Article

Conceptualizing engineering as an applied science: Hidetsugu Yagi as a promoter of engineering research

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abstract

Hidetsugu Yagi, renowned as one of the inventors of the Yagi-Uda Antenna, acted as a reformer of a Japanese engineering institution during the interwar period. He promoted *engineering research* and strove to transform a Japanese Imperial University Faculty of Engineering from a professional school to a research institution.

This paper examines Yagi's philosophy, which underpinned his promotion of engineering research. First, it explains why he needed to examine the nature of engineering, focusing on two factors: (1) the unique history of Japanese engineering education and research; and (2) the transformation of industrial technology before the First World War (WWI). It then outlines how he conceptualized engineering. According to his characterization, engineering was an applied science that applied mathematics and physical science for the purpose of *invention*, enabling what was previously impossible. This conceptualization helped him transform the Faculty of Engineering at Imperial University to a place of scientific research, and call for the autonomy of the faculty of engineering in the Japanese research and development system.

1 Introduction

Hidetsugu Yagi (1886–1976), a Japanese electrical engineer, is largely known for his contributions to radio science via his introduction of the ultra-short wave directional antenna (the Yagi-Uda Antenna). Simultaneously, the Department of Electrical Engineering at Tohoku University, which Yagi chaired from the late 1910s to the early 1930s, has been referred to as the cradle of Japanese electronics research. Although his life and work have been well documented in previous studies, Yagi's ideology, which underpinned his promotion of original research in the field of communication engineering, has not been adequately examined[1]. This paper focuses on Yagi's thoughts as a leader and champion of "engineering research," which he helped establish at Tohoku Imperial University. It

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[1] For more information about the research conducted under his leadership, see Tohoku Daigaku (1960, pp. 932–946); Erekutoronikusu Hatten no Ayumi Chōsakai (1998, pp. 16-30); for the beginning of original research on electrical technology, see Nihon Kagakushi Gakkai (1969, chap. 8).

also explores the history of Japanese research and development systems after WWI[2].

Japanese historians of science, technology, and education have accumulated a vast historiography of Japanese research and development systems, industrial education systems, and all kinds of industrial technologies[3]. However, how what we call *basic research* (*Kiso Kenkyū*) started in Japan has not been examined sufficiently. As we will see later, Yagi's concept of *engineering research* clearly includes the meaning of "pure science with a practical aim."[4]

From this perspective, the most important previous work was by Kamatani (1988), who investigated Japanese industrial laboratories from the Meiji through Taisho eras (1870s–1920s), clarifying that it was the national laboratories incorporated in government agencies, including the Geological Survey of Japan, the Central Industrial Laboratory, and the Electrotechnical Laboratory that conducted research for industry in the Japanese R&D system until around WWI. As implied by the name, however, the main duties of these laboratories were surveys and testing, rather than creating new knowledge. They were responsible for geological mapping for agricultural purposes, quality inspections of imported goods, and the selection of building materials that suited the Japanese environment, among other things. With advances in industrial technology, these institutions strengthened their research functions and expanded their in-house research facilities. However, given their organizational character, it was impossible for these institutions to chiefly prioritize research. The first Japanese institution dedicated to basic research was the Institute of Physical and Chemical Research (Riken), established in 1917[5].

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[2] Previous research about Yagi, from our perspective, lacks in-depth analyses. While Matsuo (1992) is the most comprehensive book about Yagi, it mixes fact and fiction to tell an intriguing story, making it difficult to use in an academic context. Although Sawai (2013) is a reliable source of information that deals with Yagi's whole life in a relatively balanced way, it does not include an in-depth analysis of his thoughts.

[3] The most important historian of Japanese industrial technology is Tetsuro Nakaoka (Nakaoka 2006 ; Nakaoka 2013). Nobuhiro Miyoshi (Miyoshi 2005 ; Miyoshi 2012 ; Miyoshi 2016) and Ikuo Amano (Amano 1997 ; Amano 2009 ; Amano 2017) made important contributions to the history of industrial higher education. The historiography of Japanese research and development systems includes the works of Tetsu Hiroshige (Hiroshige 1973), Chikayoshi Kamatani (Kamatani 1988), Minoru Sawai (Sawai 2012), and Atsushi Hiramoto (Hiramoto 2014). Among studies in English, Bartholomew (1989) and Morris-Suzuki (1994) are still the best works on the modern history of Japanese science and technology.

[4] Clarke 2010. *Basic research* is an ambiguous and flexible concept that scientists often draw on for boundary work to acquire prestige and resources (Calvert 2006). It has also been connected to the linear model of innovation, whose validity has long been in question (Edgerton 2004; Godin 2006; Schauz 2014). Therefore, using it as an analytical framework is somewhat problematic. However, the discourse of basic research and pure science was actually at work in the period of interwar Japan. This paper focuses on how this discourse was used by Yagi, a leader among Japanese engineering academics.

[5] For the establishment of Riken, see Kamatani 1988, pp. 199-220; Miyata 1983; Saito 1987; Bartholomew 1989, pp. 212-217. As for corporate research laboratories, Japanese firms generally regarded their research arms as channels through which technological knowledge from overseas was translated to actual manufacturing processes adapted to local conditions. This was the case until around the Second Sino-

However, the question of how basic research for industry began in *universities* still remains unanswered. Until WWI, the Colleges of Engineering in Japan's Imperial Universities were primarily educational institutions, and research was not their principal business[6]. The university science faculties shared a similar situation due to the lack of any research subsidization system. Only in the post-WWI period was a subventionary system established, allowing university professors to begin full-fledged scientific, and especially experimental research[7]. From this perspective, Yagi emerges as a figure who was no less important than those who promoted the establishment and development of Riken. Yagi can be considered one of the ideologues who contributed to transform university engineering departments from training schools into places for *engineering research*.

Let me discuss the term and concept of "engineering" before proceeding to the main topic. "Engineering" in the present paper is a translation from *kōgaku* in Japanese. *Kōgaku* was introduced into the Japanese vocabulary, presumably as a translation of the English term *engineering*[8]. The problem is that *gaku* incorporates the meanings of science, scholarship, and learning; thus, *kōgaku* strongly suggests "engineering science," and thus, has a slightly different connotation than its English counterpart[9]. Although I use "engineering" as a translation of *kōgaku*, the reader should note that this correspondence is somewhat problematic.

