The Emergence of Technological Paradigms: The Evolutionary Process of Science and Technology in Economic Development

Keiichiro Suenaga

Abstract While the prospects for the world economy, especially advanced economies, are uncertain, and the fundamental solutions to important problems such as environmental problems have not yet been found, the emergence or development of new technological paradigms is expected. The emergence of technological paradigms is a most important phenomenon in economic development. In this paper, the relationship between science and technology will be classified using four diagrammatic models, and the hierarchy of technological paradigms and the characteristics of each hierarchy will be clarified in order to consider the emergence of these technological paradigms. In addition, this paper mentions the implications for the corporate strategy of R&D, science and technology policy, and economic theory.

1 Introduction

While the prospects for the world economy, especially advanced economies, are uncertain, and the fundamental solutions to important problems such as environmental problems have not yet been found, the emergence or development of new 'technological paradigms' is expected. The concept of 'technological paradigms' was introduced by Dosi (1982), and has been a great influence on the development of evolutionary economics, etc. (e.g. see the special section of *Industrial and Corporate Change*, 2008, vol. 17 (3), "Technological Paradigms: Past, Present and Future"). Thirty years have passed since Dosi's paper was published, but the potential of this concept is not exhausted. In the meantime, while science has been playing an increasingly important role in the emergence of technological paradigms, the so-called 'new economics of science' has accomplished surprising advances during the last several decades. However, the emergence of technological paradigms has not yet been clarified. Although Dosi (1982) discusses the economic, institutional, and social factors through which technological paradigms are selected

K. Suenaga (✉)
Faculty of Economics, Josai University, 1-1 Keyakidai, Sakado, Saitama, Japan
e-mail: od03008@yahoo.co.jp

A. Pyka, J. Foster (eds.), *The Evolution of Economic and Innovation Systems*, Economic Complexity and Evolution, DOI 10.1007/978-3-319-13299-0_10

from existing scientific knowledge, he does not fully consider the factor of the emergence of technological paradigms. It is necessary for economists, particularly neo-Schumpeterian and evolutionary economists, to pay attention to the factors and processes of the emergence of technological paradigms, which are very important in economic development. In this paper, the relationship between science and technology will be classified via some diagrammatic models, and will be further discussed. In particular, the paper focuses on the emergence of technological paradigms, and explores the factors and processes involved in this emergence. Moreover, it pays particular attention to the hierarchy of technological paradigms, clarifying the characteristics of each hierarchy, and considers the ways in which the paradigms have emerged, based on a diagrammatic model.

1.1 Differences Between Science and Technology

Science aims to provide an elucidation of natural phenomena, while the purpose of technology is to create artifacts. Moreover, scientific knowledge is much more codified than technological knowledge, and much technological knowledge is implicit in experience and skill (e.g. Dosi 1982). However, not all scientific knowledge is necessarily codified, and tacit knowledge, which cannot be codified, also plays an important role in many cases. Nevertheless, generally speaking, scientific knowledge is easier to spread compared to technological knowledge.

Advances in science build mainly on already existing scientific knowledge (scientific papers cite other scientific papers much more frequently than patents), while advances in technology build mainly on technological knowledge (e.g. patents cite other patents much more frequently than scientific papers) (Price 1965; Stokes 1997; Pavitt 1998).[1] Furthermore, academic institutions dominate advances in science, while business firms do so for advances in technology (e.g. Pavitt 1998).

> One of the main purposes of academic research is to produce codified theories and models that explain and predict natural reality. To achieve analytical tractability, this requires simplification and reduction of the number of variables . . . . On the other hand, the main purpose of business research and development is to design and develop produceable and useful artefacts. These are often complex, involving numerous components, materials, performance constraints and interactions, and are therefore analytically intractable . . . . Knowledge is therefore accumulated through trial and error. As a consequence, the methodologies of 'experiments' in the two types of laboratories are often very different (Pavitt 1998, p. 795).

[1]When discussing advances in science and technology, it is necessary to divide each stock and flow clearly. That is, existing scientific or technological knowledge is a 'stock', and advances in scientific or technological knowledge are a 'flow'. Although the knowledge of science or technology is a state function and it can accumulate, the progress of science or technology is a process and is transitional. [With regard to this paragraph, see also Kline (1990) and Stokes (1997)].

Scientists are concerned with the discovery and publication of new knowledge, but they are not concerned with its application. On the other hand, the concern of technologists or engineers is the practical application of knowledge and professional recognition, and not the publication of knowledge (Price 1965; Freeman and Soete 1997). Relatively speaking, scientists (or academic institutions) act with the aim of achieving social rewards, such as a reputation, rather than economic rewards, such as profit.[2] On the other hand, engineers (or businesses) act with the purpose of earning economic rewards rather than social rewards (Merton 1973; Dasgupta and David 1994; Pavitt 1998; Bach and Matt 2005; Yamaguchi 2006; Aghion et al. 2009).[3]

1.2 Relationship Between Science and Technology

Price (1965) argues that science and technology are two subsystems which develop autonomously, and he uses the metaphor of two dancing partners that have their own steps although dancing to the same music.[4] Freeman and Soete (1997, p. 15) point out that this relationship between science and technology has changed since the nineteenth century, and sometimes they are 'cheek to cheek'. That is, the relationship between science and technology has become much more intimate, and the professional industrial R&D department is the cause and consequence of this new intimacy. With respect to the relationship between science and technology, Brooks (1994) uses the metaphor of two strands of DNA which can exist independently, but cannot be truly functional until they are paired.

