MICHAEL D. GORDIN*

The organic roots of Mendeleev's periodic law

THE PERIODIC LAW has become firmly associated with D.I. Mendeleev (1834-1907). In its graphic representation as the periodic table, it has achieved a place in chemistry classrooms across the world. Nevertheless, despite voluminous studies on the cognitive origins of the law, there has been little investigation of the social and conceptual roots of the periodic system in the actual practice of the historical Mendeleev. This paper addresses this issue by placing the creation of the law into the context of the reform of education in St. Petersburg in the 1860s. Mendeleev approached textbook writing as a simultaneous solution to the pedagogical and financial demands upon him. When faced with an organizational crisis in his work-in-progress in early 1869, he turned to a prior exemplar of effective classification: the type theory of the organic chemist Charles Frédéric Gerhardt. The periodic system has its roots firmly embedded in type-theoretical classifications of mid-century *organic* chemistry. This recognition provides a consistent interpretation of the social and cognitive origins of the periodic law, and also accounts for Mendeleev's lifelong adherence to Gerhardt's ideas and for his hostility to organic structure theory.

* Society of Fellows, 78 Mount Auburn Street, Harvard University, Cambridge, MA 02138; mgordin@fas.harvard.edu. I would like to thank Mario Biagioli, W. H. Brock, Nathan Brooks, Igor S. Dmitriev, Peter Galison, Loren Graham, Karl Hall, John Heilbron, Matthew Jones, and Sam Schweber for many helpful discussions and suggestions on earlier drafts of this paper. I also gratefully acknowledge the research assistance of the D.I. Mendeleev Archive-Museum (ADIM) and the Russian State Historical Archive (RGIA). Part of this research was funded by a National Science Foundation Graduate Research Fellowship and the International Research and Exchanges Board (IREX).

The following abbreviations are used: ADIM, Arkhiv-Muzei D.I. Mendeleeva (D.I. Mendeleev Archive-Museum); *MS*, followed by volume number in roman numerals, D.I. Mendeleev, *Sochineniia* (25 vols., Leningrad: Izd. AN SSSR, 1934-1954); RGIA, Rossiiskii Gosudarstvennyi Istoricheskii Arkhiv (Russian State Historical Archive); *TIIEiT*, *Trudy Instituta istorii estestvoznaniia i tekhniki*; *VIET*, *Voprosy istorii estestvoznaniia i tekhniki*; *ZhRFKhO*, *Zhurnal Russkogo Fiziko-Khimicheskogo Obshchestva.* Most dates are given in the Julian calendar, which lagged 12 days behind the Gregorian calendar (N.S.) in the 19th century, and 13 days in the 20th. Transliterations follow a modification of the standard Library of Congress format.

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At the middle of the 19th century, probably the dominant theory of organic chemistry was type theory. In brief, this theory based its arguments on a clear conceptual understanding of the "molecule." Type theorists held that chemists have no knowledge of the interior structure of molecules, but could discuss their interactions as units. Type theory was eventually supplanted in the early 1860s by structure theory, developed by August Kekulé and later elaborated by Aleksandr Butlerov. Structure theory took the basic insights of type theory and combined them with a new doctrine of valency to argue that chemists could predict the natures of reactions by developing models of the topology of organic compounds. In order to claim access to such knowledge, structure theorists took vague theories of "combining strengths" and transmuted them into valency, a unit of chemical combination oriented in a specific direction, almost an "atom" of attraction. Much of the discussion that follows centers on Mendeleev's navigation through these domains of type theory, structure theory, and valency, the latter two of which he strongly resisted.

The first section describes Mendeleev's path from his study period in Heidelberg (1859-1861) to his acceptance of the post of Professor of General Chemistry at St. Petersburg University. The demands of teaching and opportunities provided by the Russian Chemical Society occupy the next section. Then come a close description of the origins of the periodic law in Mendeleev's textbook, the *Principles of chemistry*, and extensive evidence for type-theoretical reasoning in the creation of the periodic law.

1. MENDELEEV'S EARLY RESEARCH

When Mendeleev's mother brought him from Tobol'sk, Siberia, to European Russia to further his education in the early 1850s, she first tried to enroll him at Moscow University, the nation's oldest and most prestigious institution. She did not succeed, and eventually settled for the Chief Pedagogical Institute of St. Petersburg, the same institution at which Mendeleev's father had studied. The Institute, which had opened in 1829, was directed during Mendeleev's years of attendance (1851-1855) by Ivan Ivanovich Davydov, who shifted the previous focus on practical pedagogy to independent research so that students could later attain higher academic degrees.[1] While some noted graduates of the Institute, such as the radical thinkers N.G. Chernyshevskii and N.A. Dobroliubov, disliked the closed structure of the establishment, which housed all students on the premises and forbade contact with outsiders, the sickly adolescent Mendeleev thrived in the environment. He had access to distinguished University faculty members (who also taught at the Institute, which was located on the University's grounds), among them the mathematician M.V. Ostrogradskii, mineralogist S.S. Kutorga, physicist Heinrich F.E. Lenz, and chemist A.A. Voskresenskii.[2] Mendeleev was exposed to a variety of sciences, a desire for synthesis, and a cultivated pedagogical expertise. He drew on it all in constructing the periodic system.

1. *Kratkoe istoricheskoe obozrenie deistviia Glavnago pedagogicheskago instituta, 1828-1859 g.* (St. Petersburg, 1859), 2-5.

Mendeleev's earliest chemical work was on the isomorphism of crystals with different chemical composition. Discovered by Eilhard Mitscherlich in 1822, this phenomenon cast into disrepute the long-standing notion that crystalline structure was a unique reflection of underlying chemical composition.[3] Mendeleev's master's thesis of 1856, "Isomorphism in connection with other relations of crystalline form to content," reflects an early interest in connecting internal properties to external structure.[4] Heavily influenced by French chemist Charles Gerhardt, Mendeleev concluded that specific volume provided the best means to examine the influence of composition on form. Mendeleev continued to explore this theory in his candidate thesis, also published in 1856, which dealt with specific volumes.[5] Like the master's thesis it was basically a literature review, but it gave Mendeleev the opportunity to declare adherence to the "new chemistry" of Gerhardt, which involved a reevaluation of atomic weights from the older system of Jacob Berzelius and rejected the electrochemical theory of bonding. According to R.B. Dobrotin, some essential elements of the periodic system can be discerned in these early works, namely a concern with ordering elements by physical, not chemical, properties, attention to problems of classification, and a reconsideration of atomic weights.[6]

Mendeleev was authorized to go abroad to further his studies in chemistry on January 9, 1859. He left for his destination, Heidelberg, on April 14, when the semester in St. Petersburg ended. He approached Bunsen for a spot in his laboratory, but the fumes and the noise so annoyed him that he worked instead in his apartment, which he transformed into a "very nice laboratory" that had its own gas

2. V.E. Tishchenko, "Dmitrii Ivanovich Mendeleev. Kratkii biograficheskii ocherk," in V. E. Tishchenko, ed., *Trudy pervago mendeleevskogo s"ezda po obshchei i prikladnoi khimii, sostoiavshagosia v S.-Peterburge 20-go po 30-go dekabria 1907 g.* (St. Petersburg, 1909), 8-32, on 13-14. S.A. Shchukarev, "D.I. Mendeleev i Leningradskii gosudarstvennyi universitet," *Vestnik Leningradskogo universiteta*, no. 6 (1947), 148-154.

3. Evan M. Melhado, "Mitscherlich's discovery of isomorphism," *HSPS, 11:1* (1980), 87-123; Hans-Werner Schütt, *Eilhard Mitscherlich: Prince of Prussian chemistry*, tr. William E. Russey (Philadelphia, 1992).

4. *MS*, I, 7-137.

5. *MS*, I, 139-311. Mendeleev's concern for internal-external connections is also evident in the materials for his dissertation on specific volumes, 1856, ADIM II-A-17-3-3.

6. R.B. Dobrotin, "Rannii period nauchnoi deiatel'nosti D.I. Mendeleeva kak etap na puti k otkrytiiu periodicheskogo zakona" (Candidate dissertation, Leningrad State University, 1953); S. A. Shchukarev and R.B. Dobrotin, "Pervye nauchnye raboty D.I. Mendeleeva kak etap na puti k otkrytiiu periodicheskogo zakona," *Vestnik Leningradskogo universiteta*, no. 2 (1954), 165-177. Cf. Masanori Kaji, *Mendeleev's discovery of the periodic law of the chemical elements—The scientific and social context of his discovery* (in Japanese) (Sapporo, 1997), 365-380 (English summary).

supply.[7] Mendeleev soon was deeply immersed in the capillarity of liquids, which eventuated in his doctoral thesis on alcohol solutions and his discovery of the critical point of liquids. He had time for a social life, mainly with Russian students or travelers. Those who left accounts of their encounters with him remarked that he was the center of the Russian student community, his powerful personality organizing and dominating his peers. As I.M. Sechenov recalled: "Mendeleev made himself, of course, the center of the circle, and all the more since, despite his youth (he is years younger than I), he was already a trained chemist, and we were students."[8]

Mendeleev was one of the few Russians to attend the first International Chemical Congress held in Karlsruhe in September 1860. As Dobrotin, who usually underestimated the impact of Mendeleev's foreign experiences on the development of the periodic system, recognized, the Karlsruhe Congress made a deep impression on the young chemist. The idea for the Congress began with the August Kekulé, who was eager to resolve crucial disagreements over the conventions of chemistry. Recent impressive advances in organic chemistry had flooded the discipline with a myriad of new compounds, each represented by a chemical formula and molecular weight that differed according to the theoretical commitments of the researcher. A major cause of the disparity was the number of volumes of the reference gas, commonly hydrogen, taken as the standard of comparison.

In the early 1850s, Charles Gerhardt, partisan of the type theory that Mendeleev would later use as the centerpiece of his organic chemistry work, proposed calibrating all compounds to a two-volume standard.[9] Mendeleev used the same convention in his master's thesis on isomorphism. Like Gerhardt, however, Mendeleev used the formulas inconsistently, occasionally preserving older values for some inorganic elements, perpetuating an oversight likely caused by Gerhardt's exclusive concern with organic compounds.[10] Some metals consequently had atomic weights half of today's recognized values. The resultant confusion was bound to exist as long as there remained separate conventions for inorganic and organic chemistry. Another contributor to the confusion was the imperfect distinction between "atomic weights" and "equivalent weights." For example, the equivalent weight of oxygen (from the relative weight of the compound water) was 8, while its atomic weight was 16. These were issues of convention. The chemists meeting in Karlsruhe did not contest matters of fact, but struggled to agree on a consensual

7. A.P. Borodin to Avdot'ia Konstantinovna Kleineka, 5 Nov 1859, in A.P. Borodin, *Pis'ma A.P. Borodina: Polnoe sobranie, kriticheski sverennoe s podlinnymi tekstami*, vol. 1 (Moscow, 1927-1928), 34; M.D. Mendeleeva, "Novye materialy o zhizni i tvorchestve D.I. Mendeleeva v nachale 60-kh godov," *Nauchnoe nasledstvo, 2* (1951), 85-94, on 90-92.

8. I.M. Sechenov, *Avtobiograficheskie zapiski Ivana Mikhailovicha Sechenova* (Moscow, 1945), 96-97.

9. Marya Novitski, *Auguste Laurent and the prehistory of valence* (Philadelphia, 1992), 64-68; J.R. Partington, *A history of chemistry*, vol. 4 (London, 1964), 419.

10. D.I. Mendeleev, *Polozheniia, izbrannyia dlia zashchishcheniia na stepen' magistra khimii*, 9 Sep 1856 (St. Petersburg, 1856), 4n and 5.

standard that would serve as a fundamental set of definitions for all chemists.

The appeal soliciting attendance was sent out on July 10, 1860 over the signatures of some of the most prominent names in chemistry, including Bunsen, Jean-Baptiste Dumas, Kekulé, Pasteur, Liebig, Mitscherlich, Adolphe Wurtz, and the Russian N.N. Zinin. It read in part:[11]

> Chemistry has reached a state of development when to the undersigned, it seems necessary that a meeting of a great number of chemists, active in this science, who are called upon to do research and teach, be held so that a unification of a few important points [can] be approached....Such a congress in the opinion of the undersigned would not be in the position to make definite binding conclusions, but through a thorough discussion misunderstandings might be removed.

Mendeleev, conveniently located nearby, could not pass up the opportunity to attend such an event. He was in good company. About 20 percent of the attendees had studied at Heidelberg.

The first meeting of the Congress, on Monday, September 3, consisted chiefly of a banquet for 120 people. Thus fortified, they heard a talk on Tuesday by Stanislao Cannizzaro, "an impromptu speech, at once remarkable both for profundity and style, [which] combated the ideas of M. Kékulé."[12] Cannizzaro dwelt on the definitions of atom and molecule, which bore on the debates over type theory within organic chemistry as well as on the determination of atomic weights. The definition Cannizzaro articulated was essentially Gerhardt's: a molecule is the smallest part of a compound and an atom is the smallest part of an element capable of entering into chemical combination. To resolve the main difficulty in specifying weights, Cannizzaro recommended accepting the old hypothesis of his countryman Amedeo Avogadro, which postulated that equal volumes of vapors at the same temperature and pressure contain equal numbers of molecules. Whatever the causes for the half-century neglect of this useful hypothesis,[13] Cannizzaro managed to inject it into the mainstream of chemistry, thus extending to inorganic compounds the atomic weight reform Gerhardt had offered a decade earlier.

By 1864, just over three years after the Congress, Cannizzaro's proposed reform of atomic weights based on Avogadro's hypothesis had conquered both inorganic and organic chemistry. Of great importance in this transformation was the role of pedagogy. Cannizzaro had come to recognize the utility of Avogadro's hy-

11. Quoted in Clara DeMilt, "The Congress at Karlsruhe," *Journal of chemical education* (1951), 421-425.

12. "The Congress of Chemists at Carlsruhe," *Chemical news, 2* (1860), 226-227; Aaron J. Ihde, "The Karlsruhe Congress: A centennial retrospect," *Journal of chemical education, 38* (1961), 83-86.

13. N.W. Fisher, "Avogadro, the chemists, and historians of chemistry: Parts I and II," *History of science, 20* (1982), 77-102, 212-231; John Hedley Brooke, "Avogadro's hypothesis and its fate: A case-study in the failure of case studies," *History of science, 19* (1981), 235-273.

pothesis through his extensive teaching. Not surprisingly, students assimilated a consistent method of atomic-weight determination more easily than they did the welter of the literature. As new textbooks proliferated in the 1860s, so did the new atomic weights, raising a new generation of chemists in the modern system.[14] The desire for pedagogical consistency had been one of the central motivations for holding the Congress and would be an important theme in the periodic law's creation.

Without the new atomic weights, Mendeleev's ordering of the periodic system would have been impossible. In turn, the periodic law served to further the regime of atomic-weight determination agreed to in Karlsruhe.[15] Mendeleev saw Cannizzaro's reform as the completion of Gerhardt's initial revision. As he stated in the first edition of the *Principles of chemistry* (1869), written before he produced the periodic system: "This law was guessed by Ampère and Avogadro, but Gerhardt expressed it, drew out its consequences and applied it to chemistry, although apparently he did not attribute to his discovery the great significance that his successors have uncovered [in it]. Henceforth this law is called 'Gerhardt's law.'"[16] Even after the formulation of the periodic law, ten years after Karlsruhe, Mendeleev insisted on explicitly citing the Karlsruhe regime for atomic-weight determination.[17]

Soon after Karlsruhe, on February 14, 1861, Mendeleev arrived back in St. Petersburg from his two years' study in Heidelberg. He returned encumbered with debt and with no prospects of making money soon. He recognized resignedly before he left Heidelberg that "in Russia I'll have to get a little poorer—not a big misfortune."[18] He had to find an apartment and obtain food in the northern winter, pay back a 1,000 ruble loan for the laboratory equipment he had purchased in Heidelberg, and locate resources for new equipment and research material. In the middle of the academic year he was unlikely to find a speedy appointment at one of the capital's many teaching establishments. Soon after his return he contacted the Social Good Press (*Obshchestvennaia Pol'za*) about a translation of J.R.

14. John Hedley Brooke, "Methods and methodology in the development of organic chemistry," *Ambix, 34* (1987), 147-155; Fisher (ref. 13), 218.
15. Fisher (ref. 13), 222; Mendeleev, "Estestvennaia sistema elementov (December 1870)," *MS*, II, 145.
16. D.I. Mendeleev, *Osnovy khimii* (1869), *MS*, XIII, 476. It is hard to see how M.G. Faershtein, "O roli D.I. Mendeleeva v utverzhdenii zakona Avogadro," *TIIEiT, 6* (1955), 68-85, and S.A. Shchukarev and R.B. Dobrotin, "O rabotakh D.I. Mendeleeva v oblasti atomno-molekuliarnoi teorii v period 1856-1859 gg.," *TIIEiT, 12* (1956), 3-11 could hold that Mendeleev independently discovered Avogadro's hypothesis. Mendeleev called Karlsruhe "the decisive moment in my thought on the periodic system." Quoted in S.A. Pogodin, "Otkrytie periodicheskogo zakona D.I. Mendeleevym i ego bor'ba za pervenstvo russkoi nauki," *Nauka i zhizn'*, no. 3 (1949), 37-40, on 37.
17. Mendeleev in protocol of the Russian Chemical Society, 12 Oct 1872, *MS*, II, 224-225.
18. Mendeleev diary entry, 11 Jan 1861 (N.S.), in D.I. Mendeleev, "Dnevnik 1861 g.," *Nauchnoe nasledstvo, 2* (1951), 111-212, on 115; T.V. Volkova, "Molodoi Mendeleev i otechestvennaia promyshlennost'," *Zhurnal prikladnoi khimii, 20*, no. 6 (1947), 469-473.

Wagner's German text on chemical technology and about a contract for his own proposed organic chemistry textbook, sorely needed for Russian higher education.[19]

It was the beginning of a rapid rise. By 1871 Mendeleev was Professor of General Chemistry at St. Petersburg University, the most important chemistry chair in the country. He taught the lucrative first-year course, which was light in workload and attracted a large number of fee-paying students, all of whom used his new textbook, the *Principles of chemistry*. He had published two highly successful textbooks, joined the ranks of the Ministry of Finances as advisor on alcohol taxation and agricultural reform, and served as a private consultant for the burgeoning Baku oil industry.

2. ST. PETERSBURG UNIVERSITY AND THE RUSSIAN CHEMICAL SOCIETY

The Russian university began to come into its own only at the beginning of the 19th century. In 1809, legislation made university-level examinations mandatory for advancement up the bureaucratic system. The educational statute of 1835, which prescribed the administrative regulations of the educational system as a whole, further cemented the connection between education and the bureaucracy.[20] Attending university in the Imperial capital was perceived as the surest way to advancement. The Emancipation of 1861 changed the situation. Once legally freed of their obligations to the landowners, former serfs and sons of serfs began to attend the universities. During the 1860s and 1870s, 40 to 60 percent of university students needed and received financial assistance, and 2,000 a year received tuition exemptions.[21] This was particularly so at St. Petersburg University, which in fall 1861 became the center of student turmoil.

The unrest that broke out that September resulted from the slowness of the bureaucracy to adapt to new views about the body politic generated by the policies of Alexander II. During the spring and summer of 1861, new regulations substantially relaxed restrictions on student assembly and university policing. These changes were kept secret and not published until the very last minute; rumors gave

19. N.A. Figurovskii, *Dmitrii Ivanovich Mendeleev, 1834-1907* (Moscow, 1961), 56; Nathan Marc Brooks, "The formation of a community of chemists in Russia: 1700-1870" (Ph.D. dissertation, Columbia University, 1989), 402; K.Ia. Parmenov, *Khimiia kak uchebnyi predmet v dorevoliutsionnoi i sovetskoi shkole* (Moscow, 1963).
20. Patrick L. Alston, "The dynamics of educational expansion in Russia," in Konrad H. Jarausch, ed., *The transformation of higher learning, 1860-1930: Expansion, diversification, social opening and professionalization in England, Germany, Russia and the United States* (Stuttgart, 1982), 89-107; Cynthia H. Whittaker, *The origins of modern Russian education: An intellectual biography of Count Sergei Uvarov, 1786-1855* (DeKalb, IL, 1984).
21. Michael Pushkin, "*Raznochintsy* in the university: Government policy and social change in nineteenth-century Russia," *International review of social history, 26* (1981), 25-65, on 36; Alston (ref. 20).

the impression that the reforms were moving towards stricter regulation; and the students walked out. The collapse of the old inspection system in institutions of higher education after the loss of the Crimean War in 1855 and the influx of poorer students dispersed in inexpensive housing all over St. Petersburg allowed the situation to explode into rampant protests on the streets.[22] The professoriate was caught in the middle. Uneasy in their role as civil servants, unaccustomed to enforcing police orders, and under pressure by their own liberal sympathies and the desire to gain popularity among the student body, professors throughout the Imperial period walked a tightrope. Their sympathies made them unreliable in the eyes of the Ministry of Popular Enlightenment, their employer, and, when they followed orders, they drew the antipathy of their students. The professoriate never managed to cobble together a workable compromise.[23]

Mendeleev was eyewitness to the disorders in the capital and supported the government's solution to the stalemate in Petersburg, the University Statute of 1863. (St. Petersburg University remained closed into 1862 and did not resume normal operations until fall 1863.) Mendeleev became an eyewitness because when the riots broke out he was at the university in search of financial support. He had approached his undergraduate mentor, A.A. Voskresenskii, professor of chemistry at St. Petersburg University, lauded by his many students as the "grandfather of Russian chemistry."[24] On March 25, 1861, Voskresenskii offered him a position lecturing on practical chemistry at the Free Economic Society, but Mendeleev, who was already writing *Organic chemistry*, turned it down since it would take time and provide no resources for experimentation. He wrote in his diary: "Life flows smoothly and uniformly. Work, only work illuminates this gloom."[25] Mendeleev worked on his textbook for the remainder of that summer, secured a docent position for the fall, and gravitated to the university when courses were to begin.

The student disturbances started on September 7. On the 23rd Mendeleev gave a lecture, filling in for Voskresenskii, and worried: "Is it my last one?" He rushed "to get to the more interesting [part], to the new, to the Gerhardtian revolution." Gerhardt was the bearer of a positive form of "revolution" as contrasted with the negative unrest raging on the streets. Police had received authorization to shoot and beat students: "Horrible things. It is impossible that this went through the

22. William L. Mathes, "The origins of confrontation politics in Russian universities: Student activism, 1855-1861," *Canadian slavic studies, 2* (1968), 28-45, esp. 31-39.
23. Samuel D. Kassow, *Students, professors, and the state in Tsarist Russia* (Berkeley, 1989), 5-6.
24. N.A. Figurovskii and K.Ts. Elagina, "Aleksandr Abramovich Voskresenskii (1809-1880)," *TIIEiT, 18* (1958), 213-235; Iu. V. Pletner, *Dedushka russkoi khimii* (Kalinin, 1959); A.A. Makarenia, "A.A. Voskresenskii i ego nauchnaia shkola," *VIET*, no. 11 (1961), 141-144. Mendeleev wrote an obituary for Voskresenskii in the Petersburg daily *Golos* (23 Jan 1880) and an encyclopedia entry on his life; *MS*, XV, 335, 625, resp.
25. Mendeleev (ref. 18), 138.

hands of the ministers and the sovereign in our times."[26] The problem, as Mendeleev saw it, was that there was inadequate mediation and advising between the government and the students. The next day the university was shut down until further notice.

The University Statute of 1863 resulted in the recruitment of nineteen new professors per university (mostly in the natural sciences) and a considerable gain in institutional autonomy. The statute provided for faculty election of deans, faculty disciplinary jurisdiction over student behavior, tenure within the university without brokering by the Ministry, and money to aid poor students. The statute of 1863 came closer than any other university legislation during the Imperial period to meeting the demands of the professoriate.[27] The statute was a ramshackle collection of regulations designed to bolster the professionalization of science and academics. The absence of a unified philosophy of the relations between universities and the government meant that, ironically, the more successful the professionalization of the schools, the more the government regarded them as hotbeds of dissent, and the less the proposed "moral bond" between faculty and students seemed able to provide stability.[28]

After the concordat of 1863, Mendeleev advanced into more and more secure academic positions, including St. Petersburg University, where he would remain until 1890. On December 19, 1863 he was hired as an extraordinary professor of chemistry by the Technological Institute in Petersburg, a technical training school founded by Tsar Nicholas I to provide engineering education for a modernizing Russia, and was confirmed by the Ministry of Finances (which ran this particular school, just as the Ministry of Popular Enlightenment controlled the university) in late January 1864. He had a moderate teaching load (compared to the previous generation of chemists) consisting of three lectures a week on organic chemistry for sophomores, one lecture a week on analytic chemistry for upperclassmen, and the supervision of laboratory exercises. He became an ordinary professor of technical chemistry in late 1865. In that year he was also appointed extraordinary professor of general chemistry at the university. He held both jobs simultaneously, but not equally. The Technological Institute claimed less and less of his time after he succeeded Voskresenskii in October 1867 and became department head for the chemistry division of the physico-mathematical faculty the following year. He resigned his post at the institute in 1871, after calculating that he no longer needed the extra income and after petitioning to have his laboratory teaching load elimi-

26. Mendeleev (ibid.), 170-171.
27. Allen Sinel, *The classroom and the chancellery: State educational reform in Russia under Count Dmitry Tolstoi* (Cambridge, 1973), 30-31; Samuel D. Kassow, "The University Statute of 1863: A reconsideration," in Ben Eklof, John Bushnell, and Larissa Zakharova, eds., *Russia's great reforms, 1855-1881* (Bloomington, 1994), 247-263, on 249.
28. Kassow (ref. 27), 256; Mathes (ref. 22), 43; R.G. Eimontova, *Russkie universiteti na grani dvukh epokh: Ot Rossii krepostnoi k Rossii kapitalisticheskoi* (Moscow, 1985), 322.

nated or reduced.[29] The university gave him the institutional base to train new chemists. To organize them after graduation, he and other established chemists endeavored to create a viable chemical community in Petersburg.

Early efforts to provide an infrastructure for a chemical community outside of the universities included the attempt by chemists N.N. Sokolov and A.N. Engel'gardt to establish a private chemical laboratory in St. Petersburg with an ancillary *Chemical journal* (*Khimicheskii zhurnal*) that would publish the researches of Russian chemists in their native language. That obviated the need to publish almost every finding in French or German in the journals of the St. Petersburg Academy of Sciences, or in the pro-Russian *Zeitschrift für Chemie*.[30] These domestic efforts collapsed in the 1850s owing to internal conflicts and inadequate local support. The German journals continued to provide the principal outlets until the late 1860s. The state's program, consequent to the Crimean defeat, of letting Russian science students study abroad prompted an end to the stalemate between the groupings of Russian chemists. Mendeleev's experience in Heidelberg as the center of a chemical circle that included A.P. Borodin, V. Savich, V.I. Olevinskii, P.P. Alekseev, A.S. Famintsyn, N.P. Il'in, and I.A. Vyshnegradskii gave him and them a strong sense of community. On their return home, they resolved to continue their joint activities.[31]

A formal organization was now legally easier than before as a consequence of the Great Reforms. The loosening of rigid restrictions against independent (non-state) organizations and free assembly caused charters for new voluntary associations, from charitable societies to learned gatherings, to proliferate in the 1860s. When it came into being, the Russian Chemical Society emerged in this atmosphere of Emancipation, when the autocratic state encouraged groups to encroach on its monopoly of the public sphere.[32] Russian chemists had turned to the Free

29. RGIA, f. 733, op. 158, d. 45, ll. 45-46ob.; A.Ia. Averbukh and A.A. Makarenia, *Mendeleev v Tekhnologicheskom Institute* (Leningrad, 1976).
30. Iu.S. Musabekov, "Pervyi russkii khimicheskii zhurnal i ego osnovateli," in N.A. Figurovskii et al., eds., *Materialy po istorii otechestvennoi khimii* (Moscow, 1953), 288-302; Nathan M. Brooks, "Russian chemistry in the 1850s: A failed attempt at institutionalization," *Annals of science, 52* (1995), 577-589. The *Zeitschrift für Chemie*, functionally the organ of the Russian chemical community until the *ZhRFKhO* was established in 1869, was a German periodical that catered to Russian publications. G.V. Bykov and Z.I. Sheptunova, "Nemetskii 'Zhurnal Khimii' (1858-1871) i russkie khimiki. (K istorii khimicheskoi periodiki)," *TIIEiT, 30* (1960), 97-110.
31. V.V. Kozlov, *Vsesoiuznoe khimicheskoe obshchestvo imeni D.I. Mendeleeva, 1868-1968* (Moscow, 1971); Brooks (ref. 19), and N.M. Brooks, "The evolution of chemistry in Russia during the eighteenth and nineteenth centuries," in David Knight and Helge Kragh, eds., *The making of the chemist: The social history of chemistry in Europe, 1789-1914* (Cambridge, 1998), 163-176; T.V. Volkova, "Russkoe fiziko-khimicheskoe obshchestvo i Petersburgskii-Leningradskii universitet," *Vestnik leningradskogo universiteta*, no. 5 (1950), 120-125.
32. Joseph Bradley, "Voluntary associations, civic culture, and *obshchestvennost'* in Moscow," in Edith W. Clowes, Samuel D. Kassow, and James L. West, eds., *Between Tsar and*

Economic Society as one of the few forums willing to grant a hearing to young scholars in the natural sciences. This society, founded by Empress Catherine the Great in 1765 as an independent consulting body for the state on agricultural matters, lost influence when Emancipation undercut the need for many of its services, and even the good offices of chemist A.I. Khodnev, the society's president, could not keep chemists interested in it.[33]

Active agitation for a chemical society began in the daily newspapers of the capital, one of the benefits of the loosening of censorship. An anonymous note in the *Russian invalid* on August 17, 1861, probably written by Mendeleev, stated the case clearly:[34]

> A chemical society, in our opinion, is entirely possible in Petersburg. Our most famous chemists—Voskresenskii, Zinin, Mendeleev, Sokolov, Shishkov, Khodnev, and Engel'gardt—live there, and in general in Petersburg many young people study chemistry. Why can't our scientists gather around themselves an entire society?
>
> We consider it unnecessary to discuss the utility of such a society. Under the society there could be a public laboratory, which there isn't in Petersburg at this time. The university laboratory is too small and serves only for university students....It is too hard to get access to the Academy's laboratory....It is almost impossible to study physics in Petersburg. We suggest that it is possible to find funds, although, of course, with great difficulty; but is it necessary to prove to anyone the danger of isolated studies? The establishment of a physico-chemical society could enable the publication of a "Chemical Journal," in which a division could also be opened for physics.

In the end, the Russian Chemical Society was founded without a physics complement, which came into being in the early 1870s and was fused to it in 1878.

Not every chemist (or physical scientist) in the capital wanted a formal society. Recognition meant publication, but it also meant a degree of official scrutiny. Mendeleev noted that N.I. Lavrov, N.P. Fedorov, N.P. Nechaev, A.K. Krupskii, F.K. Beilstein, Mendeleev himself, Iu. F. Fritzsche, F.R. Vreden, N.A. Menshutkin, V.F. Petrushevskii, E.F. Radlov, G.A. Shmidt, V.V. Bek, P.P. Alekseev, F.N. Savcheikov, G.V. Struve, and L.N. Shishkov favored formality, and that A.R. Shuliachenko, A.N. Engel'gardt, P.A. Lachinov, and G.G. Gustavson opposed it.[35]

people: Educated society and the quest for public identity in late Imperial Russia (Princeton, 1991), 131-148; E.V. Soboleva, *Organizatsiia nauki v poreformennoi Rossii* (Leningrad, 1983), 142-160.
33. V.V. Oreshkin, *Vol'noe ekonomicheskoe obshchestvo v Rossii, 1765-1917* (Moscow, 1963); N. A. Figurovskii and Iu. I. Solov'ev, "Aleksei Ivanovich Khodnev," *TIIEiT, 2* (1954), 19-45.
34. "Vnutrennie izvestiia," *Russkii Invalid*, no. 17 (17 Aug 1861), p. 733, quoted in Kozlov (ref. 31), 13.
35. Kozlov (ref. 31), 13-14.

After a series of petitions to the Ministry of Popular Enlightenment, the formalists prevailed. In January 1868, the first Russian Congress of Natural Scientists and Physicians took place in St. Petersburg, part of a government effort to sponsor communication among Russian naturalists. The Chemical Division of the congress turned the occasion into a plea for a chemical society. Their petition read in part: "The chemical section stated a unanimous desire to form a Chemical Society for gathering Russian chemists, whose forces are already formed. The section proposes that this Society have members in all Russian cities and that its publication include the works of Russian chemists, printed in Russian. The section asks the Congress to petition for the establishment of a Russian Chemical Society."[36] The proposed charter, revised three times that year, was approved on October 26. At the first organizational meeting on November 6, Mendeleev presided until N.N. Zinin was elected the first president.[37] The Chemical Society had been formed, in the spirit of the University Statute of 1863, as part of the government's willingness to let scholars manage their own affairs.

Petersburgers comprised forty-one of the original members, compared with four from Moscow, two from Kiev, and a few from other areas.[38] This centering of the Society on Petersburg had marked implications for Mendeleev's activities in the organization. On the one hand, given that he taught the most popular chemistry course at the university, a large proportion of the incoming members had some personal relationship with him. In addition, through its journal, Mendeleev could address not only a national audience—impossible from the local "chemical circles" he had organized earlier in the decade—but also an international one.[39] This journal carried Mendeleev's first writings on the periodic system. Had he had only the university audience, his textbook would have been sufficient; the presence of the Society, created three months before the formulation of the system of elements, prompted him to publish his findings more broadly.

3. THE PRINCIPLES OF CHEMISTRY

B.M. Kedrov gave a painstaking microhistorical investigation of the course of Mendeleev's discovery of the periodic law, which he localized to a single day, February 17, 1869.[40] Kedrov's central contribution was to couple Mendeleev's

36. Quoted in V.V. Kozlov and A.I. Lazarev, "Tri chetverti veka Russkogo khimicheskogo obshchestva," in S.I. Vol'fkovich and V.S. Kiselev, eds., *75 let periodicheskogo zakona D.I. Mendeleeva i Russkogo khimicheskogo obshchestva* (Moscow, 1947), 97-114, on 128.

37. V.A. Krotikov, "K istorii organizatsii Russkogo khimicheskogo obshchestva," *VIET*, no. 13 (1962), 83-88, on 83.

38. Kozlov and Lazarev (ref. 36), 134-135; Brooks (ref. 19), 541.

39. D.I. Mendeleev, "Pis'mo v redaktoru-izdateliu A.V. Peliu (1892)," *Zhurnal meditsinskoi khimii i farmatsii*, reprinted in *MS*, XV, 619-621.

40. B.M. Kedrov, *Den' odnogo velikogo otkrytiia* (Moscow, 1958); *Filosofskii analiz pervykh trudov D.I. Mendeleeva o periodicheskom zakone* (Moscow, 1959); *Mikroanatomiia velikogo otkrytiia: K 100-letiiu zakona Mendeleeva* (Moscow, 1970); and the compelling criticism

construction of the periodic system to the writing of the first edition of his *Principles of chemistry* (1869). Kedrov's realization of the importance of textbooks in creating communities antedated by several decades the plethora of recent studies that argue the same point at great length. Textbooks not only codify knowledge but may also serve as valuable tools for exploring the sociological construction of a scientific discipline. Particularly in chemistry, which underwent tremendous transformations during the 19th century centered on the definitions of basic terms (affinity, valency, atom, element, atomic weight, molecule), textbooks created the set of standard concepts they codified. Mendeleev's *Organic chemistry* of 1861, discussed below, is another clear instance of this discipline building.

In 1860, Russia was still largely dependent on translations of foreign textbooks. Earlier in the century, when chemical knowledge developed comparatively slowly, the inevitable delays in publication of translations did little damage; but after Karlsruhe changes came so rapidly that any textbook would be outdated by the time its translation appeared in print. In addition, foreign texts, like A. Cahours's *Cours* (Russian translation, 1859-1862), which Mendeleev helped to translate, were pedagogically handicapped by their lack of a coherent structure to introduce inorganic chemistry.[41] Cahours's text was commonly used before Mendeleev's *Principles* appeared, and thus offers a useful contrast to it. Cahours split the elements into "metals" and "non-metals," and then treated the two groups in dictionary style, giving a catalog of properties of one element without substantial comparison with similar properties in other elements.

This technique, and similar uninspired arrangements in other books, caused the journal *Teacher* (*Uchitel'*) to bemoan in 1866: "The [curricular] program in chemistry is worked out in the weakest fashion of all. The course of inorganic chemistry is built on the plan of our textbooks in this science; instead of a concept of chemical phenomena, of simple and complex bodies, [the course] traces a completely disconnected description of all elements and their most important compounds."[42]

Mendeleev's future colleague A.M. Butlerov lamented in 1859 that the lack of chemical textbooks is "the chief obstacle to the dissemination of chemical knowledge in Russia." A good one, he predicted, would create new theoretical frameworks that would further the science itself.[43] There was pressure and opportunity

of the one-day thesis in D.N. Trifonov, "Versiia-2. (K istorii otkrytiia periodicheskogo zakona D.I. Mendeleevym)," *VIET*, no. 2 (1990), 24-36, no. 3 (1990), 20-32. Kedrov makes his case in English in "Mendeleev, Dmitry Ivanovich," in Charles Coulston Gillsipie, ed., *Dictionary of scientific biography* (New York, 1980), *9*, 286-295; cf. Loren R. Graham, "Textbook writing and scientific creativity: The case of Mendeleev," *National forum* (Winter 1983), 22-23.

41. A. Kagur [Cahours], *Kurs elementarnoi khimii*, tr. I.Il'in and D. Dverkiev (2 vols., St. Petersburg, 1859-1862).

42. Quoted in Parmenov (ref. 19), 56.

43. A.M. Butlerov, "Zametki po povodu 'Predlozheniia o naznachenii komissii dlia sostavleniia khimicheskoi russkoi nomenklatury,'" *Moskovskie vedomosti*, no. 168 (17 Jul

for someone to write a textbook that synthesized inorganic chemistry in a pedagogically useful format; sizable profits might accrue from university sales and from adaptations for lower-level students. This is what the *Principles of chemistry* did, and what Mendeleev had intended it to do. Its first edition (1869-1871) was quickly adapted for chemistry students at every level.[44]

Mendeleev started writing his textbook of inorganic chemistry (or "general chemistry," as he liked to call it) in 1868 for the freshman chemistry course he had taken over upon succeeding to Voskresenskii's chair in October 1867. This large lecture course lasted all year. It contained integrated laboratory demonstrations meant to provide an introduction to all students in the natural sciences faculty. Mendeleev lectured, assistants supervised the laboratory. The lecture required a text; Mendeleev provided one, in two volumes with two parts each.[45] When he began his work in 1868, there were sixty-three known elements for him to discuss in a pedagogically useful fashion. Instead of employing the dominant division into metals and metalloids, Mendeleev structured his first volume around the chemical practices through which knowledge of the chemical world was acquired. In an early part of volume 1, written before the inception of the periodic system in February 1869, Mendeleev defined chemistry as follows: "[Chemistry] is a natural science that describes homogeneous bodies, studies the specific phenomena by which such bodies undergo transformations into new homogeneous bodies, and as an exact science it strives…to attribute weight and measure to all bodies and phenomena, and to recognize the exact numerical laws that govern the variety of its studied forms."[46] There is no concept of element here, nor any theory of chemical combination.

Volume 1 is littered with basic definitions, plans for chemical experiments to be performed by the students, and natural historical information. The first and second chapters define homogeneity, simple substances, and compound substances, and posit the laws of conservation of mass and the immutability of chemical elements. Mendeleev first listed the elements alphabetically by symbol, included qualitative data (color, smell) as descriptors, and did not indicate their atomic weights.[47] Chapter 3 begins with water, its properties, its provenance, and methods to obtain it in a pure state. This pattern repeats itself with other substances. In Chapter 4, when he discussed water solutions, Mendeleev expanded on chemistry as the study of homogeneity. He gradually led his readers from nature into the laboratory, and into deeper and deeper levels of analysis. He postponed introducing equivalents to Chapter 7 and the atomic hypothesis to Chapter 10.[48]

1859), reprinted in A.M. Butlerov, *Sochineniia* (3 vols., Moscow, 1953-1958), *3*, 141-144, quotation on 143.

44. Parmenov (ref. 19), 65-71; and Brooks (ref. 19), 503.

45. I. Kablukov, "Obzor izdanii 'Osnov khimii' D.I. Mendeleeva," in D.I. Mendeleev, *Osnovy khimii*, 9th edn. (2 vols., Moscow, 1927), *1*, xli-xlvi.

46. *MS*, XIII, 60-61.

47. *MS*, XIII, 77-82.

48. See *MS*, XIII, 277, on equivalents.

The periodic system is often viewed as an outgrowth of Mendeleev's support of atomism. It is true that physical atomism was contested in the 19th century and that the periodic law eventually served as one of the strongest arguments in its favor.[49] Mendeleev recapitulated this path. In his master's thesis of 1856, he explained that although the atomic hypothesis was a useful explanation, "it does not possess even now a part of that tangible visualizability, that experimental reliability, which has been achieved, for example, by the wave hypothesis, not to mention Copernicus's theory, which can no longer be called a hypothesis."[50] In a lecture on theoretical chemistry in 1864, Mendeleev argued that since definite compounds pointed towards atomic theory and indefinite compounds (like solutions) pointed away from it, "the foundation for the creation of the atomic system should not be sought in chemistry."[51] Mendeleev remained of two minds about atomism, preferring "elemental weight" to "atomic weight" as carrying less metaphysical baggage, and accepting atomism (as late as 1903!) as only a "superior generalization," chiefly valuable for its pedagogical usefulness.[52] Atomism only figures in the first edition of the *Principles* in these pedagogical terms.

Mendeleev began to near the periodic system in Chapter 20: Table salt. By then he had treated only four elements in detail: oxygen, carbon, nitrogen, and hydrogen, the so-called "organogens." Precisely these elements provided the link between type theory and the periodic law. Mendeleev opened the salt chapter as usual by identifying its sources in seawater or mines. There followed a discussion of sodium and chlorine, and then the halogens. Thus, in late January 1869, Mendeleev had sent volume 1 off to the publishers, but had only dealt with eight elements, one-eighth of the total.[53] He needed a more efficient organizational method for volume 2 if he was to finish his book in the agreed time and space. As he recalled in his first research article on the periodic law in April 1869:[54]

> Having undertaken the compilation of a guidebook to chemistry, called "The Principles of Chemistry," I had to set up simple bodies in some kind of system so that

49. Alan J. Rocke, *Chemical atomism in the nineteenth century: From Dalton to Cannizzaro* (Columbus, 1984); Mary Jo Nye, "The nineteenth century atomic debates and the dilemma of an 'indifferent hypothesis,'" *Studies in history and philosophy of science, 7* (1976), 245-268; David M. Knight, *Atoms and elements: A study of theories of matter in England in the nineteenth century* (London, 1967); W.H. Brock, ed., *The atomic debates: Brodie and the rejection of the atomic theory* (Leicester, 1967).

50. *MS*, I, 15.

51. From a published typescript (1864), ADIM II-A-17-9-5, reprinted in D.I. Mendeleev, *Izbrannye lektsii po khimii* (Moscow, 1968), 25.

52. Quotations from D.I. Mendeleev, "Periodicheskaia zakonnost' khimicheskikh elementov (1871)," in D.I. Mendeleev, *Novye materialy po istorii otkrytiia periodicheskogo zakona*, ed. N.A. Figurovskii (Moscow, 1950), 21; and in the seventh edition of *Osnovy khimii* (1903), *MS*, II, 448.

53. Kedrov, *Den' odnogo velikogo otkrytiia* (ref. 40), 21.

54. Mendeleev, "Sootnoshenie svoistv s atomnym vesom elementov," *ZhRFKhO, 1*, no. 2-3 (1869), 60-77, reprinted in *MS*, II, 3-16, quotation on 7; S.A. Shchukarev, "D.I. Mendeleev

> their distribution was not governed by accidents, by instinctive guesses, but by some definite exact principle. [In contemporary chemistry] we see the almost complete absence of numerical relations in the establishment of a system of simple bodies; but any system based on exactly observed numbers, of course, will already in this manner deserve preference over other systems that do not have numerical foundations, in which there remains little place for arbitrariness.

Mendeleev's old organizational system in terms of laboratory practices could no longer sustain the burden of exposition. Mendeleev needed a new system and hit on the idea of using a numerical marker for each element. Atomic weight was the most likely candidate. Mendeleev now had to construct a system that would account for all the remaining elements in a limited space while maintaining his pedagogical standard. His solution, the periodic system, remains one of the most useful teaching tools in chemistry.

Early in February 1869, while Mendeleev was writing Chapter 2 of volume 2 on the alkali metals, he listed them in order of increasing atomic weight and compared them with the halogens, similarly arranged. By examining a set of five documents that were (possibly) written on February 17, Kedrov has argued that Mendeleev came to see that the numerical increase of atomic weights within each family followed a similar arithmetical pattern.[55] By Chapter 4, on the alkaline earths, Mendeleev was entirely converted to the periodic system as an organizational scheme; he began on the first page of this chapter to show that the arithmetical difference between rows follows a similar pattern in all three groups: halogens, alkali metals, and alkaline earths.[56] These elements, with a valency of two, succeeded the alkali metals, with a valency of one. While Mendeleev still resisted valency theory, his system followed the progression of combining power across the elements. Atomic weight here was a secondary quality that showed the hierarchical ordering within families. As volume 2 proceeded, Mendeleev elevated atomic weights to a position of dominance so that they were listed even in chapter titles (as in Chapter 12), and elements were always introduced with their atomic weight.

Kedrov argues that Mendeleev came to his periodic system of elements by comparing groups, not by building rows. Traditionally, historians assumed Mendeleev placed the elements in order of increasing atomic weight and then found periodic repetitions. Mendeleev himself offered this explanation in his first article on the system in April 1869.[57] Kedrov stressed, however, and it is evident in the *Principles*, that the system was constructed by building groups and then making comparisons between them.[58] For Kedrov, these groups were families organized

i Leningradskii gosudarstvennyi universitet," *Vestnik Leningradskogo universiteta*, no. 6 (1947), 148-154, on 150.

55. Kedrov, *Den' odnogo velikogo otkrytiia* (ref. 40), 24-26.

56. *MS*, XIV, 122.

57. *MS*, II, 11-12.

58. Kedrov's "group" analysis is criticized in K.G. Khomiakov, "K istorii otkrytiia

by chemical affinity according to atomic weight. It is better to regard these eight "groups" as types in a sense derived from Mendeleev's earlier organic textbook. Mendeleev had found classification by "types" or "sorts" pedagogically useful in his textbook, and he turned to it again in 1869 when his practice-oriented pedagogy threatened to burst the bounds of his inorganic text.

The critical acclaim that greeted the *Principles* also points in this direction. Several reviews compared his new text and his *Organic chemistry*. A reviewer of volume 1 from August 1869 (before the publication of the periodic system) was bewildered by its structure: "The very order of exposition of the *Principles of chemistry* is significantly different from the exposition generally employed in other textbooks, which are all more or less similar to each other." Confused by the voluminous text that detailed mostly four elements, the author lamented that while the book was a welcome introduction to inorganic chemistry, "the *Principles of chemistry* can hardly have the same significance for people who study chemistry as the same author's *Organic chemistry* had."[59]

Mendeleev had experimented with many different presentations of inorganic chemistry in lectures in the 1860s. Before the *Principles* his preferred format was closely akin to that of volume 1: use common substances to elucidate the most basic elements, then add the halogens and alkali metals. Mendeleev used a wide variety of approaches for the other elements.[60] The periodic system was the most useful of these, as he wrote in 1871: "I note also that the outlining of the facts of chemistry and their generalization for beginners benefits very much from using the periodic law, as I became convinced not only in lectures in the last two years, but also upon the preparation of a course of inorganic chemistry I published (in Russian), now finished. I placed the periodic law at the foundation of the presentation."[61] Even in his research articles, such as his note on peroxides, Mendeleev stressed the experiments' benefits for the beginning student.[62]

4. TYPE THEORY AND THE PERIODIC SYSTEM

When Mendeleev returned to Petersburg from Heidelberg in February 1861, his oeuvre consisted of research on isomorphism, specific volumes, and the capillarity of organic solutions. He was not a luminary among the St. Petersburg chem-

periodicheskogo zakona D.I. Mendeleeva," *Vestnik Moskovskogo universiteta*, no. 12 (1953), 17-23.

59. Review of volume 1 of *Osnovy khimii* from *Vsemirnaia illustratsiia, 2*, no. 33 (9 Aug 1869), 111-112, reprinted in D.I. Mendeleev, *Nauchnyi arkhiv, t.1. Periodicheskii zakon*, ed. B.M. Kedrov (Moscow, 1953), 215-216. Another review by K. Lisenko in the *Gornyi zhurnal* (1871) of both volumes began with praise for *Organic chemistry*. Ibid., 762.

60. Lecture notes from 1864 and 1870, in Mendeleev (ref. 51).

61. Mendeleev (ref. 52), 43. Similar statements appear in almost every subsequent publication by Mendeleev on the periodic law.

62. Mendeleev, "Zametka o perekisiakh," *MS*, II, 218.

ists and bore the reputation of a competent organic chemist.[63] So when Mendeleev had to earn money quickly, and textbook writing seemed to be one of the best ways to guarantee a stable income, an organic textbook was the logical choice. There was little to choose from in the Russian language. Also, he knew he could submit his own textbook for the Demidov Prize of the Academy of Sciences, potentially earning yet more money. Mendeleev started writing *Organic chemistry* on February 28, 1861, two weeks after his return. He soon became absorbed in writing, as his diary entries attest: "Wrote and wrote all day. Finished the introduction. Getting kind of ill. Sit a lot" (March 3); "This chemistry has already started to bore me, but I have to work hard and quickly" (April 26); "I can't ever again work on anything [as hard] as I worked on this book" (June 8). Early reception of the text among his friends was favorable: "They read my Chemistry and made many comments, but in general it went better than I had expected—they liked it" (March 10).[64] The final text covered over 600 pages. He submitted it for the Demidov Prize and—two of his patrons, N.N. Zinin and Iu.F. Fritzsche, were the deciding committee—won. "This will be helpful to me not only in money" (April 6, 1862).[65] Shortly afterward Mendeleev considered himself financially secure enough to propose to Feozva Nikitichna Lesheva.

In the judgment of Fritzsche and Zinin, most textbooks were either an abbreviation of data under a particular system or a catalog of limited facts. Not Mendeleev's: "Mr. Mendeleev's book *Organic chemistry* presents us with the rare occurrence of an autonomous development of a science in a brief textbook; a development, in our opinion, which is very successful and in the highest degree appropriate to the mission of the book as a textbook."[66] Students also were enthusiastic. N.A. Menshutkin, Professor of Analytic Chemistry at St. Petersburg University, recalled in 1880: "I remember with what interest we, still students, greeted the appearance in 1861 of his *Organic chemistry*. At that time this book was the only one in Russia, standing at the height of science, distinguished even in comparison to foreign works in its interest, clarity of exposition, and completely unique integrity."[67] The book came out in two editions, 1861 and 1863, before being entirely

63. K. Timiriazev, *Razvitie estestvoznaniia v Rossii v epokhu 60-kh godov* (Moscow, 1920), 22; V.M. Rodionov, "D.I. Mendeleev kak organik," in A.F. Kapustinskii, ed., *D.I. Mendeleev—Velikii russkii khimik* (Moscow, 1949), 132-138; and *MS*, VIII.

64. Excerpts from Mendeleev (ref. 18), 134, 136, 143, and 149.

65. Mendeleev (ref. 18), 237.

66. "Razbor sochineniia D.I. Mendeleeva 'Organicheskaia khimiia,' sostavlennyi akademikami Iu.F. Fritsshe i N.N. Zininym," 25 May 1862, reprinted in G.A. Kniazev, "D.I. Mendeleev i tsarskaia Akademiia nauk (1858-1907 gg.)," *Arkhiv istorii nauk i tekhniki, 6* (1935), 299-331.

67. Quoted in B.N. Menshutkin, *Zhizn' i deiatel'nost' Nikolaia Aleksandrovicha Menshutkina* (St. Petersburg, 1908), 7. K.A. Timiriazev similarly praised the text in 1939: "In the beginning of the sixties [Mendeleev] was primarily an organic chemist; his excellently clear and simply articulated textbook, *Organic chemistry*, was peerless in European literature, and who knows precisely how much this book helped the next generation of Russian chemists

eclipsed by A.M. Butlerov's structure-theory textbook, *Introduction to a complete study of organic chemistry* (1864).[68] Mendeleev's book was among the last of its kind, defending type theory as it was being erased by structure theory.

Type theory was in mid-19th-century Europe the cutting edge of organic chemistry, overturning the theories of Lavoisier and Berzelius in a fit of positivism. The explosion of data in organic chemistry, particularly the discovery of substitution reactions, made revising Berzelian electrochemical dualism necessary. Berzelius had generalized to organic chemistry Lavoisier's analysis of combination in inorganic chemistry, arguing that all compounds were composed of two parts, one electropositive and one electronegative, which neutralized each other upon chemical combination.[69] The direction of the analogy is important: from inorganic to organic. Gerhardt reversed this pattern, modeling inorganic reactions on organic ones. The discovery of chlorine substitution led to the downfall of the electrochemical theory of organic compounds. Methane, which has one carbon atom for four hydrogen atoms, can substitute a chlorine atom for one of its hydrogens without radically changing its properties. On Berzelius' theory, replacement of electropositive hydrogen with electronegative chlorine should have had a major effect. A new breed of organic chemistry was created which no longer focused on how combination occurred, but on how the cornucopia of new compounds could be classified.

Charles Frédéric Gerhardt (1816-1856) was one of the most influential chemical thinkers of the 19th century. He was born in Strasbourg to a merchant family and there developed the bilingualism in French and German that would enable him to communicate between two distinct chemical traditions. He attended the Polytechnicum in Karlsruhe in 1831/2, then business school in Leipzig in 1833, and took over the family lead-carbonate business in 1834, as his father had intended. The next year he fled to Giessen to work with Liebig until 1837, when he returned home again only to abandon the business for good to study with Dumas in Paris.[70] Of a difficult and argumentative temperament, Gerhardt was exiled to Montpellier by the Parisian chemical community, who could not stomach his criti-

to move forward in this specific path." Reprinted in A.A. Makarenia, I.N. Filimonova, and N.G. Karpilo, eds., *D.I. Mendeleev v vospominaniiakh sovremennikov*, 2nd. edn. (Moscow, 1973), 24.

68. Butlerov's textbook appeared in two editions during his lifetime: the Russian original in Kazan (1864-1866) and a German translation in Leipzig (1867-1868). The original is reprinted as Butlerov (ref. 43), vol. 2. Cf. G.V. Bykov, "Materialy k istorii trekh pervykh izdanii 'Vvedeniia k polnomu izucheniiu organicheskoi khimii' A.M. Butlerova," *TIIEiT, 6* (1955), 243-291.

69. Colin A. Russell, "The electrochemical theory of Berzelius," *Annals of science, 19* (1963), 117-145.

70. Édouard Grimaux and Charles Gerhardt [fils], *Charles Gerhardt, sa vie, son œuvre, sa correspondance, 1816-1856* (Paris, 1900); Novitski (ref. 9), 61; Partington (ref. 9), chapt. 13.

cisms.[71] Gerhardt did not invent type theory, only adding to the framework constructed by A.W. Hoffman and Alexander Williamson, but his construction of a type system, completed in 1856, exerted tremendous influence until it was supplanted by Kekulé's structuralism.

Type theory argued that organic compounds could be categorized as belonging to one of several families. Each compound was considered a unit, without any attention to the roles individual atoms may play in reactions. There were four "types"—the ammonia, water, hydrogen, and hydrogen chloride types—the last two added by Gerhardt:

$$N\left\{\begin{matrix}H\\H\\H\end{matrix}\right.,\quad O\left\{\begin{matrix}H\\H\end{matrix}\right.,\quad \left\{\begin{matrix}H\\H\end{matrix}\right.,\quad \left\{\begin{matrix}H\\Cl\end{matrix}\right..$$

In a reaction, one of the atoms to the right of the bracket ("radical" atoms as opposed to the "typical" atoms to the left of the bracket) could be replaced by another atom or radical with the same combining power (H by CH_3 or OH, etc.). The last two groups have no element to the left of the bracket; they designate "binary" compounds dominated by the upper hydrogen. (Gerhardt included the hydrogen chloride group to account for electrochemical effects that do not impinge on the present narrative.) Each type was named for a standard compound that it instantiated. Hierarchies were structured around each to encapsulate economically a large amount of chemical information. The theory explicitly took a phenomenon from organic chemistry (chlorine substitution) and used it to reorganize inorganic chemistry. Chemists had always reasoned by analogies between the two domains, but the dominant Berzelian mode had elevated the inorganic; Gerhardt reversed the analogical arrow.[72]

The authors of type theory had doubts about its pedagogical utility. Gerhardt did not expect it to help beginners; "my classification is not for those who are just beginning the study of chemistry...it is intended primarily for those who already understand the subject, and who are looking for precise relationships to help them

71. Terry Shinn, "Orthodoxy and innovation in science: The atomist controversy in French chemistry," *Minerva, 18* (1980), 539-555.
72. Cf. John Hedley Brooke, "Organic synthesis and the unification of chemistry—A reappraisal," *British journal for the history of science, 5* (1971), 363-392, "Chlorine substitution and the future of organic chemistry: Methodological issues in the Laurent-Berzelius correspondence (1843-1844)," *Studies in history and philosophy of science, 4* (1973), 47-94, and "Laurent, Gerhardt, and the philosophy of chemistry," *HSPS, 6* (1975), 405-429; Trevor H. Levere, "Affinity or structure: An early problem in organic chemistry," *Ambix, 17* (1970), 111-126; Colin A. Russell, "The changing role of synthesis in organic chemistry," *Ambix, 34* (1987), 169-180.

discover new facts."[73] Laurent was even more doubtful in private to Gerhardt:[74]

> Your classification is bad....Without a dominating idea, it is impossible to do anything. Will you ever get anything from your classification? No, nothing, because there is no idea there. A classification must show a series of relationships. And I am persuaded that, whatever may be the point of departure, one will always be able to come to interesting relationships. But this point of departure must be an idea....It is well and good to keep repeating that we need neutral ground on which the whole world can meet. Well! Good grief! How about alphabetical order?!

Both of them underestimated the theory's appeal. Mendeleev's advisor Voskresenskii was an early adherent to Laurent's variant in 1839 and type theory enjoyed substantial success in Russia until Butlerov displaced it. Interestingly, perhaps the only book-length biography of Gerhardt not in French is in Russian. It is littered with comments by Butlerov and Mendeleev about his impact on their thought.[75]

Mendeleev considered himself a disciple of Gerhardt until the end of his life. In his famous article of 1871 on the periodic law, Mendeleev began with a paean to Gerhardt: "The concept and words *simple body* and *element* are often confused with each other, just as before Laurent and Gerhardt people confused the terms particle, equivalent, and atom, and yet for the clarity of chemical ideas we must clearly differentiate these words."[76] He articulated various advantages of the periodic law for predicting the properties of new elements and correcting atomic weights, but he also developed a sustained critique of structure theory from Gerhardt's point of view. The fascination began in the 1850s, when Mendeleev occasionally taught Voskresenskii's course on the history of chemistry, which featured biographies of major chemists. Mendeleev's notes on these biographies award more pages to Gerhardt (seven) than to anyone else except Newton (eight).[77] A few months after completing his textbook on organic chemistry, Mendeleev defended Gerhardt against friends who were swayed by structure theory: "[T]ype theory in its idea, of course..., always will remain useful for the generalization of substitution phenomena, but is not yet sufficient for other compounds, and atomic theory is the child of type theory."[78] In the seventh edition of the *Principles* (1903), Mendeleev wrote: "Having been for almost half a century a small but active par-

73. Quoted in N.W. Fisher, "Organic classification before Kekulé," *Ambix, 20* (1973), 106-131, 209-235, on 214.
74. Quoted in Alan J. Rocke, "Convention versus ontology in nineteenth century organic chemistry," in James G. Traynham, ed., *Essays on the history of organic chemistry* (Baton Rouge, 1987), 1-20, on 9-10.
75. M.G. Faershtein, *Sharl' Zherar, 1816-1856* (Moscow, 1968); G.V. Bykov, "Dostrukturnye teorii organicheskoi khimii v Rossii," *TIIEiT, 18* (1958), 165-212.
76. Mendeleev (ref. 52), 19.
77. "Biografii N'iutona, Zherara i Gei-Liussaka, Louvuaz'e i dr.," ADIM II-A-17-1-5.
78. Diary entry of 21 Dec 1861, in Mendeleev (ref. 18), 204.

ticipant in the development of chemistry, I would like traces to remain in my book of how a convinced follower of Gerhardt looks at the basic tasks of the doctrine of chemical elements at the beginning of the 20th century."[79] His opposition to radioactivity and his support of the ether, in turn, were later extensions of Gerhardt's framework.[80] References could be multiplied.[81] Mendeleev never reconciled himself to structure theory or valency, which led to the professional rise of his rival Butlerov, largely on the philosophical grounds that they violated Newton's third law of motion.[82]

In 1857, Mendeleev wrote a lengthy review of Adolph Strecker's introductory textbook on organic chemistry. It recommended Gerhardt's approach over Strecker's. The need for a new textbook was acute: [83]

> It is even more important to have textbooks in organic chemistry, which in the present time of all of chemistry...has received a completely different direction due to the efforts of this new age, and especially of Laurent and Gerhardt, so early extinguished by death, who closely connected the phenomena of organic chemistry with the phenomena of inorganic chemistry and gave the entire science an entirely different direction.

Mendeleev compared Gerhardt to Copernicus and berated Strecker for offering a "mix of concepts of the old and new eras." Mendeleev then offered his most extended observations on textbook writing:

> [T]he author [here] had some special reasons to begin with two different theories of both types of bodies and to convince [the reader] of this difference, which the author overturns in the following pages. This means of hiding the truth, possibly, was necessary to the author for his local goals, where it was necessary to battle with already formed concepts; but each obfuscation of the truth seems to us entirely superfluous: here we can speak directly, without even revisiting and refuting the old way of seeing, because no one needs to be armed with old concepts against new and vital ones. They usually say that it is impossible to lay out new views in all their clarity, especially in a textbook, because then it would be impossible for our students to read the majority of books on this subject, because they are written in the sense of the old theories. We don't believe this. Everyone who takes and begins to read any textbook will want either to become acquainted with science through it, or to study the doctrines of science. You don't want to give the first reader old views and facts because he, clearly, is limited to your book. If you acquaint the second reader with the old form of thoughts, then it will be necessary for him, when he goes further, to demand much effort in order to learn the new and to replace the opinion already learned.

79. *MS*, II, 447.
80. Michael D. Gordin, "Making Newtons: Mendeleev, metrology, and the chemical ether," *Ambix, 45* (1998), 96-115.
81. *MS*, IV, 151; XV, 50n4, 378, 462; XVII, 849.
82. Mendeleev's article of 1871, "Periodicheskaia zakonnost' khimicheskikh elementov" (ref. 52), is his most sustained criticism. Mendeleev considered structure theory to be a debased form of type theory: "Although from the outside I do not agree with the doctrine of structure (not with the determination of the number of affinity, nor with the presentation of the connection of atoms by a number of affinities, nor with the doctrines of chains and open formulas, etc.), all the same I think that in essence there is no basic difference between structuralists like you and Butlerov and type theorists, among whom you always class me because of my article. If the structuralists refrained from absolutes, if they changed their language a bit, if they purged from their presentation of types the ugly parts they brought to it primarily after Gerhardt, then they would be type theorists." Mendeleev to Emil Erlenmeyer, 1871, in Mendeleev (ref. 59), 706. On Mendeleev's opposition to valency theory, see *MS*, V, 46; *MS*, II, 4-5, 35. Cf. Colin A. Russell, *The history of valency* (Leicester, 1971); Trevor H. Levere, *Affinity and matter: Elements of chemical philosophy, 1800-1865* (Oxford, 1971); Anthony N. Stranges, *Electrons and valence: Development of the theory, 1900-1925* (College Station, 1982), chapt. 1.
83. Mendeleev, review of Adolph Strecker, *Kratkii uchebnik organicheskoi khimii*, tr. A. Andreev (St. Petersburg, 1856), reprinted in *MS*, XV, 149-153, quotations from 150, 152.

While writing *Organic chemistry*, Mendeleev developed a modified form of type theory, called the "theory of limits," which he expanded in the second edition as structure theory dismantled more and more of Gerhardt's legacy.[84] The structure of *Organic chemistry* was novel for Russian-language books at that time. Mendeleev began with a theoretical exposition where he defined organic chemistry, molecule, and atomic weight, and listed the atomic weights of the relevant elements for the book. He did not use the modernized Cannizzaro weight system, which fixed the weights of carbon and oxygen to their modern values, but retained half-size atomic weights for many metals (silicon, barium, iron, zinc, tin, lead, copper, mercury, and platinum), although others, such as silver, he listed with the revised values. Even in the revision of 1863 he did not fix these errors.[85] This clearly shows Gerhardt's influence. Mendeleev's marginal notes on Gerhardt's course (1853-56) provided the outline for his own textbook.[86] Mendeleev introduced the theory with the ammonia, water, and hydrogen types, and then he reduced them all to another hierarchy: "It is obvious that one and the same body can produce this [result] from various combinations of typical bodies, because they are all themselves produced

84. Mendeleev, "Opyt teorii predelov organicheskikh soedinenii," *MS*, VIII, 23-27; R.B. Dobrotin, "Teoriia predelov Mendeleeva," *TIIEiT, 35* (1961), 143-148; Bykov (ref. 75), and *Istoriia klassicheskoi teorii khimicheskogo stroeniia* (Moscow, 1960), 71-72; N.A. Menshutkin, *Ocherk razvitiia khimicheskikh vozrenii* (St. Petersburg, 1888), 290-291. On Mendeleev's *Organic chemistry*, see Iu.S. Zal'kind, "Pervyi russkii uchebnik po organicheskoi khimii 'Organicheskaia khimiia' D.I. Mendeleeva," in A.E. Arbuzov, ed., *Materialy po istorii otechestvennoi khimii* (Moscow, 1950), 195-205; G.G. Gustavson, "D.I. Mendeleev i organicheskaia khimiia," in Tishchenko (ref. 2), 50-57; Iu.A. Zhdanov, "Nekotorye osobennosti nauchnogo metoda D.I. Mendeleeva," in M.A. Markov et al., eds., *Filosofiia i estestvoznanie: K semidesiatiletiiu akademika Bonifatiia Mikhailovicha Kedrova* (Moscow, 1974), 225-237, on 226-227.
85. *MS*, VIII, 39.
86. R.B. Dobrotin and N.G. Karpilo, *Biblioteka D.I. Mendeleeva* (Leningrad, 1980), 39.

from one general type—hydrogen."[87] The hydrogen type generated the others. The following chapters discussed the major classificatory groups of organic molecules and then worked them into the framework of the "typical" groups.

This notion of "typicality" links the textbooks on organic and inorganic chemistry. In Mendeleev's early writings on the periodic system and his textbook he repeatedly mentioned the importance of the "typical elements" (the elements from hydrogen to sodium) for the periodic system: not only were they the lightest elements in the system—and Mendeleev would have a lifelong fascination with the lightest elements—but they contained a representative of each group.[88] To be more precise, these were not "representatives," they were generative of the subsidiary hierarchy. Each "type" could stand in for its heavier family members and embody the entire periodic law. In April 1869 Mendeleev wrote: "Speaking generally, elements with small atomic weight merit...the greatest scientific interest, compared with elements whose atomic weight is large....The most widely distributed simple bodies in nature have small atomic weight, and all elements with small atomic weight are characterized by a sharpness of properties. They are thus typical elements. Hydrogen, as the lightest element, is justly picked out as the most typical."[89] Hydrogen was the backbone of Mendeleev's conception of type theory as well. Mendeleev maintained his concept of typical elements as late as 1898: "These lightest elements from H to Na are called typical because in them are expressed, as in exemplars and in the clearest form, all types and properties with their particularities."[90]

Typical elements were central to the discovery of the periodic system. After Mendeleev noticed some regularity in the spacing of elements within families, he began to write two tables on a blank piece of paper, beginning with F, O, N, a blank, and then H. These typical elements were the transition points between groups, which Mendeleev then arrayed below them.[91] Kedrov's "group" version of the periodic system and also the "row" version he attacked were correct: first Mendeleev constructed the row of typical elements, which he then used as a framework for arraying his groups. The analogy was explicit with the organization of his *Organic chemistry*. In the *Principles of chemistry* textbook he started with hydrogen, oxygen, nitrogen, carbon (the organogens), and then the halogens and alkali metals, basically the array of typical elements. An analysis of their properties and relations produced the periodic system.

Mendeleev later reversed the arrow of the analogy again: "Elements with the lowest atomic weights are called *typical*. Their correspondence to the others can be compared with the correspondence of higher [sic: lower] homologs (e.g., CH^4,

87. *MS*, VIII, 62.
88. *MS*, II, 19 and 36n1; Bernadette Bensaude-Vincent, "Mendeleev's periodic system of chemical elements," *British journal for the history of science, 19* (1986), 3-17, on 9.
89. *MS*, II, 15-16.
90. *MS*, II, 421.
91. Kedrov, *Den' odnogo velikogo otkrytiia* (ref. 40), 33-47.

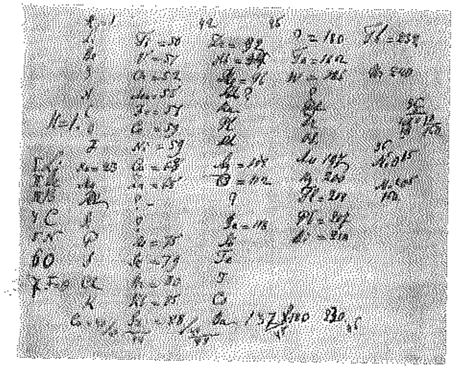

FIG. 1 Draft of a periodic system, drawn by Mendeleev in late 1870. The typical elements here play both the roles of members of the table and designators of group status. This is also the first table with groups labeled by number. *Source:* Mendeleev (ref. 59), 108, photocopy 14.

C^2H^2, CH^2O^2, etc.) and higher."[92] In late summer 1870, while still developing the final form of the periodic system, Mendeleev arranged the elements below their typical headstones (figure 1). He arrayed the typical elements at the left of the table and then repeated them again at the top of the second column, as the table was splayed out horizontally to the right. Mendeleev was not just including the elements in the system as simple bodies, but he was giving them place-holding status. This was the first time that Mendeleev used numbers to indicate the groups. He did not do this, as he would later, by indicating the degree of oxidation, but by labeling each family as its typical element.[93]

This analogy with type theory helps explain how Mendeleev could avoid using valency. Organic types accounted for organic reactions by replacing a hydrogen on the right side of the bracket with a radical or element with the same combining power. This vaguer "combining power" explained how elements followed the hierarchy of the capstone typical element. Likewise, type theory did not pronounce about composition within the molecule, which correlates well with Mendeleev's hostility to discussing decompositions or substructures to the elements, as suggested by William Prout. The purpose of both type theory and Mendeleev's original periodic system was to order multiple chemical entities into a few major headings, without further physical speculation. Mendeleev did not remove type theory's footprints from his system. The graphical periodic system from even the seventh edition of the *Principles* (1903) exemplifies this perseverence. The row of ele-

92. Mendeleev, "O polozhenii tseriia (1871)," *MS*, II, 138. Note that 19th century chemists were of two minds about sub- or superscripting. The quotation reflects the fact that Mendeleev usually superscripted.
93. Mendeleev, *Nauchnyi Arkhiv* (ref. 59), 109 and 116.

										(типические элементы)						
										H						
										Li	Be	B	C	N	O	F
										Na	Mg...					
I	II	III	IV	V	VI	VII		VIII		I	II	III	IV	V	VI	VII
			Четные ряды													
											Mg	Al	Si	P	S	Cl
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br
Rb	Sr	Y	Zr	Nb	Mo	—	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	J
Cs	Ba	La	Ce	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	Yb	—	Ta	W	—	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	—	—
—	—	—	Th	—	U								Нечетные ряды			

FIG. 2 Periodic system from *Principles of chemistry* (7th edn., 1903). The typical elements are isolated at the upper right. *Source*: D.I. Mendeleev, *Periodicheskii zakon. Klassiki nauki,* ed. B.M. Kedrov (Moscow, 1958), 385.

ments from hydrogen to fluorine is bracketed off and designated "typical elements" (figure 2).

The analogy between type theory and the periodic law is far from perfect, which no doubt explains Mendeleev's reluctance to extend the comparison fully. Type theory encoded a potentially infinite series of compounds within a finite ordering system, whereas the periodic system had a finite number of elements, probably not much larger than the sixty-three Mendeleev knew. Second, Mendeleev used the type theory to transmute between groups, bootstrapping from the water type to the hydrogen type; yet, in the periodic system, he consistently rejected any form of transmutation.[94] Similarly, type theory was far from the only intellectual resource used by Mendeleev, who also drew upon isomorphism, recent atomic-weight determinations, and a long history of inorganic classifications. Type theory was not the only source for the system, but an important and neglected one.

The connection extends into the linguistic and pedagogical. The Russian word Mendeleev used, "*tipicheskii*," is not the standard word used to designate "typical," which is "*tipichnyi*."[95] Where did Mendeleev's term come from? The first source was type theory. The affinity between types in organic chemistry and the periodic law is evident in Mendeleev's definition of them in the *Principles*:[96]

> Seeking out affine bodies, the unitary doctrine divides them into two groups which share between them one well known "type," studies the general reactions and properties of the entire group, and then relates them to the type. According to this doctrine, water is the acid type. Although this is a very important transformation from artificial systematics to natural ones, this is not the chief virtue and strength of the unitary doctrine. By a simple glance at the wide reserve of data on reactions of typical [*tipicheskie*] bodies it managed upon its first appearance to establish a new, important law, [and] introduced into science a new concept, namely the concept of *a particle.*

94. Gordin (ref. 80).
95. This linguistic peculiarity was first pointed out in V. Kurbatov, *Zakon D. I. Mendeleeva* (Leningrad, 1925), 23.
96. *MS*, XIII, 280, emphasis in original.

Mendeleev's theory of limits in organic chemistry also hinged on the distinction between typical and radical oxygen, with typical oxygen defining the properties of the entire group.[97] Mendeleev also considered "typical" (*tipicheskii*) theories or processes that were accessible to a complete theoretical analysis. For example, he called complete burning "typical" during his gunpowder research in the 1890s since it made gunpowder analytically tractable.[98] When lecturing on theoretical chemistry to women in 1886/7, he introduced some of his more advanced research on solutions "through the examination of some kind of separate typical example," in this case sulfuric acid solutions.[99] Mendeleev even extended the metaphor to the social level. In 1901, commenting on the long-standing secretary of the Russian Chemical Society, N.A. Menshutkin, he indicated that just as "among chemical elements one can pick out typical ones, so in the Russian Chemical Society Nikolai Aleksandrovich holds the place of the typical representative of all our activity in the scientific sphere."[100] We have come full circle, with typicality forming the binding link: organic chemistry was the link between the periodic system and atomic weight reform, and both of those were centered around notions of pedagogy, which again was the product of a vision of typicality.

5. CONCLUSION

While Mendeleev would later champion the periodic system as the capstone of his career, such a vision was clearly a retrospective reconstruction. Mendeleev was not concerned in February 1869 with establishing a basic law of chemistry. Had Mendeleev been cognizant of the implications of the periodic system, he would likely not have relegated its presentation to the Russian Chemical Society in March 1869 to N.A. Menshutkin while he went off to inspect cheese-making cooperatives. By 1871, Mendeleev was quite clear on his belief that he had isolated a new law of chemistry. Mendeleev first used the Russian word "*zakon*" (law) in April 1869, but he did not incorporate it as such into the *Principles* until the third edition in 1877, after the discovery of gallium had assured it of that status. Mendeleev's own account of this evolution in the status of the periodic law can be seen in this

97. *MS*, VIII, 24-25.
98. *MS*, IX, 257.
99. *MS*, XV, 528.
100. Quoted in V.V. Kozlov, *Ocherki istorii khimicheskikh obshchestv SSSR* (Moscow, 1958), 164.

statement of 1879: "Formerly it was only a grouping, a scheme, a subordination to a given fact; while the periodic law furnishes the facts, and tends to strengthen the philosophical question, which brings to light the mysterious nature of the elements....It proclaims loudly that the nature of the elements depends above all on their mass, and it considers this function as periodic."[101] Instead of founding a law of nature, in 1869 he was writing a textbook—hopefully on sound pedagogical principles—and he turned to his other achievement in this area to guide him. Organic chemistry was the dominant theme of the chemical life of the young Mendeleev, and he integrated textbook writing, new atomic weights, professorial autonomy, the Russian Chemical Society, and type theory into what he saw as the completion of Gerhardt's "revolution" in chemistry.

Mendeleev's story in the 1860s is embodied in the concept of "typicality." Mendeleev was not trying to break new ground—he was trying to stay afloat. He needed money, and so took the typical course to solving that problem. He needed a job, and his pedagogy was a way to do that. He needed an organization of chemical peers, and he had learned from other European nations and at Karlsruhe that a chemical society would be a feasible and typical way to proceed. These were local problems, and Mendeleev took his local resources and fashioned solutions to them, many of them to his great credit. His periodic system, however it is understood today, was originally rooted in a school of organic chemistry, type theory, which is now almost forgotten. By following Mendeleev's path from his earliest school days, through the seminal Karlsruhe Congress, we come to a new understanding of the law, an understanding based on reversing the analogical arrow between inorganic and organic chemistry and importing Gerhardt's classificatory schemes to meet novel tasks posed by Russian university conditions.

101. D. Mendeleef [Mendeleev], "The periodic law of chemical elements," *Chemical news, 40* (1879), 231-232, on 231.