Focus: What's in a Name? Chemistry as a Nonclassical Approach to the World

Introduction

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Abstract: The linkages and interactions of scientific disciplines with industry, politics, and society have long been a staple in the history of science, the history of technology, and science studies. However, it is arguable that the impact of this intertwining on the epistemic and social core of scientific disciplines has not yet been sufficiently explored. Chemistry is an ideal case in point, given that it has emerged as one of the largest scientific disciplines while at the same time becoming one of the world's most powerful technologies. Specifically, chemistry's power lies in its ability to gain knowledge of the natural world by transforming it, along with the society in which it is embedded. The four contributions to this Focus section all address chemistry's border permeability, based on its transformative powers; they focus on the feedback mechanisms that transformed chemistry and thereby altered the very concept of a scientific discipline. So successful has this "nonclassical approach" become that, in the opinion of the contributors to this Focus section, it is now both necessary and advisable to study the history of chemistry's embeddedness and power *in* science and technology.

Even given the recognized border permeability of other scientific disciplines, chemistry has uniquely fuzzy edges. This Focus section investigates the causes and consequences of that fuzziness, not just with respect to other disciplines, but also as it relates to industry and society. The very word "chemistry" carries multiple meanings. In addition to naming a scientific discipline, it refers to industries, environmental hazards, and—some might add—personal relationships. Though we could point to similar industrial and societal connections for many other disciplines, certainly physics and biology among them, none of their names is as multiply ambivalent as "chemistry."[1] Furthermore, it is striking that during the nineteenth and twentieth

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[1] The term "nonclassical" in the title of this Focus section refers to a publication by Stephen J. Weininger that analyzes one of the major controversies in twentieth-century chemistry. The dispute among chemists over the meaning of the name "nonclassical cation" for molecules with puzzling reaction behavior points to an episode when the boundaries between chemistry and

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centuries chemistry actually became more rather than less multivalent, during a period when science was increasingly characterized by strong and clearly demarcated scientific disciplines.[2] In order to trace the embeddedness of chemistry in science, industry, and society at the very time when its life as a scientific discipline prospered, the following essays will focus on these last two hundred years. In doing so, we understand chemistry in its broadest terms as a scientific approach to the world that presupposes that nature can be manipulated and thereby transformed.[3] This refers to the fact that technological and scientific manipulations—usually taking place in laboratories—are recognized by chemists as their characteristic gateway to nature: chemists reach knowledge of the natural world by transforming it.

The baseline of chemistry's multifaceted interactions with society is its very material productivity, and this is the starting point of Ernst Homburg's contribution to this section, which analyzes the relationship of science and industry during the period when both first appeared in their modern form. Isolation, transformation, and synthesis of (artificial) substances created an immediate and almost indestructible link between chemistry and manufacturing—before, during, and after the "Second Industrial Revolution" of the late nineteenth century, as Homburg emphasizes. In presenting an array of fascinating cases, Homburg shows how industrial, artisanal, mining, pharmaceutical, and medical cultures affected and were in turn affected by chemistry. Around 1800, for example, the history of chlorine-based bleaching agents shows the impact of Claude-Louis Berthollet's scientific analytical methods, while the options for manufacturing the pigment white lead via different methods were enlarged with the help of chemical theory. For the period after 1870, in contrast, Homburg uses the development of synthetic dyestuffs to present the important roles of technical know-how and economic considerations. Through the steady stream of new substances produced, chemistry linked its fate to industrial and societal development.[4] This was a gradual development, though, and it would be misleading to tie it to a single date or attribute it to a single cause. Even in the early nineteenth century, scientific approaches impacted industry; contrariwise, craft-like activities, and economic considerations, continued to have an important share in research and development. Moreover, after World

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physics became fluid. In the end, "nonclassical" ions could not be explained by widely accepted ("classical") structural ideas of how a molecule should be represented. See Stephen J. Weininger, "What's in a Name? From Designation to Denunciation—The Nonclassical Cation Controversy," *Bulletin for the History of Chemistry*, 2000, 25:123–131. For a very useful historiography of recent chemistry see Peter J. T. Morris, "The Fall and Rise of the History of Recent Chemistry," *Ambix*, 2011, 58:238–256; for an argument for history's role in understanding chemistry's place in science see Hasok Chang, "What History Tells Us about the Distinct Nature of Chemistry," *ibid.*, 2018, 65:360–374. For an analysis of chemistry's forgotten inroads into biology, and a plea to write the history of biology as part of the history of chemistry, see Angela N. H. Creager, "A Chemical Reaction to the Historiography of Biology," *ibid.*, pp. 343–359.