According to Rosenberg (1990), one of the reasons why some firms do basic research is to resolve practical problems and/or to exploit the first-mover advantage. Moreover, it is extremely difficult to distinguish between basic research and applied research, and the relationship between them is highly complex. As contributions which science gives to technology Brooks (1994) mentions: it provides a direct source of ideas, it is a source of tools and techniques, it aids development of new human skills, etc., and as contributions which technology gives to science: it is a fertile source of novel scientific questions, and a source of otherwise unavailable instrumentation and techniques.

Kuznets (1966) indicates the importance of applying science to economic production as the main characteristic of modern economic growth, but does not suggest that modern technological innovation is triggered by scientific discovery. Rosenberg (1982) also insists that technological knowledge has preceded scientific knowledge, and that, even in industries founded on scientific research, practical experience with the new technology often precedes scientific knowledge.

[2] Needless to say, scientists may obtain economic rewards through IPR or academic spin-offs.

[3] Although there are many engineers who do not personally operate for economic reward, they aim for the economic reward of their company.

[4] It goes without saying that Price did not deny that science and technology have interacted.

However, it is particularly important to mention that the relationship varies, subject to the stage of industrial development: the role of science is more important in the initial stage of industrial development. Dosi (1988) points out that scientific knowledge plays a crucial role in opening up new possibilities for major technological advances, and that in the twentieth century the emergence of major new technological paradigms has frequently been directly dependent on and directly linked with major scientific breakthroughs. However, although at least the first ten years of the history of the semiconductor industry were characterized by a crucial inter-relationship between science and technology, the distance between the two has increased since the 1960s. Basic semiconductor technology has become established and its development path no longer needs a direct 'coupling' with 'Big Science' (Dosi 1984, p. 28).

1.3 Diagrammatic Illustrations of the Relationship Between Science and Technology

Some studies have tried to express this relationship between science and technology in a diagram.[5] Kline (1990) argues about the relationship between science and technology by using the 'revised chain-linked model'. Kline points out that science contributes to innovation only in the KITS (Knowledge Interface of Technology and Science) of the revised chain-linked model; the research which is born from KITS is not as difficult as the research which is produced from scientific knowledge; the problems extracted from KITS are connected with advances in science and mathematics. Kline's model demonstrates that scientific and technological knowledge are intertwined in the production process from the point of market discovery up to the point of sales.

Stokes (1997) also discusses the relationship between science and technology, based on 'a revised dynamic model'. Existing understanding can bring about improved understanding through pure basic research, and existing technology can produce improved technology through purely applied research and development. Furthermore, science and technology are semiautonomous, and are only loosely coupled. However, they are at times strongly influenced by each other, with 'use-inspired' basic research often cast in the linking role. The use-inspired basic research is also known as 'Pasteur's quadrant'. Through use-inspired basic research, existing understanding can bring about improved understanding and/or technology, and existing technology can produce improved understanding and/or technology.[6]

[5]Although Chesbrough (2003) illustrates the relationship between science and technology (research and development) in order to compare 'closed innovation' with 'open innovation', the relationship takes a linear form in his model.

[6]Stokes's model does not illustrate the technological paradigms.

Yamaguchi (2006, 2008) illustrates innovation processes in a two-dimensional diagram, an ‘innovation diagram’, plotting the concepts of ‘knowledge creation’ on a horizontal axis and the concepts of ‘knowledge realization’ on a vertical axis. According to him, ‘knowledge creation’ means to discover things which nobody knows, and the intellectual workings for the discovery are termed as ‘science’. On the contrary, ‘knowledge realization’ refers to intellectual workings to realize feasible things by collecting and integrating scientific and technological knowledge, and the intellectual workings are limited to workings of ‘technology’. In this diagram, science and technology are not a unified evolutionary system, but a chain of their actions forms an evolutionary system. In addition, in his diagram, science is located in ‘soil’, because it is not economically valued.

By using the concepts of technological paradigms and technological trajectories, Dosi (1982) argues about the processes by which technology is chosen from existing scientific knowledge.[7] Cimoli and Dosi (1995) attempt to illustrate technological paradigms and technological trajectories by plotting two factors of production on vertical and horizontal axes. However, the relationship between science and technology is not illustrated in a model.

In Sect. 2, based on Yamaguchi’s innovation diagram which is partly amended, the relationship between science and technology is classified into four models. Suenaga (2011) clarified the hierarchy of technological paradigms and the characteristics of each soil layer, based on the analysis of Yamaguchi (2006) with regard to the transistor and MOSFET. However, the discussion is refined and the relationship between the four models and the emergences of technological paradigms are considered in Sects. 3 and 4 respectively to clarify. Finally, Sect. 5 concludes the article and points out some theoretical and political implications.

