The Emergence and Evolution of New Industries: The Evolutionary Process of Heat Engines

Abstract

While the long-term prospects for the world economy are unclear, the emergence of new industries is expected. The emergence of new industries or technological paradigms is a most important phenomenon in innovation and economic development. However, it is negligent of economists, particularly neo-Schumpeterians and researchers of innovation, that the understanding of this process is still limited (see also Krafft et al., 2014).

The economic development under consideration in this paper is the emergence of technological paradigms. 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'. A chain of science and technology forms an evolutionary system and the evolution generates economic development.

Although Suenaga (2015a) demonstrates that the 'new theory of economic development' can be applied to the semiconductor industry, can this theory be applied to other industries? This paper examines heat engines, which started to develop more than 300 years ago. Through this analysis, the relationship between science and technology, the hierarchy of technological paradigms and scientific knowledge, and a field of combining science and technology are clarified. In addition, this makes it easier to compare with other examples, to express the long-term process of economic development, and to create plans for corporate strategy and governmental policy. Furthermore, in the current era of open innovation, the difficulty of combining science and technology properly is significant. However, this problem was also important more than 300 years ago. In this sense, this paper has a purpose in rethinking various discussions about long-term economic development.

Keywords: emergence of new industries; technological paradigms; economic development; industrial development; S&T; innovation diagram; heat engine

1. Introduction

While the long-term prospects for the world economy are unclear, the emergence of new industries is expected. The emergence of new industries or technological paradigms is a most important phenomenon in innovation and economic development, and is one of the most significant themes in economics. Although a special section on the 'emergence and evolution of new industries' has appeared in *Research Policy*, Krafft et al. (2014), who are the editors of this special section, depict it as follows: 'the understanding of this process is still limited in the field of economics of innovation. This is all more surprising since economic development all times has been essentially nurtured by the emergence of new industries... This special section of Research Policy aims in improving our understanding of the processes of industry emergence' (p. 1664).[1] However, it is negligent of economists, particularly neo-Schumpeterians and researchers of innovation, that the understanding of this process is still limited.

However, some neo-Schumpeterians have discussed the emergence of new industries. For example, Freeman and Perez (1988) talk about factors relating to the emergence of new industries and technological paradigms. '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).

Moreover, 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. However, the actual factors relating to the emergence of technological paradigms and advances in scientific knowledge are not discussed.

Schumpeter (1934, p. 66) recognizes economic development as five cases of new combinations: production of new types of goods, or a change in the properties of the existing goods; introduction of new methods of production that may be based on new scientific discoveries; opening of new markets; use of new sources of raw materials and intermediate goods; new organization of production. He then states that the 'introduction of a new method of production' 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, as Kuznets (1966, p.9) points out, the main characteristic of modern economic growth is 'the extended application of science to problems of economic production'. For generating new industries and technological paradigms, we have to endogenize 'advances in science' in order to

[1] In this special section, although Sanderson and Simons (2014) pay specific attention to the light emitting diode industry, the evolution of the industry is more of a focus than the emergence of the industry. We focus on not only the evolution of industries but also on the emergence of industries.

theorize the essence of economic development and discuss corporate strategy and S&T policy. Advances in science are not exogenous factors for economic development.

The most important factors in the theory of economic development in this paper are (1) 'advances in scientific knowledge', and (2) 'advances in technological knowledge'. The chain evolution (co-evolution) of scientific and technological knowledge generates new technological paradigms and economic development. In an era when Schumpeter wrote a book, *The theory of economic development*, new combinations like the opening of new markets and use of new sources of raw materials might be important because globalization spread rapidly and the world market became a combined one. However, such a phenomenon is transitional and is not important for the essence of economic development.

The economic development under consideration in this paper is the emergence of technological paradigms. 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'. A new combination of scientific and technological knowledge generates new technological paradigms, even if scientific knowledge precedes technological knowledge, or technological knowledge precedes scientific knowledge. Whether advances in science precede advances in technology or not is not important here. A chain of science and technology forms an evolutionary system and the evolution generates economic development. Although advances along a technological trajectory, diffusions of knowledge, and increases of capital and labor are important for 'economic growth', they are supplementary factors for 'economic development' in this paper. Existing technological paradigms have a limit (or a characteristic of diminishing returns) and the emergence of technological paradigms generates economic development. This paper pays particular attention to the process of the emergence of technological paradigms.

