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# BIOGRAPHICAL MEMOIR

OF

# ARTHUR EDWIN KENNELLY

1861–1939

BY

VANNEVAR BUSH

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Arthur E. Kennelly

# ARTHUR EDWIN KENNELLY

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To few, and only to the few, has been granted the inestimable privilege of active and close participation in almost the entire range of development of such an enormous and such a useful field as that of electrical engineering, from the pioneer days of the telegraph and submarine cable, through the earliest stages of practical application of the storage battery, the electric light, and the telephone, and on to the flowering of the art as represented by the present status of electric power generation, transmission, and utilization and of electrical communication. And to few only has there been granted the friendship, esteem, and professional respect of so many outstanding contemporaries in any art as are represented by such names as Rowland, Elihu Thomson, Edison, Steinmetz, Sprague, Houston, and Brush in the United States; Heaviside, Clark, Lord Kelvin, Fleeming-Jenkin, and Preece in England; Mascart, Blondel, and Ferrié in France; von Helmholtz in Germany, Marconi and Giorgi in Italy; Nagaoka in Japan; and many others throughout the world. But to Arthur Edwin Kennelly was granted both the privilege of such a participation in an art and such a friendship and esteem from the principal joint authors of its development. With his death on June 18, 1939, Harvard University and the Massachusetts Institute of Technology lost a deeply respected professor emeritus of electrical engineering, the profession lost one of its early pioneers and most striking figures, and the National Academy of Sciences lost a distinguished and valued member.

Dr. Kennelly was born at Colaba, Bombay, India, on December 17, 1861. His father, David Joseph Kennelly of Cork, Ireland, had gone to sea as a midshipman in 1845, served as a frigate commander in the Indian Mutiny of 1856-58, and was harbor master at Bombay from 1858-1868. His mother, Katherine Heycock Kennelly, born in Leeds, England, was a daughter of Edwin and Mary Heycock, who had settled in Bombay and built the first cotton mill in East India. Mrs. Kennelly died of

Indian fever in 1864 [1] when Arthur was only three years old, and the child was sent to England because of the unfavorable climate of Bombay for rearing white children. He attended schools in France, Belgium, Scotland, and England, and particularly the University College School at Gower Street, London, where he received prizes in language and stenography. In later years his linguistic accomplishments were attested by his fluent command of French, German, and Italian. More significantly, he had inherited from his father an aptitude for arithmetic and geometry, although he modestly contended that his skill in mental arithmetic was only half that of his father.

Inspired at the age of twelve by a public lecture on "Submarine Telegraphy," given in Albert Hall, London, by Latimer Clark, the well-known telegraph engineer and inventor of the Clark potentiometer and the Clark cell, he decided to enter telegraph engineering, which, except for electroplating, represented the only industrial application of electricity at that time. This was before electrotechnical schools had been anywhere established. At fourteen he left school and entered the London office of the Society of Telegraph Engineers (later to become the Institution of Electrical Engineers) as office boy and assistant secretary. In this office he found the Ronalds' Electrical Library, and all his spare time was spent in studying electro-physics in the excellent collection of Ronalds' books, bequeathed to the Society by that pioneer telegrapher.

In 1876 at the age of fifteen he was appointed probationer telegraph clerk in the service of the Eastern Telegraph Company at its Porthcurno station near Land's End in Cornwall, England. This company owned and operated an extensive network of submarine telegraph cables connecting England with the continent of Europe, and through the Mediterranean Sea with Egypt, India, and the Far East. A year later he was sent to the Eastern Telegraph Company's Malta station as a junior operator, where he was allowed to assist in the periodical elec-

[1] Autobiographical notes sent to the National Academy of Sciences, Washington, D. C., give the date as 1863. In an *Abridged Record of Family Traits,* also in possession of the National Academy of Sciences, Kennelly gives the date as 1864.

trical tests of the cables landing at Malta. In 1878 he was transferred from the operating staff to the cable-ship staff as assistant electrician on board the *S. S. Chiltern,* remaining in this branch of service for eight years. In 1881 he was promoted to chief electrician on cable ships. His duties in this capacity were to test, repair, and lay submarine cables in various parts of the Eastern Telegraph Company's system, sharing the engineering responsibilities with the captains of the ships.