2 Diagrammatic Models of Science and Technology

This section discusses the relationship between science and technology based on a revised model of Yamaguchi’s innovation diagram. Yamaguchi’s model has not been developed in the neo-Schumpeterian tradition, and thus it could be further developed by utilizing neo-Schumpeterian research results.

Although he uses the concepts of ‘knowledge creation’ and ‘knowledge realization’, the intellectual workings for ‘knowledge creation’ are called ‘science’ and the intellectual workings for ‘knowledge realization’ are called ‘technology’, so that we

[7] A technological paradigm is a ‘“model” and a “pattern” of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies’; a technological trajectory is ‘the pattern of “normal” problem solving activity (i.e. of “progress”) on the ground of a technological paradigm’ (Dosi 1982, p. 152).

use the terms, ‘science’ instead of ‘knowledge creation’, and ‘technology’ instead of ‘knowledge realization’.[8]

In this section, based on Yamaguchi’s innovation diagram, the relationship between science and technology is classified into four models. These are the Price model, which analyses the autonomy of science and technology, the Bush model, which focuses on science-driven technological progress, the Rosenberg model, which is based on technology-driven scientific progress, and the Dosi model, which considers the relationship between science and technology from the viewpoint of technological paradigms and trajectories.

2.1 Autonomy of Science and Technology

Figure 1 represents the case where science and technology autonomously develop. Existing scientific knowledge (S) advances through scientific research etc. ($S \rightarrow S'$). Advances in scientific knowledge are indicated by a rightward arrow in soil because they are not valued economically. Existing technological knowledge (T) advances through technological development etc. ($T \rightarrow T'$). This is illustrated as the upward arrow above the soil. Here, the case in which science and technology autonomously develop, as shown in Fig. 1, is referred to as the ‘Price model’, after Price (1965).

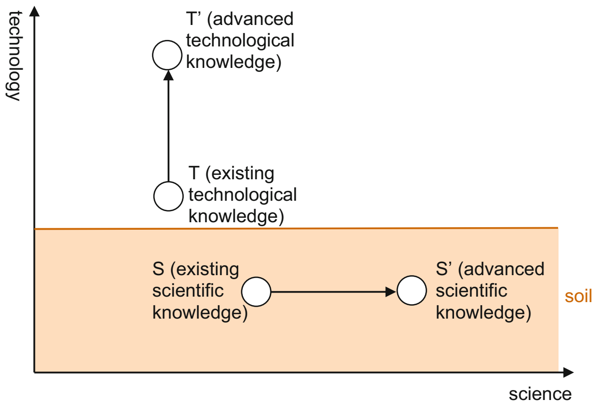

Fig. 1 Price model: a case in which science and technology autonomously develop. *Note*: Although this figure is described, based on the innovation diagram of Yamaguchi (2006), I distinguish between existing scientific knowledge and technological knowledge

[8]Although, in Yamaguchi’s diagram, technology, such as the refinement method of a hermetic art, and knowledge of a chemical reaction are contained in ‘knowledge creation’, they are not contained in ‘science’ in this paper.

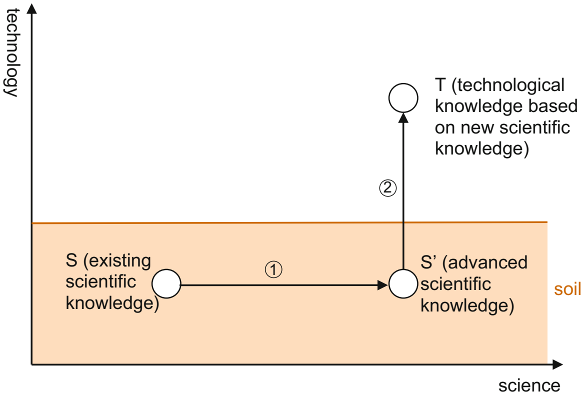

Fig. 2 Bush model (linear model): science → technology. *Note*: This figure expresses the characteristics of a linear model, based on Yamaguchi's innovation diagram

2.2 Science-Driven Technological Progress

Although science and technology develop autonomously, they are not completely independent. Regarding the relationship between science and technology, although Freeman and Soete (1997) describe it as 'cheek to cheek', and Brooks (1994) uses the metaphor of 'two strands of DNA', what is the actual relationship like in detail? Figure 2 illustrates the case in which advances in scientific knowledge ($S \rightarrow S'$) bring about advances in technological knowledge (T). The circled numbers indicate the order of the relationship between science and technology. This relationship is generally called a linear model. In this paper, this model is called the 'Bush model', after Bush (1945), who is regarded as a representative advocate of the linear model.[9]

2.3 Technology-Driven Scientific Progress

Figure 3 shows a case where existing technological knowledge triggers advances in scientific knowledge, and then scientific understanding encourages further advances in technology. As Rosenberg (1982) points out, technological knowledge without scientific understanding exists in many cases, and the existence of technological knowledge (T) promotes scientific understanding ($S \rightarrow S'$). Furthermore, advanced scientific knowledge (S') enforces advances in technological knowledge ($T \rightarrow T'$). For example, although Duralumin was brought into existence by an engineer's trial and error, the associated scientific understanding only came about much later. In addition, scientific understanding drives the advances in Duralumin technology (Rosenberg 1982). In this paper, this model is called the 'Rosenberg model'.

