Printing Lines and Letters: How Structural Formulae Became the Standard Notation of Organic Chemistry

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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Though few people know it, the beginnings of this thesis go back to my final year as a grammar school student in Heidelberg, where I was introduced to the fascinating history of chemistry by my former chemistry teacher Peter Schmieder. Since then, one particular question has never left my mind: why do structural diagrams look exactly the way they do? I quickly realised that the science of chemistry itself does not hold an answer to this question. After a brief stint in chemistry at the University of Heidelberg, I decided to pursue my growing interest in the history and philosophy of chemistry at the Technical University of Berlin. During my years as a student and research assistant at this institution, I benefitted greatly from the advice and guidance of my former manager and supervisor Friedrich Steinle. After graduating, my obsession with chemical formulae took me to the Centre for History and Philosophy of Science at the University of Leeds, where my curiosity and enthusiasm for the history of chemical representations was shared by my supervisors Jon Topham and Graeme Gooday. Over the last four years, Jon and Graeme have provided constant support and much-needed encouragement, and this project would not have been possible without them. I would like to thank all of my teachers, past and present, for making this intellectual journey possible.

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ABSTRACT

This thesis investigates how structural formulae became established as the default graphic notation of organic chemistry during the last third of the nineteenth century. Focusing on the period 1857 to 1892, it provides an alternative account of the development of modern chemical diagrams by examining the different communication practices that drove the inception, circulation, and appropriation of structural formulae in Britain and Germany, and which eventually led to an international convention on the iconography of the new symbols.

In the thesis I advance three main claims. First, I argue that the communication of structural formulae was a complex and gradual process that followed different patterns in different countries. Secondly, I contend that the iconography of the modern chemical notation was not the result of the work of a small number of individual scientists, but that it was rather the outcome of the combined efforts of a large body of authors, teachers, editors, publishers, printers, and readers from different national backgrounds. Thirdly, I claim that the success of line-and-letter diagrams was not built on theoretical considerations alone, but was rooted in a number of practical and economic considerations that most historians have overlooked.

In order to study these processes, the thesis develops a highly innovative approach that integrates the history of chemistry with the history of education and studies in science communication and print culture to analyse the communication of chemical knowledge across national borders and scientific communities. By following this approach, the thesis demonstrates that the establishment of the new chemical notation depended on the complex interaction of such factors as the function of print media in education, typographical constraints, and the active role of authors, teachers, editors, publishers, printers, and readers in shaping national and international markets for scientific print. In doing this, the thesis offers an original alternative to the theory-based account of the making of chemical knowledge and the formation of chemistry as a modern scientific discipline.

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CONVENTIONS AND ABBREVIATIONS

Note on Translations

The original French and German wording of translated published and unpublished sources is provided in footnotes where assumed that the reader will not have immediate access to those documents. Except where otherwise indicated, all translations are my own.

Abbreviations

ACS	American Chemical Society
ADM	Archiv des Deutschen Museums, München
Annales de Chimie	*Annales de Chimie et de Physique*
Annalen der Chemie	*Annalen der Chemie (und Pharmacie)*
Annalen der Physik	*Annalen der Physik und Chemie*
Berichte	*Berichte der Deutschen Chemischen Gesellschaft*
BJHS	*British Journal for the History of Science*
DSA	Department of Science and Art
DCG	Deutsche Chemische Gesellschaft
JACS	*Journal of the American Chemical Society*
J. Chem. Soc.	*Journal of the Chemical Society*
J. Chem. Soc. Abstr.	*Journal of the Chemical Society Abstracts*
KGLB	Königliche Geologische Landesanstalt und Bergakademie, Berlin
KTHB	Königliche Technische Hochschule zu Berlin
KTHM	Königliche Technische Hochschule zu München
LARS	Library and Archives of the Royal Society, London
Notes and Records	*Notes and Records of the Royal Society*
RCC	Royal College of Chemistry
VV	Vieweg Verlagsarchiv, Braunschweig
UBHD	Universitätsbibliothek Heidelberg
UML	University of Manchester Library

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CHAPTER 1

Introduction

> Chemical structures are among the trademarks of our profession, as surely chemical as flasks, beakers and distillation columns. When someone sees one of us busily scribbling formulas or structures, he or she has no trouble identifying a chemist.
>
> — Pierre Laszlo and Roald Hoffmann, 1989.[1]

Ubiquitous in chemistry today, so-called structural formulae function not only as shorthand notations and heuristic tools in research and education, but also as a means for communicating and debating chemical knowledge outside the laboratory. Consisting mainly of lines, letters, and numerals (Figure 1.1), such diagrams with their typical minimalistic design are easily recognised by scientists and laymen alike, as Pierre Laszlo and Roald Hoffmann explain in the epigraph above.[2] Since the first appearance of these chemical representations – which I call *line-and-letter diagrams* in this thesis – during the late 1850s, the diagrams have not only become the trademarks of the chemical profession (Figure 1.2), but also an important repository of chemical information about the unobservable microworld. Because of their role as an indispensable tool of chemical research and communication, line-and-letter formulae constitute one of the cornerstones of the methodological framework of modern chemistry. Yet despite their pivotal role in the history of chemistry, the historical development of the modern chemical notation is still poorly understood. In this thesis, I address two questions. First, why do line-and-letter formulae look the way they do? And secondly, how did the diagrams become the standard notation of organic chemistry? As we shall see, the current historical account of the development of the formulae does not provide adequate answers to these highly relevant questions. The object of this thesis is to offer a more complete and historically accurate explanation of the evolution of the modern chemical notation, showing how and why the formulae became an indispensable tool of chemical research and communication during the second half of the nineteenth century.

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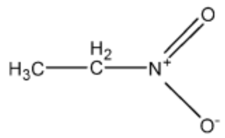
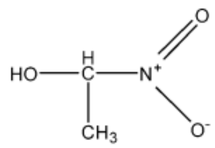
[1] Hoffmann, Roald, and Pierre Laszlo, ‘Representation in Chemistry’, *Diogenes*, 37.147 (1989), 23–51 (p. 23).

[2] Pierre Laszlo (b. 1938) is a French chemist, historian, philosopher, and popular science writer who has worked extensively on the philosophy of ‘chemical language’ as well as on science communication. See Laszlo, Pierre, *La parole des choses: Ou le langage de la chimie* (Paris: Herrmann, 1993); idem, *Communicating Science: A Practical Guide* (Berlin: Springer, 2006). Roald Hoffmann (b. 1937) is a Polish-American theoretical chemist and 1981 Nobel Laureate in Chemistry.



(1)



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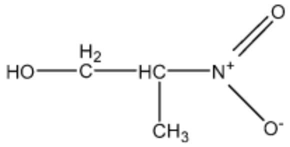

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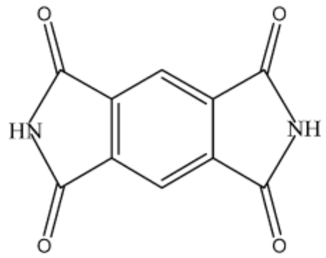

(4)

Figure 1.1: Present-day line-and-letter formulae of four different carbohydrate compound.[3]

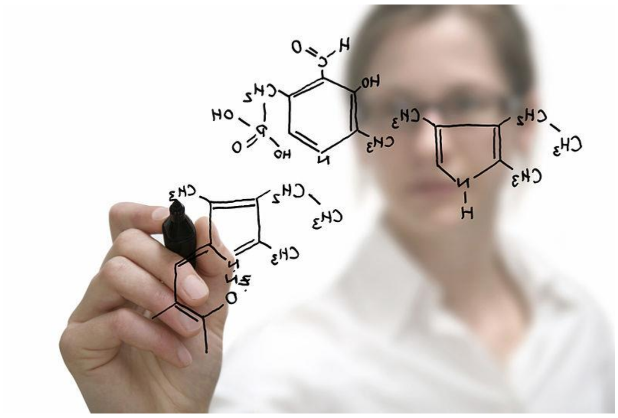

Figure 1.2: Set of line-and-letter formulae being drawn by a chemist.[4]

Focusing on the period from 1857 to 1892, I provide an alternative account of the evolution of the modern chemical language by outlining the different communication practices that drove the inception, dissemination, transformation, and appropriation of line-and-letter formulae in Britain and Germany. I claim that these formulae acquired their iconographic form and epistemic power primarily by being subjected to, and shaped by, the practices of university teaching and

[3] Zhang, Dan-Feng, and Hong-Jian Yang, 'Combination Effects of Nitrocompounds, Pyromellitic Diimide, and 2-Bromoethanesulfonate on in Vitro Ruminal Methane Production and Fermentation of a Grain-Rich Feed', *Journal of Agricultural and Food Chemistry*, 60 (2012), 364–71 (p. 365).

[4] This image is a work of the Defense Advanced Research Projects Agency (DARPA), an agency of the United States Department of Defense. As a work of the U.S. federal government, the image is in the public domain. Available at <https://d32ogoqmya1dw8.cloudfront.net/images/spatialworkbook/chemical_compound_being_drawn.jpg> [accessed 30 July 2018].

print communication. Building on the works of Colin Russell (1996), James Secord (2004), David Kaiser (2005), Alan Rocke (2010), and Josep Simon (2011), among others, I have developed an innovative approach which draws on history and philosophy of chemistry, history of science communication and print culture, and history of education to study those processes.[5] By applying my methodology to trace the circulation of chemical representations across Britain and Germany, the thesis offers an innovative practice-based account of the establishment of line-and-letter diagrams as an indispensable tool of chemical research and communication.[6] The thesis is organised in three parts which are concerned with the inception (Part I), circulation and appropriation (Part II), and internalisation and standardisation (Part III) of the chemical formulae. In following these processes, the thesis achieves three main objectives. First, it shows that the inception, circulation, and appropriation of line-and-letter formulae was a complex and gradual process that followed different patterns in different countries. Secondly, the thesis reveals that the iconography of the modern chemical notation was not the result of the work of individual scientists, but that it was rather the outcome of the combined efforts of a large score of authors, teachers, editors, publishers, and printers from different national backgrounds. Thirdly, it demonstrates that the success of line-and-letter diagrams was not built on theoretical considerations alone, but was rooted in a number of practical and economic considerations that most historians have overlooked.

The introductory chapter falls into three sections. The first section provides an overview of the historiography of line-and-letter formulae and flags up its most severe shortcomings. In doing that, the section achieves three purposes. First, it introduces the reader to the key works in the history of chemical representations. Secondly, it critically reviews those works in order to flag up major discrepancies and historiographic shortcomings that the thesis aims to challenge and revise. Thirdly, the section serves the purpose of clarifying some of the key concepts that might be unfamiliar to the unspecialised reader. The second section outlines the methodology and approach adopted in this thesis in order to develop applicable solutions to the research problems and questions outlined in the first section of this chapter. The section does that by means of discussing several historiographical themes upon which I draw to develop an

[5] Russell, Colin A., *Edward Frankland. Chemistry, Controversy and Conspiracy in Victorian England* (Cambridge: Cambridge University Press, 1996); Secord, James A., 'Knowledge in Transit', *Isis*, 95.4 (2004), 654–72; Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago, IL: University of Chicago Press, 2005); Rocke, Alan, *Image and Reality: Kekulé, Kopp, and the Scientific Imagination* (Chicago, IL: University of Chicago Press, 2010); and Simon, Josep, *Communicating Physics: The Production, Circulation and Appropriation of Ganot's Textbooks in France and England, 1851-1887* (London: Pickering & Chatto, 2011). This book is based on Simon's dissertation 'Communicating Physics in Nineteenth-Century France and England: The Production, Distribution and Use of Ganot's Textbooks' (unpublished doctoral thesis, University of Leeds, 2009).

[6] I explain and justify my decision to exclude France – the other leading chemical nation – from the analysis in further detail below.

alternative account of the making of modern chemical notation. In this section, I reconceptualise the history of line-and-letter formulae as a history of communication, adopting an interdisciplinary and transnational approach that integrates perspectives from the study of representational practices with the histories of scientific printing and print culture, on the one hand, and the history of scientific education, on the other. In this section, I argue that it is only through this communication-centred approach to the history of chemistry that we can arrive at more complete and historically accurate account of the making of line-and-letter formulae in the nineteenth century. The third section, finally, provides an outline of the entire thesis.

1.1. Rethinking the History of Line-and-Letter Formulae

In this thesis, I have developed and adopted the terms *line-and-letter diagrams* and *line-and-letter formulae* to refer to two-dimensional images representing the hypothetical chemical relationship between the constituents of a chemical compounds according to the rules of the structure theory, realised by means of basic typographic elements such as letters, figures, punctuation marks, dashes and brackets.[7] These formulae, as well as other forms of chemical representations, have been under the attention of historians and philosophers of science for several decades.[8] Systematic studies into the history of chemical symbols began with Paul Walden's chronological account of the 'historical development of chemical signs' ('Zur

[7] The evolution of these diagrams was accompanied by a conceptual ambiguity which saw the application of various historic names, ranging from 'constitutional' and 'structural' to 'graphic' and 'graphical formula' to 'graphic representation'. Yet even today, two-dimensional representations of a compound's chemical structure can be referred to by different names. In addition, we have to be aware of the existence of language-specific differences between terminologies. The terms 'constitutional' and 'structural formula' are most common in English literature, whereas most French scientists use the term 'représentation graphiques de molécules' and most German scientists the name 'Strukturformel'. Since this ambiguity prevents the use of a specific historic terminology, I have developed my own analytical terminology. I use the terms *line-and-letter diagram* and *line-and-line formula* interchangeably throughout this thesis.

[8] Chemical diagrams are a part of scientific representational practices which, apart from two-dimensional representations, also include the use of physical models as well as specific chemical names according to a nomenclatural convention. However, this thesis is not concerned with the history of chemical models and names because it was the development of chemical diagrams that drove the development of models and nomenclature, not the other way around. I elaborate on the historical relation between chemical diagrams and chemical names in the Section 1.2 of this chapter. Seminal works in the history of physical models in chemistry include Meinel, Christoph, 'Molecules and Crocket Balls', in *Models: The Third Dimension of Science*, ed. by Soraya de Chadarevian and Nick Hopwood (Stanford, CA: Stanford University Press, 2004), pp. 242-75; and Van der Spek, Trienke M., 'Selling a Theory: The Role of Molecular Models in J. H. van't Hoff's Stereochemistry Theory', *Annals of Science*, 63.2 (2006), 157–77. The practices of using physical models in chemical research have also been studied in anthropological and sociological perspectives by Myers, Natasha, *Rendering Life Molecular: Models, Modelers, and Excitable Matter* (Durham: Duke University Press, 2015); and Francoeur, Eric, 'The Forgotten Tool: A Socio-Historical Analysis of the Development and Use of Mechanical Molecular Models in Chemistry and Allied Disciplines' (unpublished doctoral thesis, McGill University, 1998).

Entwicklungsgeschichte der chemischen Zeichen') of 1927.[9] Walden's study represents the first attempt to provide a coherent overview of the long history of chemical symbols by offering an account from their first appearance in Greek manuscripts to the beginning of the twentieth century. Walden's pioneering work was fundamentally revised and updated by Maurice Crosland in 1962.[10] Despite the fact that Crosland's *Historical Studies in the Language of Chemistry* does not cover the period after the first appearance of representations of chemical structure in the early 1860s, his book remains a major reference work on the subject. During the 1970s, Ogden Ramsay extended the scope of Crosland's account by adding several studies on the history of stereochemical formulae, which had slowly emerged between the late 1880 and early 1900s.[11] Through Walden's, Crosland's, and Ramsay's work, we have gained a reasonably detailed understanding of the historical developments of chemical symbols up to the late nineteenth century.

More recent works by Colin A. Russell and Peter J. Ramberg have extended this account by providing further important insights into the development of modern chemical notation. Russell's seminal biography of the English chemist and educator Edward Frankland (1825-99) includes a fundamental study of the dissemination and appropriation of line-and-letter formulae in Victorian Britain, as I explain in more detail further below.[12] Finally, Ramberg's thorough investigation of the early history of stereochemistry provides insightful descriptions of the essential contribution of different chemical diagrams to the study of the spatial qualities of chemical compounds.[13] Together, these works constitute the foundation of the account which currently dominates our understanding of the historical development of chemical diagrams in general, as well as line-and-letter formulae in particular. I refer to this as the *standard account* in my dissertation, and it is the purpose of my work to challenge and revise this account in the light of its several shortcomings that I explain in more detail below.[14]

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[9] Walden, Paul, 'Zur Entwicklungsgeschichte der chemischen Zeichen', in *Studien zur Geschichte der Chemie: Festgabe Edmund O. v. Lippmann zum siebzigsten Geburtstage*, ed. by Julius Ruska (Berlin: Springer, 1927), pp. 80–105.

[10] Crosland, Maurice P., *Historical Studies in the Language of Chemistry* (London: Heinemann, 1962).

[11] Ramsay, Ogden B., *Stereochemistry* (London: Heyden, 1981); idem, *Van't Hoff-Le Bel Centennial* (Washington, DC: American Chemical Society, 1975); idem, 'Molecules in Three Dimensions', *Chemistry (ACS)*, 47.1 & 2 (1974), 6-9 (issue 1), 6-11 (issue 2).

[12] Russell, *Frankland*.

[13] Ramberg, Peter J., *Chemical Structure, Spatial Arrangement: The Early History of Stereochemistry, 1874-1914* (Aldershot: Ashgate, 2003).

[14] This account is often reproduced in reference works on the history of chemistry, such as Fruton, Joseph S., *Methods and Styles in the Development of Chemistry* (Philadelphia, PA: American Philosophical Society, 2002); Levere, Trevor H., *Transforming Matter: A History of Chemistry from Alchemy to the Buckyball* (Baltimore, MD: Johns Hopkins University Press, 2001); Brock, William H., *The Fontana History of Chemistry* (London: Fontana Press, 1992). The account is also reproduced and thereby further reinforced in Klaus Hentschel's recent study *Visual Cultures in Science and Technology: A Comparative History* (Oxford: Oxford University Press, 2014), pp. 96-97.

Historians usually trace the origins of the modern notation system to the so-called Berzelian symbols, introduced by the Swedish chemist Jöns Jacob Berzelius (1779-1848) in 1814. As I explain in more detail in Chapter 2, line-and-letter diagrams were developed from the type-based Berzelian symbols in the second half of the nineteenth century. The emergence of line-and-letter diagrams is standardly seen as a natural corollary of the gradual emergence of so-called theory of chemical structure – or structure theory – during the 1850s and 1860s. According to the standard account, it was Archibald Scott Couper (1831-92) and Alexander Crum Brown (1838-1922) who proposed a new form of typography-based notation to represent structural ideas, and it was due to the didactic value of this specific kind of graphic notation that line-and-letter formulae were quickly adopted by teachers in their chemistry classes and introduced to a large number of students by means of Frankland's popular textbook *Lecture Notes* (1866, 1870-72).[15] This account of the dissemination of the new formulae was formulated by Russell in his aforementioned biography of Frankland in 1996 and it is generally accepted as the explanation for the formulae's supposed instant adoption.[16]

However, my research shows that the standard account does not fit the new evidence from printed sources that I present in this thesis. The main problems of the standard account are as follows. First, existing historical and philosophical studies do not provide a convincing explanation for the long-term success of line-and-letter formulae. Why, exactly, were those diagrams so popular with structural chemists, and for what reasons did they become the only accepted symbolic notation of late nineteenth-century organic chemistry? Although some textbooks in the history of chemistry mention competing structural diagrams that were invented around 1860,[17] most works in the field tend to bypass this question altogether. By way of illustration, Mary Jo Nye does not provide any detailed explanations of the success of line-and-letter formulae, merely stating in her book *Before Big Science* (1996) that the 'power of these structural representations was immediately apparent.'[18] Other studies engage in philosophical discussions of the formulae's presumed epistemic advantages which, as I explain in more detail in Chapter 2, are inherently ahistorical because the representations are not investigated within

[15] Frankland, Edward, *Lecture Notes for Chemical Students: Embracing Mineral and Organic Chemistry* (London: Van Voorst, 1866); idem, *Lecture Notes*, 2nd edn, 2 vols (London: Van Voorst, 1870-72).
[16] Russell, *Frankland*, Chapter 10.
[17] As we shall see in Chapter 2, line-and-letter formulae faced competition from diagrams invented by August Kekulé (1829-1896) in 1857-58, and Johann Josef Loschmidt (1821-1895) in 1861.
[18] Nye, Mary J., *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800-1940* (Cambridge, MA: Harvard University Press, 1996), p. 131. Similarly, neither Crosland nor Ramsay, Brock, or Levere provide any explanation for the disappearance of alternative representations such as Kekulé's or Loschmidt's formulae. Cf. Crosland, *Historical Studies*, pp. 333-36; Ramsay, *Stereochemistry*, pp. 57-63; Brock, *Fontana History*, pp. 256-57; Levere, *Transforming Matter*, pp. 140-41. It is also important to note that even Colin Russell's fundamental investigation of the evolution of the concept of valence does not explain why chemists came to use line-and-letter formulae instead of other possible representations of that concept. Cf. Russell, *The History of Valency* (Leicester: Leicester University Press, 1971), pp. 233-35.

the context of the publications in which they appeared, but are examined as isolated entities instead.

Secondly, the standard account exhibits a strong national bias towards Britain and, more specifically, towards England. Although Russell's work has produced a very helpful explanation of the essential contribution of Frankland's didactic work and his textbook *Lecture Notes* to the proliferation of the new formulae in Victorian Britain, we still lack any insights into the processes through which the diagrams were circulated in other countries, such as France and Germany. This account is not only reproduced in historical works, but also in recent works in philosophy of chemistry. By way of illustration, Robin F. Hendry states in his chapter on the chemical bond that 'Frankland adapted Crum Brown's notation [...] and popularised it in successive editions of his *Lecture Notes for Chemical Students* [...]' without providing any further information about the communication and appropriation of line-and-letter formulae.[19] Equally important, this strong national bias gave rise to the historiographical stereotype that line-and-letter formulae were rapidly and universally adopted by the majority of British and, by extension, the rest of European chemists during the late 1860s and early 1870s. This stereotype is still upheld in the most recent works in the history of chemistry such as Evan Hepler-Smith's paper on the 1892 Geneva Congress for the Reform of Chemical Nomenclature.[20] Yet again, this account is inconsistent with the appearance of line-and-letter formulae on the printed page. For example, while line-and-letter formulae began to appear in a rapidly growing number of English textbooks from around 1866, the number of German textbooks with line-and-letter formulae remained low until the mid-1870s, and French textbooks were effectively devoid of any form of structural diagrams well into the mid-1880s. In contrast, large numbers of the new diagrams began to populate the pages of German periodicals in the 1860s, yet they were mostly absent from British journals well into the late 1870s. In the case of French periodicals, we can see that similar formulae were introduced into research papers only during the 1880s. This clearly shows that line-and-letter formulae were introduced to different forms of literature at different times, and that the proliferation and appropriation of those diagrams was not a uniform process, but that it occurred differently in different countries.

Thirdly, a close comparison of printed sources reveals a development that has been overlooked by the majority of previous historical studies. As mentioned above, German

[19] Hendry, Robin Findlay, 'The Chemical Bond', in *Philosophy of Chemistry*, ed. by Andrea I. Woody, Robin Findlay Hendry, and Paul Needham (Oxford: Elsevier, 2012), pp. 293-307 (p. 294). Italics in original.

[20] In this paper, Hepler-Smith reproduces the received narrative by stating that '[b]y the end of the 1860s, Crum Brown's formulas were in broad use […].' (Hepler-Smith, Evan, '"Just as the Structural Formula Does": Names, Diagrams, and the Structure of Organic Chemistry at the 1892 Geneva Nomenclature Congress', *Ambix*, 62.1 (2015), 1–28 (p. 8).)

periodicals published in the late 1860s and throughout the 1870s were experiencing an unprecedentedly rapid increase in the number as well as the size of the line-and-letter diagrams. During those years, structural diagrams also displayed a high degree of iconographic diversity, as I illustrate in Chapter 6. Tracing the development of line-and-letter formulae in printed sources over the following decades, we can see that from the early 1880s to the early 1890s the formulae underwent a significant transformation, which eventually resulted in a reduction of iconographic diversity and a much more uniform appearance on the printed page. The chemist-turned-historian Pierre Laszlo was the first to pay attention to this process. In his seminal 2001 paper, he claimed that a tacit iconographic convention was established at some point during the period between 1865 and 1905.[21] However, Laszlo did not investigate this process in detail, and he did not provide a convincing explanation for the establishment of the said iconographic convention. Picking up where Laszlo left off, Chapter 6 investigates the transformation which line-and-letter formulae underwent on the printed page. By describing how editors, publishers, and printers dealt with line-and-letter formulae during the last third of the nineteenth century, the chapter shows that it was predominantly economic and practical concerns which drove the gradual emergence of a tacit iconographic convention during that period, ultimately resulting in the formulae's modern appearance. In doing that, my thesis is the first work to investigate and explain the historical complexities of the making of modern chemical diagrams.

By comparing previous historical works with evidence from primary printed sources, we are thus presented with a complex picture. The comparison strongly suggests that the reception and appropriation of the new line-and-letter diagrams varied from one European country to another, and from one publication format to the next. All this provides us with enough evidence to contest the alleged uniform and simultaneous appropriation of the new notation as claimed in the standard account. Furthermore, we are presented with the fact that the iconography of line-and-letter formulae changed over the course of more than thirty years. In leaving out these important historical details, the existing narrative fails to recognise the various complex processes that eventually led to the consolidation of the form and function of line-and-letter formulae in the 1890s. By contrast, my thesis offers an answer to the question of how, exactly, line-and-letter formulae became the standard notation of organic chemistry by employing an interdisciplinary and comparative approach to study the various processes which drove and facilitated the communication of chemical knowledge across and between different audiences in Britain and Germany. The following section outlines the methodology and sources that I use

[21] Laszlo, 'Conventionalities in Formula Writing', in *Tools and Modes of Representation in the Laboratory Sciences*, ed. by Ursula Klein (Dordrecht: Kluwer, 2001), pp. 47–60.

to study the various communication practices which played a crucial part in the making of the modern chemical notation.

1.2. Chemical Knowledge in Transit

In this section, I contend that the historiographical challenges outlined above can only be addressed and overcome if we conceptualise the history of the modern chemical notation as a history of communication. My thesis builds on James Secord's knowledge-in-transit approach to trace the various communication practices that drove the production, circulation, appropriation, and standardisation of line-and-letter formulae in the nineteenth century. In his seminal 2004 paper, Secord stressed the fact that the circulation of knowledge constitutes an essential part of the making of scientific knowledge, and that historians should therefore pay closer attention to the practices by which scientific knowledge is communicated and transformed in the process.[22] He argued for the necessity of rethinking the history of science as an ongoing circulation of knowledge, and of grounding historical narratives in the analysis of the processes of 'movement, translation, and transmission' of knowledge among historical actors from different professional and social backgrounds, whereby all actors play an active role in shaping the form and content of scientific knowledge.[23] In other words, Secord's understanding of the process of knowledge making is based on a pluralistic and continuous model of how different kinds of scientific knowledge were circulated among different historical actors, thus making it clear that knowledge was not shaped by a small number of influential scientists alone. Secord's approach also makes it clear that knowledge was not "complete" or "finished" after leaving its dedicated place of production (e.g. the scientist's laboratory or the engineer's drawing board), but that it was further transformed during various processes of communication (printing and publishing, teaching, reading, etc.), and that it was only by means of those processes that particular knowledge-claims were gradually turned into established scientific knowledge. The knowledge-in-transit approach thus presents a very effective way to contest and revise historiographical models of linear knowledge transmission, and to overcome the positivistic notion of a steady and linear progress of scientific truth.[24]

Building on Secord's approach, this thesis reconceptualises the history of line-and-letter formulae as a history of communication by examining the processes of production, circulation, appropriation, and standardisation of the diagrams from a comparative and transnational

[22] Secord, 'Knowledge in Transit'.
[23] Ibid, p. 654.
[24] Ibid, p. 665.

perspective. This approach allows for a more complete and historically accurate account of the development of the new formulae for several reasons. First, the rigorous focus on the material culture and cultural practices of communication provides the means for challenging and revising the standard account, because it reveals that the circulation and appropriation of line-and-letter formulae in the German lands occurred in different ways than in Britain. Secondly, it is only by following the production and circulation of line-and-letter formulae by means of letterpress and moveable type across different markets that we can understand the crucial role which nineteenth-century printing technologies played in the shaping of the formulae's unique iconography. Thirdly, and most tellingly, the communication-centred approach to the history of line-and-letter formulae reveals that it was not primarily theoretical considerations, but rather communication practices that drove the evolution and dissemination of the line-and-letter formulae, and which also accounted for the notation's long-term success and codification as the default notation of organic chemistry. By re-telling the story of chemical diagrams as a story of science communication, however, I do not mean to draw a sharp distinction between knowledge making and knowledge dissemination. Instead, I argue that all of the tasks which chemists performed to develop and assert their views about the unobservable microworld must be seen as equal and integral parts of the knowledge-making process. I elaborate further on this argument in Chapter 2.

The present section discusses three different historiographical themes that helped me to develop the methodology adopted in this thesis. The first part of this section is concerned with the heuristic function and material dimension of so-called paper tools, where I show that the development of those tools was in part dependent upon the technical possibilities and constraints of nineteenth-century printing technology. The second part is concerned with the essential role of periodicals in the making of nineteenth-century chemistry, where I explain that the economic dimension of the production and publication of serial literature was a decisive factor in the gradual development of the modern chemical notation. In addition, I use this part to flag up differences between British and German historiographies of scientific printing as well as to highlight the very practical difficulties of locating adequate primary sources. Finally, the third part elaborates on the important role of pedagogy, didactic practices, and education systems in the circulation and appropriation of scientific knowledge in different national contexts.

Heuristics and the Materiality of Paper Tools

Over the last fifteen years, a number of historians of chemistry have undertaken innovative studies of chemical representations which diverge from the standard account outlined in the previous section. Some scholars, notably Alan Rocke and Ursula Klein, have drawn attention to the role of representations in the work of chemical science, exploring how they often function as heuristic devices. In what follows, we shall see that such work is grounded in a growing perception of the materiality of chemical representations. However, while a small number of studies have been devoted more centrally to this aspect, such work is still in its infancy.

One of the most important contributions towards a better understanding of chemical representations is without any doubt Alan Rocke's most recent monograph *Image and Reality: Kekulé, Kopp, and the Scientific Imagination* (2010). The book investigates the historical development of a new kind of creative, methodological thinking about the unobservable microworld in that frequently relied upon – but was not reducible to – the use of heuristic aids such as visual formulae or physical models. Rocke claims that nineteenth-century chemistry 'holds a special place in this story' for the reason that chemists had to deal with objects that 'were and are beyond the direct reach of our bodily senses […].'[25] However, it is important to note that Rocke is not primarily concerned with chemical representations as individual objects of study, but is rather interested in historic diagrams and models as a source for investigating the imagination-powered thought processes that happened inside the minds of his historical actors. In other words, Rocke aims to bring out what chemists had 'in mind' when they were looking at their diagrams and models.[26]

Although Rocke is not concerned with the making of those representations, he makes it very clear that as material manifestations of the thinking processes of nineteenth-century chemists, chemical representations were situated in the very midst of knowledge-making processes because they enabled chemists to construct elaborate chains of inference that linked experimental data with unobservable entities such as atoms and molecules.[27] This thesis builds on Rocke's research in two ways. First, it considers diagrams not as static displays of ready-made chemical knowledge, but as essential tools that contributed to the making of new knowledge through being circulated between different users and thereby inscribed with new layers of meaning, as we shall see in the final chapter. Secondly, the thesis aims to expand Rocke's account by outlining the material prerequisites that enabled chemical diagrams to be circulated

[25] Rocke, *Image and Reality*, p. xii.
[26] Ibid, pp. 5-6.
[27] Ibid, xiii-xiv.

between different audiences, thereby providing both students and practising chemists with new problem-solving techniques that led to the formulation of new research questions and the establishment of new and exciting research fields.

My thesis also draws on Ursula Klein's foundational work in the history of chemical symbols and diagrams during the first half of the nineteenth century. Building on the science studies approach championed by Bruno Latour, Andrew Pickering, Peter Galison, and Andrew Warwick, Ursula Klein's Habilitation thesis *Experiments, Models, Paper Tools* investigates how European chemists employed Berzelian formulae as active research tools to make sense of the growing number of organic compounds during the first four decades of the nineteenth century.[28] By treating the paper-based Berzelian notation just as any other physical instrument in the chemical laboratory, Klein is able to analyse the modelling practices by which chemists tried to bring order into the 'Jungle of Organic Chemistry'.[29] Using this approach and focusing on the theoretical as well as the practical activities of nineteenth-century scientists, Klein is able to examine how the combination of new experimental objects, competing chemical concepts and theories, and paper-based representations contributed to the making of new chemical knowledge. Her detailed study reveals that the manipulation of Berzelian formulae enabled chemists to bring order to experimental results by playing out various possible arrangements of organic compounds until the model complied with the established theoretical framework of that time. More importantly, it demonstrates not only that Berzelian formulae allowed practising chemists to classify substances previously analysed in the laboratory, but also that this kind of formula was successfully applied to simulate possible outcomes of hypothetical chemical processes, thereby playing an active role in the exploration of new questions and the production of new research agendas.

Asserting that Berzelian formulae could be applied to various areas of chemical research allows Klein to demonstrate that paper-based inscriptions constituted an essential part of the theoretical and experimental practices of early nineteenth-century chemistry. Yet due to the focus on the time period between the late 1820s and early 1840s, it is obvious that line-and-letter formulae do not fall within the scope of Klein's study. More importantly, the range of Klein's study does not extend beyond the walls of the chemical laboratory, meaning that Klein's analysis accounts only for those knowledge-making processes that take place within a narrowly-defined space of knowledge production. As result, the study does not investigate those

[28] Klein, *Experiments, Models, Paper Tools: Cultures of Organic Chemistry in the Nineteenth Century* (Stanford, CA: Stanford University Press, 2003).
[29] Idem, 'Paving a Way through the Jungle of Organic Chemistry – Experimenting within Changing Systems of Order', in *Experimental Essays - Versuche zum Experiment*, ed. by Michael Heidelberger and Friedrich Steinle (Baden-Baden: Nomos, 1998), pp. 251–71.

processes by which inscriptions are further transformed after leaving the designated space of knowledge production. Yet, as I explained at the beginning of this section, communication has always played a crucial role in the making of chemical knowledge. It is therefore the goal of this thesis to complement Klein's groundbreaking work by accounting for those communication practices that shaped the form and function of chemical formulae outside of the chemical laboratory.

And, indeed, there can be no doubt that it is absolutely crucial to pay attention to the material dimension of paper tools, because chemical diagrams were printed in textbooks and journals, which were material objects produced by professional print makers in workshops by means of printing presses and other types of equipment. The practical, material, and economic aspects of the printing of scientific formalisms such as mathematical equations and different forms of technical notation are therefore of the utmost importance to my research. There are, however, only a small number of historical studies on these subjects. The most relevant and enlightening historical works on the composition of scientific and, notably, mathematical formalism are David Wishart's 'The Printing of Mathematics' (1988), Robin Rider's 'Early Modern Mathematics in Print' (1993), and James Secord's 'Science, Technology, and Mathematics' (2009).[30] Of equal importance are historical studies in the making of book and journal illustrations, notably Topham's chapter 'Redrawing the Image of Science' (forthcoming 2019), Anne Secord's 'Botany on a Plate' (2002), and Martin Rudwick's 'The Emergence of a Visual Language for Geological Science 1760-1840' (1976).[31] These works show how the making of

[30] Wishart, David, 'The Printing of Mathematics', *Matrix*, 8 (1988), 149-57; Rider, Robin, 'Early Modern Mathematics in Print', in *Non-Verbal Communication in Science Prior to 1900*, ed. by Renato G. Mazzolini (Firenze: Olschki, 1993), pp. 91–113; Secord, James A., 'Science, Technology, and Mathematics', in *The Cambridge History of the Book in Britain*, ed. by John Barnard, David McKitterick, and I. R. Willison, 7 vols (Cambridge: Cambridge University Press, 1999-2019), VI: *1830-1914*, ed. by David McKitterick (2009), pp. 443–74. Additional research undertaken by Rider provides further valuable insights into the relationship between typography and mathematics. Cf. Rider, 'Shaping Information: Mathematics, Computing, and Typography', in *Inscribing Science: Scientific Texts and the Materiality of Communication*, ed. by Timothy Lenoir (Stanford, CA: Stanford University Press, 1998), pp. 39–54; and idem, 'Textbooks in the Early American Republic', in *Science in Print: Essays on the History of Science and the Culture of Print*, ed. by Stephen Vaughn, Gregory J. Downey, and Rima D. Apple (Madison, WI: The University of Wisconsin Press, 2012). However, it is only in recent years that the printing of mathematics has received increased attention from historians of different disciplines. The results of the first systematic historical investigation of the typographical practices and challenges of mathematical printing in the early modern period were presented at a two-day workshop in autumn 2013. See Wardhaugh, Benjamin, 'Printing Mathematics in the Early Modern World Research Symposium', *BSHM Bulletin: Journal of the British Society for the History of Mathematics*, 29.3 (2014), 215-16.

[31] Topham, 'Redrawing the Image of Science: Scientific Periodicals, Technologies of Illustration, and the Politics of Knowledge in Britain, 1790-1840', in *Constructing Scientific Communities: Science Periodicals in Nineteenth-Century Britain*, ed. by Gowan Dawson, Bernard V. Lightman, Sally Shuttleworth, and Jonathan R. Topham (Chicago, IL: University of Chicago Press, forthcoming 2019); Secord, Anne, 'Botany on a Plate: Pleasure and the Power of Pictures in Promoting Early Nineteenth-Century Scientific Knowledge', *Isis*, 93.1 (2002), 28-57; Rudwick, Martin, 'The Emergence of a Visual Language for Geological Science 1760-1840', *History of Science*, 14 (1976), 149-95. A comprehensive study of the

scientific illustrations and diagrams impinged on the processes by which scientific knowledge was circulated and appropriated by different audiences, be it in the form of books or periodicals. Drawing on these seminal works, I undertake an investigation of the practices involved in typesetting chemical formalisms during the second half of the nineteenth century. By doing that, my research demonstrates that it was mostly due to the economic advantages of typeset formulae over other kinds of illustrations that line-and-letter diagrams became successful, as we shall see in Chapter 3 of this thesis.

It is important to emphasise that chemical printing has never previously been separately addressed by historians. This thesis is the first work to undertake that task. I address the lack of relevant research literature by making extensive use of historic typographical manuals to gain further insights into the practical and economic difficulties of producing complex scientific formalisms by hand. In providing this account of the arduous processes of producing different kinds of chemical diagrams, I am able to include a range of actors that are often left aside in standard historiographies of science, including editors, printers, composers, illustrators, publishers, and readers. In addition, Chapter 6 demonstrates that economic and practical concerns about the printing of line-and-letter formulae obliged editors of scientific journals to develop different strategies to cope with rising printing costs, thereby leading to a gradual standardisation of the new chemical notation. By providing this technical account of the production of paper tools, I also highlight the key role that scientific journals played in the shaping of the modern chemical notation. Yet in order to understand the key position of periodicals in my story, we must look beyond the context of print production and pay close attention to the role of audiences, market forces, and the resulting economic pressures under which nineteenth-century chemistry journals operated. I discuss the histories and historiographies of British and German scientific periodicals in the following part of this section.

Scientific Periodicals in Nineteenth-Century Britain and Germany

Scholarship on the history of the science periodical has experienced an unpreceded growth over the last three decades, during which time a number of studies were conducted that profoundly changed our understanding of the essential part those periodicals played in the making of modern science. The majority of studies, however, concentrate on Britain and the Anglophone

materiality and functions of scientific illustrations in the early modern period was undertaken by Renzo Baldasso in his dissertation 'Illustrating the Book of Nature in the Renaissance: Drawing, Painting, and Printing Geometric Diagrams and Scientific Figures' (unpublished doctoral thesis, Columbia University, 2007).

world of science communication. By comparison, scholarship concerning the role of French and German periodicals in the making of modern science is still wanting.[32] In what follows, I first explain which of the new insights produced in the history of British science journals I have incorporated in the methodology of my thesis. I then proceed to discuss existing scholarship in the history of science publishing in nineteenth-century Germany, where I also outline the various methodological challenges that I have encountered in the course of my research, which include the severe lack of primary sources due to wartime destruction of archives, and the pluricentric and diverse nature of the German academic landscape.

Much of the recent scholarship on the history of commercial science and medicine journals draws on Bill Brock's seminal case studies in those areas.[33] In recent years a number of in-depth studies into the origins and evolution of the modern science journals were conducted by Alex Csiszar, Melinda Baldwin, Jon Topham, and Aileen Fyfe together with Julie McDougall-Waters and Noah Moxham. Each of these studies has made a significant contribution to a more nuanced and historically accurate understanding not only of the form and function, but also the very nature of (Anglophone) science periodicals. Csiszar's much-anticipated work *The Scientific Journal* (2018) investigates the emergence of the commercial science journal in the nineteenth century and explains, among other things, how those periodicals became the predominant publication outlet for scientific research as well as the main social institution for claiming, contesting, and asserting scientific authority.[34] Baldwin's and Topham's research produced new insights into the various ways in which publishers contested for different audiences in order to ensure their periodicals' long-term economic success, and how the strong competition shaped

[32] For an overview of recent scholarship and the most relevant findings for the Anglophone context, see Fyfe, Aileen, 'Journals and Periodicals', in *Companion to the History of Science*, ed. by Bernard V. Lightman (Chichester: Wiley Blackwell, 2016), pp. 387-99; and Shuttleworth, Sally, and Berris Charnley, 'Science Periodicals in the Nineteenth and Twenty-First Centuries', *Notes and Records*, 70 (2016), 297-304. In this essay, Shuttleworth and Charnley reiterate the need for further studies into print markets on the periphery of the Anglophone, Francophone, and Germanophone areas (p. 297). For a more detailed discussion of recent scholarship concerning the history of science journals, see Dawson, Gowan, and Jonathan R. Topham, 'Introduction: Constructing Scientific Communities', in *Constructing Scientific Communities*. For an introduction to methodology and sources relevant to historical research in scientific print, see Topham, 'Scientific Publishing and the Reading of Science in Nineteenth-Century Britain', *Studies in History and Philosophy of Science A*, 31.4 (2000), 559-612.

[33] Brock, 'The Development of Commercial Science Journals in Victorian Britain', in *The Development of Science Publishing in Europe*, ed. by Arthur J. Meadows (Amsterdam: Elsevier, 1980), pp. 95–122; idem, 'Medicine and the Victorian Scientific Press', in *Medical Journals and Medical Knowledge: Historical Essays*, ed. by W. F. Bynum, S. Lock, and Roy Porter (London: Routledge, 1992), pp. 70–89: idem and Arthur J. Meadows, *The Lamp of Learning: Two Centuries of Publishing at Taylor & Francis*, 2nd edn (London: Taylor & Francis, 1998); idem, 'The Making of an Editor: The Case of William Crookes', in *Culture and Science in the Nineteenth-Century Media*, ed. by Louise Henson and others (Aldershot: Ashgate, 2004), pp. 189–98.