The second section of this paper explains the historical background in which Yagi elaborated his ideas, focusing on the characteristics of the Tohoku Imperial University and technological changes that were occurring around WWI, which wielded an enormous influence on the Japanese intellectual elites, causing a shift in their thinking on the science and technology policy. The third section considers how Yagi viewed engineering and engineering research[10].

Japanese War in 1937. See Morris-Suzuki 1994, chap. 5.

6 See Kamatani 1988, pp. 10-11; Bartholomew 1989, pp. 123-124; Morris-Suzuki 1994, p. 140.

7 See Bartholomew 1989, p. 213; Sugiyama 1994, pp. 36-38, 79. In contrast to the fields of science and engineering, medical research in Japan evolved differently, achieving first-rate results as early as the 1890s; it was clearly the preferred field until WWI. See Bartholomew 1989, chap. 4, 6.

8 Nakaoka 2006, pp. 443-444.

9 Another difficult term is *gijutsu* in Japanese. Although the term "technology" usually translates into *gijutsu* and vice versa, the extended connotations of these terms do not overlap. *Gijutsu*, which originates from the Chinese classics and also has a long history as a Japanese word, acquired the meaning of modern industrial technology through its rendition of the English term, "mechanical arts," in approximately 1870. Due to its complex history, the term actually has a much broader meaning than its English counterpart—it was used to refer to crafts, infrastructural and public works, the design of mechanical systems, and science-based industrial technologies, such as the production of highly-complicated electronic devices. In short, the meaning of *gijutsu* overlaps with several English terms: *art*, *engineering*, and *technology*, and thus, no single English term can cover its full range of meanings. See Iida 1995; Nakaoka 2001, pp. 3-6. Its English counterpart, *technology*, is also an ambiguous and problematic term. See Schatzberg 2018.

10 Notes on the source materials: Most of the materials that Yagi wrote before the end of WWII are lost

2 Behind Engineering Research

This section discusses why Yagi problematized what engineering is and considered it necessary to promote *engineering research*. In my view, there were two factors which importantly influenced his conceptualization of engineering: the specific characteristics of Tohoku Imperial University as a research university, and the general historical situation in which Japanese industry found itself before and after WWI.

2.1 Tohoku Imperial University as a Research Center

Before discussing the specific characteristics of Tohoku Imperial University College of Engineering, we must briefly consider the history of Japanese higher education and understand what made it unique. This topic is closely linked to the history of Japanese industrialization after the Meiji Restoration.

Japanese higher education in engineering, which started in the early 1870s, initially relied on foreign teachers, particularly from Britain. The Ministry of Public Works, which was responsible for promoting industry and constructing the national infrastructure from 1870 to 1885, initially relied on foreign employees (*Oyatoi Gaikokujin*) to direct enterprises such as railroads and telegraph construction and train professional engineers[11]. The main purpose of Imperial College of Engineering (*Kōbu Daigakkō*), which reported to the Ministry of Public Works, was to replace foreign employees with its graduates, including their teaching staff. In short, graduates from the school were the replacements for foreign employees, and were expected to be agents for the country' s rapid industrialization.

After the Ministry of Public Works was abolished in 1885, the College was transferred to the Ministry of Education, then incorporated into the Imperial University, created in 1886 with the Imperial University Ordinance (*Teikoku Daigaku Rei*), as its College of Engineering (later the Faculty of Engineering at the University of Tokyo). The responsibility for training high-ranking engineers was assumed by the Imperial University, although some were opposed to incorporating the College of Engineering into the university, in light of the German conception of the university[12]. However, the installation of an engineering department in the university with a degree system leading to a doctorate degree in engineering as early as 1887 became a remarkable feature of the Japanese education system. Furthermore, the Ordinance stated that its mission included not only education, but also *research*[13]. These characteristics partly explain why Yagi thought that university engineers should conduct *engineering research*.

The university engineering education system continued to expand. Kyoto Imperial Uni-

or missing, partly as a consequence of war damage. I have therefore relied on writings published in newspapers, magazines, and academic journals.

11 See Umetani 2007.

12 Sugiyama 1994, p. 8.

13 Monbusho 1972, pp. 363-367.

versity, the second university in Japan, opened its Science and Engineering College in 1897. The third was Kyushu Imperial University, founded in 1911, which had the Engineering College separated from the College of Science. The fourth was the Tohoku Faculty of Engineering established in 1919, while Tohoku Imperial University opened its College of Science in 1911[14].

Tohoku Imperial University was established with the expectation that it would promote research in natural science and mathematics, using the University of Göttingen as its model[15]. During the founding era, the College of Science (reorganized into the Faculty of Science in 1919) always held the central place in the university[16]. Although the Imperial University Ordinance defined the Imperial University—its graduate school in particular—as a place of research, most research carried out until the turn of the century did not go beyond the level of "student experiments," which applied established techniques to new materials and objects, with some exceptions that prove the rule[17]. From the turn of the century, several scientists, especially those who achieved exceptional results, came to believe that the Japanese nation needed to promote original research in order to be recognized as one of the world's leading powers against the backdrop of rising nationalistic sentiment around the Russo-Japanese War[18]. Tohoku Imperial University was established at least partly to satisfy this need, and its faculty members successfully fulfilled the demand, achieving eminent results in both quantity and quality from the outset[19].

Among Japanese scientists who promoted original research in the field of science, one of the most vocal figures was Hantarō Nagaoka, a professor of physics at Tokyo Imperial University and one of the first internationally known Japanese physicists, for his work on magnetism and the structure of the atom. Nagaoka was deeply involved in establishing

[14] The belated establishment of the engineering department is attributed to financial problems and an imbalance in the department configuration. When the decision to found Tohoku Imperial University was made, Tokyo and Kyoto universities already had engineering colleges, and Kyushu Imperial University, established at the same time as Tohoku, was located in an industrial area where an engineering college was expected to be built. In contrast, the only university with a college of science was in Tokyo, causing an imbalance. Tohoku district, where Tohoku University is based, had no industry worthy of attention, and local residents did not express opinions on what should be taught and researched in the University. For these reasons, the College of Science was established prior to the College of Engineering in Tohoku. See Tohoku Daigaku (1960, pp. 19-22, 897-900).

