Architectural or Paradigm-disruptive Innovation?:
The Case of the Bow and Arrow, which Promoted Globalisation

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This paper focuses on the bow and arrow, which was an epoch-making innovation in the early stages of humankind. Then, while examining various innovation theories, we will try to compare these theories, and at the same time, we will attempt to build a theory that can explain the long-term history of innovation. In this paper, we emphasise the importance of science from a long-term perspective, and focus on the primary factors involved in the creation of innovation rather than the structural aspects of artefacts. The bow and arrow was a paradigm-disruptive innovation that utilised new scientific knowledge, and helped prompt the 'technological revolution' that changed the standard of living and society of *Homo sapiens*.

Keywords: Paradigm-disruptive innovation; Bow and arrow; Science and technology; Globalisation

1. Introduction

Richard Baldwin (2016) divides the history of globalisation into four phases from a long-term perspective, and discusses in detail the factors that led to it and its implications. In Phase 1 of globalisation, which began around 200,000 BC, innovations in the Palaeolithic era brought about the spread of humankind on earth, while in Phase 2, which started around 10,000 BC, the agricultural revolution led to localisation of the economy. Then, in Phase 3, which began around 1820, the steam revolution facilitated the movement of goods and the local economy became globalised ('old globalisation'), whereas in Phase 4, which started around 1990, the ICT (information and communication technology) revolution made it easier to move ideas and caused the globalisation of factories ('new globalisation').

Innovation and globalisation are inextricably linked, as his interesting analysis shows, but he does not discuss how these innovations were created. This paper focuses specifically on the innovation in Phase 1 and analyses how the bow and arrow, which played a special role in it, was created (see also Suenaga (2019b) for Phases 1 and 2, Suenaga (2019a) for Phase 3 and Suenaga (2015a) and Bui et al. (2019) for Phase 4).[1]

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[1] While economists often call inventions with commercial value 'innovations', inventions and innovations are often used

In the Palaeolithic era, various innovations other than the bow and arrow were created.[2] About 2.6 million years ago, stones were intentionally processed and used as tools (Oldowan stone tools),[3] and after about 1.76 million years ago, Acheulian stone tools such as hand axes became popular (Lepre et al., 2011). About 500,000 years ago, these advances, combined with knowledge of wood, led to the emergence of composite tools such as the spear with a stone point (Hoffecker, 2009; Wilkins et al., 2012), and about 100,000 years ago, a new innovation called the spear-thrower was born. Moreover, around 71,000 to 64,000 years ago, the bow and arrow was used in South Africa (Lombard and Phillipson, 2010; Brown et al., 2012) and about 43,000 to 24,000 years ago, the bow and arrow using poison was also used.

The bow and arrow enormously influenced human life in various areas, from hunting technology to life style and globalisation (Crosby, 2002; Sisk and Shea, 2009) and this form of mechanical projectile weaponry had a major impact on the spread of humans to late Pleistocene Eurasia from approximately 50,000 years ago (Shea and Sisk 2010; Lombard and Haidle, 2012). In addition, it is said that the bow and arrow was used only by *Homo sapiens* (Shea and Sisk 2010; Coolidge et al. 2016).

This paper focuses on the bow and arrow, which was a significant innovation in the early stages of humanity. Then, while examining various innovation theories, we will try to compare the innovation theories, and at the same time, attempt to build a theory that can explain the long-term history of innovation (see also Suenaga, 2015a; 2015b; 2019a; 2019b; 2020; 2021b for the theory).

2. Reviews of previous studies

As is well known, there are various studies on innovation (e.g. Dosi, 1988; Freeman, 1994b; Fagerberg et al., 2006; Suenaga, 2015b; 2016 for the surveys). Although it is not possible to review all of them in this paper, we examine some of the most important theories related to the bow and arrow and to the purpose of this paper.

Although Schumpeter (1934) played the most important and pioneering role in innovation research, researchers described as Neo-Schumpeterian, who inherited his tradition, have developed various innovation theories. For example,

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interchangeably in archaeology and anthropology. It may be adequate for definition of invention and innovation in the prehistoric era that O'Brien and Bentley (2011) refer to widely diffused inventions as innovations.

[2] See Gärdenfors and Lombard (2018) for the era.

[3] Although it is said that *Homo habilis* made the Oldwan stone tools, there are also reports that the stone tools were already being used about 3.3 million years ago, a period from which no Homo genus fossil has been found (e.g. Harmand et al. 2015; Lewis and Harmand 2016).

Freeman (1994a) classified innovation into four categories according to their impact: incremental innovation, radical innovation, changes in the 'technology system', and changes in the 'techno-economic paradigm' ('technological revolution'). According to him, incremental innovation is a gradual improvement of an existing array of products, processes, organisations and systems of production, distribution and communication; radical innovation is characterised by discontinuity in products, processes, organisations and systems of production, distribution and communication; a new technology system refers to economically and technically inter-related clusters of innovations; a new techno-economic paradigm is a pervasive combination of system innovations affecting the entire economy and typical 'common-sense' for humans.

