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Kelvin and the Development of Science in Meiji Japan

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INTRODUCTION

The modern era in Japan is normally considered as beginning in 1868 when the feudal age, or Edo era, finally ended. Under the rule of the Edo Shogunate headed by the Tokugawa family, the whole country had existed in a state of peace and virtual isolation, essentially sealed off from the rest of the world, for over 250 years. The country was ruled by the *bakfu* government in Edo (Tokyo) while the Emperor continued to reside in Kyoto. Japanese who left and returned were executed to prevent the introduction of outside ideas. Society was highly organized with clearly defined classes and a similar fate awaited those who failed to carry out orders.

Under the isolationist policy, foreign trade and literature were strictly prohibited. Japan was an agrarian non-industrialized nation and the construction of ocean-going ships was banned until 1853. The traditional shipbuilding technology was suitable only for the construction of small wooden boats required for coastal navigation[1]. Financial difficulties exacerbated by natural disasters, including large scale famine, followed by foreign pressure for Japan to open its doors to trade, eventually resulted in the Shogunate stepping down. The Emperor Meiji declared the restoration of Imperial rule in January 1868 (the Meiji restoration) and he and his entourage transferred from Kyoto to Tokyo (Edo was renamed Tokyo) in September 1868. The following year the Diet was established and a constitutional monarchy headed by the Emperor was formed.

The new and globally ambitious Meiji government quickly realized the importance of science and technology. They introduced a programme of importing expertise on short term contracts from the west, called *oyatoi gaikokujin,* or 'honourable foreign employees', generally referred to simply as *oyatoi*. This programme was especially important in shipbuilding which was urgently required for globalization, and became the leading sector industry through which the Japanese gained access to the advanced technology of the day[2]. They also recognized from the beginning that applied science and engineering were essential prerequisites for success, and here again the *oyatoi* programme played a vital role. One of the first schools set up in 1873 was *Kobu Diagakko* (The Imperial College of Engineering), run by the Ministry of Public Works to promote industrial education, which 14 years later was amalgamated with the Science School of the University of Tokyo to form the Imperial University of Tokyo.

A major problem was the shortage of teachers capable of teaching advanced courses. Scottish merchants, businessmen, and bankers had, however, fostered links with Scottish universities which had become highly regarded by the Japanese[2]. Furthermore in the realm of pure and applied science, Sir William Thomson (later Lord Kelvin) was clearly considered an intellectual giant of international renown and:

> around Thomson clustered a galaxy of professors, as pupils, teachers and business partners—Lewis Gordon, Fleeming Jenkin, P G Tait, Alfred Ewing—active in university science in Scotland and entrepreneurship in the electrical industry. Products of the Scottish universities, and usually of the Cambridge Mathematical Tripos also, were amongst the finest flower of Scottish Victorian culture, and in their presence the Scottish universities were confident enough to hold to the traditions[3].

Kelvin's applied research interests included those related to shipbuilding and navigation. He had 11 patents including his mariner's compass, depth sounding device, and his tidal machines. His 45 others included topics such as telegraphy and electrical instrumentation. He had formed companies to exploit his inventions. All this was exactly what the Japanese wanted to foster and it was only natural that they should seek Kelvin's involvement in the appointment of teaching staff. As we shall see he was happy to oblige and essentially all the *oyatoi* appointments in natural philosophy and engineering were made on Kelvin's recommendation. In addition to their teaching duties, these *oyatoi* founded a number of research programmes. After 1879 when the first Imperial College of Engineering students graduated, some were selected to go abroad for further study. Not surprisingly a significant number ended up in Glasgow to work with Lord Kelvin, and on their return home many were to take up important positions in the new Japan.

KELVIN'S PROTÉGÉS IN TOKYO

The two days of celebrations convened by the Royal Society in London in 1924 to celebrate the centenary of Kelvin's birth 'in a manner befitting the memory of one to whose achievements mankind are so greatly indebted', included addresses commemorative from all over the world[4]. The presentation that came from Japan stated:

> The National Research Council of Japan specially desires to recall with gratitude the interest he took in developing physical science and in encouraging research in this part of the world. At the time when Japan was remodelling her education on modern lines, she was fortunate to have his eminent disciples as organisers. Dyer, Gray, Ayrton, Perry, Ewing and Knott, personally recommended by Lord Kelvin himself, came to the Far East, and by their personal examples, inspired the young students with the spirit of research and love for the pursuit of truth, a spirit which sprang from the soul of the Great Master.