[2] For an argument for the stabilization of disciplines through their educational and industrial relations, explaining their distribution, demarcation, and endurance, see Rudolf Stichweh, "Wissenschaftliche Disziplinen: Bedingungen ihrer Stabilität im 19. und 20. Jahrhundert," in *Sozialer Raum und akademische Kulturen: Studien zur europäischen Hochschul- und Wissenschaftsgeschichte*, ed. Jürgen Schriewer, Edwin Keiner, and Christophe Charle (Frankfurt am Main: Lang, 1993), pp. 235–250.

[3] The phrase "approach to the world" captures what Bernadette Bensaude-Vincent has referred to as a "style of thinking" (recalling Alistair Crombie's phrase) and what John Pickstone calls "ways of knowing." However, "approach" includes technical and especially industrial gateways to the world, as well as their societal and environmental consequences. See Bernadette Bensaude-Vincent, "The Chemists' Style of Thinking," *Berichte zur Wissenschaftsgeschichte*, 2009, 32:365–378; and John V. Pickstone, *Ways of Knowing: A New History of Science, Technology, and Medicine* (Chicago: Univ. Chicago Press, 2001).

[4] Materials are a crucial topic in much recent work in the history of science and technology—and beyond. For the modern period some examples are Anthony S. Travis, *The Rainbow Makers: The Origins of the Synthetic Dyestuffs Industry in Western Europe* (Bethlehem, Pa.: Lehigh Univ. Press, 1993); Ursula Klein and Wolfgang Lefèvre, *Materials in Eighteenth-Century Science: A Historical Ontology* (Cambridge, Mass.: MIT Press, 2007); Klein and Carsten Reinhardt, eds., *Objects of Chemical Inquiry* (Sagamore Beach, Mass.: Science History, 2014); and Lissa L. Roberts and Simon Werrett, eds., *Compound Histories: Materials, Governance, and Production, 1760–1840* (Leiden: Brill, 2018).

War I, industry, through its research facilities, affected scientific output—even when gauged by a decisive marker of scientific excellence, the Nobel Prize.

The industrial research laboratory takes center stage in Homburg's narrative; within that context, more informal interactions, such as consultancies, ensure that any transformation of the relation between science and industry is seen as a gradual one. Moreover, theories that we today interpret as nuts-and-bolts empirical trappings might in their own time have been seen as state-of-the-art conceptual accounts—another argument for gradual change in the relationship between science and industry. Adding another perspective, Homburg takes up the approach of *Begriffsgeschichte*, à la Reinhart Koselleck, and combines it with his thorough studies of social organization and practice. Most important, he argues that the shifting meanings of notions such as chemistry, industry, the arts, and technology obscure any black-or-white interpretation as seen from our present understanding. Thus we should not take for granted our own notions—or, indeed, anyone's notions—but, rather, seek to recognize the dynamics involved. For this reason, often-repeated statements that the chemical industry is the archetype of a science-based industry are at best at least somewhat misleading. The very notion of the Second Industrial Revolution itself connotes a primarily science-based endeavor—yet this impression is founded solely on the views of the notion's originator, the scientist and historian of science John D. Bernal.

The second essay highlights the realm of theory. From the vantage point of intellectual history, Alan Rocke aims at the conceptual core of the discipline and addresses the changing meanings and roles of chemical theory over the course of the nineteenth century. Analyzing the peculiar chemical ways of thinking about theories as being "law-like" or "constructive," rather than built up from fixed *a priori* principles, Rocke points toward the pragmatic capacity of chemistry to transform the world by means of a flexible and dynamic theoretical framework that privileges interventions over explanations. Rocke contrasts the case of chemical theory with the much more fully elaborated case of theory in physics with the help of a prominent figure in the history of physics, Albert Einstein. In 1919 Einstein distinguished what he called "principle" theories from "constructive" theories. In taking up Einstein's notions and language, Rocke establishes that measuring nineteenth-century chemistry (and other fields of science, even including physics itself) with the yardstick of twentieth-century physics does not lead us to a satisfying understanding of the peculiarities of theories in chemistry in particular or science in general. Chemistry faced a particularly steep uphill battle to be accepted as scientific, when judged by standards of principle theory.