[9]The problems of the Bush model (linear model) are pointed out in Sect. 4.

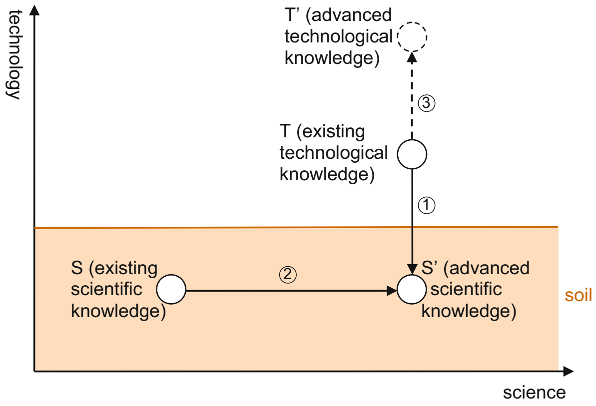

Fig. 3 Rosenberg model: technology → science (→ technology). *Note*: This figure illustrates the view of Rosenberg (1982), based on Yamaguchi's innovation diagram (2006)

2.4 Technological Paradigms and Trajectories

Dosi (1982) tries to capture the relationship between science and technology from the viewpoint of technological paradigms and trajectories. Figure 4 illustrates Dosi's 'technological paradigms' and 'technological trajectories' (1982). With regard to Dosi's (1982) definitions, this paper defines 'technological paradigms' as 'a "model" and a "pattern" of a solution to *selected* technological problems, based on *selected* scientific knowledge', and defines' technological trajectories' as' the progressing process of technological knowledge, based on a technological paradigm'.[10] Although Dosi, given the stock of scientific knowledge, discusses the process whereby technology is selected from existing scientific knowledge, scientific progress such as progress from S_1 to S_2 is illustrated in this figure. Advanced scientific knowledge, S_2, may induce new technological knowledge, T_2, such as the Bush model, or may be triggered by existing technological knowledge, T_2, according to the Rosenberg model. Therefore, Fig. 4 includes both the Bush model and the Rosenberg model. In Fig. 4, technological paradigms are expressed as a dotted line, and technological trajectories are illustrated as upward arrows within technological paradigms. The model which shows the relationship between science and technology, as shown in Fig. 4, is called the 'Dosi model' here.

[10]Whether these advances are improvements along a technological trajectory or a shift in paradigm, with new technological trajectories emerging, depends on whether the 'selected scientific knowledge' as the basis of the technological trajectory is new or not (even if scientific knowledge precedes technological knowledge as in the Bush model, or technological knowledge precedes scientific knowledge as in the Rosenberg model).

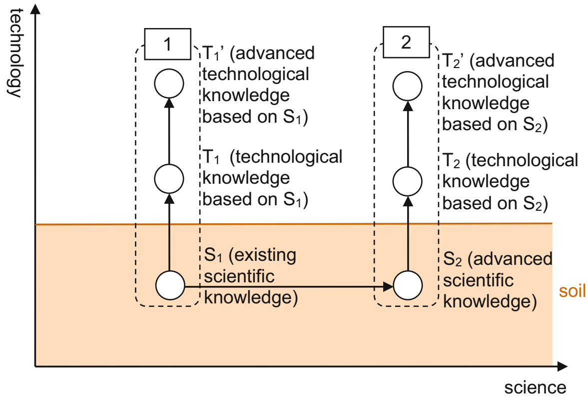

Fig. 4 Dosi model: Technological paradigms and technological trajectories. *Note*: This figure illustrates the view of Dosi (1982), based on Yamaguchi's innovation diagram (2006)

3 The Hierarchy of Technological Paradigms

The discussion in this section is based on the Dosi model, and considers the hierarchy of technological paradigms (Fig. 5). Although advances in scientific knowledge have been located in soil up to this point, there are various layers of soil. For example, in the process by which the semiconductor industry came into being and developed, while the academic framework itself changed from classical electromagnetics (3-a), the basis of tube technology, to quantum mechanics (3-b), the basis of semiconductor technology, there were also advances in science within the academic framework of quantum mechanics. For example, although the transformation of operating principles from current injection (2-a), the basis of bipolar transistor technology, to field effect (2-b), the basis of FET technology is based on the specific academic framework of quantum mechanics, it is less significant than the transformation of the academic framework. Moreover, the transformation of connection methods from point type (1-a) to junction type (1-b) is less significant than the transformation of the operating principles, because point and junction type are based on a specific operating principle, current injection. With regard to the diagram above, the transformation of the academic framework is described as being located in the deeper layer of soil (referred to here as the third layer), while the transformation of the operating principles is located in a middle layer of soil (referred to here as the second layer), and the transformation of the connection methods is located in a shallower layer of soil (referred to here as the first layer).[11]

As already mentioned, the 'technological paradigms' in this paper are 'a "model" and a "pattern" of a solution to *selected* technological problems, based on *selected* scientific knowledge'. This '*selected* scientific knowledge' sometimes refers to the *selected* academic framework, such as quantum mechanics. However, it sometimes

[11] See also Suenaga (2011) for the discussion in detail.