How do new technological paradigms emerge? Suenaga (2015a) 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 IC. Although, in Suenaga (2015b), the discussion is refined, the relationship between science and technology is classified into four models (Price model, Bush (linear) model, Rosenberg model, and Dosi model), and the emergence of technological paradigms is discussed.[2]

Although Suenaga (2015a) demonstrates that the model in Suenaga (2015b) can be applied to the semiconductor industry, can this theory be applied to other industries? This paper examines heat engines, which started to develop more than 300 years ago. Although there should be a future discussion on whether the theory in this paper can be applied to other industries,[3] it is significant,

[2] The concept of 'the great knowledge transcendence' in Jin (forthcoming) has a close relationship with the discussion in this paper.

[3] Yamaguchi (2006; 2008; 2009; 2014) illustrates that his innovation diagram can be applied to various industries.

when considering long-term economic development, to examine old and new industries such as heat engines and semiconductors.

The evaluation of the relationship between science and technology in the emergence of the technological paradigm of heat engines differs, depending on the researcher. For example, Landes (1969) insists that 'the growth of scientific knowledge owed much to the concerns and achievements of technology; there was far less flow of ideas or methods the other way' (p. 61). 'This was true even of the steam-engine, which is often put forward as the prime example of science-spawned innovation' (p. 61, n. 1).[4]

Furthermore, some studies which discuss the relationship between science and technology in heat engines do not sufficiently discuss the advances in science in the 17th century which had effects on the development of the heat engine, because they pay too much attention to the process after the emergence of the heat engine (e.g. Jewkes et al., 1962).

Allen (2011, pp. 35-36) insists as follows: 'Steam power was a spin-off of the Scientific Revolution... The science of the engine was pan-European, but the R&D was conducted in England because that was where it paid to use the steam engine… Despite the scientific breakthroughs, the steam engine would not have been developed had the British coal industry not existed'. However, this paper discusses a chain of science and technology before an innovation of Newcomen. In this process, not only the British coal industry, which Allen emphasizes, but also various motivations for scientists and technologists played an important role. For example, the Parisian Science Academy, which Jean Baptiste Colbert established in order to propel technological development, had a great effect on the emergence of the steam engine. In order to understand the essence of economic development, we have to consider not only when the innovation was realized, but also a chain of science and technology before the innovation.

On the other hand, some studies which analyze the process of the emergence of the heat engine evaluate the role of science properly. For example, Dickinson (1958, pp. 168-170) describes this as follows: 'An important step leading to the invention of the steam-engine was the discovery of the pressure of the atmosphere... The discovery suggested the possibility of using atmospheric pressure to do work on a piston beneath which a vacuum could be created… culminated in the invention of the steam-engine.' In addition, 'by combining the expansive properties of steam with the recently discovered pressure of the atmosphere' (Cardwell, 1972, p.56), the steam engine was put into practice. Lipsey et al. (2005) also describe the process of the emergence of the heat engine and insist as follows: 'Clearly, science played an important role in the development of the steam engine' (p. 253).

[4] While Landes (1969, p. 104) insists that there 'is no doubt some truth' in that Newcomen and Watt were affected by science, he states 'how much is impossible to say. One thing is clear, however: once the principle of the separate condenser was established, subsequent advances owed little or nothing to theory'. However, it is significant for us to clarify the role of science on the emergence of new technological paradigms.

In this paper, based on a model which is presented in Section 2, the process by which a technological paradigm of the heat engine emerges and develops is analyzed. Through this analysis, the relationship between science and technology, the hierarchy of technological paradigms and scientific knowledge, and a field of combining science and technology are clarified. In addition, this makes it easier to compare with other examples, to express the long-term process of economic development, and to create plans for corporate strategy and governmental policy.

Finally, we conclude the article, making comparisons with the semiconductor industry, and it re-examines economic development from the long-term viewpoint. Although an industry like heat engines, which started to develop more than 300 years ago, is used, a model in Suenaga (2015b) can be applied to this old industry. This illustrates that this model has great potential for considering economic development. Furthermore, in the current era of open innovation, the difficulty of combining science and technology properly is significant. However, this problem was also important more than 300 years ago. In this sense, this paper has a purpose in rethinking various discussions about long-term economic development.

2. Innovation diagram, technological paradigms, and hierarchy[5]

Figure 1 illustrates Dosi's 'technological paradigms' and 'technological trajectories' (1982), based on the innovation diagram of Yamaguchi (2006). In the diagram of Yamaguchi, existing scientific knowledge (S) advances through scientific research etc. ($S_1 \rightarrow S_2$). 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. ($T_1 \rightarrow T_1'$). This is illustrated as the upward arrow above the soil.[6]

[5] About this section, see Suenaga (2015b).

[6] In Suenaga (2015b), 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 (linear) 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 like Figure 1.

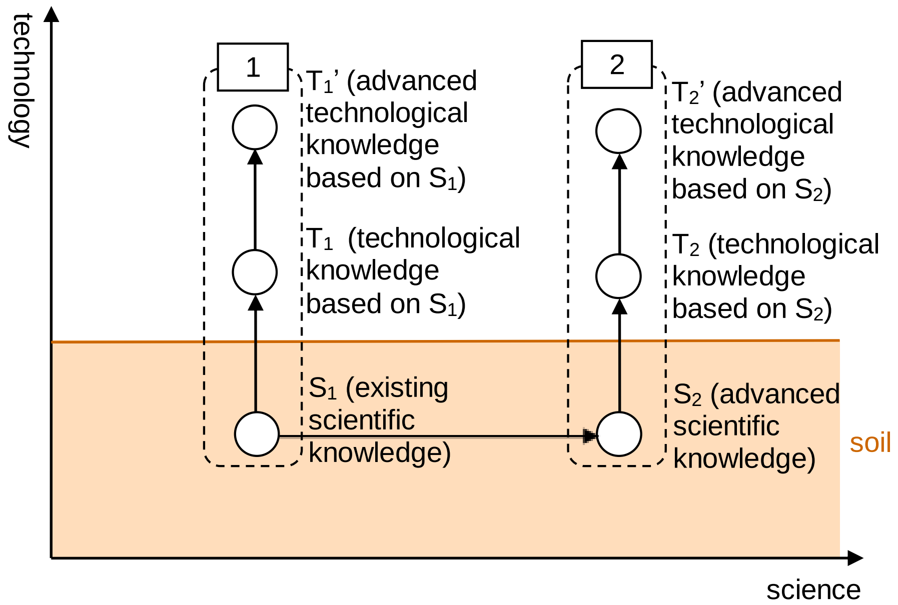

Figure 1: Technological paradigms and technological trajectories, based on innovation diagram

Source: Suenaga (2015b, Figure 4).

Note: This figure illustrates the view of Dosi (1982), based on Yamaguchi's innovation diagram (2006).

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'. In Figure 1, technological paradigms are expressed as a dotted line, and technological trajectories are illustrated as upward arrows within technological paradigms. 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, or may be triggered by existing technological knowledge, T_2. Therefore, Figure 1 includes both cases. 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, or technological knowledge precedes scientific knowledge).

In addition, although advances in scientific knowledge have been located in soil up to this point, there are various layers of soil. For example, while the academic framework itself changed, there were also advances in science within the academic framework. With regard to the diagram above, advances in the former are expressed as being located in the deeper layer of soil (referred to here as the third layer), and advances in the latter are expressed as those which are produced in a shallower layer of soil (referred to here as the first layer). Advances in scientific knowledge in the third layer form more extensive technological paradigms, and advances in scientific knowledge in the first layer form smaller technological paradigms. Advances in scientific knowledge in the second layer are not as extensive as in the third layer, but they are more extensive than in the first layer. As a result, the hierarchy is also formed in technological paradigms when the hierarchy of scientific knowledge exists. In addition, the hierarchical development of scientific knowledge and technological paradigms results in industrial and economic development.

3. Innovation diagram of thermodynamics and heat engines

How do we illustrate the development of thermodynamics and heat engines based on the innovation diagram in Section 2? Although Yamaguchi (2008; 2014) also describes his innovation diagram with regard to heat engines, his analysis is reconsidered in detail and the concept of hierarchy is introduced in this section.[7] Figure 2 illustrates a chain of science and technology regarding thermodynamics and heat engines, and the hierarchy of the scientific knowledge and technological paradigm.