Most chemical phenomena could be approached theoretically only in an indirect fashion. As Rocke points out, the early developers of chemical atomism—the idea that is at the very heart of what chemistry became—could operate only by first making some assumptions based loosely (at best) on empirical data. The data referring today to atomic weights, for example, were based only on *relations* between experimentally measured data sets and were not accessible in absolute terms. As a result, only long series of recursive trials could justify the chemist's choices for a particular formula, and even these usually did not yield unequivocal results. Similarly, organic chemistry was famously described as a "jungle" where even insiders got lost. Thus, for scientist-philosophers of the nineteenth century—and after—chemistry resembled "stamp collecting" more than "real science." As a consequence of this "defect," chemical theories were, and still are, primarily design strategies for further laboratory work.

However—and this is supported by Homburg's argument—chemical theory building created a whole range of possibilities that scientists and industrialists could mine. In Rocke's view, the chemists' mental imaginary was boosted by the specificities of their theory building, greatly enhancing their productivity and creativity. It is not by chance that perhaps the earliest historian of these developments, the German chemist Hermann Kopp, published in 1882 a fantasy of the chemists' imagination, introducing the visual imaginary of the molecular world. Kopp's personified molecules react, interact, dance together and apart, and share their "affinities," all while illuminating the contemporary theoretical-chemical dialogue—and the central importance of constructive theory to the evolution of that dialectic.

Rocke's *tour d'horizon* enables us to understand more fully the many dead ends, complex pathways, and missed opportunities in which nineteenth-century chemistry is so rich. As with Homburg's approach, we recognize gradual development rather than sudden revolution. The archetypes of chemical "revolutions" in the nineteenth century, Dalton's atomic theory and Kekulé's structure theory, and many scientific events in between, can now be seen with more nuance, and contrast, than before. We can only speculate, but have good reason to imagine, that histories of other scientific fields would benefit from such a reinvigorated turn toward studying constructive theory.

The period from about 1850 to 1930 can be regarded as the first period of expansion for chemistry, fixing its alliance with industry and making it the largest scientific discipline in terms of the number of practitioners employed in academia, industry, and government.[5] Here chemistry was led by a specific momentum that favored understanding through making, blocking off alternative approaches as not belonging to the core of the field. As Mary Jo Nye reminds us, such a blockade famously occurred when the discipline builders of physical chemistry in the early 1900s mistakenly thought that the reign of synthetic chemistry was over. Until the mid-1900s, to their chagrin, synthesis of novel compounds remained the keystone of "real" chemical achievement. After World War I, however, when the first blow to chemistry's image was struck owing to the role of chemical warfare in that conflict, an existential threat to the standing of chemistry emerged in the form of the inroads of physics into the territory of its sister discipline.[6]

These transformations are the subject of Mary Jo Nye's essay, which centers on the crucial period between 1920 and 1960. Her foci are X-rays and electrons, arguably the two most important theoretical entities emerging around 1900. Both were swiftly appropriated by chemists as explanatory concepts in their thinking about molecules and reactions and, perhaps even more crucially, as research instruments. Along these lines, Nye studies the impact of electrons and X-rays on chemical practice and self-understanding. Seen as "particle," the electron constituted a newly known and accessible building block of matter. Understood as "wave," the electron was behind the establishment of a new foundation of chemistry in quantum mechanics and led to an influx of mathematical concepts and techniques. These developments relate to the emergence of a whole range of novel hybrid fields: among Nye's cases are physical organic chemistry, quantum chemistry, chemical physics, and X-ray crystallography.

