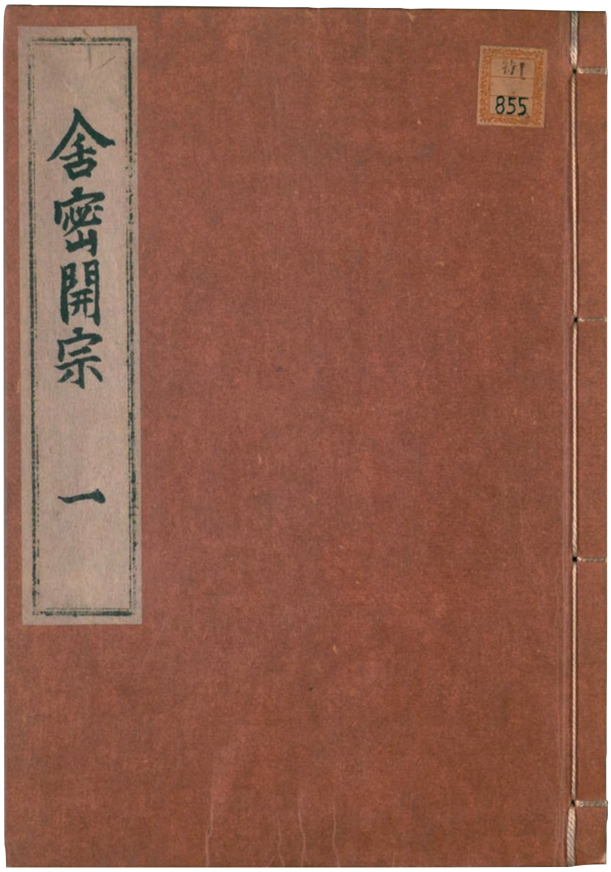
A History of Chemistry in Japan 1820-1955



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THE HISTORY OF chemistry in Japan is a chronicle of how Japanese learned Western chemistry and contributed to its further development.[2] The Meiji Restoration in 1868 is often credited as the starting point of Japan's introduction to Western science. In fact, Japanese encounter with chemistry started earlier, in the early nineteenth century during the Tokugawa period (1603-1868). Medical doctors took the lead in the reception of chemistry because of their interest in the medicinal properties of chemicals. The development of manufacturing and military industries such as mining and smelting, pottery, brewing, dyeing, photography, and gunpowder manufacturing further stimulated Japanese interest in chemistry. Historical developments of chemistry in Japan thus reflected the process of Japanese modernization and industrialization that eventually led to its prosperity in the twentieth century.[3]

Translations and Chemistry in Tokugawa Japan

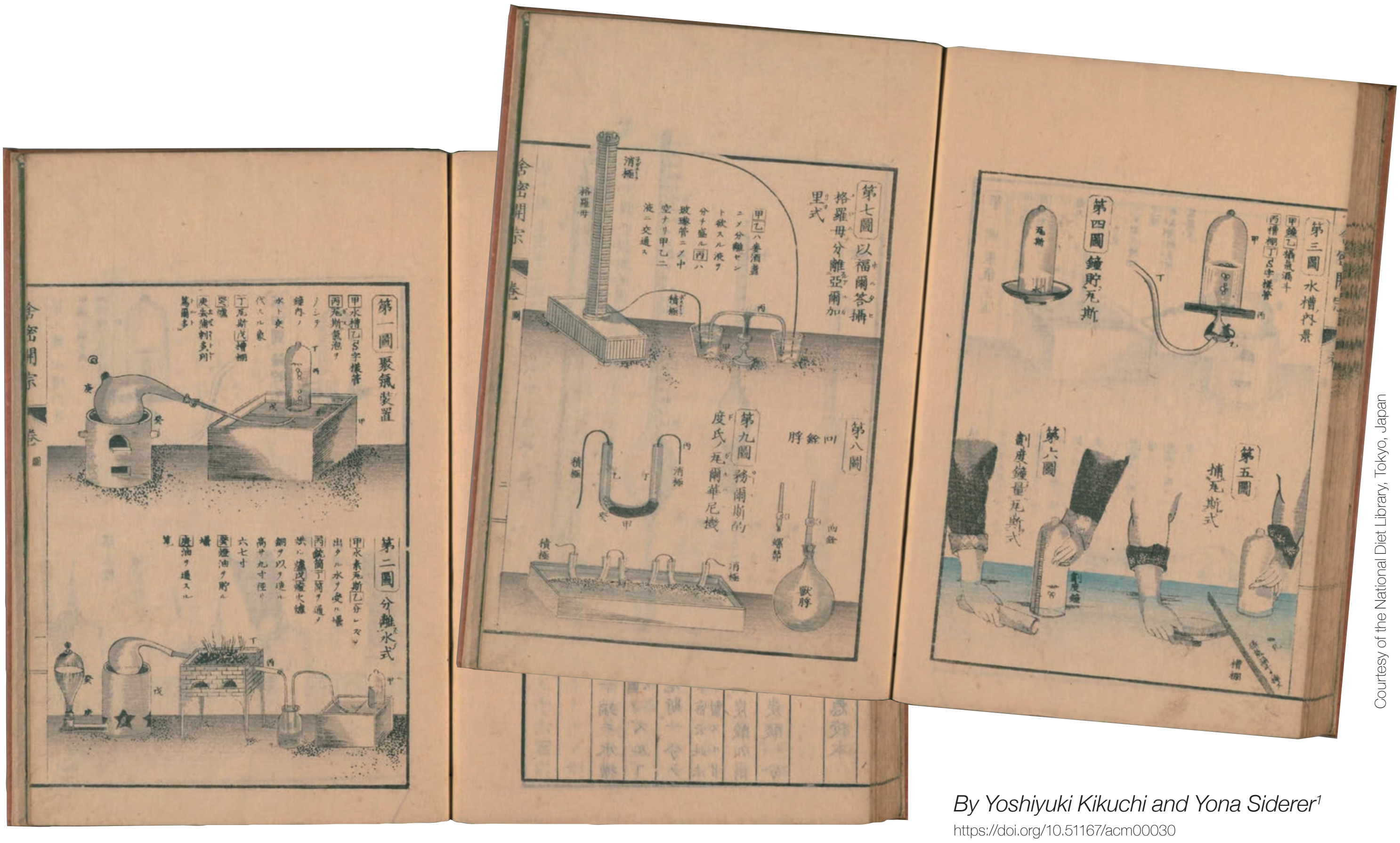
In most of the Tokugawa period, the only Western country with which Japan had trade relationships was the Netherlands.[4] Foreign traders were required to live in Dejima, an artificial fan-shaped island on the Nagasaki Bay. Overseas travel of common Japanese was strictly forbidden. For those reasons, until the mid-nineteenth century Japanese intellectuals studied Western science through translating Dutch books, hence the term "Dutch learning" (*rangaku*) for Western scholarship practiced in Tokugawa Japan.[5]

Pioneers in Dutch learning were mainly medical doctors by profession. The two most famous of them, Maeno Ryōtaku 前野良澤 (1723-1803) and Sugita Genpaku 杉田玄白 (1733-1817), were both physicians serving daimyos (feudal lords). They translated a Dutch illustrated book of anatomy, itself a translation from German, and published it as the *Kaitai shinsho* ("New book on anatomy") in 1774.[6] Medical doctors practicing Dutch learning started to pay attention to chemistry in the 1820s, copying and translating textbooks of chemistry as well as chapters on chemistry in pharmacopoeia in Dutch into Japanese. The culmination of this trend was the publication between 1837 and 1847 of the massive 21-volume *Seimi kaisō* ("Introduction to chemistry") by Udagawa Yōan 宇田川榕菴 (1798-1846).

Udagawa Yōan: The Creator of Chemical Nomenclature in Japanese

Udagawa was a talented scholar who touched many topics during his lifetime. His work might be divided into three main categories: 1. Botany, 2. Chemistry, 3. Variety of other topics. He was a medical doctor serving the daimyo of the Tsuyama Domain in today's Okayama Prefecture.[7]

In his youth, Udagawa studied Chinese Classics in the house of his teacher and adoptive father, Genshin. In 1826 Udagawa joined the translation office of the Tokugawa Shogunate, *Bansho Wage Goyō* that was established in 1811. He could choose appropriate Chinese-Japanese characters to transfer the meaning of words from Dutch to Japanese. For the new ideas in chemistry, he tried to choose characters that would not have the connotation of, and would distinguish the terms from, Confucian thought on nature. Udagawa studied foreign languages, first



Courtesy of the National Diet Library, Tokyo, Japan

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Dutch, to some level German, even Latin and Greek, English, Russian, and copied a list of Arabic letters.

Figure 1. Udagawa Yōan.

Courtesy of the Kyō-U Library, Takeda Science Foundation

Published from 1837 to 1847, Udagawa Yōan's *Seimi kaisō* is considered the first extensive book on chemistry in Japan. It includes seven books; each is divided into three volumes and numbered chapters. Six books are considered inner, main text; the seventh book is called an external book. Altogether it has more than 1100 pages, printed in kanji and katakana, including drawings of tools for chemical experiments (see the drawings above).

