Technical Documents." *American Documentation* 17 (1966): 186–189.

With Robert W. Taylor and Evan Herbert. "Computer as a Communication Device." *Science & Technology* 76 (1968): 21–31.

With A. Vezza. "Applications of Information Technology." *Proceedings of the IEEE* 66 (1978): 1330–1346.

OTHER SOURCES

Aspray, William, and Arthur L. Norberg. "J. C. R. Licklider." OH 150. 28 October 1988, Cambridge, MA; Charles Babbage Institute, University of Minnesota, Minneapolis. A scholarly oral history record.

"Bolt Beranek and Newman: The First 40 Years." Special issues, *IEEE Annals of the History of Computing* 27, no. 2 (2005); 28, no. 1 (2006). Some of these papers refer to Licklider's contribution in the establishment of BBN's role in the history of computing and networking: Leo Beranek, "BBN's Earliest Days: Founding a Culture of Engineering Creativity" (27, no. 2: 6–14); John A. Swets, "ABC's of BBN: From Acoustics to Behavioral Sciences to Computers" (27, no. 2: 15–29); Sheldon Baron, "Control Systems R&D at BBN" (27, no. 2: 52–64); Wallace Feurzig, "Educational Technology at BBN" (28, no. 1: 18–31); John Makhoul "Speech Processing at BBN" (28, no. 1: 32–45); Ralph Weischedel, "Natural-Language Understanding at BBN" (28, no. 1: 46–55).

Fano, Robert M. "Joseph Carl Robnett Licklider: March 11, 1915–June 26, 1990." *Biographic Memoirs* 75 (1998): 190–213.

Garfinkel, Simon L. *Architects of the Information Society: 35 Years of the Laboratory for Computer Science at MIT*. Edited by Hal Abelson. Cambridge: MIT Press, 1999. As a book on the history of Project MAC and LCS, it refers to Licklider and contains a few images of him. It is based on an MIT-centered history account and stresses the importance of Licklider's idea of the "Intergalactic Computer Network" as the origin of the network development at the ARPA.

Kita, Chigusa Ishikawa. "J. C. R. Licklider's Vision for the IPTO." *IEEE Annals of the History of Computing* 25, no. 3 (2003): 62–77. An extended version of this work is published as a book in Japanese, *J. C. R. Licklider and His Age*. Tokyo: Seido-sha, 2003.

Lee, John A. N., and Robert Rosin. "The Project MAC Interviews." *IEEE Annals of the History of Computing* 14, no. 2 (1992): 14–35. This is a record of group interview (10 October 1988) that includes a biographical sketch of Licklider related to the early history of interactive computing at MIT. Participants are Fernando J. Corbató, Robert M. Fano, Martin Greenberger, Joseph C. R. Licklider, Douglas T. Ross, and Allan L. Scherr, as listed. (This entire *Annals* issue is dedicated to Project MAC.)

Norberg, Arthur L. "Changing Computing: The Computing Community and DARPA." *IEEE Annals of the History of Computing* 18, no. 2 (1996): 40–53.

Norberg, Arthur L., and Judy E. O'Neill, with contributions by Kerry J. Freedman. *Transforming Computer Technology: Information Processing for the Pentagon, 1962–1986*. Baltimore: Johns Hopkins University Press, 1996. Most reliable history book on IPTO based on the historical documents of the agency that include normally inaccessible records.

O'Neill, Judy E. "The Role of ARPA in the Development of the ARPANET, 1961–1972." *IEEE Annals of the History of Computing* 17, no. 4 (1995): 76–81.

Waldrop, M. Mitchell. *The Dream Machine: J. C. R. Licklider and the Revolution That Made Computing Personal*. New York: Viking, 2001. Biographical history book for general readers based on documents and interviews. Author's interviews with Louise Licklider and others result in a lively description of Licklider's personality.

Chigusa Ishikawa Kita

LIE, MARIUS SOPHUS

(*b.* Nordfjordeide, Norway, 17 December 1842; *d.* Christiania [now Oslo], Norway, 18 February 1899), *mathematics*. For the original article on Lie see *DSB,* vol. 8.

Hans Freudenthal's essay in the original *DSB* offers a perceptive account of Lie's mathematical interests, the conflicts he experienced, and those parts of his legacy of greatest importance for the mathematics of the twentieth century. As a leading expert on topological groups and geometric aspects of exceptional Lie groups, Freudenthal had a deep appreciation of modern Lie theory. At the same time, his familiarity with Lie's original ideas enabled him to recognize the yawning gap that separated Lie's grandiose vision from that which he and his disciples were able to realize. Freudenthal was less familiar with Lie's biography (Lie had two daughters and one son), and he relied to some extent on folklore, as in his recounting of Lie's hostility toward Wilhelm Killing. Since then much new documentary evidence has become available that helps clarify important episodes in Lie's career.