In addition, Henderson and Clark (1990) used the concept of architectural and modular innovation to clarify the difference between incremental and radical innovation and they call innovations that change both architecture and modules radical innovations. However, while they state that 'radical innovation… is based on a different set of engineering and scientific principles' (p.9), the relationship between radical innovation and scientific principles is hardly clarified.

Allen (2009) states that 'Invention and the evolution of technology can be illustrated with a standard isoquant model' (p.151) and makes a distinction between macro- and micro-inventions. In addition, he states that 'Macro-inventions are characterized by a radical change in factor proportions' (p.151) and that 'Micro-inventions … refer to all of the improvements in the trajectory of advance' (p.136). Moreover, while he insists that 'We can clarify the influence of prices on invention' (p.141), he states that 'The important thing about the inspiration of the macro-inventions is that the idea they embodied came from outside the experience of the industry concerned' (p. 141). Then, according to him, 'these ideas resulted in radical changes in factor proportions' (p.141). Nevertheless, based on Edison's observation that 'invention was 1% inspiration and 99% perspiration', he concentrates more on 'research and development (perspiration)' than 'scientific discovery (inspiration)' as an analytic object (p.136). In his model, ideas and scientific discoveries that play critical roles in macro-level invention are treated as exogenous factors and little emphasised (see also Suenaga 2019a; 2020 for the details).

Moreover, the 'new combinations' play an important role in these innovations. Although the five new combinations of Schumpeter (1934) are particularly well known, Nelson and Winter (1982) state the following about new combinations: 'innovation in the economic system – and indeed the creation of any sort of novelty in art, science, or practical life – consists to a substantial extent of a recombination of conceptual and physical materials that were previously in existence.' (p.130). In addition, Arthur (2009) discusses Schumpeter's theory of new combinations in detail and suggests general propositions or principles that 'all technologies are combinations of elements' (p. 203). Moreover, he insists that 'these elements themselves are technologies' (p. 203) and calls this mechanism 'combinatorial evolution' (p. 22) (see also Grebel, 2013; Suenaga, 2016; 2018).

Moreover, there are many archaeologists and anthropologists who pay attention to the new combinations (e.g. Ambrose, 2001; 2010; Hoffecker, 2012; Tattersall, 2012; Barham, 2013). For example, Tattersall (2012) states ‘A major innovation in the technological history of hominids was the invention of the “composite” tool, made from more than one component’ (p. 140) and Hoffecker (2012) insists ‘creativity is the recombination of informational units into novel arrangements or structures’ (p.89). Furthermore, Barham (2013) calls the combinations of multiple components since five hundred thousand years ago ‘the hafting revolution’ or ‘the first industrial revolution’.

While these various innovation theories were being developed, how was the bow and arrow analysed? Archaeologist Schiffer (2005) presents a ‘cascade’ model for investigating the invention process in the state of a ‘complex technological system’ (CTS) and tries to build a general theory and model of the invention process. According to him, although the bow and arrow is also a CTS, this vision of a CTS was acquired while looking at hunters in other societies or manipulating bows and arrows made elsewhere. Moreover, to achieve a CTS, trial and error with new materials was promoted, and in order to achieve higher performance, a further invention cascade was stimulated. However, as he confesses honestly, ‘the cascade model does not explain how or why the development of a CTS is initiated’ (p. 486) (see also Suenaga (2019b) for the innovation theory of archaeologists and anthropologists).

Lombard and Phillipson (2010) note that string traps required an understanding of how to use the energy stored in bent branches, and with that understanding, they insist that the simultaneous use of two separate tools created the innovation of the bow and arrow. Sisk and Shea (2009) call this projectile technology a ‘niche-broadening technology’. As the throwing spear evolved to target large animals, the bow and arrow for targeting small animals, for which demand had gradually increased, might be similar to Christensen’s ‘disruptive innovation’.[4]

Here, let us consider the technological progress of the throwing spear and the bow and arrow, using the figure of Christensen (1997) on disruptive innovation (Fig. 1). The performance of the throwing spear would increase with improvements in thrower skills, wood and point processing techniques, techniques for joining the components, and techniques for group hunting. With the advances in technology, the number of large animals might decrease and the level of technology required to hunt them might increase, but the number of large animals might also decrease further with the improvement of technological capabilities. People who were confident in their muscular strength could focus solely on improving the performance of their spear, while people who were weak, but scientifically knowledgeable, might use their comparative advantage to look at different weapons. Although the bow and arrow, which had been of little use in hunting,

[4] Christensen’s disruptive innovation here refers to innovation that is very fruitful in the long run, but reduces performance at least in the short term.

might have initially been used only on small animals that were easy to catch, those who could only hunt such small animals (in terms of ability or environmentally) might gradually have succeeded in improving the performance of the bow and arrow. Even if the level of technology required to hunt small animals gradually increased, the technological level was improved far beyond that and it might have been possible to hunt a wider variety of prey and previously difficult prey with less effort.[5] This was exactly what Christensen called a disruptive innovation. However, this does not mean that the throwing spear was no longer used, and both coexisted and co-evolved. After that, the invention of the bow and arrow using poison dramatically increased the effectiveness of the bow and arrow.