[15] Tohoku Daigaku 1960, pp. 37, 63-71;Hatsuyama and Ihara 2014.

[16] Tohoku Daigaku 1960, pp. 19, 133-138.

[17] See Sugiyama 1994, pp. 65-70.

[18] Moreover, when Kyoto Imperial University was established, its founding faculties attempted to cultivate student originality, adopting a German model that integrated education and research. That said, the anticipated goal was to expand engineering education and reduce the chronic shortage of industrial engineers. See Kyoto Daigaku Hyakunen Shi Henshū Iinkai 1998, pp. 118–120; Amano 2009, pp. 18–20.

[19] To name but a few, the contributions of Jun Ishihara to the old quantum theory in theoretical physics and the physical metallurgy research led by Kotaro Honda constitute key early accomplishments. See Tohoku Daigaku 1960, pp. 626–627

Tohoku Imperial University, contributing to everything from the selection of professorial candidates to the purchase of experimental equipment. Nagaoka intended to move from Tokyo to Tohoku Imperial University to chair the new College of Science, but decided against this plan after the president of Tokyo Imperial University strongly urged him to stay[20].

As a graduate of Tokyo Imperial University and as one who had attended Nagaoka's physics class, Yagi respected Nagaoka and shared his aspiration to contribute to the advancement of science. Nagaoka also trusted Yagi on the question of electricity, in proof of which Nagaoka later recruited Yagi as the first Head of the Department of Physics (not Engineering) of Osaka Imperial University, where Nagaoka had served as its first president since 1931[21].

The Tohoku Imperial University Faculty of Engineering has its roots in the Sendai Polytechnic Institute (*Sendai Kōtō Kōgyō Gakkō*) which was planned to be incorporated into the Tohoku University, and in the department of applied chemistry placed in the College of Science. Before its installment, almost all the candidates for the professors of the planned Faculty of Engineering, including Yagi, belonged to the Sendai Polytechnic Institute. However, they also belonged to the College of Science, although that was strictly unofficially. They frequented and interacted with the physicists and chemists of the College of Science, sharing a highly academic environment[22]. Yagi was especially close to Kotarō Honda, a physicist known for his work for physical metallurgy, and participated in the weekly journal club launched at Honda's laboratory[23].

Born into an old merchant family fallen from prosperity, Yagi initially intended to work in industry. He enrolled at Tokyo Imperial University and chose electrical engineering as his major[24]. However, he was more interested in physics than engineering, saying, for example, that "the news of the destruction of atoms is a great deal more exciting to me than that of the 300,000 volt transmission."[25] Tohoku University must have been an ideal environment for him, given his interest in the physical sciences.

The attempt to promote original research in electrical engineering can be interpreted as an extension of Nagaoka's project of building the research university into the Faculty of Engineering. However, Yagi had another important reason to promote research in engineering fields: the rise of science-based technology.

[20] Tohoku Daigaku 1960, pp. 26-27; Itakura et al. 1973, pp. 326–336. For more on Nagaoka, also see Bartholomew 1989, pp. 178-179. Other important figures who were outspoken in promoting research included Jōkichi Takamine and Jōji Sakurai, distinguished chemists who influenced the establishment of Riken in the 1910s. See note 5.

[21] Kiyasu 1976; Osaka Daigaku Goju Nenshi Henshū Jikkō Iinkai 1983, pp. 137–139.

[22] Tohoku Daigaku 1960, pp. 897-888.

[23] For the culture of Honda's laboratory and his personality as its director, see, Bartholomew 1989, pp.186-191.

[24] Sawai 2013, pp. 1-6.

[25] Yagi 1918a, p. 277.

2.2 The Rise of Science-Based Industry

WWI and the emergence of science-based technology (chemical and electrical technology in particular) constituted the backdrop against which Yagi developed his ideas on what engineering is and why university is the appropriate place for *engineering research*. In technical fields where Japanese artisans had their own traditions, such as textiles and steel making, the main technology-transfer challenge was in finding ways to adapt completed technologies closely rooted in European culture to the Japanese environment and/or hybridize them within Japanese traditional arts. Before WWI, such techniques were successfully appropriated[26]. In contrast, in the emerging fields of electric power, communication, and chemical industries—arising in the second industrial revolution—Japanese industries became steadily subordinated to Europe and the U.S., despite painstaking efforts of Japanese engineers.

One characteristic of these technologies is the closer relationship with scientific knowledge than it used to be, although inventors in the late nineteenth and early twentieth century did not necessarily need deep understanding of science[27]. As David Noble's classic work argues, the rise of science-based industry in the U.S. after the Civil War led to the capitalistic marriage of science to the useful arts[28]. Science was incorporated into corporate business, as an important way to protect a company's monopoly through patent politics. Especially in the electrical industry, making an invention work efficiently required a large technological system composed of various elements, such as power plants, transmission networks, and organizations that maintained and operated the system[29]. When multiple corporate bodies owned patent rights of separate system components, patent-infringement cases inevitably occurred, hindering the operation of the whole system. To resolve this, companies like GE and AT&T dominated the whole range of relevant patents and became powerful monopolistic enterprises. In addition, these huge companies established in-house corporate research laboratories as a means to protect their monopolies, fully exploiting the exclusive rights that those laboratories provided.

Although Japanese electrical engineers endeavored to appropriate science-based technology since the 1890s, their attempts were unsuccessful. Tokyo Electric (later Toshiba), despite successfully producing incandescent lamps for the domestic market, could not compete with huge Western enterprises and became a subsidiary of GE in 1905. Other Japanese companies chose to become subsidiaries of the U.S. or German companies from the beginning. For example, Nippon Electric Company, established in 1899, started as a sales and service subsidiary of Western Electric, the manufacturing arm of the Bell System. Mitsubishi Electric also sought out a U.S. partner, offering 10 percent of its stock

[26] See Nakaoka 2006.