Background to Conflicts. During his lifetime Lie was a highly controversial figure, and his legend lives on in Norway even in the early twenty-first century. As new facets of his life and work have been brought to light, a picture emerges of a brilliant but troubled man whose career was filled with inner and outer conflicts. His long-forgotten early work with Felix Klein has been reexamined, leading to new assessments of their partnership and its significance for Lie's gradual immersion in the theory of continuous groups. Lie's work in this field eventually spawned what became modern Lie theory, a field of central importance for quantum mechanics. Yet while nearly every theoretical physicist knows about Lie groups, certainly very few have ever read a word of his work. In his pioneering studies, Thomas Hawkins helps remedy that problem. Hawkins not only uncovers the main sources of Lie's

Lie

Sophus Lie. **SPL / PHOTO RESEARCHERS, INC.**

inspiration but he also lays bare the thorny paths followed afterward by numerous others—Killing, Georg Frobenius, Issai Schur, Élie Cartan, Hermann Weyl, and others—whose work created the modern theory of Lie groups. None of these figures, to be sure, was allied with Lie's Leipzig school; indeed, Killing and Frobenius, both trained in Berlin, actively opposed Lie's claims to authority.

Lie drew on two main sources of inspiration in developing his ideas for a theory of continuous groups. The first involved a wide range of geometrical problems that culminated with his discovery of the line-to-sphere transformation in 1870, a breakthrough that opened the way to his investigations on general contact transformations. Much of this work was undertaken in collaboration with Klein, whose "Erlangen Programm" of 1872 (*Vergleichende Betrachtungen über neuere geometrische Forsuchungen*) strongly reflects the impact of Lie's ideas. Soon afterward Lie found a second major source of inspiration in Carl Gustav Jacob's analytic methods in the theory of differential equations. In this he was aided by the Leipzig analyst Adolf Mayer, who encouraged Lie to translate his geometric ideas into the language of Jacobian analysis. By 1874 Mayer had become Lie's most important mathematical resource.

Part of the tragedy surrounding Sophus Lie's life stemmed from his involvement in clashes between prominent mathematicians, many of whom were associated with leading mathematical schools in Germany. Avoiding such entanglements would have been virtually impossible because of his close association with Klein, Leipzig's controversial professor of geometry during the early 1880s. Against strong opposition, both within the Leipzig faculty and in Berlin, Klein managed to orchestrate Lie's appointment as his successor in 1886. From the moment the Norwegian arrived, Leipzig's senior mathematician, Carl Neumann, sought to undermine his position by offering courses and seminars on geometrical topics. Nevertheless, during the course of his twelve-year tenure there, Lie managed to build up an important school whose members specialized in one facet or another of the master's vast research program. Still, he paid a heavy personal price in exchanging the calm tranquillity of Christiania, where he held a parliamentary professorship since 1872, for the dreary urban life he encountered in Leipzig. He found his teaching responsibilities time-consuming, particularly because of difficulties with the German language, and he worried about his wife's health after a tumor was detected in one of her breasts. On top of these daily pressures, he became concerned about a new competitor who suddenly appeared on the horizon: Wilhelm Killing.

Lie had always been suspicions of potential rivals—the French geometers Gaston Darboux and Georges Halphen being two notable cases—but these feelings intensified and spread once he arrived in Leipzig, a far more competitive environment than Christiania. By 1888 he was deeply convinced that his principal disciple, Friedrich Engel, had betrayed his trust. Thus began a long, painful period during which Lie gradually broke off relations with nearly all his friends and supporters in Germany. It was this factor—betrayal, whether real or imagined—that played a major role during the last decade of Lie's ultimately tragic life.

Illness. Initially no apparent signs of conflict arose when Killing met with Lie and Engel in the summer of 1886. Lie presumably knew all along that Engel had been writing to Killing and hoped that the latter's work would enhance the stature of his theory. He changed his mind, however, in early 1888 when he saw the first installment of Killing's four-part study in *Mathematische Annalen.* Lie wrote to Klein: "Mr. Killing's work … is a gross outrage against me, and I hold Engel responsible. He has certainly

Lie

also worked on the proof corrections" (Rowe, 1988, p. 41). Lie concluded that too many of his ideas had been communicated to Killing by Engel, ideas Lie regarded as his exclusive intellectual property. His relationship with Engel never fully recovered from this bitter episode.