The first named in this role of honour, Henry Dyer (1848–1918), had been appointed founding Principal and Professor of Engineering of The Imperial College of Engineering at the remarkably young age of 24 with the brief from Prince Ito, the Japanese Prime Minister, 'to train men who would be able to design and superintend the works which were necessary for Japan to carry on if she adopted Western methods'[5]. Dyer was born in Bothwell near Glasgow and was an engineering apprentice from 1863 for five years at James Aitken and Co., Foundrymen. During this time he attended evening classes at Anderson's College in Glasgow which ran scientific and technical classes for artisans to augment their practical skills with theoretical knowledge. There he met Yozo Yamao, who was gaining work experience at Napier's shipyard before returning to Japan to join the Ministry of Public Works where he helped draw up plans for what was later to become The Imperial College of Engineering.

In 1868, Dyer entered the University of Glasgow and obtained the Certificate of Proficiency in Engineering Science which enabled him to proceed on to the new BSc degree which Kelvin and John McQuorn Rankine, the Professor of Civil Engineering and Mechanics, introduced in 1872. About this time Ito was in the UK with the Iwakura Mission to recruit staff for the new Imperial College of Engineering in Tokyo. Rankine, just before he died suddenly—probably of diabetes—at the end of 1872, recommended Dyer, his most brilliant recent engineering graduate, for the position of Principal and Professor of Engineering. Testimonials in support of Dyer's application were prepared early the next year and came from Kelvin and several other colleagues at the University of Glasgow. It has been claimed that Kelvin had some reservations about Dyer's suitability for the position[6]. Nevertheless the 24 year old Dyer was appointed and special dispensation given for him to graduate early in 1873, having passed exam papers specially set for him.

Dyer spent the voyage out to Japan planning the curriculum which 'combined the best of the British and continental systems for training engineers'[7]. This was immediately agreed to by his former fellow student, Yamao, and teaching began in August 1873 with 56 students embarking on a six-year course. This included, in the later years, practical classes along the lines pioneered in Glasgow by Kelvin, who had introduced the first experimental facilities for undergraduate students in Britain almost 20 years earlier in 'a deserted wine cellar of an old professorial house'[8]. This highly successful educational scheme introduced by Dyer and later colleagues was eventually to return with them to Britain where it was replicated at, amongst other places, Finsbury Technical College, later to become Imperial College London. As Brock has noted,[9] how far Dyer chose his fellow professors is unclear'. However, they were all remarkably young men in their 20s and early 30s with Dyer the youngest, and the majority of them had clear links with Kelvin.

The first to arrive, in 1873, was William Edward Ayrton who had read mathematics at University College London, followed by a short period of service in the Indian Government before spending a year working on electrical research with Kelvin in Glasgow. He later described his year with Kelvin as 'the inspiration of his life'[10]. He arrived in Japan, having been recommended by Kelvin, accompanied by his wife Matilda. 'She, in contrast, was a refugee from Edinburgh University's expulsion of women medical students forced to qualify at the Sorbonne and retrain as a midwife in London'[11]. Thus they each brought new forms of expertise to Japan, although sadly Matilda was dogged by ill health and returned to Britain a year before William in 1877. In addition to his other teaching duties, Ayrton was given the task of supervizing the design and construction of the new laboratory facilities.