[27] See, e.g., Hughes 2004.

[28] Noble 1977.

[29] Hughes 1983.

to Westinghouse in return for access to technical information[30]. Without doubt, Japan's technological dependence on foreign countries stemmed from the enormous disparity in R&D capacity in the industry[31].

While weak research capacity might not matter during peacetime, it becomes fatal once technological communication breaks down. The outbreak of WWI, and the ensuing suspension of the importation of German industrial chemicals, pharmaceuticals, and precision instruments sent a strong warning to Japanese intellectuals about the dangers of depending on foreign technology and triggered a sequence of research promotion movements[32]. While the chemical industry became the focus of attention during WWI, the electrical industry shared the same problem, i.e., easily falling into crisis if the communication was cut off.

Against this backdrop, a growing awareness of the need to promote research that is "science-based and beneficial to the [national] economy" spread throughout Japan[33]. Japan's government and industrialists aggressively promoted the domestic production of industrial goods and invested in building several research laboratories, including the Institute for Metal Research at Tohoku Imperial University, headed by Kotaro Honda[34]. Honda, who originally specialized in the theory of magnetism, capitalized on the situation to initiate systematic research into the physical properties of steel[35]. His metallurgy research, which exemplified the early successful application of physical science to industrial technology, had a considerable influence on Yagi's thoughts.

In addition, Yagi's personal experiences influenced his understanding of the modern industrial technology. In July 1914, when WWI broke out, he was in Zurich. As a professorial candidate for the planned Tohoku Imperial University Department of Engineering, he had studied abroad from 1913 to 1916. He was then a visiting researcher at Technische Hochschule Dresden, accidentally on vacation in Zurich. As the war made it impossible to return to Germany, he moved to England, where he continued his research under the direction of John Ambrose Fleming. He then moved to the U.S., directly witnessing the rise of corporate research[36]. The 1910s were characterized by the rise and tremendous success of basic research in American corporate laboratories, including those of GE and Western Electric. A coast-to-coast telephone service, implemented in January 1915 was made possible by a telephone amplifier developed by a research team led by Harold Arnold, a physicist working at the Research Branch of Western Electric. This invention was based

[30] Morris-Suzuki 1994, pp. 111-113.

[31] Nakaoka 2006, pp. 460-464.

[32] Hiroshige 1973, ch. 3; Bartholomew 1989, pp. 111; Sawai 2012, ch. 2.

[33] Takamine 1913, p. 189. The establishment of Riken in 1917 reflects this context. See Kamatani 1988, pp. 180ff.

[34] Sawai 2012, ch.1–2.

[35] Ishikawa 1964, pp. 183–193.

[36] Yagi 1915a, p. 986.

on extensive research on the physics of the triode valve[37]. Yagi was well acquainted with the actualities of total war and industrial laboratories in various countries, i.e., how to mobilize science for the military and commercial purposes.

Returning to Japan in June 1916, Yagi highlighted the significance of organized research and the close relationship between industry and academia, in an interview with a journalist:

> Large manufacturers [in Europe and the U.S.] employ scholars by establishing an in-house laboratory, while smaller manufacturers commission research to be conducted by the affiliated universities. In short, research is conducted by necessity, overseas scholars start research under the pressure of private demand or on the government' s orders, and not much research is derived from the scholar's inventiveness. The private sector has always submitted the problems to be investigated. Though the National Institute of Physical and Chemical Research is about to be established in our country, such laboratories are also actively established in foreign countries and are already engaged in research. I would like to discuss industrial research and physical-scientific research in another paper, but what the private sector wants most is *research with an intermediate character between the industrial and the scientific*, which can be readily applied to society and will benefit the private sector.[38]

Yagi believed that research with this in-between character should be conducted at his Department of Electrical Engineering; he actively promoted the cause. However, some questions arise here: what is "the research with an intermediate character between the industrial and the scientific"; how can we distinguish this from other kinds of research; and why does it have to be conducted at Japanese Imperial University. These were the questions Yagi tried to answer, which we will consider in the next section.

3 Conceptualizing Engineering as an Applied Science

After being appointed as the Chair of the Tohoku Department of Electrical Engineering in 1919, Yagi immediately began to promote what he called *engineering research* (*kōgaku kenkyū*) in his department. Simultaneously, he deliberated about conceptual problems, such as what engineering was, and what constituted engineering research, presumably motivated by strong opposition to his advocacy of *research* at the Imperial University Engineering Department, which came from various quarters throughout the 1920s. According to his recollection, a journal editor demanded that members of Tohoku University refrain from submitting articles, stating that their esoteric content was alienating read-

[37] Reich 1985.

[38] Yagi 1916b. Emphasis added. We can find similar arguments in Yagi 1915a. The aforementioned National Institute of Physical and Chemical Research, (*Rikagaku Kenkyū Sho*) was founded in 1917.

ers[39]. He also suggested that industrialists had complained that the studies were useless when it came to making money[40]. In 1922, he complained that "our country remains in such an immature state as hardly any engineering research had been done until a few years ago, and most of us recognized its necessity through the experience of WWI for the first time."[41] As the idea of *engineering research* was novel and unfamiliar to most Japanese people, he needed justification to further its progress.

As we will demonstrate, Yagi tried to conceptualize engineering (*Kōgaku*) as an applied science. However, he resisted subordinating engineering to science, arguing that engineering was autonomous and separate from both science and technology. The engineering research he had in mind was closely connected to the place he felt it ought to be performed, i.e., a university with a faculty of pure science. University engineers, as applied scientists, should learn state-of-the-art scientific knowledge in real time from their colleagues, use it to invent items of utilitarian value, and then pass on the resulting inventions to industry, which produced industrial goods and made technology work in real life. He understood those who researched engineering at the university as *engineering scientists* (*Kōgaku-sha*) who bridged the gap between academe and industry through application. At the same time, he distinguished them from engineers (*Gijutsu-sha* or *Gishi*) who worked in industry and dealt with technology (*Gijutsu*)[42].