[34] Csiszar, Alex, *The Scientific Journal: Authorship and the Politics of Knowledge in the Nineteenth Century* (Chicago, IL: University of Chicago Press, 2018). For a synopsis of Csiszar's main findings, see idem, 'Seriality and the Search for Order: Scientific Print and its Problems during the Late Nineteenth Century', *History of Science*, 48.3-4 (2010), 399-434.

the content, purpose, and form of scientific journals.[35] Finally, Fyfe, McDougall-Waters, and Moxham undertook a monumental longue durée study of the *Philosophical Transactions* of the Royal Society, arguably the oldest science journal still in publication. The team has produced exciting results that shed new light on the origins and transformation of some of the key feature and practices which define a scientific journal today, including editing and peer review practices, budgeting, and printing and worldwide distribution of the finished product.[36]

My thesis draws on these studies to develop a more accurate historical understanding of the many ways in which different kinds of journals contributed to the circulation and transformation of line-and-letter formulae in the nineteenth century, and the essential role of the print market in that process. By way of illustration, Chapter 6 undertakes a close examination of the different editorial approaches toward line-and-letter diagrams that a number of leading British periodicals had adopted by the 1870s. In that chapter, I show that journals of the Chemical Society suffered from negative economic consequences because they published abstracts that featured a rapidly growing number of space-consuming line-and-letter formulae. As a result, the editor-in-chief of the Chemical Society chose to implement editorial guidelines to curb the size of line-and-letter formulae, while other British science journals decided to avoid printing the formulae altogether. By comparing audiences, production costs, sales figures, and print runs, amongst other things, I show in Chapter 6 that the journals' editorial strategies were highly contingent on the specific position of those journals in the British print market. It is therefore only by integrating the perspective of the print market that we can see just how much the distribution patterns as well as the iconography of line-and-letter formulae depended on the economic and practical aspects of science communication.

In addition, my approach is informed by existing studies in the history of German periodicals. In the second half of the nineteenth century, the German periodicals *Annalen der Chemie* (f. 1832) and *Berichte der Deutschen Chemische Gesellschaft* (f. 1868) emerged as the world's leading research journals for chemistry, and it was in German chemistry journals that

[35] Baldwin, Melinda, *Making Nature: The History of a Scientific Journal* (Chicago, IL: University of Chicago Press, 2015); Topham, 'The Scientific, the Literary and the Popular: Commerce and the Reimagining of the Scientific Journal in Britain, 1813–1825', *Notes and Records*, 70 (2016), 305–25; and idem, 'Anthologizing the Book of Nature: The Circulation of Knowledge and the Origins of the Scientific Journal in Late Georgian Britain', in *The Circulation of Knowledge between Britain, India, and China: The Early-Modern World to the Twentieth Century*, ed. by Bernard V. Lightman, Gordon McOuat, and Larry Stewart (Leiden: Brill, 2013), pp. 119–52.

[36] The agenda of this research project is outlined in Fyfe, Julie McDougall-Waters, and Noah Moxham, '350 Years of Scientific Periodicals', *Notes and Records*, 69.3 (2015), 227–39. The results are published as a series of individual articles. See Fyfe, 'Journals, Learned Societies and Money: Philosophical Transactions ca. 1750–1900', *Notes and Records*, 69.3 (2015), 277–99; Fyfe and Moxham, 'Making Public Ahead of Print: Meetings and Publications at the Royal Society, 1752–1892', *Notes and Records*, 70 (2016), 361–79, and Moxham and Fyfe, 'The Royal Society and the Prehistory of Peer Review, 1665-1965', *Historical Journal*, 61.4 (2018), 863–89.

line-and-letter formulae began to appear in large numbers. In addition, the abstract journal *Chemisches Zentralblatt* (f. 1830) had a large international audience and, for that reason, played a central part in the international circulation of line-and-letter formulae in the 1860s and 1870s. The history of German science journals is therefore of paramount importance to this thesis. Yet, due to reason outlined below, scholarship in the history of German science journals of the eighteenth and nineteenth centuries is still wanting. Although written more than sixty years ago, Joachim Kirchner's comprehensive study *Das deutsche Zeitschriftenwesen* (1958-1962) still offers the best overview on this subject.[37] Useful resources for the history of specialist chemical journals in the German-speaking area are Horst Harff's *Entwicklung der deutschen chemischen Fachzeitschrift* (1941), Maurice Crosland's seminal study of the history of the leading French periodical *Annales de Chimie* (1994), Christoph Meinel's work on 'Structural Changes in International Scientific Communication' (1993), and Anna Gielas' recent paper on the 'Editorial Beginnings' of eighteenth-century chemistry journals (2016).[38] In Chapter 5 and 6, I build on these foundational works to explain the wide circulation and global success of German chemistry journals during the second half of the nineteenth century.

Compared to the growing number of ground-breaking studies on the history of scientific print in Britain, research on the history of scientific print from the German-speaking area of Europe is quite patchy. One of the main reasons for this shortcoming is the fact that the German tradition of 'Buchwissenschaft' is focused on broad social, cultural, and economic themes in book history and print culture, but pays very little attention the role which print communication played in the production of scientific knowledge.[39] The number of historical studies on publication strategies and commercial activities of German science publishers remains relatively

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[37] Kirchner, Joachim, *Das deutsche Zeitschriftenwesen: Seine Geschichte und seine Probleme*, 2nd edn, 2 vols (Wiesbaden: Harrassowitz, 1958-62). For Kirchner's controversial biography and his association with the National Socialist Party, see Klee, Ernst, *Das Kulturlexikon zum Dritten Reich: Wer war was vor und nach 1945?* (Frankfurt am Main: S. Fischer, 2007), p. 278.

[38] Harff, Horst, *Die Entwicklung der deutschen chemischen Fachzeitschrift: Ein Beitrag zur Wesensbestimmung der wissenschaftlichen Fachzeitschrift* (Berlin: Verlag Chemie, 1941); Crosland, Maurice P., *In the Shadow of Lavoisier: The Annales de Chimie and the Establishment of a New Science* (Chalfont St. Giles: British Society for the History of Science, 1994), pp. 245-73. Crosland provides a very useful list of major chemical periodicals published in the eighteenth and nineteenth centuries by language and country on pp. 352-54. Gielas, Anna, '"I do have a chemical magazine in the works": The Editorial Beginnings of the First Chemical Journal', *FORUM: University of Edinburgh Postgraduate Journal of Culture & the Arts*, 23 (2016), 2–12; and Meinel, 'Structural Changes in International Scientific Communication: The Case of Chemistry', in *Atti del V. Convegno Nazionale di Storia e Fondamenti della Chimica*, ed. by Gianlorenzo Marino (Roma: Accademia Nazionale delle Scienze, 1993), 47–61. An extended version of this paper was published in German as Meinel, 'Die wissenschaftliche Fachzeitschrift: Struktur- und Funktionswandel eines Kommunikationsmediums', in *Fachschrifttum, Bibliothek und Naturwissenschaft im 19. und 20. Jahrhundert*, ed. by Christoph Meinel (Wiesbaden: Harrassowitz, 1997), pp. 137–55.

[39] See Rautenberg, Ursula, *Buchwissenschaft in Deutschland: Ein Handbuch* (Berlin: de Gruyter, 2010); and Füssel, Stephan, and Corinna Norrick, *Einführung in die Buchwissenschaft* (Darmstadt: Wissenschaftliche Buchgesellschaft, 2014).

low, and it was only in recent years that book historians turned their attention to the history of some of the largest academic publishing houses such as Springer, J. C. B. Mohr (Paul Siebeck), Walter de Gruyter, and Oldenbourg.[40] However, the future looks more promising. Alrun Schmidtke's interdisciplinary study of the role of external advisors in scientific publishing, for instance, integrates perspectives from the history of science and print history to explore how those advisors acted as mediators between scientists and businessmen and thereby shaped the publishing practices and strategies of the respective publishing house.[41]

Another very practical reason for the lack of studies in the history of German science publishing, and notably in the history of scientific journals, is the lack of relevant archival material. As in the case of other countries, this lack of suitable sources is sometimes the result of the volatile nature of the book trade itself: scientific publishing has always been a risky business, and bankruptcies or mergers were – and still are – very common. As publishing houses relocated, merged with other publishing houses, or went out of business, their archives were often sold off or discarded.[42] Finally, the lack of relevant resources is also in part the result of Germany's turbulent history. The violent wars and the separation of the country which Germany experienced in the twentieth century, for instance, resulted in the loss of the entire archive of the publisher of the *Berichte der Deutschen Chemischen Gesellschaft*. As the publisher of its own journal, the Gesellschaft's headquarters – including the journal's offices – were located in the Hofmann-Haus in the centre of Berlin.[43] However, the Hofmann-Haus was entirely destroyed in

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[40] Knappenberger-Jans, Silke, *Verlagspolitik und Wissenschaft: Der Verlag J. C. B. Mohr (Paul Siebeck) im frühen 20. Jahrhundert* (Wiesbaden: Harrassowitz, 2001); Müller, Helen, *Wissenschaft und Markt um 1900: Das Verlagsunternehmen Walter de Gruyters im literarischen Feld der Jahrhundertwende* (Tübingen: Max Niemeyer, 2004); Sarkowski, Heinz, and Heinz Götze, *Der Springer-Verlag: Stationen seiner Geschichte*, 2 vols (Berlin: Springer, 1992-94); Wesolowski, Tilmann, *Verleger und Verlagspolitik: Der Wissenschaftsverlag R. Oldenbourg zwischen Kaiserreich und Nationalsozialismus* (München: Meidenbauer, 2010).

[41] Schmidtke, Alrun, 'Ein Berater zwischen Konferenz und Cocktailparty: Textakquise im Wissenschaftsverlag, 1927-1963' (doctoral thesis, Humboldt-Universität Berlin, forthcoming 2020).

[42] By way of illustration, this was the case with the archive of the C. H. Winter publishing house, which for the most part of the nineteenth century was the publisher of the world-leading journal *Annalen der Chemie*. According to Dr Carl Winter, heir to the Winter family and former director of the Winter Universitätsverlag in Heidelberg, the publishing house discarded its archival stock when it was taken over by a new owner in 1854, which resulted in the loss of a significant number of invaluable sources documenting Liebig's work as an editor of the journal. In a letter dated 30 August 2015, Dr Winter stated that his own persistent attempts to track down the lost company archive of C. H. Winter did not produce any relevant results. Dr Winter also explained that the letters which Liebig had written to the Winter publishing house in his capacity as editor of the *Annalen* were auctioned off by the piece and are now in private hands ([Dr Carl Winter, letter to the author, 30 August 2015]).

[43] The different rooms inside the Hofmann-Haus are described in Pinner, A., 'Bericht über die am 20. October 1900 erfolgte Einweihung des Hofmann-Hauses', *Berichte*, 34.1 (1901), iii-xxiv. The editorial offices as well as the library are also mentioned in March, Otto, 'Baubeschreibung', *Berichte*, 34.1 (1901), xxv-xxviii (p. xxv).

the Second World War, and major parts of the society's collections, archives, and libraries were confiscated by Soviet forces and relocated to Moscow.[44]

Due to the limited number of historical studies, my account of the crucial role of German periodicals in the circulation and transformation of line-and-letter diagrams is therefore not based solely on secondary literature, but is to large extent informed by my careful and systematic analysis of what limited primary sources are available. Furthermore, it is only by means of a transnational comparison of print markets, publishers, and audiences that we are able to understand the unique conditions that led to the establishment of German chemistry journals as the world's leading publication outlets for cutting-edge chemical research. For example, I explain in Chapter 5 that several unique conditions facilitated the rise of German chemistry journals in the nineteenth century, namely the existence of successful commercial academic publishers and a competitive market for scientific print, the institutionalisation of chemical research and chemistry as a scientific discipline at German universities, and the expansion of organic chemistry as a domain of intellectual endeavour as well as a driving force of industrial productivity. As a result, German chemistry journals quickly became one of the main vehicles for the proliferation of line-and-letter formulae in the 1860s. Furthermore, the literature cited above also informs my critical analysis of the learning resources that were available to German chemistry students in the 1860s and 1870s. By critically examining how German students accessed and made use of different kinds of printed matter during their studies, I demonstrate in Chapter 5 that specialist journals formed one of the main learning resources through which German students encountered the new structural notation. My approach to the use of scientific literature in the context of teaching and learning is further informed by recent studies in the history of scientific education, as I explain in more detail in the final part of this section.

Pedagogy and the Role of Teaching and Learning Practices in the Making of Scientific Knowledge

The context of pedagogy is central to the argument of this thesis because learning and teaching practices were major driving forces of the communication of line-and-letter formulae. The

[44] Maier, Helmut, *Chemiker im Dritten Reich: Die Deutsche Chemische Gesellschaft und der Verein Deutscher Chemiker im NS-Herrschaftsapparat* (Weinheim: Wiley-VCH, 2015), pp. 613-16. For further details on the fate of Berlin's academic libraries in the Second World War, see Wienhaus, Otto, 'Wie der Beilstein den Krieg überstand', *Nachrichten aus der Chemie*, 65.7-8 (2017), 803-06.

benefits of studying the crucial role of didactic practices in the making of scientific knowledge are explicated in works by Graeme Gooday (1990), Kathryn Olesko (1991), Andrew Warwick (2003), David Kaiser (2005), Josep Simon (2011), and others.[45] These studies stress three important points that have informed my approach. First, the studies emphasise that we cannot understand the formation and operation of scientific disciplines without understanding how they are produced, reproduced, and gradually transformed by systems of pedagogy. Secondly, historians concerned with scientific education and training have emphasised that the acquisition of new skills and practices – including the use of paper tools – can only be understood in the local institutional context, for instance in the context of laboratory teaching and learning. This focus on practical laboratory work is particularly strong in the history of chemistry, whereby historians have expended much effort exploring how practice-based chemical training in the laboratory contributed to the making of the modern professional chemist and the rise of organic chemistry.[46] Yet as I demonstrate in this thesis, the focus on laboratory instruction is only one side of the story, since reading and writing exercises were equally important to the acquisition and cultivation of practical skills and theoretical knowledge. Thirdly, studies in scientific education and training have shown that the production and reproduction of knowledge has relied on a variety of didactic practices and institutional arrangements, ranging from formalised syllabi and regular examinations to classroom instruction and the reading of textbooks. As we shall see in this thesis, textbooks were by no means the only teaching and learning resources utilised by educators and students in the nineteenth century.

Textbooks are situated at the intersection between the history of science, history of education, and book history, thereby working as a converging lens by bringing all three perspectives into analytical focus.[47] As my own research demonstrates, the study of textbooks can be very rewarding, especially with respect to the role of communication practices in the making of scientific knowledge. In addition, works of Warwick and Simon challenge Thomas Kuhn's notion of textbooks as repositories of 'normal science' by assigning textbooks an active

[45] Gooday, Graeme, 'Precision Measurement and the Genesis of Physics Teaching Laboratories in Victorian Britain', *BJHS*, 23.1 (1990), 25-51; Olesko, Kathryn, *Physics as a Calling: Discipline and Practice in the Königsberg Seminar for Physics* (Ithaca, NY: Cornell University Press, 1991); Warwick, Andrew, *Masters of Theory: Cambridge and the Rise of Mathematical Physics* (Chicago, IL: University of Chicago Press, 2003); Kaiser, *Drawing Theories Apart*; Simon, *Communicating Physics*.

[46] See, for instance, Jackson, Catherine M., 'Analysis and Synthesis in Nineteenth-Century Organic Chemistry' (unpublished doctoral thesis, University of London, 2008). Jackson provides a review and discussion of laboratory-focused historical accounts of chemical research and teaching in Chapter 1.

[47] Simon's thesis offers an excellent survey of the existing scholarship in the history of textbooks and book history more broadly. Cf. Simon, 'Communicating Physics', pp. 6-21. In a first approach, a textbook can be defined as a book specifically conceived for instructional purposes within the context of a system of formal education. However, as Simon points out, recent scholarship has revealed that the defining features of this genre have changed over time. Our contemporary understanding of the textbook is that of a printed work with a 'complex ontology, due to the multiplicity of actors, purposes, and functions intervening in its making, and the transformative power of its use.' (Ibid, p. 26.)

role in the making of scientific knowledge.[48] Similarly, Kathryn Olesko's study of the emergence of physics as modern scientific discipline demonstrates how textbooks used in eighteenth and nineteenth-century German secondary education shaped university curricula and thereby made a major contribution to the shaping of the whole discipline.[49] Undoubtedly the most influential and truly groundbreaking work in the history of textbooks is *Communicating Chemistry: Textbooks and Their Audiences* (2000), edited by Bernadette Bensaude-Vincent and Anders Lundgren.[50] As Simon explains in his dissertation, the highly innovative international case studies included in this edited volume revolutionised historical studies of textbooks by 'making clear the greater complexity of these sources and their important potential for the study of the making and communication of science.'[51] The various roles of textbooks in shaping the teaching of science and history of science in elementary and secondary education continue to attract considerable scholarly interest, as the doctoral dissertations of Jo Elcoat and Luis Moreno Martínez demonstrate.[52]

My thesis draws on the recent scholarship in the history of education and didactic literature to critically assess and qualify the role that textbooks such as Frankland's *Lecture Notes* played as learning resources in specific educational contexts. We have already seen in the previous paragraph that the usefulness of textbooks was highly contingent on the existence of formal curricula. But what if there was no official curriculum, and if no suitable textbooks were

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[48] Kuhn, Thomas S., *The Structure of Scientific Revolutions*, 4th edn (Chicago, IL: University of Chicago Press, 2012), pp. 10, 20.

[49] Olesko, 'The Foundations of a Canon: Kohlrausch's Practical Physics', in *Pedagogy and the Practice of Science: Historical and Contemporary Perspectives*, ed. by David Kaiser (Cambridge, MA: MIT Press, 2005), pp. 323-55; idem, *Physics as a Calling*.

[50] Lundgren, Anders, and Bernadette Bensaude-Vincent, eds., *Communicating Chemistry: Textbooks and their Audiences, 1789-1939* (Canton, MA: Watson Publishing International, 2000). Bensaude-Vincent continued her investigation of French textbooks together with Antonio García Belmar and José Ramón Bertomeu Sánchez in *L'émergence d'une science des manuels: Les livres de chimie en France (1789-1852)* (Paris: Éditions des Archives Contemporaines, 2003), which provides a comprehensive case study of the evolution of didactic literature in France during the first half of the nineteenth century. Further seminal studies in the history of (chemistry) textbooks include Frercks, Jan, and Michael Markert, 'The Invention of Theoretische Chemie: Forms and Uses of German Chemistry Textbooks, 1775–1820', *Ambix*, 54.2 (2007), 146–71; Gordin, Michael D., 'Beilstein Unbound: The Pedagogical Unraveling of a Man and his Handbuch', in *Pedagogy and the Practice of Science: Historical and Contemporary Perspectives*, ed. by David Kaiser (Cambridge, MA: MIT Press, 2005), pp. 11–39; idem, 'Translating Textbooks: Russian, German, and the Language of Chemistry', *Isis*, 103.1 (2012), 88–98; Haupt, Bettina*, Deutschsprachige Chemielehrbücher (1775-1850)* (Stuttgart: Deutscher Apotheker Verlag, 1987); Kaiser, David, 'A Tale of Two Textbooks: Experiments in Genre', *Isis*, 103.1 (2012), 126–38; and Stray, Christopher, and Gillian Sutherland, 'Educational Publishing', in *The Cambridge History of the Book in Britain*, VI, pp. 359–81.

[51] Simon, 'Communicating Physics', p. 12.

[52] Martínez, Luis Moreno, 'La historia de la química en el currículo y los libros de texto de Educación Secundaria Obligatoria y Bachillerato (LOE). Un estudio desde la didáctica y la historia de la ciencia' (unpublished doctoral thesis, Universidad Autónoma de Madrid, 2017). Jo Elcoat is currently completing her PhD thesis on the production, circulation, and use of schoolbooks in science education for children in the late Georgian period. The current title of her work is 'Reading the Schoolbook: Science Education in Private Schools in England, 1760 to 1800' (unpublished doctoral thesis, University of Leeds, forthcoming).

available to serve the demands of students attending classes at local universities? As we shall see in the case of German chemistry education in Chapter 5 of this thesis, the absence of a centralised science education scheme not only resulted in a smaller market for chemistry textbooks, but also in the use of alternative learning resources such as specialist science periodicals that students were able to access at their local library. By including scientific journals as an integral part of local teaching and learning practices at German universities, I show that, despite the importance of textbooks stressed by the above studies, their power was highly contingent on the national and local educational framework and must therefore not be taken for granted.

Particularly informative for the purposes of this thesis is the analysis of David Kaiser in his pioneering monograph *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (2005), and the account of the distribution patterns of line-and-letter formulae developed in this thesis is deeply informed by his work.[53] In what follows, I explain how my thesis builds on Kaiser's study by flagging up the parallels as well as the main differences between our accounts. I show that Kaiser's account of dispersion is not applicable to the case of line-and-letter formulae, and I explain how this thesis develops a new approach to chart the circulation and appropriation of line-and-letter formulae in nineteenth-century Britain and Germany.

In *Drawing Theories Apart*, Kaiser investigates how Richard Feynman's (1918-1988) famous diagrams representing the behaviour of subatomic particles spread across the scientific world in the postwar period and were adapted by different communities of physicists to different theoretical and practical applications, thereby revolutionising almost every aspect of theoretical physics since the middle of the twentieth century. Following the paths of the diagrams 'once they made the leap out of Feynman's head' and focusing on the pedagogical work involved in the training of a large numbers of prospective diagram users, Kaiser presents a compelling and intricate account of the different stages of communication in which the circulation and appropriation of the diagrams took place.[54] According to Kaiser, the pedagogical context is crucial in understanding the popularity and longevity of the diagrams as multi-purpose calculation tools because 'Feynman diagrams never apply themselves; physicists have to be trained to use them, and to interpret and evaluate the results in certain ways.' Kaiser's work demonstrates that the study of didactic practices is also important because it was not the older generation of scientists who became the predominant users of Feynman's new tool, but the new generation of postdoctoral researchers who were subjected to revised curricula and new training programmes after World War II. The stabilisation of the new tool can therefore only be

[53] Kaiser, *Drawing Theories Apart.*
[54] Ibid, p. 5.

understood by observing and analysing the various communication practices involved in the training of the new generation of theoretical physicists during the postwar period of rapid and profound institutional change.[55]

Feynman originally devised the diagram as a bookkeeping device and paper tool to navigate and solve complicated mathematical calculations in quantum electrodynamics (QED). He first introduced his diagrams during a private working retreat attended by 28 young physicists in the spring of 1948. Over the following six or so years, the diagrams spread almost exclusively by means of personal communication with Feynman himself as well as his 'fist apprentice' and 'diagrammatic ambassador' Freeman Dyson (b. 1923).[56] During this first stage of dispersion, it was Dyson who 'contributed more than anyone else to putting Feynman diagrams into circulation' because his explanation of the diagrams showed other physicists how to use them, and postdocs trained at the Institute for Advanced Study in Princeton during Dyson's residency there 'spread the use of the diagrams to other institutions.'[57] This 'postdoc cascade' describes the second stage of dispersion, during which Feynman diagrams reached leading research institutions such as Cornell, Princeton, Berkeley, Harvard, and Princeton, among many others, where the former Institute postdocs incorporated the diagrams in their lectures and classes. Consequently, a growing number of American graduate students were exposed to the new diagrams through personal instruction and local interaction in the context of their respective educational establishments during the first half of the 1950s.[58] At the international level, too, personal relations were crucial to the spread of the diagrams. In the case of the Soviet Union, for example, it was only after personal encounters with Dyson during international conferences and visits to the United States in the late 1950s that Soviet physicists began to make use of the diagrams. In this process, the different communities appropriated the diagrams as problem-solving techniques to their own particular research problems.[59] Textbooks, by contrast, played practically no role in the first two stages of rapid dispersion during the period 1948-1954 and therefore enter the story at a much later point of Kaiser's study.[60]

There are some parallels between Kaiser's model of dispersion and my account of the circulation of line-and-letter diagrams in the nineteenth century. As we shall see in Chapters 4 and 5, the context of pedagogy and training is as important to the understanding of the

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[55] Ibid, p. 6. Kaiser's notion of 'pedagogy' is not restricted to the context of classroom teaching and learning, but is applied more broadly in the sense of different kinds of 'institutions of training by means of which young physicists became working theorists during the decades after World War II.' (Ibid, p. 14.)
[56] Ibid, pp. 65-87.
[57] Kaiser, 'Physics and Feynman's Diagrams', *American Scientist*, 93.2 (2005), 156-65 (p. 160).
[58] Idem, *Drawing Theories Apart*, pp. 93-111.
[59] Ibid, Chapter 4.
[60] Ibid, Chapter 7.

circulation and appropriation of line-and-letter formulae as it is to Feynman diagrams, mostly because it was predominantly students and young researchers and not senior academics who formed the new generations of diagram users. In addition, my story features a number of actors who fulfilled roles similar to Freeman Dyson and his postdocs. My research shows that a number of influential British and German chemists had embraced line-and-letter formulae within three years after the publication of Crum Brown's 1864 article that featured the new diagrams. Those chemists were progenitors or early supporters of the new theoretical framework based on valence and chemical structure, and worked as researchers and educators at different institutions in Britain and the German lands. I call these actors *diagrammatic pioneers* in order to distinguish them from Kaiser's notion of ambassador. Similar to Kaiser's account, the pioneers in my story played a key role in the communication of line-and-letter formulae at the early stage by introducing them to an increasing number of students and junior colleagues within a relatively short period of time. In the case of chemical education in Victorian Britain, it was Frankland who played the leading role in the dissemination of the new formulae, which he achieved by occupying a highly influential position within the British science education system. In the case of the German states, the communication process followed a more complex pattern due to the pluricentric structure of the German education system. At the same time, the lack of biographical sources as well as primary sources related to the teaching activities of German educators makes it very difficult to identify diagrammatic pioneers with certainty. In spite of these historiographical challenges, I have identified a number of German pioneers, such as Emil Erlenmeyer (1825-1909) and Adolf von Baeyer (1835-1917), who functioned as promoters of the new formulae.

However, there are also significant historical and historiographical differences between the two cases, which mean that Kaiser's account cannot be directly applied to my account. Above all, line-and-letter formulae were not invented by a single scientist, but were independently developed and introduced by Archibald Scott Couper in 1858 and Alexander Crum Brown in 1861. Secondly, Kaiser's study focuses on the second half of twentieth century, whereas my thesis is concerned with the second half of the nineteenth century. Although concerned with the circulation of scientific diagrams, our stories are therefore set in two entirely different educational, social, economic, and geopolitical contexts. By way of illustration, the institution of postdoctoral training plays a crucial role in Kaiser's account,[61] yet it is an invention of the twentieth century and simply did not exist in nineteenth-century British and German universities. Thirdly, Kaiser claims that printed matter such as textbooks played only a tangential, if any, role in the rapid global dispersion of Feynman diagrams. By contrast, print

[61] Ibid, pp. 15-16.

communication played a crucial part not only in the inception, but also in the circulation, appropriation, and standardisation of line-and-letter diagrams in my story. These differences, I believe, make it clear that Kaiser's account cannot be directly applied to the case of nineteenth-century chemical diagrams. To overcome the existing historiographical shortcomings, my thesis develops a new approach to achieve a comprehensive and historically accurate understanding of the circulation and appropriation of line-and-letter formulae in Britain and Germany. I discuss my approach to the study of the circulation and appropriation of line-and-letter diagrams in more detail at the beginning of Chapter 5.

Building on the above works in the history of science, history of pedagogy, and history of scientific print, my thesis develops a communication model that does not portray the evolution and communication of line-and-letter formulae as a linear progress, but rather as the result of a multitude of processes linking scientific, institutional and commercial actors and interests with markets, audiences and printing technologies. By showing how these various processes interlocked and eventually produced a specific form of visual representations that has retained its relevance to chemical research and education until the present day, I also stress the important contribution that a narrative based on scientific media can make to a new and more profound understanding of the history of science. The next section explains how this approach gives rise to a new account of how line-and-letter formulae acquired their characteristic appearance and why the diagrams became the standard notation of organic chemistry by the end of the nineteenth century.

1.3. Thesis Outline

The thesis examines the various communication practices that drove the production, circulation, appropriation of line-and-letter diagrams in Britain and Germany between 1857 and 1892, thereby covering the period from the first appearance of line-and-letter formulae and competing diagrams to the de-facto codification of line-and-letter formulae as the international graphic notation of organic chemistry. Visual representations of the principle of valence and the theory of chemical structure were put into circulation in the late 1850s when August Kekulé began using his 'sausage diagrams' in 1857 and Archibald Scott Couper published his version of line-and-letter formulae in 1858. My choice of the year 1892 as the end date of this thesis is informed by Evan Hepler-Smith's recent dissertation on the history of the international system of chemical nomenclature.[62] In his work, Hepler-Smith explains that the first international

[62] Hepler-Smith, 'Nominally Rational'.

convention on chemical names, established at the Geneva Congress for the Reform of Chemical Nomenclature in 1892, was effectively a set of rules for turning line-and-letter formulae into chemical names. The existence of a tacit understanding of how to draw, print, manipulate, and interpret line-and-letter formulae was thus a necessary prerequisite for the establishment of the official nomenclatural convention achieved in 1892, which by implication means that a tacit convention on the iconography and use of line-and-letter diagrams was already in place before the international meeting in Geneva. And indeed, we shall see in Chapter 6 of this thesis that such a tacit convention was reached during the 1880s and early 1890s.

In this thesis, I examine the making of the modern chemical notation through a comparison of the various communication practices that drove the circulation, appropriation, and gradual transformation of line-and-letter formulae in Britain and Germany.[63] In following this approach, the thesis pays only marginal attention to the circulation and reception of line-and-letter diagrams in France. This was the case because French chemistry experienced a period of very strong opposition to atomistic and, as a consequence, structural ideas, which had the effect that visual representations linked to those ideas effectively did not appear in French publications until the early 1890s.[64] Consequently, French editors, publishers, and printers contributed very little to the shaping of line-and-letter formulae during the diagrams' formative period because French authors did not use the formulae. Nor did French print makers face the same economic and practical challenges as their British and German colleagues. However, while it is beyond the scope of this thesis, the communication of line-and-letter formulae in France remains a rich topic for future research, not least in relation to the question of how French chemists appropriated the diagrams prior to the Geneva Conference in 1892.[65]

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[63] In this thesis, the notion of *Germany* refers to the territories of the German Confederation (Deutscher Bund, 1815-1848, 1850-1866) and the German Empire (Deutsches Kaiserreich, 1871-1918), but excludes the territories of the Austrian Empire (Kaisertum Österreich, 1804-1867) and Austria-Hungary (Österreichisch-Ungarische Monarchie, 1867-1918).

[64] The seminal works on the development and mixed reception of different notions of atomism in nineteenth-century chemistry are Brock, ed., *The Atomic Debates* (Leicester: Leicester University Press, 1967); and Rocke, *Chemical Atomism.*

[65] As we shall see in Chapter 2, one of the key elements of the theory of chemical structure was the notion of the chemical atom. However, opposition to atomisitic ideas was widespread among French scientific elites during the second half of the nineteenth century. Prominent opponents of the atomic theory included the influential chemist Pierre Eugène Marcellin Berthelot (1827-1907), professor at the Collège de France since 1865 and member of the prestigious Académie des Sciences since 1873. This strong antiatomist attitude was the main reason why the vast majority of French chemists avoided the use of any kind of structural representations in French textbooks and journals for the most part of the nineteenth century. It was only after the Geneva Conference of 1892 that the structure theory was vindicated and that structural thinking was gradually introduced in French chemical education on a national level (cf. Hepler-Smith, 'Nominally Rational'). For more details on the reception of the structure theory in nineteenth-century France, see Danielle Fauque's 'La réception de la théorie atomique en France sous le Second Empire et au début de la IIIe République', *Archives Internationales d'Histoire des Sciences*, 53 (2003), 64-112. The prolonged French debate, fittingly labelled 'The Atomic War' by Alan

In this thesis, I argue that it was not only for theoretical reasons, but also to a very significant extent for practical reasons concerning the technologies, practices, and economics of print communication, that line-and-letter formulae became established as the default graphic notation of organic chemistry by the end of the nineteenth century. The thesis follows the evolution of line-and-letter formulae from the first appearance of the diagrams in the late 1850s to the time when the formulae became universally established as the standard notation of organic chemistry in the 1890s. The thesis is organised in three parts. Part I of the thesis is concerned with the inception of line-and-letter formulae. Chapters 2 and 3 demonstrate that the form and function of the formulae were shaped not only by theoretical considerations, but predominantly by the economic and practical concerns of authors, editors, publishers, and printers of scientific literature. Part II offers a comparative study of the circulation and appropriation of line-and-letter formulae in Britain and Germany. Focusing on chemical training, Chapters 4 and 5 contend that chemistry students in the two countries mastered the formulae through different teaching and learning practices which were contingent on specific factors such as educational infrastructure and the size and dynamics of the national markets for scientific print. Finally, Part III is concerned with the internalisation and standardisation of line-and-letter formulae in the 1870s and 1880s. I argue in Chapter 6 that the processes that led to a more uniform and standardised appearance of the formulae towards the end of the nineteenth century were not driven by official agreements between chemists, but rather by market forces governing the production and distribution of scientific print. I conclude that it was this common understanding of how line-and-letter formulae are supposed to look on the printed page that provided the foundation for the first official international agreement on systematic organic nomenclature that chemists achieved at the Geneva Conference in 1892.

Part I begins with Chapter 2. The chapter opens with a systematic overview of the theoretical and institutional contexts in which different forms of type-based notations were developed, and how they came to dominate the visual culture of nineteenth-century chemistry. Building on this account, I argue that the iconography of line-and-letter formulae was to a very large degree shaped by the printing technology of letterpress, and that this formed the necessary condition for the formulae to develop their iconographic flexibility and heuristic power. Chapter 3 continues the theme of scientific printing by critically analysing the impact of the different printing practices they entailed on the circulation of the various forms of chemical formulae that were used during the 1860s. The chapter contends that, through being printed by means of moveable type, line-and-letter formulae acquired a number of practical and economic

Rocke, is covered at length in Rocke, *Nationalizing Science: Adolphe Wurtz and the Battle for French Chemistry* (Cambridge, MA: MIT Press, 2001), pp. 301-31.

advantages over competing forms of representation that were proposed by Josef Loschmidt and August Kekulé in the period. I argue that these advantages made line-and-letter formulae particularly suitable for the competitive and rapidly changing print market characterised by the emergence of specialist scientific periodicals, thus making structural formulae so successful in the long run.

Part II of the thesis comprises a comparative study that is concerned with the circulation and appropriation of line-and-letter formulae in Britain and Germany during the 1860s and 1870s. Chapter 4 provides a detailed account of the communication practices that drove the proliferation of the formulae in Britain during the 1860s and 1870s. In this chapter, I argue that it was Edward Frankland's integrated scheme of chemical education that promoted the wide dissemination and relatively fast appropriation of line-and-letter diagrams in Britain. Frankland's scheme was built on the framework of the Department of Science and Art (DSA) and included chemistry teacher training, lectures, textbooks, examinations, and mandatory writing exercises. By analysing the elements of Frankland's education scheme, I demonstrate that the distribution pattern of line-and-letter diagrams described in this chapter was unique to Britain and did not apply to any other country. Chapter 5 compares the situation in Britain to the situation in Germany. In this chapter, I contend that, due to the lack of suitable textbooks and because of the tradition of research-based learning, German chemistry students predominantly used periodicals as learning resources to familiarise themselves with the new notation. By providing this account, the chapter makes an original contribution to the history of German chemistry and advances our understanding of the various roles that textbooks and journals had played in the transmission and the making of scientific knowledge.

The final part of the thesis is concerned with the internalisation and standardisation of line-and-letter formulae in the 1870s and 1880s. Chapter 6 continues the investigation of the practical and economic challenges of communicating line-and-letter formulae in periodical print. In this chapter, I contend that the communication of space-consuming line-and-letter diagrams by means of periodical literature resulted in the standardisation of the diagrams' iconography. I demonstrate that the amount of space taken up by the new formulae forced editors and publishers of British and German abstract journals to introduce editorial measures for fitting more abstracts on the page of their journals in order to secure their journals' commercial success in the highly competitive markets for periodical literature. I conclude that the editorial measures introduced by leading abstract journals contributed to reduction of their iconographic diversity. By providing this account, the chapter also demonstrates that abstract journals played a central role in the international circulation of line-and-letter formulae and thus drove the constant increase of the number of diagrams on the pages of scientific journals.

In the final chapter of my thesis, I evaluate my findings and reflect on the new and important research questions that my thesis has raised. By integrating the history of chemistry with the history of education as well as publishing and printing, the thesis has produced an innovative practice-based account of the establishment of structural formulae as an indispensable tool of chemical research and communication, thereby revealing the essential contribution of various kinds of communication practices to the formation of chemistry as a modern scientific discipline. By following these communication practices, the thesis demonstrates that it was not theoretical considerations, but predominantly practical and economic concerns that shaped the iconography of the diagrams, and that were one of the main reasons for the formulae's lasting success. I conclude the thesis by emphasising that the emergence, stabilisation, and success of the modern notation can only be understood in the specific historical context of nineteenth-century print markets and educational infrastructures.

PART I

Inception

We have seen in Chapter 1 that the standard account is not able to explain in convincing terms why exactly line-and-letter formulae became such a success in organic chemistry, and that most existing historical studies simply do not address the issue. This question becomes even more pertinent and pressing if we acknowledge that line-and-letter formulae were by no means the only possible way to visualise the principles of the structure theory. As we shall see in Chapter 2 of my dissertation, alternative diagrams were proposed by August Kekulé in 1857-58 and Johann Josef Loschmidt in 1861. So why did not one of the competing diagrams become the default notation of organic chemistry? Tentative answers to this question were proposed by A. A. Baker (1966) and, more recently, by Christopher Ritter (2001), amongst others.[1] However, these studies focused on the epistemic properties of line-and-letter formulae. Baker claimed that line-and-letter diagrams were simply the best suited to represent one or several principles of the new structure theory more clearly than other forms of representations.[2] Ritter, in turn, argued that line-and-letter formulae became so popular because they performed exceptionally well in chemistry teaching.[3]

Upon closer examination, we can find testimonies that indicate that many contemporary researchers and educators preferred Kekulé's and Loschmidt's formulae for their unique heuristic and epistemic qualities, as I explain in more detail in Chapter 2. Any future investigation into the success of line-and-letter formulae must therefore make sure to approach competing diagrams as serious contenders instead of applying an ahistorical reading and treating those diagrams as a "lost cause". Chapter 2 demonstrates that, whatever the reasons, the success of line-and-letter formulae was not founded on epistemic and heuristic grounds alone, meaning that epistemic and heuristic explanations are not enough to account for the complex historical processes which led to the establishment of line-and-letter formulae as the default notation of organic chemistry. It is for this reason that I employ aninterdisciplinary and comparative approach to challenge and supplement the previous accounts. I argue in Part I of

[1] Baker, A. A., 'The Development of the Understanding of Unsaturation: 1858-1870', in *Kekulé Centennial*, ed. by Benfey, Otto Theodor, Advances in Chemistry Series, 61 (American Chemical Society, 1966), pp. 81-90; Ritter, Christopher Owen, 'Re-Presenting Science: Visual and Didactic Practice in Nineteenth-Century Chemistry' (unpublished doctoral thesis, University of Califonia, Berkeley, 2001).
[2] For instance, Baker argues that Crum Brown's version of line-and-letter formulae represented double bonds more clearly and was therefore more popular than any graphic notation at that time. Cf. Baker, 'Unsaturation', p. 90. Also see Russell, *Valency*, p. 234.
[3] Ritter, 'Re-Presenting Science', p. 150.

this thesis that the success of line-and-letter formulae can only be sufficiently explained if we also account for historical practices through which chemical knowledge was communicated. Chapters 2 and 3 show that it was notably due to the economics and limitations of nineteenth-century printing technologies that line-and-letter formulae proved so successful in the long run.

CHAPTER 2

Theory, Practice, and the Emergence of a Unique Visual Culture of Modern Chemistry

The nineteenth century was the formative period of chemistry as a modern scientific discipline. This complex and extended process was marked by new discoveries, the agreement of international conventions regarding key concepts and units, and the gradual formation and consolidation of a new theoretical framework – the theory of chemical structure – driven by research questions in organic chemistry. The nineteenth century also witnessed the development of physical research methods and the emergence of new research fields such as physical chemistry.[1] In addition, the nineteenth century occupies a crucial position in the social history of chemistry, as it is the period when chemical research was institutionalised, with the establishment of chemical institutes in Germany and elsewhere in Europe – a process which was amplified and soon driven by the growing industrial and economic relevance of the expanding chemical industry during the last third of the century.[2]

The period also witnessed the foundation of chemical societies as professional bodies for the growing number of academically educated chemists. The first of those societies was the Chemical Society of London, established in 1841, and this was closely followed by the Société chimique de Paris, which was established in the French capital in 1857.[3] The chemical society that later became the national society for the German lands was the Deutsche Chemische Gesellschaft zu Berlin (DCG), established on the initiative of August Wilhelm von Hofmann (1818-92) in 1867.[4] Finally, the nineteenth century saw the formation of a characteristic visual culture which gave works of chemical literature their unmistakable appearance, and this ultimately led to the emergence of structural formulae, the graphical notation which is still used in chemistry, biochemistry, and affiliated sciences today. Yet as I have outlined in the introductory chapter, it is still widely assumed that these line-and-letter formulae were invented and introduced by Alexander Crum Brown and Edward Frankland, and that the – presumptively instant – success

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[1] For an overview, see Ihde, Aaron J., *The Develoment of Modern Chemistry* (New York, NY: Harper & Row, 1964), Chapter 15.

[2] For an overview, see Smith, John K., 'The Evolution of the Chemical Industry: A Technological Perspective', in *Chemical Sciences in the Modern World*, ed. by Seymour H. Mauskopf (Philadelphia, PA: University of Pennsylvania Press, 1993), pp. 137–57.

[3] For a history of the Chemical Society, see Moore, Tom S., and James C. Philip, *The Chemical Society: 1841-1941* (London: The Chemical Society, 1947). For the French counterpart, see Rocke, *Nationalizing Science*, pp. 214-20.

[4] On the history of the DCG during its first 75 years, see Walden, Paul, '75 Jahre Deutsche Chemische Gesellschaft (1867–1942)', *Angewandte Chemie*, n.s., 55.49-50 (1942), 367–69.

of the formulae was founded on the diagrams' ability to represent the chemical structure of organic compounds in a more successful manner than any other structural notation.

The current chapter aims to challenge and qualify this account by arguing that line-and-letter formulae were not invented by a specific genius scientist at a particular point in time. Rather, it gradually developed from existing type-based notations, thus being part of an already existing visual culture of chemistry which was based on the technology of letterpress and moveable type, and which had existed since the beginning of the nineteenth century. I argue that by the mid-century type-based representations established a characteristic visual culture against which diagrams produced by other means of print technology could not compete. I develop this argument by stressing the essential part that type-based chemical diagrams played in the development of nineteenth-century chemistry in their capacity as paper tools for solving the most pressing issues of that time. By following the evolution of chemical representations in their theoretical and institutional context, we shall witness the active role that type-based chemical symbols and diagrams played in the making of chemistry as a modern scientific discipline. But why did type-based diagrams become so successful? I address this question by arguing that type-based diagrams became the preferred representations of organic compounds not only by virtue of their epistemic power or ontological status alone, but that very practical concerns about print communication played also a major part in that process.

The argument of the present chapter extends over four sections. The first section provides an overview of the unique historical setting in which the different forms of type-based notations were developed, and how they came to dominate the visual culture of nineteenth-century chemistry. The objective of this section is to demonstrate that type-based notation proved to be very flexible, meaning that any of the theories could be expressed by means of type-based signs. Those type-based forms of notation – including line-and-formulae – emerged in a specific historical context defined by on the one hand profound institutional and theoretical changes, and on the other, the economy and practices of print-based communication. However, I explain that chemical representations were not a mere by-product of those developments, but on the contrary played a leading role in the making of chemical knowledge in line with Ursula Klein's notion of the 'paper tool'. For this purpose, the first section will take us on a guided tour through the major chemical theories of the nineteenth century. By following this narrative, we will see how chemists used type-based symbols and diagrams to represent, debate, and reflect on the constitution of organic compounds, thereby further shaping and consolidating the typography-based visual culture of modern chemistry.

In the second section, I demonstrate how concerns about the printability of chemical signs played a central role in the inception of so-called Berzelian formulae, a type-based notation that was designed to overcome problems of printing alchemical symbols. The section illustrates how the representation devised by the Swedish chemist Jöns Jacob Berzelius (1779-1848) established a unique visual culture on which a whole a range of other type-based signs and formalisms were modelled during the nineteenth century. I do this by stressing the major advantages of the letterpress technology in the dispersal and lasting success of Berzelian formulae by contrasting the fate of this system with that of the so-called Daltonian formulae, which represented a major competitor to Berzelius' system at the beginning of the nineteenth century. John Dalton's (1766-1844) chemical signs were not as well received as Berzelian formulae and never became the standard notation of chemistry. I show that this was not only the result of the idea of physical atomism implied by Dalton's formulae, but also due to the fact that the formulae could not be combined with printed text because they were realised by means of intaglio plates that were printed separately from the text.[5] I conclude the section by arguing that Dalton's choice to use intaglio plates not only made his formulae difficult and thus more expensive to print, but also that this particular technology reinforced the realist reading of Daltonian signs because it did not allow for the same degree of graphic flexibility that could be found in Berzelian formulae.

The third section demonstrates how the new theory of chemical structure that gradually emerged over the course of the 1850s and 1860s prompted chemists to develop more sophisticated ways to think about, and represent, their ideas about the arrangement of atoms in a molecule. The section shows that, next to line-and-letter formulae, two competing sets of structural diagrams were developed during that period. The first set was developed by the German chemist August Kekulé (1829-96) in 1857 and first published in his textbook in 1861; the second set was devised by the Austrian school teacher Josef Loschmidt (1821-95) and printed in the same year. Yet both notations soon disappeared from the printed pages of scientific books and periodicals. In this section, I argue that although line-and-letter formulae

[5] Ritter undertakes a close examination of the material quality and characteristics of Dalton's illustrations in his doctoral thesis. He argues that based on the 'subtle indications of their provenance' (plate marks, fine lines in the figures), the formulae were printed from intaglio plates by means of copperplate etching ('Re-Presenting Science', p. 61). Although I concur with Ritter's assessment regarding the use of intaglio plates, I do not agree with his conclusion that the plates were etched, since plate marks and fine lines in the figures are also characteristic of copperplate engravings. In addition, etching and engraving were often used in combination on the same plate, which for the historian makes it very difficult to tell the two processes apart. See Gascoigne, Bamber, *How to Identify Prints: A Complete Guide to Manual and Mechanical Processes from Woodcut to Ink Jet* (London: Thames and Hudson, 1986), § 12; and Mosley, James, 'The Technologies of Printing', in *The Cambridge History of the Book in Britain*, V: *1695-1830* (2009), ed. by Michael F. Suarez and Michael L. Turner, pp. 163-99 (p. 186). Due to the lack of conclusive evidence I defer from drawing a sharp distinction between etching and engraving in this particular case, but shall refer to Dalton's illustrations as 'intaglio plates' instead.

performed in some research situations better than their competitors, a purely theory-based account of the success of line-and-letter diagrams falls short of the actual historical context.

I develop this argument further in the fourth section, where I present historical evidence which shows that there were in fact a number of chemists who promoted the use of Kekulé's diagrams, and that Loschmidt's formulae performed quite well when applied to questions of isomerism. In order to accommodate this evidence, we therefore need to go beyond theory-based accounts and look for other explanations for the success of line-and-letter formulae and the demise of their competitors. Following the suggestion of the chemist-historian Carl Graebe (1841-1927), I continue to argue that we need to focus on the practices of print communication if we want to understand why Kekulé's and Loschmidt's diagrams disappeared from the printed page. Yet as I demonstrate toward the end of the section, those communication practices must not be viewed as being distinct from other tasks that chemists performed as part of their everyday work, but were in fact part of the chemists' assorted toolkit for the production of new chemical knowledge. Nevertheless, print technology and the economics of the print market played a major role in securing the long-term success of line-and-letter formulae, as I explain in more detail in the following chapter.

2.1. Chemical Representations and the Making of the Visual Culture of Modern Chemistry

The history of modern chemical notation is inextricably linked to the profound theoretical and institutional changes that the discipline of chemistry underwent over the course of the nineteenth century. The story that is most relevant to my thesis begins with the Swedish chemist Jöns Jacob Berzelius, who conceived the kind of type-based symbols and formulae which formed the foundation for all other type-based diagrams developed in the nineteenth century, and which are still in use today. Berzelius developed his symbols and formulae as a convenient and systematic way to classify the rising number of newly discovered (inorganic) compounds according to their 'composition', which is defined by the identity and relative number of the components in a specific compound.[6] When Berzelius published his symbols and formulae in a multi-piece essays in 1814 (Figures 2.1 & 2.2), he explained that expressions like NaCl or $MgSO_4$ – sodium chloride and magnesium sulfate, respectively, according to today's nomenclatural rules – represent the composition of inorganic substances according to his own stoichiometric 'theory of chemical proportions'. According to Berzelius, the elemental symbol in each formula

[6] Cf. Klein, *Paper Tools*, pp. 9-18.

(e.g. Na for sodium and Cl for chlorine) did not represent physical atoms, but rather 'chemical proportions' – a concept describing 'scale-independent bits or portions of elements, which overlapped but was not identical with the concept of "atom" in the philosophical and physical tradition.'[7] Today, we use experimentally determined atomic weights instead of Berzelius' chemical proportions, but we still employ the same symbols and formulae to express the composition of compounds. In today's terms, for instance, we represent the composition of water and ammonia as H_2O and NH_3, respectively. These two 'empirical formulae' represent the composition of water as a 2:1 ratio of hydrogen atoms to oxygen atoms and the composition of ammonia as a 1:3 ratio of nitrogen atoms to hydrogen atoms.[8]

example. Let O be oxygen, A and B two combustible bodies. The law which we are considering admits of a combination of A + 3 O with $1\frac{1}{2}$ B O, because $1\frac{1}{2} \times 2 = 3$: and we shall see immediately that such combinations exist, though, according to the corpuscular theory, they appear absurd. On the other hand, the law does not admit the combination of A + 3 O with B + 2 O, though such a combination be conformable to the theory of atoms. The black oxide of copper is composed,

Figure 2.1: Berzelius' symbols and formulae, 1814.[9]

When we express a compound volume of the first order, we throw away the +, and place the number of volumes above the letter: for example, Cu O + S $\overset{3}{\dot{O}}$ = sulphate of copper, Cu $\overset{2}{\dot{O}}$ + 2 S $\overset{3}{\dot{O}}$ = persulphate of copper. These formulas have this advan-

Figure 2.2: Berzelius' symbols and formulae, 1814.[10]

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[7] Ibid, p. 5.

[8] 'Empirical formula' contain information about the composition of a compound by representing the number of portions or "bits" that make up that compound. Depending on the underlying theoretical framework and the ontological position held by its users, these portions were termed 'atoms' (Dalton and others), 'equivalent' (Wollaston), 'proportion' (Davy), 'combining weight' (Young), 'portion' (Thomson), or 'parcel' (Whewell). Cf. Klein, *Paper Tools*, p. 20. A 'rational formula', on the other hand, expresses the constitution of a compound by representing how the different portions or "bits" are distributed inside the molecule of a compound. To use one of Rocke's examples, 'the empirical formula for oil of bitter almonds was C_7H_6O, regarded as a simple expression of chemical analysis. One possible rational formula for this substance was $H.C_7H_5O$, which, by distinguishing one hydrogen atom from the others, goes beyond the empirical data to make a theoretical statement about the internal details within the molecule.' (Rocke, *Image and Reality*, p. 13.) The term 'rational formula' came into use in the 1830s.

[9] Berzelius, Jöns Jacob, 'Essay on the Cause of Chemical Proportions, and on some Circumstances Relating to Them: Together with a Short and Easy Method of Expressing Them', in *Annals of Philosophy*, 2 (1814), 443-54 (p. 448).

[10] Idem, 'Essay on the Cause of Chemical Proportions, and on some Circumstances Relating to Them: Together with a Short and Easy Method of Expressing Them', *Annals of Philosophy*, 3 (1814), 51-62, 93-106, 244-57, 353-64 (p. 52).

Despite having their origins in inorganic chemistry, Berzelian formulae only developed their full potential in the 1830s, when chemists began applying the formulae to problems in organic chemistry. During the period between the early 1830s and the late 1860s, chemists were mostly concerned with developing new theories to classify the rapidly increasing number of organic compounds that poured out of chemical laboratories in Germany and other European countries. This increase in the number of unknown organic compounds was the result of a shift from small-scale analysis of animal and plant matter to laboratory-based chemical research that used synthetic methods to produce and investigate artificial substances. This shift was accompanied by processes of professionalization, specialisation, and institutionalisation. Pioneered by Justus von Liebig's (1803-73) state-funded 'Giessen School' that was officially established in 1826,[11] a number of similar chemical institutes were established in Germany and – with some delay, in smaller numbers, and in slightly different forms – in other European countries over the course of the following decades.[12] As Jeffrey A. Johnson explains in his widely cited 1985 paper, by 1866 the German lands possessed a number of small yet powerful institutes that shared the same characteristic features, namely laboratory-based training and research programmes which were based to a large degree on student labour.[13] Since the majority of those institutes were run by organic chemists and therefore produced a growing number of highly-skilled students trained in organic research, the number of German-trained organic chemists began to increase drastically during that time.[14] By the early 1870s, organic research was dominated by German chemists who were trained in those institutions.

In the context of organic chemistry, Berzelian formulae proved very useful because chemists were able to manipulate the formulae as 'building-block' models on paper, as I explain in more detail below. The main challenge of the day was the classification of organic compounds, which differ from inorganic compounds in the number and variety of elements which the substances contain. Inorganic compounds are made up of a relatively large number of different elements and can therefore be classified by indicating the composition of that compound (to use some of our previous examples, NaCl for sodium chloride, $MgSO_4$ for magnesium sulfate, or

[11] We shall learn more about the history of the 'Giessen School' (sometimes also termed 'Giessen Model' and Giessen System') and its role in the proliferation of line-and-letter formulae in Germany in chapter 5, below.

[12] The most notable of the overseas institutions modelled on Liebig's institute was the Royal College of Chemistry (f. 1845) in London. I elaborate on the history of this institution in Chapter 4, below.

[13] Cf. Johnson, Jeffrey Allan, 'Academic Chemistry in Imperial Germany', *Isis*, 76.4 (1985), 500–24.

[14] For estimated student numbers at selected German teaching institutions, see Wetzel, Walter, 'Origins of and Education and Career Opportunities for the Profession of "Chemist" in the Second Half of the Nineteenth Century in Germany', in *The Making of the Chemist*, pp. 77-94. For detailed statistical data concerning the distribution of students according to different subjects in nineteenth-century and twentieth-century Germany, see Titze, Hartmut, *Wachstum und Differenzierung der deutschen Universitäten 1830-1945*, Datenhandbuch zur deutschen Bildungsgeschichte, 1.2 (Göttingen: Vandenhoek & Ruprecht, 1995).

NH_4SCN for ammonium thiocyanate). Organic compounds, on the other hand, are to a large extent composed of a limited number of elements which can be combined in numerous ways.[15] As Hepler-Smith pointedly explains in his recent thesis, this 'made their composition both more difficult to determine and less informative than that of an inorganic compound like sodium chloride. Even worse, some substances with different chemical properties had precisely the same composition: isomers, Berzelius termed such chemical twins.'[16] As I have already explained in the first chapter, isomers are compounds which share the same composition, but differ in their physical properties and chemical behaviour. In response to this problem, chemists developed different theories of constitution to account for the possible ways in which the portions, or "bits", could be arranged inside the isomeric molecules in order to tell the compounds apart and to explain the compounds' different properties and behaviour.

Over the course of the 1840s and 1850s, a large number of different and often contradictory theories of chemical constitution were proposed. In terms of the iconography of the formulae in use during that time, only minor changes occurred, since all chemists chose to appropriate Berzelian symbols to express their theories of chemical constitution. Because they consist of a small number of such basic elements as letters and figures, Berzelian formulae proved very flexible and could be used to represent any of the chemical theories in place. By way of illustration, one of the most influential theories during that time was the 'type theory' introduced by Dumas in the 1830s and further developed by Hofmann, Alexander William Willamson (1824-1904), and Charles Gerhardt (1816-56) in the 1850s.[17] In short, the theory claims that organic substances possessed a distinctive 'typical' property which is defined by one 'typical atom' in the arrangement of other (chemical) atoms inside a molecule, and that every substance could hence be classified on the basis of these properties. Consequently, the classification of substances according to Dumas' theory required the identification the one atom responsible for the typical behaviour of a given compound (e.g. density, phase, boiling point). Type formulae were then arranged in a manner which emphasised the central atom, thus making it the unmistakeable token of the represented compound.[18] By way of illustration, the typical atom is oxygen (O̶) in the formula below (Figure 2.3).

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[15] The most common elements of organic compounds are carbon, hydrogen, oxygen and nitrogen.
[16] Hepler-Smith, 'Nominally Rational', p. 38.
[17] For a concise overview of the two major constitutional theories – the 'type theory' and the 'radical theory' – that existed from the 1830s to the 1850s, see Ramberg, *Chemical Structure*, pp. 17-20; and Rocke, 'Chemical Structure Theory and its Applications', in *The Cambridge History of Science*, ed. by David C. Lindberg and Ronald L. Numbers, 7 vols (Cambridge: Cambridge University Press, 2002-2018), V: *The Modern Physical and Mathematical Sciences* (2002), ed. by Mary Jo Nye (2002), pp. 255-71. (pp. 255-62). For a more technical and philosophical discussion of those theories, I recommend Brock, *Fontana History*, pp. 210-40; and Fisher, N. W., 'Organic Classification before Kekulé. Part I', *Ambix*, 20.2 (1973), 106-31, and idem, 'Organic Classification before Kekulé. Part II', *Ambix*, 20.3 (1973), 209-33.
[18] Cf. Ramberg, *Chemical Structure*, p. 19.

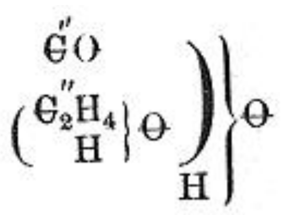

Figure 2.3: Johannes Wislicenus' (1835-1902) type formula for lactic acid.[19]

The downside of this approach was that one substance could be expressed by means of a number of different type formula because each formula 'relied on a subjective judgement about which property was central to the compound, which, of course, could vary depending on the reaction under consideration.'[20] This problem was not exclusive to type formulae, since formulae representing constitution according to other theories, too, suffered from similar issues.[21] In short, the period from the early 1830s to the late 1850s saw the rise and fall of an impressive number of different constitution theories which were all expressed by means of Berzelian type-based symbols and formulae. One particular substance could therefore be represented by a plethora of distinctive formulae which differed from each other because they represented different theories (variations of type and radical theories as well as other theoretical frameworks), and because the formulae employed different concepts of the constituent "bits" which made up the represented molecule ('atoms', 'portions' or 'proportions', 'equivalents', and much else). What made the situation even worse was the fact that the constituent "bits" could be assigned different kinds of weight, which were either different systems of 'atomic weights' derived from the measurement of physical properties of elements and compounds, or 'equivalent weights' determined by chemical reactions.[22]

The resulting confusion about formulae for common substances such as acetic acid was aptly captured by Kekulé, who identified no fewer than nineteen renditions of that substance in the first volume of his *Lehrbuch* from 1861 (Figure 2.4). Kekulé's list illustrates the many various ways in which the same compound could be represented according to different chemical theories and notational conventions, and a brief glance at the list is sufficient to see that by the 1850s the formula situation was extremely chaotic. Kekulé's list also shows that all of the formulae on the list were constructed from Berzelian formulae and are therefore entirely type-

[19] Wislicenus, Johannes, 'Studien zur Geschichte der Milchsäure und ihrer Homologen', *Annalen der Chemie*, 125.1 (1863), 41-77 (p. 44).
[20] Ramberg, *Chemical Structure*, p. 19.
[21] Klein illustrates this point by showing that Berzelius and Dumas proposed two different rational formulae for alcohol. Both formulae meant to represent the binary constitution of the compound, but Berzelius' 'constituents' differed from those identified by Dumas. See Klein, *Paper Tools*, pp. 25-26.
[22] Cf. Rocke, *The Quiet Revolution: Hermann Kolbe and the Science of Organic Chemistry* (Berkeley, CA: University of California Press), pp. 287-88; and Levere, *Transforming Matter*, pp. 84-87, 107-20.

based – no other symbols or printing techniques were used. From this, we can clearly see two things. First, Kekulé's list demonstrates that type-based representations proved very flexible in the context of organic chemistry because typographic elements could be easily arranged and re-arranged to represent different kinds of constitution theories. Second, the list illustrates that by the 1850s, the visual culture of chemistry was dominated entirely by the type-based notation that was introduced by Berzelius at the beginning of the century. In other words, type-based formulae were already firmly established as the preferred technique for communicating information about chemical constitution before the advent of line-and-letter formulae in the late 1850s.

$C_4H_4O_4$	empirische Formel.
$C_4H_3O_3 + HO$	dualistische Formel.
$C_4H_3O_4 \,.\, H$	Wasserstoffsäure-Theorie.
$C_4H_4 + O_4$	Kerntheorie.
$C_4H_3O_2 + HO_2$	Longchamp's Ansicht.
$C_4H + H_3O_4$	Graham's Ansicht.
$C_4H_3O_2.O + HO$	Radicaltheorie.
$C_4H_3 \,.\, O_3 + HO$	Radicaltheorie.
$\left.\begin{matrix} C_4H_3O_2 \\ H \end{matrix}\right\} O_2$	Gerhardt. Typentheorie.
$\left.\begin{matrix} C_4H_3 \\ H \end{matrix}\right\} O_4$	Typentheorie (Schischkoff etc.
$C_2O_3 + C_2H_3 + HO$ . . .	Berzelius' Paarlingstheorie.
$HO.(C_2H_3)C_2,O_3$	Kolbe's Ansicht.
$HO.(C_2H_3)C_2,O.O_2$	ditto
$\left.\begin{matrix} C_2(C_2H_3)O_2 \\ H \end{matrix}\right\} O_2$	Wurtz
$\left.\begin{matrix} C_2H_3(C_2O_2) \\ H \end{matrix}\right\} O_2$	Mendius.
$C_2H_2 \,.\, \left.\begin{matrix} HO \\ HO \end{matrix}\right\} C_2O_2$	Geuther.
$C_2 \left\{\begin{matrix} C_2H_3 \\ O \\ O \end{matrix}\right\} O + HO$	Rochleder.
$\left(C_2 \frac{H_3}{CO} + CO_2\right) + HO$.	Persoz.
$C_2 \left\{\begin{matrix} C_2 \left\{\begin{matrix} O_2 \\ H \end{matrix}\right. \\ H \end{matrix}\right.$ $\left.\frac{H}{H}\right\} O_2$	Buff.

Figure 2.4: Kekulé's compilation of nineteen different formulae for acetic acid.[23]

In this section, we have seen that the constitution formulae which began to appear in the 1830s and then proliferated in the 1840s and 1850s were all built from Berzelian type-based formulae.

[23] Kekulé, August, *Lehrbuch der organischen Chemie*, 3 vols (Erlangen: Enke, 1861-67), I (1861), p. 58. Note that all of these formulae are typeset and utilise only a small number of typographic elements.

Due to their flexibility and 'maneuverability',[24] those formulae played a major role in the making of chemical knowledge because they were the means by which chemists thought about, represented, and communicated ideas concerning the constitution of substances. The formulae were the very means by which the theoretical debates between supporters of different theories were fought and compromises were negotiated, thereby ever further developing the theoretical understanding of the chemical constitution of substances.[25] It was the constant exchange of ideas made possible by means of type-based formulae during this period of creative chaos that led to the gradual emergence of the structure theory in the late 1850s and 1860s; this was when a number of chemists began to draw the existing knowledge together, and made attempts to consolidate it within a new theoretical framework. As we shall see in the third section of this chapter, the line-and-letter formulae that chemists began to use in the 1860s were in fact a continuation of the existing communication practices of using type-based notation in line with the existing visual culture of nineteenth-century chemistry.

But why, exactly, did Berzelian symbols and formulae become so successful during the first half of the nineteenth century? I have explained above that Berzelius' efforts to devise new symbols and formulae were motivated by the problem of classification of inorganic compounds in early nineteenth-century chemistry, and that by the 1830s they became very useful for tackling related problems in organic chemistry. As we have seen above, Berzelius made it very clear that his formulae did not represent physical atoms, but were instead meant to express scale-independent portions without making any ontological claims about their physical nature. Ursula Klein has therefore argued that the long-term success of Berzelian formulae was due to the fact that the representations were ontologically unspecified, which allowed chemists to use the formulae for representing virtually any chemical theory of the day. In other words, the semiotic 'ambiguity' or 'flexibility' of the Berzelian notational system allowed the symbols and formulae to occupy any philosophical position associated with the underlying constitutional theory, ranging from the 'extreme ontological to the purely numerical', as Rocke explains in his 2010 book.[26] Furthermore, Klein has also demonstrated that chemists moved the letters around on paper in a building-block fashion to try out different combinations.[27] In the next chapter, we shall see that this semiotic flexibility also applied to the printed page because the formulae were rendered by means of letterpress and could therefore be printed in any possible arrangement

[24] Klein, *Paper Tools*, p. 6.
[25] Hermann Kolbe (1818-84) was a fierce and regular participants in those debates. For details on the major controversies about chemical constitution and Kolbe's role in that story, see Rocke, *Quiet Revolution*.
[26] Rocke, *Image and Reality*, p. 7.
[27] Klein, *Paper Tools*, pp. 24-27.

with relatively little effort. Consequently, the formulae's success was to a very large degree due to the fact that the formulae were rendered by means of moveable type.

But why did Berzelius chose a type-based notation instead of symbols and diagrams realised by means of wood engravings, copper plates, or any other illustrative technology that was available at that time?[28] In the next section, I argue that this was a strategic decision informed by Berzelius practical concerns about chemical communication and printing. By comparing the printability of Berzelian formulae to that of a competing system of chemical symbols devised by the famous English chemist John Dalton, I demonstrate that Dalton's choice to use intaglio plates limited the circulation of his formulae because they proved to be more difficult and thus more expensive to print than the competing set of type-based Berzelian formulae.

2.2. The Origins of the Visual Culture of Modern Chemistry: Print Communication and the Lasting Success of Berzelian Formulae

The second section shows that the success of Berzelian formulae was not only due to the formulae's semantic properties and unspecified ontological nature, but also to the fact that the notation was realised by means of moveable type and not any other kind of illustration technique. In this section, I argue that Berzelius was very aware of the advantages of using type-based symbols and formulae by demonstrating that practical and economic concerns about printing were very much on his mind when he conceived the formulae. Berzelius, however, was not the first one to use Latin characters as abbreviations for chemical symbols: common shorthands such as 'A.F.' for 'aqua fortis' or 'B.M.' for 'balneum mariae' were found in published tables of chemical symbols from the seventeenth and eighteenth centuries.[29] At the beginning of the nineteenth century, Theodor Grotthuss and Thomas Young continued to make occasional use of abbreviations for denoting chemical substances.[30] As a means of overcoming the existing inconsistencies of mineralogical nomenclature at the beginning of the nineteenth century, the Scottish chemist and mineralogist Thomas Thomson used expressions such as 'As' and 'Amc' in the third volume of his textbook *System of Chemistry* (1802) to denote minerals which, according

[28] For a comprehensive overview, see Twyman, Michael, 'The Illustration Revolution', in *The Cambridge History of the Book in Britain*, VI, pp. 117–43; and Topham, 'Redrawing'.
[29] For details and references, see Crosland, *Historical Studies*, pp. 265-70.
[30] Grotthuss, Theodor, *Mémoire sur la décomposition de l'eau et des corps qu'elle tient en dissolution à l'aide de l'électricité galvanique* (Roma: [n. pub.], 1805); Young, Thomas, *Introduction to Medical Literature: Including a System of Practical Nosology* (London: Underwood & Blacks, 1813).

to his own taxonomy, belong to the same ‘genus’ of natural substances (Figure 2.5).[31] It was this notational system which had the strongest influence on Berzelius, who stated in 1814 that in the process of developing his own symbols and formulae he had closely ‘follow[ed] the rules given by Thomson in his System of Chemistry.’[32] We thus see that there was a longstanding typographical tradition within the (al-)chemical and mineralogical literature to employ abbreviations as a shorthand for chemical substances.

I. A.
- 1. Sapphire
- 2. Corundum
- 3. Native alumina

II. S.
- 1. Quartz
- 2. Flint
- 3. Opal
- 4. Pitchstone
- 5. Chrysoprasium

III. L.
- Native lime

IV. Amc
- Ruby

V. Aim
- Ceylanite

VI. 1. As
- 1. Topaz
- 2. Sommite
- 3. Shorlite

2. sa
- 4. Rubellite
- 5. Hornslate
- 6. Hornstone
- 7. Chalcedony
- 8. Jasper
- 9. Tripoli

VII. Asi

1.
- 1. Micarell
- 2. Shorl
- 3. Granatite

2. sai

Figure 2.5: Sample of Thomson’s symbols for genera of natural substances.[33]

As I have mentioned previously, it was the abbreviations devised by Berzelius which became the foundation of the modern chemical formulae, thereby having a profound and permanent impact on the visual culture of modern chemistry. Yet the success of the new formulae was not only due to their successful application as paper tools in inorganic – and, later, organic – chemistry, but was also driven by very practical typographical considerations. There are several instances which demonstrate that Berzelius was very aware of the importance of typography and the practicalities as well as limitations of printing technology and book production. He pointed out on several occasions that he chose to use type-based formulae in order to ensure that the

[31] Thomson, Thomas, *A System of Chemistry*, 4 vols (Edinburgh: Bell, Bradfute and Balfour, 1802), III, p. 431. For more details on Thomson’s use of abbreviations, see Partington, James Riddick, ‘Thomas Thomson, 1773–1852’, *Annals of Science*, 6.2 (1949), 115-26 (p. 118); and Crosland, *Historical Studies,* pp. 268-69.

[32] Berzelius’ bibliographical reference is incomplete, but we can deduce from the publication date of Berzelius *Attempt* (1814) that he refers to the third or fourth edition of Thomson’s *A System of Chemistry*. The third edition was published in 5 volumes in 1807 by Bell, Bradfute and Balfour, Edinburgh. The fourth edition was published in 4 volumes in 1810 by Bell and Bradfute, Edinburgh. Cf. Partington, ‘Thomson’, p. 125, n. 61.

[33] Thomson, *System*, III, p. 431.

notation would be printable. In the seminal paper titled 'On the Chemical Signs and the Method of Employing Them to Express Chemical Proportions' (1814), for instance, Berzelius made it clear that he intentionally chose to use the letterpress in order to avoid the problems which earlier alchemical and chemical representations encountered with regard to scientific print, stating that he would 'endeavour to avoid the inconveniences which rendered the old ones of little utility.'[34]

And Berzelius did not hesitate to provide examples. With regard to the symbols devised by Pierre August Adet and Jean Henri Hassenfratz as a contribution to the French endeavour to reform chemical nomenclature in 1787,[35] Berzelius pointed out that, although the new symbols were 'very well contrived, and very ingenious, they were of no use' due to the difficulty of actually reading them, since any custom-made (chemical) symbol used in a printed text 'must be made of a larger size than our ordinary writing.'[36] Indeed, Adet and Hassenfratz had encountered problems with getting their chemical symbols (Figure 2.6) printed due to the constraints of printing technology; in practice their symbols did not appear in other works of chemistry from that time for that reason.[37] Berzelius further emphasised the role which printing technology played in his choice of type-based formulae in his lengthy treatise *Essai sur la théorie des proportions chimiques et sur l'influence chimique de l'électricité* in 1819, stating that 'chemical signs should be letters of the alphabet so that they can be easily drawn and printed without disfiguring the text.'[38] This, again, emphasises that Berzelius was very aware of the significance of the printability of chemical signs in determining the success of the associated notation. The reference to Adet and Hassenfratz bears witness to Berzelius' strong intention to avoid the disadvantages of symbols printed by other methods than letterpress and moveable type. Such disadvantages became very apparent in the case of John Dalton's singular representations of atoms and molecules, which were first published in 1808 and thus appeared only a few years before Berzelius' notation was published in 1814.

[34] Berzelius, 'Chemical Signs', p. 51.
[35] Adet's and Hassenfratz' symbols were published as an addendum to Louis-Bernard Guyton-Morveau's, Antoine Lavoisier's, Claude Louis Berthollet's, and Antoine-François Fourcroy's famous *Méthode de nomenclature chimique: On y a joint un nouveau système de caractères chimiques, adaptés à cette nomenclature, par MM. Hassenfratz et Adet* (Paris: Cuchet, 1787). For details, see Crosland, *Historical Studies*, pp. 245-55.
[36] Berzelius, 'Chemical Signs', p. 51.
[37] Cf. Crosland, *Historical Studies*, p. 251. Ritter, too, suggested that Adet and Hassenfratz might have encountered problems with having their symbols printed. Cf. Ritter, 'Re-Presenting Science', p. 61.
[38] Berzelius, *Essai sur la théorie des proportions chimiques et sur l'influence chimique de l'électricité: Traduit du suédois sous les yeux de l'auteur et publié par lui-même* (Paris: Méquignon-Marvis, 1819), p. 111.

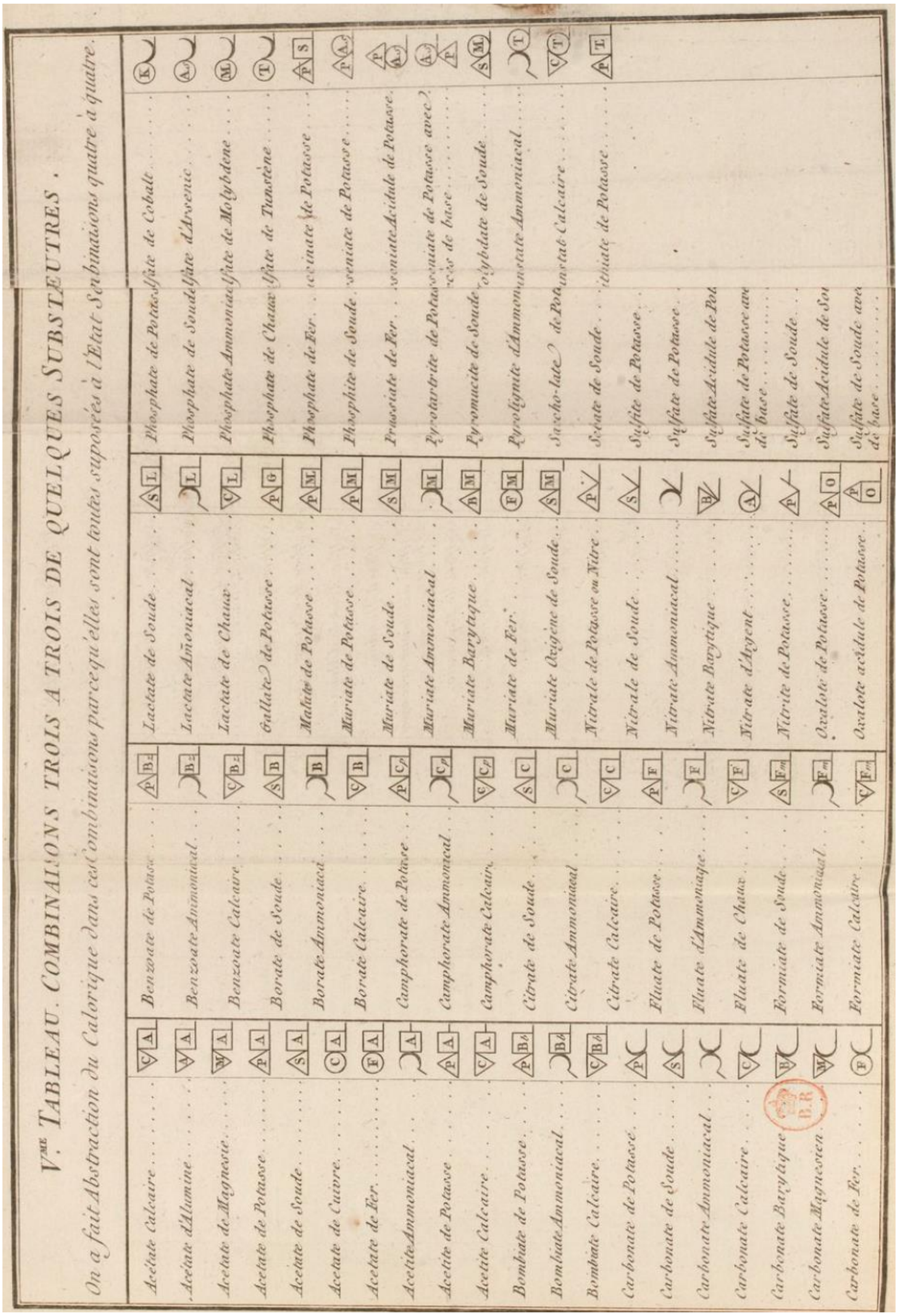

Figure 2.6: Adet's and Hassenfratz' symbols on a plate attached to *Méthode* (1787).[39]

[39] Guyton-Morveau et al., *Méthode de nomenclature chimique*, Plate v.

John Dalton had reportedly been using his unique symbols since at least 1804 in his own notebooks and continued to further develop and expand his notation over the following decades. As we have already seen in the introduction of my thesis, the first comprehensive list of these symbols was published in 1808 (Figure 2.7). Dalton is generally portrayed as one of the founders of modern atomism, and most of Dalton's experimental work was concerned with determining the ratios in which different elements combined in a chemical compound by determining the atomic weights of those elements and compounds. Dalton's work was therefore grounded in his belief in physical atoms. In other words, Dalton assumed the ontological position that atoms are not mere hypothetic entities that chemists use solely for heuristic purposes, but exist in the real world as the building blocks of all matter. Accordingly, Dalton's symbols and formulae were meant to represent the atoms which made up chemical elements, as well as the ratio in which those atoms combined to make up the molecules of chemical compounds (although he did not use the term 'molecule'). By way of illustration, the first group of symbols in the example below (designated as 'Simple' in Figure 2.7) represented the indivisible atoms in chemical elements, whereby each element is made up of only one kind of identical atoms. The remaining groups of symbols (designated as 'Binary', 'Ternary', and so on) represent the ratio in which the atoms of different elements combined to form various chemical compounds.[40] The symbols were printed from intaglio plates and attached to the end of Dalton's textbook as part of a series of four separate sheets.

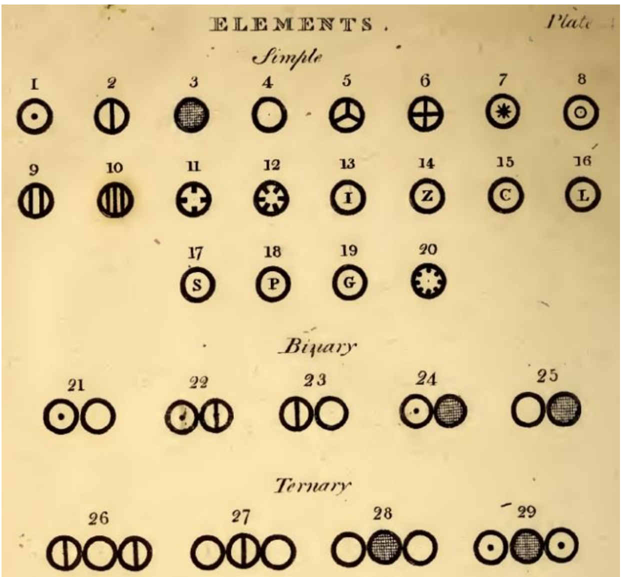

Figure 2.7: Sample of Dalton's symbols on a separate plate, 1808.[41]

[40] Cf. Levere, *Transforming Matter*, pp. 83-87.
[41] Dalton, *New System*, I, Plate 4.

While Dalton's formulae managed to attract a limited degree of attention from some European chemists during the 1820s, the notation did not become popular in the long run.[42] Berzelian formulae, on the other hand, proved much more successful. Discussing the major differences between the systems of Berzelius and Dalton, Klein argues that Dalton's formulae were rejected because they were conceived with a specific theory in mind from which they could not be separated. According to this argument, the rejection of Dalton's formulae was primarily due to the strong anti-atomist attitude which was shared by the majority of British, French, and German chemists for the most part of the nineteenth century.[43] The immediate reception of Dalton's work in Britain during the years 1804 and 1805, for instance, was mixed at best, as chemists attempted to retain the "empirical" and therefore uncontroversial parts of Dalton's theories whilst refusing the more "speculative" aspects of his work.[44] Even the supporters of Dalton's atomistic ideas, such as William Hyde Wollaston (1766-1828), often preferred to replace the term 'atom' with other terms such as 'equivalent' in order to avoid speculative terminology.[45] The reception in France during the first decades of the nineteenth century was not much better, and although Dalton's metaphysical ideas found some sympathisers amongst the German Naturphilosophen for a short period of time, most chemists remained very cautious and sceptical.[46] Berzelius' symbols, on the other hand, were not modelled upon the idea of the physical existence of mechanistic atoms in the unobservable microworld, since, as I have mentioned earlier, the symbols represented scale-independent 'chemical proportions'. Since Berzelius did not provide any metaphysical definition of these 'proportions', the concept remained theoretically unspecified, so that Berzelian formulae could be applied to represent the constitution of chemical substances according to any chemical theory.[47]

Historians and philosophers of science thus generally assume that it was primarily for those reasons that Dalton's formulae received very little attention and were soon abandoned. Yet Maurice Crosland and, more recently, Christopher Ritter, have suggested that there might be another, hitherto neglected reason for the demise of Daltonian symbols, namely the challenge of printing the formulae from intaglio plates. In his dissertation, Ritter claims that

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[42] Dalton's symbols were reproduced in a small number of – primarily Anglophone – publications. Cf. Crosland, *Historical Studies*, pp. 258-60.

[43] The general assumption that there was a strong opposition to all conceivable forms of atomism, however, has been challenged and revised by Rocke. Rocke argues that we must not conflate chemical atomism with physical atomism, since 'the chemical theory was as successful and as uncontroversial as the physical theory was reviled and often rejected.' (Rocke, *Chemical Atomism*, p. xii.)

[44] Cf. ibid, pp. 49-97.

[45] Cf. ibid, pp. 63-65; and Ritter, 'Re-Presenting Science', p. 109.

[46] Cf. Rocke, *Chemical Atomism*, pp. 99-152.

[47] Cf. Klein, *Paper Tools*, pp. 14-15. According to Klein, Berzelius terminology 'chemical proportion' was intentionally set apart from Dalton's 'atoms' in order to avoid any ontological implications about the nature of the former (ibid, p. 15). Dumas remained equally cautious in his formulation of type-theoretical ideas about chemical constitution (cf. Rocke, *Image and Reality*, p. 9).

Dalton's symbols did not became as popular as Berzelian formulae because Dalton's illustrations could only be produced by time-consuming and expensive printing methods such as copperplate etching or engraving.[48] We are going to explore the illustrative technology of copperplate engraving in more detail in the following chapter. For now, it suffices to say that this particular technology had several disadvantages compared to letterpress, namely higher printing costs, much slower printing rates, and the practical impossibility of combining the printed images with the main body of the text. With regard to Dalton's symbols, the use of copperplate techniques might therefore have had severe negative consequences for the understanding and reception of those representations.

On the one hand, this meant that Dalton was not able to include as many diagrams in his textbook as he wanted, because he 'would have kept the number of "characters and combinations" printed at the end of *A New System* to the minimum', according to Ritter. The relatively small number of symbols and diagrams – there are only thirty-seven of them on the plate – might thus not have been enough for the readers to understand in detail what the diagrams actually represented, and according to which rules the depicted atoms were meant to combine.[49] On the other hand, it was more difficult to copy and reproduce diagrams from copperplates in another book or journal article, which placed strong practical constraints on the circulation of Dalton's representations. Ritter therefore concludes that, regardless of whether Berzelian formulae were able to express different ontological positions or not, 'the fact that it required no special typographical methods was crucial to the acceptance of Berzelian notation.'[50] I completely agree with this hypothesis. Picking up where Ritter leaves off, I provide new historical evidence in support of this hypothesis in the following chapter by demonstrating that letterpress and moveable type were indeed the most economical and practical technology to render and communicate chemical diagrams in the nineteenth century.

In conclusion of this section, let us summarise the main points. We have seen at the beginning of the section that not just Berzelius, but also other chemists before him were concerned about the practicality of printing, which strongly implies that chemists conceived new symbols and notational systems not only with theoretical, but often also with very practical considerations in mind. Building on the experience of predecessors such as Adet, Hassenfratz, and Thomson, we have seen that Berzelius made a very conscious decision to use moveable type for his symbols. This gave Berzelian formulae the kind of flexibility that allowed them to be appropriated to different theoretical frameworks, since they could be used to portray the

[48] Crosland, *Historical Studies*, p. 260; Ritter, 'Re-Presenting Science', pp. 61-62.
[49] Ritter, 'Re-Presenting Science', p. 62. Italics in original.
[50] Ibid, p. 65.

constitution of compounds in different ways by means of only a small number of typographic elements. Looking back at Kekulé's list in the first section (Figure 2.4), for instance, we can see that chemical composition according to different theories could be expressed by using only Latin characters, subscript figures, parentheses, and the plus and equals signs. Type formula were slightly larger in size, but they too employed only a small number of different sorts.

These findings call for a critical reassessment of our current historical understanding of the success of Berzelian symbols, for we have seen in this section that the flexibility of Berzelian formulae was not only defined in epistemic and ontological terms – as Klein suggested – but also in very practical terms with regard to the material conditions of print communication. Each of the formulae in Kekulé's list could be realised by a skilled compositor in a printing workshop by using only the standard equipment, which gave Berzelian formulae several advantages over symbols that were realised by other means. Not only were type-based symbols and diagrams easier and therefore faster and cheaper to print, but they could also be combined with the body of the written text, which was not possible with illustrations from intaglio plates or wood engravings, as we shall see in the next chapter. Thus driven by practical as well as theoretical concerns, it was the proliferation of type-based chemical notations during the first half of the nineteenth century that eventually created the unique visual culture of modern chemistry. In the next section, we will see that practical and economic considerations also played a major role in the making of modern structural notation. As in the case of Berzelian symbols, line-and-letter diagrams did not become so successful due to their epistemic power alone, but also due to the fact that they were printed by means of letterpress and moveable type.

2.3. The Rise of the Structure Theory and the Emergence of New Diagrams to Navigate the Jungle of Organic Chemistry

The confusion about different possible constitutions of organic compounds came gradually to an end when a new theoretical framework – the theory of chemical structure, or structure theory – began to emerge between the late 1850s and the late 1860s. On the one hand, the new theory consolidated a large part of the existing theoretical and empirical knowledge, and on the other, it was built upon, and thereby promoted, the use of just one set of atomic weights. The question of atomic weights was discussed at the first international chemical congress in the South-German town of Karlsruhe (also spelled Carlsruhe) in 1860. The Karlsruhe Congress, attended by 140 delegates, was organised by August Kekulé together with Adolphe Wurtz and aimed not only at standardising the atomic weights of elements, but also at establishing a working system of chemical nomenclature that would bring order to the existing confusion about chemical names and formulae.[51] With regard to regulating and standardising chemical nomenclature, the Congress was not successful at all. And although the decisions made by the delegates with regard to atomic weights had, in Hepler-Smith's words, 'little direct influence on chemical practice', the resolutions 'may have accelerated a general shift toward the atomic weight, especially among the younger chemists present at Karlsruhe.'[52] It goes without saying that the more chemists were using the same atomic weights in their formulae, the less ambiguous and confusing those formulae became. For this reason the 1860s marked the beginning of the consolidation and standardisation of chemical theory and chemical notation.

The Concept of Valency and the Theory of Chemical Structure

The confusion stemming from the plurality of different and often competing theories gradually came to an end in the late 1850s when a number of prolific organic chemists that included Jean-Baptiste Dumas, Charles Gerhardt, Adolphe Wurtz, Archibald Scott Couper, August Kekulé, Edward Frankland, and Aleksandr Butlerov began to consolidate the existing empirical and theoretical knowledge produced over the course of the 1840s and 1850s within a new theoretical framework that came to be known as the structure theory, or the theory of chemical structure. Alan Rocke has termed this period of profound theoretical change the 'Quiet Revolution' because the development of the structure theory cannot be attributed to one individual scientist, but occurred only gradually in stages and therefore "quietly" over an extended period of time. By the mid-1860s, however, the structure theory began to take shape as a more or less coherent theoretical framework that could be identified and characterised by a number of key principles on which it was built. The most important of those principles included the notions of 'chemical atomism' and 'valence' (also called 'valency' or 'atomicity'), as well as the 'tetravalence' and 'self-linking' capability of carbon atoms.[53]

The notion of chemical atomism had its origins in Dalton's atomic hypothesis and it described the idea that chemical elements were made up of sub-microscopic atoms, which were indestructible, indivisible, and had invariable and measurable properties such as atomic

[51] For more details on the history of this congress, see Rocke, *Nationalizing Science,* pp. 226–33; and Bensaude-Vincent, Bernadette, 'Languages in Chemistry', in *The Cambridge History of Science*, V, pp. 174–90.
[52] Hepler-Smith, 'Nominally Rational', p. 41.
[53] Cf. Rocke, 'Chemical Structure'. The most comprehensive work on the history of the structure theory is Rocke's *Quiet Revolution*. On the difficult question of priority claims, see idem, 'Kekulé, Butlerov, and the Historiography of the Theory of Chemical Structure', *BJHS*, 14 (1981), 27–57.

weight.[54] Atoms of different elements combined in specific ways and in specific numerical ratios to form the molecules of particular chemical compounds. The way in which the atoms combined with each other by means of a 'chemical bond' – a term coined by Edward Frankland in 1866[55] – was dictated by the principle of valence. Valence was the experimentally determined degree of 'combining power' that was assigned to the atoms of each element, and it was represented by a number between one and four.[56] A valence of one, for instance, meant that an atom can combine with only one other atom, whereas atoms with the valence of four were able to connect with up to four other atoms directly (e.g. one carbon atom connecting to four hydrogen atoms in the methane molecule CH_4). In short, valence was the principle that atoms of each element can bond with other atoms to form a specific arrangement of bonds within a molecule – the molecule's chemical structure or 'constitution' – which accounted for the compound's chemical and physical properties and behaviour.[57] It is for this reason that valence was the fundamental principle of the structure theory.[58] Finally, the notions of the tetravalence and the self-linking ability of carbon atoms specified that each carbon atom formed four bonds, and that carbon atoms could link directly with other carbon atoms to form lengthy carbon chains as well as complicated ring structures such as the famous hexagonal benzene molecule.[59]

It soon became apparent that the structure theory offered a number of significant advantages over previous theoretical frameworks, since now chemists were able to explain the physical properties and chemical behaviour of substances by referring to the respective molecules' specific chemical structure. This meant that by means of the structure theory, chemists were now able to explain the existence of some isomers which previous theories such as the type theory were not able to explain. In fact, the structure theory proved to be a very effective system for classifying not only different kinds of isomers, but all sorts of organic compounds. I have already mentioned above that both the radical and the type theory were developed with the problem of chemical classification in mind. The problem, however, was that

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[54] Sutcliffe, Brian T., and R. Guy Woolley, 'Atoms and Molecules in Classical Chemistry and Quantum Mechanics', in *Philosophy of Chemistry*, pp. 387-426 (p. 393). For a critical historical study of this fundamental concept, see Rocke, *Chemical Atomism*.

[55] Cf. Russell, *Valency*, p. 90.

[56] The term 'combining power' was first used by Frankland in 1849. Cf. Ramberg, *Chemical Structure*, pp. 20-21.

[57] The notion of 'constitution' is also used in other theoretical frameworks and does not apply to the structure theory alone. In broad terms, the notion describes the hypothetical internal arrangements of different kinds of constituents in a molecule.

[58] Cf. Rocke, *Image and Reality*, p. xx. The concept of valence (or valency) originated in the early nineteenth century. For an in-depth historical study of that concept, see Russell, *Valency*. August Kekulé provided the modern definition of the concept – namely that atoms of each element can form only a certain number of bonds, and that – in two papers in 1857 and 1858. In those papers, Kekulé also systematically applied the concept of valence to the carbon atom, thereby suggesting that carbon atoms can link with each other to form 'skeletons' and 'chains'. Cf. Rocke, 'Chemical Structure', pp. 263-64.

[59] Cf. ibid; and Hepler-Smith, 'Nominally Rational', pp. 42-43.

before 1860 chemists disagreed about whether it was better to use equivalents or atomic weights, nor could they agree on the meaning of fundamental concepts such as 'atom' and 'radical'.[60] As a result, pre-1860 chemistry lacked a sound conceptual footing on which a working system of classification of chemical compounds could be erected. The structure theory, by contrast, had the notion of chemical atomism at its heart and employed atomic weights. This meant that the structure theory was built on the convention that (chemical) atoms were the building blocks from which molecules are constructed, and that those atoms were identified by a specific weight. Arranging and linking different atoms in a molecule in a specific manner by means of chemical bonds would therefore yield the structure of one particular compound. Representing the structure of that compound by means of diagrams thus yielded a formula according to which that compound can be classified.

In addition, the structure theory opened up new areas of research such as synthetic dyes. The systematic investigation of the structure of chemical compounds 'not only gave important insight into the details of molecular architecture in an invisibly small realm of nature,' as Rocke concludes, 'but also furnished heuristic guidance in the technological manipulation of those molecules, providing assistance in the creation of an important fine chemicals industry.'[61] Practically all of the British, French, and notably German chemical industries that had been experiencing a period of rapid growth since the 1860s were concerned with finding methods to synthesise natural substances, or with designing entirely new substances from scratch. All this was made possible by the new insights into the chemical constitution that the structure theory provided, as well as by the new possibilities which the new line-and-letter formulae offered, as we shall see in the following paragraphs. Finally, the structure theory also led to a new of way of thinking about the spatial arrangement of bonds and atoms within a molecule. This way of thinking about the physical properties of molecules resulted in the gradual development of the so-called stereochemical theory and the formation of stereochemistry as a new subdiscipline of chemistry during the last three decades of the nineteenth century.[62]

In short, stereochemistry is a subdiscipline of chemistry concerned with the 'study of the three-dimensional spatial configurations of molecules.'[63] Research in stereochemistry focused on the different kinds of 'stereoisomers', compounds that had the same chemical

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[60] It is important to stress that in the 1850s chemistry was suffering from profound conceptual ambiguity and confusion regarding the meaning of key terms such as 'atom', 'radical', 'equivalent', 'molecule', or 'atomicity'. Chemists often employed the terms freely in their writings without providing a clear definition of those terms.
[61] Rocke, 'Chemical Structure', p. 255.
[62] On the 'Limits of Structure Theory' and the formulation of early stereochemical ideas in the 1870s, see Ramberg, *Chemical Structure*, pp. 39-52.
[63] Hawley, Gessner Goodrich, *Hawley's Condensed Chemical Dictionary*, 14 edn, rev. by Richard J. Lewis, Sr. (New York, NY: Wiley, 2001), p. 1044.

constitution, but differed in the three-dimensional spatial arrangement of their atoms and functional groups.[64] At the core of the stereochemcial theory was the notion of the asymmetrical tetrahedral carbon atom with its four valences projected into different directions in space. The notion of the three-dimensional tetrahedral atom was introduced independently by Henricus van't Hoff (1852-1911) and Joseph Achille Le Bel (1847-1930) in 1874 as an explanation for the existence of so-called optical and geometrical isomers that could not be explained under the structure theory.[65] In the following years, Van't Hoff's and Le Bel's radically new understanding of the carbon atom received little attention, and it was not until the German organic chemist Johannes Wislicenus began to employ and actively promote the new ideas among members of the German chemical community in the late 1880s that more and more chemists began to engage with stereochemistry, eventually opening up new avenues and opportunities in chemical research.[66]

Enter Sausages, Circles, Lines and Letters: New Forms of Representing Structural Ideas

The late 1850s and 1860s saw the emergence of different forms of diagrams through which chemists meant to teach and explain the theory's underlying principles, on the one hand, and to further explore the theory's epistemic potential, on the other. Line-and-letter formulae – the structural notation which we use today – began to appear in different variations from the 1850s onwards. In those diagrams, type-based Berzelian symbols were used to represent atoms of a given element, and its corresponding valence was represented by the number of dashes or dotted lines grouped around it. Archibald Scott Couper was the first chemist to use this kind of diagram to express his ideas about the tetravalence and the self-linking ability of carbon atoms in 1858 (Figure 2.8).[67] Alexander Crum Brown employed and further developed those line-and-letter diagrams in his handwritten MD dissertation in 1861, and a major theoretical paper with those formulae was published in the *Transactions of the Royal Society of Edinburgh* in 1864

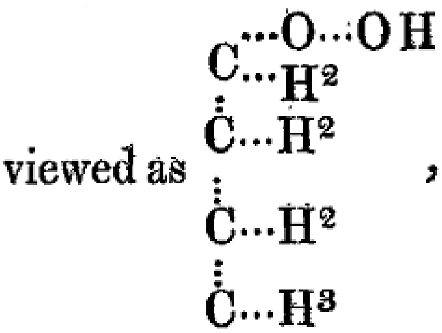
[64] Ibid.

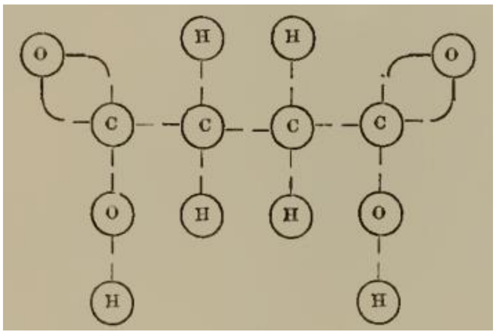
[65] Cf. Ramberg, *Chemical Structure*, pp. 53-66. In short, there are structural isomers which are accounted for by the structure theory, and there are stereoisomers which can only be explained by the stereochemical theory. Optical and geometrical isomers constitute the two main classes of stereoisomers (cf. Hawley, *Dictionary*, p. 1044). Louis Pasteur (1822-95) was among the first chemists to systematically study and identify asymmetric compounds. For details on Pasteur's crystallographic work, see Geison, Gerald, *The Private Science of Louis Pasteur* (Princeton, NJ: Princeton University Press, 1995).

[66] On the early reception of Van't Hoff's and Le Bel's hypotheses, see Ramberg, *Chemical Structure*, Chapter 4. On the pivotal role of Wislicenus in promoting stereochemical ideas, see ibid, Chapter 5.

[67] On Couper's work and often-neglected legacy, see Rocke, *Image and Reality*, pp. 119-28.

(Figure 2.9).[68] However, line-and-letter diagrams were not the only form of structural representation that existed around 1860. Alternative sets of diagrams were proposed by August Kekulé in 1857 (Figure 2.10) and Johann Josef Loschmidt in 1861 (Figure 2.11). Kekulé reportedly began using his unique formulae in his lectures on organic chemistry delivered in Heidelberg during the Wintersemester of 1857-58, and the formulae first appeared in print in the first volume of Kekulé's monumental textbook *Lehrbuch der Organischen Chemie* in 1861.[69] Loschmidt's diagrams were laid out in a pamphlet called *Constitutions-Formeln der organischen Chemie in graphischer Darstellung* that the author published himself – presumably at his own expense – in 1861.[70]





Figures 2.8 & 2.9: Couper's formula for 'butyle alcohol', 1858 (left), and Crum Brown's 'constitutional formula' for 'succinic acid', 1864 (right).[71]

[68] Cf. ibid, pp. 143-54.
[69] A record of these lectures survived in the form of Moritz Holzmann's student notes (München, Archiv des Deutschen Museum (ADM), Nachlass August Kekulé, NL 228, vorl. Nr. 1834). Holzmann's notes cover the period from October 1857 to March 1858 and are made up of two parts. The first part covers Kekulé's experimental lecture, whereas the second part addresses the 'Constitution and Classification of Organic Compounds' ('Ueber Constitution u. Systematik der organischen Verbindungen'). Kekulé introduces his sausage formulae in the second part of his lecture as didactic aids in order to explain the constitution of molecules according to the valence principle.
[70] Loschmidt, Johann Josef, *Chemische Studien* (Vienna: [printed by Carl Gerold's Sohn], 1861). For a critical discussion and reappraisal of Loschmidt's contributions to modern chemistry, see Fleischhacker, Wilhelm, and Thomas Schönfeld, eds, *Pioneering Ideas for the Physical and Chemical Sciences: Josef Loschmidt's Contributions and Modern Developments in Structural Organic Chemistry, Atomistics, and Statistical Mechanics* (New York, NY: Plenum Press, 1997).
[71] Crum Brown, Alexander, 'On the Theory of Isomeric Compounds', *Transactions of the Royal Society of Edinburgh*, 23 (1864), 707-19 (p. 709). Couper, Archibald Scott, 'On A New Chemical Theory', *Philosophical Magazine*, 4th ser., 16 (1858), 104-16 (p. 114). The formulae were also included in two French papers. See idem, 'Sur une nouvelle théorie chimique', *Comptes rendus de l'Académie des Sciences*, 46 (1858), 1157-60; and idem, 'Sur une nouvelle théorie chimique', *Annales de Chimie*, 3rd ser., 53 (1858), 469-89.

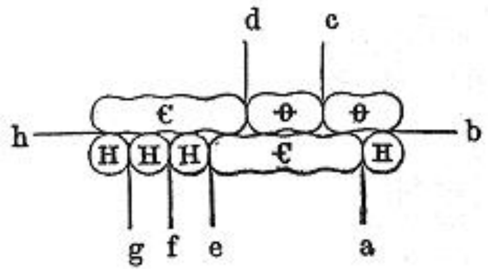


Figure 2.10: Kekulé's sausage formula for acetic acid, 1861.[72]

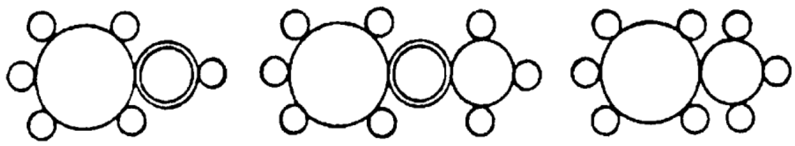


Figure 2.11: Loschmidt's formulae for various aromatic compounds, 1861.[73]

In Kekulé's sausage formulae,[74] the atomicity (or valence) of an element is represented by the number of "bulbs", ranging between one and four. Each bulb of a given element is equivalent to one unit of atomic binding power. By way of illustration, a carbon atom was represented by a chain of four bulbs, whilst each hydrogen atom was assigned only one bulb. Oxygen was represented by a chain of two bulbs, thus being assigned the valence of two (Figure 2.10). Atoms were linked by attractive forces where the bulbs touched each other. Kekulé used his sausage formulae well into the last years of the 1860s to represent the structure of chemical compounds before finally converting to Crum Brown's and Frankland's notation at the end of the decade. Like Kekulé, Loschmidt used circles to represent both atoms and what he called 'Pollenz'- another term for the binding forces between atoms. For instance, a small circle might represent a hydrogen atom and a larger one was used for carbon, whereas a double-rimmed circle stood for oxygen. Nitrogen, chlorine and other elements were all assigned their own specific symbols. As with Kekulé's notation, the binding forces between atoms were represented by the two circles touching each other (Figure 2.11). Today we are no longer familiar with these diagrams

[72] Kekulé, *Lehrbuch*, I (1861), p. 523.
[73] Loschmidt, *Chemische Studien*, Plate 1.
[74] The origin of the term 'sausage formulae' ('Wurstformeln') is disputed among historians. For instance, Rocke suggests that the term was coined by Alexander Williamson in 1866 (cf. Rocke, *Image and Reality,* pp. 101-02, n. 25). Alternatively, the term might also have been coined by Otto Nikolaus Witt (1853-1915). Cf. Hentschel, *Visual Studies*, p. 93. The formulae were also sometimes referred to by the derogative name "bread roll formulae" which goes back to Hermann Kolbe's remark that the formulae had the 'form of bread rolls' ('Form von Semmeln'). Cf. Meyer, Rita, 'Emil Erlenmeyer (1825–1909) als Chemietheoretiker und sein Beitrag zur Entwicklung der Strukturtheorie' (unpublished doctoral thesis, Ludwig-Maximilians-Universität München, 1984), p. 159. A detailed discussion of how the formulae reflected Kekulé's own 'subatomic' speculations, as well as his ontological and epistemological precautions regarding the uncritical use of those representations, is offered by Rocke in *Image and Reality*, pp. 98-103.

because neither Kekulé's nor Loschmidt's formulae could compete with line-and-letter formulae. Yet as I mentioned in the introductory chapter, we still lack a clear understanding of why exactly chemists did not pick Kekulé's or Loschmidt's formulae as their preferred structural notation, and why line-and-letter became so successful in the long run. There are, however, some historical works that provide a good first approach to this problem.

The existing explanations of the long-term success of line-and-letter diagrams often emphasise the epistemic advantages of these formulae for the investigation of the structure of complex organic compounds, and rightly so. One of the reasons was certainly the very effective application of line-and-letter formulae to problems of isomerism, as Baker argues in his paper on 'Unsaturation' from 1966. In that paper, Baker explains that Crum Brown successfully used line-and-letter formulae to demonstrate the structural difference between primary propyl alcohol and secondary propyl alcohol (propan-1-ol and propan-2-ol according to the current IUPAC rules), both of which have the identical empirical formula C_3H_8O.[75] A very similar argument is also made by Alan Rocke and Christopher Ritter, who draw on the works of Crum Brown and Kekulé in order to compare sausage formulae to line-and-letter formulae in terms of their capacity and effectiveness to explain and predict the existence of certain isomers. Rocke's and Ritter's studies show that some of Kekulé's linear sausage formulae failed to predict the correct number for isomeric compounds such as 'pyrotartaric acid': whereas it is only possible to render two isomers of that compound using sausage formulae, line-and-letter formulae suggest the existence of three isomers.[76] Since Crum Brown was able to provide a sufficiently convincing argument for the existence of each of the three isomers which his diagrams predicted, Rocke concludes that the line-and-letter formulae 'had greater heuristic power' in dealing with isomeric compounds than Kekulé's diagrams.[77] Consequently, the works of Baker, Rocke, and Ritter show that line-and-letter formulae did have some epistemic advantages over Kekulé's sausage formulae when dealing with isomers. However, this is only one side of the story.

Another explanation for the lasting success of line-and-letter formulae is provided by Christopher Ritter. Ritter agrees that the diagrams proved very productive in the context of research, where they were used to make sense of empirical data and to develop new agendas for experimental research. Yet Ritter goes further and argues that in addition to the epistemic value of line-and-letter diagrams, the success of the representations was due to their didactic value in the context of classroom teaching, where the formulae were used by Frankland and

[75] Baker, 'Unsaturation', pp. 84-85.
[76] Rocke, *Image and Reality*, p. 151-52.
[77] Ibid, p. 150.

others to explain and promote the new concepts of valence and structure. By being introduced as heuristic aids to learn and understand the new theory of chemical constitution, so Ritter, line-and-letter formulae became very popular with students and thereby gained 'rapid acceptance' during the 1860s and 1870s.[78] Ritter concludes that the formulae's success can only be understood if we consider all purposes for which the diagrams were used, since it 'was through their insertion into robust theoretical, didactic, and laboratory practices in chemistry by which Crum Brown's graphical formulas became enormously productive paper tools.'[79] Ritter's claim is certainly true, and forms a very important part of the diagrams' success. I follow the trajectory of Ritter's argument in Chapter 4, where I demonstrate that Frankland's systematic use of line-and-letter formulae as didactic tools was indeed the main reason for the formulae's dissemination and appropriation in Britain. However, neither the epistemic nor the didactic values of the diagrams can sufficiently account for the disappearance of Kekulé's and Loschmidt's formulae, as historical evidence demonstrates.

Following theory-based accounts of the success of line-and-letter formulae, we might be inclined to believe that all of those historical actors who were interested in structural ideas instantly rejected Kekulé's "inferior" diagrams and automatically appropriated line-and-letter diagrams because the latter performed exceptionally well in the investigation of specific isomers. We are therefore prone to believe that line-and-letter formulae were the only forms of structural representations which teachers used in their classes and textbooks. Yet historical evidence suggests otherwise. For instance, testimonies of successful educators and textbook authors show that Kekulé's sausages were more popular than historians have previously assumed. And why were Loschmidt's diagrams not taken up by other chemists in the 1860s? Were those diagrams also epistemically "inferior"? In this case, too, we have historical evidence which suggests a different story: comparing the various structural representations which chemists proposed in the 1860s, the historian-chemist and early supporter of the structure theory Carl Graebe attests that Loschmidt's formulae, too, were well suited for exploring problems of chemical isomerism. So why had Loschmidt's or Kekulé's notation disappeared from the pages of European textbooks and journals by the end of the 1860s? The rest of the present chapter is concerned with that question. In what follows, I show that Kekulé's and Loschmidt's diagrams were not instantly rejected by historical actors, and that there is not enough historical evidence to claim that those diagrams disappeared on epistemic grounds alone. Consequently, I argue that we need to broaden our historiographical perspective and consider additional reasons to explain the demise of Kekulé's and Loschmidt's formulae.

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[78] Ritter, 'An Early History of Alexander Crum Brown's Graphical Formulas', in *Tools and Modes of Representation in the Laboratory Sciences*, pp. 35-46 (p. 43).
[79] Ibid, p. 42.

2.4. The Theoretical and the Practical in the History of Kekulé's and Loschmidt's Diagrams

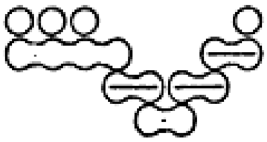
Although Kekulé's and Loschmidt's diagrams look distinctively different from line-and-letter formulae, they were meant to represent the same thing: all three kinds of formulae portrayed how different atoms linked with each other according to the principle of valence to form a specific molecule. In that capacity, all three sets of diagrams fulfilled the same function, namely to show how the principle of valence governed the constitution of the organic compound in question, and how empirical data about the chemical behaviour and physical properties of that compound could be explained through the compound's chemical structure that was expressed by the diagrams. In this respect Kekulé's and Loschmidt's representations were in no way inferior to line-and-letter formulae, as was attested by two contemporaries who encountered and used the formulae themselves. In what follows, I present two highly enlightening examples to illustrate this: firstly, statements by the Swedish chemist and experienced teacher Christian Wilhelm Blomstrand (1826-97), and secondly, the famous German industrial chemist and historian Carl Graebe.

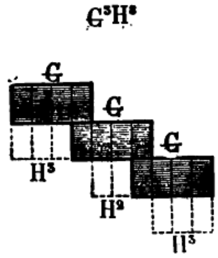
Blomstrand embraced Kekule's formulae in his textbook *Die Chemie der Jetztzeit* (1869), where he also made frequent use of the diagrams throughout the book, whose pages were populated by more than seventy diagrams of this kind (Figure 2.12).[80] Line-and-letter formulae, on the other hand, were – with the exception of two specimen – nowhere to be found in the book, which clearly indicates that Blomstrand himself preferred Kekulé's diagrams over any other representation of the constitution of compounds according to the valence principle.[81] Speaking about the contribution of Kekulé's sausage formulae to the recent advancement in chemical theory – which in this context means the principle of valence – Blomstrand also made it very clear that the diagrams 'undoubtedly marked the most important advancement this theory has ever made since its foundation […]' because the valence ('Sättigungscapacität') of elements ('Grundstoffe') is expressed by those formulae in a much clearer way than by the

[80] Blomstrand, Christian Wilhelm, *Die Chemie der Jetztzeit vom Standpunkte der elektrochemischen Auffassung aus Berzelius' Lehre entwickelt* (Heidelberg: Carl Winter, 1869). Blomstrand explains that the book was written for students as well as for 'a much larger audience' (p. vi). The formulae appear on pp. 93, 155, 156, 157, 164, 165, 166, 167, 168, 169, 171, 211, 213, 234, 235, 236, 237, 238, 242, 243, 244, 245, 247, 248, 249, 250, 251, 252, 273, 275, 276, 277, 279, 307, 308, 309, 312, 314, 318, 319, 320, 321, 335, 343, 351, 353, 355, 360, 361, 362, 363, 364, 365, 367, 368, 369, 370, 376, 377, 378, 379, 380, 382, 385, 387, 397, 411, 412, and 413.

[81] Blomstrand does not explicitly say why he decided not to use line-and-letter formulae. However, we might deduce from the tone of the book, as well as from casual remarks, that he considered line-and-letter diagrams to be too 'artificial' ('künstlich') and therefore more speculative than sausage formulae (ibid, pp. 314-15).

representations proposed by other chemists.[82] From this, we can see that Blomstrand was an avid supporter of the formulae and preferred the sausage diagrams over other forms of notation. Evidence from other printed sources from that period suggests that Blomstrand was in fact not alone in using Kekulé's sausage formulae. In at least one other instance, we have evidence that other chemists also used modifications of Kekulé's formulae: the second example presented below demonstrates how Adolphe Wurtz used his own version of the sausage formulae in his textbook *Leçons de philosophie chimique* (1864), whereby the carbon atom – which has a valence of four – was represented by a shaded and segmented "box" (Figure 2.13). I argue then that we must view this as additional evidence that those diagrams were more widely used than the standard account leads us to believe.





Figures 2.12 & 2.13: Blomstrand's sausage formula for 'Methyläther', 1869 (left); and Wurtz's version of Kekulé's sausage formula, 1864 (right).[83]

Carl Graebe is best known as a prolific industrial chemist who, together with Carl Liebermann (1842-1914), developed a method to synthesise the dye alizarin in 1868 and thereby kickstarted the growth and rise of the chemical industry in Germany.[84] Graebe was also one of the very early supporters of the structure theory, as we shall see in more detail in Chapter 5. In addition, he was also a dedicated historian and author of the highly influential and frequently-cited work *Geschichte der organischen Chemie* (1920).[85] Graebe was one of the leading organic chemists of the late nineteenth century, and the opinions which he expressed in this historical work were based on his lifelong experience in synthesising complex organic compounds.[86] In *Geschichte der organischen Chemie*, Graebe examined Loschmidt's formulae and found that the diagrams were well suited to express the constitution of molecules according to the valence principle. Graebe

[82] Ibid, p. 67.
[83] Ibid, p. 156; Wurtz, Adolphe, *Leçons de philosophie chimique* (Paris: Hachette, 1864), p. 135.
[84] The premierbiography is Elisabeth Vaupel's 'Carl Graebe (1841-1927): Leben, Werk und Wirken im Spiegel seines brieflichen Nachlasses' (unpublished doctoral thesis, Ludwigs-Maximilian-Universität München, 1987).
[85] Graebe, Carl, *Geschichte der organischen Chemie* (Berlin: Springer, 1920). A second volume was planned, but Graebe was not able to finish it. Cf. Vaupel, 'Carl Graebe', p. 407-08.
[86] Cf. Vaupel, 'Carl Graebe'.

concluded that 'Loschmidt has extended his constitutional studies with great skill and diligence to the entire field of organic chemistry. Of the 368 graphic formulae contained in his work, quite a few proved to be correct at a later time', although Graebe also added that some formulae were in fact incorrect.[87] This, I argue, demonstrates that Loschmidt's formulae performed well when applied to the investigation of the structure of organic substances, which means that the diagrams could have served as an effective paper tool for the study of isomers and other groups of compounds if they had been adopted and used by more chemists during that time. So why did Loschmidt's circles not find more users and supporters if they performed so well?

In his work of history, Graebe suggested a number of plausible reasons for the disappearance of Kekulé's and Loschmidt's diagrams. In so doing, Graebe's *Geschichte* was – at least to my knowledge – the first historical work to go beyond theory-based accounts of the success of line-and-letter formulae due to it having sketched a more diverse historical picture of the development of the modern chemical notation. More specifically, Graebe suggested that Loschmidt's diagrams were not picked up by other chemists because they were published in an obscure 'pamphlet' ('Broschüre') that did not enjoy wide circulation, and as a consequence, had a limited readership.[88] Furthermore, Graebe claimed that Kekulé's and Loschmidt's diagrams – in fact all of the 'schematic figures' which were different from Couper's type-based formulae – proved to be 'rather inconvenient' to reproduce by means of type and printing.[89] With this statement, Graebe made it very clear that he did not consider the epistemic advantages of Couper's and Crum Brown's formulae, or ontological reservations against any other kind of diagrams, to be the only possible reasons for the lasting success of line-and-letter diagrams, but that very practical aspects of print communication also played a major part in that story. As I have mentioned before, similar hypotheses were also formulated by Crosland in 1962 and Ritter in 2001, but never explored in greater historical detail.[90] It is for this reason that I intend to follow Graebe's, Crosland's, and Ritter's lead by including the role of communication practices in our revised account of the inception, proliferation, and consolidation of the modern chemical notation.

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[87] 'Loschmidt hat seine Konstitutionsbetrachtungen mit großem Geschick und Fleiß über das ganze Gebiet der organischen Chemie ausgedehnt. Unter den 368 graphischen Formeln, die in seiner Schrift enthalten sind, haben sich ziemlich viele später als richtig erwiesen [...]; bei anderen hat er sich geirrt.' (Graebe, *Geschichte*, p. 237.) Richard Anschütz (1852-1937) prepared an annotated edition of Loschmidt's brochure in 1913. In this edition, Anschütz critically compares Loschmidt's diagrams to the modern line-and-letter formulae and records whether Loschmidt was right or wrong. Cf. Loschmidt, *Konstitutions-Formeln der organischen Chemie in graphischer Darstellung*, ed. by Richard Anschütz, Ostwald's Klassiker der exakten Wissenschaften, 190 (Leipzig: Engelmann, 1913).
[88] Ibid, p. 237.
[89] 'Für die Wiedergabe durch Schrift und Druck waren aber die verschiedenen schematischen Figuren wenig bequem […].' (Ibid, p. 238.)
[90] Crosland, *Historical Studies*; Ritter, 'Re-Presenting Science'.

We have seen above that theoretical reasons were, indeed, important to the success of line-and-letter formulae, since they performed well as paper tools in the investigation of isomers. However, we have also witnessed in this section that stressing those theoretical advantages is not enough to account for the disappearance of the competing diagrams, since some chemists did use Kekulé's formulae in the 1860s. In addition, we have seen that existing historical studies tend to ignore the existence of Loschmidt's diagrams altogether and therefore do not account for the disappearance of those representations. Yet evidence provided by Graebe strongly indicates that Loschmidt's diagrams, too, were in fact very effective paper tools for investigating the structure of isomers. Finally, Graebe's suggestion that the rejection of Kekulé's and Loschmidt's diagrams was as much due to the practicalities of printing as to epistemic reasons makes it very clear that purely theoretical explanations are not sufficient to account for the long-term success of line-and-letter formulae.

Rocke has rightly pointed out that new ideas about the chemical microworld originated in the minds of chemists before those ideas were further fleshed out on paper (or, for that matter, by means of physical models).[91] In most cases, chemists then went on to design and perform different kinds of experiments to gather empirical data about the compound under investigation, which served the purpose of supporting or refuting their hypothesis about the structure of that compound.[92] Yet it was in university classes, public lectures and, most notably, on the printed pages of journals, monographs, and textbooks where those ideas were made public and subsequently debated among members of the scientific community. Each of these tasks formed an integral part of the knowledge-making process and – as Jim Secord has stressed in his seminal 2004 paper – must therefore be seen as a continuum rather than separate categories of knowledge-making practices.[93] In our case, this means that we can only understand the process that resulted in the establishment of line-and-letter formulae as the default notation of organic chemistry if we account for the entirety of those practices which, eventually, proved line-and-letter formulae more successful than the competing notational systems of Kekulé and Loschmidt. In the final part of this section, I draw on a particular debate between Kekulé and Crum Brown concerning the concept of valence and the existence of certain isomers that took place between 1864 and 1866. In tracing this debate, I illustrate how the two chemists constructed their arguments about valence and the constitution of isomers by combining

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[91] Rocke, *Image and Reality*, pp. xii-xiii.

[92] For an account of the work of nineteenth-century organic chemists, see Klein, *Paper Tools.* Foundational works in the history and philosophy of experimental practices include Hacking, Ian, *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science* (Cambridge: Cambridge University Press, 1983); and Shapin, Steven, and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton, NJ: Princeton University Press, 1985).

[93] Secord, 'Knowledge in Transit'.

theoretical and practical aspects of chemical research with different communication strategies, and how those communication strategies, in turn, affected the way in which their arguments were read and interpreted, thus making clear that communication practices played an integral in the making of new knowledge about the unobservable microworld.

Making Chemical Knowledge: Debating Valence and Understanding Isomers, 1864-66

Alexander Crum Brown received his MD degree from the University of Edinburgh in 1861. Entitled 'On the Theory of Chemical Combination', his doctoral thesis undertook a close study of nineteenth-century atomic theory with emphasis on the development of the concept of valence (or 'atomicity', as Crum Brown called it in his thesis).[94] The thesis addressed two main questions, namely: '(1) What is the nature of the forces which retain the several molecules or atoms of a compound together? and (2) How may their direction and amount be determined?'[95] Crum Brown's proposed answer to these questions was that all atoms in a molecule were connected by 'lines of forces', and that the number of lines connecting the atoms was directly depended on the atoms' individual valences.[96] In particular, the thesis tackled the disputed question about the possibility of 'alternative atomicity' (variable valence) of atoms such as nitrogen and carbon. In his discussion of the concept of valence, Crum Brown drew heavily on the previous work of Kekulé, but went against Kekulé's claim that valence is fixed and that atoms with variable valence did not exist. In opposition to Kekulé and others, Crum Brown claimed that atoms with two or more 'degrees of atomicity' (meaning atoms with 'alternative atomicity') were indeed possible, and he supported his claim with line-and-letter renderings of a number of selected carbohydrate compounds.[97]

Crum Brown's thesis was a purely theoretical piece of work that did not involve any new experimental results. Rather, Crum Brown developed his arguments by using a wide range of heuristic and representational techniques such as imaginative visual thinking, locating and reading relevant research literature, processing experimental data, making notes and writing

[94] Crum Brown, 'On the Theory of Chemical Combination' (unpublished doctoral thesis, University of Edinburgh, 1861). Crum Brown's original thesis was handwritten. A printed version of that thesis was published 'as a contribution to the history of the subject' in 1879 (idem, *On the Theory of Chemical Combination: A Thesis Presented to the Faculty of Medicine of the University of Edinburgh* (Edinburgh: [printed by Neill & Co], 1879)), p. 2.
[95] Idem, *Theory of Chemical Combination*, p. 3.
[96] Ibid, p. 16. It was exactly those lines of force what under Frankland would soon be known as the 'chemical bond'.
[97] Crum Brown, *Theory of Chemical Combination*, pp. 17-18.

down his findings, and – of course – manipulating paper tools such as sausage formulae and line-and-letter diagrams with the help of pen and paper. However, it is important to note that some of Crum Brown's proposed structures rendered by means of line-and-letter diagrams were in fact not accurate, and that, as the historian Ritter notes, 'Kekulé's formulas, we know now, more correctly reflect the structures of [those] substances.'[98] This, I believe, makes it evident that the use of line-and-letter diagrams did by no means guarantee correct results, and that we must not assume that line-and-letter formulae were always superior to other forms of structural diagrams. Yet Ritter and Rocke also pointed out that regardless whether it was right or wrong, Crum Brown's thesis stood out because of the central role of chemical diagrams in Crum Brown's argument structure.[99] But as sophisticated as Crum Brown's argument might have been, it never came to the attention of Kekulé or, in fact, the vast majority of chemists because Crum Brown's original 1861 thesis was handwritten and therefore not circulated widely. Kekulé and other chemists only became aware of Crum Brown's work on the concept of valence when the latter published his first printed research paper in 1864.

Crum Brown's first published research paper was entitled 'On the Theory of Isomeric Compounds' and appeared in volume 23 of the *Transactions of the Royal Society of Edinburgh* in 1864.[100] The article was also reprinted in the *Journal of the Chemical Society* in the following year.[101] In that article, Crum Brown discussed how his understanding of the concept of valence could be used to explain 'all cases of isomerism known at that time, and if it was not, what modifications to the theory might be proposed to widen its explanatory scope.'[102] Like his doctoral thesis, the paper was a piece of theoretical work that drew on published sources rather than Crum Brown's own laboratory work to provide empirical evidence in support of his argument. Where experimental data was not available, Crum Brown also suggested possible pathways of experimental research to test his hypothesis, thereby delegating future research to the readers of his article.[103] As in his thesis, Crum Brown built on Kekulé previous work, but contested Kekulé's claims about the possible constitution of a number of isomeric compounds. At the centre of the paper was Crum Brown's investigation of a group of compounds that he

[98] Ritter, 'Re-Presenting Science', p. 166.
[99] Ritter concluded that '[w]hat is salient […] is how Crum Brown combined graphical conjecture with a proposal for synthetic investigation in the laboratory to resolve a chemical question.' (Ibid.) Rocke expanded on this point: 'In a footnote, he suggested a plausible experimental plan that one might apply to discern which kind of formula, his symmetrical or Kekulé's unsymmetrical ones, should be given preference.' (Rocke, *Image and Reality*, p. 146.)
[100] Crum Brown, 'Isomeric Compounds' (1864).
[101] Idem, 'On the Theory of Isomeric Compounds', *Journal of the Chemical Society*, 18 (1865), 230-45.
[102] Rocke, *Image and Reality*, p. 147.
[103] Crum Brown, 'Isomeric Compounds' (1864), pp. 711-12.

called 'absolute isomers',[104] and it was in this paper where he demonstrated in one case that line-and-letter formulae were capable to predict the existence of three isomers of pyrotartaric acid, whereas sausage formulae generated only two different isomers of that compound.[105] Unlike in the case of his handwritten and unpublished doctoral thesis, this time Crum Brown's criticism of Kekulé's ideas about valence and, especially, Kekulé's usage of sausage formulae did not go unnoticed.

In 1865 Kekulé published an article with a first draft of his theory of benzene in the French journal *Bulletin de la société chimique*, where he continued to make consequent use of sausage formulae to represent the structure of aromatic substances that included benzene as well as other isomeric and non-isomeric compounds.[106] The *Bulletin* article featured a set of 32 wood-engraved sausage diagrams that filled the final one and a half pages of the paper. Aware of Crum Brown's 1864 article as well as Loschmidt's competing formulae, Kekulé commented that his own diagrams seemed to him 'to be preferable to the modifications proposed by MM. Loschmidt and Crum Brown.'[107] As in the case of Crum Brown's previous work, Kekulé's article was theoretical in nature and did not feature any new experimental research. Instead, Kekulé relied on a small number of published works on aromatic compounds and employed diagrammatic tools – in the form of his own sausage formulae – to demonstrate how the structure theory can yield new and important insights into the constitution of those compounds.[108] Like Crum Brown, Kekulé was using his diagrams as a heuristic device to make sense of available experimental data in order to understand the constitution of substances that had never been viewed in the light of the structure theory before. In hindsight, it becomes apparent that some of the proposed formulae were in fact very close to the actual constitution of those compounds. Yet in a number of other cases, Kekulé proposed sausage formulae that – as we know today – did not represent the correct structure of the compounds in question.

[104] In Rocke's words, absolute isomers can be described as 'chemically distinct substances that nevertheless appeared to possess identical fully resolved formulas. […] Absolute isomers thus represented chemical phenomena that were as yet outside the scope of the theory. Such cases were rare but known to exist.' (Rocke, *Image and Reality*, p. 147.)
[105] Crum Brown, 'Isomeric Compounds' (1864), pp. 710, 717-18.
[106] Kekulé, 'Sur la constitution des substances aromatiques', *Bulletin de la société chimique*, 3.1 (1865), 98–110. This foundational paper was the result of the work that Kekulé's had undertaken in Wurtz's laboratory in Paris over the previous year. Cf. Rocke, *Image and Reality*, pp. 198-99.
[107] Ibid, p. 100, n. 2. Cited after Rocke, *Image and Reality*, p. 152.
[108] Just like Crum Brown, Kekulé suggested pathways for future experimental investigations to test his diagrammatic speculations. For a synopsis and discussion of Kekulé's 1865 article, see Rocke, *Image and Reality*, pp. 199-205.

Following the work of his paragon and figurative "mentor" very closely, it was again Crum Brown who seized upon the mistakes.[109]

Crum Brown responded to Kekulé's *Bulletin* article with a paper that was read before the *Royal Society of Edinburgh* on 3 April 1865 and published in the *Proceedings of the Royal Society of Edinburgh* in the following year. In that paper, Crum Brown argued that sausage formulae suffered from significant deficiencies because the notation was 'limited in its application to those compounds in which the polyatomic atoms form a single chain', and because the diagrams displayed a considerable degree of 'obscurity and ambiguity.'[110] To point out the shortcomings of sausage formulae, Crum Brown compared Kekulé's diagrams of the presumed isomers 'methylic ethyl alcohol' ('Alcool méthyle-éthylique') and 'acetonic alcohol' ('Alcool acetonique') to his own line-and-letter diagrams of these substances in order to illustrate that the structure of both compounds was in fact identical. In doing so, Crum Brown demonstrated that the use of sausage diagrams had led Kekulé to the assumption that there were two distinct isomers, whereas the application of the line-and-letter notation revealed that those isomers were in fact one and the same substance.[111] There is, however, no evidence that Kekulé was aware of Crum Brown's critical commentary of his sausage diagrams, since he included the same formulae that he had used in the *Bulletin* article in a German paper that was published in *Annalen der Chemie* one year later.[112] Rocke argued that one possible reason for Kekulé's failure to take Crum Brown's critique into account was the fact that the Scottish chemist had published his 1865 article in the *Proceedings of the Royal Society*, which at that time was a little-known journal with a comparatively small readership.[113] Assuming that this was indeed the case, the Crum Brown-Kekulé case serves as an excellent illustration of how different means of print communication influenced the positive or negative reception of competing sets of chemical diagrams, either promoting or hampering their appropriation by members of the wider scientific community.

[109] In a letter to Kekulé, Crum Brown declared: '[a]lthough I have never studied in your laboratory I have always considered myself as, in a sense, your disciple […].' (Letter Crum Brown to Kekulé, 18 February 1864. Cited after Rocke, *Image and Reality*, p. 154, n. 74.)
[110] Crum Brown, 'On the Use of Graphic Representations of Chemical Formula', *Proceedings of the Royal Society of Edinburgh*, 5 (1866), 429-31 (pp. 429-30).
[111] Ibid, p. 431.
[112] Kekulé, 'Untersuchungen über aromatische Verbindungen', *Annalen der Chemie,* 137.2 (1866), 129-96. I discuss the sausage diagrams in this article in more detail in Chapter 3.
[113] Rocke, *Image and Reality*, pp. 153-54.

2.5. Conclusion

In this chapter, we have seen that the history of the modern chemical formulae forms an integral part of the theoretical and institutional development of nineteenth-century chemistry. As a response to the predominant theoretical challenges of his time – namely how to classify first inorganic and then organic compounds – Berzelius had developed his type-based symbols and formulae in 1814. Since the third decade of the nineteenth century, these typeset chemical formulae had been the predominant way of representing competing chemical ideas and worldviews during a time of rapid and profound theoretical change, thereby shaping the visual culture of modern chemistry. Typeset notations thus became not only the main communication devices to express theoretical worldviews, but the very weapons by means of which the fights between competing and often contradicting chemical theories were carried out.

Yet I have also demonstrated in this chapter that the success of Berzelian formulae and the visual culture of type-based notation was not only due to the formulae's semantic or ontological properties, but to a significant extent due to the fact that the notation was realised by means of moveable type. We have also seen that Berzelius was well aware of the significant advantages of using type-based symbols for the rapid and uncomplicated communication of his chemical ideas, and that type-based line-and-letter formulae modelled on Berzelian symbols proved to be very effective paper tools for the investigation and communication of the structure of organic compounds. We also witnessed that that chemists like Crum Brown and Kekulé relied on a broad spectrum of practices to develop, debate, and assert their conflicting views about the constitution of isomeric compounds. In so doing, the chapter demonstrated that there was no distinction between knowledge making and knowledge dissemination, but that communication practices were instead an essential and integral part of the knowledge-making process. Finally, the chapter also made it clear that we can only arrive at a more elaborate and convincing explanation of the success of line-and-letter formulae and the demise of all other kinds of representations if we focus on the material and practical aspects of print.

By following this trajectory with a strong emphasis on the material and technical aspects of print communication in the following chapters, we shall be able to understand that, on the one hand, Kekulé's and Loschmidt's formulae were phased out because they were printed by means of wood engravings, lithography, and custom-made type. Letterpress technology, on the other hand, allowed for a high degree of iconographical, semiotic, and epistemic flexibility which enabled type-based formulae to represent the many different chemical theories that were proposed over the course of the nineteenth century. From the 1860s onwards, line-and-letter formulae proved to be very effective paper tools for theorising about the structure of organic compounds, but it was ultimately the fact that the diagrams could be circulated relatively quickly and at low costs that ensured the type-based formulae's long-term success.

CHAPTER 3

Type over Blocks and Plates: How Printing Practices Facilitated the Circulation of Line-and-Letter Formulae

By following the gradual evolution of chemical formulae from the beginning of the nineteenth century to the 1860s and beyond, we have seen in the previous chapter that line-and-letter formulae were in fact not invented by a single individual, but were introduced by multiple individuals and were reflective of a wider community of representation. Furthermore, we have also seen that the formulae's distinct visual appearance were not shaped by theoretical considerations alone. Quite to the contrary, we have seen that line-and-letter formulae developed from previous type-based notations and must therefore be considered as an integral part of a visual culture that was, to a very large degree, shaped by typographical methods and very practical concerns about scientific printing. The present chapter continues the theme of scientific printing by critically analysing the impact of different printing practices on the circulation of the various forms of chemical formulae that were used during the 1860s. For that purpose, the chapter undertakes a pioneering investigation of the practices of typesetting chemical formalisms – a subject that has never been studied in historical perspective before.

I argue that, as a result of being printed by means of letterpress and moveable type, line-and-letter formulae acquired a number of practical and economic advantages over the competing diagrams that were proposed by Josef Loschmidt and August Kekulé in the said period. First, the composition of typeset formalisms did not require special hardware and could consequently be produced by skilled compositors in different locations with minimal material effort. Secondly, the use of moveable type meant that compositors were able to produce all different kinds of typeset notations, ranging from linear empirical formulae to space-consuming line-and-letter diagrams, as we have seen in the previous chapter. Thirdly, typeset diagrams were faster to print and easier to reproduce than diagrams rendered by means of other illustration techniques such as wood engraving or copperplate engravings.[1] I conclude that these advantages made line-and-letter the most convenient representation of chemical structure with regard to the highly competitive and rapidly changing market for specialist chemical literature characterised by the growing number of textbooks and journal articles on topics in organic chemistry. This, finally, makes it clear that the lasting success of line-and-letter formulae did not

[1] Very good introductions to nineteenth-century printing technologies are Mosley,'The Technologies of Printing'; and Twyman, *Printing 1770-1970: An Illustrated History of its Development and Uses in England* (London: Eyre & Spottiswoode, 1970).

derive from theoretical reasons alone, but was to a very large degree based on economic and practical aspects of print communication.

The argument of the present chapter extends over five sections. The first section focuses on the composition of mathematical formulae by hand, whereas the second section undertakes a close investigation of the practices of chemical typesetting. By comparing the application of moveable type to the printing of complex mathematical and chemical formalisms, I am able to show that that every printing workshop that specialised in the printing of mathematics was also able to produce type-based chemical notations because of the similarity of the two types of scientific composition. The third and the fourth sections undertake a detailed study of how the technologies of lithography and wood engraving restricted the circulation of Kekulé's and Loschmidt's diagrams. Finally, the fifth section offers a historical case study of the practical difficulties that the English publishing house Macmillan and the German scientific publisher Vieweg encountered with regard to sharing the wood blocks and lithographs used for the English and German editions of the highly successful chemistry textbooks by Henry Enfield Roscoe (1833-1915) and his German co-author Carl Schorlemmer (1834-92). By elucidating the different challenges that the partners faced when dealing with wood blocks and other illustrative techniques, I demonstrate that it was the limited availability of wood blocks and lithographs and the resulting slow production rate of images rendered by means of the said technologies that limited the circulation of illustrations such as Loschmidt's and Kekulé's diagrams.

3.1. Printing Practices and the Challenge of Tacit Knowledge

> No handicraft can be learned by one who merely reads about it; as all the instruction in the world will not enable a man to swim who does not venture into the water. [...] Words cannot adequately indicate the method of even the simplest operation of printing.
>
> — John Southward, preface to the second edition of *Practical Printing* (1884).[2]

Before we proceed to the discussion of the practicalities and costs of the composition of scientific matter by hand, some historiographical remarks are in order. It is striking that, while we can observe the steady increase in the number of type-based chemical formulae in printed sources over the course of the nineteenth century, historians have still very little knowledge

[2] Southward, John, *Practical Printing: A Handbook of the Art of Typography*, 2nd edn (London: J. M. Powell & Sons, 1884), pp. xiv-xv.

about the manual process of typesetting those notations, and even less about the practical challenges that came with this job. There can be little doubt that the printing of chemical formulae by means of letterpress and moveable type required a high degree of skill and experience on behalf of the compositor. Yet we have still very little understanding of how and where compositors might have acquired this kind of specialised knowledge because we are almost completely devoid of sources that might shed some light on the training and daily working routine of those specialists. Indeed, chemical symbols and formulae are rarely mentioned in Anglophone, Francophone, or Germanophone nineteenth-century handbooks and manuals made for the education of apprentices as well as for frequent consultation at the workplace, thus functioning both as works of didactic literature and practical companions. Practical knowledge not documented and circulated by means of handwritten or printed sources is commonly referred to as tacit knowledge, which often eludes close historical analysis because of this very lack of reliable sources.[3]

This issue raises two important questions. First, how can we access information about those practices in order to study them in detail? And secondly, why exactly are these composition jobs not represented in those handbooks and manuals? In this section, I address these two questions by drawing on the composition of mathematical formalisms as a parallel case, which I use to demonstrate that compositors working on mathematical and chemical formalisms in the nineteenth century faced very similar challenges and possessed a very similar set of practical skills that they had acquired through training and experience on the job. I supplement my account with references to twentieth-century printers' handbooks and manuals in order to provide more accurate insights into the practice of chemical composition. In so doing, I demonstrate that the publishing of chemistry remained highly dependent on the manual labour of specialised scientific compositors for almost a century, and that the work of skilled compositors thus remained a quintessential part in the making of the visual language of chemistry.

Although printers' manuals and handbooks from the nineteenth century never address the composition of chemical works directly, these sources make it clear that the composition of chemical and mathematical matter was closely related. It is for this reason that the manuals and handbooks are able to give us a good understanding of the challenges that the compositors of those works – we might call them scientific compositors – encountered on the job. German

[3] Broadly speaking, the notion of *tacit knowledge* refers to informal skills and practices that are gained through practical training rather than formal education, and which cannot be communicated and appropriated through written or verbal instruction alone. Cf. Polanyi, Michael, *Personal Knowledge: Towards a Post-Critical Philosophy* (Chicago, IL: University of Chicago Press, 1958); and idem, *The Tacit Dimension* (London: Routledge & K. Paul, 1967). One of the best-known works to address this historiographical challenge is Shapin's and Schaffer's *Leviathan and the Air-Pump.*

sources provide very good evidence of the similarity of mathematical and chemical composition, since these books often group the composition of mathematical and chemical matter, together with other rare and demanding jobs, under the headings 'gemischter Satz' or 'komplizierter Satz', which translate as 'miscellaneous' and 'complicated composition', respectively.

By way of illustration, Carl August Franke's highly esteemed and popular handbook *Katechismus der Buchdruckerkunst* (1856) categorised 'mathematical', 'musical', and 'tabular' composition as 'miscellaneous or complicated composition',[4] whereas J. H. Bachmann outlined in his *Neues Handbuch der Buchdruckerkunst* (1876) that jobs labelled as 'gemischter Satz' might, among other things, include the composition of encyclopaedias, catalogues, calendars, and mathematics. Bachmann's described 'gemischter Satz' as 'composition which features different fonts and symbols',[5] to which the printer August Marahrens added: 'Miscellaneous composition [...] is one in which not only a more or less great variety of fonts occurs', but also where the composition includes changes in the relative position of words and lines to each other, and which requires a more-than-usual amount of justification.[6] The similarity of 'the composition of medical and chemical works' ('Satz medicinischer und chemischer Werke') to the practice of typesetting other forms of technical literature is further stressed in Alexander Waldow's monumental three-volume handbook *Die Buchdruckerkunst in ihrem technischen und kaufmännischen Betriebe* (1874-77).[7] Finally, the best evidence for the said similarity is provided by the printer Wilhelm Hellwig, who stated in his treatise *Der Satz chemischer und mathematischer Formeln* (1909) that the composition of chemical and mathematical matter entailed the same practical difficulties and challenges, with the only difference that the composition of line-and-letter formulae was generally regarded as being less difficult than the setting of mathematical expressions.[8] We can therefore achieve a more comprehensive and detailed understanding of the practices and challenges of chemical composition by studying the typesetting of mathematical works.

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[4] 'Was ist über das Setzen mathematischer, tabellarischer, musikalischer und dergleichen Werke zu sagen? Den mathematischen, tabellarischen und ähnlichen Satz nennt man […] gemischten oder komplizierten.' (Franke, Carl August, *Katechismus der Buchdruckerkunst und der verwandten Geschäftszweige* (Leipzig: J. J. Weber, 1856), p. 76.) The expression 'komplizierter Satz' is also used by Alexander Waldow in his revised edition of Franke's *Katechismus*. Cf. Waldow, *Katechismus der Buchdruckerkunst von Carl August Franke*, 5th edn (Leipzig: J. J. Weber, 1886), p. 95.

[5] Bachmann, J. H., *Neues Handbuch der Buchdruckerkunst* (Weimar: Bernhard Friedrich Voigt, 1876), p. 156.

[6] Marahrens, August, *Vollständiges theoretisch-praktisches Handbuch der Typographie nach ihrem heutigen Standpunkt*, 2 vols (Leipzig: Verlag der Leipziger Vereinsbuchdruckerei, 1870), I, p. 153.

[7] Waldow, Alexander, *Die Buchdruckerkunst in ihrem technischen und kaufmännischen Betriebe*, 3 vols (Leipzig: Druck und Verlag von Alexander Waldow, 1874-77), I (1874), p. 266.

[8] Hellwig, Wilhelm, *Der Satz chemischer und mathematischer Formeln* (Leipzig: Verlag des Deutschen Buchgewerbevereins, 1909), p. 3.

In 1874 the General Committee of the British Association for the Advancement of Science (BAAS) established a sub-committee of experts to investigate whether there were ways to facilitate the printing of mathematical works by means of using symbols and formalisms ('forms') that could be 'more easily put into type'.[9] The report of this committee on 'Mathematical Notation and Printing', published in 1875, provides us with a concise description of the main 'difficulties' that made the composition of 'mathematical matter' so much more arduous and complex than the composition of ordinary print matter. The first difficulty was that of the strenuous and time-consuming process of justifying mathematical expression with letters of different sizes, which was described in the report as 'filling up the difference between the bodies of the larger and smaller types with suitable pieces of metal, if such exist, or in cutting away a portion of the larger, so as to admit the insertion of the smaller types.' The second problem was that of justifying equations with fraction bars (Figure 3.1), which was even more complex if not only figures, but also different letters and mathematical signs were involved. The report pointed out that these two difficulties of composing mathematical matter accounted for extraordinarily high costs of mathematical printing, which 'may in general be estimated at three times that of ordinary or plain matter.'[10]

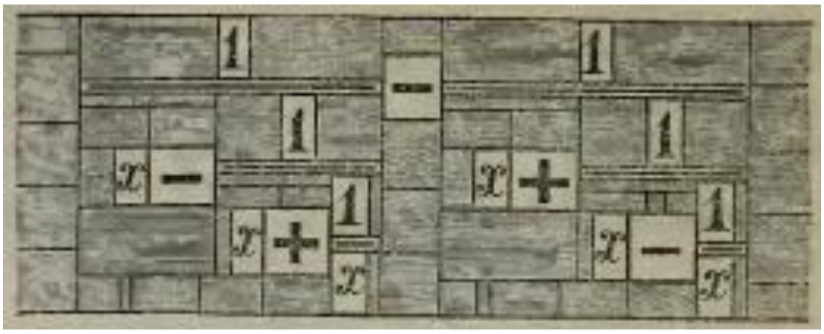


Figure 3.1: Example of how different spacing material can be arranged to justify a fraction.[11]

[9] 'Recommendations Adopted by the General Committee at the Belfast Meeting in August 1874', in *Report of the Forty-Fourth Meeting of the British Association for the Advancement of Science: Held at Belfast in August 1874* (London: John Murray, 1875), pt 1, pp. li–lvii (p. liii).
[10] 'Report of the Committee […] on Mathematical Notation and Printing', in *Report of the Forty-Fifth Meeting of the British Association for the Advancement of Science: Held at Bristol in August 1875* (London: John Murray, 1876), pt 1, pp. 337–39.
[11] Ibid.

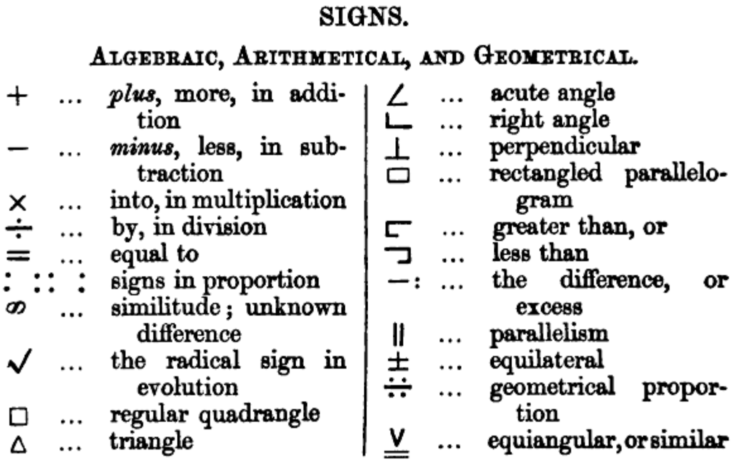
As the BAAS committee report suggests, it was primarily the additional justification work that accounted for the comparatively high costs of typesetting mathematical expressions such as the fraction illustrated above. Echoing the BAAS report, the practising printer and prolific author of typographical handbooks John Southward explained with regard to the composition of algebra that it was not only the special figures and mathematical symbols, but above all 'the proper arrangement of the matter (which cannot always be indicated on the manuscript copy) that gives troubles to the compositor.'[12] And indeed, the composition of mathematical matter was much more laborious than the setting of ordinary matter, which becomes apparent when we compare the two processes.

The composition of text by assembling pieces of moveable type remained essentially unchanged from its inception in the fifteenth century until the introduction of mechanical typesetting methods at the end of the nineteenth century. The process of typesetting a handwritten manuscript involved a sequence of manual operations carried out by the compositor.[13] The process began with the compositor or his superior – usually the master or overseer – making decision about the format, typographic design, and length of the book. The compositor then read the manuscript and divided it into lines of text of approximately equal length. Next, the compositor proceeded to setting one line of text at a time on the composing stick by plucking individual pieces of leaden type from the type case in front of him and placing the letters, upside down and in mirror fashion, on the composing stick held in his left hand. Finished words were separated from each other by pieces of space of the appropriate width.[14] Once a line of text was completed, the compositor had to justify the line, which meant making the line a 'tight sliding fit in the stick'.[15] He was able to achieve this either by changing some of the spaces between the words, or by adding additional spaces to the end of the line. The compositor then went on to set the next line, which was stacked on top of the previous one, and he continued to do so until the composing stick was full. The typeset passage was then transferred onto the 'galley', a large wooden or metal tray of the exact page size of the forthcoming book.[16] Once the page of text on the galley was completed, the compositor placed the assembled page – usually together with other pages – in a 'forme', which was a metal frame

[12] Southward, *Practical Printing*, p. 279.
[13] This general description of the main steps of setting a text by hand is based on Gaskell, *Bibliography*, pp. 40-51.
[14] Pieces of space were available in a variety of different widths, such as en and em spaces. In addition, there were wider spaces such as quads. Cf. Gaskell, *Bibliography*, pp. 45-56.
[15] Ibid, p. 45.
[16] Sometimes the compositor would slip 'thin strips of typemetal, reglet, or card' between each line 'in order to spread the lines out vertically.' (Ibid, p. 46.) Also, there was no set rule for when the composing stick had to be emptied. Gaskell explains that it was the common practice of French compositors to empty the stick after each line, whereas their English counterparts would do this only after having set four of five lines on the stick. (Ibid, p. 47.)

where the type is fixed for printing. If each of the described steps was carried out correctly, the type would not move and sit tightly in the frame. If, however, the justification was not done properly and gaps between pieces of type appeared, the whole page could easily disintegrate into a large pile of 'muddled pie', and the page had to be reset from scratch.[17]

The composition of mathematics differed from the setting of ordinary – meaning linear – matter in two ways. First, mathematical expressions were made up of many typographical elements that were not part of the standard typographical equipment. The following two examples taken from nineteenth-century typographical handbooks (Figures 3.2 & 3.3) demonstrate that every typographer who aspired to excel in mathematical printing first had to understand and memorise the special sorts required for this task. Yet we will see in the following passage that the compositor not only had to become familiar with these sorts, but he also had to learn how the different pieces can be combined with each so that the type would not move during printing. In other words, it was the justification of a complex mathematical expression made up of those unfamiliar pieces that posed the greatest challenge to the compositor.



SIGNS.

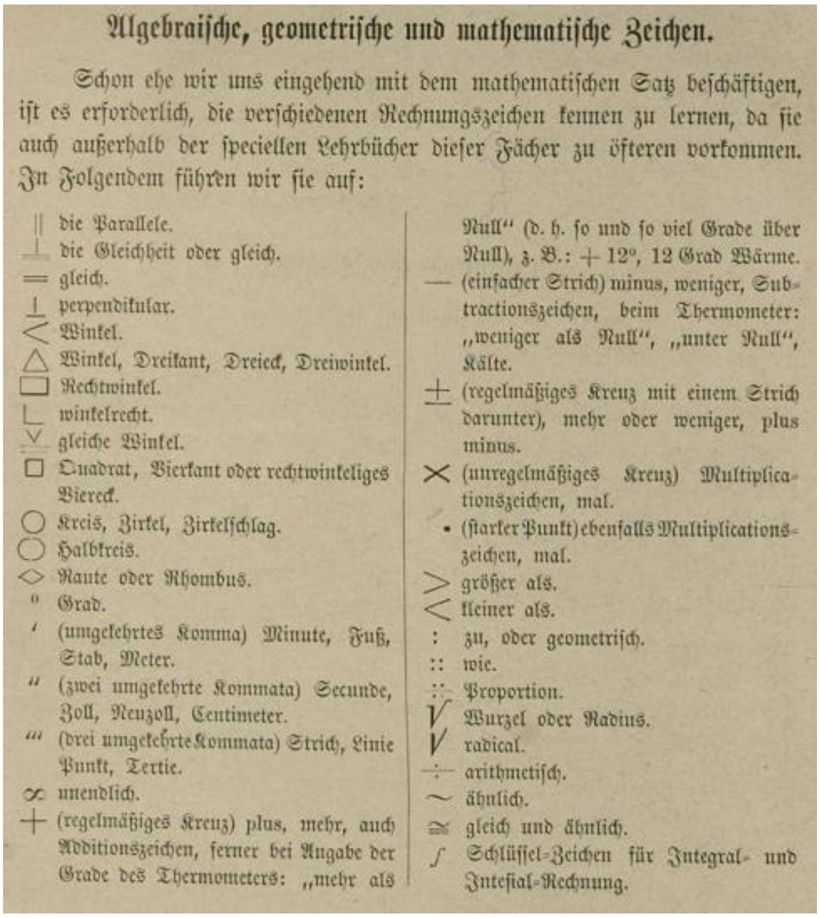
ALGEBRAIC, ARITHMETICAL, AND GEOMETRICAL.

+ ... *plus*, more, in addition
− ... *minus*, less, in subtraction
× ... into, in multiplication
÷ ... by, in division
= ... equal to
: :: : signs in proportion
∽ ... similitude; unknown difference
√ ... the radical sign in evolution
□ ... regular quadrangle
△ ... triangle
∠ ... acute angle
∟ ... right angle
⊥ ... perpendicular
▭ ... rectangled parallelogram
⊏ ... greater than, or
⊐ ... less than
−: ... the difference, or excess
∥ ... parallelism
± ... equilateral
∺ ... geometrical proportion
≚ ... equiangular, or similar

Figure 3.2: 'Algebraic, Arithmetical, and Geometrical' signs in Ford's *Handbook* (1854).[18]

[17] Ibid, pp. 46, 78.

[18] Ford, Thomas, *The Compositor's Handbook: Designed as a Guide in the Composing Room* (London: Simpkin, Marshall, and Co, 1854), p. 224.



Algebraische, geometrische und mathematische Zeichen.

Schon ehe wir uns eingehend mit dem mathematischen Satz beschäftigen, ist es erforderlich, die verschiedenen Rechnungszeichen kennen zu lernen, da sie auch außerhalb der speciellen Lehrbücher dieser Fächer zu öfteren vorkommen. In Folgendem führen wir sie auf:

|| die Parallele.
⊥ die Gleichheit oder gleich.
= gleich.
⊥ perpendikular.
< Winkel.
△ Winkel, Dreikant, Dreieck, Dreiwinkel.
▭ Rechtwinkel.
∟ winkelrecht.
≚ gleiche Winkel.
□ Quadrat, Vierkant oder rechtwinkeliges Viereck.
○ Kreis, Zirkel, Zirkelschlag.
◯ Halbkreis.
◇ Raute oder Rhombus.
° Grad.
′ (umgekehrtes Komma) Minute, Fuß, Stab, Meter.
″ (zwei umgekehrte Kommata) Secunde, Zoll, Neuzoll, Centimeter.
‴ (drei umgekehrte Kommata) Strich, Linie Punkt, Tertie.
∞ unendlich.
+ (regelmäßiges Kreuz) plus, mehr, auch Additionszeichen, ferner bei Angabe der Grade des Thermometers: „mehr als Null“ (d. h. so und so viel Grade über Null), z. B.: + 12°, 12 Grad Wärme.
— (einfacher Strich) minus, weniger, Subtractionszeichen, beim Thermometer: „weniger als Null“, „unter Null“, Kälte.
± (regelmäßiges Kreuz mit einem Strich darunter), mehr oder weniger, plus minus.
× (unregelmäßiges Kreuz) Multiplicationszeichen, mal.
• (starker Punkt) ebenfalls Multiplicationszeichen, mal.
> größer als.
< kleiner als.
: zu, oder geometrisch.
:: wie.
∷ Proportion.
√ Wurzel oder Radius.
√ radical.
÷ arithmetisch.
∼ ähnlich.
≅ gleich und ähnlich.
∫ Schlüssel-Zeichen für Integral- und Intesial-Rechnung.

Figure 3.3: ‘Algebraic, geometrical, and mathematical signs’ in Marahrens’ *Handbuch der Typographie* (1870).[19]

Simple mathematical formulae did not represent a special challenge to the compositor because they were usually made up of a single line of numerals and mathematical symbols and, occasionally, letters (for example, expressions such as “1 + 2 + 3” or “1x + 2y + 3z”). However, more complex algebraic expression featured a much larger number of typographical elements of different point size, and for this reason these complex formulae had to be composed in a different way than ordinary matter. Historical sources indicate that works containing such complex formalisms all had in common that they were set according to the same technique, which in the nineteenth century was known as ‘parangonnage’ in French,[20] and ‘parangonierte[r] Satz’, ‘Parangonage’, or ‘Parangonnage’ in German, as explained in Franke’s *Handbuch der Buchdruckerkunst* from 1886.[21] The most appropriate English translation of this term is “interlocked composition”. We can find the most detailed description of the practical

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19 Marahrens, *Handbuch*, I, p. 219.
20 Irmisch’s typographical *Wörterbuch* explains that the original French spelling is ‘[p]arangonnage’. Cf. Linus Irmisch, *Wörterbuch der Buchdrucker und Schriftgießer* (Braunschweig: [George Westermann], 1901), p. 53.
21 Franke, *Handbuch der Buchdruckerkunst: Nach eigenen Erfahrungen und nach denen andrer namhafter Buchdrucker*, 5th edn, rev. by R. Wagner (Weimar: Voigt, 1886), p. 119.

challenges of composing algebraic works in Franke's *Handbuch*. The handbook makes it clear that the greatest challenge of composing algebraic expressions is that of careful justification, since these expressions – especially complex fractions – can be very large and feature mathematical symbols as well as subscript and superscript characters, and numerals and letters of different point sizes. The compositor must therefore align the type not only horizontally, but also vertically, for which he has to use a large amount of additional spacing material.[22] Above all, the handbook points out that 'great care is to be taken to make sure that no letters, characters, or numerals fall out, or are pulled out' when transferring the type onto a galley or locking it up in a forme, 'which is most likely the case with mathematical composition.'[23]

We have thus seen in this section that compositors of mathematical formalisms faced many practical challenges. The biggest challenge of all was the justification of expressions that were not only large in size, but also contained a big number of different typographical elements such as Latin and Greek letters, mathematical symbols, subscript and superscript numerals and letters, as well as parentheses and fraction bars in different sizes. And, indeed, we have already learned from the BAAS report cited above that it was not the typographical elements alone that posed a challenge to the compositor, but rather the proper combination and arrangement of those special sorts. Hence compositors of mathematical literature required not only a high degree of practical experience, but also at least a basic understanding of the mathematical symbols.

However, the large number of books and journal articles containing mathematical and physical formulae published over the course nineteenth century clearly indicates that there were many printing workshops all across Europe that were capable of typesetting and printing simple works with technical matter.[24] It thus becomes apparent that during the second half of the nineteenth century, mathematical literature could be printed at several locations across Europe. In the next section, we will see that those printing companies that produced mathematical and physical works were also likely to be engaged in printing chemical literature with typeset formulae because both jobs required the careful justification of space-consuming and highly technical formalisms. Composing mathematics and chemistry were thus closely related. It is therefore most likely the close similarity between these two kinds of jobs that made the publication of specialised manuals redundant. In addition, the similarity also strongly suggests that the costs of typesetting mathematical and chemical formalisms were

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[22] Cf. Franke, *Handbuch*, pp. 119-22.

[23] Ibid, p. 120.

[24] For German publishing houses that began to specialise in mathematical and, often, also physical works during the first half of the nineteenth century, see Remmert, Volker R. and Ute Schneider, *Eine Disziplin und ihre Verleger: Disziplinenkultur und Publikationswesen der Mathematik in Deutschland, 1871-1949* (Bielefeld: transcript, 2010).

approximately the same. Yet, by contrasting the practices of chemical and mathematical typesetting, we will also see that even the composition of line-and-letter formulae was less demanding than the rendering of complex algebraic formalisms. This, I argue, suggests that every printing workshop capable of printing of mathematics was also able to print type-based chemical notations of every kind, and that no additional training in typesetting chemical literature was required on behalf of the compositor.

3.2. Typesetting Chemistry

In this section, I draw on twentieth-century works of typographical literature that explicitly addressed the composition of chemical formalisms. Hellwig's article 'Der Satz chemischer Formeln' from 1908, republished as part of a short monograph entitled *Der Satz chemischer und mathematischer Formeln* in the following year, was to my knowledge the first piece of writing concerned explicitly with the composition of chemical print. [25] We can find more detailed instructions and practical guidelines to the actual procedures of typesetting of scientific works – including mathematical and chemical formulae – in three comprehensive monographs that were published in the early 1950s. Paul Fritzsche's and Herbert Wunderlich's *Der Formelsatz in Mathematik, Chemie und Technik* (1952), Karl Klemm's *Der wissenschaftliche Satz* (1953), and James Roderer's *Über den Satz wissenschaftlicher Formeln* (1955)[26] were conceived as means to address the strong demand for qualified compositors of mathematics and chemistry that was keenly felt after the Second World War on both sides of the Iron Curtain. This rise in demand was a consequence of the shortage of qualified compositors and the diminished capacities of the publishing industry, on the one hand, and the strong and rapid increase in scientific works, on the other.[27] The authors pointed out that their books were written by practitioners for practitioners, and that they served the purpose of making the specialist knowledge about the composition of scientific texts accessible to non-specialised practitioners without any prior expertise in that area. However, it should be understood that these guidelines were written for practising compositors who were expected to have already acquired a significant degree of practical experience in setting various kinds of literary works. The authors also emphasised that mathematical and chemical typesetting techniques could only be learned through practical

[25] Hellwig, 'Der Satz chemischer Formeln', *Archiv für Buchgewerbe*, 45.7 (1908), pp. 287 ff.; idem, *Satz.*
[26] Fritzsche, Paul, and Herbert Wunderlich, *Der Formelsatz in Mathematik, Chemie und Technik* (Leipzig: VEB Fachbuchverlag, 1952); Klemm, Karl, *Der wissenschaftliche Satz* (Halle: Wilhelm Knapp, 1953); Roderer, James, *Über den Satz wissenschaftlicher Formeln* (St. Gallen: Zollikofer & Co, [1955]).
[27] Cf. Chaundy et al., *Printing of Mathematics*, p. iii; and Fritzsche and Wunderlich, *Formelsatz*, p. v.

training, and that their books could thus serve only as a supplement to that practical experience.[28]

All of the aforementioned books served the purpose of providing guidance for those who were planning to engage in typesetting scientific works, including mathematics and chemistry. Works in these two disciplines usually contained a considerable number of chemical and mathematical formalisms which, as we have already established above, presented compositors with a set of specific challenges. By outlining some of the challenges addressed in the cited works on chemical typesetting, the next section will first demonstrate that the composition of chemical formalisms was indeed very similar to the composition of mathematical formulae. Secondly, my close analysis of the practice of typesetting chemistry will show that even the most space-consuming forms of line-and-letter formulae could be realised with a relatively small number of sorts, and that most of those sorts could be found in every well-stocked printing workshop. Put another way, I will show that in contrast to mathematics, chemical typesetting required only a small number of special sorts. I conclude by arguing that it was notably these limited material requirements that enabled line-and-letter formulae to be reproduced easily and rapidly in different textbooks and journals, thereby circulating widely across markets and national borders.

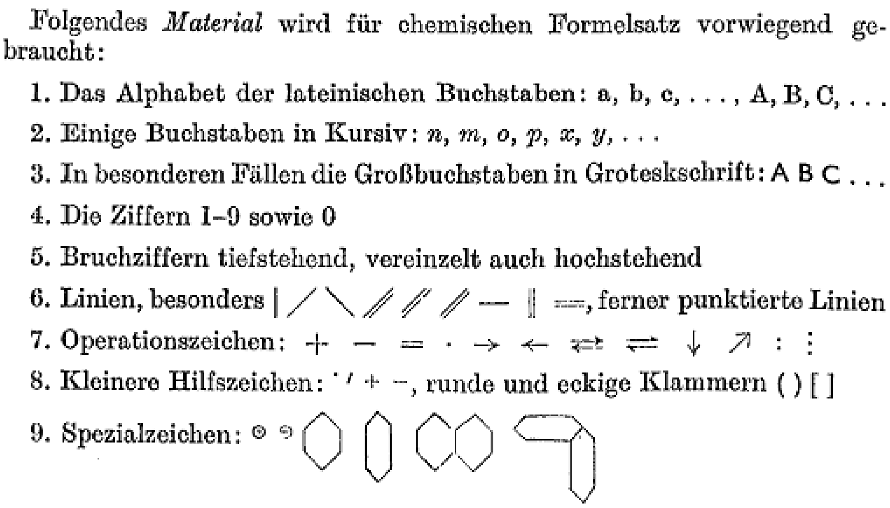
A Practical Lesson in Typesetting Chemistry

Hellwig, Fritzsche, Wunderlich, Klemm, and Roderer all agreed that the ultimate challenge facing every compositor of chemical literature was the accurate arrangement of spacing material to justify the formulae, especially where space-consuming ring formulae and formulae with lengthy carbon chains are concerned.[29] All of the cited works provided more or less detailed guidelines for typesetting chemical formulae. Among these works, it is Klemm's *Der wissenschaftliche Satz* that offers the most valuable insights for the historian of scientific print because the manual provided a detailed account of the process of typesetting chemical literature, and because Klemm's work also flagged up the main challenges that compositors faced in that process. The section on the setting of chemical formulae ('Der chemische Formelsatz') began with an

[28] Cf. Roderer, *Satz*, p. 10.

[29] Cf. Hellwig, *Satz,* pp. 10-11; Fritzsche and Wunderlich*, Formelsatz*, pp. 11-13; Klemm, *Satz*, p. 129. To this, Roderer adds that the reading and interpreting of handwritten formulae authors' manuscripts represents another major challenge to typesetters and requires at least a basic understanding of the subject matter at hand, since the compositor is expected to 'have the necessary feeling and the necessary knowledge to interpret and compile the handwritten formula' without any further help. (Roderer, *Satz*, p. 59.)

overview of the letters, numerals, and signs that made up the modern chemical notation. The section then elaborated briefly on the composition of chemical equations, which was followed by a detailed explanation of how to typeset line-and-letter formulae.[30] The first part of the section offered a list of metal sorts used for the composition of the most common forms of chemical formalisms (Figure 3.4). This set included letters of a Latin typeface (1); 'some letters' in Italic (2); uppercase sans serif letters (3); Arabic numerals (4); subscript and superscript numerals (5); hyphenated and solid lines (6); mathematical symbols (7); auxillary characters and brackets (8); and special symbols (9). In addition, the compositor was instructed that he should have a sufficient amount of spacing material of different kinds and sizes (spaces, quads, slugs, etc.) at his disposal.[31] Compared to the lists of mathematical signs above (Figures 3.2 & 3.3), we can clearly see that the number of characters used for chemical formulae is much smaller than the number of those characters employed in mathematical typesetting. In addition, Klemm pointed out that with the exception of a small number of special symbols, all other parts ought to be found in every printer's well-equipped workshop.[32] The named exceptions were 'special symbols' with simplified depictions of ring formulae (see 'Spezialzeichen' in Figure 3.4), and the two symbols for free electrons (Figure 3.5). It thus becomes evident that chemical formulae featured a much smaller number of special sorts than were used in mathematical formalisms.


Folgendes *Material* wird für chemischen Formelsatz vorwiegend gebraucht:

1. Das Alphabet der lateinischen Buchstaben: a, b, c, . . . , A, B, C, . . .
2. Einige Buchstaben in Kursiv: *n*, *m*, *o*, *p*, *x*, *y*, . . .
3. In besonderen Fällen die Großbuchstaben in Groteskschrift: A B C . . .
4. Die Ziffern 1–9 sowie 0
5. Bruchziffern tiefstehend, vereinzelt auch hochstehend
6. Linien, besonders | ╱ ╲ ⫽ ⫽ ⫽ — ‖ ═, ferner punktierte Linien
7. Operationszeichen: + − = · → ← ⇄ ⇌ ↓ ↗ : ⋮
8. Kleinere Hilfszeichen: ˙ ′ + −, runde und eckige Klammern ( ) [ ]
9. Spezialzeichen: ⊖ ⊕

Figure 3.4: List of sorts used in modern chemical notation.[33]

Zeichen für ein freies Elektron ⊖ ⊕

Figure 3.5: Special symbols for free electrons.[34]

[30] Klemm, *Satz*, pp. 129-42.
[31] Ibid, p. 130.
[32] Ibid, p. 132.
[33] Ibid, p. 130.
[34] Ibid, p. 132.

The section continued with precise instructions for the composition of various types and sizes of chemical formulae. For instance, Klemm explained that bond lines required two different sets of typographic elements: while the majority of formulae could be realised by means of 'short pieces' such as the conventional minus sign (single bond), the double-bar equality sign (double bond), and the triple-bar congruence sign (triple bond), some other formulae might require less common forms of diagonal lines on 8-point or 10-point square blocks (quads).[35] Simple, linear formulae based on Berzelian symbols were set in the same point size as the body text. The font size could be reduced in the case of lengthy expressions to avoid line breaks. The preferred size for body text and formulae should be 9 or 10 point. Special attention must be paid to consistent spacing between each element of the formula to ensure good readability.[36] Two-dimensional structural formulae, on the other hand, were not part of the written text and should be set separately in a font size not larger than 8 point.[37]

There are two basic layouts of structural formulae, the so-called chain formula ('Kettenformel') and the ring formula. According to Klemm it was the composition of ring formulae that posed the biggest challenges to compositors of chemical texts. Compositors were therefore advised to use the special symbols for the benzene ring and its derivatives (Figure 3.6) where practicable in order to save time. The book made it very clear that one of the biggest challenges of typesetting formulae of aromatic compounds were additional elements such as numerals or letters placed inside the polygon (Figure 3.7). Each additional element threatened to break the geometric uniformity of the whole arrangement, thus sometimes forcing the compositor to 'stretch' the aromatic formula by adding more vertical, horizontal, or diagonal lines (Figure 3.8). The more elements that were added, the more difficult it became to justify the formula. Sophisticated aromatic formulae hence required a large amount of spacing material.[38]

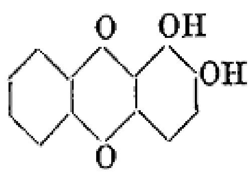
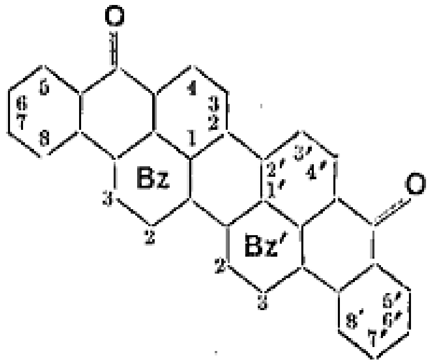
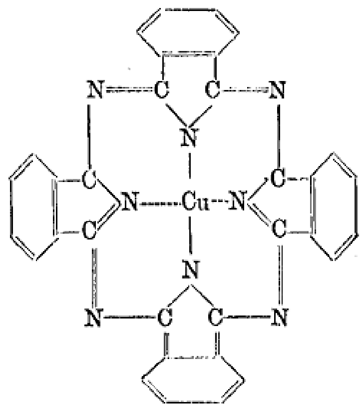


Figure 3.6: Special symbol for a three-ring aromatic compound.[39]

[35] Ibid, p. 131.
[36] Ibid, pp. 133-34.
[37] Ibid, p. 134.
[38] Ibid, p. 137-38.
[39] Ibid, p. 137.





Figures 3.7 & 3.8: Large formula with enclosed numerals and letters (left); large formula with elongated, or 'stretched', bond lines (right).[40]

Smaller formulae could be set in one piece on the composing stick, while larger formulae were set in parts and later assembled directly on the galley. The ultimate challenge facing every compositor of chemical literature was the accurate arrangement of spacing material to justify the formulae so that it made a neat and coherent appearance on the page. As with mathematical typesetting, this was no easy task, since the compositor had to match and assemble a large number of very small pieces of space of different size (hairs, thins, ens, ems, quads, etc.) in order to align the different part of the formulae, which meant that he had to put together something akin to a sophisticated jigsaw puzzle, as illustrated in Klemm's layout of spacing material below (Figure 3.9). We can thus picture how the compositor had to use all of his visual imagination when filling in the various gaps between the lines, letters, numerals, and mathematical signs in order to tightly fix the formula in the forme. As with the algebraic equation that we saw in the first section of this chapter (Figure 3.1), the necessary justification work was required because each line-and-letter diagram that extended vertically above and below the text line was composed of a very large number of type pieces and spacing material that could be assembled and aligned in many different ways. As a result, the comparison between mathematical and chemical typesetting shows clearly that the two tasks were very similar because they involved the same practical challenges, which meant that nineteenth-century compositors proficient in setting algebraic equations and other kinds of technical literature were also able to typeset line-and-letter formulae. Indeed, we shall see toward the end of this section that printing houses specialising in mathematical works and other kinds of scientific literature had no problems with printing line-and-letter formulae when chemists began to use the new notation in the 1860s.

[40] Ibid, pp. 138, 139.

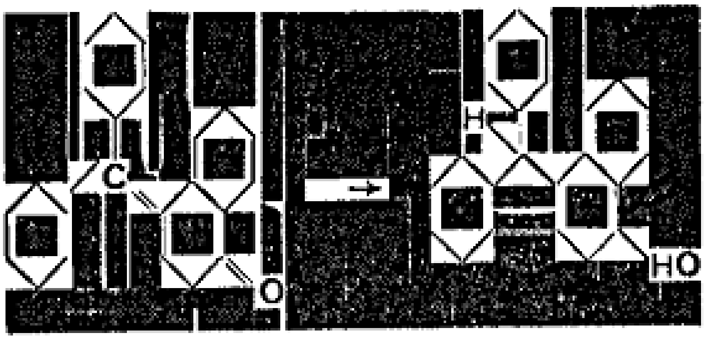


Figure 3.9: Possible layout of spacing material (in black) for justification of ring formulae.[41]

However, as challenging as the typesetting process might have been to the composer because of the myriad of moving pieces on his stick or galley, we need to understand that it was exactly this considerable degree of flexibility offered by moveable type that made typeset chemical notation so successful. As we have seen from Kekulé's compilation of different formulae for acetic acid in the previous chapter, moveable type was used to render all of the diagrams that chemists had developed to communicate their particular ideas about chemical constitution during a period of profound theoretical debates and theoretical change. Moveable type allowed for this large degree of freedom because it did not put any limitations on the size of formulae, and because typeset diagrams could be set together with the body of the text. As a result, the 1860s and 1870s saw line-and-letter diagrams in various shapes and sizes gradually populate the pages of chemical journals and textbooks. Equally important, typeset diagrams did not require sophisticated equipment and could therefore be produced with only a very small set of special symbols, as we saw at the beginning of this section (Figures 3.4 & 3.5). It was due to these practical advantages that typeset notation became ubiquitous in chemical print by the mid-nineteenth century.

To summarise, the comparison between the practices of mathematical and chemical typesetting has demonstrated that the two tasks were closely related. This, I argue, means two things. First, the very close similarity between mathematical and chemical typesetting implies that the two jobs were charged at a similar rate. As a general rule, nineteenth-century trade agreements, such as the London Scale of Prices for Compositor's Work or the Allgemeiner Deutscher Buchdruckertarifvertrag for the whole of the German Empire, do not list chemical composition as a separate job.[42] Yet on the supposition that mathematical and chemical

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[41] Ibid, p. 139.

[42] The original London Scale of Prices for book work took effect in 1810 and remained in force until a new scale was introduced in 1891. Cf. Howe, Ellic, *The London Compositor: Documents Relating to Wages, Working Conditions and Customs of the London Printing Trade 1785-1900* (London: Bibliographical Society, 1947), p. 58. The Allgemeiner Deutscher Buchdruckertarifvertrag took effect in

typesetting required the same amount of work, it is reasonable to posit that London-based compositors charged double the price of ordinary matter for chemical works with a significant number of typeset diagrams, and that German compositors charged – depending on the number of formalisms in a piece of work – between double and treble the price of ordinary matter according to the Buchdruckertarifvertrag of 1873.[43] As we shall see at the end of this chapter, science publishers were not concerned about the costs of typesetting line-and-letter formulae in the 1860s, and it does not seem that printing costs were an issue as long as the number and size of the diagrams remained relatively low. Yet, as we shall see in Chapter 6, rising printing costs associated with the growing number and size of line-and-letter formulae became a major concern for the editors and publishers of chemical periodicals in the 1870s.

Secondly, the close similarity between mathematical and chemical typesetting explains why nineteenth-century typographical manuals and handbooks did not list chemical formalisms as a special case – after all, the comparison between the practices of mathematical and chemical typesetting has demonstrated that both types of composition were very similar. Both complex mathematical formalisms such as algebraic equations and line-and-letter formulae were realised by means of metal type, made up of a large range of individual components, and extended into the two dimensions of the printed page – which, as I have mentioned before, required a large amount of spacing material. It was also for this reason that the layout of spacing material for the justification of a mathematical formulae included in the first section of this chapter (Figure 3.1) looks strikingly similar to the layout of spacing material for a line-and-letter diagram above (Figure 3.9). In what follows, we shall see that number of printing workshop that had previously been in charge of producing scientific works with complex technical formalisms already possessed the necessary know-how to produce space-consuming line-and-letter formulae when the new chemical notation arrived in the 1860s.

Nineteenth-Century Scientific Printers in Britain and the German Lands

The 1860s saw the appearance of line-and-letter diagrams in a number of British and German textbooks and periodicals. During that decade, the number of textbooks that featured the new diagrams remained relatively low, as I explain in more detail in Chapters 4 and 5 of this thesis. Yet it is striking that there was already a range of printing companies that were able to produce

1873. Cf. Kuczynski, Jürgen, *Arbeitslohn und Arbeitszeit in Europa und Amerika, 1870-1909* (Berlin: Springer, 1913), p. 565.

[43] Cf. Howe, *Compositor*, p. 345; and 'Der Setzertarif aus 1873 und seine Mängel', *Typographisches Jahrbuch*, 1 (1876), 61-74 (p. 65).

those textbooks. Line-and-letter formulae also began to appear in British and, predominantly, German periodicals that were produced by specialist printers in London, Leipzig, and elsewhere. This, I argue, means that line-and-letter formulae did not represent a new or unprecedented challenge to printers, but rather built on the know-how that had been developed and cultivated by those printers during the first half of the nineteenth century. By way of illustration, Taylor & Francis was in charge of printing the *Philosophical Transactions*, the *Proceedings of the Royal Society*, as well as Frankland's highly influential textbook *Lecture Notes* (1866). Harrison & Sons printed the *Journal of the Chemical Society* as well as Ughtred James Kay-Shuttleworth's *First Principles of Modern Chemistry* (1868). Wilhelm Keller of Giessen printed the all-important *Annalen der Chemie und Pharmacie*, A. W. Schade's Buchdruckerei (L. Schade) of Berlin printed the *Berichte der Deutschen Chemischen Gesellschaft*, Fischer & Wittig of Leipzig the *Journal für praktische Chemie*, and J. B. Hirschfeld of Leipzig the *Zeitschrift für Chemie*. The majority of the English and German volumes of the Roscoe-Schorlemmer textbook franchise were printed by Vieweg in Braunschweig, and Emil Erlenmeyer's *Lehrbuch der Organischen Chemie* (1868-69) was printed by Erdmann Polz in Leipzig.[44]

Unfortunately I have not been able to find reliable historical records on the background of some of the German printers that were involved in the printing of early works with line-and-letter formulae. I therefore leave it to future historians to study the company histories of Wilhelm Keller, Fischer & Wittig, J. B. Hirschfeld, and Erdmann Polz.[45] However, enough historical data exists to explain how the other British and German printing companies had built up the know-how that enabled them to produce sophisticated works with line-and-letter formulae in the 1860s. The London-based companies Taylor & Francis and Harrison & Sons were leading the field in Britain. In 1822 Richard Taylor became co-editor and co-proprietor and in 1825 sole owner of the *Philosophical Magazine* (f. 1798) that he had printed since shortly after its inception and which, over the course of the first half of the nineteenth century, developed into the leading commercial periodical for the physical sciences on the British market.[46] During

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[44] Frankland, *Lecture Notes* (1866); Kay-Shuttleworth, Ughtred James, *First Principles of Modern Chemistry: A Manual of Inorganic Chemistry* (London: Churchill, 1868); Roscoe, Henry Enfield, *Lessons in Elementary Chemistry* (London: Macmillan, 1866); Roscoe, *Kurzes Lehrbuch der Chemie nach den neuesten Ansichten der Wissenschaft*, ed. by Carl Schorlemmer (Braunschweig: Vieweg, 1867); Erlenmeyer, Emil, *Lehrbuch der organischen Chemie* (Leipzig: C. F. Winter, 1868-69). Erlenmeyer's book was published in two fascicles. The first fascicle appeared in 1868 and the second fascicle was released in 1869.

[45] Two nineteenth-century sources indicate that Hirschfeld's printing house (est. 1800) specialised in scientific and medical works, but do not provide any further details. Cf. Lorck, Carl B., *Handbuch der Geschichte der Buchdruckerkunst*, 2 vols (Leipzig: J. J. Weber, 1882-83), II: *Wiedererwachen und neue Blüte der Kunst 1751-1882* (1883), p. 347; and *J. B. Hirschfeld: Hundert Jahre einer Leipziger Buchdruckerei* (Leipzig: J. B. Hirschfeld, 1900), p. 36.

[46] Brock and Arthur Jack Meadows, *The Lamp of Learning: Two Centuries of Publishing at Taylor & Francis*, 2nd edn (London: Taylor & Francis, 1998), pp. 96-97, 261. For a concise history of the journal, see ibid, chs. 4 and 9.

the first half of the century, the *Philosophical Magazine* published papers on chemical, mathematical, and physical subjects, which often featured papers with complex equations. Between 1828 and 1877, Richard Taylor (from 1852 Taylor & Francis) also acted as printer of the prestigious *Philosophical Transactions* and *Proceedings of the Royal Society*.[47] With regard to the company's expertise in printing technical literature, it is therefore no surprise that Taylor & Francis were commissioned to print the first and second edition of Frankland's *Lecture Notes* (1866, 1870-72), with its very large number of space-consuming line-and-letter formulae. Similarly, Harrison & Sons had developed their know-how in the periodical trade. The company was nominated printer of the *Journal of the Chemical Society* (f. 1848) in 1857.[48] At this point, it is important to note that since its foundation, the *Journal* had been publishing papers on all fields of chemistry, and that many of those papers featured lengthy mathematical expressions.[49] Like Taylor & Francis, Harrison & Sons were therefore well suited to print works with all different kinds of scientific formalisms.

In Germany, the situation was very similar, where early works with a large number of the new chemical diagrams were printed by companies with long-standing experience in technical works.[50] Among the German companies, Vieweg stood out, since the Braunschweig-based firm published and printed two of the earliest German textbooks that employed the new chemical notation: Henry Roscoe's and Carl Schorlemmer's *Kurzes Lehrbuch der Chemie* (1868) and Adolf Strecker's *Kurzes Lehrbuch der organischen Chemie* (1868).[51] As I explain further below, Vieweg's company was also in charge of printing parts of the English volumes of the Roscoe-Schorlemmer textbook franchise, which were published by Macmillan in London. The publishing house of Ferdinand Vieweg and Sons was founded in 1786.[52] Over the course of the first half of the nineteenth century, Ferdinand's successors Eduard and Heinrich Vieweg systematically developed the company from a general publisher into one of the leading scientific

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[47] Fyfe, 'Journals, Learned Societies and Money', pp. 286-87.
[48] 'Publications', in *Jubilee of the Chemical Society of London: Record of the Proceedings together with an Account of the History and Development of the Society, 1841-1891* (London: [The Chemical Society], 1891), pp. 237-51 (p. 241).
[49] The most comprehensive study on the history of this journal is Watchurst, Edgar G., 'The Journal of the Chemical Society 1862-1900: Enquiries into some Aspects of Nineteenth Century Chemical Publishing' (unpublished master's thesis, University of Bristol, 1974).
[50] For a history of mathematical publishing in Germany, see Remmert and Schneider, *Disziplin*; and idem, eds., *Publikationsstrategien einer Disziplin: Mathematik in Kaiserreich und Weimarer Republik* (Wiesbaden: Harrassowitz, 2008).
[51] Roscoe*, Kurzes Lehrbuch der Chemie*, 2nd rev. edn, ed. by Carl Schorlemmer, (Braunschweig: Vieweg, 1868); Strecker, Adolf, *Kurzes Lehrbuch der organischen Chemie*, 5th edn (Braunschweig: Vieweg, 1868).
[52] For a more comprehensive history of this highly successful scientific publisher and printer, see Dreyer, Ernst A., ed, *Friedr. Vieweg & Sohn in 150 Jahren deutscher Geistesgeschichte: 1786-1936* (Braunschweig: Vieweg, 1936); and Lube, Frank, Ulrich Wechsler, and Rudolf Wendorff, eds., *Der Verlag Friedr. Vieweg & Sohn 1786-1986: Die Reden im Vieweg-Haus zu Braunschweig am 25. April 1986* (Braunschweig: Vieweg, [1986]).

publishers in Germany with a strong profile in physical, mathematical and, notably, chemical literature.[53] From the beginning of the nineteenth century, the company included a printing office with type-casting facilities, and it also acquired a paper mill in 1836 and a 'xylographic' workshop ('Xylographisches Atelier') in 1841.[54] Vieweg & Sons thus constituted an all-in-one company for the mass production of high-quality scientific books and journals. By contrast, Schade of Berlin specialised primarily in the printing of physical and chemical journals. Although we know very little about the history of this company, surviving archival records show that Schade was the nominated printer of Johann Christian Poggendorff's (1796-1877) *Annalen der Physik und Chemie* in 1828.[55] From its foundation as the *Journal der Physik* in 1790, the journal was published by Ambrosius Barth (later Johann Ambrosius Barth) in Leipzig and specialised in all branches of the physical sciences and often included technical formalisms that extended over several printed pages.[56] There can thus be no doubt that the experience derived from typesetting those expressions formed one of the main reasons why Schade became the printer of the formula-ladden chemical journal *Berichte der Deutschen Chemischen Gesellschaft* in 1868.

To summarise, the examples above have demonstrated two things. First, the comparison of British and German printers has revealed that there was no strong division between the composition of mathematical, physical, and chemical formulaisms, since all of the aforementioned companies had been producing works on more than one subject. In other words, none of the above printers specialised in just mathematical or just chemical literature. This, I conclude, is no surprise, because notably the volumes of periodicals such as the *Philosophical Magazine*, *Journal of the Chemical Society*, or *Annalen der Physik und Chemie*, often featured lengthy mathematical equations alongside different forms of chemical formulae for the reason that those journals covered a variety of subjects ranging from organic and inorganic chemistry to galvanism and thermodynamics. Secondly, the comparison has made it evident that all of the aforementioned printers had already developed a considerable degree of know-how in typesetting complex scientific works before the advent of the space-consuming

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[53] Cf. Walther A. Roth's chapter 'Chemie', Karl Scheel's chapter 'Physik', and Heinrich E. Timerding's chapter 'Mathematik', in *Friedr. Vieweg & Sohn*, pp. 93-104, 105-116, 117-37. One of Vieweg's most successful authors was Justus von Liebig, and the company benefitted very much from this collaboration. Cf. Langfeld, Michael, 'Die Umsetzung von Autorenidee in ein Verlagsprogramm: Beispiele aus der Zusammenarbit Justus von Liebigs und Eduard Viewegs', in *Fachschrifttum,* pp. 103–23. The correspondence between Liebig and the Viewegs was edited by Margarete and Wolfgang Schneider and published as Scheider and Scheider, eds., *Justus von Liebig: Briefe and Vieweg* (Braunschweig: Vieweg, 1986).

[54] Dreyer, 'Entwicklung und Gestalt', in *Friedr. Vieweg & Sohn*, pp. 1-68 (p. 35).

[55] Leipzig, Sächsisches Staatsarchiv Leipzig, 21101 Johann Ambrosius Barth Verlag, Nr. 0814, microfilm frames 107-08: 'Contract / zwischen Herrn Buchdrucker Schade in Berlin, / und Herrn Johann Ambrosius Barth in Leipzig, / über den Druck von Annalen der Physik und Chemie […]', 10 December 1827.

[56] For a brief overview of the journal's history, see Hund, Friedrich, 'Die Annalen der Physik im Wandel ihrer Aufgabe', *Annalen der Physik*, 502 (1990), 289-95; and Hilz, Helmut, 'Die "Annalen der Physik"', *Kultur und Technik*, 29.2 (2005), 46-47.

line-and-letter diagrams in the 1860s. As a result, the composition of the new chemical diagrams did not present new practical challenges to scientific printers in Britain or Germany when chemists began to use the line-and-letter formulae in their research articles and textbooks. Publishers in both countries could therefore choose from a number of established printing houses when they commissioned works that dealt with the new theory of chemical structure. Because the typesetting of line-and-letter formulae was in practical terms very similar to the composition of other formalisms, scientific printers were able to render the new formulae without having to develop new typesetting practices or purchasing new equipment.

Of course there can be no doubt that hand composition of line-and-letter formulae was more challenging and more expensive than the composition of ordinary matter, as we have already seen in this section. As we shall see in Chapter 6, composition costs did in fact become a major economic problem for chemical journals in the 1870s and resulted in the introduction of different measures aimed at reducing the number and size of the diagrams. Yet we shall see in the remainder of this chapter that typesetting costs did not present a problem in the 1860s. In what follows, I demonstrate that it was not the costs of composition but rather the timely production of chemical representations that publishers of chemical works were mostly concerned about. The following two sections elaborate on the printing technique that were used to render Loschmidt's and Kekulé's diagrams on paper. By following this account, we will see that typeset line-and-letter diagrams proved much more flexible and therefore easier to reproduce than illustrations produced by means of wood engraving, lithography, and other printing technologies that were available in the second half of the nineteenth century. The last section shows the very practical problems that authors and publishers faced when preparing books that included wood engravings or copperplate engravings. It is thus only by comparison to the use of other printing technologies in scientific publishing that we can see the line-and-letter formulae's biggest advantage, which allowed for a wide and rapid circulation of the new notation.

3.3. An Inconvenient Choice: Lithography and Loschmidt's Diagrams

We have already explored the iconography of Josef Loschmidt's circular formulae in the previous chapter. The diagrams were attached to the end of Loschmidt's short treatise *Chemische Studien* (1861) on seven fold-out sheets of the approximate scale of 23 cm x 60 cm. Loschmidt's pamphlet was printed and, most likely, also distributed by the son of the Viennese printer, publisher, and bookseller Carl Gerold (1783-1854).[57] The complete work consisted of a title page, 53 numbered pages, an unpaginated page of errata, and the said seven fold-out sheets. The reason for the separation between text and images lies in the fact that the illustrations were printed by means of the lithographic method and could therefore not be easily integrated in the text. Although no artist or printer is indicated anywhere on the printed sheets, there are several strong indicators that characterise Loschmidt's diagrams as a lithographic print.[58] First, there is an impression mark along the right-hand edge of each of the seven sheets. Such marks result from the high pressure that is executed upon the printing paper by the lithographic press during the printing process.[59] In addition, the edges of the impressed areas of all seven plates are not perfectly straight, which is an additional indicator of a lithographic print.[60] Secondly, the characteristic appearance of letters and figures (Figures 3.10 & 3.11) strongly indicates that Loschmidt's diagrams were printed by means of lithography, as the figures and letters inscribed into the diagrams seem to have been written by hand and not carved into a metal plate or out of a block of wood. In other words, the figures and letters look as if they came straight from an artist's – or perhaps even Loschmidt's – own hand instead of being rendered by means of an engraving tool.[61] Again, the figures and letters appear very similar to characters written with ink and pen on paper, and it is exactly this versatility and natural appearance that led to lithography's rising popularity not only with commercial printers, but also with artists. It is also for this reason that during the first half of the nineteenth century, lithography developed into a form of art in its own right.[62] However, the use of lithography was also one of the main reasons why the diagrams did not reach many readers, as I explain in more detail further below.

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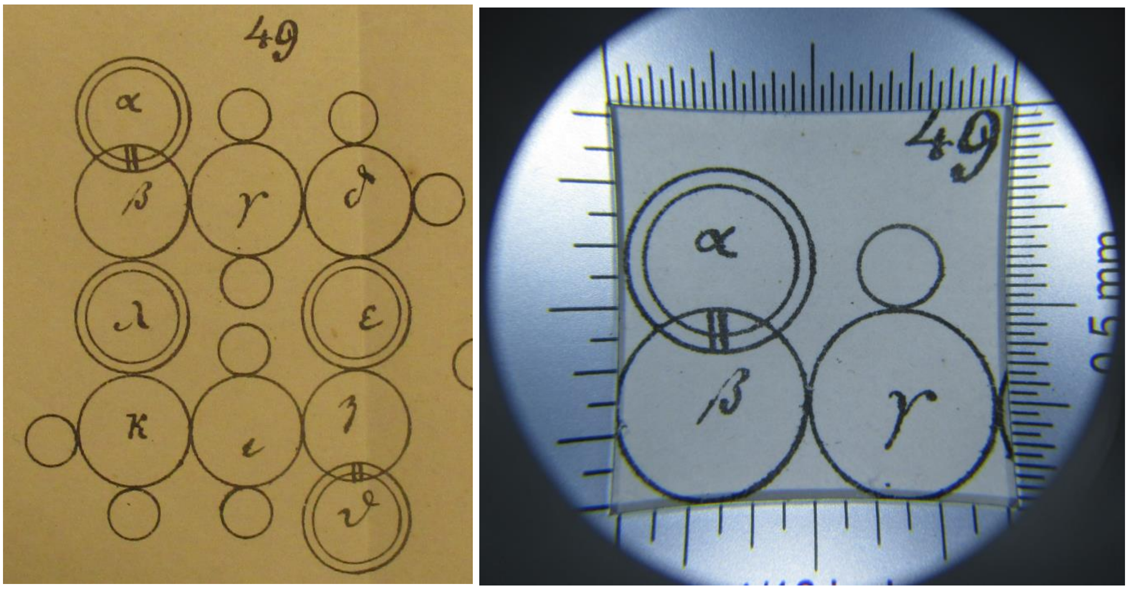
[57] Unfortunately we do not have any first-hand evidence that might explain Loschmidt's decision to have his pamphlet printed by Gerold. However, it is possible that Loschmidt chose this particular publisher and printer because the company had previously handled highly technical mathematical works such as Adam von Burg's *Compendium der höheren Mathematik*, 2nd edn (Vienna: Carl Gerold, 1851).
[58] My analysis is based on Bamber Gascoigne's seminal guide *How to Identify Prints*.
[59] For an overview of the many different varieties of lithographic hand presses developed in the first half of the nineteenth century, see Twyman, 'The Lithographic Hand Press 1796-1850', *Journal of the Printing Historical Society* 3 (1967), 3-50.
[60] Gascoigne explains that these irregularities along the edges of the impressed areas 'result from chips in the stone. By contrast the copper plate is likely to have a perfectly straight edge, providing a regular and unbroken line in the plate mark.' (Gascoigne, *How to Identify Prints*, § 50 d.)
[61] I discuss the tools used for wood engraving in the following section.
[62] Cf. Gascoigne, *How to Identify Prints*, § 19; and Twyman, *Printing*, pp. 26-28.



Figures. 3.10 & 3.11: Loschmidt's diagrams for 'Lactid oder Milchsäureanhydrid' and close-up.[63]

Lithography is a printing method based on the use of a flat surface on which the image is drawn by means of special pens with hydrophobic, or water-repellent, ink. The lithographic process was developed by the German artist and printer Alois Senefelder (1771-1834) in 1796. The process was learned and widely adopted by European printers by the 1820s,[64] soon becoming – together with wood engravings – the preferred technology for printing music scores and maps, as well as a wide range of scientific illustrations in geology, anatomy, natural history, chemistry, and other areas of scientific inquiry.[65] The preparation of a lithographic print includes the following steps: first, the lithographer or trained artist draws the image onto the porous lithographic stone with greasy ink. The ink is then fixed with an acidic solution and the stone is washed with water. As the ink is hydrophobic, only the unmarked parts of the stone will be covered with a thin water film. In the next step, the whole stone is 'rolled' with greasy printing ink that is accepted by the marks of the drawn image, but repelled by the water-covered parts of the stone. Lastly, a sheet of printing paper is placed on the surface of the stone, which is then run through a rolling press, resulting in the mirror image of the drawn image being printed on the paper.[66] The main advantage of lithography over other printing methods of the period, such

[63] Loschmidt, *Chemische Studien*, Plate 1, diagram no. 49. This rare copy of Loschmidt's pamphlet is located in the Austrian National Library in Vienna (Vienna, Österreichische Nationalbibliothek, Signatur 116837-B).
[64] David Bland suggests that the illustration used in J. T. Smith's *Antiquities of Westminster* (1807) was probably the first lithograph to appear in a book published in Britain. Cf. David Bland, *A History of Book Illustration: The Illuminated Manuscript and the Printed Book*, 2nd edn (London: Faber & Faber, 1969), p. 250.
[65] Gaskell, *Bibliography*, p. 268; and Topham, 'Redrawing'.
[66] Gaskell, *Bibliography*, pp. 267-68.

as copperplate and wood engravings, was that the person drawing the image required relatively little training to be able to produce a printable image of high quality and detail, as the process of drawing on the lithographic stones was very similar to that of drawing on paper.[67]

However, the lithographic method also suffered from several disadvantages, especially where scientific literature was concerned. The main problem with lithography was that the technology was, for a long time, not combinable with letterpress printing because illustrations drawn on the lithographic stone had to be printed on a separate lithographic press. As a result, lithographs were printed on separate unpaginated sheets and either inserted between the pages of typeset text, or attached to the end of a periodical or book. This feature of lithographed illustrations meant that the readers of Loschmidt's *Chemische Studien* had to change frequently between the text and the illustrated sheets at the end of the volume, thus constantly having to interrupt their reading flow. This, one might argue, was likely to have an adverse effect on the readers' interpretation and understanding of the formulae. Indeed, there is strong evidence that readers found the frequent unfolding of the sheets at least 'troublesome' and inconvenient, as the chemist-turned-historian Richard Anschütz remarked in his annotated and revised edition of Loschmidt's book.[68] In this revised edition, Anschütz consequently decided to print the diagrams, scaled down and placed in the appropriate position, together with the text 'in order to directly relate the schemes [diagrams] to the text'.[69] The reading experience was thus much improved in comparison to Loschmidt's original work.

The lithographic method had another major disadvantage that restricted the wider circulation of Loschmidt's formulae, which was the difficulty of reproducing lithographic images. The common approach to reproducing lithographs was to make a lithographic copy of the original image. Yet although transfer lithography had in fact become the preferred method for the reproduction of practically any form of images during the second half of the nineteenth century,[70] the process itself was time-consuming and could only be carried out by specially trained personnel. By way of illustration, the reproduction of illustrations such as Loschmidt's circular formulae by means of transfer lithography was carried out in the following manner. First, a sheet of semi-transparent gelatin-coated transfer paper was placed on the original image. The lithographer then made a copy on the paper by tracing the image with a lithographic pen or crayon. After that, the paper was wetted and placed, face down, onto the lithographic stone, which resulted in the greasy lithographic ink sticking to the surface of the stone. The paper backing and the soluble gelatine, on the other hand, were washed away. In the final step, the

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[67] Gascoigne, *How to Identify Prints*, § 19.
[68] Anschütz, 'Joseph Loschmidt', in *Konstitutions-Formeln*, pp. 99-109 (p. 101n).
[69] Ibid.
[70] Gascoigne, *How to Identify Prints*, § 20 c.

image was printed from the stone in the normal way.[71] We can thus see that each of the described lithographic methods required special equipment and had to be carried out by specialists, which meant that only specialised workshops had the capacity to (re)produce illustrations and diagrams such as those devised by Loschmidt's. In other words, not every printing house was able to take on that task. I conclude that this was one of the main reasons for the very limited circulation and the resulting lack of attention that Loschmidt's formulae received from the scientific community.

Yet lithography was not the only technology that was available to printmakers for the purpose of printing illustrations. Next to lithography, the technology of wood engraving was widely used during the most part of the nineteenth century for illustrations in newspapers, serial literature, and books on any imaginable topic. Wood engravings were also used in scientific literature. We will see in the next section that both technologies, lithography and wood engravings, were used to print Kekulé's so-called sausage formulae. The next section analyses the various renditions of Kekulé's formulae with regard to how editors and publishers of chemical journals and textbooks applied these methods to circulate the formulae. By following those different attempts, we will see that just as in the case of Loschmidt's diagrams, Kekulé's formulae were difficult to (re)produce, which had a negative impact on their dissemination. I expand on this argument in the final section of this chapter by drawing on the correspondence between English chemist Henry Roscoe and the German publisher Eduard Vieweg. The Roscoe-Vieweg case study shows the many practical difficulties that authors and publishers faced when dealing with scientific illustrations realised by means of wood engravings and other illustrative technologies.

3.4. Communicating Sausages in Print: The Circulation of Kekulé's Sausage Formulae

Sausages on Wooden Blocks: The First Printed Appearances of Kekulé's Formulae in 1859

We saw in the previous chapter that Kekulé first used his sausage formulae in his winter 1857-58 lecture on organic chemistry. The formulae began appearing in print in 1859. A small number of Kekulé's sausage formulae appeared in the first fascicle of his textbook *Lehrbuch der organischen Chemie* published in 1859, with two more formulae of the same kind appearing in

[71] Gascoigne, *How to Identify Prints*, § 20 a.

the second and third fascicles, published in 1860 and 1861, respectively. The last of the four fascicles that make up the first volume of the textbook does not contain any sausage formulae at all. Of the 26 formulae in the first volume, 25 appear in footnotes and are placed within the text of the footnote.[72] The height of each sausage corresponds roughly to the height, or point size, of the font used in the footnotes, which means that the formulae are very small in size and do not occupy much space on the corresponding page in the book. The close examination of the original print copy of Kekulé's work by means of a magnifying glass reveals that the formulae are approximately only 3 mm in height, which equals a point size of about 8 point (Figure 3.12). (The only formula to appear outside a footnote in the middle of the page is slightly larger in size.) More formulae of the same kind appear in the second volume of his *Lehrbuch* (completed in 1866), where sausage formulae are sometimes combined with the benzene hexagon to form some sort of hybrid representation; including these hybrids in the final count, only 15 sausage formulae are used throughout the second volume.[73]

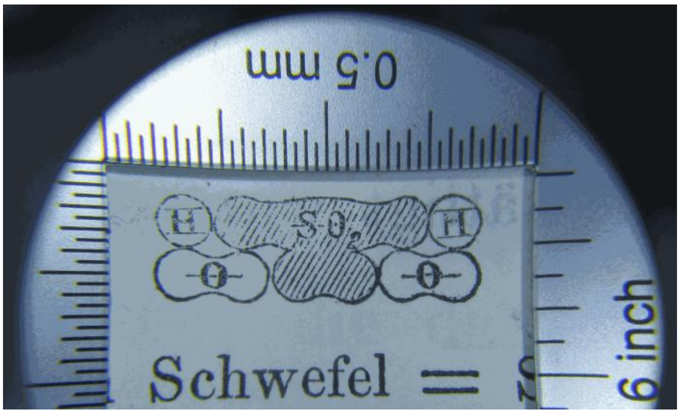

Figure 3.12: Sausage formula for 'Schwefelsäurehydrat' in Kekulé's *Lehrbuch* (1861).[74]

The unique iconography of sausage formulae implies that these representations were not composed from ordinary moveable type like line-and-letter formulae. But which technology was used to print the formulae in the first two volumes of Kekulé's *Lehrbuch*? We find the first clue in the circumstance that the illustrations appear together with text and not separately on fold-out sheets, which indicates that a relief printing technique was used to print the formulae.[75] This hypothesis is further supported by the fact that Kekulé's book was printed on a steam press – as

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[72] Kekulé, *Lehrbuch*, I (1861). The formulae appear on pp. 160n, 162n, 164n, 165n, 444n, and 523.
[73] Kekulé, *Lehrbuch*, II (1866). The second volume of Kekulé's *Lehrbuch der Organischen Chemie* was published in three fascicles between 1863 and 1866. The said formulae appear on pp. 410-11, 496, 501, 515, 672, and 744.
[74] Kekulé, *Lehrbuch*, I (1861), p. 160n.
[75] Gascoigne, *How to Identify Prints*, § 47.

indicated by the note 'Schnellpressendruck von C. H. Kunstmann in Erlangen' on the reverse title page – since intaglio and planographic illustration techniques had not yet been adapted to the steam press when the book was published.[76] The examination further reveals that the lines of the circles and sausages have a clear edge with a rim of ink, also known as ink squash, which is characteristic of a relief print.[77] This assumption is further supported by the palpable embossing on the reverse side of the page comparable to the quality and strength of the marks left by the regular type of the accompanying text. The only relief printing techniques employed in the 1850s and 1860s and suitable for the steam printing process were relief blocks – usually wood engravings – and moveable type.

In the present case, it is very unlikely that custom-made type was used for the formulae in the *Lehrbuch*, since there is strong evidence that the above formulae were rendered by means of engraved wood blocks. The most important indicator here is the slight yet clearly visible variation in thickness and length of the lines that make up the sausages (Figure 3.13), which is the result of the process of carving away wood on both sides of the black lines,[78] as I shall explain in more detail further below. In addition, we can notice clear differences between shapes of the letters inscribed into the sausages – differences that would not occur if the formulae and letters were type cast from the same mould. Finally, we can see that some of the circles are not perfectly round, and that the black lines that make up the shading of the ~~SO~~$_2$ sausage are neither perfectly straight nor perfectly aligned to each other (Figure 3.13). These minor disproportions strongly imply that the said formulae were not composed from uniform pieces of cast type, but produced by means of a manual process which, like in many other cases of handicraft, was prone variations in the quality of the final product.

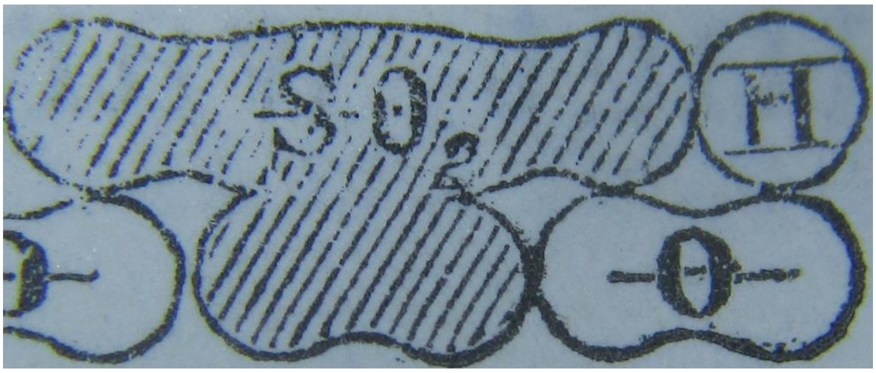


Figure 3.13: Close-up of the above formula for 'Schwefelsäurehydrat'.[79]

[76] Gaskell, *Bibliography*, pp. 268-69.
[77] Gascoigne, *How to Identify Prints*, § 51 a.
[78] Ibid, § 55.
[79] Kekulé, *Lehrbuch*, I (1861), p. 160n.

The art of wood engraving evolved from the much older technique of woodcuts, which predates the invention of printing from moveable type and was practised in Europe from at least the thirteenth century. The fundamental principles of wood engraving were gradually developed by the Newcastle-based engraver Thomas Bewick (1753-1828) during the last third of the eighteenth century. In short, wood engraving is a relief technique that involves graving away pieces of wood by means of a 'graver' or 'burin', a hand tool with a long metal shaft and a sharp cutting face at the tip, as well as other engraving tools adapted from copperplate engraving.[80] By the mid-nineteenth century, wood engraving had replaced copperplate engraving as the predominant printing method for illustrations in all kinds of printed matter,[81] and in the domain of science communication, the advancement of wood engravings had a significant impact on the appearance and, more importantly, the economics of scientific books and periodicals.[82]

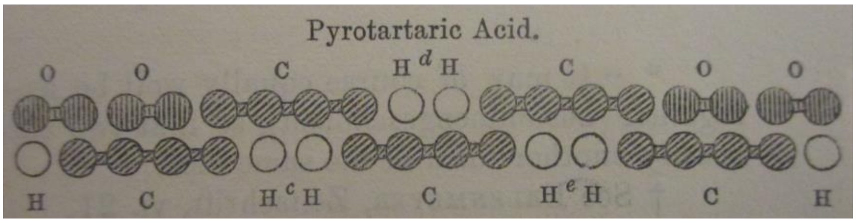
The basic process of engraving wood is described as follows. The engraver places a block of hard, close-grained wood – traditionally box wood – on a sand-filled cushion and grips the block with the left hand. Firmly holding the appropriate engraving tool in the right hand, the engraver drives the sharp tool away from the body and across the grain of the wood in order to 'dig out' those lines and spaces that are to appear white in the final print. The areas that carry the design and are to appear black in the illustration, on the other hand, are left standing so that they form the printing surfaces from which the impression is made in the printing press.[83] By using a range of engraving tools with different cutting faces, and by applying different degrees of pressure with the right hand, the engraver is able to dig out both relatively broad and very narrow spaces of wood, and to produce precise incisions of varying depth.[84] Using those tools, a well-trained and experienced engraver was capable to produce illustrations of very intricate design and small size, as can be seen from the numerous sophisticated vignettes produced by Bewick himself.[85] One of the main advantages of wood engravings over other illustrative techniques such as copperplate engravings and lithography was not only the relatively low production costs of the former, but also the fact that wood engravings could be printed together

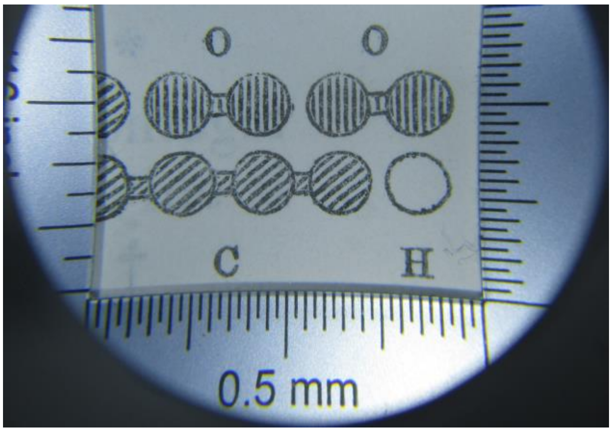
[80] Hans W. Singer and William Strang, *Etching, Engraving and the other Methods of Printing Pictures* (London: Kegan Paul, Trench, Trübner & Co, 1897), p. 10.
[81] McLean, Ruari, *Victorian Book Design and Colour Printing* (London: Faber & Faber, 1963), p. 121; and Twyman, Michael, 'The Illustration Revolution', in *The Cambridge History of the Book in Britain*, VI, pp. 117–43.
[82] Cf. Topham, 'Redrawing'.
[83] Singer and Strang, *Etching*, pp. 10-11.
[84] John Jackson distinguishes between four different kinds of wood engraving tools, which he calls 'gravers', 'tint-tools', 'gouges' or 'scoopers', and 'flat tools' or 'chisels'. These tools come in different sizes and are used by the engraver for different jobs, which can range from engraving hair-thin lines to scooping out large white spaces. Cf. Jackson, John, *A Treatise on Wood Engraving, Historical and Practical* (London: Charles Knight & Co, 1839), p. 653.
[85] See Gascoigne, *How to Identify Prints*, § 6 a. Two of Bewick's vignettes are reproduced as figs. 16 and 18 on the same page.

with type on the same page.[86] It is most likely for this reason that Ferdinand Enke, the publisher of Kekulé's *Lehrbuch*, chose wood engravings to print the sausage formulae illustrated above.

The Reproduction of Sausage Formulae by Means of Wood Engravings and Lithography

Most of the sausage formulae that we can find in printed sources date from the 1860s and were printed from engraved wood blocks. By way of illustration, the formulae appearing in Alexander Crum Brown article 'On the Theory of Isomeric Compounds', published in the *Transactions of the Royal Society of Edinburgh* in 1864 (Figures 3.14 & 3.15), exhibit clear characteristics of wood engravings.[87] Yet the fact that the original sausage formulae were printed by means of wood blocks meant that the formulae could not be reproduced as easily and quickly as representations composed from ordinary type matter, which – just like in the case of Loschmidt's diagrams – resulted in the formulae's limited circulation. Evidence from printed sources implies that other publishers and printers did not use the original wood blocks from Kekulé's *Lehrbuch*, but employed other methods to include sausage formulae in their own textbooks and journals.





Figures 3.14 & 3.15: Crum Brown's rendition of sausage formula for 'Pyrotartaric Acid' (above) and close-up (below).[88]

[86] McLean, Ruari, *Victorian Book Design*, p. 121.
[87] Crum Brown, 'Isomeric Compounds' (1864); Wurtz, *Leçons*, p. 133.
[88] Crum Brown, 'Isomeric Compounds' (1864), p. 717n.

We can observe a similar case in the formulae that were published in a French and a German periodical in 1865 and 1866. Kekulé made repeated use of his sausage formulae in a journal article on aromatic compounds published under the title 'Sur la constitution des substances aromatiques' in the *Bulletin de la Société Chimique* in 1865 (Figure 3.16). An extended version of the same article with almost identical sausage formulae (Figures 3.17 & 3.18) appeared in German in the *Annalen der Chemie und Pharmacie* in the February issue of 1866, thus making it clear that the formulae in the German periodical were reproduced from the formulae that appeared in the French journal a few months earlier.[89] Yet in both cases the formulae looked distinctively different from those that appeared in the first two volumes of Kekulé's textbook, which indicates that the *Lehrbuch* wood blocks were not used to print the formulae in the *Bulletin* and the *Annalen.* The most plausible reason for this is that the wood blocks from the textbook did not encompass formulae of the compounds that Kekulé described in the two journal articles – the old blocks simply did not relate to Kekulé's current research so that new formulae had to be produced. In the case of the *Bulletin*, this was done by means a new set of 32 wood engravings that filled the final one and a half pages of that paper.[90] The *Annalen* paper, on the other hand, was accompanied by a list of formulae on a separate lithographed plate and attached to the end of the journal issue.[91]

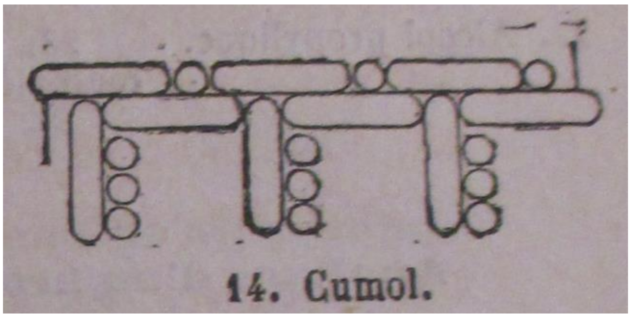
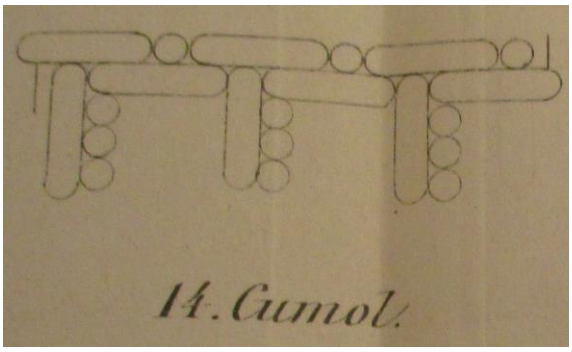
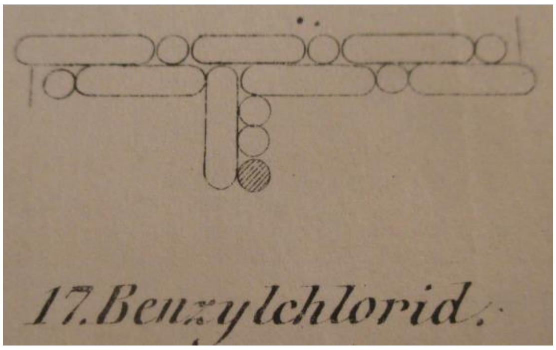


Figure 3.16: Sausage formula for 'Cumol' in *Bulletin de la chimie,* 3.1 (1865).[92]

[89] Kekulé, 'Sur la constitution'; idem, , 'Untersuchungen', Plate II. The issue of the *Annalen* was released on 8 February 1866 ('Ausgegeben den 8. Februar 1866').
[90] Kekulé, 'Sur la constitution'. The said compilation of formulae begins at the end of page 108 and ends on page 110.
[91] Idem, 'Untersuchungen'. The formulae are found on a separate plate ('Tafel II') at the end of the volume.
[92] Kekulé, 'Sur la constitution', p. 109.





Figures 3.17 & 3.18: Sausage formulae for 'Cumol' and 'Benzylchloride' in *Annalen der Chemie*, 137.2 (1865-66).[93]

Although the formulae in the *Bulletin* and the *Annalen* look almost identical, there are several minor yet noticeable differences that indicate that the formulae were printed by different means, and which are characteristic of the printing methods employed. The formulae in the French journal are without any doubt a relief print because an embossing can be seen and felt on the back of the printed pages, and because the captions underneath the formulae are composed from conventional type. We can tell by close examination that the illustrations in the *Bulletin* were produced from wood engravings because of minor disproportions similar to the ones we have already observed in Kekulé's original formulae from 1861: some of the circles of the *Bulletin* formulae are not perfectly round, and the distance between the sausages and the circles is in places inconsistent, as seen in the formulae for 'Cumol' (Figure 3.16). The formulae in the *Annalen*, by contrast, were produced by means of lithography: the single fold-out sheet with the formulae carries the inscription 'Lith. Anst. v. M. Singer, Leipzig' near its bottom right corner, which clearly indicates that the plate was made in the lithographic workshop of a certain M. Singer in Leipzig. As a result, the formulae in the German periodical display all the characteristics of a lithographic print, such as the relatively thin lines of the diagrams, the flatness of the ink, and the handwritten appearance of the captions underneath the formulae (Figures 3.17 & 3.18).[94]

There are several possible reasons why the publishers or editors of the *Annalen* chose the lithographic method over other illustrative technologies. First, the printer of the *Bulletin* might not have agreed to share the wood blocks used for the sausage formulae in the 1865 issue with the printer of the *Annalen*, or the blocks might have been damaged in the process of printing. Assuming that the blocks were not available for one reason or the other, the editors might have viewed lithographs as a fast and cost-effective alternative to commissioning a new

[93] Kekulé, 'Untersuchungen', Plate II.
[94] Cf. Gascoigne, *How to Identify Prints*, §§ 49 c, 51 c, 95.

set wood engravings. However, all of the illustrative techniques that I have just mentioned suffered from the same disadvantage, namely that the (re)production of images was a relatively slow process that could only be carried out by highly skilled craftsmen. In addition, both wood engravings and lithographs displayed specific disadvantages in relation to the task of integrating a large number of formulae together with the text: while lithography could be used to print a large number of diagrams on one plate – as we have seen in the case of Loschmidt's *Chemische Studien* – those plates had to be printed separately from the text. Wood engravings, on the other hand, could be printed together with moveable type, yet the engraving of a large number of individual wood blocks would have consumed a large amount of time and, most likely, also a considerable amount of money.

The use of illustrative technologies other than type – such as wood engravings and lithographs – posed serious problems for the production and circulation of scientific literature. Drawing on the collaboration between Roscoe and Vieweg, we will see in the next section that using lithographs and wood engravings often delayed the printing of scientific literature, which authors and publishers regarded as a serious problem for the reason that those delays could jeopardise the whole publishing endeavour. Typeset formulae, on the other hand, do not seem to have posed any difficulties to the publishing enterprise, since the composition of those formulae is not mentioned even once in the correspondence between Roscoe and his business partner Vieweg. This, I argue, demonstrates very clearly that type-based formulae, rendered by means of standard equipment, proved to be the least problematic method of printing chemical notation. I am going to do this by highlighting some of the difficulties that leading nineteenth-century scientific book publishers and journal editors from Germany and Britain encountered with regard to the reproducibility of scientific illustrations. I illustrate this by focusing on the very practical difficulties that the English publishing house Macmillan and the German scientific publisher Vieweg encountered with regard to sharing the wood blocks and lithographs used for the English and German editions of the highly successful chemistry textbooks by Henry Enfield Roscoe and Carl Schorlemmer. Focusing on the different challenges that publishers and editors of scientific texts faced when dealing with wood blocks and other illustrative techniques, I demonstrate that it was the limited availability of wood blocks and lithographs and the resulting slow production rate of images rendered by means of the said technologies that restrained the circulation of illustrations such as Loschmidt's and Kekulé's diagrams.

3.5. Publishing Chemistry across Borders: The Collaboration between Henry Enfield Roscoe and Vieweg

Preserved in the archive of the publishing house of Ferdinand Vieweg and Sons, the business letters of the English chemist, educator, and prolific textbook author Henry Enfield Roscoe offer many original and highly valuable insights into the international collaboration between a leading German and several British scientific publishers, including Walton & Maberly and, notably, Macmillan. Furthermore, the correspondence also provides valuable information on the many essential contributions that Roscoe made to the international publishing enterprises in his function as translator, author, scientific advisor, and facilitator between German and British stakeholders.[95] The foundation for the long-running and fruitful collaboration between Roscoe and Vieweg was laid in 1856, with the translation and printing of the English copyright edition of Robert Bunsen's textbook *Gasometry* that was published in Britain by the London-based company Walton & Maberly.[96] The collaboration between Vieweg, Roscoe, and Macmillan began on 7 January 1867 with Roscoe's written proposal to have the first edition of his highly popular textbook *Lessons in Elementary Chemistry*, published by Macmillan in 1866,[97] translated and adapted to the German readership by his colleague and friend Carl Schorlemmer.[98] The first edition of Schorlemmer's revised German translation appeared under the title *Kurzes Lehrbuch der Chemie nach den neuesten Ansichten der Wissenschaft* in 1867.[99] New and revised editions of the German title were released in 1868 and 1869, respectively.[100] In 1873, a new enterprise

[95] Braunschweig, Universitätsbibliothek Braunschweig, Vieweg Verlagsarchiv (VV), V1R: 101 Roscoe, Henry Enfield. The file contains a total number 74 letters by Roscoe addressed to various members of the Vieweg family as well as to Franz Varrentrapp, Vieweg's partner, associate, and scientific advisor since the late 1860s (see below). The correspondence spans the period from 29 September 1856 to 23 November 1901. The larger part of Roscoe's letters are written in English, but some are written in German. Vieweg's and Varrentrapp's response letters have, unfortunately, not survived.

[96] Bunsen, Robert W., *Gasometry: Comprising the Leading Physical and Chemical Properties of Gases*, trans. by Henry E. Roscoe (London: Walton & Maberly, 1857). The original German edition is *Gasometrische Methoden* (Braunschweig: Vieweg, 1857). The progress of this enterprise is recorded in Roscoe's letters to Vieweg from 29 September, 15 October, 30 October, 11 November, and 8 December 1856; and 7 January, 12 January, 11 February, 28 February, 16 March, 21 March, 21 April, 28 April, 5 May, and 29 June 1857 (VV, V1R: 101).

[97] Roscoe, *Lessons* (1866).

[98] 'My proposal with regard to the translation is as follows. My assistant Herr Schorlemmer will undertake the translation at the rate of 3 [L]ouis d'or per sheet of 16 pages, it being understood that it is not to be a mere translation, but a complete Edition suited to the German schools.' (Letter Roscoe to Vieweg & Son, 7 January 1867. Details of this deal between Roscoe, Schorlemmer, Vieweg, and Macmillan are discussed in the letters from 23 January and 2 February 1867 (VV, V1R: 101).

[99] Roscoe, *Kurzes Lehrbuch* (1867).

[100] Idem*, Kurzes Lehrbuch der Chemie* (1868); idem, *Kurzes Lehrbuch der Chemie*, 2nd rev. edn, 2nd print, ed. by Carl Schorlemmer (Braunschweig: Vieweg, 1869).

was set up to publish a new textbook series simultaneously in Britain and Germany.[101] The series – a multi-volume work bearing the English title *A Treatise on Chemistry* and the German title *Ausführliches Lehrbuch der Chemie* – was co-authored by Roscoe and Schorlemmer.[102] The two chemists were based in Manchester, where both worked as professors of chemistry at Owens College. The English volumes of the series were administered by Macmillan. Vieweg was in charge of publishing and marketing the German version, and Roscoe – besides being the first author – acted as advisor and mediator between the two publishing houses. In addition to writing the English books together with Roscoe, Schorlemmer was also charged with preparing the German translation. The collaboration between Roscoe and Vieweg continued until the publication of the last German volume of the said textbook series in 1902.

An important part of the collaboration was the printing of books and illustrations. Several of Roscoe's letters make it very clear that British publishers chose to work with Vieweg's company because of its high reputation not only as a scientific publisher, but also as a printer. Writing to Vieweg about the forthcoming translation of Bunsen's *Gasometry* in 1857, Roscoe stated: 'both Mr. Walton & myself are much pleased with the manner in which the sheets were finished, and the clearness of the type.' He continued in the same letter: 'I also must say that the number of typographical errors which I had to correct was less than in most books printed in England.'[103] Yet it was not only the quality of the text, but also the quality of illustration that made Vieweg a promising partner is this international joint venture. Writing to Vieweg in 1867 about the forthcoming first edition of *Kurzes Lehrbuch*, Roscoe made this explicit by stating: 'the German woodcuts (especially yours) are much better than anything we can do in England.'[104] When the printing work began on the German edition, it was agreed that Macmillan would supply Vieweg with existing 'electrotypes' – metal casts of cut or engraved wood blocks produced by means of electroplating – of the illustrations that had been already used in the English edition.[105] Yet it was also agreed that additional illustrations, to be prepared by Vieweg,

[101] 'I [have] told Mr. Schorlemmer that we will write a book (Inorganic & Organic) to be published in our joint names simultaneously in England & Germany.' (VV, V1R: 101, letter Roscoe to Varrentrapp, 26 March 1873.)

[102] Roscoe and Schorlemmer, *A Treatise on Chemistry*, 3 vols (London: Macmillan, 1877-92). Some volumes of this series underwent more editions and reprints than others. By way of illustration, the first edition of the first volume on non-metallic elements appeared in 1877 and was reprinted in 1878. It was again reprinted with alterations in 1881 and with slight corrections in 1884. After that, it was reprinted with many alterations in 1888 and again in 1892. More detailed information on all three volumes available at <https://wellcomelibrary.org/item/b28122409> [accessed 19 September 2018]. The German title of the series is *Ausführliches Lehrbuch der Chemie*, 9 vols (Braunschweig: Vieweg, 1877-1901). After Schorlemmer's death in 1892 Vieweg commissioned a number of other German chemists to continue the series.

[103] Letter Roscoe to Vieweg, 29 June 1857 (VV, V1R: 101).

[104] Letter Roscoe to Vieweg, 2 February 1867 (VV, V1R: 101).

[105] Cf. Lorck, 'Etwas über die Holzschneidekunst', *Die Gartenlaube*, 30 (1882), 688-91, 704-06.

should be included in the German edition of the *Lessons*.[106] These additional wood engravings were, in turn, converted into electrotypes and shipped to Macmillan, where they were used to adorn the revised editions of the *Lessons* published in 1869.[107]

In addition, Roscoe made frequent requests on behalf of Macmillan to reuse existing clichés which had been produced by Vieweg for other book titles.[108] Thereafter clichés of wood engravings from Viewegs xylographic workshop were shipped to Macmillan on a regular basis and subsequently used for all illustrations that appeared in the English as well as German editions of Roscoe's and Schorlemmer's textbooks. The regular exchange of electrotypes – as well as the occasional lithographic plates – thus lasted from 1867 to at least 1892, when the final English volume of the Roscoe-Schorlemmer series *A Treatise in Chemistry* was published by Macmillan in London.[109] However, the arrangement to share and exchange illustrations over a long distance and across international borders also had severe negative consequences for the publishing enterprise. The following extracts from the correspondence between Roscoe and Vieweg demonstrate some of the difficulties which the joint publishing enterprise faced during the 1870s and 1880s, many of which resulted from very practical problems such as the slow production and problematic exchange of the original wood blocks as well as electrotype clichés used in the anglophone and the germanophone versions of the textbooks.

A Lasting Source of Concern: the Problematic Exchange of Wood Blocks, Electrotypes, and Lithographic Plates

Above all, the letters to Vieweg illustrate that it was notably the frequent delays in the production and exchange of engraved wood blocks, electrotyped clichés, chromolithographs,

[106] Letter Roscoe to Vieweg, 7 January 1867 (VV, V1R: 101). Roscoe's terminology is confusing. In his letters to Vieweg, Roscoe uses the term 'woodcuts', although there can be little doubt that he meant wood engravings. This assumption is further supported by the fact that the copyright pages of the German editions explicitly mention 'Holzstiche' (wood engravings). Further adding to the confusion, Roscoe uses the terms 'cliché' and 'electrotypes' interchangeably when referring to copies of the woodcuts discussed in the correspondence.
[107] Roscoe, *Lessons*, 2nd edn (London: Macmillan, 1869).
[108] This also strongly suggests that Vieweg's printing section had built up a large archive of electrotype clichés over the years.
[109] The continuous exchange of clichés between Vieweg and Mcmillan was again discussed in Roscoe's letter from 26 March 1870. This arrangemend was renewed for the simultaneous publication of the *Treatise* and its German edition *Ausführliches Lehrbuch*, as discussed in Roscoe's letters to Vieweg from 4 March 1873 and 6 October 1874 (VV, V1R: 101).

and also photographic plates[110] that constituted a steady source of concern to Roscoe and his London-based publisher Macmillan. Some of these concerns are illustrated in Roscoe's letter to Vieweg from 26 March 1870, in which illustrations for the second English editions of his *Lessons*, as well as the second edition of the *Kurzes Lehrbuch* are discussed in detail. The tone of Roscoe's letter clearly reflects his annoyance with the problematic exchange of the equipment, and demonstrates how crucial the timely production of illustrations was to the publishing enterprise as a whole:

> I shall be much obliged if you would inform me by return of post how soon you will be able to forward the clichés platen from Schellen? I am very anxious that as little delay as possible should occur as my second English Edition is now waiting for these clichés. You will understand […] that I do not require the tinted picture from Zöllners [sic] paper. The Chromo: [sic] for the German Edition were sent off to you by Mr. Macmillans [sic] printer yesterday, so I hope you will get them in a day or two. Again begging you to forward the Electros: [sic] of the 3 Figs from Schellen as early as possible […].[111]

The above quotation also makes it evident that it was not the shipping of blocks, clichés, and plates that caused the delays, but Vieweg's inability to produce those items on time. More evidence for this slow production rate and the resulting long waiting period is found in one of Roscoe's letters from 8 June 1880, where the chemist complained that Macmillan 'had to wait 2 or 3 months for the clichés in the first 3 or 4 sheets [...].'[112] Similar concerns were voiced in many more of Roscoe's surviving letters in the archive of the Vieweg publishing house. By way of illustration, problems with the production and exchange of wood blocks, electrotypes, and chromolithographic and photographic plates – often together with Roscoe's and Schorlemmer's concerns about missing illustrations – were discussed in Roscoe's letters of 26 March and 25 June 1870; 4 March and 26 June 1873; 6 October 1874; 1 April, 6 October, and 14 October 1875; 24 January 1877; 24 April and 11 August 1879; 8 June and 4 November 1880; and 3 October 1886.

The poor availability of those crucial items, caused by the slow production rate typical of those illustrative technologies, posed a serious problem to the publishing enterprise as a whole and must therefore not be underestimated. In his letter to Vieweg from 6 October 1875,

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[110] The process of chromolithography was developed in the late 1830s by Engelmann in France and Hullmandel in England. The technique made it possible to print illustrations in full colour and remained in frequent use until the end of the nineteenth century. Cf. Gaskell, *Bibliography*, p. 268.
[111] VV, V1R: 101, letter Roscoe to Vieweg, 26 March 1870. Emphasis in original.
[112] VV, V1R: 101, letter Roscoe to Vieweg, 8 June 1880.

Roscoe complained that the printing of the new edition of the *Lessons in Elementary Chemistry* has been delayed over the summer because 'the English Edition' was 'waiting for the woodcuts.'[113] The same concern was repeated in Roscoe's letter of 24 January 1877, where the chemist explained that the printing of the forthcoming first volume of the *Treatise* previously came to a standstill because of the missing clichés. Roscoe wrote in this letter that the English printers were 'now waiting for more clichés for Roscoe & Schorlemmers Chemistry', adding that he would 'be obliged' by Vieweg 'sending a fresh lot to Messr [sic] Macmillan & Co as soon as possible.'[114] It seems that either Roscoe or his publisher Macmillan had anticipated or even experienced similar delays before, since unlike the *Lessons* – which continued to be printed in Braunschweig – the *Treatise* series was typeset and printed by the local printing firm Richard Clay, Sons, and Taylor in London.[115]

In addition, the quality of the illustrations was not guaranteed and could be left wanting. In cases where the quality of the clichés proved to be unsatisfactory to the eyes of Roscoe and his English publishers, the chemist decided to have the wood blocks reproduced on location in London rather than endure another delay by Vieweg. Roscoe writes to Vieweg on 11 August 1879: 'I am going to have figs. 195 & 196 for the second vol. of Roscoe-Schorlemmer, which I have just received from you, re-cut in England in order to save time.'[116] All this demonstrates that the use of illustrations produced by wood engraving and other means always consumed a considerable amount of time and effort – not only because of the slow production rate of those illustrations, but also because the images sometimes underwent the additional process of alteration and adaptation to the specific aesthetics of the book.[117]

Typography, on the other hand, is not mentioned at any point in the Roscoe-Vieweg correspondence. This, I argue, strongly implies that there were no issues with the composition of Roscoe's and Schorlemmer's chemical textbooks, which, after all, contained large numbers of empirical and different rational formulae, and featured line-and-letter formulae from a very

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[113] VV, V1R: 101, letter Roscoe to Vieweg, 6 October 1875. Although not specified, it is most likely that Roscoe's letter refers to the following edition: Roscoe, *Lessons in Elementary Chemistry: Inorganic and Organic*, new edn (London: Macmillan, 1875).
[114] VV, V1R: 101, letter Roscoe to Vieweg, 24 January 1877.
[115] See end matter of Roscoe, *Treatise* (1877) and verso of the title page in subsequent editions.
[116] 'Die von Ihnen soeben erhaltene [sic] Fig 195.196 Zweite [sic] Bd. Roscoe-Schorlemmer werde ich, um Zeit zu ersparen, gleich in England neu schneiden lassen.' (VV, V1R: 101, letter Roscoe to Vieweg, 11 August 1879.)
[117] In a letter addressed to Franz Varrentrapp (1815-77), Vieweg's partner, associate, and scientific advisor since the late 1860s, Roscoe states that although 'the production of a facsimile of the original drawings [...] of the Dumas' & Lavoisier's apparatus [...] would be of historical interest', Vieweg is allowed to 'make them more nearly resemble the other woodcuts' in the book if this makes sense from the printer's 'aesthetic point of view'. (VV, V1R: 101, letter Roscoe to Varrentrapp, 14 October 1875.) On Varrentrapp, see Pingel, Norman-Mathias, 'Varrentrapp, Franz', in *Braunschweiger Stadtlexikon – Ergänzungsband*, ed. by Luitgard Camerer and Manfred R. W. Garzmann (Braunschweig: Meyer, 1996), p. 133.

early stage. The first line-and-letter formulae appeared in small numbers in the 1867 and 1868 editions of *Elementary Lessons in Chemistry* and *Kurzes Lehrbuch der Chemie*, respectively. Line-and-letter formulae were ubiquitous in the second volume of the *Kurzes Lehrbuch,* which was authored by Schorlemmer and published in 1871.[118] Concerned with organic chemistry, this book was among the first German textbooks to make systematic and extensive use of line-and-letter formulae. Large numbers of line-and-letter formulae also appeared in each of the volumes of *Treatise on Chemistry* (1877-92) and *Ausführliches Lehrbuch der Chemie* (1877-1901). Yet despite the dominating presence of type-based formulae in the books of the Roscoe-Schorlemmer franchise, the printing of those formulae seem to have been so natural to Vieweg that it was not even worth mentioning in the correspondence with Roscoe.

The Roscoe-Vieweg case study thus demonstrates that the (re)production of images by means of wood engraving and lithography entailed many practical problems that were typical of the corresponding printing technologies, and which impeded the timely circulation of illustrations produced by those technologies, especially if images were exchanged across international borders. Typography and composition, on the other hand, were not among the problems that Roscoe discussed with his German business partner Vieweg. Above all, we have seen in the Roscoe-Vieweg case study that the relatively slow exchange of engraved and lithographed images had the potential of seriously delaying the printing and release of a book, which naturally entailed a huge financial risk to all stakeholders of that publishing enterprise. There can be no doubt that the practical problems discussed above were not unique to Roscoe's and Vieweg's case, but applied to many other joint ventures in scientific publishing, and especially to those cases that involved a close (international) collaboration between authors, editors, publishers, and printers. It is therefore very likely that the circulation of Kekulé's sausage formulae by means of chemical periodicals in 1865 and 1866 presented the editors and publishers of the *Bulletin* and the *Annalen* with very similar problems with regard to the printing of those formulae. We need to keep in mind that delays in printing posed an even bigger problem to periodicals than to scientific textbooks, because the success of periodicals depended heavily on timely publication, as I will explain in Chapter 5. Yet by relating what we have learned about chemical composition to the Roscoe-Vieweg case study, we can clearly see that the same problems did not arise with type-based formulae because the latter could be set in every printing workshop by means of standard typographic equipment. Put another way, chemical diagrams produced by means of such illustrative technologies as wood engraving and lithography posed

[118] Schorlemmer, *Kurzes Lehrbuch der Chemie nach den neuesten Ansichten der Wissenschaft. Von H. E. Roscoe. Deutsche Ausgabe, unter Mitwirkung des Verfassers bearbeitet von Carl Schorlemmer*, 3rd rev. edn (Braunschweig: Vieweg, 1871).

serious risks to the publishing enterprise – risks that could be avoided if diagrams were rendered by means of standard typographical equipment.

3.6. Conclusion

This chapter has demonstrated that the use of moveable type proved to be the deciding factor for the long-term success of line-and-letter for the reason that skilled printers everywhere in Europe were able to (re)produce the formulae with their own equipment on site. Through the comparison between mathematical and chemical typesetting, we were able to see that printing houses specialising in mathematical print were also capable of producing chemical literature with the new structural notation because the skills and the equipment required for mathematical typesetting could also be applied to the printing of the novel chemical formulae.

Yet the close analysis of the practices of typesetting mathematical and chemical formalisms has also made it clear that the composition of mathematical and chemical formalisms was indeed a task that required a high level of practical know-how and expertise on behalf of the composer – or, to use the words of the twentieth-century typographer James Roderer, '[t]o the expert, the formula is […] like a crystal which emerges unpolished from unskilled hands, but cut and smoothed from the skilled ones.'[119] However, through the comparison between chemical formulae printed from moveable type and illustrations originally printed by means of wood engraving and lithography, we have seen how difficult and time-consuming it was to print and circulate Kekulé's and Loschmidt's diagrams. Most importantly, the Roscoe-Vieweg case study has demonstrated that the use of illustrative technologies such as wood engraving and lithography posed serious risks to the publishing enterprise – risks that could be avoided if diagrams were rendered on location by means of standard typographical equipment.

In addition, typeset formulae offered clear economic advantages in scientific publishing, especially with regards to periodical literature. The fact that line-and-letter formulae could be produced relatively quickly and with little risks of delays proved to be a major advantage to the scientific journals, whose economic success depended on timely publication. The use of line-and-letter formulae thus provided the economic advantage that was needed in a competitive market environment, and which could not be provided by any other form of printing technology. And, in fact, the relative ease with which early line-and-letter formulae were (re)produced by

[119] Roderer, *Satz*, p. 10.

different printing workshops is reflected in the number of printers engaged in printing the new chemical notation at the end of the 1860s. By way of illustration, during the period 1864-68, there were at least twelve printing houses in Britain, France, and Germany that were printing textbooks and journals containing a large number of line-and-letter formulae.[120] This number further increased during the following decade.

Furthermore, there can be little doubt that another important advantage of typeset line-and-letter formulae was the high degree of flexibility and versatility of this notation, to be understood in iconographical, epistemic, and economic terms: the visual appearance of type-based notations such as line-and-letter formulae could be altered with very little effort by adding further basic typographical elements. It was only through this versatile iconography that chemists were able to use the formulae as paper tools for different research and teaching purposes, not only in handwritten notes, but also in their print communications, thereby further developing the epistemic functions of the formulae by applying the notation to the rising number of novel research problems in organic chemistry.

This chapter has thus made it very clear that the use of moveable type technology facilitated the circulation of line-and-letter across different markets and international borders and thereby contributed to the long term success of the formulae as the new notation in organic chemistry. Yet we will see in the subsequent two chapters that this was by no means a guarantee of the rapid dispersion of the new notation, since the availability of scientific print was contingent on highly specific factors such as local institutional arrangements, or the size and dynamics of the given marketplace.

[120] In addition to the aforementioned companies of Taylor & Francis, Harrison & Sons, Vieweg & Sons, Wilhelm Keller, A. W. Schade, Fischer & Wittig, J. B. Hischfeld, and Erdmann Polz, a number of other printing houses produced literature that featured line-and-letter formulae in smaller numbers. The Paris-based printing company Imprimerie de Gauthier-Villars was in charge of the *Annales de Chimie* and the Edinburgh-based printers Neill & Co. were in charge of the *Transactions of the Royal Society of Edinburgh*. Heinrich Ludwig Buff's textbook *Grundlehren der theoretischen Chemie* (Erlangen: Ferdinand Enke, 1866) was printed in Erlangen by C. H. Kunstmann and his second textbook *Kurzes Lehrbuch der anorganischen Chemie* (Erlangen: Ferdinand Enke, 1868) by Universitäts-Buchdruckerei von Junge & Sohn, also in Erlangen.

PART II

Circulation and Appropriation

We have seen in the first part of this thesis that practical and economic aspects of print communication played a major role in shaping the distinct iconography of line-and-letter formulae. As I have demonstrated in the previous chapter, print technology and the print market played a major role in the inception of the new diagrams. Being based entirely on typeset symbols was one of the necessary conditions for the diagrams' lasting success because line-and-letter formulae could be (re)produced faster and with less effort than representations rendered by means of other illustration techniques. This facilitated the circulation and gradual appropriation of the formulae as more and more line-and-letter formulae began to appear on the pages of textbooks and chemical journals during the 1860s and 1870s. Yet we still lack a clear and detailed understanding of the mechanisms and patterns of the circulation and appropriation of the new line-and-letter formulae during that period. The second part of my thesis addresses this shortcoming through a critical comparison of the different ways in which line-and-letter formulae were circulated and received in Britain and Germany.

Although educators in both countries began to use line-and-letter formulae in their lectures and science classes in the 1860s, so that a relatively large number of chemistry students were exposed to the new notation, the communication processes through which the formulae were conveyed and received in Britain and Germany followed different pathways. This is reflected by the diverging patterns of distribution of the new diagrams in different kinds of print media. Whereas a relatively large number of new textbooks with line-and-letter diagrams were available on the British print market in the late 1860s, British authors remained much more reluctant to use the diagrams in specialist periodicals such as the *Journal of the Chemical Society* well into the mid-1870s. In Germany, on the other hand, only four textbook titles with line-and-letter formulae were published during the 1860s, whereas the number of German research articles that contained the notation and that appeared in German periodicals rose sharply during the late 1860s. The difference between the number of line-and-letter formulae that appeared in English and German textbooks and periodicals indicates that there were two different groups of diagram users, and that the diagrams were communicated to those groups of users in different ways.

In the second part of my thesis, I claim that although line-and-letter formulae were included in British and German chemistry curricula from the mid-1860s onwards, British and German students constituted two different groups of diagram users because they appropriated the formulae for different purposes. I argue that the majority of British students who attended lectures at the Royal College of Chemistry (RCC) and, notably, science classes under the Department of Science and Art (DSA) were introduced to line-and-letter diagrams as learning aids with the primary function to facilitate understanding of the new concepts of valence and chemical structure. In the present chapter, we shall see that due to this centralised and highly formalised education scheme, British students adopted the formulae as problem-solving tools to rehearse and answer exam questions. The German territories, on the other hand, did not have a national science curriculum due to the pluricentric structure of the German Confederation and the German Empire so that university students encountered the notation in the localised context of the chemical institute where they were enrolled. Those institutes were not only teaching institutions, but also locations of original research. At those establishments, the curriculum was shaped by the individual research agenda of the institute's director, and students were equipped with the necessary research methods at an early stage of their university training. It was due to this model of research-based training that chemistry students at German universities learned and embraced the new line-and-letter diagrams as research tools that allowed them to navigate and understand the most recent challenges and results of research in organic chemistry, as I explain in the next chapter. Consequently, the learning experience of British and German students showed considerable differences. It is thus only through the comparison between the teaching and learning practices, as well as available learning resources such as textbooks, that we can achieve a historically accurate understanding of how and where British and German student audiences had encountered the new structural notation.

CHAPTER 4

Teaching, Tests, and Textbooks: The Systematic Dispersion of Line-and-Letter Formulae in Britain

The fourth chapter is concerned with the communication practices that drove the proliferation of the new diagrams in Britain. As I have mentioned before, British specialist journals featured only a very small number of line-and-letter formulae well into the mid-1870s. This can be explained in part by the 'atomic scepticism' prevalent among Britain's university-trained chemists over the course of the late 1850s and 1860s that prompted resistance to both the structure theory and visual representations of hypothetical entities such as atoms and molecules. From the late 1850s onwards, the opposition to atomistic thinking was led by Benjamin C. Brodie (1817-80), a prominent professor of chemistry at Oxford and member of the Chemical Society, being its Secretary from 1850 to 1854, and its president in 1860. Rejecting every aspect of the atomic theory of that time due to its hypothetical character, Brodie suggested the abandonment of the idea of atoms altogether in favour of his own theory, the 'Calculus of Chemical Operations'.[1] Brodie had also mounted an exceptionally strong attack on Crum Brown's and Frankland's visual notation in 1867, claiming that those symbols clearly indicated

> that the science must have got, somehow or another, upon a wrong track; that the science of chemistry must have got, in its modes of representation, altogether off the rules of philosophy, for it really could only be a long series of errors and of misconceptions which could have landed us in such a bathos as this.[2]

Brodie's strong resistance against any form of atomism and its representations was not long-lived and gradually died down after he was defeated in a major debate between himself, Frankland, Alexander William Williamson, John Tyndall, and James Clerk Maxwell in 1869.[3] However, the historian Colin A. Russell claims that a certain attitude of doubt remained among

[1] Rocke, *Chemical Atomism*, p. 313.
[2] Brodie, Benjamin C., 'On the Mode of Representation Afforded by the Chemical Calculus, as Contrasted with the Atomic Theory', *Chemical News*, 15 (14 June 1867), 295-305 (p. 296). Stephen T. Irish has recently suggested that the main purpose of Brodie's Calculus was to justify a new theory of chemical elements. See Irish, 'Brodie's Calculus and Chemical Classification', *Ambix*, 60.3 (2013), 234-54.
[3] Brock, *Fontana History*, p. 170.

the members of the British chemical community throughout the 1870s and has to some degree delayed the acceptance and appropriation of line-and-letter diagrams among professional chemists.[4] And, indeed, primary sources indicate that only a very small number of the most dedicated and outspoken proponents of the structure theory – namely Frankland, Schorlemmer, Baldwin F. Duppa, and Ernest T. Chapman and William Thorp – dared to publish articles with line-and-letter formulae in British research journals during that period (see Appendix).[5]

This theoretical bias, however, had no effect on the proliferation and use of line-and-letter formulae in the context of chemical education, since critics of the new notation could be kept at bay if textbook authors made it clear that the diagrams were introduced as heuristic instruments only and were not meant to be understood as representations of atoms as actual physical entities in the microworld.[6] As we shall see further below, no less than nine textbooks with various numbers of the new diagrams had appeared on the British market by 1869. Based on the observation that the new notation proved very successful with literature intended for didactic use, Russell claims that the proliferation of line-and-letter formulae in Britain occurred not in the 'world of chemical research', but primarily in the 'world chemical education'.[7] In his foundational biography of Edward Frankland, Russell argues that the successful communication of line-and-letter formulae was the direct result of Frankland's 'concerted campaign' to improve chemical education in Britain by establishing an integrated teaching scheme which was made up of several parts. These parts included chemistry lectures at the RCC and the Royal Institution (RI), the production of a supplementary textbook – the famous *Lecture Notes* (1866, 1870-72) – and the implementation of a modernised syllabus for chemistry classes and exams under the DSA's national science education scheme. According to Russell's account, Frankland single-handedly changed the entire curriculum of chemical education by making theoretical knowledge of valence and structure as well as familiarity with line-and-letter formulae the necessary requirements to pass his DSA exams.[8] By providing this model of Frankland's education scheme, Russell made a very important and much-needed contribution to our understanding of the communication and institutionalisation of modern chemistry in Victorian Britain. Yet upon closer

[4] Russell, *Frankland*, p. 286.
[5] The Appendix is a near-complete compilation of original research articles with line-and-letter formulae that appeared in major British, French, and German specialist journals between 1864 and 1868. The compilation records research articles published in *Berichte der Deutschen Chemischen Gesellschaft*, *Annalen der Chemie*, *Zeitschrift für Chemie*, *Journal für praktische Chemie*, *Transactions of the Royal Society of Edinburg*, *Journal of the Chemical Society*, *Philosophical Transactions* and *Proceedings of the Royal Society*, *Annales de Chimie*, and *Bulletin de la Société Chimique*. The compilation excludes line-and-letter diagrams that appeared in abstracts.
[6] Russell, *Frankland*, p. 285; Ramberg, *Chemical Structure*, p. 332; and Ritter, 'Early History', p. 43.
[7] Russell, *Frankland*, p. 286.
[8] Ibid, pp. 288-98.

examination it becomes apparent that Russell's account suffers from two major historiographical shortcomings.

First, the account conveys very little information about Frankland's didactic approach to the teaching of line-and-letter formulae because it does not explain in detail how chemistry students learned to use the new notation. Secondly, Russell's account does not make it clear which role Frankland's *Lecture Notes* and other textbooks played in that learning process. In this chapter, I build on Russell's study as well as a number of historical sources to develop a historically more accurate account of how line-and-letter formulae were circulated and appropriated in Britain. I claim that Frankland attached as much significance and value to paper-based learning practices – especially writing exercises – as he did to practical training in the laboratory, and that RCC students as well as those attending DSA classes were required to learn how to wield line-and-letter formulae from the very beginning of their studies. I demonstrate that British students were introduced to line-and-letter formulae as a learning aids to facilitate the correct understanding of the new concepts of valence and structure, and that the students had to master the formulae if they wanted to succeed in the DSA exams which were set by Frankland himself. By illustrating that the new formulae had formed an integral part of how students engaged with chemistry in the class room and at home, the chapter also demonstrates that the commercial success of the *Lecture Notes* and comparable textbooks was only possible because the books figured as a highly valuable learning resource in Frankland's education scheme. Consequently, it was the amalgamation of writing and reading practices within Frankland's integrated education scheme that ultimately led to the dissemination and appropriation of the new formulae in Britain.

The first section is concerned with the structure of Frankland's education scheme. The section pursues two objectives. First, the section explains the didactic benefits that led Frankland to make line-and-letter a crucial element in his approach to chemistry teaching. When Frankland succeeded August Wilhelm Hofmann as the RCC's director in 1865, he did not only modernise the syllabus by introducing the concepts of valence and structure, but also began to make extensive use of line-and-letter formulae in his lectures. It was therefore in the context of teaching at the RCC where the diagrams made their debut. Secondly, the section explains how Frankland used his central position and influence as 'Professional Examiner' to the DSA – an office which he held since 1868 – to create a teaching scheme that allowed him to propagate line-and-letter formulae to a much larger student audience. In this section, I provide an outline of the administrative structure and functions of the Department, and explain its unique features which led to the gradual implementation of science education in Britain through the training of science teachers and the system of nationwide public examinations. I argue that it was not in the context of Frankland's teaching at the RCC, but rather through popular education that the new line-and-letter formulae were rapidly appropriated by a large number of vocational students during the late 1860s and early 1870s.

The second section explains how Frankland made sure that line-and-letter formulae were used in chemistry classes throughout the country. The section describes the main parts of Frankland's pedagogical agenda, which consisted of a new DSA chemistry syllabus that introduced Frankland's 'graphic formulae' at the elementary level; classes delivered by qualified teachers trained by Frankland in South Kensington; recommended textbooks for the preparation of DSA classes and exams; and examination papers that regularly featured questions on the new formulae. By analysing Frankland's approach to teaching in great historical detail, the section demonstrates that writing and reading practices were at the very core of Frankland's pedagogical agenda of popular education, and that it was Frankland's particular paper-based approach to teaching and learning chemistry that drove the dissemination and appropriation of the new formulae in Britain. By providing this account, the section also explains how the DSA system contributed to the rapid expansion of the market for textbooks with line-and-letter formulae so that at least nine different titles with the new notation had appeared in Britain by 1869.

The third section explores the impact of Frankland's pedagogical agenda on the British population by investigating how the British public responded to line-and-letter diagrams during the 1870s. The section demonstrates that line-and-letter formulae were often mentioned and debated in popular science magazines such as the *English Mechanic*, where discussions often referred to educational literature as well as Frankland's DSA syllabus and exam papers. I argue that, although a very large number of DSA students learned how to read and apply line-and-letter formulae to formalised problems as part of their elementary training in chemistry, those students regarded the formulae as nothing else than learning tools that facilitated engagement with Frankland's revised syllabus. In doing so, I not only demonstrate that there was a strong public interest in recent developments in the field of chemistry, but also that mass education of the sort developed in the DSA and popular science magazines were much more pertinent to the circulation and appropriation of the new formulae than specialist periodicals, which by the early 1870s were still conspicuously devoid of the new notation.

4.1. Teaching Chemistry to the Nation: Chemical Education in Victorian Britain

The first section is concerned with the structure of Edward Frankland's unique education scheme through which line-and-letter formulae were communicated to a large number of chemistry students in the late 1860s and early 1870s. Frankland was one of the most successful and influential chemistry educators in Victorian Britain. Over the course of his long career, Frankland had been teaching chemistry at some of the most prestigious institutions in the country, including St Bartholomew Hospital (1857-64) and the Royal Institution in London (1861-68). From 1865 to 1885, Frankland was lecturing on all areas of chemistry at the Royal College of Chemistry. From 1868 to 1880, Frankland also served as examiner in chemistry to the Department of Science and Art, which had organised science classes since 1853. As examiner to the Department, Frankland changed the existing syllabus by placing line-and-letter formulae at the very centre of his pedagogical agenda. The first part of this section explains the historical development of British chemical education during the second half of the nineteenth century. The second part of the section analyses Frankland's teaching practices with the purpose to explain the didactic benefits that led Frankland to make line-and-letter a crucial element of his pedagogical agenda.

Giessen to London and Beyond: Chemistry Education and the Department of Science and Art in Nineteenth-Century Britain

The development of chemical education in Britain was highly influenced by processes of institutionalisation and professionalization that had taken place in German chemistry during the first half of the nineteenth century.[9] The period between the 1830s and the 1860s witnessed the institutionalisation of chemical research at German universities in the form of chemical

[9] Key texts on the history of chemical education in Britain include Knight, David, 'Chemistry on an Offshore Island: Britain, 1789-1840', and Roberts, Gerrylynn K., '"A Plea for Pure Science": The Ascendancy of Academia in the Making of the English Chemist, 1841-1914', in *The Making of the Chemist: The Social History of Chemistry in Europe, 1789-1914*, ed. by David Knight and Helge Kragh (Cambridge: Cambridge University Press, 1998), pp. 95-106, 107-19; Bud, Robert F., and Roberts, *Science versus Practice: Chemistry in Victorian Britain* (Manchester: Manchester University Press, 1984); Byrne, Michael S., 'The Development of the Teaching of Chemistry in England, 1799-1853 (unpublished master's thesis, University of Durham, 1968); and Donnelly, James Francis, 'Chemical Education and the Chemical Industry in England from the Mid-Nineteenth to the Early Twentieth Century' (unpublished doctoral thesis, University of Leeds, 1987). For a concise overview of the development of science education in England and Wales between 1800 and 1851, see Timmons, George, 'Science and Education in the First Half of the Nineteenth Century', *Endeavour*, 20.4 (1996), 140-43.

institutes that were modelled on Liebig's famous research school in Giessen.[10] As I have mentioned in Chapter 2, these chemical institutes followed a pedagogical agenda which combined lectures and practical training in the laboratory with research work that was offered to advanced students. The basic idea was that students acquired practical research methods during their elementary studies before moving on to the more advanced stages of the curriculum. As a result, all students who trained at one of the German institutes received systematic training in practical research methods which they then could apply in their future jobs inside and outside of the academic context. According to Catherine M. Jackson, the German chemical institutes were among the very first scientific institutions where teaching and research did not constitute two alternative goals, but were in fact 'necessarily complementary activities'.[11] The productivity of the German chemical institutes was reflected in the large number of analyses carried out in those institutions as well as the large number of German and international students who received their training from those places.[12]

Compared to the situation in Germany during the first half on the nineteenth century, British provision for practical training in chemistry were very limited.[13] Yet at the same time, the demand for instruction in practical chemistry was growing. On the one hand, English medical curricula underwent profound revisions in the 1830s and 1840s and henceforth required laboratory instructions in analytical chemistry for all students who wished to graduate as general practitioners or apothecaries from one of the official degree-granting institutions in London.[14] On the other hand, training in applied science and, notably, practical chemistry was sought after by manufacturers, engineers, agriculturalists, and representatives of other professions.[15] British students as well as artisans therefore often chose to obtain the necessary skills from Liebig's institute in Giessen and, upon returning home, actively contributed to the growing sense of German superiority in the areas of chemical education and research.[16] For academic researchers, the time spent at Liebig's institute often proved to be a major asset in their career, since, according to Jack Morrell, 'by the 1850s the Liebig clan had assumed most of the "plums"

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[10] Cf. Johnson, 'Academic Chemistry'.
[11] Jackson, 'Re-Examining the Research School: August Wilhelm Hofmann and the Re-Creation of a Liebigian Research School in London', *History of Science*, 44 (2006), 1–39 (p. 10).
[12] By way of illustration, Liebig's Giessen institute was capable to churn out 400 analyses per year. Cf. Brock, *Justus von Liebig: The Chemical Gatekeeper* (Cambridge: Cambridge University Press, 1997), p. 48.
[13] For an overview of English chemistry teaching institutions before 1850, see Byrne, 'Development'.
[14] Cf. Roberts, 'The Establishment of the Royal College of Chemistry: An Investigation of the Social Context of Early Victorian Chemistry', *Historical Studies in the Physical Sciences*, 7 (1976), 437-85 (pp. 440-50).
[15] Ibid, pp. 457-60.
[16] Jackson, 'Research School', p. 15. For a survey of Liebig's students, see Fruton, *Contrasts in Scientific Style: Research Groups in the Chemical and Biochemical Sciences* (Philadelphia, PA: American Philosophical Society, 1990), Appendix 1. For a list of Liebig's British students, see Brock, *Liebig*, Appendix 2.

available in English university chemistry.'[17] Driven partly by the domestic demands for practical training, partly by the perceived German superiority in all areas of chemistry, and partly by personal ambitions, the chemist and druggist John Lloyd Bullock (1814-1906) and the apothecary and medical man John Gardener (1804-80) started a campaign for the establishment of a practical chemistry college on British soil in 1843. After gaining political and financial support from a wide range of practically-minded benefactors, the Royal College of Chemistry opened for business in October 1845.[18]

Headed by Liebig's stellar student August Wilhelm Hofmann from 1845 to 1865, the College was initially intended to replicate Liebig's training system in Britain, but very soon developed into an institution that catered to the specific demands of British students.[19] Originally conceived as a private institution, however, the College had never been able to create enough revenue to sustain itself. In 1853, the Department of Science and Art purchased the struggling RCC from its shareholders and merged the College with the Government School of Mines (f. 1851).[20] The DSA was set up by the British government in 1853 as a central body to promote and coordinate popular scientific education in the whole of Britain after a series of public debates, staged during and after the Great Exhibition in 1851, had established a strong public demand for better teaching provision as a means to keep up with the development of state-sponsored establishments for scientific education in France and Germany. The main purpose of the Department was to encourage the establishment of science and technology ('Art') classes for working adults across the nation. After 1858, this was done through a network of evening classes for working adults at local schools throughout the country. These classes were led by science teachers who were paid by results, whereby teachers received a set amount of money for each student who was able to pass the DSA's formal written exams. In addition, from 1859 onward teachers were given the opportunity to become accredited DSA Science Teachers

[17] Morrell, Jack B., 'The Chemist Breeders: The Research Schools of Liebig and Thomas Thomson', *Ambix*, 19.1 (1972), 1–46 (p. 19).
[18] For details concerning the various groups of shareholders who supported the project, see Roberts, 'The Royal College of Chemistry (1845-1853): A Social History of Chemistry in Early-Victorian England' (unpublished doctoral thesis, Johns Hopkins University, 1973), ch. 4. The institution did not carry the designation 'Royal College' until a month after its opening (ibid, p. 1). Besides Roberts' dissertation, seminal literature on the history of the RCC and its successor includes Bentley, Jonathan, 'The Chemical Department of The Royal School of Mines: Its Origins and Development under A. W. Hofmann', *Ambix*, 17.3 (1970), 153-81; Gay, Hannah, '''Pillars of the College': Assistants at The Royal College of Chemistry, 1846–1871', *Ambix*, 47.3 (2000), 135-69; idem, *The History of Imperial College London, 1907-2007: Higher Education and Research in Science, Technology and Medicine* (London: World Scientific, 2007); and Gay and William P. Griffith, *The Chemistry Department at Imperial College London* (London: World Scientific, 2017).
[19] Roberts, '"Plea"', p. 108.
[20] Between 1853 and 1857, the merged institution operated under the name Metropolitan School of Science Applied to Mining and the Arts. In 1857, the name was changed to Government School of Mines, and again in 1863 to Royal School of Mines (Bentley, 'Chemical Department', pp. 173-74).

by passing the Department's examinations for teaching certificates held annually in November in London.[21]

By 1871, students were able to choose between classes in twenty one different subjects, with chemistry permanently ranking among the most favourite subjects between 1859 and 1867.[22] By way of illustration, out of a total of 2,980 students who sat for DSA exams in 1866, 1,043 students were examined in inorganic chemistry (35%) and 121 students were examined in organic chemistry (4%). This figure increased more than twofold over the next four years: in 1870, a total of 2,694 students took exams in inorganic chemistry and 235 students were examined in organic chemistry.[23] This figure rose to more than 48,000 students who took examinations in inorganic and organic chemistry in 1881, reflecting the Department's success in delivering chemical education to tens of thousands of British students each year.[24] The popularity of chemistry as a DSA subject was reflected by the increase in the number of certified DSA science teachers over the same period. There were 237 certificated science teachers who were delivering classes in one or more subjects by 1863, and more than 700 teachers were working for the Department in 1871.[25] From 1869 onward, an annual summer school was offered to those teachers who desired additional practical training in the laboratory. The training consisted of a number of lectures on chemical pedagogy as well as a three-week course in laboratory skills. The instruction took place in the RCC's laboratory in London and was undertaken by Frankland himself. This arrangement resulted in a growing number of chemistry teachers who had received personal training from Frankland before assuming teaching positions at various locations across Britain.[26]

Despite being assimilated into the DSA's organisational structure and thereby effectively made into its chemistry department, the RCC remained semi-independent until 1871, as the College was allowed to retain its own identity as well as its own curriculum.[27] In its new capacity as the DSA's chemistry department, the RCC fulfilled a double role. On the one hand, it provided higher technical education for those students who aimed for professional careers in

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[21] Uzzell, P.S., 'The Science and Art Department and the Teaching of Chemistry', *Vocational Aspect of Education*, 29 (1977), 127-32 (pp. 127-28). The most comprehensive study of the Department's history is Butterworth, Harry, 'The Science and Art Department, 1853-1900' (unpublished doctoral thesis, University of Sheffield, 1968).
[22] Twining, Thomas, *Technical Training* (London: Macmillan, 1874), p. xiv.
[23] Cf. Uzzell, 'Teaching of Chemistry', pp. 127-28, Table 1 and 2.
[24] Russell, *Frankland*, p. 287.
[25] Uzzell, 'Teaching of Chemistry', p. 128; Science and Art Department, *Eighteenth Report of the Science and Art Department of the Committee of Council on Education* (London: [printed by Eyre & Spottiswoode], 1871), p. viii.
[26] Cf. Russell, *Frankland*, p. 294. Russell states that 120 teachers took part in Frankland's summer school in July 1870, whereby the 'teachers were not only from DSA course but also from schools and other places where practical chemistry was valued.' (Ibid.)
[27] Cf. ibid, p. 311; Roberts, '"Plea'", p. 109; and Gay, *History*, pp. 21-22.

manufacturing and engineering.[28] On the other hand, although appropriate biographical sources on the career choices of RCC students from the post-1853 period are wanting, we have also some circumstantial evidence suggesting that, from the early 1870s onwards, a growing number of RCC students went on to have careers in academic research as well as higher education.[29] The directors of the College were in charge of drawing up the syllabus for DSA science classes and setting the exam questions for DSA examinations. The syllabi specified not only the content of DSA classes, but also the manner in which certified teachers were meant to deliver the classes. As a result, the position of the RCC within the DSA system put College directors in near-to-absolute control of the entire system of chemical education and training in Britain.[30]

This also meant that teaching practices pioneered and tested in the context of higher education could be appropriated to popular education if deemed appropriate by the person in charge. As we shall see below, this is exactly what happened in the case of line-and-letter diagrams, as Frankland had first tested the new notation in the context of his RCC lectures before making the diagrams a compulsory element of his DSA exam papers. When Frankland succeeded Hofmann as head of the Royal College of Chemistry in 1865 and DSA examiner for chemistry in 1868,[31] he found a firmly established and effective system in place through which he was able to propagate his ideas on a national scale. Russell was therefore right to claim that the DSA system of popular education put examiners like Hofmann and Frankland in positions of

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[28] Cf. Bud and Roberts, *Science versus Practice*, Appendix C, p. 179.

[29] The biographies of some of Frankland's assistants demonstrate that RCC training often proved to be a stepping stone to careers in academic research and higher education. By way of illustration, Hofmann's and Frankland's longstanding assistant Herbert McLeod (1841-1923) became a professor at the Royal Indian Engineering College in 1871. William Valentin became Frankland's laboratory assistant in the late 1860s, authored several textbooks in the 1870s, and was appointed assistant professor at the RCC shortly before his death in 1879. Henry E. Armstrong joined the RCC in 1865. He was appointed lecturer at St. Bartholomew's Hospital Medical School in 1870 and later became professor at the London Institution. Yet there are also instances in which students succeeded in their careers without having held assistant positions. Raphael Meldola (1849-1915) and Silvanus Phillips Thompson (1851-1916), for instance, were appointed professors at Finsbury Technical College in 1885. Both men had studied under Frankland in the 1860s and 1870s. For short biographical accounts of some Hofmann's and Frankland's assistants, see Gay, '''Pillars"'; and Gay and Griffith, *Chemistry Department*, pp. 36-47, 55-57.

[30] Bud and Roberts, for instance, argue that the RCC's curriculum and teaching methods 'dominated' chemical teaching in England 'till well into the twentieth century.' (Bud and Roberts, *Science versus Practice*, p. 71.)

[31] Frankland first appeared on the list of 'Professional Examiners' in the Department's annual *Directory* for 1865. Cf. Science and Art Department, *Directory: Revised to August 1865*, 12th edn (London: [printed by Eyre and Spottiswoode], 1865), p. 3. However, it seems that for most part of the remaining decade Frankland was only filling in for Hofmann, who is listed as examiner in the *Directories* for 1866 to 1867. The *Directories* for 1868 do not seem to have survived, as these sources are conspicuously absent from catalogues of British and international academic libraries and relevant archives. F. E. Foden suggested that Hofmann remained examiner until 1867, which in turn implies that Frankland took over in 1868. Cf. Foden, 'Popular Science Examinations of the Nineteenth Century', *Journal of the Royal Institute of Chemistry*, 87.1 (1963), 6–9 (p. 7). From 1869 to 1876, Frankland is listed in the *Directories* as the sole examiner for chemistry. From 1877 until his retirement as DSA examiner in 1880, Frankland worked together with Henry Enfield Roscoe. Cf. Russell, *Frankland*, p. 290.

‘immense influence’,[32] as they were given the power to shape and execute control over their subject’s syllabus with little interference from the government.[33] It was therefore the existing DSA system of popular education that Frankland appropriated to his purpose of delivering the new graphic notation to a large number of students across the nation.[34]

Line-and-Letter Diagrams at the Centre of Frankland’s Chemical Pedagogy: How Frankland Used the New Diagrams in his RCC Lectures and his Textbook

Frankland began using line-and-letter formulae in his RCC lectures as soon as he had succeeded Hofmann as the College’s professor of chemistry in autumn 1865.[35] When Frankland assumed his new role, he introduced some changes to the syllabus in order to reflect the most recent advances in chemical theory, but continued Hofmann’s original pattern of instruction.[36] In his approach to teaching, Hofmann valued informal “learning by doing” through practical work in the laboratory over lectures and book learning. The Royal School of Mines’ general ‘Plan of Instruction’ specified that students could either attend a full course of lectures in order to obtain a ‘Certificate of Attendance’, or complete a course of lectures and laboratory instructions in different subjects within two or three years to earn a ‘Certificate of Proficiency’.[37] In chemistry, formal lectures were given by Hofmann and a number of hand-picked assistant professors only during the first year of study. The theoretical training was accompanied by practical training in the laboratory, where first-year students were given instructions in basic qualitative and quantitative inorganic analysis. Those students who decided stay at the College for another year received training in organic chemistry through a blend of laboratory work and informal verbal

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[32] Russell, *Frankland*, p. 290. Hofmann outlined his pedagogical vision and principles of teaching chemistry in Hofmann, *On the Importance of the Study of Chemistry*, Lectures Addressed to Teachers on Preparation for Obtaining Science Certificates and the Method of Teaching a Science Class, 7 (London: [printed by Eyre & Spottiswoode], 1861).

[33] Cole, Henry, *The Functions of the Science and Art Department*, Introductory Addresses on the Science and Art Department and the South Kensington Museum, 1 (London: Chapman and Hall, 1857), p. 6.

[34] The syllabi of later chemistry examiners to the DSA were all based on Hofmann’s syllabus which he had developed and enhanced over the course of the twelve years in which he held that position. Cf. Foden, ‘Popular Science Examinations’, p. 7.

[35] Cf. Russell, *Frankland*, pp. 288-89.

[36] Printed sources with information about the RCC’s syllabi are very rare. Hofmann’s syllabus for the session 1853-54 is reproduced in Bentley, ‘Chemical Department’, pp. 180-81. The syllabus for the session 1862-63 is found in Science and Art Department, *Geological Survey of the United Kingdom. Museum of Practical Geology, and Royal School of Mines. 12th Session. 1862-63* (London: [printed by Eyre and Spottiswoode], 1863).

[37] The Plan of Instruction outlined in the 1862-63 syllabus states that the ‘courses of instruction are distributed over three years, but those Students who possess sufficient preliminary training may, if they think fit, pass through the whole in two years [...]’ (ibid, p. 13).

instructions from Hofmann himself.[38] Formal written examinations were introduced after the RCC's takeover by the DSA in 1853 and over the course of the following years continued to increase in complexity and length. In Hofmann's final year at the College, the length of the written examination was increased to a total of six hours.[39] This development toward routine and formalised instruction with a focus on organic and theoretical chemistry was continued by Edward Frankland after Hofmann's departure in 1865.

According to his students as well as by his own admission, Frankland was not a gifted lecturer and lacked many of the rhetorical skills of his predecessor.[40] Yet the famous chemist Henry E. Armstrong (1848-1937), who was Frankland's first student assistant at the RCC, recalled that Frankland's lectures 'were clear, straightforward, and logical and he took particular pains to illustrate them by well-thought-out, practical demonstrations.'[41] In addition to the lecture demonstrations – and perhaps to compensate for his deficient performance as a public speaker – Frankland also used a number of representation techniques to facilitate the understanding of the new concept of valence and the emerging theory of chemical structure.[42] Those techniques included not only Hofmann's physical ball-and-stick models ('glyptic formulae'), but also line-and-letter formulae that Frankland employed in large numbers.[43] Frankland's strong emphasis on visual teaching aids was directly linked to the key position that the concept of valence and the theory of structure occupied in his lectures. Both Hofmann's and Frankland's syllabi had a strong theoretical focus, yet according to Russell, Hofmann gave 'no concession to modern theories of structure.'[44] Frankland, on the other hand, structured all of his lectures around the new theoretical principles which he himself had helped to develop. As Frankland's own lecture notes from that period demonstrate, his lectures were filled with a wide array of line-and-letter formulae from beginning to end. In what follows, I draw on these notes as well as Frankland's pedagogical writings to illustrate and analyse how and for what purpose, exactly, Frankland used line-and-letter diagrams in his RCC lectures.

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[38] Gay and Griffith, *Chemistry Department*, pp. 28-37.
[39] Jackson, 'Research School', p. 23.
[40] Russell, *Frankland*, p. 307.
[41] Cited after Brock, 'Editor's Introduction', in *H. E. Armstrong and the Teaching of Science 1880-1930*, ed. by William H. Brock (Cambridge: Cambridge University Press, 1973), pp. 1-54 (p. 4).
[42] Frankland used the term 'atomicity'. The term 'valence' was introduced by Hofmann in his textbook *Introduction to Modern Chemistry, Experimental and Theoretical: Embodying Twelve Lectures Delivered in the Royal College of Chemistry* (London: Walton & Maberley, 1865).
[43] Hofmann had used these ball-and-stick models in two lectures at the Chemical Society and the Royal Institution in 1865. The models were well received and were soon made by a number of professional instrument makers in London. Yet despite the models' evident didactic benefits, there is no evidence that Hofmann had ever made use of the models in his RCC lectures. Cf. Meinel, 'Molecules and Crocket Balls'; and Ramsay, *Stereochemistry*, p. 62. Frankland advocated the use of such models in his didactic treatise *How to Teach Chemistry: Hints to Science Teachers and Students*, ed. by George Chaloner (London: Churchill, 1875), p. 55.
[44] Russell, *Frankland*, p. 290.

Frankland's lecture manuscripts, referred to as 'Lecture notes' in the inventory list, are part of the Frankland Papers collection that is located at the University of Manchester's John Rylands Library. The collection includes a number of undated and unpaginated notebooks in Frankland's own handwriting.[45] Russell – who was the first historian to analyse these invaluable historical sources – argued that the surviving notebooks in the collection are none other than the manuscripts on which Frankland's very first RCC lectures were based. Given the fact that the formulae had appeared in print as part of Frankland's *Lecture Notes* in 1866, this hypothesis seems plausible.[46] The left and the right pages of the notebooks serve two different functions. While the right-hand pages contain the text of Frankland's oral presentation, the left-hand pages include instructions regarding the use of experiments and various kinds of representations that were meant to accompany each lesson. In a lecture on alcohols, for example, the right-hand page contains information on the general properties of this class of compounds. The left-hand page gives the instruction 'Distil SO_4ELH with H_2O & show alcohol', thus indicating that Frankland or one of his lecture assistants was supposed to show an experiment at this particular point of the lecture.[47] Many more instructions of this kind can be found throughout the volumes of Frankland's lecture notes. In addition to lecture demonstrations, the notebooks feature a selection of different diagrams and a very large number of empirical and rational formulae.[48]

Following this approach, line-and-letter diagrams are found on the left-hand page of the lessons on organic chemistry (Figure 4.1), suggesting that the formulae were either drawn on the blackboard by Frankland or his assistant, or that the formulae had been prepared prior to the lecture and then revealed to the students. The arrangement of the diagrams in the notebook makes it clear that the line-and-letter formulae were meant to represent the constitution of organic substances whose physical properties and behaviour are described on the right-hand page of the notebook. As I explain in the rest of the section, this mode of application served two interrelated purposes. First, the diagrams meant to represent how the principle of valence defined the exact structure of each compound. Secondly, the diagrams functioned as classificatory tools and bookkeeping devices that allowed students to see and remember the structure of a specific molecule at the first glance whilst also being able to recognise the structural differences between that molecule and another one. This function of line-and-letter

[45] Manchester, University of Manchester Library (UML), Sir Edward Frankland Papers, Lecture notes, sort nos. 3301, 3390, 3391.
[46] Cf. Russell, *Frankland*, pp. 288-89, 308-10.
[47] UML, Sir Edward Frankland Papers, Lecture notes, sort no. 3301.
[48] By way of illustration, one of the very first lectures on the concept of valence (Frankland preferred the term 'atomicity') includes a number of rectangular diagrams that are very similar to Wurtz's interpretation of Kekulé's sausage formulae (UML, Sir Edward Frankland Papers, Lecture notes, sort no. 3391).

diagrams can be witnessed in the example below (Figure 4.1.), where each of the three compounds on the left-hand page of the notebook has a distinct appearance.

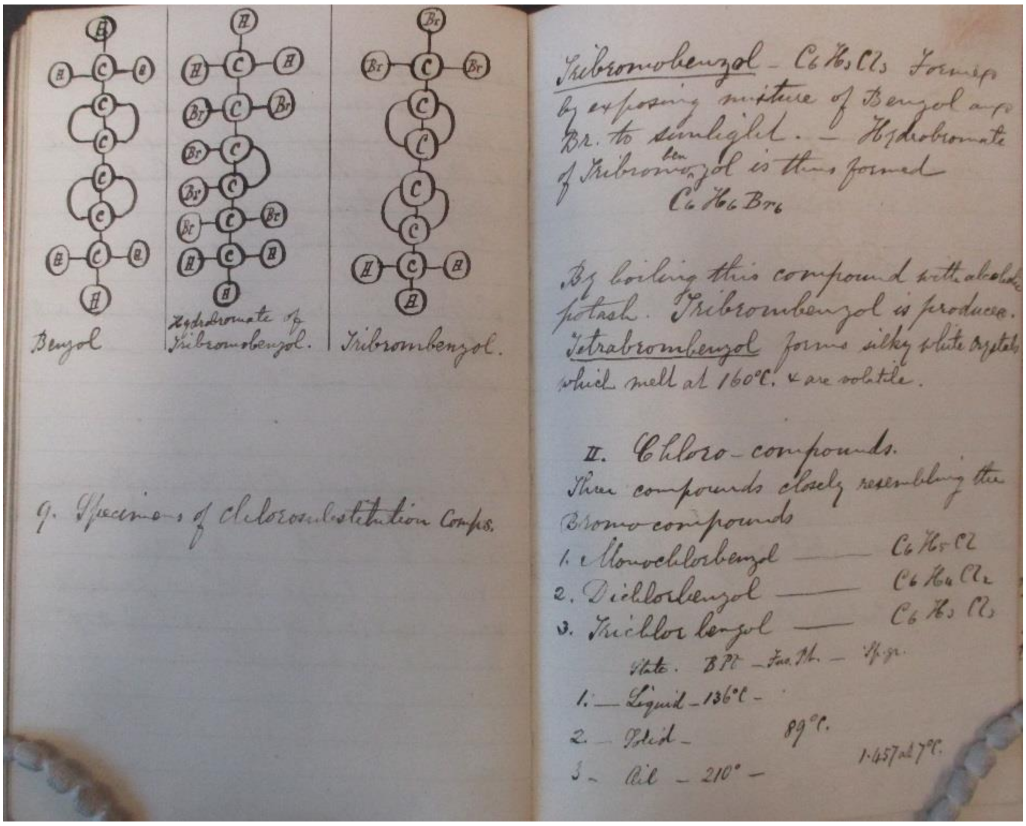

Figure 4.1: Page from Frankland's lecture manuscripts, c. 1866.[49]

So why did Frankland employ line-and-letter formulae in his RCC lectures? We have already established that Frankland placed valence and structure at the very centre of the RCC syllabus when he succeeded Hofmann as professor of chemistry in 1865. As I have already explained above, the diagrams were brought forward to demonstrate a specific aspect of the chemical theory, namely the idea that atoms link together in a specific way according to their different degrees of valence to form a specific molecule. Frankland's pedagogical writings leave no doubt that he introduced line-and-letter formulae as well as other kinds of symbols and synoptic tables to his lectures because of the high didactic value of those visual teaching aids to the understanding of abstract chemical ideas. In a series of lectures delivered to prospective science teachers in 1872, for instance, Frankland gave the advice that 'copious use should be made of the black-board and of symbols.'[50] Such visual aids could include different kinds of drawn symbols as well as tables with atomic weights and other helpful information. According to

[49] UML, Sir Edward Frankland Papers, Lecture notes, sort no. 3301.
[50] Frankland, *How to Teach Chemistry*, p. 62.

Frankland, these visual aids are of great benefit if placed 'in every class-room' and displayed frequently to the students.[51] Line-and-letter formulae were thus only one part of Frankland's approach to classroom teaching, albeit a crucial one.[52] The centrality of line-and-letter formulae to Frankland's teaching is made more explicit in Frankland's preface to the 1866 edition of his textbook *Lecture Notes*, which is to a large degree based on the RCC lectures delivered during the winter term 1865-66. In that preface, Frankland explains that line-and-letter formulae afford 'most valuable aid to the teacher in rendering intelligible the constitution of chemical compounds, especially when it is supplemented by what may be called the glyptic formulae of Hofmann.'[53] This, again, makes it very clear that Frankland chose to employ line-and-letter formulae together with other teaching aids such as Hofmann's ball-and-stick models to demonstrate in an effective and systematic way how the principle of valence dictated the constitution of complex molecules without explaining the basic theoretical details every single time.

Line-and-letter diagrams also functioned as classificatory tools and bookkeeping devices. I have already explained that Frankland employed a large number of the diagrams in his lectures to classify organic compounds and to flesh out their main chemical and physical properties. Line-and-letter formulae were thus used as shorthands for the large number of compounds discussed in Frankland's lectures. Yet this also meant that students could be easily overwhelmed by the large number of new formulae. To ease the situation, Frankland published his famous *Lecture Notes*. The content of this book was highly technical and consisted of almost nothing else than quantitative data (molecular weight, boiling point, etc.) and a very large number of line-and-letter formulae. Before anything else, Frankland's *Lecture Notes* was a compendium of tables, chemical equations, and diagrams which the majority of chemistry students would not have been able to understand without at least some degree of personal instruction. And, indeed, in the book's preface Frankland made it very clear that in order to 'render the work as concise as possible, all formal description of the properties of the bodies treated of has been, for the most part, entirely omitted […]' because such details 'would, even if brief, have swollen the book to more than double its present size.'[54] The main purpose of the *Lecture Notes* was therefore not to be used as a stand-alone textbook, but rather to serve as a complementary learning resource to live lectures that followed Frankland's syllabus. Frankland expanded on this rationale by saying that

[51] Ibid, p. 81.
[52] Christopher Ritter has suggested that Frankland's decision to employ various illustration techniques in his teaching was grounded in Friedrich Fröbel's and Johann Heinrich Pestallozi's pedagogical ideology (Ritter, 'Re-Presenting Science', p. 147).
[53] Frankland, *Lecture Notes* (1866), p. v.
[54] Ibid, p. iii.

> I have often noticed with regret the great amount of labour which an earnest student expends in noting down the reactions and the names and formulae of substances which are presented to his notice in the lecture-theatre. He is thus greatly interrupted in following the arguments and explanations of the speaker, and he often loses more important generalizations in securing a record of details. One of my chief objects in the preparation of this book has been to relieve him from such distractions. For this purpose very full lists of names and formulae are given, and a comparatively large amount of space is devoted to equations expressing the reactions occurring in the formation and decomposition of the substances treated of.[55]

Frankland's explanation makes two things very clear. First, it becomes evident that *Lecture Notes* formed an integral part of Frankland's approach to teaching – an approach characterised by live presentations and the simultaneous use of prescribed books as learning resources. Secondly, Frankland's statement quoted above exemplifies that he devised his textbook as a means to rationalise teaching and learning practices as well as to streamline and formalise his newly developed RCC syllabus. From the students' perspective, this meant that every student who attended Frankland's RCC lectures was introduced to line-and-letter formulae in one of the very first sessions and, most likely, also made extensive use of the *Lecture Notes* throughout the course, especially if the student intended to sit for the Certificate of Proficiency exam. Consequently, it was through the integration of personal instruction and textbook-based learning that RCC students became proficient in understanding and using the new diagrams. The fact that Frankland continued to employ large numbers of line-and-letter formulae in his lectures and that he included the diagrams in the second edition of his *Lecture Notes* (1870-72) evidently testifies to the notation's didactic success.[56]

But how were the formulae circulated to a wider audience, and by what means did the formulae reach new users? Did RCC graduates make any significant contributions to the proliferation of the line-and-letter notation in Britain? Building on Gerrylynn Roberts' and James Donnelly's pioneering studies of the history of the RCC, I argue that neither RCC students nor Frankland's *Lecture Notes* were the main reason for the dissemination of the new formulae in Britain.[57] On the one hand, the vast majority of students who attended RCC chemistry classes in the 1860s did not become school teachers or academic researchers with teaching positions, but

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[55] Ibid, p. iv.
[56] In the second edition of the *Lecture Notes*, line-and-letter diagrams were printed without circles. Frankland justified this simplification of the notation by stating that 'even young students prefer to draw the formulae without the circles, hence there is no reason for retaining them.' (Frankland, *Lecture Notes* (1870-72), I: *Inorganic Chemistry* (1870), pp. iv-v.)
[57] Roberts, 'Royal College of Chemistry'; Donnelly, 'Chemical Education'.

pursued careers in manufacture and industry instead. To be more precise, only a small number of regular students matriculated at the College and stayed for the whole duration of two or three years in order to take the final exam and to obtain Certificates of Proficiency. Instead, the vast majority of students spent only a short time at the College in order to acquire knowledge that they deemed to be useful for their immediate practical needs. In addition, not all students of those occasional students followed the lectures, but often attended only laboratory courses for a few months.[58] Statistical data compiled by Donnelly shows that from the 369 registered students who had attended RCC chemistry classes by 1870, only 10% secured 'academic' jobs and just 2% became 'schoolteachers', whereas approximately 48% of students found employment in different branches of manufacture.[59] These figures make it clear that only small number of RCC chemistry students acquired positions in which they were able to contribute to the proliferation of the formulae through teaching or publishing activities.

On the other hand, we have seen in this section that Frankland's book was not suitable to be used without personal instruction due to the very technical nature of its contents. Yet the commercial success of the *Lecture Notes* indicates that the book reached a large number of readers. The first edition appeared in 1866 and was soon followed by a second edition that was published in two volumes in 1870 and 1872, respectively. A reprint of volume 1 of the second edition was published in 1876, and a third revised edition of volume 2 was released in 1881. By 1876, volume 1 of the *Lecture Notes* had already sold more than 6000 copies.[60] The high sales figures demonstrate that the book was used by a very large number of students during the 1860s and 1870s. However, only a small proportion of those students attended RCC classes, since we have seen in the previous paragraph that less than four hundred students had attended the College by 1870.[61] In addition, my research shows that Frankland's *Lecture Notes* was by no means the only title with line-and-letter formulae that was available on the British print market by the end of the 1860s. Between 1866 and 1869, at least eight other textbook titles with line-and-letter formulae were published, and some of those books made very explicit references to

[58] Cf. Bud and Roberts, *Science versus Practice*, Appendix C. Roberts' data for the period from October 1845 to March 1853 shows that 'only 21% of the 356 students attended the Royal College of Chemistry for three or more semesters [...]', and that '50% of those who enrolled left after only one semester.' (Roberts, 'Royal College of Chemistry', p. 318.)
[59] Donnelly, 'Chemical Education', p. 192.
[60] Russell, *Frankland*, p. 300.
[61] Reliable statistical data is inconsistent and very difficult to obtain. Bud and Roberts, for instance, identified 469 'occasional students' who had attended classes at the RCC between 1853 and 1870 (*Science versus Practice*, Appendix C). It is not entirely clear whether Bud's and Roberts' number includes Donnelly's 369 registered students or not. In spite of these inconsistencies, the available data makes it very clear that throughout the 1850s and 1860s RCC student numbers remained in the low hundreds.

Frankland's use of the new diagrams as well as his *Lecture Notes*. Yet who were the readers of those textbooks if not RCC students?

In light of the above findings – and drawing on Russell's original albeit incomplete account of the dissemination of line-and-letter formulae in Britain – I show in the next section that the books were intended for the large numbers of DSA students who attended evening chemistry classes at their local schools. This section examined Frankland's teaching practices by illustrating how Frankland was using line-and-letter formulae in RCC lectures from 1865 onwards, where the formulae proved their didactic value in the context of Frankland's modernised RCC syllabus. Yet judging by the comparatively small number of RCC students who were able to secure some sort of teaching positions, either as academics or as schoolteachers, we have also seen that RCC students contributed very little to the dispersion of the new formulae. The next section argues that although Frankland began using line-and-letter formulae in the context of chemistry teaching at the RCC, it was only in the context of DSA classes that the formulae were circulated widely and reached a large number of users in the late 1860s and the early 1870s.

4.2. Spreading Formulae Far and Wide: Line-and-Letter Diagrams as Teaching and Learning Aids in Popular Education

When Frankland finally succeeded Hofmann as DSA examiner for chemistry in 1868, he was put in charge of the Department's syllabus and examinations through which he was able to propagate the concept of valence and the emerging theory of chemical structure to a much larger number of students than through his teaching activities at the RCC. Having successfully tested line-and-letter formulae as valuable teaching aids in his RCC lectures, Frankland placed the new notation at the very centre of his revised DSA syllabus in 1869. Within a few years, hundreds of DSA teachers and thousands of DSA students appropriated line-and-letter formulae in the context of formalised instruction under Britain's unique popular education system. In this section, I demonstrate how teachers and students who studied for DSA qualifications were trained to interpret and use the new diagrams. Frankland's approach to popular education consisted of a graded DSA syllabus that introduced all teacher candidates to line-and-letter formulae at the very beginning of their studies, which meant that every certified DSA teacher was trained to conduct DSA science classes with the aid of the diagrams. Chemistry students who attended those classes were familiarised with the diagrams through a blend of didactic practices that included personal instruction in the classroom, note taking in the classroom, and writing exercises in conjecture with the reading of textbooks at home. The main objective of this strategy was to prepare students for the annual exams. As a result, by 1869 a pedagogical agenda was in place that urged line-and-letter formulae onto everyone who studied under the DSA system.

The DSA Chemistry Syllabus

The DSA's printed chemistry syllabus served 'to afford candidates for certificates as teachers of Science, some guide to their reading' in preparation for the annual exams held in November. After obtaining the relevant certificates, DSA teachers were entitled to earn payments by successful teaching according to the aforementioned payment-by-results scheme.[62] The main objective of the whole system was to train teachers who would implement the specified DSA syllabus in their local classes. In other words, teacher training according to a formalised syllabus guaranteed that chemistry teachers, once certified by the DSA, replicated the content and pedagogical agenda of the syllabus in their science classes. Between 1865 and 1867, Hofmann's original DSA syllabus remained practically unchanged, and line-and-letter diagrams did not appear on the list of required subjects. However, evidence from the Department's printed *Directory* from 1869 indicates that Frankland made substantial changes to the syllabus when he finally assumed the office of 'Professional Examiner' in 1868.[63] While Frankland's 1869 syllabus retained Hofmann's gradation of chemistry classes into three grades according to various degrees of difficulty, it boasted a large number of new subjects.[64] In the syllabus for each of the three classes, Frankland put a strong emphasis on the handling of different forms of chemical representations. By way of illustration, we find line-and-letter formulae – which, as I have explained before, Frankland called 'graphic notation' or 'graphic formulae' – at the very beginning of the two syllabi for the 'First Stage or Elementary Course' in inorganic and organic chemistry, respectively (Figures 4.2 & 4.3).

[62] DSA, *Directory: Revised to August 1865*, 12th edn (1865), pp. 7, 32.
[63] DSA, *Directory: Revised to February 1869*, 19th edn (1869), pp. 91-95.
[64] Hofmann's original syllabus was subdivided into three grades: elementary, advanced, and honours.

First Stage or Elementary Course.

Pupils presenting themselves for examination will be expected to possess a knowledge of the following subjects :—

Definition of chemistry. Simple and compound matter. Different modes of chemical action. Combining weights. Volume weights. Principles of chemical nomenclature. Symbolic notation. Graphic notation. Chemical formulæ. Chemical equations. Atomicity of elements. Simple and compound radicals. Definition of a compound radical. Classification of elements into metals and non-metals, into chlorous and basylous elements. Classification according to atomicity.

Figure 4.2: Extract from the DSA syllabus for the elementary course in inorganic chemistry, 1869.[65]

First Stage or Elementary Course.

Pupils presenting themselves for examination will be expected to possess a knowledge of the following subjects :—

Definition of organic bodies; their ultimate analysis. Calculation of empirical formulæ. Compound organic radicals. Notation of organic compounds. Graphic and symbolic formulæ.

Figure 4.3: Extract from the DSA syllabus for the elementary course in organic chemistry, 1869.[66]

From this, we can see that the new notation was introduced to teacher candidates – and, by extension, to their prospective students – at the earliest stage of their occupation with chemistry, which in turn makes it very clear that Frankland considered the formulae as an indispensable tool for the successful teaching of chemical knowledge. Frankland's syllabus thus demonstrates that all those who studied for DSA qualifications, be it teacher candidates or working adults taking the night classes, were required to master the formulae, regardless whether they chose inorganic or organic chemistry as their preferred subject. But in which setting, and how exactly, did British students learn how to handle the formulae? In what follows, I argue that the learning process was built on personal instruction as well as formula writing and reading exercises that students had to undertake at home in order to be prepared for the next classroom session and to well in the upcoming exams.

Learning to Write Chemistry

An important part of the teaching in the local schools consisted of classroom instruction by DSA-certified teachers. Yet classroom instruction was not the only pillar upon which Frankland's approach to popular education rested. Having noticed that the majority of students attending

[65] DSA, *Directory: Revised to February 1869*, 19th edn (1869), p. 91.
[66] Ibid, p. 93.

elementary classes in chemistry lacked the ability to express their ideas on paper, Frankland insisted that all chemistry teachers were to make absolutely sure that students took notes during the class and prepared abstracts of the lessons at home in order to practice "writing" chemistry. Frankland stressed the importance of those writing exercises as an integral part of his pedagogical agenda in the aforementioned pamphlet *How to Teach Chemistry* (1875), stating that

> […] teachers ought to strive to appreciate the importance of requiring their pupils to take notes during class lessons, and of themselves looking over and revising these notes as frequently as possible. This is a most valuable adjunct to teaching. A pupil who is made to take notes not only has the lecture or lesson much more firmly fixed in his mind, but he acquires the habit of expressing his ideas in writing, and will, on this account alone, be much more likely to work a satisfactory paper in the annual examination. Pupils ought also to be encouraged, if not required, to write out at home an abstract of the lessons from the notes they have taken while the lessons were in progress. Questions should also be given out at the close of a lesson, and the answers when brought in examined by the teacher.[67]

Frankland's statement portrays writing as a text-based cognitive and communicative practice. And, indeed, recent historical studies by Matthew D. Eddy (2016), and Ann M. Blair (2010), and Lorraine Daston (2004) have demonstrated that writing has been an integral part of producing, sharing, and appropriating knowledge since at least the sixteenth century. In addition, the studies show that note-taking at European and – later on – American teaching institutions served a large number of different didactic, heuristic, and mnemonic purposes [68] Eddy's case study of students' manuscripts produced at the universities of Edinburgh, Glasgow, St. Andrews, and Aberdeen during the Scottish Enlightenment demonstrates that taking notes was an 'interactive' activity involving the use of different media (oral presentation, blackboards, paper displays and handouts, and printed syllabi) and serving the purpose of interpreting, systematising, and memorising lectures and classes.[69] Eddy's case study shows that the process usually involved several steps:[70] rough notes or 'Mitschriften' were taken in longhand or shorthand during the lecture, then painstakingly turned into 'Reinschriften' or neat copies through the process of

[67] Frankland, *How to Teach Chemistry*, p. 61.
[68] Eddy, Matthew D., 'The Interactive Notebook: How Students Learned to Keep Notes during the Scottish Enlightenment', *Book History*, 19 (2016), 87–131; Blair, Ann, *Too Much to Know: Managing Scholarly Information before the Modern Age* (New Haven, CT: Yale University Press, 2010), Chapter 2; Daston, Lorraine, 'Taking Note(s)', *Isis*, 95.3 (2004), 443–48.
[69] Eddy, 'Notebook', pp. 86-87, 99-110.
[70] Ibid, pp. 86-87.

iterated copying, rewriting, enhancing, and editing. Students' notes thus often underwent many transformations.[71] Going through those different stages, students were able to engage deeply with the content by processing and organising a large amount of information – which, as it seems, is exactly what Frankland was aiming at. In addition, Frankland's above quote leaves no doubt that the writing exercises were not only beneficial to understanding and memorising the content of individual chemistry lessons, but also served the long-term purpose of preparing students for the written examinations of the Department.

Frankland's above statement also makes it very clear that students were required to undertake a considerable amount of work at home, including working on questions which were assessed by their teachers in the following session. To support and complement out-of-class work as well as to 'afford a candidate some assistance in selection and a general idea of the scope of the examination', each printed DSA syllabus listed a number of recommended textbooks for each subject.[72] Frankland's *Lecture Notes* appeared in the syllabus of August 1867 for the first time, where it was listed together with five other titles as a recommended reading for inorganic and organic chemistry.[73] In the 1869 syllabus and all throughout the 1870s, *Lecture Notes* continued to appear on the textbook lists, thereby contributing to the book's continuous commercial success. We have seen in the previous section that Frankland's approach to chemistry teaching at the RCC integrated live lectures with the use of learning resources such his own *Lecture Notes.* The existence of DSA reading lists strongly implies that the same didactic method also applied to DSA classes. In what follows, we shall see how this demand for supplementary reading material resulted in the growth of the domestic market for textbooks with line-and-letter formulae in the late 1860s. I argue that the growing significance of line-and-letter formulae in the context of chemical education in Britain was reflected by the fact that apart from the *Lecture Notes*, at least eight other titles with the new notation had appeared on the British print market by 1869.

[71] Rough notes were made in different ways and therefore captured different kinds of information. Some students recorded only the essential parts of the lecture, while others attempted to produce a complete and continuous record of the teacher's oral presentation. Some students also attended the same lecture several times in subsequent years to fill in gaps and to augment their record. Cf. ibid, pp. 90-91.

[72] DSA, *Directory: Revised to August 1867*, 15th edn (1867), p. 32.

[73] Ibid, p. 43.

Frankland's influential position at the very heart of British chemical education was, without any doubt, the main reason for the publication of new textbooks with line-and-letter diagrams. Frankland was not only the director of the RCC – which was the most important higher education teaching establishment for chemistry in the country – but also in charge of the DSA chemistry syllabus as well as the Department's chemistry exams. In addition, Frankland's *Lecture Notes* of 1866 was the very first English textbook that featured the new chemical notation. As we shall see in the final section of this chapter, it was for those reasons that *Lecture Notes* was widely read and discussed by members of the British public. Yet other textbooks with line-and-letter formulae began to appear as early as 1867. The first three titles to include the new notation were Charles Loudon Bloxam's *Chemistry* (1867), Kay-Shuttleworth's *First Principles of Modern Chemistry* (1868), and the tenth and revised edition of George Fownes' *Manual of Elementary Chemistry* (1868).[74] Five more books with line-and-letter formulae followed in 1869. These were John Attfield's *Chemistry*, Charles Haughton Gill's *Chemistry for Schools*, the second edition of Roscoe's *Lessons*, the fifth and revised edition of John Charles Buckmaster's *Elements of Inorganic Chemistry*, and the third volume of the fourth edition of William A. Miller's *Elements of Chemistry*.[75] However, none of those textbooks featured as many line-and-letter formulae as Frankland's *Lecture Notes*, and some titles included only a small and representative sample of the new diagrams. We might therefore ask the question: why did authors, editors, or publishers decide to include the new notation even though some of the books did not expand on the formulae? In what follows, I demonstrate that in the majority of cases, the appearance of line-and-letter diagrams was always linked, in one way or another, to Frankland's own textbook, his teaching practices, or his RCC and DSA syllabi.

By way of illustration, the preface of Kay-Shuttleworth's *First Principles* (1868) makes it clear that the use of line-and-letter formulae was directly inspired by Frankland's teaching practices as well as his *Lecture Notes*. Kay-Shuttleworth stated in the preface of his book: 'Dr. Frankland […] has assisted me by most valuable advice as well as by revising the whole of the

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[74] Bloxam, Charles Loudon*, Chemistry: Inorganic and Organic. With Experiments and a Comparison of Equivalent and Molecular Formulae* (London: Churchill, 1867); Kay-Shuttleworth, *First Principles* (1868); Fownes, George, *Manual of Elementary Chemistry: Theoretical and Practical*, 10th edn, rev. by H. Bence Jones and Henry Watts (London: Churchill, 1868).

[75] Attfield, John, *Chemistry: General, Medical, and Pharmaceutical* (London: Van Voorst, 1869); Gill, Charles Haughton, *Chemistry for Schools: An Introduction to the Practical Study of Chemistry* (London: James Walton, 1869); Roscoe, *Lessons*, 2nd ['new'] edn (1869); Buckmaster, John Charles, *Elements of Inorganic Chemistry*, 5th edn, rev. by G. Jarmain (London: Longmans and Co, 1869); Miller, William A., *Elements of Chemistry: Theoretical and Practical*, 4th edn, 3 vols (London: Longmans, Green, Reader and Dyer, 1867-69), III: *Organic Chemistry* (1869).

manuscripts and proofs […]', thus leaving no doubt that Frankland was directly and deeply involved in the preparation of the book.[76] In addition, Kay-Shuttleworth pointed out that *First Principles* drew directly on Frankland's RCC lectures of 1865-66 which, together with Alexander William Williamson's UCL lectures of 1864-65, supplied him 'with a considerable part of the matter here collected together.'[77] