What did Gustav Robert Kirchhoff stumble upon 150 years ago?

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***Abstract*-Gustav Robert Kirchhoff is, without a doubt, one of the founding fathers of electrical engineering. The two circuit laws named after him, formulated in 1845 at age 21, constitute the foundation of electric circuit theory. Most electrical engineers assume that Kirchhoff is well known because of these two laws and are unaware of his other important contributions to science. About 150 years ago in 1859, while performing an experiment with a spectroscope, Kirchhoff unexpectedly made a major discovery that brought him and his colleague Robert Wilhelm Bunsen their greatest scientific fame: the spectrum analysis. The purpose of this article is to use this special 150th anniversary of his discovery as an opportunity to commemorate Kirchhoff's life and bring attention to his many accomplishments.**

I. Introduction

In the early part of their undergraduate education, all electrical engineering students are taught Kirchhoff's circuit (voltage and current) laws formulated in 1845. However, few are aware that these laws were derived by someone who was just about their age. At the time, the German physicist Gustav Robert Kirchhoff (1824-1887) was a twenty-one year old graduate student at Albertus University in Königsberg, Prussia (now Kaliningrad, Russia), studying under the supervision of Franz Ernst Neumann (1798-1895). Although electrical engineers know Kirchhoff's name through his two circuit laws, most are unaware that Kirchhoff made other major, fundamental contributions to physics. Indeed, Kirchhoff's true fame began in 1854 when he was appointed a Professor of Physics at Heidelberg University. There he teamed up with his former colleague Robert Wilhelm Bunsen (1811-1899) and pursued his investigations on the emission and absorption of light, leading to his groundbreaking research in spectral analysis.

About 150 years ago this autumn, while conducting an experiment with a spectroscope, Kirchhoff accidentally stumbled onto something he thought was fundamental. "Kirchhoff has made a most beautiful and most unexpected discovery: he has found the cause of the dark lines in the solar spectrum…," wrote Bunsen in 1859. On the 150th anniversary of this special occasion, this article will help us remember Kirchhoff, his life and some of his achievements in science of which most of us electrical engineers are generally unaware [1-12].

II. Kirchhoff's Early Life and Education

Kirchhoff was born on March 12, 1824, in Königsberg, Prussia. At the time, Königsberg was known as the "City of Pure Reason," where a nucleus of enterprising tradesmen and able officials had fostered a thriving intellectual circle. Kirchhoff's parents Carl Friedrich Kirchhoff and Juliane Johanne Henriette von Wittke married in 1819. Carl Friedrich was a law counselor who belonged to a strong, disciplined body of state functionaries including university professors. He became a judge at the Royal East Prussian state court in Königsberg in 1823 and was named counsel of justice in 1845. Kirchhoff had two older brothers, Carl Johann and Otto Friedrich. Kirchhoff's parents expected as a matter of course that their sons live up to their diverse talents, underlying the family's loyalty to the service of the Prussian state. They both died in 1853, within a few months of each another.

When Kirchhoff was young, he was rather small for his age and later never reached more than a medium height. He was lively and talkative and constantly had to be reminded to be quiet. He and his brothers had a joyful childhood in their parents' home and they all attended Kneiphofische High School located south of Königsberg, right next to Albertus University. Kirchhoff received his diploma in 1842 at age eighteen. Languages were his weak point, but otherwise his examinations were particularly well accomplished. His final grade report states that he intended to study mathematics.

Immediately after his graduation from high school, Kirchhoff entered Albertus University of Königsberg, to study mathematics and physics. Here, he was taught mathematics by Friedrich Julius Richelot (1808-1875); however, his primary research mentor was Franz Ernst Neumann. Neumann joined Königsberg University in 1828. At first, Neumann was a mineralogist interested in crystallography, but later his work was influenced by Friedrich Wilhelm Bessel (1784-1846) and Carl Gustav Jacob Jacobi (1804-1851). As a result, Neumann's interests gradually shifted toward the study of the new science of electromagnetism and mathematical physics. Neumann became one of the great founders of mathematical physics. In 1833, Neumann and his mathematician colleague Jacobi began mathematics-physics seminars at Königsberg University and used these to introduce their students to

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methods of research. Jacobi was widely considered to be one of the most inspiring teachers of his time and one of the greatest mathematicians of all time. Unfortunately, in 1843 Jacobi suffered a breakdown from overwork and he never regained his health.