Fig. 13.1. John Perry (1850–1920) studied under James Thomson in Belfast, and acted as William Thomson's assistant in Glasgow before arriving in Tokyo in 1875. (From Proceedings of the Royal Society A, volume 111 (1926), opposite page i)

The next to arrive, in 1875, was John Perry who was an Irishman from Garvagh in Ulster. In 1868–70 he had attended the engineering classes of Professor James Thomson (brother of Kelvin) at the Queen's College, Belfast. During the summer months he worked at the Lagan Foundry to supplement his theoretical instruction with practical work—an educational experience which in Tokyo, and later life, he was to promote with great enthusiasm. He then became a lecturer in physics at Clifton College, Bristol where he established a physical laboratory and workshop in 1871. He left there in 1874 to become the Honorary Assistant to Kelvin in Glasgow for a year, before Kelvin recommended him for the Professorship of Civil Engineering at the ICE in Tokyo. Upon arrival it was the teaching laboratories of Ayrton that impressed him most. In later life, 35 years on, he wrote:[12]

> When I arrived in Japan in 1875, I found a marvellous laboratory, such as the world had not seen elsewhere. At Glasgow, at Cambridge and at Berlin, there were three great personalities; the laboratories of Kelvin, and of Maxwell, and of Helmholtz, however, were not to be mentioned in comparison with that of Ayrton. Fine buildings, splendid apparatus, well chosen, a never-resting keen-eyed chief of great originality and individuality: these are what I found in Japan.

Today, however, general opinion is of the view that he was not being strictly accurate and that he was eliding the early laboratory of 1873 with that opened in 1877[11]. Nevertheless, Ayrton and his laboratories clearly impressed the new arrival. The two Kelvin protégés obviously gelled and formed a working partnership to the benefit of both, which was to continue even after their return to England. The partnership was so congenial that for a time they shared equally all their receipts, even the lecture fees that either of them earned. They became known as 'the Japanese twins'. Ayrton 'was the worldly practical member of the firm, Perry the dreamer'[13]. Together they worked tirelessly to improve teaching methods in Japan and Britain. This included stressing the importance of practical work and spending time working in industry. However, as Hirayama has recorded, 'special mention should be made of the fact that the professors occupied themselves ardently in researches besides their teaching duties'. Together they researched a wide range of topics from the electric and magnetic properties of common materials such as beeswax, stone, and lead chloride to measurements of gravity. They also investigated the Japanese 'magic mirrors' which were a great fascination to Europeans. These mirrors were thin pieces of bronze coated with mercury with figures invisibly etched on the back. When the mirror was illuminated with intense light, the figures could mysteriously be projected on to a wall[14]. Following the Kelvin approach they involved their students, here mainly former *samurai* unused to practical work, in these research activities.

Ayrton and Perry wrote approximately 26 papers during the 4 years they were together in Japan, and their first, on 'Studies on ice as an electrolyte' (*Philosophical*

Magazine Series v4 (1877)114), was the first piece of physics ever reported from Japan[14]. The volume of their work was so great as to draw from Maxwell the jest that 'the centre of electrical gravity seemed to have shifted to Japan'. However, perhaps Ayrton and Perry's most noteworthy work was their scientific investigation of earthquakes in 1877 using a seismometer (a device that indicates the occurrence of an earthquake but does not produce a record) that they had developed themselves. In the history of seismology, Hudson has singled out Ayrton and Perry as, 'so far ahead of their time that they scarcely influenced their contemporaries'[15]. It is worth noting that at that time seismology was also receiving considerable attention in Britain. There had been a substantial earthquake in Comrie, near Perth, in Scotland in 1839, which had caused a large dam to burst, and as a result the British Association for the Advancement of Science had formed a Committee for Seismological Investigations which included Lord Kelvin. Ayrton and Perry left Japan in 1878 and 1879 respectively, both returning to teach at Finsbury, later the City and Guilds' College, and eventually at Imperial College London. In the 1890s, Perry would become one of Kelvin's leading opponents in his arguments over the age of the Earth, as described by Patrick Wyse Jackson in this book.