In *Seimi kaiso,* Udagawa dealt with topics such as chemical affinity, solution, caloric, alkali, salts, phosphoric acid, ammonia, oxidation and reductions of metals, glass, and constituents of plants. He studied the ingredients of water in hot springs in Japan and described chemical ingredients of hot springs in foreign countries.[8] He cited fifty-eight elements, and five of them were found to be mistakes, among which are caloric and light.[9] The chemistry studies that Udagawa started continued after him, and some of the chemistry terms that he coined are still in use today.[10]

Where did those foreign books come from? A thorough survey in archives was carried out by J. MacLean, searching for the years 1712-1854. He studied the records of the Dutch Factory in Japan, preserved in the *Rijksarchief* (State Archive) in The Hague. MacLean listed the year that a ship arrived in Japan, its name, its captain's name, and the scientific instruments and books that were imported;[11] Udagawa Yōan might have had access to some of those books and instruments.

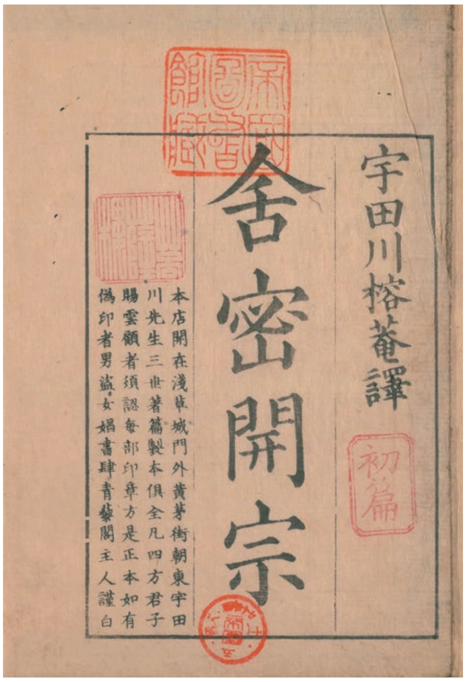

Figure 2. Title Page of *Seimi kaisō,* Book 1, First volume.

Courtesy of the National Diet Library

Seimi kaisō is based on more than 24 chemistry books from Europe of the late eighteenth and early nineteenth centuries, including William Henry (1774-1836), A. L. Lavoisier (1743-1794), and Adolph Ypey (1749-1822).[12] A partial list of authors that Yōan mentions in the first book of *Seimi kaisō* includes: P. J. Kasteleyn, (1746-1794), J. F. Blumenbach, (1752-1840), J.J Plenck, (1735–1807) G. Niewenhuis, L. B. Guiton de Morveau (1737-1816), J.B. Trommsdorff, (1770-1837), O. Ségur (1779-1818), Dutch Pharmacopeaia 1826, and Catz Smallenburg. Udagawa studied other contemporary European authors who were cited in the books that he had, e.g., Berzelius (1779-1848), Davy (1778-1829), Dulong (1785-1838), Gay-Lussac (1778-1850) and others.[13] He actually considered and chose which text and authors to cite.

In 1975 Udagawa Yōan's *Seimi kaisō* was translated into modern Japanese with translators' commentaries. The translation is written in kanji, hiragana, and katakana. The editor who contributed a preface is Tanaka Minoru, and five Japanese scholars joined in this important project.[14] In 2014 Endō Shōji and his colleagues published *Studies on Udagawa Yōan's Botanical Works housed in the Kyō-U Library, Takeda Science Foundation.*[15] These two research books are excellent sources for further research of Udagawa Yōan. Udagawa's successful pioneering of chemistry translation and terminology served as a milestone on the road towards Japanese modernization.

Seimi or *kagaku*? Chemistry in Tokugawa Japan after Udagawa

As discussed above, Udagawa Yōan coined a variety of chemical terms still used today, but arguably the most important of his coinage eventually became obsolete: *seimi* 舎密, meaning chemistry, included in the title of his opus magnum.[16] It was the transliteration of a Dutch word for chemistry, *chemie,* and was widely used as such until the early Meiji period.

Another term for chemistry, *kagaku* 化學 ("the study of change") was first used in Japan by Kawamoto Kōmin 川本幸民 (1810-71). Being aware of the emergence of a Chinese term for chemistry, *huaxue* 化學, in the 1850s, Kawamoto adopted the Japanese reading of *huaxue*, *kagaku*, as part of the title of his chemistry books. The most well-known of Kawamoto's works, *Kagaku shinsho* ("A new book of chemistry," 1861) is a Japanese translation from the Dutch translation of *Die Schule der Chemie* (1846) by Julius Adolph Stöckhardt (1809-86). Through *Kagaku shinsho* he updated Japanese chemistry by transmitting Dalton's chemical atomism with the stoichiometric concept of atomic weights and equivalents and the electrochemical dualism of Berzelius.

The fact that Kawamoto worked at the Tokugawa Shogunate's *Bansho Shirabesho* ("Institute for the Study of Barbarian Books") from its establishment in 1856 was an important factor in *kagaku* becoming the current Japanese term for chemistry. That did not happen overnight. When a section of the *Bansho Shirabesho* devoted to chemistry was established in 1860, it was named the *Seiren kata* ("Department of Refining"). The Seiren kata assumed the new name *Kagaku kata* ("Department of Chemistry") in 1865, indicating that *kagaku* established itself as the term for chemistry in this institution around this year.

The *Bansho Shirabesho* (renamed the *Yōsho Shirabesho* in 1860 and *Kaiseijo* in 1865) was one of the antecedent schools of Tokyo University, established in 1877,[17] and Tokyo Imperial University, established in 1886.[18] Former professors and students at the *Kaiseijo* dominated Japanese education mostly as university administrators and education officials in the early Meiji period, ensuring that *kagaku* became a wide-spread translation for chemistry by the mid-Meiji period.

Kawamoto was also a good example of how Western chemistry got related to Japanese industrialization in the 1850s and 1860s.[19] His first chemical work, *Heika sudoku seimi shingen* ("A true foundation of chemistry that military officers should read") in 1856, was translated from the Dutch translation of Moritz Meyer's *Grundzüge der Militair-Chemie* (1834) with a strong emphasis on combustion and gunpowder and was widely used in Japan as a textbook of chemistry for training in Western-style artillery. Kawamoto was also involved with the production of matches, beer, telegraphs, and photographs with his extensive knowledge of chemistry and physics. By the 1860s Western chemistry became an essential part of the Japanese endeavor for industrialization for both military and peaceful purposes.

Institutionalization of Higher Chemical Education in Meiji Japan

Western-style higher education in science and technology, chemistry not the least, was fully established in the Meiji period between 1868 and 1912. As we discussed above in the case of Kawamoto and *kagaku*, there were connections between the pre-Meiji *Kaiseijo* and Tokyo Imperial University, the pillar of early Meiji higher education. The same applies to the *Igakusho* ("The Medical Institute"), another antecedent school of Tokyo Imperial University. However, there were also discontinuities as the scientific and technical education and research at Tokyo University and other institutions created in the Meiji period were undertaken by foreign professors (who taught in Western languages, usually their mother tongues) and their Japanese students.[20,21]

Four institutions, all established in the 1870s, were particularly important for the development of Japanese chemistry and eventually converged into Tokyo Imperial University in the 1880s and early 1890s.

1) The Faculty of Medicine at Tokyo University (successor institution of the *Igakusho* and Tokyo Medical School) became the College of Medicine at Tokyo Imperial University in 1886, including a Department of Pharmacy and a chair in medical chemistry. Chemistry was taught there first by the German, Alexander Langgaard (1847-1917), and later by the Dutch Johan Frederik Eijkman (1851-1915).[22]

2) The Faculty of Science at Tokyo University (successor institution of the *Kaiseijo* and Tokyo Kaisei School) became the College of Science at Tokyo, including the Department of Chemistry. Chemistry was taught there by the British, Robert William Atkinson (1850-1929), the German Georg Hermann Ritter (1827-74), and Frank Fanning Jewett (1844-1926) from the United States.

3) The Imperial College of Engineering, Tokyo, became the core of the College of Engineering, including the Department of Applied Chemistry. Chemistry was taught by the British chemist Edward Divers (1837-1912) who later became professor at the College of Science, Tokyo Imperial University.

4) The Komaba Agricultural School (renamed the Tokyo Agricultural and Forestry School in 1886 by merger with the Tokyo Forestry School) became Tokyo's College of Agriculture in 1890, including a Department of Agricultural Chemistry. Chemistry was taught at Komaba first by the British chemist Edward Kinch (1848-1920) and later by the German, Oskar Kellner (1851-1911).