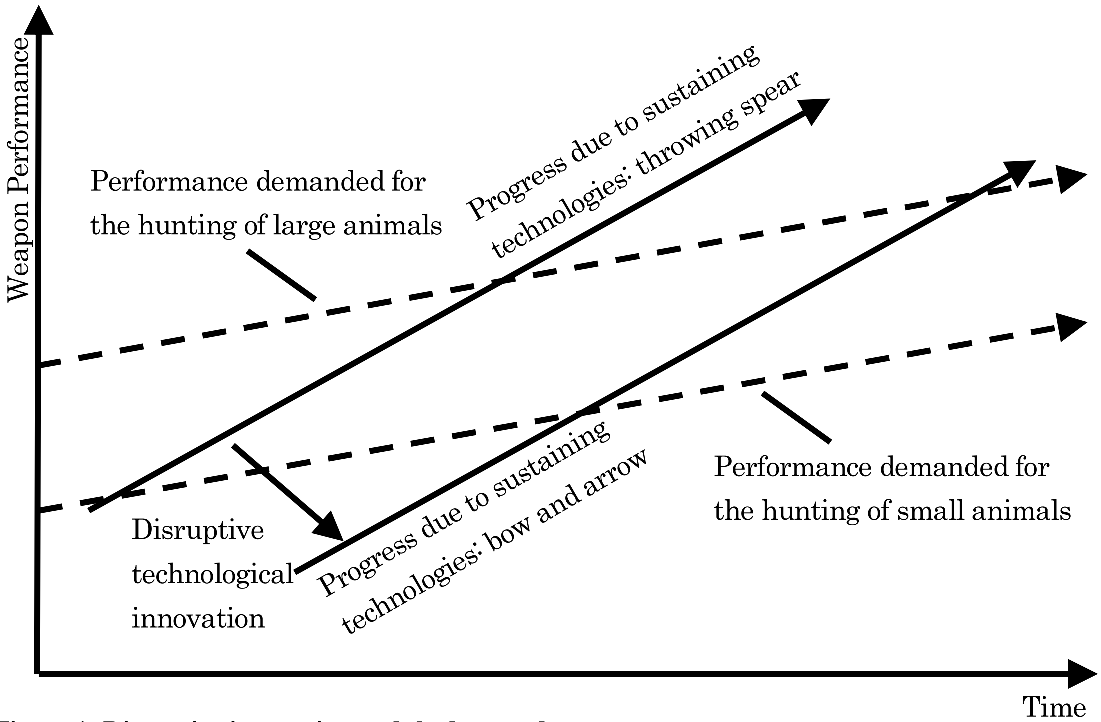

Figure 1: Disruptive innovation and the bow and arrow
Source: Adapted from Fig. 1 of Christensen (1997).

As mentioned above, Christensen's framework gives some very interesting suggestions. However, while his discussion emphasises whether the innovation is performance-degrading, the focus of this paper is on whether new scientific knowledge is used, as discussed in detail below. This is the essential difference between Christensen's disruptive innovation and the paradigm-disruptive innovation highlighted in Section 3 of this paper. The former may explain the growth of a particular industry through qualitative and quantitative expansion of the market, while the latter is also

[5] This may have been one (major) factor in the extinction of *Homo Neanderthalensis* and the prosperity of *Homo sapiens*.

important in explaining the emergence of the industry itself.[6] This is a very significant point when considering long-term growth.

While Carignani (2016) points out 'the lack of a theory explaining the causal chain leading to radical invention' (p.316), he analyses the bow and arrow by using the framework of Henderson and Clark (1990). Then, he insists that 'both the core concepts and the linkages between core concepts and components (in comparison with previously existing hand-thrown weapons) were overturned' (p.321) and calls the bow and arrow a radical innovation. In addition, he emphasises the importance of 'horizontal transfer', which is the use of conventional tools in different ways. This concept of 'horizontal transfer' was discussed in detail by the biologist Woese (e.g. Woese, 2002). While vertical inheritance plays an important role in the evolution of eukaryotes, in bacterial evolution, some or clusters of genes are said to transfer to other species of different strains through horizontal transfer. Although the concept of horizontal transfer in innovation is similar to the concept of new combinations in the physical sense, Carignani (2016)'s attempt to systematically apply biological concepts to innovation by linking the 'vertical inheritance' of biology to 'incremental innovation' and 'horizontal transfer' to 'radical innovation' is very interesting.