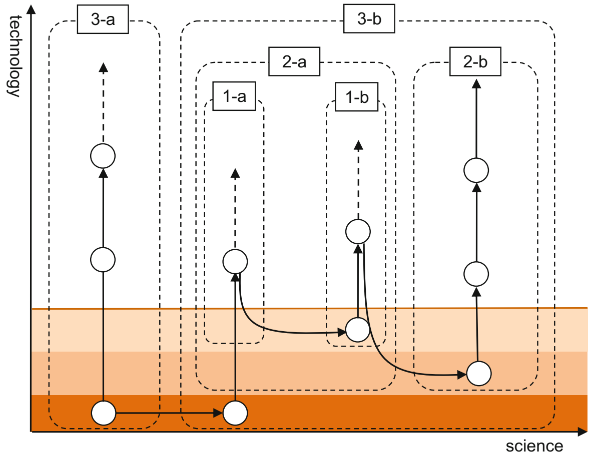

Fig. 5 Soil layers and hierarchy of technological paradigms

refers to the *selected* operating principles, such as current injection within the academic framework, and it sometimes refers to the *selected* connection methods, such as point type and junction type, within the operating principles such as current injection.

Advances in scientific knowledge in the third layer form more extensive technological paradigms (e.g. '3-b'), advances in scientific knowledge in the second layer form middle-sized technological paradigms (e.g. '2-a', which is included in '3-b'), and advances in scientific knowledge in the first layer form smaller technological paradigms (e.g. '1-b', which is included in '2-a'). As a result, layers are also formed in technological paradigms when a difference in the dimension (the depth of soil) of scientific knowledge exists.[12]

[12]Therefore, it can also be interpreted as follows: If seen from the 3rd layer, the change from '1-a' to '1-b' and the change from '2-a' to '2-b' will be the technological trajectory in the technological paradigm '3-b'. If seen from the 2nd layer, the change from '1-a' to '1-b' will be the technological trajectory in the technological paradigm '2-a'. If seen from the 1st layer, the change from the grown junction method to the alloy junction method will be the technological trajectory in the technological paradigm '1-b'. According to this interpretation, whether a specific change is an improvement along a technological trajectory or a shift in paradigm, with new technological trajectories emerging, depends on the layer from which it is seen. Moreover, although the scientific knowledge can also still be classified in detail, it will be enough just to clarify the existence of the hierarchy of scientific knowledge, or a technological paradigm, since the purpose here is to discuss essentials.

Of course, an old technological paradigm and a new technological paradigm may coexist. The vacuum tube and the semiconductor coexist, and the same may be said about the bipolar transistor and MOSFET. Moreover, science and technology affect each other mutually, and the chain (co-evolution) of science and technology forms an evolutionary system. For example, the invention of the point contact type transistor, based on the discovery of Walter H. Brattain and John Bardeen, led to William B. Shockley's scientific knowledge about the junction type transistor, and the grown junction technology was based on Shockley's scientific knowledge. Furthermore, the invention of MOSFET also led to advances in scientific knowledge about the quantum Hall effect by Klaus von

Table 1 Soil layers and technological paradigms/scientific knowledge

1st layer: Connections		1-a Ge point/ Point	1-b Ge junction/ Junction	
2nd layer: Operating principles		2-a Bipolar/ Current injection		2-b FET/ Field effect
3rd layer: Academic frameworks	3-a Tube/ Electromagnetics	3-b Semiconductor/ Quantum mechanics		

Source: This table is the revised version of Suenaga (2011)

Table 1 sums up the characteristics of technological paradigms and scientific knowledge regarding the basis of each technological paradigm. Although Table 1 is drawn from the example of the transistor and MOSFET, the same argument can also be developed in other examples. That is, layers are formed in the soil, and the hierarchy of technological paradigms based on these layers is built, although the characteristics of each layer may differ.[13] In this way, by clarifying the characteristics of the hierarchy of technological paradigms or soil layers, part of the method of producing new technological paradigms may become clear.

4 The Emergence of Technological Paradigms

How do new technological paradigms emerge? According to the Bush model (linear model), there are advances in scientific knowledge which have the possibility of producing a new technological paradigm. However, there are many cases where an advance in scientific knowledge does not produce a new technological paradigm. Moreover, there is a time-lag until advances in scientific knowledge produce new technological paradigms; sometimes this happens quickly (or almost immediately), and in other cases it takes a long time (tens of years or more than that). However, as there is much criticism about this, it is insufficient to just understand advances in scientific knowledge and new technological paradigms in terms of linear relationships (for example, Dosi 1982; Kline 1990; Stokes 1997; Nightingale 1998). Many economic factors affect advances in scientific knowledge, and the

Klitzing. That is, science provides the technological sources of a scientific question, technology also does so, and various feedback mechanisms exist between science and technology (also refer to Sect. 1.2).