These four institutions produced the first generation of Japanese chemists who established the first chemical society in Japan, the Tokyo Kagakukai or Tokyo Chemical Society in 1878.[23] It was renamed the Chemical Society of Japan in 1921 and has become the national society for chemistry in Japan. The second imperial university, Kyoto Imperial University, was established in 1897, followed by Tohoku (est. 1907), Kyushu (est. 1911), Hokkaido (est. 1918),[24] Keijō (est. 1924 in today's Seoul, Republic of Korea), Taihoku (est. 1928 in today's Taipei, Republic of China), Osaka (est. 1931), and Nagoya (est. 1939). These nine imperial universities (seven inland and two colonial) and their successor institutions were major, if not the only, players in the history of science in Japan (and in Korea and Taiwan) in the pre-World-War-II and later periods.

Meiji Japan's Practical Chemists in Pharmacy, Industry and Agriculture

Figure 3: Nagai Nagayoshi.
Courtesy of the Ochanomizu University History Museum

As chemistry became an essential part of Japanese industrialization, it is unsurprising that a large number of young talents were drawn to the practical fields of chemistry such as pharmaceutical, industrial and agricultural chemistry. Nagai Nagayoshi 長井長義 (1844-1929), for example, was a pioneering Japanese organic chemist with strong interests in pharmacy. Originally from the Awa Domain in today's Tokushima Prefecture, he was trained first with Dutch medical doctors in Nagasaki and then attended the Tokyo Medical School for a short period. Nagai was then sent to Germany for overseas study and studied organic chemistry at the University of Berlin with August Wilhelm von Hofmann (1818-92) between 1870 and 1884. Back in Japan, Nagai taught at the Department of Pharmacy, College of Medicine, Tokyo Imperial University and made great contributions to pharmaceutical chemistry both by his research (the most important of which was the isolation of ephedrine, the active ingredient of drugs for asthma, from the Chinese herbal medicine *Ephedra vulgaris*) and his involvement with the Pharmaceutical Society of Japan (established in 1880) as its long-term president and a couple of pharmaceutical companies as a technical advisor. In his later life Nagai technically supported indigo dye manufacturers in his native Tokushima Prefecture.[25]

Takamine Jōkichi 高峰譲吉 (1854-1922) was an industrial chemist trained with Edward Divers at the Imperial College of Engineering, Tokyo. After working as an engineer at the Ministry of Agriculture and Commerce, Takamine established the Tokyo Artificial Fertilizer Company and then moved to the United States to establish an independent industrial laboratory. In the United States Takamine first undertook the project of applying Japanese brewing techniques to whiskey brewing and to the development of digestive enzyme marketed as “Taka Diastase.” He is best-known internationally for the crystallization with Uenaka Keizō 上中啓三 (1876-1960), a student of Nagai, and commercialization of adrenaline, a hormone used as a hemostatic and cardiotonic agent.[26]

Figure 4: Takamine Jōkichi

Courtesy of the Science History Institute, Philadelphia

Takamatsu Toyokichi 高松豊吉 (1852-1937) and Nakazawa Iwata 中澤岩太(1858-1943), two alumni of Tokyo University and former students of Atkinson, contributed to the establishment of applied chemistry teaching at the College of Engineering, Tokyo Imperial University.[27] After graduation from Tokyo University, Takamatsu studied with chemists Henry Enfield Roscoe (1833-1915)[28] and Carl Schorlemmer (1834-92), and chemical technologist Watson Smith (1845-1920) at Owens College Manchester (today’s University of Manchester) and with Hofmann at the University of Berlin. Nakazawa used his time abroad mainly inspecting various chemical factories in Germany to observe the actual working of the chemical industry. For Tokyo’s Department of Applied Chemistry, Takamatsu and Nakazawa blended chemical and practical machine-operating components to design a curriculum suited to the training of chemical technologists much needed in the Meiji period. They also gave technical advice to government and private chemical companies in their respective specialties of applied organic chemistry (especially dyeing and dye manufacturing) and inorganic chemistry (especially alkali-acid manufacture and pottery).

Suzuki Umetarō 鈴木梅太郎 (1874-1943) belonged to a later generation of Japanese chemists. He was trained at the College of Agriculture, Tokyo Imperial University with Kozai Yoshinao 古在由直 (1864-1934), Kellner’s student in agricultural chemistry. Kozai became well known for his analysis of soil from rice paddies contaminated by copper-containing streams from nearby Ashio copper mines in Tochigi Prefecture, which caused serious damage to agriculture and fishery.[29] After overseas study with Emil Fischer (1852-1919) at the University of Berlin in 1903-1906, Suzuki was appointed full professor at his alma mater and published in 1911 his discovery of what he called *oryzanin* (today’s Vitamin B) from rice bran, the deficiency of which caused beriberi, a life-threatening disease that especially plagued the Imperial Japanese Army. Suzuki thereafter successfully undertook other practical research projects such as extracting vitamins and other nutrients from natural products and the synthesis of sake, a Japanese alcoholic beverage, mainly at RIKEN, the Institute of Physical and Chemical Research established in 1917 (cf. the next section on Sakurai).[30]

The above paragraphs described only part of many early Japanese contributions to applied chemistry broadly construed. That being said, Japanese chemistry is not all about applied chemistry, and there were also important developments in pure chemistry, or the ideal of chemical research for its own sake, in Japan. Together with Divers, Sakurai Jōji 櫻井錠二 (1858-1939) was responsible for nurturing the idea of pure chemistry in Japan as one of the founding professors of the Department of Chemistry at the College of Science, Tokyo Imperial University.

Sakurai Jōji: Pioneer in Pure Chemistry, Scientific Diplomat, and Institution Builder

Sakurai studied at the Tokyo Kaisei School and its antecedents between 1871 and 1876.[31] As one of his chemistry teachers was Atkinson, a student of Alexander William Williamson (1824-1904) at University College London (UCL), it is natural that Sakurai chose to do overseas study at UCL with Williamson. This choice had a tremendous impact on Sakurai’s character formation as a scholar. First, under the influence of Williamson, Sakurai came to believe that pure science should be at the core of university curricula. According to Williamson, education in pure science would discipline students’ minds and hands through the systematic learning of theoretical principles and by laboratory training. He further argued that these trainings in pure science would provide a sound basis for subsequent employment in a wide variety of science-related fields such as pharmacy, medicine, agriculture, metallurgy, manufacturing and teaching.[32] It is important to note that Williamson and Sakurai’s idea of “pure” science was not detached from the concern of their colleagues in “practical” chemistry outlined in the previous section. It was more about the role of university education and what should be taught there.

Figure 5. Sakurai Jōji.

Courtesy of the Ishikawa Prefectural Museum of History

Second, in starting his career as a “pure” chemist as the founding professor of the Department of Chemistry at the College of Science, Tokyo Imperial University, he chose organic chemistry and the emerging field of physical chemistry as his specialties and promoted physics and mathematics in departmental teaching. Williamson’s own penchant for chemical theories and physical chemistry such as the three-dimensional imaging of molecules, reaction mechanism and thermochemistry revealed itself in his research on Williamson ether synthesis and was reflected in Sakurai’s research interests as well.[33] Sakurai’s research outputs include the modification of Beckmann’s method of measuring molecular weights by the rise in boiling points of solutions and the structural investigation of glycine (glycocol) by means of measuring its electric conductivity, both falling within the realms of organic and physical chemistry.[34]

Amid his busy student life at UCL, Sakurai also enjoyed a cultural life in London, visiting his friends there, reading Victorian novels and poetry, watching Shakespeare's plays, and visiting parliamentary debates. He thereby gained near-native fluency in English and a strong command of French and German and underwent a process of indoctrination into British and more general Western culture, thereby laying the foundation of his later career as a "scientific diplomat." Sakurai frequently became a Japanese representative attending international conferences and participating in the management of international organizations in the twentieth century. For example, he served the International Union of Pure and Applied Chemistry (IUPAC), established in 1919, as a vice-president twice, first in 1923-25 and again in 1928-30.[35] It signifies Japan's surprisingly early entry to international chemistry, and his "diplomacy" played a crucial role in it.

The discussion of Sakurai's life would not be complete without mentioning his outstanding roles as an "institution builder." Scarcity of research opportunities for his students had been a major issue for him since he was appointed professor at Tokyo in the 1880s, and the outbreak of World War I gave him a once-in-a-lifetime opportunity ("a blessing from heaven" according to him) to realize his long-cherished wish to promote scientific research in Japan. Building on Takamine's pioneering activities toward the establishment of a "Nation's Scientific Research Institute" in 1913, Sakurai collaborated with Takamine, Takamatsu and entrepreneur Shibusawa Eiichi 澁澤榮一(1840-1931) to tirelessly advance this cause and became the foremost institution builder for Japanese science between the 1910s and 1930s, creating scientific research organizations such as RIKEN (*Rikagaku Kenkyūsho,* the Institute of Physical and Chemical Research established in 1917) and GAKUSHIN (*Nihon Gakujutsu Shinkōkai*, Japan Society for the Promotion of Science established in 1932).[36] These research institutes and funding bodies immensely benefited the following generations of Japanese chemists, including his own students.