However, the evolution of human knowledge and technology, from the Palaeolithic era to the present day, has often been the result of intentional actions by humans, rather than caused by mutations or horizontal transfer. Although the term 'serendipity' is sometimes used to emphasise that new discoveries were made by chance, it was not a matter of chance in many cases. As people face many challenges, through trial and error, 'chance favours the prepared minds' (Pasteur, 1854). In that sense, in order to explain the causal chain leading to radical invention', we need to focus on the human beings who created such innovations, rather than on biological concepts such as mutations and horizontal transfer.[7]

Understanding natural phenomena, or science (including primitive science), plays a very significant role in the advance of technology. Arthur (2009) states that 'technology is always based on some phenomenon or truism of nature' (p. 46) and that at 'the very start of technological time, we directly picked up and used phenomena: the heat of fire, the sharpness of flaked obsidian, the momentum of stone in motion. All that we have achieved since comes from harnessing these and other phenomena, and combining the pieces that result' (p. 22). Arthur calls 'the formal knowledge of phenomena' science (p.

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[6] In archaeology, the term 'industry' is often used. In archaeology, 'industry' refers to an assemblage recognised as a single group such as the Oldowan stone tools.

[7] Carignani et al. (2019) also discuss the turbojet revolution in terms of horizontal transfer. However, in examining long-term development, it is more important to consider how heat engines such as Newcomen's were invented. Suenaga (2019a) considers the processes and factors before and after the emergence of heat engines from both scientific and technological perspectives. Moreover, see also Suenaga (2019b) for the controversy between cognitive and cultural niche theories about genetic and cultural changes.

60) and insists that 'supporting any novel device or method is a pyramid of causality. … Particularly important in this pyramid of causality is knowledge—both of the scientific and technical type' (p. 124).

However, we need to be careful about the concept of 'science'. Generally speaking, when we refer to 'science', 'modern science', which is expressed mathematically and requires examination with observation or experiment, is imagined (e.g. Weinberg, 2015); however, 'science' in this paper includes not only 'modern science' but also 'primitive science' such as a simple understanding of natural phenomena. For example, imagine the situation in which when someone cracks nuts with a stone, the stone is broken and a sharp part is made. Understanding that the part can be used as a knife is included in primitive science.[8]

Mokyr (2002) states 'useful knowledge … deals with natural phenomena that potentially lend themselves to manipulation, such as artifacts, materials, energy, and living beings' (p.3) and 'useful knowledge … describes two types of knowledge' (p.4). And he describes knowledge of 'what' about natural phenomena and regularities as 'propositional knowledge' (or 'Ω-knowledge'), and describes knowledge of 'how' as 'prescriptive knowledge' (or 'λ-knowledge').[9] While he argues that we may call prescriptive knowledge techniques, he insists that the distinctions between propositional and prescriptive knowledge differ 'in important respects from the standard distinctions between science and technology' (p. 4). Nevertheless, 'propositional knowledge takes two forms: one is the observation, classification, measurement, and cataloguing of natural phenomena. The other is the establishment of regularities, principles, and "natural laws" that govern these phenomena and allow us to make sense of them' (p. 5). In addition, propositional knowledge includes 'practical informal knowledge about nature such as the properties of materials, heat, motion, plants, and animals; an intuitive grasp of basic mechanics (including the six "basic machines" of classical antiquity: the lever, pulley, screw, balance, wedge, and wheel); regularities of ocean currents and the weather; and folk wisdoms in the "an-apple-a-day-keeps-the-doctor-away" tradition' (p. 5). Thus, the definition of propositional knowledge is almost the same as science (including both primitive and modern science) in this paper.[10]

In addition, the archaeologist and evolutionary psychologist Mithen (1996) presents the concepts of 'natural history intelligence' and 'technical intelligence' based on the theory of multiple intelligence of Gardner (1983). The 'natural history intelligence' is 'a bundle of modules concerned with understanding the natural world, an understanding essential to life as a hunter-gatherer' (p. 74) and is a concept similar to 'science' in this paper. Moreover, he suggests that multicomponent composite tools 'could only have arisen owing to a new connection between natural history and technical intelligence' (p.

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[8] See also Beaune (2009) for analogy and invention.

[9] See also Ryle (1949), Shiozawa (2019) and Suenaga (2015b).

[10] However, if 'useful knowledge', such as where the village exists, is also included in propositional knowledge, it differs slightly from the science in this paper.

169), and they were 'markedly different from the monotony of the hunting tools of Early Humans' (p. 169). Moreover, the evolutionary psychologist Dunbar (1995) claims that science 'is a method for finding out about the world' (p. 16) and that it 'cover[s] the full range of empirical science from pure cookbook science to genuine attempts at explanation' (p. 43). Mesoudi et al. (2013) also state that '[t]echnological and scientific knowledge is accumulated over successive generations' (p. 194) and that 'science and technology interrelate' (p. 194) (see also Lévi-Strauss, 1962; Schiffer and Skibo, 1987; Stout, 2002; Lombard and Haidle, 2012).

