing in the product business.

In the Philips case, similar to Apple we can discern evidence of:

- Attention to the industry S-curves; Philips were able to catch a brand-new S-curve at the very beginning

- As per the Porter framework Philips ensured that by broadening the market base through a common standard it was able to build up a position that gave it scale and cost advantages that is crucial for success in a networked industry.
- The Smiling Curve; by partnering with even competitors, Philips hoped to reduce their costs of R&D and branding, thus increasing their ROI at the two high value ends of the curve.
- The Henderson taxonomy; Philips chose and successfully implemented a radical innovation but reduced its risks from competition by sharing common standards and making sure it had the necessary manufacturing and other complementary assets in place to reap substantial rewards.
- The Galbraith model; the successful launch of CDs was clear evidence of tightly coupled innovation teams working in tandem across the organization.

3. ***Indian Watch Industry***: The case covers two parallel narratives; one, the Swiss watch industry and its response first to digital and then to quartz watch technology during the 70s and the 80s; and two, the Indian watch industry as it made its transition from a government-run monopoly to a growing industry with an international presence in the 1990s. The Swiss industry bounced back successfully to a dominant position globally after being badly mauled in the 70s by digital technology from Japan initially and then low cost mass manufacturers like Taiwan, through innovative strategies and products embracing quartz technology, and rebranding “made in Switzerland” watches through exceptionally sophisticated marketing of initially the Swatch and then a host of other brands. In contrast, the government-run HMT failed to capitalize on the opportunities presented to it due to a closed top-management mindset, and ceded the dominant position to Titan Watches, which learnt well from the Swiss experience and came up with innovative products, marketing and business strategies.

The Indian watch industry case offers clear evidence of:

- The importance of monitoring S-curves; HMT clearly missed the bus on recognizing the potential of new digital technologies, while Titan seized the opportunity
- The Swiss watch industry recovery from the digital disruption is a classic case of a major shift in strategy from a differentiation to a cost leadership strategy as per the Porter Framework.
- The Smiling Curve; the Swiss watch industry's recovery is a classic example at working at the high value branding end of the Smiling Curve
- The Henderson taxonomy; the watch was seen by digital watch companies as amenable to modular and architectural innovations, capable of both of opening new markets as well as lowering costs, while HMT was still stuck in the incremental innovation approach in analog technologies.
- The Galbraith model; its absence was evident in HMT's failure, while present in both the Swiss industry and Titan

4. ***China Anti-Ship Ballistic Missile***: This case deals with innovation at a national strategic level. The strategic military defence problem faced by China as it grew in geopolitical importance in the 1990s and 2000s was very clear: How to stop a US Navy Carrier Strike Group at a distance beyond its operational radius of 1000 km, say at 2000 km, using conventional weaponry and thereby avoiding the risk of nuclear escalation? This would ensure that the US Navy would not be able to protect Taiwan, and other islands close to China, in the event of a conflict.

   The Chinese succeeded in building a deterrent that is an innovative component of land-based assets, sea-based assets, air-based assets, and space-based assets. The resultant system has been termed the Chinese Anti-Ship Ballistic Missile system, and has been regarded as one of the most innovative developments so far in military technologies (Chandrasekhar, et al., 2011).

   Although a very large-scale case, the ASBM offers compelling evidence of:

   - A National Level Ecosystem that can come up with radical solutions to major national challenges and implement them through a large and complex system of systems. To be able to capitalize on the radical solution the case also emphasizes the need to create complementary assets cutting across China's military industry complex.

- The importance of the Galbraith model principle of tightly coupled teams; in this case, very large teams working in tandem across entire organizations
- The Henderson model; the usefulness of modular and architectural innovations in crafting solutions to seemingly intractable problems
- The Henderson model and the usefulness of a radical concept, even if finally implemented as a combination of modular and architectural solutions.

5. ***Sony Trinitron***: This case is situated during the 1960s, when Sony Corporation faced the business problem of not expanding fast enough to overtake its two principal competitors (Miyaoka, 1990-91). The problem was refined down to the lack of a TV product that was compelling enough to provide a competitive edge in the distribution network and consumer base. It was decided to develop a colour TV, the first type of which had only recently made its appearance in the TV industry. For this objective, two alternatives were available; acquire the technology from outside or make it in-house. The alternative of acquiring from outside was chosen but did not lead to success. Sony had placed a gifted engineer at the head of the development effort, reporting directly to top management. Ultimately, this individual came up with an innovative way of modifying the technology, and so was born the Sony Trinitron, which catapulted Sony to the top of the international TV industry.