Pure Chemists from Tokyo's Department of Chemistry and their Students

Tokyo's Department of Chemistry under the leadership of Divers and Sakurai produced a sizeable number of pure chemists. Here we introduce only some of the most important students from there, namely: Ikeda Kikunae 池田菊苗 (1864-1936), Katayama Masao 片山正夫 (1877-1961), Ogawa Masataka 小川正孝 (1865-1930), and Majima Rikō 眞島利行 (1874-1962).[37]

Ikeda started his career as a physical chemist. He first studied with Sakurai at Tokyo's Department's Chemistry and later did an overseas study under Wilhelm Ostwald (1853-1932) at the University of Leipzig between 1899 and 1901. Upon returning to Japan, he became full professor at his alma mater and held this position until 1923. Ikeda was also appointed head of the chemistry section of RIKEN when it was established in 1917 and was one of its chief researchers in 1923-1932.

Figure 6: Ikeda Kikunae.
In: Ikeda Kikunae hakushi tsuiokuroku (Tokyo, 1956)

Ikeda's research topics in physical chemistry would be broadly categorized into chemical kinetics (including catalysts) and the theory of solutions,[38] and he was also an active proselytizer for Ostwald's energetics, especially in the educational and philosophical circles in Japan.[39] Today, however, Ikeda is well known internationally first and foremost as the inventor of the flavor enhancer, *l*-monosodium glutamate marketed as *Ajinomoto* and the originator of the umami concept in the science of taste.[40] Just like his mentor Ostwald, who invented his namesake process to turn ammonia into nitric acid, Ikeda is the kind of chemists moving flexibly between pure and applied chemistry.

The most important student of Ikeda in physical chemistry was Sameshima Jitsusaburō 鮫島實三郎 (1890-1973).[41] Graduated from Tokyo's Department of Chemistry in 1914, he originally tackled the research topic of the vapor pressure of binary mixture of solutions under Ikeda's guidance. During overseas study in 1917-21, Sameshima worked with Theodore W. Richards (1868-1928) at Harvard University, Frederick G. Donnan (1870-1956) at UCL, and Heike Kamerlingh-Onnes (1853-1926) at Leiden University. He was then appointed assistant professor at the Department of Chemistry, Faculty of Science, Tohoku Imperial University in 1922. He succeeded Ikeda as professor of physical chemistry at Tokyo's Department of Chemistry in 1925 and stayed in this office until his retirement in 1951.

Publishing the well-received textbook, *Butsuri kagaku jikken hō* ("Experimental Methods in Physical Chemistry") in 1927, Sameshima was a superb experimentalist and worked broadly on the study of physical properties of materials (called *bussei kenkyū* in Japanese), especially in colloid and surface chemistry. His research was centered on gas absorption by porous materials such as charcoal and dehydrated zeolite, which impacted colloid chemist James William McBain (1882-1953) in formulating the concept of "molecular sieve," and the dynamic phenomena of colloids such as the formation of monomolecular film, viscosity, lubricity, and foamability which made him a Japanese pioneer in rheology. Sameshima was succeeded by one of his students, Akamatsu Hideo 赤松秀雄 (1910-88) who published an important research in *Nature* on the electric conductivities of polycyclic aromatic hydrocarbons with his student, Inokuchi Hiroo 井口洋夫 (1927-2014) in 1954 that led to the concept of "organic semiconductor."[42]

Katayama was another chemistry student at Tokyo who chose physical chemistry as his specialty under Sakurai's influence.[43] Graduated from the Department of Chemistry at Tokyo in 1900, Katayama studied overseas at the University of Zurich with Richard Lorenz (1863-1929) and at the University of Berlin, Germany, with Walter Nernst (1864-1941) and Max Bodenstein (1871-1942) between 1905 and 1909. He was appointed the first professor of physical chemistry at the newly established Tohoku Imperial University in Sendai in 1911, succeeded Sakurai as the professor of physical chemistry at Tokyo in 1919 and stayed in this office until his retirement in 1938 with an extra position as chief researcher at RIKEN.

Following Sakurai's pro-atomistic view, Katayama positively adopted atomism as a working hypothesis and published an influential textbook of physical chemistry based on chemical thermodynamics in Japanese, *Kagaku honron* ("Fundamentals of Chemistry") in 1914. Like Sameshima, Katayama specialized in surface and colloid chemistry but chose to do theoretical investigations based on his molecular interpretation of thermodynamics and the quantum theory. His most important research outcome was "Katayama's equation" published in 1916, an equation describing the relationship between the surface tension and temperature of liquids.

Katayama trained quite a few Japanese physical chemists who became internationally known in a variety of fields like colloids, catalysts, and molecular structures. Mizushima San-ichirō 水島三一郎 (1899-1983), for example, first undertook research, while working with Katayama at Tokyo as a student, on the dispersion of radio waves by glycerin and monovalent alcohols to give experimental proofs to the polar molecular theory of organic substances postulated by Dutch physicist Peter Debye (1884-1966).[44] With his student-day research recognized, Mizushima was appointed assistant professor at Tokyo's Department of Chemistry in 1927 and then traveled to Europe to work at the University of Leipzig with Debye himself in 1929-31. While in Germany he learned quantum mechanics first-hand from Debye and became one of the first Japanese chemists who introduced quantum mechanics to Japan in the 1930s.[45]

Upon returning to Tokyo Imperial University, Mizushima started with his student, Morino Yonezō 森野米三 (1908-95), a path-breaking research in conformational analysis, coining around 1940 the "gauche" form for a conformation where two vicinal groups are separated by a 60-degree torsion angle. This research was made possible by Mizushima's additional post from 1934 as chief researcher at RIKEN and his promotion to full professorship in 1938 as the successor of Katayama. His "gauche" research garnered him an international reputation and brought him a scholarly network with first-class colleagues in physical chemistry such as the two-time Nobel laureate Linus Pauling (1901-1994). Mizushima's work as a bureau member of the IUPAC in 1955-67 would not have been possible without his growing reputation and international network. One of Mizushima's students, Nagakura Saburō 長倉三郎 (1920-2020) developed the intermolecular charge-transfer theory of chemical reactions postulated by his American teacher, Robert S. Mulliken (1896-1986), starting with the publication of two papers in the *Journal of Chemical Physics* and the *Journal of the American Chemical Society* in 1955. Nagakura became a leading figure in postwar Japanese physical chemistry together with Akamatsu, Inokuchi, Morino, and Fukui Kenichi (cf. the section on the Kyoto school and the first Japanese Nobel Laureate in Chemistry below).[46]

Ogawa Masataka was first trained as an inorganic chemist and honed his analytical skills with Divers at Tokyo.[47] Ogawa then studied overseas in 1904-1906 with William Ramsay (1852-1916) at UCL and encountered his life-long research project on a new element by means of analyzing the newfound mineral, thorianite. After getting back to Japan, he continued the same project with another mineral, molybdenite, and announced the discovery of element 43, naming "Nipponium" (Np) in 1908 after the name of his country, Nippon 日本.

Ogawa was appointed professor at the Tohoku Imperial University in 1911, and his assistants and students there worked on the Nipponium project, though without success in reproducing Ogawa's result. The discovery of element 43, later named technetium (Tc), in 1937 meant that Ogawa's research was in the wrong. Recent reassessments of Ogawa's work by chemist historian Yoshihara Kenji, however, claimed that Ogawa did discover a new element but that it was not the 43rd element as he had claimed but the 75th element, today's rhenium (Rh). He is now considered in Japan as a great pioneer in searching new elements in his country, especially in the wake of the successful synthesis of the transuranium element of atomic number 113 in 2004 by RIKEN researchers. Their proposed name, *nihonium* (Nh) (after another reading of the country name, Nihon 日本), was approved by the IUPAC in November 2016.

Figure 7: Ogawa Masataka.
Courtesy of the Tohoku University Archives.

Majima Rikō (born Toshiyuki but generally referred to as "Rikō" by himself and his colleagues) majored in organic chemistry at Tokyo and worked with Sakurai, who was originally trained as organic chemist by Williamson.[48] Majima however received little advice from Sakurai and taught largely himself the craft of organic chemical research. He started his first structural research of urushiol, the main component of raw lacquer juice, based on his research strategy to compete with Western chemists by studying Japanese local products with analytical techniques of Western chemistry, taking advantage of the proximity to the localities of these products.