During these years Kennelly took part in numerous important cable repairs and the laying of cables from Gibraltar to Tangier, from Alexandria to Port Said, and in other places and served as chief electrician on a number of cable ships in all parts of the Eastern Telegraph Company's network between England and Bombay.

In 1887 after Kennelly had reached the position of senior chief electrician on the ship's staff of the Eastern Telegraph Company, he left that service to become assistant to Thomas A. Edison at his new laboratory in West Orange, New Jersey. He remained as Mr. Edison's principal electrical laboratory assistant for six years and during that time carried on a number of electrical researches. Between the years 1893 and 1901 he did a large amount of consulting electrical engineering work, first with the Edison General Electric Company and the General Electric Company of New York for a year and then with Edwin J. Houston in the firm of Houston and Kennelly in Philadelphia.

In 1902 the Mexican Government and the Safety Insulated Wire and Cable Company of New York placed Kennelly in charge of laying submarine telegraph cables from Vera Cruz to Frontera and Campeche. In the same year he was appointed professor of electrical engineering at Harvard, where he remained until his retirement as professor emeritus in 1930. From 1913-1925 he was also professor of electrical communication at the Massachusetts Institute of Technology; he directed its electrical engineering research for many years, was chairman of its faculty from 1917-1919, and became professor emeritus in 1930.

Besides his regular teaching at Harvard and Massachusetts Institute of Technology, Kennelly responded to invitations to lecture at many other universities in the United States, in

Canada, and in Europe. In 1921-22 he was sent by seven co-operating American universities (Columbia, Cornell, Harvard, Johns Hopkins, Massachusetts Institute of Technology, Pennsylvania, and Yale), to lecture as their first exchange professor in engineering and applied sciences at six universities of France. And in 1931 he was appointed first visiting lecturer on the Iwadare Foundation at five universities in Japan. During the War he served as Civilian Liaison Officer in the Signal Corps of the United States Army overseas.

His publications were numerous and broad in scope. Of the twenty-eight books bearing his name on their title pages, he was sole author of ten. And in the course of his career he presented more than 350 papers before the leading scientific and technical societies here and abroad.[2]

Honorary degrees were conferred upon him by four universities: the University of Pittsburgh, 1895; Harvard University, 1906; the University of Toulouse, 1922; and the Technische Hochschule of Darmstadt, Germany, 1936. In 1939 he was made a member of the Royal Swedish Academy of Sciences. Among the many honors and awards received by him were the Institution Premium in 1887 and the Fahie Premium in 1889 from the Institution of Electrical Engineers, London; the Howard Potts gold medal from the Franklin Institute at Philadelphia for his invention of a hot wire anemometer, 1917; the Cross of a Chevalier de la Légion d'Honneur from France, 1922; the silver Volta medal, the Centenary medal of the Italian Government, received at the Como Convention, the annual gold medal of honor of the Institute of Radio Engineers, 1932; and the Edison Medal for 1933 from the American Institute of Electrical Engineers, awarded in January 1934. He was President for two terms of the American Institute of Electrical Engineers, 1898-1900; President of the American Metric Society, Washington, 1904; President of the Illuminating Engineering Society, New York, 1911; President of the Metric Association, 1915-1934; President of the Institute of Radio Engineers, New

[2] See List of Books and Papers by Dr. A. E. Kennelly, *Journal of the Electrotechnical Society of Waseda,* XIII (June-Aug. 1932), No. 7-8. See also bibliography below.