His thoughts about engineering (*Kōgaku*) are expressed fragmentarily in his writings; the periods when these materials were written were widely dispersed, from the late 1910s to the early 1940s. Nonetheless, his ideas had not seemingly changed much throughout the interwar period. This study therefore extracts and summarizes his thoughts scattered across several source materials. These are grouped into three distinct categories: the characterization of engineering as applied science (3.1), the typology of engineering research and its consequences (3.2 and 3.3), and the appropriate place where engineering research should be conducted (3.4). After discussing how he conceptualized engineering, the last part of this section analyzes the implication of his conceptual work.

3.1 Engineering as an Applied Science

Yagi was consistent in considering engineering to be an applied science; he generally identified himself as an applied physicist[43]. He described engineering as the part of science that deals with phenomena happening in artificial things. If physical science explores how the world is governed by natural laws, engineering investigates how these laws work

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39 Yagi 1936, pp. 1070–1072.

40 Yagi 1927, p. 48.

41 Yagi 1922a.

42 Since Yagi distinguished clearly between *Kōgaku-sha* and *Gijutsu-sha*, this study uses *engineering scientists* for the former, and *engineer* for the latter, although both of these Japanese words are usually translated as *engineer*.

43 Yagi 1941, p. 1.

in various kinds of artifacts, in order to derive design rules or principles. Engineering is, for instance, the physics of electronic discharges in vacuum tubes, electromagnetic waves radiated from antennas, gases in steam turbines, and the mechanics of ship hulls[44].

However, Yagi understood engineering as more than just the application of science, because engineering also had a relationship with technology. According to him, "technology is a part of human action which combines natural and humane forces, with its principal focus on utility or economic value to human society," while "engineering covers the academic and natural-scientific part of technology-related affairs in a very multifaceted fashion." Because of its connection to technology, a messy concept in itself, engineering defied simple or congruous definitions[45].

Yagi argued that the difference between technology and engineering was that technology was a practice, while engineering was a science[46]. Simultaneously, he distinguished engineering from other sciences by its research results. Engineering explores how universal laws work within certain artifacts. Accordingly, the methodology of engineering is analogous to that of physical science. However, while the results of the inquiry of natural sciences appear in the form of *discovery*, in engineering they appear as *invention*[47], which includes not only the design of concrete things, but also ideas and concepts[48]. What constitutes a distinction between invention and discovery, or between engineering and physical science, is whether it has a "utilitarian" (*kōri-teki*) element. While physical science engages in the experimental elucidation of truth, engineering has "utilitarian significance," providing a base for industry, which entails the ethical ideals of advancing human civilization and happiness[49].

Yagi conceptualized engineering as the bridge between the natural sciences and technology. Engineering uses science for utilitarian purposes; then industry uses the results of engineering research to create something practical. He considered engineering and science to be very similar in terms of their methodology and epistemology, distinguishing them through the aims of their research (invention or discovery). He also distinguished engineering from technology by whether it was an epistemological or practical activity. These distinctions were closely related to his views on research organization (see Section 3.4). Before moving on to that topic, we must confirm what *engineering research* is.

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[44] Yagi 1927, p. 50.

[45] Yagi 1941, p. 22. Yagi repeated almost the same argument in Yagi 1953, pp. 52-58.

[46] Yagi 1941, pp. 24-25.

[47] Yagi 1927, p. 50; Yagi 1941, p. 24.

[48] Yagi also treats agriculture, forestry, fisheries, and medicine in the same way as engineering, noting that "their purpose is invention in a broad sense." (Yagi 1941, p. 25)

[49] Yagi 1922a, p. 31; Yagi 1926, p. 9. Yagi cautioned against confusing patents with inventions. A patent is "something given if nothing else is confirmed to be the same," and "its permission is irrelevant to whether it is practical or not." In contrast, inventions must be useful and made available to the public. (Yagi 1932, pp. 39)

3.2 Three Stages of Engineering Research

Yagi divided engineering research into three stages with a hierarchical relationship: the first involved calculation, namely the application of mathematics; the second involved experimental research—the application of the methodology of physical science; and the third involved invention, the most essential of engineering research. He depreciated the first kind of research openly, stating that it often "attempts to solve very simple problems by the most cumbersome means," in order to "show off the author's ability of mathematical analysis and to satisfy themselves."[50] In a letter written during his stay in the U.S. in 1915, Yagi strongly criticized studies of this kind, which he felt made up most of the research conducted in Japan at that time.[51] However, he came to regard this step as indispensable to become a genuine engineering scientist, as he believed it was impossible to proceed to the second and third stages without having the necessary knowledge of mathematics[52].

The second stage was experimental research. According to Yagi, the difficulties that engineering students experienced after acquiring the necessary calculation ability were their lack of experimental skills and experience, which made it difficult for engineering students to select relevant problems, devise appropriate research methods, and judge observation results. As Yagi considered the methodology of engineering and science to be almost identical, engineering scientists, he argued, must acquire the attitude and mentality of "pure scientists," and undergo a period of "humbly standing before the truth in an extremely pious manner, earnestly longing for the truth."[53]

Only after learning to perform the first and second stages of research could engineering students reach the third stage, which was characterized by originality and inventiveness[54]. Noting that "at today's level of civilization, coming up with meaningful inventions is impossible without a deep understanding of basic science," Yagi demanded that his colleagues and students be engineers as well as (pure) scientists[55].

Yagi's view that useful inventions could not be made without basic knowledge was not necessarily shared among the Japanese elite of his time. For example, in a speech at the graduation ceremony of a private technical school, Hantarō Nagaoka made the following statement, after mentioning that Edison never received any higher education but still succeeded in making numerous significant inventions:

> Inventions are rather few in academia, and I do not believe that physicists are superior in making "inventions." Rather, I think that "inventiveness" should be

[50] Yagi 1922a, p. 32.

[51] Yagi 1915a, p. 986.

[52] Yagi 1922a, p. 32.

[53] Ibid. Yagi referred to research on the characteristics of X-ray tubes and electric lamps as examples.

[54] Yagi 1922a, p. 33.

[55] Yagi 1926, p. 10. Yagi repeated this argument in several places. See, e.g., Yagi 1941, pp. 19ff.

> sought among those who did not pass the barrier.[56]

Nagaoka disagreed with Yagi and thought that it was possible to make meaningful inventions without having a profound understanding of basic science.