In the mid-twentieth century, and on the basis of newly accessible research instrumentation, chemical analysis came to be based largely on physical theory and electrotechnical gadgetry. But rather than reducing chemistry to physics, the new instrumental methods instead greatly expanded the range of the underlying chemical theories. While retaining and even enlarging the effects of

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[5] For the numbers of chemists in Germany see Helmut Maier, *Chemiker im "Dritten Reich": Die Deutsche Chemische Gesellschaft und der Verein Deutscher Chemiker im NS-Herrschaftsapparat* (Weinheim: Wiley-VCH, 2015), pp. 11, 19; and Jeffrey A. Johnson, "Germany: Discipline—Industry—Profession: German Chemical Organizations, 1867–1914," in *Creating Networks in Chemistry: The Founding and Early History of Chemical Societies in Europe*, ed. Anita Kildebæk Nielsen and Soná Strbánová (London: Royal Society of Chemistry, 2008), pp. 113–138.

[6] On the role of chemical warfare in World War I see, most recently, Bretislav Friedrich, Dieter Hoffmann, Jürgen Renn, Florian Schmaltz, and Martin Wolf, eds., *One Hundred Years of Chemical Warfare: Research, Deployment, Consequences* (Cham: Springer Open, 2017). For armaments research, especially on explosives, see Jeffrey A. Johnson and Roy MacLeod, eds., *Frontline and Factory: Comparative Perspectives on the Chemical Industry at War, 1914–1924* (Dordrecht: Springer Netherlands, 2006).

the synthesis of materials, chemistry's well-entrenched habit of thinking in terms of molecular blueprints continued to create new sciences and technologies. But often these new fields were no longer called chemistry, instead coming to be known as molecular biology, genetic engineering, and nanotechnology—to name but a few. Neither the discipline of chemistry itself nor the chemical industry managed to confine this growth strictly within their own boundaries. As a result, even the histories of those new fields are often no longer part of the history of chemistry. Aptly, Nye concludes her essay with an analysis of the history of recent chemistry, highlighting the impact of chemist-historians on the content and the directions of chemical historiography.

While the epistemic core of chemistry remained largely intact during this development, and the new physical methods were successfully adapted to it, the disciplinary and industrial landscape around it changed completely. The "molecular sciences" expanded far beyond the traditional turf of chemistry, building new alliances with new industries. In this still-ongoing process, chemistry became a sophisticated support system for scientific and industrial fields ranging from solid-state physics, through materials science, nanotechnology, biotechnology, and genetic engineering, to medicine. In the last essay of this Focus section, Bernadette Bensaude-Vincent, using the metaphor of the rhizome, envisages chemistry's expansion as a kind of diffusion into the other sciences, perhaps under the guise of technology. She analyzes four crucial fields at the close of the twentieth century that, although "impregnated" with chemistry, do not carry its name. These "terrains" are nuclear technology, materials science and engineering, synthetic biology, and nanotechnology. In Bensaude-Vincent's view, there is no such thing as a single territory of chemistry with sharply defined boundaries. Instead, chemistry's "epistemic profile" is elaborated by the various fields of technoscience.

In characterizing the latter notion, while avoiding postmodern jargon, Bensaude-Vincent describes a close interaction of science and technology, a policy-ruled regime of transdisciplinary knowledge production, and the intermingling of epistemic and societal values in research motivations. Her cases are well chosen to instantiate these characteristics of technoscience. Nuclear technology, for example, involved a good deal of chemistry and chemical technology from the start. It was not by chance that an iconic chemical company, DuPont of Wilmington, Delaware, was the crucial industrial player in the early development of the project leading to the atomic bomb. Materials science and engineering in the 1960s and 1970s was shaped by governmental policy, which was itself built on perceived military and industrial needs. Synthetic biology was (and is) a chemist's dream come true (and literally Emil Fischer's dream, among others more metaphorical) in making the living world accessible to a molecular approach.[7] Finally, nanotechnology addressed (and addresses) chemistry's potential in manipulating matter at the atomic level, now in selectively and staggeringly precisely controlled ways. Bensaude-Vincent rightly does not regard her cases as complete, for there could be many more to name. In her view, "chemistry grows horizontally in a rhizomatic fashion," in co-construction with other scientific fields. Her last (though only briefly presented) example is the Earth system sciences that, in the coinage of one of their protagonists, Paul Crutzen, gave rise to the notion of the Anthropocene. Here, novel perspectives on the Earth system have been co-constructed by chemists, geologists, climate scientists, and even social scientists. In Bensaude-Vincent's words, with this expansion, and armed with the chemists' "style of thinking," "chemistry may well have turned the entire Earth into a laboratory, a world laboratory."