During his overseas study in 1907-1911, Majima worked with Carl Harries (1866-1923) at the University of Kiel and Richard Willstätter (1872-1942) at the Zurich Polytechnic to learn the cutting-edge techniques of organic chemistry such as vacuum distillation, ozonolysis, and catalytic reduction that could be applied to his urushiol project. He was appointed professor (as Ogawa) at Tohoku Imperial University in 1911, completed the urushiol project and established influential research schools in organic and natural product chemistry first at Tohoku and later at RIKEN and other universities such as Osaka Imperial University (est. 1931). In so doing, Majima paid great attention to equipping laboratories with adequate facilities to support experiments with the technique he brought back from Europe. For example, he carefully designed water supply facilities on the Tohoku Imperial University campus in Sendai, where there was no running water yet, to provide enough water pressure to be used for vacuum (reduced pressure) distillation.[49]

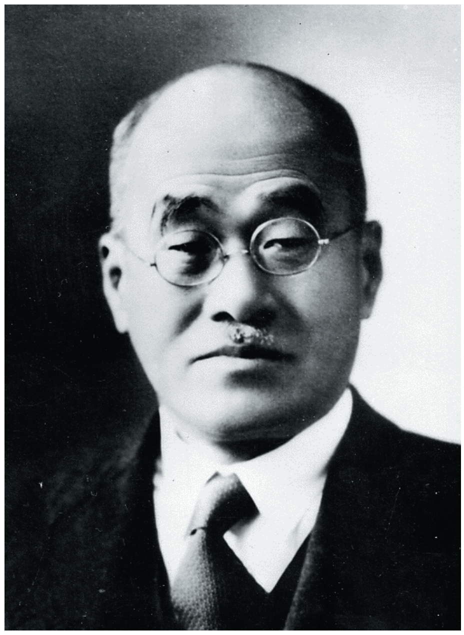

Figure 8: Majima Rikō.
Courtesy of the Tohoku University Archives

Nozoe Tetsuo 野副鐵男 (1902-96), arguably the most important student of Majima, was graduated in 1926 from the Department of Chemistry at Tohoku Imperial University with Majima as his thesis advisor.[50,51] Nozoe moved to the then Japanese colony of Formosa (Taiwan) to take up a research appointment at the Laboratory attached to the Government of the Governor-general of Taiwan in Taipei ("Taihoku" in Japanese) in 1926. He was appointed assistant professor at the newly founded Taihoku Imperial University in 1929 and promoted to a full professorship in 1937. Following in the footstep of his mentor, Nozoe started his research on the structure of hinokitiol, the oil extracted from *Chamaecyparis taiwanensis*, a species of cypress native to Taiwanese mountains in 1935. He confirmed by 1940 that hinokitiol has a seven-member ring structure and yet exhibits aromaticity. After the end of World War II and Taiwan's retrocession to Chinese sovereignty, Nozoe stayed in Taipei until 1948 as the chemistry professor at the National Taiwan University (reorganized from Taihoku Imperial University in 1945). Appointed a chemistry professor of his alma mater, the Department of Chemistry at Tohoku University, in 1948, Nozoe's hinokitiol research gradually became internationally known and made him one of the pioneers of nonbenzenoid aromatic chemistry. Nozoe was a prime example of Majima's research style of tackling local products contributing to the creation of a universal scientific discipline.

Kuroda Chika: Pioneer Woman Chemist in Twentieth Century Japan

An early student of Majima in organic and natural product chemistry at Tohoku, Kuroda Chika 黑田チカ (1884-1968) became a pioneer woman chemist in early Twentieth Century Japan.

Kuroda Chika was born in Saga, Kyushu Island in 1884. Her father, Heihachi, made sure that his children, including his daughters, were well educated. In 1902, aged 18, she entered the Division of Science, Women's Higher Normal School (Joshi Kōtō Shihan Gakkō or Jokōshi), where she graduated in 1906. She was invited as a teacher to Fukui Normal School where she spent one year, training teachers. In 1907-1909 she completed the graduate course at the Women's Higher Normal School and became assistant professor at Tokyo Women's Higher Normal School.[52]

Kuroda was one of the first two women who studied at the recently established Tohoku Imperial University in Sendai, north of Tokyo. In 1913 she passed the entrance examination after Nagai, who was a champion of women's education in Japan, recommended that she apply. A director at the Ministry of Education sent a critical letter to the president of Tohoku Imperial University against letting women start their education there, pointing out that it had not happened previously. However, Kuroda Chika was allowed to continue her studies and graduated in 1916.[53]

It is important to note here that the issue of hindrance of women participation in science was not unique to Japan.[54] Studies on women in science in Japan and the global context of this issue were published by Otsubo Sumiko,[55] Kodate Kashiko and Kodate Naonori,[56] and Ogawa Mariko.[57] An introductory Japanese book on the history of chemistry includes a chapter on gender and the history of chemistry featuring Marie-Anne Lavoisier (1758-1936), Marie Curie (1867-1934), and Kuroda.[58] Kuroda's case is therefore a part of the long-term and worldwide phenomenon awaiting full scrutiny.

The study of natural dyes had a long history in Japan.[59] Majima Rikō, who started modern organic chemistry studies in Japan, focused on plants; Kuroda Chika, his student, continued and deepened the chemical studies of plant dyes.[60] In 1918 she was the first woman to publish the results of her research "On the Pigment of Purple Root," an important fabric-dyeing material, and presented her findings in front of the assembly of Tokyo Chemical Society.[61] In 1918 she became a full professor at Tokyo Women's Higher Normal School.

Figure 9. Kuroda Chika at RIKEN, 1924.

Kindly provided and permitted to use by Ochanomizu University History Museum.

During 1921-1923 Kuroda was at Oxford University in England, sent there by the Ministry of Education, and continued research work in the laboratory of William Henry Perkin Jr. (1860-1929), with a letter of recommendation from Sakurai who had been acquainted with Perkin.[62] In her memories she tells how she enjoyed her time in Oxford and the Perkin family's hospitality. During summer vacation she traveled to Switzerland, climbed the Jungfrau Mountain, and visited Italy.

After returning to Japan Kuroda reentered Tokyo Women's Higher Normal School. However, the earthquake of September 1923 destroyed the buildings of that school. Majima offered her a commissioned position in the recently established RIKEN, the Institute of Physical and Chemical Research founded in 1917. There Kuroda continued her research and published her research results titled "About the structure of safflower pigment" (1929) that was her doctoral thesis. In 1929, at 45 years old Kuroda Chika received the title Doctor of Science (D.Sc.) from Tohoku Imperial University. She received the first Majima Award from the Chemical Society of Japan in 1936. In 1949 Kuroda Chika became professor of the newly established Ochanomizu University, formerly Jokōshi.

In dozens of articles, she described detailed processes for isolation, crystallization, as well as synthesis, and determination of the structure of the dyes extracted from plants and a sea animal that were traditionally used in Japan. In 1936 she concluded that many of those substances were derivatives of anthocyanin. Robert Robinson (1886-1975), Nobel chemistry laureate in 1947, cited her research in 1955.[63] In her memoirs written in 1957 Kuroda acknowledged and included photos of those scientists from whom she learned: Majima, W. H. Perkin Jr., Arthur George Perkin (1861-1937, Perkin Jr.'s younger brother) and Robinson. It should be realized that Kuroda Chika's research and achievements were on topics similar to those of the leading organic chemists in England, though there was far less support for laboratory facilities in Japan, and less recognition of her work. She continued part time research and teaching as a professor emeritus after her retirement in 1952.

Kuroda Chika started her memoirs by writing "Since I've learned about the endless world of academic study and the joy of walking that path, I was just drawn to the joy of discovering something I hadn't seen yet; and before I knew it, I had reached the age of 72. I am grateful that I still have enough energy to continue my research.

At the end of last year, the research on substances in onion skin that act against high blood pressure which I had been working on for a long time, finally came to fruition, and it was made the blood pressure medicine 'Keltin C'; I am incredibly happy that it will be useful to many people, it will be my honor."[64]

In 1959 (aged 75) Kuroda Chika received the Medal with Purple Ribbon and in 1965 she received the Order of the Precious Crown. Together with her friend the first woman biologist Yasui Kono 保井コノ (1880 –1971) they established a prize for young students that is awarded annually. Kuroda Chika died in Fukuoka City in Kyushu on 8 November 1968 at 84 years of age. Her memory is cherished in Japan as a pioneering woman chemist.

The "Kyoto School" and the First Japanese Nobel Laureate in Chemistry

This short article on the history of chemistry in Japan ends with Fukui Kenichi 福井謙一 (1918-98), who became the first Japanese Nobel Laureate in Chemistry in 1981 for his pathbreaking quantum mechanical theory on the course of chemical reactions, the frontier orbital theory. An interesting point about his career and work is that, despite the highly theoretical character of his research, Fukui was trained at and affiliated to the Faculty of Engineering, not Science, of Kyoto (Imperial)[65] University. This is best understood by considering the fact that Fukui was a member of the "Kyoto school" of chemistry, established by industrial chemist Kita Gen-itsu 喜多源逸 (1883-1952) and thoroughly studied by historian of chemistry Furukawa Yasu, on whose works this section is based.[66] The Kyoto school epitomized how the traditions of pure and applied chemistry in Japan, outlined above, converged in the twentieth century.