The following year Lie had to be placed in a psychological clinic as he could no longer sleep at night. His wife brought him home in the summer of 1890, but his condition did not improve until long afterward. This dark interlude strongly colored the last decade of Lie's life. Whether or not it affected Lie's personality, as Freudenthal wrote based on Engel's original claims, it undoubtedly affected the way he saw the world and especially his relationships within the German mathematical community.

Conflict with Klein. During the period 1889–1892, when Lie was severely depressed, Klein was returning to several topics in geometry that he had pursued twenty years earlier, the period when he had collaborated closely with Lie. He was also approached by the algebraic geometer Corrado Segre, whose student, Gino Fano, prepared an Italian translation of Klein's "Erlangen Programm" from 1872. This famous survey underscored the role of transformation groups and their invariants in geometry; indeed, it proclaimed that all other aspects (even the dimension of the manifold in question) were of secondary significance for geometrical studies. Soon afterward, the Erlangen program appeared in French and English translations, and Klein wanted to republish it in German too, along with several of Lie's earlier works.

By calling attention to this earlier work, Klein hoped to draw the lines between the intuitive geometric style of mathematics he favored and the dominant research ethos of the period, typified by the trend toward "arithmetization" as practiced in Berlin by Karl Weierstrass and Leopold Kronecker. Lie had become very troubled by Klein's sudden interest in resurrecting their earlier work, and he became increasingly distrustful of the Göttingen mathematician's schemes. Yet he failed to signal these concerns to Klein, who continued to view Lie as his principal ally in an ongoing battle with the Berlin mathematicians. Klein hoped their alliance was still intact in the late summer of 1893 when he delivered his Evanston Colloquium Lectures, two of which gave a highly personal synopsis of Lie's mathematics in which he emphasized the geometrical inspiration behind Lie's work on continuous groups as well as differential equations.

These circumstances loomed in the background when Klein began pressuring Lie regarding his plan to republish their earlier work in *Mathematische Annalen*. Klein even wrote two drafts for an introductory essay on their collaboration during the period 1869–1872 only to learn that Lie profoundly disagreed with his portrayal of these events. Lie rightly noted that his own subsequent research program had little to do with Klein's Erlangen program. Had he confined his critical remarks to their private correspondence, few probably would have known that his relationship with Klein had by this time soured completely. Instead, however, he chose to "set the record straight" in the introduction to the third volume of his treatise on transformation groups (all three were largely written by Engel) by proclaiming: "I am no pupil of Klein's. Nor is the reverse the case, even though it perhaps comes closer to the truth. I value Klein's talent highly and will never forget the sympathetic interest with which he has always followed my scientific endeavors. But I do not feel that he has a satisfactory understanding of the difference between induction and proof, or between a concept and its application" (Lie, 1893, p. xvii). These remarks, not surprisingly, scandalized many within Klein's extensive network, but several others were also criticized by name, including Hermann von Helmholtz, Joseph-Marie de Tilly, Ferdinand von Lindemann, and Killing.

Although prone to outbursts, Lie was tenaciously firm when it came to protecting what he regarded as his intellectual property rights. During the years following his estrangement from Engel, he acquired the services of a new assistant, Georg Scheffers, who edited several of Lie's lecture courses for publication. Reacting to the volume on Lie's theory of contact transformations prepared by Scheffers, Klein privately expressed these revealing remarks:

> That is the true Lie, as he was from 1869–1872, supplemented and completed by careful historical and comparative studies along with excellent drawings by Scheffers. But he breaks off everywhere where my complementary investigations or our collaborative work begins. Why? That's the spirit of latent jealousy. The impression could otherwise possibly arise that I had some kind of share in the ideas that Lie regards as his exclusive property. (Niedersächsische Staats- und Universitätsbibliothek Göttingen, Cod. Ms. F. Klein, 22f)

The Turn to France. Much to Klein's chagrin, Lie lost all interest in the German domestic scene and turned toward France, where the younger generation showed a keen interest in his group-theoretic approach to differential equations. Lie's interest in the reactions of the French community went hand in hand with growing disillusionment with the reception of his work in the German mathematical world. Craving recognition for his theory, he was not content with the kind of support he got from the likes of Engel and Eduard Study, whom he regarded as marginal figures in the German mathematical community. Darboux had shown an early interest in Lie's work, and in 1888 he encouraged two graduates of the École Normale, Vladimir de Tannenberg and Ernest Vessiot, to study with

Lie in Leipzig. Vessiot, following the lead of Émile Picard, took up Lie's original vision, namely to develop a Galois theory of differential equations. Nearly all the French mathematicians were primarily interested in applications of Lie's theory, not in the structure theory itself; even Cartan shared this viewpoint to some extent.