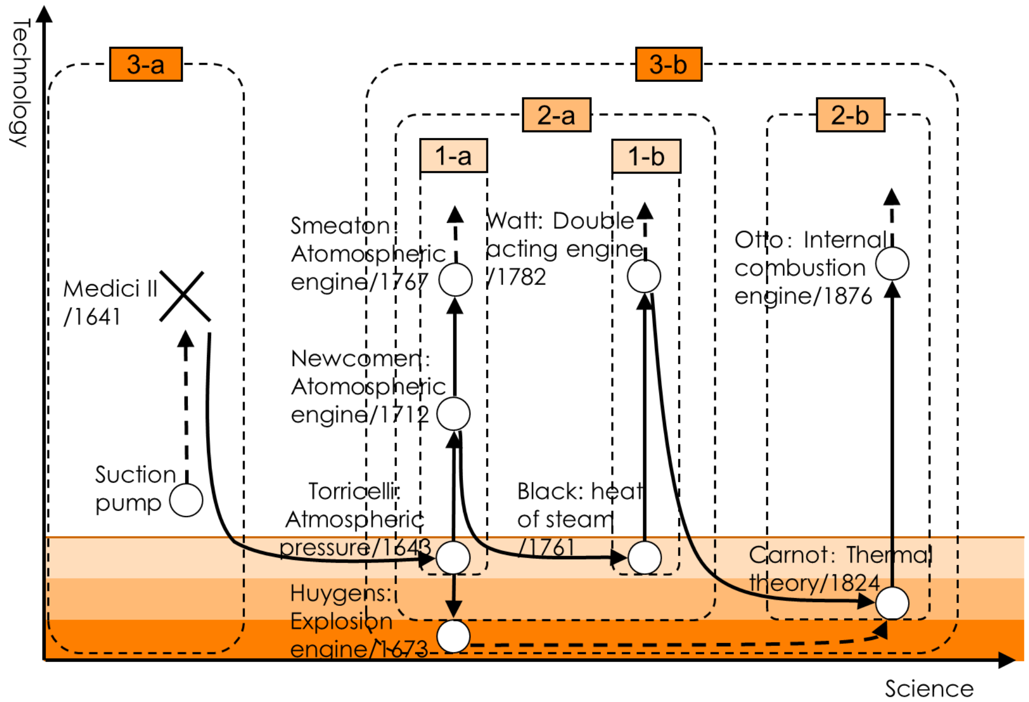

Figure 2: Innovation diagram: thermodynamics and heat engines

Although a simple suction pump had a limit, an opportunity to overcome this limit was provided by the discovery of atmospheric pressure by Torricelli in 1643. This advance in scientific knowledge

[7] He was originally a physicist and is teaching MOT, management of technology, in Kyoto University. Yamaguchi's model could be further developed by utilizing neo-Schumpeterian view points and research results.

induced various vacuum pumps by Guericke and Boyle and stimulated advances in science such as Boyle's law. In particular, the invention of the gunpowder engine and the illustration of its fundamental principles by Huygens in 1673 was the most significant advance in scientific knowledge in the development of the heat engine. It needed a long time to put Huygens' internal combustion engine into practice. Although Papin's invention, which used steam instead of gunpowder, was not an internal combustion engine like Huygens' gunpowder engine, it was an external combustion engine which used fire outside the cylinder. This technology then had an economic value through the inventions of Savery and Newcomen. Newcomen's engine was an external combustion engine among heat engines and, in particular, was an engine which utilized atmospheric pressure.

After that, although technologists such as Smeaton improved Newcomen's engine, it was Watt who perceived the limit of the atmospheric engine and he separated the condenser from the cylinder in order to increase thermal efficiency. While Watt was influenced by Black's scientific knowledge regarding the heat of steam, he succeeded in putting such scientific knowledge into practice as technological knowledge with an economic value. Watt continued to improve the efficiency of steam engines and took out a patent for double acting engines in 1782. This new engine did not utilize atmospheric pressure but made use of the power of steam on both the ascent and descent of pistons within a cylinder; it was an external combustion engine which made most use of the power of steam, using scientific knowledge of the heat of steam.

It was Carnot who perceived the limit of the external combustion engine and he constructed scientific knowledge in order to increase thermal efficiency further. Although Carnot's theory emphasized the advantage of the internal combustion engine versus the external combustion engine, it needed about 200 years until Huygens' scientific knowledge about internal combustion engines was put into practice as a technology, for example Otto's engine, while related technology was accumulated.[8]

4. The hierarchical development of scientific knowledge and technological paradigms

In this section, the hierarchy of scientific and technological knowledge related to thermodynamics and heat engines is clarified (Table 1). Although the evolution of the heat engine forms a technological paradigm (3-b), a study by Huygens which clarified the principle of heat engines had gradually been systematized according to the research conducted later. Thermodynamics, the basis of the heat engine, is an academic framework which completely differs from simple dynamics, the basis of a suction pump. Although Huygens' internal combustion engine needed a long time to be put into practice because of technological difficulties, advances in scientific knowledge by

[8] Although the development of the heat engine after that is very interesting, it may be sufficient for us to discuss it up to this point.

researchers such as Boyle and Papin built the basis of a technological paradigm of external combustion engines (2-a). In addition, an advance in scientific knowledge concerning atmospheric pressure by Torricelli induced the invention of Newcomen's atmospheric engine and formed a technological paradigm (1-a). Watt's double acting engine, based on a technological paradigm of the external combustion engine (2-a), was not based on atmospheric pressure but on a technological paradigm (1-b) which was influenced by Black's study of the heat of steam. Furthermore, although the internal combustion engine which was developed by many technologists such as Otto was based on a large-scale technological paradigm of heat engines (3-b), it was a medium-scale technological paradigm (2-b) based on the scientific knowledge of thermal efficiency by scientists such as Carnot.

Table 1: Technological paradigms / scientific knowledge: thermodynamics and heat engines

<table>
<tr><td>1st layer:
Methods of
connection</td><td></td><td>1-a
Cylinder/
Atmosphere</td><td>1-b
Condenser/
Heat of steam</td><td></td></tr>
<tr><td>2nd layer:
Operating
principles</td><td></td><td colspan="2">2-a
External combustion/
Theory of steam</td><td>2-b
Internal combustion/
Theory of heat</td></tr>
<tr><td>3rd layer:
Academic
frameworks</td><td>3-a
Pump/
Dynamics</td><td colspan="3">3-b
Heat engine/
Thermodynamics</td></tr>
</table>

Although the scientific knowledge which forms the basis of the heat engine is an academic framework of thermodynamics (3-b), there are some theories about the heat of steam and efficiency of heat within thermodynamics. These theories are useful to develop the operating principles of a heat engine; the theory of steam contributes to the development of the external combustion engine (2-a), and the theory of the efficiency of heat helped to develop the internal combustion engine (2-b). With regard to the external combustion engine, the discovery of atmospheric pressure generated the invention of Newcomen's atmospheric engine (1-a), and the theory of the heat of steam contributed to Watt's invention, which separated the condenser from the cylinder (1-b). These relationships between science and technology cannot be explained in a linear model,[9] and they have been developed through the interaction between science and technology. The hierarchy of scientific knowledge forms the hierarchy of technological paradigms and the hierarchical evolution of technological paradigms generates economic development.[10]

[9] This is Bush's model in Suenaga (2015b).

[10] In this sense, the theory of economic development of Schumpeter (1934) and the theory of technological paradigms of Dosi (1982), which does not endogenize advances in science, have a limit for elucidating the essential factors of economic development.

5. The emergence of technological paradigms and the field of combining science and technology

In addition, as we can see, a field where scientists and technologists studied collaboratively played a significant role in the emergence of technological paradigms. In Huygens' studies within the Parisian Science Academy, technologists like Papin, an assistant of Huygens, played an important role and scientists like Leibnitz, who studied the gunpowder engine as an assistant of Huygens, had an influence on the success of Huygens' studies. Although Papin's invention of the steam engine was not put into practice, his knowledge was influenced by Huygens, Leibnitz, and Boyle (Papin was also an assistant of Boyle in England).

The Parisian Science Academy, which was established in 1666, sought not only scientific knowledge but also technological results. For example, it pursued geometry, mechanics, optics, astronomy, geography, physics, medicine, chemistry and anatomy, as well as architecture, fortification, sculpture, painting and design, driving and elevating water, metallurgy, agriculture, and navigation (Huygens, 1663; 1891, p.328). This was a result of combining the desires of scientists who aimed to elucidate scientific knowledge but had no research resources, and the desires of Louis XIV and Colbert, who pursued technological usefulness and had funds to spare.[11] Within the organization, which sought after both science and technology, collaboration between scientists such as Huygens, who created new scientific knowledge in various areas, and technologists such as Papin, who had enormous capability, contributed remarkably to the emergence of technological paradigms which had great potential.

In addition, within the Royal Society of London, which was established in 1660, not only scientific knowledge but also practical technology were pursued.[12] Papin's digester was demonstrated in 1679, and his steam engine of 1690 was reviewed in the Society's *Philosophical Transactions* of 1697. This fusion of science and technology built the basis for a technological paradigm of steam engines which led to a great leap after 1700.