Kita was born in Nara Prefecture and graduated from the Department of Applied Chemistry, College of Engineering, Tokyo Imperial University in 1906.[67] His original research field was fermentation, especially the chemistry of enzymes, and was appointed assistant professor in 1908 at his alma mater. In spite of his seemingly smooth career development, Kita was not happy at Tokyo because of the discrepancy between his own philosophy and the teaching policy of Tokyo's Department of Applied Chemistry. Whereas Kita believed that industrial chemists should thoroughly understand the basics of pure chemistry and have the ability to do basic research, the chemical component in applied chemistry teaching at Tokyo was diluted, so to speak, as Takamatsu and Nakazawa blended chemical and practical machine-operating aspects of the chemical industry to design a curriculum suited to the training of chemical technologists (cf. the previous section on Meiji Japan's practical chemists).

Kita's move in 1916 to the Department of Industrial Chemistry, Faculty of Engineering, Kyoto Imperial University, together with his research appointment at the RIKEN in 1917 (most probably based on a recommendation from Sakurai), opened the way to realize his ideal. His experience of working at the Massachusetts Institute of Technology (MIT) with Arthur Amos Noyes (1866-1936) during his overseas study in 1918-1921 reaffirmed his conviction and arguably taught him the relevance of physics and mathematics to chemistry, for Noyes was a physical chemist and a vocal advocate of the importance of basic scientific education and research in an engineering school.[68] Kita also probably learned from what Noyes' rival at MIT, industrial chemist William H. Walker (1869-1964), was doing to establish a Department of Chemical Engineering in 1922: Kita brought teaching materials about the unit operation, the key concept of chemical engineering, from MIT to Kyoto.[69]

Once he resumed his teaching at Kyoto and was promoted to full professor in 1921, Kita moved quickly to realize his vision of "To aim at the application, study the basic." The first is the curricular reform to lay more emphasis on basic scientific subjects like inorganic, organic and physical chemistry, mathematics, and theoretical physics. In so doing, Kita enabled students of the Department of Industrial Chemistry to enroll in scientific courses of Kyoto's Faculty of Science,[70] including the Department of Chemistry, by working closely with professors there. One of the chemistry professors of Kyoto's Department of Chemistry then was physical chemist Horiba Shinkichi 堀場信吉 (1886-1968). A graduate from the Department of Chemistry at Kyoto in 1910 taught by Ōsaka Yūkichi 大幸勇吉 (1867-1950), another student of Sakurai and Ostwald, Horiba was appointed assistant professor in 1913 and full professor in 1924 at Kyoto's Department of Chemistry.

Horiba pursued research on the rates of a variety of reactions using the thermal analysis method and built a research tradition in chemical kinetics at Kyoto and indeed the whole field of physical chemistry. His leading position in physical chemistry in Japan is exemplified by Horiba's editorship (co-editorship with Sameshima at Tokyo from 1939) of *Butsuri kagaku no shimpo* ("Review of Physical Chemistry of Japan") launched in 1926 by the Horiba laboratory at Kyoto.[71] From the Horiba school emerged quite a few kineticists of international standing. Ree Taikyue 李泰圭 (Ri Taikei in Japanese reading, 1902-92), of the "Ree-Eyring theory" (1955) fame, played a pioneering role in Japan, as well as in his native Korea after World War II, in introducing quantum chemistry into chemical kinetics.[72] Satō Shin 佐藤伸 (b. 1928), a student of Horiba's student Shida Shōji 志田正二 (1912-2001) who taught at the Tokyo Institute of Technology, published in 1955 a substantial modification of the London-Eyring-Polanyi (LEP) method[73] of calculating the potential energy reaction surface of bimolecular systems based on a simplified quantum mechanical equation (the London equation), which is now recognized as the LEPS method.[74]

Simultaneously with departmental curricular reforms, Kita established a research school encompassing fermentation (his original research field), textile, fuel, and rubber. This broadening of his research horizon reflected Kita's growing sense of mission to contribute to Japan's "autarky" in the 1930s and 1940s in the context of Japan's worsening international relations leading to the outbreak of the Second Sino-Japanese War in 1937 and the Pacific War in 1941. In this process Kita attracted various talents. Sakurada Ichirō 櫻田一郎 (1904-86), for example, was sent by Kita to Germany and spent two years in 1929-1931 with Kurt Hess (1888-1961), who was a cellulose chemist and the main opponent of the macromolecular theory of polymers postulated by Hermann Staudinger (1881-65).[75] Sakurada first joined the polymer controversy in his mentor's favor but later converted to the macromolecular theory and became a pioneer in polymer and textile chemistry in Japan. Sakurada invented Japan's first synthetic fiber, vinylon, with Korean chemist Ri Sung-gi 李升基 (Ri Shōki in Japanese reading, 1905-96) and many other collaborators in 1939.[76]

Kodama Shinjirō 兒玉信次郎 (1906-96), the most loyal supporter of Kita's vision, was an industrial chemist with working experiences in chemical factories. He was sent by Kita to Germany and worked with Michael Polanyi (1891-1976) on research in chemical kinetics and learned quantum mechanics in 1930-1932. Through these experiences Kodama turned his mentor's vision into a concrete research methodology, i.e. solving technical problems "first by theories as much as possible and then by experimental measuring if no theory is available for them."[77] Kita and Kodama were also aware of the needs to turn their laboratory findings into factory products. They put a considerable effort to solving the chemical engineering problem of scaling-up in the pilot study of synthetic petroleum production by the Fischer-Tropsch process before moving to the factory scale during World War II.[78] These developments were recognized with the establishment of the Department of Fuel Chemistry in 1939 and the Department of Textile Chemistry in 1941, both at Kyoto's Faculty of Engineering.

Fukui Kenichi was another talent attracted to Kita's vision of "To aim at the application, study the basic" and quite literally a product of the Kyoto school without any experience in overseas study.[79] A distant relative of Kita coming from the same Nara Prefecture, Fukui chose chemistry as his major and entered the Department of Industrial Chemistry, Faculty of Engineering at Kyoto in 1938 following Kita's advice that "if you are good at mathematics, study chemistry." Considering quantum mechanics as the basis of chemistry and the best tool to "mathematize" it, he spent much time in his undergraduate days teaching himself quantum mechanics by reading library holdings at Kyoto's Department of Physics. Fukui later deepened his knowledge of quantum mechanics with Kodama, Fukui's supervisor at the graduate school, who had brought many up-to-date reading materials on quantum mechanics and statistical thermodynamics from Germany.

Figure 10. Fukui Kenichi

In: Yamabe, Tokio (ed.) (1982). Nōberu shō kagakusha Fukui Ken-ichi: Kagaku to watashi (Kyoto: Kagaku Dōjin). Courtesy of the publisher, ***Kagaku Dōjin***

Another key to Fukui's success as quantum chemist was his familiarity with the reactions of hydrocarbons, both theoretically and experimentally. That he gained from his undergraduate thesis advisor and later colleague at the Department of Fuel Chemistry, synthetic organic chemist Shingū Haruo 新宮春男 (1913-88) and from his wartime research experience at the Army's Fuel Research Institute in 1941-45. Fukui was appointed lecturer in 1943 and assistant professor in 1945 at Kyoto's Department of Fuel Chemistry while retaining his military affiliation and got back to his full-time teaching position at Kyoto after the end of World War II. In spite of its strong military connotations, the Department of Fuel Chemistry at Kyoto was allowed to keep this name after the war due to the strenuous effort of Kodama, who redefined the mission of the department as the postwar economic reconstruction of the country by means of science-based technology (it was renamed the Department of Petroleum Chemistry in 1966).[80]

Fukui's first postwar research project was for his doctorate, awarded in 1948, and supervised by Kodama. Titled "the theoretical investigation of temperature distribution within industrial research apparatuses," his thesis was a highly mathematical treatment of the chemical engineering problem that Kodama had encountered while he was working at a chemical factory. Now with a doctorate, his own laboratory, and students, and being promoted to full professorship in 1951, Fukui was in a good position to start something new. It is much owing to the intense discussion with Shingū, and Shingū's vocal critique of the then influential electronic theory of organic chemistry postulated by Robinson and Christopher Kelk Ingold (1893-1970), that Fukui formulated the "Frontier Orbital Theory" of organic reactions in 1951. He published its first paper in 1952 with his student Yonezawa Teijirō 米澤貞次郎 (1923-2008), and with Shingū as its authors in the *Journal of Chemical Physics*, followed by the second paper published in the same journal in 1954. Electrons occupying the highest occupied molecular orbital (HOMO), which play the essential role in Fukui's theory together with the lowest unoccupied molecular orbital (LUMO) to explain the course of substitution reactions of hydrocarbons, was originally named "frontier electrons" at Shingū's suggestion.

Fukui's frontier orbital theory was thus born at the intersection of pure science, quantum chemistry, on the one hand, and applied science, fuel chemistry, on the other. This is in stark contrast with the research trajectories of another pioneer in quantum chemistry in Japan, Mizushima San-ichirō (cf. the previous section on pure chemists from Tokyo's Department of Chemistry), which were focused on molecular structures, not reactions. Fukui's interests in chemical reactions likely came partly from Kyoto's research traditions in chemical kinetics but mainly from industrial needs to elucidate and control reactions, which mattered less to Mizushima. Fukui succeeded because of, not in spite of, his training at and affiliation to an engineering faculty, albeit of a peculiar kind.