The dynamics behind the structures and events presented and analyzed in these four essays led to a dramatic expansion of chemistry's reach into neighboring disciplines. But this expan-

[7] Emil Fischer, "Die Kaiser-Wilhelm-Institute und der Zusammenhang von organischer Chemie und Biologie: Vortrag aus Anlaß des Besuchs der Institute durch den Vorstand des Deutschen Museums gehalten zu Berlin-Dahlem am 18. Oktober 1915," in *Untersuchungen aus verschiedenen Gebieten* (Berlin: Springer, 1924), pp. 796–809, esp. p. 808.

sion came at a price. In effect, chemistry became a toolbox for much of science and technoscience. These tools have often been used without labeling them—or even thinking of them—as chemical. Seen in this way, chemistry is neither a uniquely disciplinary, nor a predominantly industrial, nor even an environmental mind-set but, rather, an enabling scientific approach that shapes—and sometimes creates—the disposition of the world's resources. In this pursuit, analysis and synthesis constitute the hallmark features of chemistry's methodology, with a strong focus on substances (represented as molecules in chemists' understanding since the nineteenth century) in all their individuality and concreteness. Increasingly, however, the wonders of materials, having formed the basis for chemistry's success in entertaining the public through popular science lectures during the early years of the nineteenth century, gave way to more mundane expectations with regard to the broader social utility of the science and, in the second half of the twentieth century, led to fears of health-related and environmental risks. All this contributed to a shift in the public's recognition of chemistry—from being a science to becoming an industry, and then a polluting one at that—and to a history that differs in many respects from the life stories of physics and biology.[8]

In exploring the causes and consequences of the phases and topics briefly sketched above, the contributors to this Focus section highlight the linkages of making and knowing through chemistry.[9] Falling between the two stools of science and industry, chemistry often travels under the guise of diverse appellations. We are not suggesting that "everything is chemistry," as Justus Liebig did in the nineteenth century and Linus Pauling repeated in the twentieth. Rather, we want to make the point that chemical thinking and doing appear in more contexts and practices than are indicated by their names or in their self-made traditions, leading to the need to devise cross-disciplinary approaches.

When challenged by the Big Science of the 1950s and 1960s, and thus at risk of being pushed to the sidelines of federal funding, chemists responded with the slogan "Chemistry, the Central Science," which depicted chemistry as the hub of a wheel, an axis for the other disciplines and technologies arrayed around it.[10] In this image, though, "central" often means "hidden," "blocked," or even "superseded." Instead, we propose that it is preferable to view chemistry as a "nonclassical" science, a hybrid of science, industry, and potential hazard. In this sense, chemistry is best considered as a field of knowledge, a toolbox, an approach that is *delocalized over* the physical and life sciences, industries, and engineering. Thus, we believe, one can learn much that is surprising and important if one studies chemistry and its history *in* the sciences and technologies, in addition to chemistry *as* a science and a technology.

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[8] Joachim Schummer, Bernadette Bensaude-Vincent, and Brigitte Van Tiggelen, eds., "The Public Image of Chemistry," special issue, *Hyle*, 2006–2007, *12–13*.

[9] For the early modern period see Pamela H. Smith, Amy R. W. Meyers, and Harold J. Cook, eds., *Ways of Making and Knowing: The Material Culture of Empirical Knowledge* (Chicago: Univ. Chicago Press, 2017); and Smith's "Making and Knowing" project at Columbia University: http://www.makingandknowing.org/.

[10] See National Academy of Sciences and National Research Council, *Chemistry: Opportunities and Needs: A Report on Basic Research in U.S. Chemistry by the Committee for the Survey of Chemistry* (Washington, D.C.: National Academy of Sciences, 1965), p. 8.