York, 1916; Honorary President of the Union Radio Scientifique Internationale, 1935; Vice President of the Edison Pioneers, 1938-1940; and in addition held memberships or honorary memberships in a score of other technical and scientific societies both here and abroad. He held appointments from time to time on some thirty scientific commissions and conferences, among which may be mentioned the following: Secretary and later Chairman of the Standards Committee of the American Institute of Electrical Engineers from the date of its inception to 1917; official delegate from the United States to the International Electrical Congress of Paris in 1900 and its Vice President; Chairman of the Committee on Nomenclature and Standards of the Illuminating Engineering Society, New York, from 1915-1921; technical adviser to the United States Delegation of the International Commission of Weights and Measures, Paris, 1921; delegate to the International meeting of the Conference of Large Electric Systems, Paris, 1921, and its Vice President; Research Associate of the Carnegie Institution of Washington, 1924-1936; Chairman of the Engineering Section of the National Academy of Sciences, 1932; and Vice Chairman of the Division of Foreign Relations of the National Research Council in 1933.

In July 1903 Kennelly married Dr. Julia Grice of Philadelphia, whose death preceded his by a few months. Their only surviving child, Reginald Grice Kennelly, was graduated *summa cum laude* from Harvard University in 1931 and received his doctor's degree from the same institution in 1935.

Expressive of the character of Kennelly and indicative of some of the achievements which he most valued in his career was the bookplate designed for him by Mr. W. A. Dwiggins, artist of Hingham and Boston, Massachusetts, in the winter of 1915-1916. It features a central ellipse enclosing a shield and scallop of the coat of arms of the Kennelly family. The legend, "Ora et Labora," is the family heraldic motto. Around the ellipse are twelve mathematical formulae relating to electrical circuits, for the formulation of which he was largely responsible. Another revealing item is his abridged family genealogy filed with the National Academy of Sciences, in which he particularly notes that three generations of Kennellys have been total abstainers from both alcohol and tobacco.

To appreciate fully the position which Kennelly occupied in the development of the science and art of electrical engineering, one needs to have a clear idea of the roles of the originator and the interpreter. Kennelly was both; yet while his origination of theoretical matters was ample to assure him of a permanent position in history as a man of science, it was in the equally important aspect of interpretation that he was decidedly a unique figure. His carefully chosen nomenclature, his crystal clear exposition, his meticulous mathematical presentations, led thousands to employ powerful methods of analysis which would otherwise have remained abstruse and hence available only to a few. It is not too much to say that he changed the whole course of the methods of the electrical engineer by his leadership in this regard. As he interpreted mathematics for engineering use, he also originated new methods and new formulations. It is not necessary to inquire meticulously into all of these matters in regard to the ultimate credit for origination. The power of Kennelly to render clear and useful was his greatest contribution, and this often transcended the question of whether what he presented was new in an absolute sense, or new in the sometimes equally important sense of being unknown and inaccessible to those who could best employ it in bringing to the public the benefit of the applications of science in an economical manner.

This comment applies especially to Kennelly's extensive contributions in the field of circuit theory. The direct-current circuits on which the early advances in electrical engineering were based, required for their analysis only simple a'gebra. Hence, as soon as instruments for reasonably precise measurement were available, the use of such circuits proceeded without impediment from lack of analysis. Alternating-current circuits were of a very different nature, and the transient phenomena of circuits of more difficult nature still. In a field of application where the flow of energy can ordinarily be neither seen, heard, nor felt, procedure by rule of thumb, design on the basis of qualitative experience, could not have gone far. The revolution in our daily lives, due to the widespread use of alternating currents in power applications and communication, has been possible primarily because electrical engineers can precisely analyze in advance the performance of the complex electrical networks involved. This has been accomplished largely because those engineers use in their daily work mathematical methods of analysis in exceedingly convenient form and of extraordinary power. Kennelly was distinctly in the forefront of the advance which made this possible.

The mathematicians had long dealt with so-called imaginary and complex variables, and had met them in connection with the solution of some of the differential equations of physics. Heaviside had approached the problems of electrical circuits with no mathematical inhibitions whatever, and, by unorthodox methods sometimes entirely divorced from all questions of rigor, had produced the extraordinary results for which we are so greatly indebted to him. There was needed, however, some individual who could regularize, interpret, simplify, and extend the mathematical approach in order to create a keen working tool. This was Kennelly's great work.