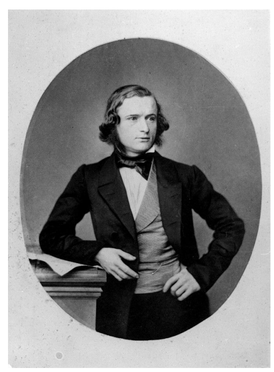
Kirchhoff was almost certainly among the students who attended Neumann's first lectures on magnetism and electrodynamics between 1843 and 1844 and it was mostly Neumann who made a significant impact and had a decisive influence on Kirchhoff's scientific education, achievements, and accomplishments. Kirchhoff studied potential theory with Neumann, who employed potential as an essential tool in his works on electromagnetic induction of 1845 and 1847. As a student at age 21, Kirchhoff published his first paper in *Annalen der Physik und Chemie* in 1845. This paper contained the well-known Kirchhoff's voltage law governing the relation between electromotive force and current in branched circuits. It also included Kirchhoff's current law. Kirchhoff states in this paper that this work is a continuation of Ohm's law, discovered by Georg Simon Ohm (1789-1854) and published in 1827. Also, while studying at Königsberg University, at Neumann's suggestion, Kirchhoff spent two semesters in Berlin in 1846, supported by a stipend obtained from the Prussian government.

III. Kirchhoff's Early Career

Kirchhoff graduated from Königsberg University in 1847. That same year, he also married Clara Richelot (1834-1869) the daughter of his mathematics teacher Friedrich Julius Richelot. Kirchhoff received a scholarship to study in Paris after his graduation, but the revolutions of 1848 intervened. Instead, Kirchhoff and his wife moved to Berlin. This was particularly a difficult time; tensions were high due to poor conditions in the German Federation. Unemployment and crop failures had led to discontent and disturbance; trouble was sparked by the news that Louis-Philippe had been overthrown by an uprising in Paris in 1848. There were revolutions in many German states and fighting in Berlin. Republican and socialist feelings meant that the monarchy was in trouble, but Kirchhoff was in a privileged position and was unaffected by events around him as he pressed forward with his career. In 1848 in Berlin, Kirchhoff attained the right to teach as a private tutor in a university. He qualified for a professorship in mathematical physics at the University of Berlin and taught there in an unpaid post for two years between 1848 and 1850. In 1850, Kirchhoff and his family moved to Breslau, Prussia (now Wroclaw, Poland) and he became the extraordinary professor of physics at University of Breslau.

From 1845 to 1857, Kirchhoff worked in Königsberg, Berlin and Breslau, focusing his attention to problems in theory of electricity. During this period, his studies and contributions were most strongly influenced by Neumann and Wilhelm Eduard Weber (1804-1891), whom he met in Berlin in 1846. Kirchhoff also incorporated Weber's model of electricity in his work during the 1850s. In a paper published in 1849, Kirchhoff successfully seated Ohm's law on a solid foundation that is in agreement with then-prevailing notions in electrostatics, by redefining the tension resulting from the contact of two different conductors as the difference of potential between the two. By reinterpreting Ohm's electroscopic force as a potential, Kirchhoff was able to retain Ohm's law while banishing the physically unacceptable notion that free electricity could exist in stable equilibrium inside a conductor.

In 1851, Robert Bunsen (1811-1899), Kirchhoff's senior by thirteen years, came to the University of Breslau for only a one-year term before he joined Heidelberg University in 1852. This brief period was adequate for the two men to establish a long-lasting friendship. Two years after Bunsen joined Heidelberg University, partly due to Bunsen's influence and partly because Kirchhoff at age thirty had already distinguished himself over many years as a researcher, he received an offer from Heidelberg University to fill an ordinary professor position as the Heidelberg physics chair. Kirchhoff missed his close connection with Bunsen after he left Breslau. In addition, this new job was a promotion with much better pay. Most importantly, Heidelberg would be a better, more congenial environment in which to develop his teaching and research. Kirchhoff accepted this offer and moved to Heidelberg in 1854. It was Heidelberg where, partly in collaboration with Bunsen, he made his greatest contributions to science.




Kirchhoff in Heidelberg/Kirchhoff with Bunsen

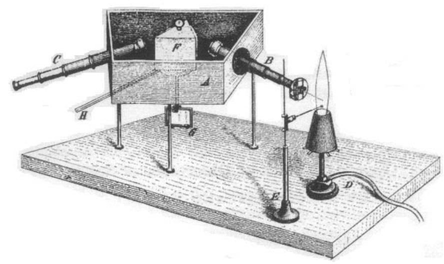
IV. Kirchhoff in Heidelberg

The richest period of Kirchhoff's life was the twenty years he taught at Heidelberg, from 1854 to 1874, where he worked jointly with Bunsen. It was during the years 1859-1862 that these two talented scientists together made the great discoveries of spectrum analysis. At the time, Bunsen was involved in photochemistry, analyzing various types of salt that impart specific colors to a flame when burned. He was using colored pieces of glass to distinguish similarly colored flames. One day, when visiting Bunsen at his laboratory, Kirchhoff suggested to him that a better analysis could be accomplished by passing the light from the flame through a prism. The two teamed up on the project, and through rigorous experimentation soon put in place a laboratory set-up incorporating this new method. The newly discovered Bunsen burner invented by Bunsen in 1857 furnished Bunsen and Kirchhoff a gas flame of fairly high temperature and low luminosity, in which chemical substances could be vaporized and a spectrum could be obtained, due purely and simply to the luminous vapor. Earlier investigators who had no Bunsen burners available were misled by the background of luminous lines and bands produced by heated carbon compounds.

Through the use of a spectroscope, it quickly became apparent to Kirchhoff and Bunsen that each chemical element produced its own characteristic pattern of colored lines when heated to incandescence. Thus, incandescent sodium vapor produced a double yellow line. Each element and compound showed a definite line spectrum which could be viewed, recorded, and measured. In a sense, elements were producing their own "fingerprints" or "barcodes" and the elementary composition of any mineral could be determined by spectroscopy. Spectroscopy, which had its origins in the demonstration by Isaac Newton (1642-1727) of the composite nature of light, suddenly had a vast new field of application. Kirchhoff and Bunsen wrote that spectral analysis promises "the chemical exploration of a domain which up until now has been completely closed."

By testing an extensive variety of chemical compounds, in 1860 Kirchhoff and Bunsen meticulously determined the unique characteristic line spectrum for each metal. (Kirchhoff's heavy use of spectroscope led to serious eye problems for him.) Their systematic application of spectroscopy to alkaline compounds demonstrated once again the power and importance of spectroscopy when it led to their discovery of two new alkaline elements. As was inevitable, a mineral water from Dürkheim displayed spectral lines that had not been recorded for any of the known metals. The conclusion was that an unknown element was involved. This led to the discovery of cesium announced in 1860. Furthermore, while studying a type of mineral called lepidolite in 1862, Bunsen discovered an alkali metal he called rubidium, an element used today in atomic clocks. Using spectroscopy, some ten more new elements were discovered by other scientists before the end of the nineteenth century and the field of spectral analysis had expanded enormously.

Kirchhoff went even further with spectroscopy. In 1859, while conducting an experiment with a spectroscope, Kirchhoff made an unexpected observation. It had long been known that two of the dark D lines of the orange-colored part of the solar spectrum observed by Joseph von Fraunhofer (1787-1826) in 1814 coincided with the yellow lines emitted by the flame of candles containing sodium. Kirchhoff allowed sunlight and sodium light to shine through the same slit in order that the dark line of the first and the bright line of the second might neutralize each other. Instead, the line was darker than ever. Kirchhoff observed that if the intensity of light increased above a certain limit, the same dark D lines were made much darker by the interposition of the sodium flame. Kirchhoff instantly felt that he had stumbled onto something fundamental, even though he had no explanation for it at that moment.



Spectroscope apparatus used by Kirchhoff and Bunsen

From this and other experiments, Kirchhoff concluded that when light passes through a gas, the light wavelengths absorbed by the gas coincide with the same wavelengths that the gas would emit when incandescent. In other words, a substance capable of emitting a certain spectral line has a strong absorptive power for the same line. In particular, the interposition of the sodium flame of low temperature is sufficient to artificially produce the dark D lines in the spectrum of an intense light source which did not show them originally.