Thus, the arguments of economists and palaeoanthropologists on science and technology are very similar, and it would be possible to combine the two arguments into a theory. New combinations of scientific knowledge, new combinations of technological knowledge, and new combinations of scientific and technological knowledge create advances in knowledge.

However, what is important here is whether to endogenise scientific progress when discussing knowledge progress and economic development. Economists, in particular, often consider these scientific advances exogenously (e.g., Schumpeter, 1934; Dosi, 1982; Arthur, 2009). However, as Kuznets (1966) points out, the main characteristic of modern economic growth is the widespread application of scientific knowledge to the problems of economic production, and as Mokyr (2005) argues, 'Industrial Enlightenment', whose intellectual origin is the Baconian movement of the 17th century, might transform slow economic growth into rapid economic development. In these processes, advances in scientific knowledge play an important role in economic development. And, as discussed in this section, even before modern economic growth, scientific understanding played a significant role, even though the progress of scientific and technological knowledge was very slow.

Although the levels of scientific and technological knowledge 2.6 million years ago, 500,000 years ago, 10,000 years ago, 2000 years ago and 260 years ago were quite different, these differences are often not taken into account. One of the reasons why these differences are ignored is that the level of per capita income had hardly changed until the Industrial Revolution. For example, according to Clark (2007), in the presence of the Malthusian trap, even if the technological level and income level rise, as a result of the population increase, per capita income drops again, falling into a Malthusian equilibrium (minimum subsistence level). But what should not be overlooked is that in the process, even if income levels have not improved, the level of scientific and technological knowledge itself does improve (see Suenaga (2019b) for details). Therefore, in order to understand such progress (especially when considering long-term progress), it is indispensable to endogenise not only technological progress but also scientific advancement. The model in this paper endogenises science and considers scientific knowledge hierarchically.[11]

[11] See also Suenaga (2015a; 2015b) for a detailed discussion.

3. Paradigm-disruptive innovation and the bow and arrow

Simply speaking, science aims to provide an elucidation of natural phenomena, while the purpose of technology is to create artefacts. In this paper, scientific knowledge is useful knowledge about natural phenomena, and technological knowledge is useful knowledge about creating artefacts.[12] In addition, science in this paper includes not only modern science but also primitive science. Combinations of technological knowledge and combinations of scientific and technological knowledge will bring about advances in knowledge and technology. In the article, I would like to explicitly illustrate the advances in knowledge using the innovation diagram of Yamaguchi (2006).[13]。

In Yamaguchi's innovation diagram, advances in scientific knowledge are shown on the horizontal axes, and advances in technological knowledge are illustrated on the vertical axes.[14] 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 progress 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 the technological paradigms. Whether these advances are improvements along a technological trajectory or a paradigm shift causing new technological trajectories to emerge depends on whether or not the 'selected scientific knowledge' as the basis of the technological trajectory is new (regardless of whether scientific knowledge precedes technological knowledge or vice versa). Improvement along a technological trajectory can be called 'paradigm-sustaining innovation', and a shift in paradigm, with new technological trajectories emerging, can be called 'paradigm-disruptive innovation'.[15]

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[12] See also Mokyr (2002) for useful knowledge. Furthermore, Suenaga (2015b) discusses the definitions, relationships, mechanisms and structures of science and technology in detail.

[13] However, some studies have tried to illustrate the relationship between S&T or the relationship between the technological paradigms and trajectories (e.g. Kline (1990); Cimoli and Dosi (1995); Stokes (1997); Chesbrough (2003); Allen (2009)). See Suenaga (2015b) for the characteristic and problem.

[14] Although Yamaguchi (2006, 2008) uses the expressions, 'knowledge creation' and 'knowledge realisation', this paper regards them as advances in 'science' and 'technology'. See Suenaga (2015b) for further discussion. In Suenaga (2015b), the relationship between science and technology is discussed in terms of 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.

[15] For clarification of 'paradigm-sustaining' and 'paradigm-disruptive' innovation, see Yamaguchi (2006).