This open-minded attitude of the Parisian community to Lie's theory contrasted sharply with the rejection voiced by Frobenius, who became Berlin's leading mathematician after Weierstrass retired in 1892. The latter considered Lie's work—presumably in the form presented by Engel in *Theorie der Transformationsgruppen*—so wobbly that it would have to be reworked from the ground up. Frobenius went even further, claiming that even if it could be made into a rigorous theory, Lie's approach to differential equations represented a retrograde step compared with the more natural and elegant techniques for solving differential equations developed by Leonhard Euler and Joseph-Louis Lagrange. Needless to say, the leading French mathematicians felt otherwise. Among the younger generation, Cartan, whose work was directly linked to Killing's, showed the strongest affinity for the abstract problems associated with Lie's theory.

In the original *DSB* article, Freudenthal suggests that Lie tried "to adapt and express in a host of formulas, ideas which would have been better without them.… [For] by yielding to this urge, he rendered his theories obscure to the geometricians and failed to convince the analysts" (p. 325). Leaving aside the issue of whether or not Lie himself felt any urge to dress up his theory for analysts, there can be no doubt that he sought their recognition. Lie had long bemoaned his isolation in Norway, and he felt frustrated over the difficulties he encountered in trying to gain an audience for his work. His two most trusted allies in Germany, Klein and his Leipzig colleague Mayer, were well aware of these circumstances. Presumably both reached the conclusion that Lie's mathematics had to be made more palatable for analysts—particularly those closely associated with Weierstrass's school in Berlin—and together they counseled young Engel to carry out this plan.

As the "ghostwriter" of Lie's three volumes on the theory of transformation groups, Engel clearly played a major role in this endeavor. Whether or not Lie valued this effort, he apparently never felt quite at home with the results. According to his student Gerhard Kowalewski, when discussing his work Lie never referred to the three volumes written by Engel, with their "function-theoretic touch," but rather always cited his own papers. This suggests that the "true Lie"—to take up Klein's image—should not be sought in the volumes produced with Engel's assistance but rather in his own earlier papers.

Kowalewski, Klein, and Engel were fascinated by Lie's powerful, Nordic mathematical persona; all three left lively recollections of their encounters with him. Numerous others, including his many students, bore witness to his brilliant originality. Yet despite his numerous achievements, the recognition he received from his many pupils and admirers, and the honors and accolades accorded him by distinguished societies, he spent the last years of his life trying to frame his place in the history of mathematics as Évariste Galois's true successor and Norway's "second [Niels Henrik] Abel." After Lie's death, Engel devoted the last twenty years of his life to preparing the publication of Lie's collected works in six volumes. The seventh volume appeared only many years afterward in 1960, but the editors chose to omit Engel's essay on the conflict between Klein and Lie.

SUPPLEMENTARY BIBLIOGRAPHY

WORK BY LIE

Theorie der Transformationsgruppen. Bd. 3. Leipzig, Germany: Teubner, 1893.

OTHER SOURCES

Hawkins, Thomas. *Emergence of the Theory of Lie Groups: An Essay in the History of Mathematics, 1869–1926.* Berlin, Heidelberg, and New York: Springer-Verlag, 2000. Surveys the broader development of Lie theory.

Rowe, David E. "Der Briefwechsel Sophus Lie–Felix Klein, eine Einsicht in ihre persönlichen und wissenschaftlichen Beziehungen." *NTM* 25, no. 11 (1988): 37–47. Discusses Lie's conflicts with Killing and Klein.

Stubhaug, Arild. *The Mathematician Sophus Lie: It Was the Audacity of My Thinking.* Translated by Richard H. Daly. Berlin, Heidelberg, and New York: Springer-Verlag, 2002. Contains many heretofore unknown aspects of Lie's life.

David E. Rowe

LIEBIG, JUSTUS VON (*b.* Darmstadt, Grand Duchy of Hesse-Darmstadt, 12 May 1803; *d.* Munich, Germany, 18 April 1873), *chemistry.* For the original article on Liebig see *DSB,* vol. 8.

Liebig's life encompassed innovation in teaching, important contributions to organic chemistry and, above all, the significant application of chemistry to agriculture, physiology, medicine, nutrition, and industry, as well as to the popularization of chemistry. He has attracted considerable attention since Frederic L. Holmes's fine article was published in 1973. Historical interest has been concentrated on the publication of critical editions of Liebig's extensive correspondence with other chemists and pharmacists, his publishers, and the chancellor of the University of Giessen; the development of a deeper