The existence of the dark D lines in the solar spectrum meant that sunlight passed through sodium vapor on its way to the earth. This is attributed to absorption by a solar atmosphere containing sodium. The only place where the sodium vapor could exist would be in the sun's own atmosphere. Consequently, it was possible to claim that sodium existed on the sun. Comparing the dark lines of the solar spectrum with the spectral lines of metals, Kirchhoff concluded that in addition to sodium, iron, magnesium, copper, zinc, barium, and nickel also existed in the solar atmosphere. Immense prospects of ascertaining the chemical composition of the sun and other stars from the study of their optical spectra thus opened up.

Kirchhoff liked to tell this story about his banker: The question of whether Fraunhofer's lines reveal the presence of gold in the sun was being investigated. Kirchhoff's banker remarked, "What do I care for gold in the sun if I can not fetch it down here?" Shortly afterwards Kirchhoff received from England a medal for his discovery, and its value in gold. While handing it over to his banker, he observed: "Look here I have succeeded at last in fetching some gold from the sun." The gold in Kirchhoff's discovery was actually much greater in value because the spectral lines proved to be a guide not only to the great world of the outer cosmos, but to the infra-tiny world within the atom.

As a consequence of his work with the Fraunhofer D lines, Kirchhoff developed a general theory of emission and radiation in terms of thermodynamics, known as Kirchhoff's law (or Kirchhoff's law of radiation). This law states that a substance's capacity to emit light is equivalent to its ability to absorb it at the same temperature. In other words, the ratio of emission and absorption powers of all materials is the same at a given temperature and a given wavelength of radiation produced. In a later elaboration of his law, in 1862 Kirchhoff introduced the concept that a perfect black body—one that absorbed all radiation falling on it, of whatever wavelengths—would, if heated to incandescence, emit all wavelengths.

Although no perfect black body actually existed, one could be constructed by the use of a trick, as pointed out by Kirchhoff. A closed container with blackened inner walls and a tiny hole would serve the purpose. Any radiation, of whatever wavelength, that entered the hole would have only an infinitesimal chance of emerging again through this hole and could therefore be considered as absorbed. Thus, if the box were heated to incandescence, all wavelengths of light ought to emerge from the hole. The study of "black-body radiation" served as a cornerstone in thermodynamics of radiation. A generation later, in the hands of Max Plank (1858-1947), Kirchhoff's successor to the chair of theoretical physics at the University of Berlin, this study also proved to be of utmost importance to Plank's development of quantum mechanics.

V. Kirchhoff's Health, Family, and Personality

Around 1869, Kirchhoff had a fall on a staircase, injured his foot, and was required to use crutches or a wheelchair for quite some time. Kirchhoff's wife Clara died in 1869, leaving him with two sons and two daughters. In 1872, Kirchhoff married Benovefa Karolina Sopie Luise Brömmel (1838-?), the superintendent of the university clinical hospital specializing in eye diseases. Despite his frequent ill health, Kirchhoff maintained his pleasant and friendly personality, making his second marriage also a happy one. His junior colleague, Ludwig Boltzmann (1844-1906), described Kirchhoff at the height of his powers as being not easily drawn out but of a cheerful and obliging disposition. Kirchhoff's disability did not alter this cheerfulness, and he bore the long illness of his later years with patience.

VI. Kirchhoff in Berlin

Kirchhoff was so happy with his environment at Heidelberg that on two occasions, he turned down offers from other universities. However in 1875, when his failing health hindered his experimental work which he so much enjoyed, he accepted an offer from the University of Berlin to become the chair of theoretical physics. He took on this task with great devotion, until his illness forced him to give up his teaching activity in 1886. A year later, physically weak but intellectually alert, on October 17, 1887, he died peacefully, presumably of a cerebral congestion.

VII. Conclusions

IEEE Circuits and Systems Society established the IEEE Gustav Robert Kirchhoff Award in 2003 and announced the first recipient of this award in December of 2004. On the 150^{th} anniversary of Kirchhoff's major discovery and the 5^{th} anniversary of the award given in his name, the author hopes that this article will serve to help us as electrical engineers learn more about Kirchhoff and his other achievements outside electric circuit theory.

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