Towards Postwar Japanese Chemistry

The aim of this article was to outline the history of chemistry in Japan in the context of its modernization, industrialization, and other historical events such as two world wars. Our choice of historical actors and cases inevitably depended on our expertise as historians, meaning that we could only cover part of the postwar period of the twentieth century. That being said, it does suggest that many of the Japanese chemists we have discussed contributed to the development of Japanese chemistry whose level was approaching the international standard in the 1950s. A couple of indicators point to the coming-of-age of Japanese chemistry by the mid-1960s.[81] One such indicator is the international conferences, symposia and seminars held in Japan: The IUPAC International Symposium on Molecular Structure and Spectroscopy held in Tokyo in 1962, in which Mizushima, Nagakura and the successor of Mizushima at Tokyo, Shimanouchi Takehiko 島内武彦 (1816-1980), were involved;[82] The Third IUPAC Symposium on the Chemistry of Natural Products held in Kyoto in 1964;[83,84] and the First Japan-US Science Seminar in physical organic chemistry co-organized by Nozoe and the American physical organic chemist, John D. Roberts (1918-2016) and held in 1965 in Kyoto.[85] As we hope to have shown here, the dynamic balance between pure and applied chemistry and internal and external forces affected the historical development of chemistry in Japan that led to its prosperity in the latter half of the twentieth century, producing seven more Nobel laureates in chemistry following Fukui to this date, overcoming difficulties of scientists from East Asia in receiving this prize.[86] ◆

Acknowledgments (Kikuchi)

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References

1. To clarify each co-author's responsibilities: Siderer contributed the sections "Udagawa Yōan: The Creator of Cchemical Nomenclature in Japanese" and "Kuroda Chika: Pioneer Woman Chemist in Twentieth Century Japan," and Kikuchi contributed the other sections of the article. The two co-authors collaborated with each other in editing and proofreading the whole article.
2. In what follows (except in "Acknowledgments"), Japanese names are rendered in the original order, i.e., family names followed by persons' names. It should also be noted that, from their second appearance, Japanese persons are referred to by their family names such as Udagawa, Kawamoto, and Sakurai (instead of Yōan, Kōmin and Jōji) unless full names are given. Macrons are used in Japanese long vowels except in some geographical names such as Tokyo (*Tōkyō*), Kyoto (*Kyōto*), Osaka (*Ōsaka*), Tohoku (*Tōhoku*), and Hokkaido (*Hokkaidō*).
3. The history of chemistry in Japan has also been briefly discussed in: Furukawa, Y. (2021). Exploring the History of Chemistry in Japan. Ambix, *68*, 302-317, on 11-16. N. Koertge (ed.), *New Dictionary of Scientific Biography* (*NDSB*), 8 vols. (Detroit, Mich.: Charles Scribner's Sons/ Thomas Gale, 2008) is an essential reference tool for anyone interested in the history of twentieth-century science. The *NDSB* includes the entries of the following four Japanese chemists: Fukui Ken-ichi (by James R Bartholomew, vol. 2, pp. 85-89), Mizushima San-ichirō (by Yoshiyuki Kikuchi, vol. 5, pp. 207-211), Nozoe Tetsuo (by Masanori Kaji, vol. 5, pp. 287-293), and Sakurada Ichirō (by Yasu Furukawa, vol. 6, pp. 330-335). This article discusses all of them in later sections.
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17. Historically and in current usage, the official translation of *Tokyo Daigaku* has been "The University of Tokyo," even