It should be noted here that despite his somewhat disdainful remark about the first stage, Yagi included the construction of mathematical theory and the derivation of engineering rules through calculation within the area of inventive engineering research. In short, Yagi thought that engineering could be applied mathematics as well as applied physics committed to invention. He expressed the relationship between physics, mathematics, and engineering in 1933 as follows:

> In classical dynamics, all you have to do is synthesize the laws and apply them. The law is applicable to an extremely broad range, and Newton's differential equation solves everything. Dynamics comes to an end when the differential equations are established. In mechanical engineering and others, the development and the solution [of these differential equations] is more important. [57]

While physics explores natural phenomena and describes them using mathematics, engineering considers the laws of nature as assumed facts and "applies them under various boundary conditions and to circuitry," thus producing rules or values as its goal[58].

Yagi emphasized the importance of calculation in engineering in contrast to physics. In physics, mathematics is a language used to describe natural phenomena, and "calculation is rather a 'proof,' which is not very helpful for finding laws." However, in engineering, calculation is much more important, because "the more you calculate a circuit, the subtler the changes appear." Engineering does not doubt or pursue the *Grund* [fundamentals]; instead, it makes reductions within the domain designated by basic theory. Yagi cited the work of Charles Proteus Steinmetz of the GE Laboratory as a model of this applied mathematical type of engineering research[59].

3.3 The Dependence of Engineering on Science

Yagi considered engineering to have two foundations: mathematics and physical science. He believed that original engineering research could not be conducted unless the researcher had obtained certain levels of training in both. In other words, engineering

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[56] Nagaoka 1917, p. 882. Translator's note: the term "barrier" in the previous citation refers to the entrance exam for imperial universities or public polytechnic institutes, which had higher status in the Japanese school system than private technical schools.

[57] Yagi 1934, p. 11.

[58] Yagi 1934, p. 9.

[59] Yagi 1934, pp. 11–12. As the original text mixed German and English terms, this paper does not translate the terms *calculation, proof, circuit, reduction* and *Grund* used in the original text. Hidetarō Hō, Yagi's former teacher and Professor of the Electrical Engineering Department at Tokyo Imperial University, studied abroad under Steinmetz in the mid-1890s. (Matsuo 1992, p. 103)

research depended heavily on knowledge drawn from these basic sciences.

Welcoming the epistemological dependence of engineering on basic sciences, physics and mathematics in particular, he struggled to create a highly academic environment in his Faculty of Engineering at Tohoku so that members could keep up with state-of-the-art developments in natural science[60]. Yagi focused particularly on the expansion and improvement of the library, which he later recalled:

> If you went into the library of the electrical engineering department at Tohoku University, you would find a lot of rare magazines, including *Comptes Rendus, Naturwissenschaften, Nature, Phil. Mag., Proc. Royal Society, Proc. Phys. Society, J. de Physique et Radium*, and many other science magazines. [...] Certainly, it is necessary for research to possess the instruments and money needed, but I think Tohoku University was different from other universities in that it had a school tradition to require such books and journals, rather than actually having such books.[61]

Yagi was definitely one of those who created the "school tradition," which considered basic science to be of central importance to engineering. The tradition did help to make Tohoku University the research center of electronics after the war. Indeed, it was Yasushi Watanabe, a colleague of Yagi at Tohoku, who laid the foundations of Japanese semiconductor engineering after the war. He had begun studying quantum mechanics seriously since the mid-1930s with engineering applications in mind[62]. With the help of Yoshio Nishina, the leading quantum physicist in Japan in the interwar period, Watanabe published some of his results between 1941 and 1943[63].

The emphasis on the importance of science (particularly physics) to engineering reflected Yagi's views on the progress of engineering and technology. Since the mid-1930s, he had often discussed the advance of technology. At that time, Yagi had already left Tohoku to serve as Chair of the Department of Physics at the newly established Osaka Imperial University. He argued that technology advances discontinuously, not continuously, through the progress of basic science. He explained this using the electron tube as a prime example:

> I believe that technological progress occurs discontinuously. *Technology progresses in such a way as the advancement of basic science, which seems to be of no use, interrupts the development of technology.* I think the future of electron tubes will be dominated by material research, but material research is not limited

[60] Fortunately for him, Otogorō Miyagi, a mechanical engineer who served as the Dean of the Faculty of Engineering from 1921 to 1923 and again from 1934 to 1945, shared Yagi's ambition and emphasized the importance of basic science in successful engineering research. See Miyagi 1925; Miyagi 1940; Miyagi 1943; Tohoku Daigaku 1960, pp. 910, 926.

[61] Yagi 1936, p. 1067.

[62] Saneyoshi 1985.

[63] Nishina's name is included in the acknowledgements of these papers. See, e.g., Watanebe 1941.

> to electron tubes. I think all electrical engineering will be dominated by materials. It applies the theories and methods of new physics to the domain of chemistry. In the domain of chemistry, materials should advance very rapidly if they are studied using new theoretical methods of physics. This should happen in the near future. I believe that it will force revolutionary changes in electron tubes.[64]

This view, which clearly subordinate engineering to science, is reminiscent of Vannevar Bush, to whom the linear model of innovation has been (mistakenly) attributed[65]. Engineers, who applies science for the purpose of invention, must play a bridging role between science and technology.

Moreover, Yagi thought engineers could contribute to this discontinuous advancement in science, for an engineering scientist was simultaneously a basic scientist in his understanding. He promoted research on nuclear physics as the theme that could cause the next "discontinuous advancement" of technology, after leaving Tohoku to preside over research at the newly-founded Osaka Imperial University in the early 1930s[66].

The idea of discontinuous advances in technology appears to have stemmed from Yagi's own experience of radio research. In wireless communication, a circuit element capable of producing high-frequency continuous wave is essential. Prior to WWI, many engineers including Yagi struggled to generate a continuous wave through the dexterous use of spark-gap transmitter, alternator, and Poulsen arc. These efforts gradually lost their value, following the introduction of vacuum-tube oscillation technology around WWI[67].