Fortunately we have Kennelly's own recital of the various steps in this process of development of electric circuit theory, and his own meticulous statements as to the specific accomplishments which he claimed as the result of his own origination, preserved in his Academy autobiography. The most important parts of this document have been quoted by Professor Dawes in a biography of Kennelly published in *Science* shortly after his death, and there is hence no need for further quotation here. The record seems rather to need expansion in order that scientists in other fields may more fully appreciate the significance of the work which Kennelly performed in the specialized fields in which he was long engaged.

As early as 1887 he published his method of localizing electrically faults in submarine cables by varying the testing current strength.[3] This method he had invented by observing the apparent resistance of a copper exposure at a break and relating

[3] A. E. Kennelly, "The Resistance of Faults in Submarine Cables," *Journal of the Society of Telegraph Engineers and Electricians*, XVI (March 17, 1887), pp. 219-249.

it to the square root of the testing current through the exposure. It should be noted that there were no ammeters in existence at the time, and the establishment of a relationship of this sort called for great ingenuity and resourcefulness in measurement. Kennelly's paper on the subject received the "Institution Premium" of the Society of Telegraph Engineers, London, and the method set forth continues to be a recognized one for fault localization.

Neat generalizations and apt formulations soon began to appear. The idea of the "center of gravity" of cable faults [4] led to the application of the same general thought in regard to the complex loads of polyphase systems.[5] The fact that certain circuits are equivalent in external reaction, so that one may be freely substituted for its equivalent in either analysis or practice, is a far-reaching thought. The most striking substitutions involve "delta" and "star" arrangements, each of three branches and arranged respectively in triangular or radial conformation. Kennelly showed the complete conditions for equivalence in very convenient form in 1899.[6]

His most notable accomplishment along these lines had to do with Ohm's law. This was the law of proportionality of current and potential difference which was basic to all work with steadily flowing currents. When alternating-current circuits appeared, with sinusoidally varying parameters, no such convenient tool was at hand. The basis of analysis resided, it is true, in the mathematical theory of vibrations, but the application to electrical circuits was far from obvious or direct. Kennelly's paper of 1893, entitled "Impedance," [7] crystallized the matter in such form that engineers soon began to use plane vectors and complex numbers with freedom and precision. Complex algebra

[4] A. E. Kennelly, "On the Analogy between the Composition of Derivations in a Telegraph Circuit into a Resultant Fault and the Composition of Gravitation on the Particles of a Rigid Body into a Center of Gravity," *Electrical Review*, New York, XI (November 5, 1887), pp. 2-3.

[5] A. E. Kennelly, "On the Determination of Current Strength in Three-Pointed Star Resistance Systems," *The Electric World and Engr.*, XXXIV (August 19. 1899), pp. 268-270.

[6] A. E. Kennelly, "The Equivalence of Triangles and Three-Pointed Stars in Conducting Networks," *ibid.* (September 16, 1899), pp. 413-414.

[7] A. E. Kennelly, "Impedance," *Transactions of the American Institute of Electrical Engineers*, X (April 18, 1893), pp. 175-216.

rendered the alternating-current circuit almost as readily amenable to treatment as had been the direct-current circuits which preceded.

After this advance the treatment of circuits of discrete parameters in the steady state was well ordered. A similar clarification soon followed in regard to those circuits, such as long transmission or communication lines, where the parameters are distributed. Again the fundamental differential equations followed immediately from those of Maxwell and had long been known. Heaviside had given in 1891 the solutions in terms of hyperbolic functions expressed in scalon form. The subject was much advanced, however, when Kennelly in 1894 [8] gave a clear and explicit solution in terms of complex hyperbolic functions, and still further when he introduced a notation for polar complex quantities and published sets of tables and charts of the trigonometrical functions of complex angles.

The same clarification also appeared in connection with circuits in free oscillations. Here there was a large mathematical background indeed in regard to the behavior of free mechanical systems, which applied as well to the equivalent electrical networks. The parallelism between this behavior and that of the steady state became fully clear to many only when Kennelly published in 1915 [9] a treatment in which notation was carefully carried over from one to the other.

It is not necessary to review in detail the work on dissymmetrical networks,[10] nor the large amount of accomplishment in regard to artificial lines.[11] In some of this, largely as a by-product, he extended the knowledge of certain types of con-

[8] A. E. Kennelly, "On the Fall of Pressure in Long Leads Traversed by Alternating Currents," *The Electrician,* XXXII (January 5, 1894), pp. 239-240.

[9] A. E. Kennelly, "The Impedances, Angular Velocities and Frequencies of Oscillating-Current Circuits," *Proceedings of the Institute of Radio Engineers,* November 1915.

[10] A. E. Kennelly, "Dissymmetrical Electrical Conducting Networks," *Journal of the American Institute of Electrical Engineers* (February 1923), pp. 112-122.

[11] A. E. Kennelly, "Artificial Lines for Continuous Currents in the Steady State," *Proceedings of the American Academy of Arts & Sciences,* XLIV (November 1908), pp. 97-130; "The Equivalent Circuits of Composite Lines in the Steady State," *ibid.,* XLV (November 1909), pp. 31-75; *Electric Lines and Nets,* New York: McGraw-Hill Book Company, 1928.

tinued fractions.[12] He also investigated at length the phenomenon of "skin-effect" by which the current crowds toward the periphery of alternating-current conductors, and followed this matter both theoretically and experimentally.[13] There was extensive work on the heating of wires carrying current,[14] and upon the performance of the telephone receiver.[15]

Lest it be thought, however, that all of Kennelly's work had to do with precise analysis, mention should be made of his accomplishments of a somewhat different nature.

Most notable of these was the brilliant inspiration by which he dissipated the mystery surrounding the progress of radio waves over the surface of the earth. In 1901 Marconi announced the reception in Nova Scotia of radio signals from a

[12] A. E. Kennelly, "The Expression of Constant and Alternating Continued Fractions in Hyperbolic Functions," *Harvard Annals of Mathematics,* IX, second series (January 1908), pp. 85-96.

[13] A. E. Kennelly, "Impedance," *Transactions of the American Institute of Elec. Engrs.,* X (April 18, 1893), pp. 175-216; A. E. Kennelly, F. A. Laws, and P. H. Pierce, "Experimental Researches on Skin Effect in Conductors," *ibid.,* XXXIV (September 1915), pp. 1953-2021; A. E. Kennelly, F. H. Achard, and A. S. Dana, "Experimental Researches on Skin Effect in Steel Rails," *Journal of the Franklin Institute,* CLXXXII (1916), pp. 135-139; A. E. Kennelly and H. A. Affel, "Skin Effect Resistance Measurements of Conductors at Radio Frequencies up to 100,000 Cycles per Second," *Proceedings of the Institute of Radio Engineers* (December 1916), pp. 523-574; A. E. Kennelly, "Notes from the Research Division Electrical Engineering Department, Mass. Inst. Tech.," *Journal of the Franklin Institute,* CLXXXIII (1917), pp. 509-511.

[14] A. E. Kennelly, "Heating Conductors by Electric Currents," Convention of the Assoc. Edison Illum. Cos., Niagara Falls, New York (August 13, 1889), pp. 11-32; A. E. Kennelly, C. A. Wright and J. S. Van Bylevelt, "The Convection of Heat from Small Copper Wires," *Transactions of the American Institute of Electrical Engineers,* XXVIII (June 1909), pp. 363-393; A. E. Kennelly and H. S. Sanborn, "The Influence of Atmospheric Pressure upon the Forced Thermal Convection from Small Electrically Heated Platinum Wires," *Proceedings of the American Phil. Society,* LIII (April 1914), pp. 55-57; A. E. Kennelly and E. R. Shepard, "The Heating of Copper Wires by Electric Currents," *Proceedings of the American Institute of Electrical Engineers,* XXVI (June 1907), pp. 969-995; A. E. Kennelly, F. D. Everett and A. A. Prior, "Thermal Insulation Tests of Electrical Ovens," *Electric World,* LXV (March 27, 1915), p. 779.