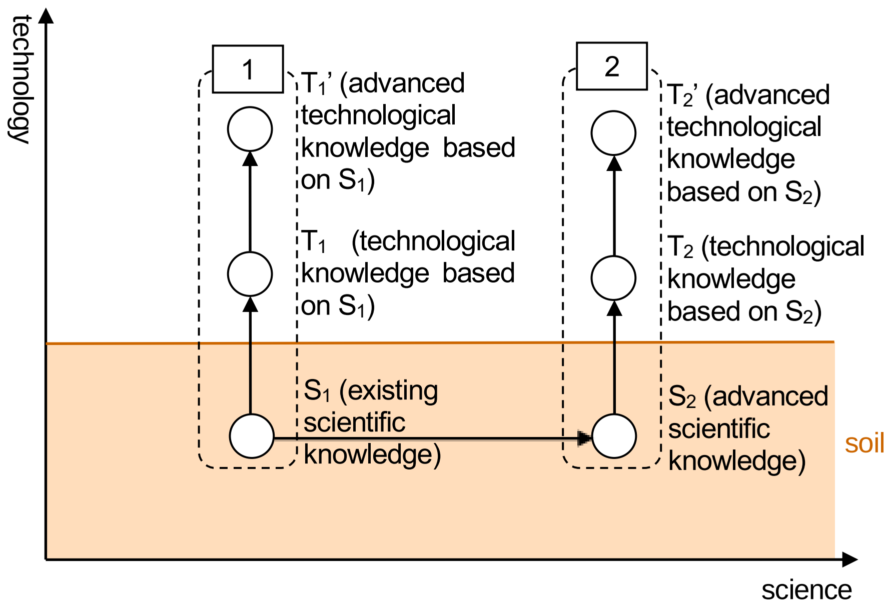

Figure 2: Technological paradigms and technological trajectories, based on innovation diagram

Source: Suenaga (2015b, Figure 4).

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

In addition, in his diagram, advance in scientific knowledge is located in 'soil', because it is not economically valued. Furthermore, although Suenaga (2015a; 2015b; 2019a; 2021b) also discusses the soil layers in detail, phenomena hidden in deeper layers may have greater potential for economic development.

How is the advance in knowledge produced? Although Arthur (2009) asserts that technology 'builds itself organically from itself' (p. 24), the reality is not so, and humans produce knowledge. People specialising in science or those who are excellent at scientific thinking seek to contribute to advances in scientific knowledge in order to understand natural phenomena or to gain a reputation. In addition, people who do technological work are willing to contribute to the advance in technology for the purpose of creating better technological devices, obtaining financial benefits, or saving labour.[16] And the advancement of knowledge enabled humans to hunt prey more efficiently and acquire previously difficult prey.

How was the bow and arrow invented? As various types of spears were developed, the bow and arrow might have been invented under a different architecture from the spears, combined with bent branches and sinews. However, as the number of large animals decreased due to climate change and excessive hunting, the need to hunt small animals increased, and the

[16] Of course, there are cases where the same person carries out both scientific and technological actions. Furthermore, the advances in knowledge also relate to social values and institutions, such as whether social and economic benefits can be guaranteed. See also Mokyr (2005); North (2005).

bow and arrow, which initially had inferior performance, might have been used to hunt prey quietly and with less effort.[17]

While these views offer very important perspectives on the innovation of the bow and arrow, what this paper focuses more on is the scientific knowledge that created the new technology of the bow and arrow. Looking back at the long-term development, such scientific understanding (even if tacit) often played a critical role.The emergence of the new technology, the bow and arrow, probably occurred because humans could understand and utilise the energy stored in bent branches. The bent branches might have been used as a trap for catching small animals (Lombard and Philipson, 2010). However, in order to use this externally stored energy more effectively as a projectile weapon, it was necessary to combine various other forms of knowledge such as in-depth knowledge in regard to the wood, strings (or chords) and arrows. At the same time, there might have been a growing need to target smaller animals instead of larger ones.

In the evolution and change on the supply and demand side, the creation of projectile weaponry utilising external energy saw the emergence of a new technological paradigm in that scientific knowledge was required concerning external energy which was completely different from before. Nevertheless, the scientific knowledge, from the point of view of modern science, was primitive and superficial, and the hierarchical and systematic characteristics of scientific knowledge found in heat engines (Suenaga 2019), modern steelmaking technology (Suenaga 2018b) and semiconductors (Suenaga 2015a, b), which are more recent technologies, could not be seen. However, paradigm-disruptive innovations, such as silently launched weapons using external energy, had a much greater long-term impact on economic activity, technological progress, and globalisation than the structural classification of innovations would suggest.[18]

These paradigm-disruptive innovations dramatically raised technological and economic standards. The innovation of stone tools was largely based on 'the fracture dynamics of stone' (Mithen, 1996), in which the sharp or pointed fractured parts of the stone were used as tools, for purposes other than cracking. In addition, the discovery that the part of the stone tool with the handle became detached and flew away vigorously when swung down, might have led to the innovation of a spear-thrower using the (tacit) scientific knowledge of the principle of leverage. Moreover, unlike the spear with a stone point and the spear-thrower, where muscular strength was critical, the ability to use external energy stored in bent branches led to the invention of the bow and arrow, and the gradual acquisition of (primitive) chemical knowledge of poisons was a major catalyst for the innovation of the bow and arrow using poison. Furthermore, the increasing scientific knowledge of animals and plants enabled their domestication; this was 'genetic manipulation' (Watson 2003: p. 6), such as the selection of only the species suitable for cultivation and animal husbandry. This was also the emergence of a technological

[17] See also Yu (2006) for relationships between the bow and arrow technology and climate changes.