[13]Although we need to analyze the various examples, Yamaguchi's analyses (2006, 2008, 2009) about the Industrial Revolution and other cases are extremely interesting.

complexity and the uncertainty of the relationship between science and technology may be overlooked in the Bush model. In the Rosenberg model, the emergence of technological paradigms happens without scientific knowledge (understanding), and the solidity of technological paradigms increases with advances in scientific knowledge (understanding). Thus, the relationship between science and technology is not a one-way thing, and a chain of science and technology forms an evolutionary system, with science and technology having a mutual influence. Nevertheless, as time goes by, the importance not only of existing scientific knowledge but advances in scientific knowledge increases. In order to produce new technological paradigms which have great potential, advances in scientific knowledge are needed at deeper layers.

Dosi (1982) discusses the economic, institutional, and social factors through which technological paradigms are selected from existing scientific knowledge. For example, the marketability, potential profitability, and labor-saving capability of technological paradigms, and industrial and social conflict, have an influence on the process by which technological paradigms are selected.[14] In this process, although the market plays a certain role, it is almost impossible to predict the long-term performance of technological paradigms. Therefore, it is not an approach like neoclassical economics (including endogenous economic growth theory) that is needed, but one like evolutionary economics (including Dosi et al.).[15] Although it is necessary to generalize as regards the factors and process of the emergence of technological paradigms through various case studies, one might not be able to find anything like a general theory of the emergence of technological paradigms, as Cimoli and Dosi (1995, p. 254) point out.

Basically, if the possibility is high that technological trajectories will develop under a specific technological paradigm, the incentive to look for other technological paradigms decreases. On the other hand, if there is a low possibility that the technological trajectories will develop, the motivation to seek other technological paradigms increases.[16] Moreover, if there is a high possibility that scientific knowledge will progress, the possibility that other technological paradigms can be selected increases. On the other hand, if the possibility is low that scientific knowledge will progress, the possibility that other technological paradigms can be selected decreases. The frequency of the emergence of technological paradigms

[14]For example, the Middle Eastern conflict affects the direction for seeking alternative energy sources. Although Dosi (1982, p. 156) mentions that 'scope for substitution ... is limited by the technology which itself defines the range of possible technological advances', Yamaguchi's model suggests that advances in scientific knowledge which generate new technological paradigms have an important role.

[15]In this process, lock-in effects or path-dependency have an important influence.

[16]About this phrase; see also Freeman and Perez (1988). 'It is only when productivity along the old trajectories shows persistent limits to growth and future profits are seriously threatened that the high risks and costs of trying the new technologies appear as clearly justified' (p. 49).

increases as the layer becomes shallower, and the potential for new paradigms increases as the layer becomes deeper.[17]

What kind of corporate strategy or policy is needed in order to generate new technological paradigms? One important point in this regard is how to combine science and technology, since this combination plays an important role in creating new technological paradigms. Although science and technology have mutually independent characteristics, they are strongly influenced by each other. In a situation where new technological paradigms are needed, how both are combined becomes important. In particular, in order to create technological paradigms based on deeper layers, 'a field' which straddles between academics or between organizations may be needed.

Regarding this field, Yamaguchi (2009) suggests the concept of 'a field of resonance'.[18] According to him, the key to what new technological paradigm emerge depends on whether those who find the existential desire for 'advances in scientific knowledge' and 'advances in technological knowledge' can succeed in resonating this desire in a realistic place which can transmit tacit knowledge . . . Such a place is called the 'field of resonance'.

Of course, there will be cases where those who have the existential desire for 'advances in scientific knowledge', and those who have the existential desire for 'advances in technological knowledge' are the same people,[19] and cases where both are alive at completely different times and places. Nevertheless, as already mentioned, the importance of not only existing scientific knowledge but advances in scientific knowledge increases as time goes by, and the importance of sharing a 'field' where both can transmit tacit knowledge is increasing.[20]

Table 2 generalizes the state of 'a field of resonance' to each soil layer of Table 1. According to the level (soil layer) at which the actor tries to create the technological paradigms, the person, organization, and scientific knowledge required for the field of resonance are different, although the state of optimal field of resonance changes with the characteristics of industry and the times. When considering the methods of research and development, or the policy of science and technology, it is important to recognize the hierarchy and characteristics in each such level.[21]

---

[17]This is an important factor for long business fluctuations.

[18]Refer also to Nonaka and Takeuchi (1995) in regard to the role of the 'field' in knowledge creation. They analyze the 'field' for changing tacit knowledge into explicit knowledge in the SECI model of knowledge creation.

[19]See also Rosenberg (1990) in regard to this example. Rosenberg also discusses the relationship between scientific knowledge and technological knowledge in detail.

[20]The reason the transistor was created in the Bell laboratory was that many specialists in various academic realms worked in the same field, transmitted tacit knowledge, and drew inspiration from each other. 'All in all, the people playing a major role at one time or another in the work which led to the transistor discovery may have numbered about thirteen' (Nelson 1962, p. 560).