The establishment of vacuum-tube technology was, to a great extent, the result of organized, large-scale, and science-based research conducted by corporate laboratories, especially those of GE, Western Electric, and Westinghouse. Experimental studies based on the physical understanding of electrons, using a theory that explained the behavior of electrons in both gas and vacuum, were indispensable for improving vacuum tubes. Both GE Laboratory and the Research Branch of Western Electric were first-rate institutes for physical and chemical research, staffed by top-rated physicists and chemists, including the future Nobel laureates Irving Langmuir and Clinton Davisson[68]. In the first quarter of the twentieth century, wireless technology was certainly making discontinuous progress due to the "interruption of basic science."

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[64] Yagi 1938, p. 242. Emphasis added. Just before this quotation, Yagi also referred to the need for a new physics, i.e., nuclear physics, to understand the nature of semiconductors. In the late 1940s, electron tubes were indeed subject to revolutionary changes and were replaced by transistors.

[65] See Bush 1945; Godin 2006. Bush and Yagi have several commonalities: both were electrical engineers, directed the mobilization of science in the Second World War, and their view of science is also similar. Although this similarity seems striking, I will consider this topic in another place.

[66] Yagi 1940.

[67] See Aitken 1985, chaps. 2, 3, 4. Yagi had published several papers on arc oscillation and its application to sound transmission in the 1910s: Yagi 1916c; Yagi 1916a; Yagi 1917; Yagi 1918b.

[68] See, Reich 1983, pp. 213ff.; Wise 1985, pp. 172–177; Russo 1981.

The problem was that engineering research, which sometimes caused "discontinuous change," did not necessarily benefit industry. Yagi cited a study of synthetic silk (rayon) as an example of discontinuous and disruptive change[69]. Research on and development of the fiber could disadvantage domestic silk manufacturers; even minor improvements can have a negative impact on the shop floor if the factory is only interested in immediate returns[70]. Yagi could not expect the Japanese private sector to carry out inventions and improvements likely to lead to disruptive consequences[71]. Thus, inventors needed to work in a place distanced from the pursuit of immediate profit. This raised the problem of the research organization.

3.4 Engineering Research and the University

From the 1920s, Yagi actively expressed his views on the distinction between scientific, engineering, and industrial research and the best places to conduct them. At that time, the Japanese education system was experiencing drastic changes. Until the late 1910s, the Japanese research and education system did not allow private colleges or public polytechnic institutes to be called or treated as "universities" (*Daigaku*), making a clear distinction between the prestigious Imperial Universities and these institutions. However, influential professional schools dissatisfied with this situation started the Campaign for Promotion to University status (*Daigaku Shōkaku Undō*), resulting in the enactment of the "University Ordinance" (*Daigaku rei*) at the end of 1918, which allowed them to be promoted to university status[72]. In this context, the role that each educational and research institution should play was actively discussed, which prompted Yagi to express his opinions on the desirable structure of national research and education system.

Yagi was well aware of the research organization in foreign countries. When he traveled abroad in 1928, he visited almost all of the leading research institutes in Western countries, and reported on the organizational structures and what was carried out in each institution[73]. From the 1910s, the Western countries had actively discussed the issue of research organizations; Yagi seems to have followed the discussions in Western countries

[69] As early as 1909, some Japanese scientists at the Ministries of Agriculture and Commerce noticed the progress made on synthetic fibers after the turn of the century and recommended promoting research in this field. However, the government agency dismissed them on the grounds of the superiority of natural silk, resulting in a large expenditure on imported foreign-made artificial textiles before WWI. See Bartholomew 1989, pp. 159, 234.

[70] Yagi 1925a.

[71] Yagi 1923c.

[72] See Amano 2009, chap. 7, 10.

[73] Yagi 1928a; Yagi 1928b. Judging from the report, he seemed most impressed by the GE Research Laboratory in the U.S. and the Munich Institute of Technology in Germany. He implied that he disliked Bell Laboratory's secretive and elitist atmosphere.

through foreign journals, such as *Electrician*[74].

Yagi proposed that research related to industry be divided into that of the *industrial* and *engineering*, stating that "I believe, apart from the training of industrial engineers and *industrial research*, there should be the engineering as a discipline, whose research I devote myself to."[75] Industrial research treats technological and practical problems closely connected to the actual production process, therefore, it should be conducted in an industry with a manufacturing facility[76]. While profitability and efficiency are the leading concerns for industrial research, engineering research borders on purely scientific research, not necessarily with pecuniary concern. Because only the practicing engineers working in industry can research "the 220,000-volt power transmission, the Niagara Queenston power plant, and the 1,000,000-volt generator," the researches of these technological objects should be left to industry and the institute of technologies, which had the close connection to industry[77]. In contrast, engineering scientists of the Imperial University should improve scientific understanding of industrially-important phenomena regardless of the size and scale, "placing themselves in between the possible and the impossible" and realizing "subtle action through ingenuity," namely, invention[78].

The division of research dovetails with his compartmentalization of science, engineering, and technology. Yagi envisioned a research organization, in which scientific research would be assigned to the science faculty in Imperial Universities, engineering research to the Engineering faculty at Imperial Universities, and industrial research to the public and private industrial laboratories with manufacturing plants or the institutes of technology, which are now permitted to obtain the status of university[79].

Yagi thought that the division should also be applied to the educational system. He proposed that while the institutes of technology train the engineer (*Gijutsusha*) who dealt with practical and technological matters, the university faculty of engineering educate engineering scientists (*Kōgakusha*)[80]. As aforementioned, the university faculties of engineering in Japan were originally expected to be professional schools responsible for the training of senior engineers working for the government and private manufacturing companies. He co-opted the promotion movement as an opportunity to take over the role of training schools from the Imperial Universities to the new institutes of technology.

[74] In Yagi (1915b) and Yagi (1924), he presented the views of Gisbert Kapp, a British electrical engineer, and Steinmetz of GE Research Laboratory on the problem of research organizations expressed in foreign journals.

[75] Yagi 1923a, p. 28. Emphasis added.

[76] Yagi 1923c.

[77] Yagi 1924.

[78] Ibid.

[79] About the private research laboratories in Japan from 1920 to the early-1930s, see Sawai 2013, pp. 43-50

[80] See, e.g., Yagi 1923a, p. 27.

3.5 Implications of the Conceptual Work

His arguments can be understood as boundary work to secure the academic status of engineering against neighboring areas: science studied in the university faculty of science and technology practiced in industry[81]. Yagi argued, in the context of the research and education system, that physical science, engineering, and technology should support each other while maintaining mutual independence and autonomy, without blurring the boundaries between them. He refuted the argument that identified science with engineering, arguing that the study of science was completely disconnected from utilitarian or humane elements; he also opposed the identification of technology and engineering with a demarcation between practice and knowledge. In addition, he denied the dominance of engineering over technology, arguing the "logic" unique to technology as practice, independent both of engineering and science[82]. However, as noted in the previous section, he blurred the distinction between science and engineering when discussing the characteristics of engineering research. By conceptualizing engineering as the application of science, the ambiguity of the concept *applied science* slipped into the discourse of engineering[83].

More importantly, however, Yagi could rely on the far more authoritative discourse of *nation*. Facing the opposition against his promotion of engineering research in the Engineering Faculty from various quarters, including government and industry, Yagi countered these criticisms by highlighting nationalistic ideology. He insisted that Japanese Imperial Universities existed not for industry, bureaucracy, or the military, but for the "desideratum of the nation," (*Kokka no Shuyō*) as prescribed in Imperial University Ordinance, Article 1. Professors of Imperial University were free to choose their own research subjects in accordance with their own judgment of whether or not the topics are essential to the nation. Thus university professors had the right to promote engineering research without outside interference[84].

Yagi's call to transform the professional schools for senior engineers into research institutions in the 1920s was in step with other developed countries. A comparison with the Massachusetts Institute of Technology (MIT), which has served as a model of higher education in the technological field since its foundation, can clarify this point. The Institute itself began as a professional school; the dominant idea of the founding era was the mass-production of skilled employees for industry[85]. In this respect, MIT and the engineering faculty of Japanese Imperial Universities shared the same situation, although their patron was different: the former served industry, while the latter served the nation.

According to Roger Geiger, while efforts to strengthen research functions began around

[81] See Gieryn 1983; Gieryn 1999.

[82] Yagi 1923b.

[83] See, e.g., Kline 1995; Bud 2012; Schatzberg 2018, pp. 64–72.

[84] Yagi 1920; Yagi 1922b; Yagi 1925a.

[85] See Wise 1985, chap. 3.

the turn of the century, pre-WWI MIT experienced an identity crisis—unsure whether to be a research university that mainly performed basic research for academic ends or a professional school that conducted applied research for industry. At the end of the 1910s, serious financial problems led MIT to choose the latter course, placing its human and physical resources at the disposal of private industry. In doing so, throughout the 1920s, MIT lost its freedom of research to a considerable degree in return for an endowment. Many faculty members devoted their non-teaching time to consulting, rather than personal research[86].

The absence of any foundational support further disabled MIT's research program. During the entire decade, the Institute received only two grants, and the Rockefeller Foundation turned down an approach from the MIT President on the grounds that MIT was an engineering school whose chief importance was to industry[87]. In contrast, the Tohoku Faculty of Engineering acquired a large amount of funding from a foundation, *Saitō Hō'onkai*, between 1923 and 1945, which induced first-rate results, including Yagi's own invention of ultra-short wave directional antenna and the research on the ultra high-frequency oscillation using magnetron. As a representative of the Faculty, Yagi led efforts to obtain research funding[88]. Since the mission of the foundation was the promotion of academic research, Yagi's conceptualization of engineering as a science fit with the policy of the fund[89].

The appointment of physicist Karl Compton as MIT' s President in 1930 heralded its transformation into an institution for basic research and interactions between physics and engineering. Ironically, the impetus to transform MIT into a research institution originated with corporate executives in industry. The decision to offer Compton the presidency of MIT, seemingly came from Gerald Swope and Frank Jewett, the presidents of GE and the Bell Telephone Laboratories, respectively. They rejected the former MIT educational idea of mass-producing skilled employees for industry, and demanded that it strengthen its basic research capabilities[90]. With a clear mandate to strengthen basic science, Compton successfully corrected MIT's over-dependence on private industry in the 1930s and transformed it into an internationally prominent institute of basic science[91].

The comparison with MIT shows that the Tohoku University Engineering Faculty held a conspicuous position within the trend to strengthen the research capability of former institutes of professional education. In promoting this cause, the strategy to conceptualize engineering as applied science worked successfully, which enabled the engineering faculty to dedicate themselves to the scientific research of an academic nature, and helped

[86] Geiger 2004, pp. 178-180.

[87] *Ibid.*, p. 180.

[88] Erekutoronikusu Hatten no Ayumi Chōsakai 1998, pp. 18-19.

[89] About *Saitō Hō'onkai*, see Yonezawa and Yoshiba 2010.

[90] Geiger 2004, pp. 181.

[91] See Wildes and Lindgren 1985, pp. 33, 69; Lecuyer 1992.

establish a research center for electrical communication and electronics in Tohoku. The historical features of professional education unique to Japan, e.g., the Japanese Imperial University's incorporation of engineering from the start and its legal status as a place for research, justified his encouragement of engineering research; his promotion of research even helped him acquire funding. The Japanese university held a historically unique position, and Yagi adroitly made use of it.

4 Conclusion

As Head of the Faculty of Engineering at Tohoku Imperial University, Yagi promoted "engineering research" which meant applied-scientific research with the purpose of invention. The concept *engineering* was both a *science* and *application* of science for him. This conceptualization helped him justify conducting scientific or mathematical research within Imperial University's faculty of engineering, and call for autonomy from technology and science.

As Tetsu Hiroshige, a distinguished Japanese historian of science, argued in his classic, it is a fallacy to see Japanese history of science and technology as a process of catching up to the West, at least from the institutional perspective[92]. The development of the Japanese research and development system was in lockstep with other Western powers, because they all shared similar historical circumstances like the rise of science-based technology, which increased the need for basic research, especially as of WWI. The discourse that Yagi deployed to promote *engineering research* should, therefore, be understood in this broader context.

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