[18] See also Crosby (2002) and Baldwin (2016) on this point.

paradigm based on new scientific knowledge.[19] Then, advances in scientific and technological knowledge concerning fire gave rise to bronze and iron tools.

Moreover, in heat engines (Suenaga, 2019a), modern steelmaking methods (Suenaga, 2020; 2021b) and semiconductors (Suenaga, 2015a), combined with new scientific knowledge, paradigm-disruptive innovations were produced, and technological and economic level improved significantly. In addition, scientific (and technological) knowledge, such as molecular biology and genetic recombination, has also played an important role in the recent development of gene therapy and mRNA vaccines (Suenaga, 2021a). In recent paradigm-disruptive innovations, modern science or academic disciplines, rather than primitive scientific understanding, have played a major role. The chemical industry and modern chemistry, the heat engine and thermodynamics, the semiconductor industry and quantum mechanics, the biotechnology industry and molecular biology, and so on, have been developed systematically through the mutual influence between industry and academia. These innovation systems also contain the hierarchy of scientific knowledge and technological paradigms, on the basis of which the hierarchical classification of paradigm-disruptive innovations has been made. Suenaga (2015a; 2015b; 2019a; 2021b) classifies paradigm-disruptive innovations into three categories: those involving the transformation or emergence of a discipline, those involving the emergence or change of an operating principle and those involving the change or birth of a connection method.

Then, in the long-term process described above, scientific knowledge has played a very important role in understanding natural phenomena, whether in modern or primitive science.[20] Of course, technological progress can be made with vague scientific understanding, and then, as scientific understanding advances, further technological progress can be achieved. Nevertheless, since technological paradigms based on existing scientific knowledge essentially face the law of diminishing returns, paradigm-disruptive innovations based on new scientific knowledge (regardless of whether scientific knowledge precedes technological knowledge or not) play a decisive role in overcoming these limitations. This has important implications that are not discussed in Christensen’s disruptive innovation that reduces performance, in Henderson and Clark’s radical innovation that combines modular and architectural innovation or in Carignani’s discussion of radical innovation as a horizontal transfer. Although the level of scientific knowledge is often taken as a given in economics and business administration, it is crucial to take an endogenous view of the progress of scientific knowledge in considering long-term development.

[19] See also Suenaga (2019b) for a detailed discussion.

[20] This is what Suenaga (2015b) calls a Rosenberg-type innovation.

4. Comparison of innovation theory

In this paper, we have discussed several theories of innovation, focusing on a primitive (but revolutionary) innovation. While the bow and arrow is an epoch-making innovation (comparable to Freeman's 'technological revolution') that had a profound impact on people's lives, on globalisation and on society as a whole,[21] the simplicity of the bow and arrow has the advantage of making it easier to clarify the differences between the various innovation theories. Although each theory has its own value in its own realm, what are the differences between these various theories? In this section, we compare various innovation theories, focusing on two viewpoints: one considers the structure of the artefact or on the primary factors involved in its creation, and the other emphasises scientific knowledge or takes it as a given (or neglects it)[22].

Christensen's (1997) discussion often focused on modules, such as auxiliary storage devices and printers, and Henderson and Clark (1990) also focused on architectural innovations. The discussion in Carignani (2016), based on the framework of Henderson and Clark, also pays attention to the structure of artefacts such as modules and architectures. Although Arthur (2009) insists that 'all technologies are combinations of elements' (p. 203) and that technology 'builds itself organically from itself' (p. 24), his discussion also shed light on the structure of artefacts rather than on the primary factors involved in the creation of innovation. Furthermore, Allen's (2009) argument, which takes notice of the ratio of factors of production (especially capital and labour), is also a theory that pay attention to the structure rather than the primary factors.

On the other hand, Schumpeter (1934), Mokyr (2002), Yamaguchi (2006) and others have focused on people as the primary factors in the creation of artefacts, rather than on the structure of artefacts, and have tried to clarify the factors and processes of innovation. However, while many arguments, such as Schumpeter and Dosi (1982), treat scientific knowledge as given, Mokyr and Yamaguchi take the progress of scientific knowledge as endogenous. Arthur (2009) also insists that 'Technology builds from harnessing phenomena largely uncovered by science' (p. 64), and emphasises the advances in scientific knowledge. Figure 3 shows a rough classification based on the above discussion.

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21 See also Lombard (2018) for the impact of the bow and arrow on human's minds.

22 Usually, when we speak of primary factors of production in economics, we refer to factors of production such as capital, labour and land, but in this paper we will refer to the scientists and technologists who are responsible for the advancement of scientific and technological knowledge.

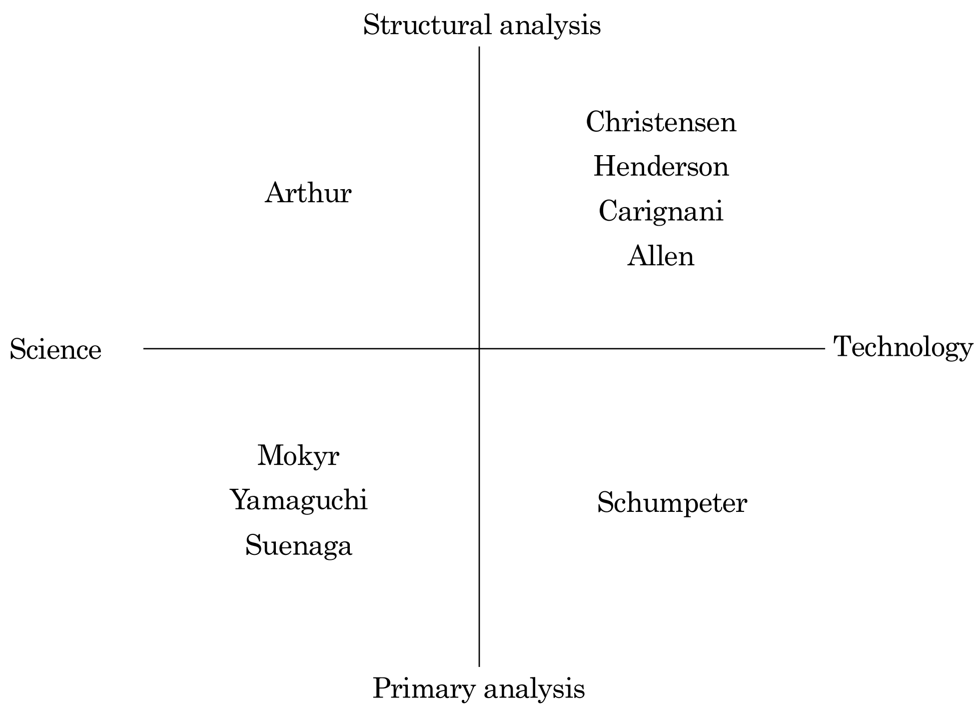

Figure 3: Classification of innovation theory

In addition, arguments that focus on the physical structure of artefacts and take the level of scientific knowledge as a given are more likely to have a managerial perspective, focusing on short- and medium-term themes, whereas arguments that shed light on the primary factors that create artefacts and scientific knowledge emphasise an economic perspective, focusing on long-term history. The arguments discussed above have been made for a variety of purposes and contexts, and it is not the case that any one argument is superior to the others, but it is important to note these differences in perspective when discussing innovation.

5. Concluding remarks

In this paper, we emphasise the importance of science from a long-term perspective, and focus our discussion on the human beings involved in the creation of innovations, rather than on the structural aspects of artefacts.[23] Another objective is to use the same model to analyse not only recent cases, but also innovations from the pre-industrial period, especially the Palaeolithic period, in order to build a theory of innovation that can deal with long-term history. This objective will be

[23] Of course, it is almost impossible to identify the person who invented the bow and arrow, but we imagined such an anonymous person in our discussion. Such inventions do not arise spontaneously in a growing population, nor do they come about unintentionally, as in mutation or horizontal transfer.

addressed in a book in the near future. This paper also compares a number of innovation theories. When considering innovation it is necessary to be aware of differences in perspective, and when examining long-term development it is indispensable to take account of advances in scientific knowledge.

The bow and arrow was a paradigm-disruptive innovation that harnessed new scientific knowledge and was a source of 'technological revolution' (Freeman, 1994a) that changed the standard of living and society of *Homo sapiens*. Although it is difficult to compare the benefits of different paradigm-disruptive innovations, these innovations are often produced in the face of difficulties under existing paradigms. Then, new paradigms based on the new scientific knowledge can often bring revolutionary benefits. Humans have gradually raised the level of technology by creating various new paradigms through a process of trial and error, while the level varied up and down.

Although not discussed in detail in this paper due to paper constraints, with regard to the new combinations of scientific and technological knowledge and their frequency, the information storage and communication technologies that connect them play a significant role (for more details, see Suenaga, 2019b). Information storage technology refers to symbols, letters, paper, printing and information storage devices; communication technology refers to vocalisation ability, language systems, translation systems and communication methods. In addition, in this new combination of knowledge, changes in values and demand also have a significant impact. While Baldwin (2016) examined long-term globalisation in terms of the bundling and unbundling of goods, ideas and people, this paper considers long-term innovation from the viewpoint of the combination (bundling) of scientific and technological knowledge. In the development of vaccines against Covid-19, scientific and technological knowledge were immediately combined through ICT, and new types of vaccine were developed at an astonishing speed (Suenaga, 2021a).

Last but not least, our civilisation originated in Africa tens of thousands of years ago and we have experienced globalisation and invasion with the advancement of technology. Nevertheless, we hope that by looking at history from a long-term perspective, we can put a stop to current conflicts and build a prosperous world.

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