   During the innovation process in this case, we can observe the following concepts referenced:

   - The S-curve, which in the colour TV industry was in Stage 1; the introductory or early stage
   - The Henderson taxonomy, with Sony accepting a radical innovation that had architectural consequences for the design and manufacture of TV tubes
   - The Galbraith organization model, with evidence of the roles played by different individuals
   - The disruption in technology that enabled Sony to shift from operating in the middle as per the Porter or Smiling Curve frameworks into a position

that enabled it to simultaneously operate at the two high value ends of the curve.

6. ***Photolithography process***: This case is set in the 1960's during the early days of the microelectronics industry. The problem faced by the industry was how to increase the number of components that could be included in an integrated circuit. This problem could be broken down into two problems with the photolithography mask at the heart of the IC manufacturing process. One part addresses the issue of the level of precision needed for defining the transistor on a silicon wafer. This can be stated as the problem of resolution. The second part deals with the precision of alignment of the surface of the wafer relative to the position of the light source? This can be stated as the problem of alignment. The case shows how these problems were resolved through four successive innovation cycles : The first cycle talks about improvements in 'contact aligner' technologies where the photolithography masks remained in contact with the silicon wafer, the second, describes 'proximity aligners' in which the mask was kept in close alignment just above the wafer, allowing the wafer to be smoothly moved; the third, generation of innovation leads us through 'scanning aligners' in which the light beam moved over a static closely aligned wafer; and finally the fourth generation of 'stepper aligners', where the beam moved in discrete steps or blocks instead of continuously., Stepper aligners became the standard for the industry.
   - The Henderson taxonomy is the only concept that can be referenced in this case, since the case documents deal exclusively with the architectural technology problem and its links with organizational rigidities and mindsets that precludes going back to basics when confronted with technology bottlenecks.
7. ***China – single crystal alloy***: This case represents a 'catch up' situation. The problem faced by the Chinese defence industry in the 1980s was how to catch up with the US in the manufacture of fighter aircraft, in particular, how to catch up with the US in 'single crystal superalloy' technology required for the manufacture of aircraft turbofan engine blades. The Chinese took the approach

of ‘reinventing the wheel’, essentially duplicating in a laboratory what they could learn from the US via published and other sources. They also published extensively in research journals as they progressed up the path. While the effort ultimately succeeded at the prototype level, it has nevertheless should be termed as an innovation failure since the technology was finally never adopted (Chandrasekhar, Nagappa, Sundaresan, & Ramani, 2011).

The failure of the project leads us to observe that two concepts were referenced:

- Just as China’s ASBM was a success story in radical innovation the single crystal alloy case demonstrates inbuilt organizational and institutional bottlenecks in adopting indigenous technologies in the operation of complex products.
- The Galbraith model. In this case there appears to have been inadequate support from the Orchestrators and Sponsors at the national levels of leadership
- The S-curve; the decision was to duplicate an already available technology that had reached the Maturity stage of the S-curve.

8. ***ISRO - Charge Coupled Device technologies***: This case provides insights into innovation in ISRO for the development of IRS , India’s operational remote sensing satellite. The problem faced by ISRO was a major challenge confronting the organization. Could ISRO successfully develop such a satellite and thereby reduce India’s dependence on foreign sources? The solution to the problem was dependent on the development of technology for the space camera which was the critical component. The choice was between the Multi-Spectral Scanner (MSS) technology used by NASA, and the relatively untested Charge Coupled Device technology that had been identified by ISRO engineers as a revolutionary technology that could change capabilities. ISRO chose the riskier CCD approach and was ultimately successful (Chandrasekhar S. , 2000). This innovation eventually catapulted ISRO to world leadership in space based remote sensing cameras (Chandrasekhar & Dasgupta, 2000).

   The case provides evidence of the following concepts:

- The Henderson taxonomy: a radical solution was accepted and proved successful
- The Galbraith model; all four of Orchestrators, Sponsors, Ideators and gatekeepers worked well as a tightly coupled team with a common goal to become state-of-art in remote sensing technology
- The S-curve; a shift in S curves as one technology at the mature phase is replaced by a new emerging technology in its very early phase.