Watt, who was engaged as an instrument maker at Glasgow University, was greatly influenced by Professor Black at this university. Communication between scientists such as Black, who sought scientific knowledge, and technologists such as Watt, who wanted technological results (although he also had great capability as a scientist) also generated a large potential for technological development.

In the emergence of technological paradigms, although scientists and technologists did not necessarily study together, there are many cases where collaborative research between scientists and technologists has been conducted.[13] In these fields, 'tacit knowledge' which scientists and

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[11] Refer also to Taton (1966) and Stroup (1990).
[12] See also the Charter of the Royal Society of London (1662) and Forbes and Dijksterhuis (1963, ch. 16).
[13] These cases can be seen in other industries (e.g. the semiconductor industry). See also Yamaguchi (2006) and Suenaga (2015a) for a detailed discussion.

technologists share also plays an important role. Because the emergence of a technological paradigm as new technological knowledge, based on new scientific knowledge, is a great innovation which surpasses the limit of existing technological paradigms, collaborative research between scientists and technologists is often needed. The emergence of such new technological paradigms generates economic development. These facts are very important for creating new technological paradigms as corporate strategies or governmental policies.

6. Conclusions and implications

As shown in Section 2, the innovation diagram of Yamaguchi (2006) has been developed from a neo-Schumpeterian viewpoint and the concept of hierarchy is introduced. The revised version of Yamaguchi's innovation diagram then clarifies that a chain evolution (co-evolution) of science and technology generates a new technological paradigm (new industry), and the hierarchical evolution results in economic development. Kuznets (1966) indicates the importance of applying science to economic production as the main characteristic of modern economic growth. However, almost all the theory of economic development, like Schumpeter (1934), treats science as an exogenous factor. Nevertheless, a true theory of economic development can be constructed by endogenizing advances in science. The hierarchical evolution of a chain of scientific and technological knowledge generates 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, this paper considers the process of economic development by plotting science and technology on these axes. 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 evolutionary process rather than an equilibrium process, and lock-in effects or path-dependency have an important influence in this process.

In addition, the model in this paper can be applied to not only the semiconductor industry (Suenaga, 2015a), but also to heat engines, which started to develop more than 300 years ago. Although the applicability of this model to other industries has to be examined in the future,[14] the model is applicable to old and new industries like heat engines and semiconductors and it has a great potential for clarifying economic development.[15]

In the case of the heat engine, similar to the case of the semiconductor, there is a hierarchy of scientific knowledge in which the third layer is an academic framework, the second layer represents the operating principles, and the first layer contains methods of connection. This similarity of

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[14] Yamaguchi (2006; 2008; 2009; 2014) illustrate that his innovation diagram can be applied to various industries.

[15] Needless to say, the degree of importance of science differs depending on the characteristics of the industry in question.

characteristics of each layer is probably a casual coincidence and the characteristics of each layer may differ in other industries. However, what is most important is that the hierarchy of scientific knowledge exists and the hierarchy of technological paradigms exists based on the hierarchy of scientific knowledge.[16]

Furthermore, organizations like the Parisian Science Academy and the Royal Society of London, which pursue both science and technology, played an important role in the emergence of technological paradigms relating to heat engines. This is similar to the case of semiconductors, where Bell Laboratories played a significant role. Although an organization which focuses on technological development plays an important role in advances in technology along a technological trajectory, a field which straddles scientists and technologists often has a significant function in the process of the emergence of technological paradigms, with advances in scientific knowledge (even if scientific knowledge precedes technological knowledge or technological knowledge precedes scientific knowledge).

Recent years are quoted as an era of open innovation (Chesbrough, 2003). Large central laboratories such as the Bell Laboratories of AT&T used to play a significant role in the emergence of technological paradigms (in particular, based on deeper layers). However, in an era of open innovation, it is difficult for a central laboratory in a large company to create new technological paradigms (based on the third layer). In particular, in an era of open innovation, it is necessary to develop a management framework and policies for producing new technological paradigms based on the third layer. In this paper, although an old case like heat engines is resurrected, the relationship between science and technology in order to generate new industry and develop the economy is a significantly important theme in any era. The researcher of innovation and the neo-Schumpeterian have to focus more seriously on the emergence of new industries which are the most fundamental phenomenon in various innovations.

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[16] The existence of the hierarchy is a factor that brings short-, middle-, and long-term economic fluctuations. See also the discussions about techno-economic paradigms and long waves, such as Freeman and Perez (1988). In addition, by clarifying the hierarchy of technological paradigms, the continuity and discontinuity of an industrial development can be discussed.

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