[21]For example, this argument is also related to arguments such as 'More Moore', 'More than Moore', and 'Beyond CMOS'. Let me define 'More Moore' as 'to pursue micro-fabrication on silicon CMOS', 'More than Moore' as 'to create new value through combinations of technology',

Table 2 Soil layers and field of resonance

1st layer: Connections	Various connections based on selected principles
2nd layer: Operating principles	Various theories based on selected academy
3rd layer: Academic frameworks	Various academies, various frameworks

5 Conclusions: Some Theoretical and Policy Implications

In Sect. 2, the relationship between science and technology is discussed in a number of models, based on Yamaguchi's innovation diagram. The models are the Price model, which pays attention to the autonomy of science and technology, the Bush model, which focuses on science-driven technological progress, the Rosenberg model, which is based on technology-driven scientific progress, and the Dosi model, which considers the relationship between science and technology from the viewpoint of technological paradigms and trajectories. There are various ways of viewing this relationship, and we should discuss it from various points of view, taking into account economic development, corporate strategy, and S&T policy.

Section 3 focuses on the hierarchy of technological paradigms in order to describe the emergence of technological paradigms. Additionally, by clarifying the characteristics of each layer of technological paradigms and scientific knowledge, it proposes a conceptual framework to create technological paradigms. The scientific knowledge which is the foundation of technological paradigms consists of deeper layers forming the academic framework, and shallower layers forming the operating principles and connection methods. Furthermore, technological paradigms, which are based on the layer of scientific knowledge, exist hierarchically, and constitute a complex system. In order to come up with strategies and policies to create technological paradigms, we should make a structure of human and material resources and organizations considering the hierarchy of technological paradigms.

Although the integrated model of this paper is, in some respects, "impressionistic", it is an interesting model which illustrates the evolutionary process of economic development. Although many economists, such as Kuznets (1966), have emphasized the role of science on economic development, we can explicitly consider the relationship between science and technology, and the one between technological paradigms and economic development, based on the integrated model. Though the relationship between science and technology is not uniform, a chain of science

and 'Beyond CMOS' as 'to bring forth new devices based on new connections or principles'. Although they do not necessarily correspond completely, it follows that 'More Moore' and 'More than Moore' represent paradigm-sustaining innovation. New devices based on new connections are paradigm-disruptive innovation in the first layer, and new devices based on new principles are paradigm-disruptive innovation in the second layer. Finally, paradigm disruptive innovation in the third layer is a device based on an academic framework, which is different to quantum mechanics (referred to here as 'Beyond Quantum').

and technology forms technological paradigms, and the hierarchical development of technological paradigms results in industrial and economic development.

While traditional economic growth theory demonstrates the process of economic growth by plotting the capital stock per capita on a horizontal axis and the output per capita on a vertical axis, Cimoli and Dosi (1995) illustrates technological paradigms and technological trajectories by plotting two factors of production on vertical and horizontal axes. Although this paper considers the process of economic development by plotting science and technology on both axes, disregarding factors such as capital and labor, on which orthodox economics places significance, this is not wrong when discussing the long-term process of economic development. The essential factors in economic development are science and technology, rather than capital and labor which neoclassical economic growth theory focuses on. Moreover, the process of economic development is an evolutional process rather than an equilibrium process, and its process cannot be described using numerical formulae.

Nevertheless, this paper has a problem of theoretical imperfection. Simply speaking, scientists (or academic institutions) act with the aim of social rewards, and advances in science are a function of the input to scientific research. On the other hand, engineers (or business firms) act with a view to earning economic rewards, and advances in technology are a function of the input to technological development. Although science and technology develop autonomously, both are complexly intertwined, as already mentioned above. As a result, although it is difficult to be theoretically explicit about the totality of the relationship between the two, it is possible to theorize about the relationship, to some degree, by classifying some models, as in this paper.

The process by which science and technology form a chain in various ways, and the process through which technological paradigms are selected and developed, are just evolutionary processes. Technological paradigms which are not suited to the economic environment in the short term might be disregarded, even if they have long-term potential.

Moreover, although this research has elucidated the hierarchy of technological paradigms by clarifying the hierarchy of scientific knowledge, the existence of the hierarchy is a factor that brings short-, middle-, and long-term economic fluctuations.[22] In addition, by clarifying the hierarchy of technological paradigms, the continuity and discontinuity of an industrial development can be discussed.

Schumpeter (1934, p. 66), in the explanation of new combinations, refers to the 'introduction of a new method of production, that is one not yet tested by experience in the branch of manufacture concerned', and states that it need by no means be founded upon a discovery that is scientifically new. Although he refers to a new method of production based on a discovery that is scientifically new as a new combination, the discovery in itself is not endogenous in his model. However, we have to endogenise 'advances in science' to theorize the essence of economic

[22] See also the discussions about techno-economic paradigms and long waves, such as Freeman and Perez (1988).

development, even if scientific knowledge precedes technological knowledge as in the Bush model, or technological knowledge precedes scientific knowledge as in the Rosenberg model.

Large central laboratories such as the Bell laboratory of AT&T used to play a significant role in the emergence of technological paradigms (in particular, based on deeper layers). However, because of the greater mobility of skilled researchers, the increased knowledge in society as a whole, and the development of venture capital, it is difficult for a central laboratory in a large company to create new technological paradigms (based on the third layer).[23] How companies efficiently produce new technological paradigms in an era of open innovation is an important topic for the collaboration of industry-academia management. Moreover, how science and technology are bound together is also a crucial problem from the viewpoint of the policy of science and technology.