9. ***Skunk Works - stealth aircraft technology:*** This case describes the development of the first stealth aircraft prototype by Skunk Works, an R&D unit of Lockheed Corporation during the 1970s (Rich, 1994). The case starts with the problem statement as given by the US Air Force: How to counter the Soviet air defense doctrine which had proved so successful in the 1973 Yom Kippur war between Israel and the Arab nations? Skunk Works responded successfully to the challenge by the successful development of the world's first stealth aircraft, the precursor to the F-117s and F-22s that are currently operational.

   As an innovation classic, the Skunk Works stealth aircraft provides clear evidence of four concepts:

   - The Henderson taxonomy; a radical concept was successfully implemented
   - The Galbraith model, the team worked well in a tightly coupled manner considering the secrecy requirements
   - The S-curve; the project started with a mathematical concept that led to the creation of a new concept
   - The high value of the Stealth enabled Lockheed to continue with its strategy of differentiation as per the Porter framework. The Smiling Curve approach can also be seen since the final product brought immense financial success to Lockheed due to the very high value capture made possible by pioneering R&D and first-in-class product branding.

10. ***Fairchild Semiconductor in the 1960s***: Fairchild is widely regarded as the first major Silicon Valley success story, a company that led directly to the formation of Intel and the microprocessor revolution. Fairchild is remarkable for the

breadth of innovation it achieved – not only in the basic physics of microprocessors and semiconductors in general, but taking these forward into the development of concepts and prototypes, in the design and development of manufacturing processes, in the adoption of radically different venture capital financing, and most important, in the evolution of a distinctly different and highly effective corporate culture that has come to be called the 'Silicon Valley way' (Griffin, Price, Maloney, Voyak, & Sim, 2009).

In the Fairchild case, we can reference the following:

- The Henderson taxonomy as Fairchild was the pioneer of integrated circuits, a truly radical innovation
- The S-curve; Fairchild successfully caught the very beginning of the IC and microprocessor S-curves
- The Galbraith model; clearly the entire company worked in a tightly coupled fashion, with all key people playing their respective roles to the hilt
- The Smiling Curve; Fairchild succeeded greatly at both high value-added ends of the S-curve.

In none of the above cases can we infer any reference to the economic models of innovation, the historical models, the societal models or the evolutionary model. Only the practitioner models find ready reference in these cases. Of them, the strategic management and disruptive innovation models can be referenced by this researcher only in the nature of commentaries.

Appendix 2

Terminologies used in supercomputing

As a prelude, to provide a perspective on how HPC performance is measured, it is necessary to provide a list of HPC related terms and definitions:

1. A *flop* is the number of floating-point operations per second executed by a processor.
2. The following table gives the accepted terms for speeds of execution expressed in multiples of flops.

Term	Abbreviation	Flops	Reference
kiloflop	KFLOPS	10^3	One thousand flops
megaflop	MFLOPS	10^6	One million flops
gigaflops	GFLOPS	10^9	One thousand mflops
teraflops	TFLOPS	10^{12}	One thousand gflops
petaflop	PFLOPS	10^{15}	One million gflops
exaflop	EFLOPS	10^{18}	One thousand pflops
zettaflops	ZFLOPS	10^{21}	One million pflops
yettaflops	YFLOPS	10^{24}	One thousand zflops

Figure 1: HPC-related terms and definitions

3. Parallel computing is a type of computing in which many calculations are carried on simultaneously, on the principle that large problems can often be successfully decomposed into smaller ones which can then be solved in parallel.
4. A multiprocessor system is one in which several central processing units (CPUs) operate with a centralized shared memory and a single operating system.

5. A multicomputer system is one in which several single processor / multiprocessor configurations operate under the control of a single umbrella operating system.
6. A core in a multicomputer system is a processor (CPU) unit capable of executing a single thread. For graphics processing unit (GPU), a core is a streaming multiprocessor handling one task.
7. Rmax is maximal performance, measured in Gflops, Tflops, or Pflops, achieved on the LINPACK benchmark (solving a dense linear programming system)
8. Rpeak is theoretical peak performance measured in Gflop/s.
9. The Linpack benchmark is a dense linear programming problem which is used to compare the performance of different HPC systems
10. Power is total power consumed by the system.

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