[15] A. E. Kennelly, "A Contribution to the Theory of Telephony," *Electrical World,* XXIII (February 27, 1894), p. 208; A. E. Kennelly and W. L. Upson, "The Humming Telephone," *Proceedings of the American Philosophical Society* (July 1908), Vol. 47, pp. 329-365; A. E. Kennelly and G. W. Pierce, "The Impedance of Telephone Receivers as Affected by the Motion of Their Diaphragms," *Electrical World,* LX (September 14, 1912), pp. 560-565.

station in England. The received energy was far greater than could have been expected from any simple three-dimensional wave expansion. Moreover, if one assumed free propagation in the entire region above the earth and complete shielding by the conducting earth itself, which would have been quite reasonable at the time, there was no reason for expecting any signal at all. Yet Marconi, perhaps because he was fortunate in not possessing the incomplete current knowledge of the phenomena involved, tried the experiment, and the signals were received. Kennelly provided the explanation,[16] by reason of the reflection of the waves from an upper stratum of ionized air, basing his explanation on some of the properties of rarefied gases which had just been announced by J. J. Thomson. The ionized reflecting layer is usually called the Kennelly-Heaviside layer in view of the fact that Heaviside published essentially the same explanation later in the same year in the Encyclopaedia Britannica. Since that time there has been much study of the phenomena, and the layer is found to be multiple with extraordinary variations in position and composition.

Kennelly made important contributions to illumination[17] at a time when the art was greatly in need of better methods of measurement. In the course of many years his influence was felt in nearly every aspect of electrical engineering. Entirely apart from his strictly scientific and technical achievements, his influence on standardization and international interchange was profound.

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[16] A. E. Kennelly, "On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere," *Elec. World and Engr.*, XXXIX (March 15, 1902), p. 473.

[17] E. J. Houston and A. E. Kennelly, "An Instrument for Measuring the Mean Spherical Candlepower of Arc Lamps," *The Electric World*, XXVII (May 9, 1896), p. 509; A. E. Kennelly and S. E. Whiting, "The Frequencies of Flicker at which Variations in Illumination Vanish," *ibid.*, XLIX (June 1907), pp. 1208-1209; A. E. Kennelly, G. R. Carter, S. C. Li, and E. A. Healey, "Flicker on Fixed and Rotating Targets," *Proceedings of the Illum. Engineering Society* (February 1911), p. 120; A. E. Kennelly, "A New Graphic Method for Determining the Mean Spherical Intensity of a Lamp by the Length of a Straight Line when the Curve of Mean Meridional Intensity is Given," *Electrical World, LI* (March 28, 1908), pp. 645-649: "A Rectilinear Graphical Construction of the Spherical Reduction Factor of a Lamp," *Proceedings of the Illum. Engineering Society* (February 1908).

All who were his students remember him as a remarkable teacher, whose clarity and precision of expression made smooth the path of those struggling with the often abstruse intricacies of electrical phenomena. Moreover, there was always a bit of humor to relieve the tedium.

He was at his best at a scientific meeting, where his geniality and ready wit enlivened many a discussion. In international gatherings in particular his precision of language, his unfailing courtesy, and his wide acquaintance aided greatly in bringing about understanding and good will.

After his formal retirement from active teaching in 1930 he remained a valued member of the academic community in Cambridge. His eyesight failed rapidly, but he continued actively, and worked at his office every day even when nearly totally blind. Under these conditions he wrote several of his last papers, aimed at simplifying and coordinating the systems of units used by electrical engineers.

Arthur Edwin Kennelly died on June eighteenth, 1939, honored by scientific men everywhere, and leaving as a monument to his work some three hundred and fifty publications of constant contribution to the art and science of electrical engineering.

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