According to the soil layer of technological paradigms which the organization aims to create, the proportion and level of human and material resources, the organization, and the scientific knowledge required for the field of resonance differ.[24] In particular, it is necessary to develop a management framework and policies for producing new technological paradigms based on the third layer. Many organizations all over the world are challenged with this difficulty, and then such case studies are a subject that should be studied further in the future.[25]

Acknowledgements The author is grateful for the valuable comments and suggestions of Eiichi Yamaguchi, Kazuo Sakai, Tim Minshall, Hans-Jürgen Engelbrecht, Thanh Le, Dengjian Jin, and all participants at the 2nd International Symposium on Innovation Strategy at the University of Cambridge, at a session of the 14th International Schumpeter Society at the University of Queensland, and at the Meeting on Higher Education for the Next Generation. The comments of anonymous referees are also gratefully acknowledged. I am especially indebted to Fumitaka Nakamura for his profound advice. All remaining errors are my own.

References

Aghion P, David PA, Foray D (2009) Science, technology and innovation for economic growth: linking policy research and practice in 'STIG Systems'. Res Policy 38:681–693

Bach L, Matt M (2005) From economic foundations to S&T policy tools: a comparative analysis of the dominant paradigms. In: Llerena P, Matt M (eds) Innovation policy in a knowledge-based economy, ch. 1. Springer, Berlin, pp 17–45

Brooks H (1994) The relationship between science and technology. Res Policy 23:477–486

[23] See Chesbrough (2003) about open innovation.

[24] This is related to the discussion about the relationship between diversity and innovation.

[25] Suenaga (2012) examines the role of local government, focusing on IMEC in Belgium. In Japan, central government plays a significant role in implementation of science and technology policy and declines the degree of globalization about research and development in Japan. The example of IMEC has significant implications for Japan.

Bush V (1945) Science the endless frontier. United States Government Printing Office, Washington, DC
Chesbrough H (2003) Open innovation: a new imperative for creating and profiting from technology. Harvard Business School Corporation, Boston, MA
Cimoli M, Dosi G (1995) Technological paradigms, patterns of learning and development: an introductory roadmap. J Evol Econ 5:243–268
Dasgupta P, David PA (1994) Toward a new economics of science. Res Policy 23:487–521
Dosi G (1982) Technological paradigms and technological trajectories. Res Policy 11:147–162
Dosi G (1984) Technical change and industrial transformation: the theory and an application to the semiconductor industry. Macmillan Press, London
Dosi G (1988) Sources, procedures, and microeconomic effects of innovation. J Econ Lit 26:1120–1171
Freeman C, Perez C (1988) Structural crises of adjustment, business cycles and investment behaviour. In: Dosi G et al (eds) Technical change and economic theory. Pinter Publishers, London, pp 38–66
Freeman C, Soete L (1997) The economics of industrial innovation, 3rd edn. Routledge, London
Kline SJ (1990) Innovation style in Japan and the United States: cultural bases; implications for competitiveness. Stanford University Press, Stanford
Kuznets SS (1966) Modern economic growth: rate, structure and spread. Yale University Press, New Haven
Merton RK (1973) The sociology of science: theoretical and empirical investigations. The University of Chicago Press, Chicago
Nelson RR (1962) The link between science and invention: the case of the transistor. In: Nelson RR (ed) The rate and direction of inventive activity: economic and social factors. Princeton University Press, Princeton
Nightingale P (1998) A cognitive model of innovation. Res Policy 27:689–709
Nonaka I, Takeuchi H (1995) The knowledge-creating company: how Japanese companies create the dynamics of innovation. Oxford University Press, New York
Pavitt K (1998) The social shaping of the national science base. Res Policy 27:793–805
de Solla Price DJ (1965) Is technology historically independent of science? A study in statistical historiography. Technol Cult 6:553–568
Rosenberg N (1982) Inside the black box: technology and economics. Cambridge University Press, Cambridge
Rosenberg N (1990) Why do firms do basic research (with their own money)? Res Policy 19:165–174
Schumpeter JA (1934) The theory of economic development. Oxford University Press, Oxford
Stokes DE (1997) Pasteur's quadrant: basic science and technological innovation. Brookings Institution Press, Washington, DC
Suenaga K (2011) The soil layers of innovation diagram. Paper presented at the Doshisha University Graduate School (in Japanese)
Suenaga K (2012) The role of local government in an era of open innovation: an analysis based on the example of a Flemish government-funded NPO. J Urban Manag Local Gov Res 27(2):1–10
Yamaguchi E (2006) Innovation: paradigm disruptions and fields of resonance. NTT Publishing (in Japanese)
Yamaguchi E (2008) Industrial revolution as paradigm disruptive innovations. Organ Sci 42(1):37–47 (in Japanese)
Yamaguchi E (2009) What is 'Mekiki-ryoku' of technology. Nikkei Tech-On, Feb–Mar (in Japanese)