James Alfred Ewing was appointed Professor of Mechanical Engineering and Physics at the Imperial University of Tokyo in 1878—a position he held until 1883. He had been a student of P. G. Tait and Fleeming Jenkin, Professor of Engineering at Edinburgh University. Both these men were close collaborators of Kelvin. Tait and Kelvin were writing their *Treatise on Natural Philosophy* (see Chapter 10 in this volume) while Jenkin collaborated on Kelvin's inventions in connection with submarine telegraphy. The two collaborators competed for Kelvin's time and attention when he came to stay with one or other of them when in Edinburgh. Tait took the view that it was a prostitution of Kelvin's great abilities to devote himself to engineering and invention[16]. Jenkin arranged for Ewing to assist in three of Kelvin's submarine cable laying expeditions to Brazil and the River Plate during the summer vacations. In Japan, Ewing, with a group of his best pupils, took up those researches which were soon to make his name famous—namely magnetism and seismology. Ewing had a noteworthy group of students which included Ryintaro Nomaro who later became the director of the South Manchurian Railway, Rynsaki who became a distinguished mining engineer, Tetso Tsuchida, Shohei Tanaka, and Aikitsu Tanakadate. In 1881 Ewing, aided, as he says in one of his papers, by his band of students, discovered magnetic hysteresis which he named, for posterity, from the Greek verb 'to be behind'. Alas, he had later to cede precedence for discovering the phenomenon to the German physicist, Warburg, who had published his work the previous year, calling it 'Elastische Nachwirkung'[17].

Ewing also devoted much time to the construction and use of seismographs, and developed a new seismograph (an instrument which produces a permanent continuous record of earth motion—a seismogram) based on a long horizontal pendulum with which he succeeded in recording the magnitude of an earthquake for the first time. Small earthquakes in Japan are of course quite common—Ewing claims to have experienced over 300 in 5 years. However a severe earthquake struck Yokohama on 22 February 1880 and this was to provide a great stimulus to the study of seismology in the country. Ewing teamed up with two colleagues at the Imperial College of Engineering, Thomas Gray and John Milne, to develop his seismograph further.

Thomas Gray had been appointed to the position of Demonstrator of Physics and Instructor of Telegraphy at the Imperial College of Engineering in 1878 for a period of three years. He was a graduate of the University of Glasgow where he had studied under Kelvin who had recommended him for the position. John Milne, a Liverpudlian who was a graduate of King's College and the Royal School of Mines in London, had been appointed Professor of Geology and Mining in 1876—the same year Perry arrived. However, it was not until after the 1880 earthquake that he found his true scientific niche in seismology. First Gray, and then Milne, made considerable improvements to the Ewing seismograph, which became known as the Ewing-Gray-Milne model, and eventually became the standard instrument used to observe earthquakes. This instrument had some similarities with Kelvin's siphon recorder for receiving telegraph messages, and Milne arranged for it to be manufactured for global use by Kelvin's instrument maker James White, the firm which eventually became Kelvin and White in 1884. This is perhaps the earliest example of technology transfer from Japan to the West[11].

In 1880, Milne was one of the main proponents of the Seismological Society of Japan, the first such society in the world. Over the next 12 years he published 20 volumes of transactions and other journals in which he, himself, contributed two thirds of the articles. The Japanese scientists, Seiki Sekiya and Fusichi Omori, also helped develop the new quantitative approach to seismology. Sekiya was able to produce a 'wire diagram'—a four dimensional (time and space) picture—of the motion of a particle on the ground moving during an earthquake[18]. Upon his return home with his Japanese wife to the Isle of Wight in 1895, he established his own private earthquake observatory and continued to collect worldwide earthquake data. In 1901 he established the International Committee of Seismology.

In January 1883, the Rector of Tokyo University (*Tokio Diagakko*) wrote to Kelvin seeking a replacement for Ewing, asking him to nominate 'one of as high scientific talent and standing as possible'[19]. Kelvin recommended Cargill Gilston Knott, a research assistant of P. G. Tait in Edinburgh, for the post of Professor of Physics. It is perhaps worth noting that Kelvin would not himself have used the term 'physics'—a neologism that he (and Faraday) objected to strenuously[20]. Ewing, who had worked alongside Knott in Edinburgh, also supported this appointment. In Tokyo, from 1883 to 1891, Knott's main research interests involved magnetism,

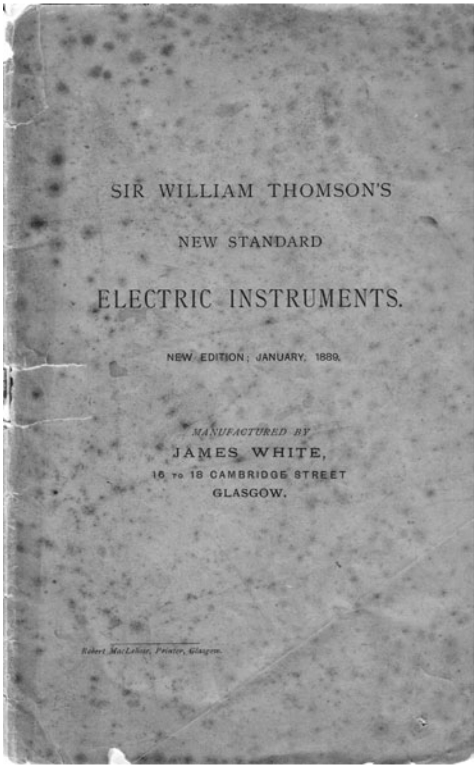

Fig. 13.2. James White's January 1889 catalogue of Sir William Thomson's Electrical Instruments. White also produced the Ewing-Gray-Milne seismograph which became the standard instrument used to observe earthquakes.

where he benefited from Ewing's legacy, and seismology where Milne was still the driving force. His published work concerned magnetostriction—the study of how magnetism varies under material stress and strain. In these studies he was assisted by a Japanese student, Hantaro Nagaoka, who was to become one of Japan's first physicists of repute—he was the first to suggest a planetary model for the atom, based on the rings of Saturn. In geomagnetism, Knott and Aikitsu Tanakadake (a former student of Ewing) organized a major magnetic survey of Japan. In seismology, Knott concentrated on the analysis of earthquake records and was able to give these a sounder physical and theoretical basis based on Fourier analysis—a favourite approach of Kelvin's. J. J. Thomson[4] records that:

> I have heard him say, though I think few will agree with the first statement, that his [Kelvin's] work on problems connected with the Earth was his most important contribution to physics, and that whenever he had done anything with which he was particularly pleased, Fourier's Theorem was always at the bottom of it.

It is interesting, therefore, to note that Kelvin, although he was clearly aware of the problem, did not contribute to the topic of the propagation of earthquake waves, leaving the problem to Knott.

With the departure of Knott in 1891 and Milne in 1895, the *oyatoi* programme drew to a close. It had served its purpose and scientific and technological self-reliance could now be achieved without further assistance from the West. Japan now had a generation of able scientists which included Tanakadate, Nagaoka, Sekiya, Omori, and Shida who were able to pick up the baton. For Kelvin's protégés in Tokyo—Dyer, Ayrton, Perry, Gray, and Ewing—and also for Milne, the Japanese experience was rewarding and pleasurable. They all displayed a great capacity for developing friendships with their students, many of whom were not much younger than themselves. In later life they all kept in contact with many they had taught, warmly welcoming those who visited them in Britain. On leaving Japan they received numerous expressions of thanks. On Perry's departure for example, 56 students presented him with a photograph of themselves, with him in their midst, along with an affectionate farewell address in which they express regret that so many of his pupils are 'scattered about in different parts of the country' and were therefore 'exceedingly sorry for their absence'[21]. When leaving Tokyo, Ewing was presented with personal gifts by the Mikado and later received the Japanese Order of the Precious Treasure. Knott and Milne were both awarded the Order of the Rising Sun by the Emperor. The future achievements of this group have been summarized by Craik[22] and Brock[9].

JAPANESE SCHOLARS IN GLASGOW

The early Meiji Government, as part of their national strategy to import Western applied science and technology, launched a programme to sponsor academic studies abroad. Between 1885 and 1912 nearly 1000 students were sent abroad, of whom two-thirds studied science, engineering, or medicine[1]. On their return to Japan they were required to work for the Government and most of them took up university teaching or research positions. Scottish universities, especially Glasgow, proved a major attraction. As Checkland has noted:

> The academic advantage which made Glasgow a desirable centre for the Japanese was the presence of teachers, including Kelvin, whose research interests lay in the problems of the Clyde industries especially shipbuilding—applied science and technology"[2].

The students enrolled in the university established a base (an Honorary Japanese Consul was created in 1890) which encouraged others to come and work as apprentices in the local industries such as Lobnitz and Co., G. & J. Weir, and later Barr and Stroud. It is said that men from Beardmore's taught Japanese to operate a forge hammer and 'for long the cries of "Awa Parkheid" and "Awa Camlachie" were used in Japan when a workpiece was being moved'[23]!

Between the years 1878 and 1898, approximately 20 students studied with Kelvin (exact numbers are difficult to ascertain as not all of Kelvin's visitors matriculated at the university), of whom 8 studied natural philosophy, thus 'Kelvin's Japanese connection was apparently directed as much or more towards engineering than physics'[24]. In the academic year 1882–3 members of the natural philosophy class voted 'for general eminence' three Japanese—in first, second, and seventh places. They were Rinzaburo Shida, who was awarded the Cleveland Gold Medal for the 'best experimental investigation of magnetic susceptibility', Naomoto Takayama, and Kiyoshi Minami. The care and concern with which Kelvin looked after these young Japanese, not only in the laboratory but also by entertaining them in his home, were greatly appreciated. Lord and Lady Kelvin were very hospitable to all their foreign visitors, although their entertaining was very correct and formal—something, however, which the Japanese could appreciate. As Agnes King, Kelvin's niece, has written, 'Numerous distinguished guests enjoyed their hospitality, and many of all nationalities who would otherwise have been very lonely, were . . . invited to the house'. A Japanese scientist had unfortunately to refuse an invitation to dinner because, as he said, he had 'no night dress' with him and 'in this country I understand men must always dine in night dress'. Another was also prevented from accepting an invitation through being 'concealed in bed by a bad cold'[25].

During the celebrations for his 80th birthday in 1904, Kelvin received a telegram expressing 'hearty birthday greetings' signed by six Japanese who had all worked with him: Masuda, Taniguchi, Watanabe, Mano, Goto, and Tanadake. Kelvin carefully preserved this telegram, keeping it in his famous green notebook that went everywhere with him. A similar telegram was also sent for the *Celebrations on the Occasion of Lord Kelvin's Jubilee as a Professor* in 1899. In his reply to the numerous addresses on this occasion, Kelvin[26] highlighted the fact that:

> I have had interesting and kindly addresses from my old Japanese students of Glasgow University, now professors in the University of Tokyo, or occupying posts in the Civil Service and Engineering Service of Japan.

Kelvin's work on behalf of his Japanese students was also officially acknowledged.

The commemorative address at the Kelvin Centenary celebrations in 1924 from the National Research Council of Japan presented by 'Professor Tanakadake [who] has come all the way from Japan to do honour to his master Lord Kelvin'[27], already quoted above[4], continued:

> And when these students came to Glasgow to receive direct instruction from Sir William, he was their father and friend guiding them by hand through the untrodden realms of physical research.

Aikitsu Tanakadate became one of Japan's most renowned physicists and the foremost of his generation[28]. He had originally intended to study and train for the traditional *samurai* duties of governing the country. At the University of Tokyo, he was a student of Ewing and the American Professor of Physics, Thomas Medenhall, and after much heart searching as to whether science was an honourable calling he decided 'to study physics, which is the basis of all sciences so as to make up in full measure for our country's deficiencies'[29]. After he was appointed to a lectureship, he collaborated with Knott on the magnetic survey before going to work with Kelvin in Glasgow in 1888 for two years. There he developed an affinity with Kelvin. As Koizumi records, 'to the end of his life Tanakadate spoke of the deep impression [Kelvin] had made on him'[29]. Indeed so deep was the impression that his own students in later life nicknamed him 'Lord Kelvin'. Kelvin's own respect for Tanakadate ensured that these students always received a warm welcome in Glasgow. Before returning to Japan, where he became Professor of Physics at the Imperial University of Tokyo and Director of the Physical Institute, Kelvin gave Tanakadate a collection of his personal cards to use as introductions to other scientists in Europe. His research interests were naturally related to those of Kelvin and consisted of developing electrical instrumentation for geomagnetic research. Japan issued a series of commemorative stamps featuring Tanakadate in 2002, 50 years after his death.

Rinzaburo Shida was a former student of Ayrton and Dyer and was the first graduate of the Imperial College of Engineering to be sent to work with Kelvin—on electromagnetism and telegraphy. He too, like Tanakadate, was able to travel widely in Europe carrying introductions from Kelvin. On his return to Japan in 1883 he was appointed to Ayrton's old position as Professor of Natural Philosophy at the Imperial College of Engineering. In contrast to wired telecommunications which were imported, radio technology was developed autonomously in Japan. The first transmission experiments, conducted in 1886, were due to Shida and used the conduction method across the River Sumida in Tokyo by immersing electrodes in the water[30]. Shida founded the Institute of Electrical Engineers of Japan in 1888, and was given the title of Doctor of Engineering. Sadly, he died of tuberculosis in1892 at the relatively young age of 37—a not uncommon occurrence in Japan at that time.

CONCLUSION

During the Meiji era, Japan, with the aid of the *oyatioi* and other programmes, made astonishingly rapid progress in modernizing from a feudal to a modern industrialized society. And, as the *Japan Weekly Mail* stated in an editorial of 1878, 'in no direction has Japan symbolised her advance toward the assimilation of the Western world more emphatically than in that of applied science'[31]. The aim, to emulate late Victorian Britain and indeed to become 'the Britain of the East', was substantially achieved over the period of a few decades. Lord Kelvin, who never visited Japan, played an important indeed unique role in the transfer of educational ideas, science, and technology. A letter from the President of 'The Lord Kelvin Association' in Utsunomiya in 1906, which describes a meeting at which 'Your Lordship's portrait was hung over the platform and some speeches were made in praise of your scientific attainment'[32], provides clear evidence of the reverence with which Kelvin became regarded in Japan.

ACKNOWLEDGEMENTS

It is a pleasure to be able to thank all my Japanese friends and collaborators, especially Professors Nobuo Koboyashi, Hiro Tawara, and Nori Kouchi, who have over the years made my visits to Japan so enjoyable and patiently educated me in the history and culture of their country. I am also grateful to Professor Alex Craik for his helpful advice and comments on the manuscript.

With the exception of Kelvin's class lists at the University of Glasgow, kindly provided some years ago by their Archives and Business Record Centre, this chapter has been compiled from secondary sources. Its aim has been to provide an easily readable rather than academic account of this under-appreciated aspect of Kelvin's life. Much of the information it contains, and further details, can be found in the scholarly articles dealing with related topics by Brock[9], Craik[22], Gooday and Low[11], Koizumi[29], and especially the book by the late Olive Checkland[2] which is a *tour de force.*

47. William Thomson, 'The Duties of the Ether for Electricity and Magnetism,' *Philosophical Magazine* **50** (1900): 305–307.
48. William Thomson, 'Aepinus Atomized,' *Philosophical Magazine* **3** (1902): 257–283, reprinted in *Baltimore Lectures* (1904), Appendix E, 541–568
49. WT1904, Lecture XX. This Lecture was rewritten between 1902 and 1904.
50. William Thomson, 'On the Motions of the Ether produced by Collisions of Atoms or Molecules, containing or not containing Electrions,' *Philosophical Magazine* **14** (1907): 317–324.
51. William Thomson, 'Plan of a Combination of Atoms having the Properties of Polonium or Radium,' *Philosophical Magazine* 8 (1904): 528–534, 'Plan of an Atom to be Capable of Storing an Electrion with enormous Energy for Radio-activity,' *Philosophical Magazine* 10 (1905): 695–698, 'An Attempt to Explain the Radioactivity of Radium,' *Philosophical Magazine,* **13** (1907): 313–316.

CHAPTER 13

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31. *Japan Weekly Mail* (1878) 2, 52.
32. Kelvin Papers, T1 and T2, 1906, University of Cambridge Library.

CHAPTER 15

Notes

1. By 'thermal effect' he means what is now called entropy production.
2. This is the so-called 'scientific' notation, as used in calculators, which enables very large and very small numbers to be written down in a way that is easily read. The notation 10^{25} stands for 1 followed by 25 zeros, i.e. 10,000,000,000,000,000,000,000,000, and 10^{-23}