though the early Meiji *Tokyo Daigaku* (mentioned here) and today's *Tokyo Daigaku* are different institutions: the former is just one of the antecedent schools of the latter, the successor institution of Tokyo Imperial University. For this reason, the early Meiji *Tokyo Daigaku* is translated as "Tokyo University" in this article to distinguish it from the current University of Tokyo.
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37. Shibata Yūji 柴田雄次 (1882-1980) was another graduate from Tokyo's Department of Chemistry who played an important role in chemistry in Japan. Trained first as an organic chemist and then converted to inorganic chemistry, Shibata was appointed assistant professor in 1913 and promoted to full professorship in 1919 at his alma mater, and undertook research projects and trained chemists in coordination chemistry and a variety of other fields: biochemistry; geochemistry; and conservation science. See: Tanaka, M. (1975). Nihon no kagaku to Shibata Yūji [Japanese Chemistry and Shibata Yūji] (Tokyo: Dai Nihon Tosho).
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39. Kikuchi, Y. (2018a). Ikeda Kikunae and Reactions to Energetics in Japan. Historia Scientiarum, *28*, 54-68. "Energetics" is the scientific and intellectual movement in the late nineteenth century that attempted at explaining natural as well as social and cultural phenomena only with reference to the concept of energy, of which Ostwald as the main advocate. See: Deltete, R. J. (2007). Wilhelm Ostwald's Energetics 1: Origins and Motivations. Foundations of Chemistry, *9*, 3-56. The antonym of "energetics" is "atomistics" advocated by Austrian physicist Ludwig Boltzmann (1844-1906).
40. Hirota, K. (1994). Kagakusha Ikeda Kikunae: Sōseki, Umami, Doitsu [The Chemist Ikeda Kikunae: Natsume Sōseki, Umami, Germany] (Tokyo: Tokyo Kagaku Dōjin).
41. Tachibana, T. (1979). Sameshima Jitsusaburō no gyōseki mokuroku to sono kaisetsu [List of publications by Sameshima Jitsusaburō with commentaries]. Kagakushi, (9), 23-36; (10), 39-47.
42. Pope, M. (1994). Professor Hiroo Inokuchi: A pioneer and major contributor to the field of electronic processes in organic materials. Synthetic Metals, ***64***, 109-113. We owe this information to Ms. Mari Yamaguchi.
43. Tamamushi, B. (1978). Kaimen Kagaku eno Michi: Katayama Masao Kyōju Seitan 100- shūnen ni chinande [The Way to Surface Chemistry: In Memory of Centennial birth of Prof. Masao Katayama]. Kagakushi, (8), 1-6.
44. Kikuchi, Y. (2008). Mizushima, San-ichirō. In NDSB (note 3), vol. 5, pp. 207-211. See also: Kikuchi, Y. (2016). San-ichiro Mizushima and the Realignment of the International Relations of Japanese Chemistry. In Kaji, M, Furukawa, Y., Tanaka, H, and Kikuchi, Y. (eds.). The International Workshop on the History of Chemistry 2015 Tokyo (IWHC 2015 Tokyo) "Transformation of Chemistry from the 1920s to the 1960s): Proceedings (Tokyo: Japanese Society for the History of Chemistry), 50-55; and Kikuchi, Y. (2018b). International Relations of the Japanese Chemical Community. In Rasmussen, S. C. (ed.). Igniting the Chemical Ring of Fire: Historical Evolution of the Chemical Communities of the Pacific Rim (Singapore: World Scientific), 139-155.
45. Furukawa, Y. (2017). Kagakusha tachi no Kyoto gakuha: Kita Gen-itsu to Nihon no kagaku [The Kyoto School for Chemists: Kita Gen-itsu and Japanese Chemisttry] (Kyoto: Kyoto Daigaku Gakujutsu Shuppankai), p. 186.
46. Hirota, N. (2016). Robert Mulliken and His Influence on Japanese Physical Chemistry. In Kaji, M, Furukawa, Y., Tanaka, H, and Kikuchi, Y. (eds.) (note 44), 192-199. Nagakura served the IUPAC as the first ever Japanese president in 1981-83. See: Kikuchi, Y. (2019). Pioneers of Japanese Participation in the IUPAC. Chemistry International, *41*, 16-19.
47. Yoshihara, K. (1997a). Glory and Collapse of the Work on Nipponium by Masataka OGAWA (in Japanese). Kagakushi, ***24***, 295-305. English article: Yoshihara, H. K. (1997b). Nipponium, the Element Ascribable to Rhenium from the Modern Chemical Viewpoint. Radiochimica Acta, *77*, 9-13. Outcomes of Yoshihara's subsequent investigations are summarized in: Yoshihara, K. (2019). Sai hakken: Nipponiumu no shinjitsu [Truth about Nipponium rediscovered]. In Kagakushi Gakkai (ed.), Kagakushi eno shōtai (note 16), 26-34. Oppositions to Yoshihara's reassessments are also expressed. See, for example: Nicholson, J. (2021). Who Discovered Rhenium? RSC Historical Group Newsletter, (79), 38-43.
48. Kaji, M. (2011). Majima Rikō to Nihon no yūki kagaku kenkyū dentō no keisei [Majima Rikō and the formation of research traditions in organic chemistry in Japan]. In Kanamori, O. (ed.), Shōwa zenki no kagaku shisōshi [History of Scientific thoughts in early Showa Japan] (Tokyo: Keisō Shobō), 185-241.
49. Majima, R. (1954). Waga shōgai no kaiko (II) [Reminiscences of my life, part II]. Kagaku no ryōiki, ***8***, 137-146, on 137-138.
50. Kaji, M. (2016). The Transformation of Organic Chemistry in Japan: From Majima Riko to the Third International Symposium on the Chemistry of Natural Products. In Kaji, Furukawa, Tanaka, and Kikuchi (eds.) (2016) (note 44), 14-19, on 15-16.
51. Kaji, M. (2018). Development of the Natural Products Chemistry by Tetsuo Nozoe in Taiwan. In Rasmussen (ed.) (note 44), pp. 357-368.
52. Kuroda, K. (2017). Kuroda Chika (1884-1968) (in Japanese). In Kagakushi jiten (note 4), 216-217. "Tokyo" was added to the name of Kuroda's alma mater in 1908 when the second women's higher normal school was established in Nara. "Jokōshi" kept widely used for the Tokyo Women's Higher Normal School.
53. Maeda, K. (2000). Chika Kuroda: Research on the Constitution of Natural coloring Matters and Her Life as a Pioneering Woman Chemist. In Kuroda Chika shiryō mokuroku [Catalogue of the Kuroda Chika Papers] (Tokyo: Ochanomizu University Gender Research Center), 8-10. Online version: http://www.igs.ocha.ac.jp/igs/IGS_publication/pdf/kuroda_archive_en.pdf (last accessed 23 June 2021).
54. Historical studies on women in science are numerous. See, for example: Schiebinger, L. (ed.) (2014). Women and Gender in Science and Technology, 4 vols. (London: Routledge).
55. Otsubo, S. (2008). Women Scientists and Gender Ideology. In Robertson, J. (ed.), A Companion to the Anthropology of Japan (Malden, Mass.: Blackwell Publishing), 467-482.
56. Kodate, N, and Kodate, K. (2016). Japanese Women in Science and Engineering: History and Policy Change (London and New York: Routledge). We owe this information to Prof. Yasu Furukawa.
57. Ogawa, M. (2017). History of Women's Participation in STEM Fields in Japan. ***Asian Women***, ***33***, 65-85. We owe this information to Prof. Yasu Furukawa.
58. Kagakushi Gakkai, ed. (2019). Kagakushi eno shōtai (note. 16), Chapter 5 (pp. 165-189).
59. Vande Walle, W. F., and Kasaya, K. (eds.) (2001). Dodonaeus in Japan: Translation and the Scientific Mind in the Tokugawa Period (Leuven: Leuven University Press). See especially the introduction written by Vande Walle on pp. 9-29.
60. Kuroda, C., and Majima, R. (1922). On the Colouring Matter of Lithospermum Erythrorhizon. Acta Phytochimica, *1*, 43-65.
61. Kuroda, C. (1918). Shikon no shikiso ni tsukite [On the Pigment of Purple Root]. Tokyo kagaku kaishi, ***39***, 1051-1115.
62. Kuroda, C., and Perkin, Jr., W. H. (1923). Derivatives of Phthalonic Acid, 4:5-Dimethoxy-phthalonic Acid, and 4:5-Dimethoxy-o-tolylglyoxylic Acid. J. Chem. Soc. Transactions, ***123***, 2094-2111.
63. Robinson, R. (1955). The Structural Relations of Natural Products, Being the First Weizmann Memorial Lectures, December 1953 (Oxford: The Clarendon Press), p. 42 and Ref. no. 87 on p. 39 and p. 130: Kuroda C. Proc. Imp. Acad. Tokyo 1929 5,32,82,86.
64. Kuroda, C. (1953). Kagaku no michi ni ikite [The Road of Chemistry in which I lived], *Fujin no tomo*, *51* (3), 28-33; *51* (4), 44-51. Reproduced in: Kuroda Chika shiryō mokuroku (note. 53), 77-64. Online version: https://teapot.lib.ocha.ac.jp/record/4093/files/catalogKurodaChika63-80.pdf (last accessed 23 June 2021).
65. The adjective "imperial" in Japanese imperial universities was removed in 1947 as part of the postwar educational reform.
66. Furukawa, Y. (2017). Kagakusha tachi no Kyoto gakuha: Kita Gen-itsu to Nihon no kagaku (note 45). For an English article on this topic by the same author, see: Furukawa, Y. (2018). Gen-itsu Kita and the Kyoto School's Formation. In Rasmussen (ed.) (note 44), 157-168. The Kyoto school is also mentioned in: Furukawa, Y. (2021) (note 3), p. 5. Discussions not from Furukawa's works are notified by endnotes.
67. Furukawa, Y. (2017), pp. 13-24.
68. Furukawa, Y. (2017), pp. 25-30.
69. On Noyes: Servos, J. W. (1990). Physical Chemistry from Ostwald to Pauling: The Making of a Science in America (Princeton, NJ: Princeton University Press), Chapter 3.
70. "Colleges (*bunka daigaku*)" as the constituent entities of imperial universities was renamed "Faculty (*gakubu*)" in 1919.
71. Suito, E. (1983). Academic Achievement and Career of Dr. Shinkichi Horiba (in Japanese). Kagakushi, (22), 19-32. Horiba was the father of entrepreneur Horiba Masao 堀場雅夫 (1924-2015), founder of the analytical instrument company HORIBA.
72. Kim, D (2005). Two Chemists in Two Koreas. Ambix, *52*, 67-84, on 68-71.
73. On the LEP method, see: Laidler, K. J. (1987). Chemical Kinetics, Third Edition (New York: Harper Collins), 68-70; and Nye, M. J. (2007). Working Tools for Theoretical Chemistry: Polanyi, Eyring, and Debates Over the "Semiempirical Method." Journal of Computational Chemistry, *28*, 98-108. In formulating the LEP method, Henry Eyring (1901-81) and Polanyi used the calculations of the Coulombic and exchange integrals in the London equation by Japanese physicist Sugiura Yoshikatsu 杉浦義勝 (1895-1960). Sugiura is now recognized as a Japanese pioneer in quantum physics and chemistry. See: Nakane, M. (2019). Yoshikatsu Sugiura's Contribution to the Development of Quantum Physics in Japan. Berichte zur Wissenschaftsgeschichte, *42*, 338-356.
74. Sato, S. (1955a). On a New Method of Drawing the Potential Energy Surface. Journal of Chemical Physics, *23*, 592-3. Sato, S. (1955b). On a New Method of Drawing Potential Energy Surface. *Ibid.*, 2465-6. Laidler, K. J. (1996). A Glossary of Terms used in Chemical Kinetics, including Reaction Dynamics (IUPAC Recommendations 1996). Pure and Applied Chemistry, *68*, 149-192, on 171. See also a recent appraisal of Satō's work in terms of its impact on computational chemist Martin Karplus (b. 1930), a 2013 Nobel laureate in chemistry: Macuglia, D., Roux, B., and Ciccotti, G. (2021). The breakthrough of a quantum chemist by classical dynamics: Martin Karplus and the birth of computer simulations of chemical reactions. The European Physical Journal H, *46*, article 12, p. 6.
75. On the history of polymer chemistry, see: Furukawa, Y. (1998). Inventing Polymer Science: Staudinger, Carothers, and the Emergence of Macromolecular Chemistry (Philadelphia: University of Pennsylvania Press).
76. Furukawa, Y. (2017), Chapter 3 (pp. 93-164). See also Kim (2005) (note 72), 72-73.
77. Furukawa, Y. (2017), p. 39.
78. Furukawa, Y. (2017), Chapter 2 (pp. 57-92) and pp. 192-202.
79. Furukawa, Y. (2017), Chapter 4 (pp. 165-251),
80. Furukawa, Y. (2017), p. 205.
81. Kaji, Furukawa, Tanaka, and Kikuchi, (eds.) (2016). The International Workshop on the History of Chemistry 2015 Tokyo (IWHC 2015 Tokyo) "Transformation of Chemistry from the 1920s to the 1960s)" (note 44).
82. http://pac.iupac.org/publications/pac/conferences/Tokyo_1962-09-10r/ (last accessed 6 September 2021).
83. Kaji, M. (2016) (note 50), pp. 17-18.
84. Seeman, J. I. (2015). Taking IUPAC Literally: An International Union of Pure and Applied Chemistry. Chemistry International, ***37***, 4-9.
85. Nozoe, T. (1991). Seventy Years in Organic Chemistry (Washington, D.C.: American Chemical Society), 103. This page is a reproduction from the Nozoe Autograph Books, published in ***The Chemical Records*** in 15 segments: https://application.wiley-vch.de/util/nozoe/online.php (last accessed 7 September 2021). We owe this information to Ms. Mari Yamaguchi.
86. Bartholomew, J. R (2010). How to Join the Scientific Mainstream: East Asian Scientists and Nobel Prizes. East Asian Science, Technology, and Medicine, ***31***, 25-43.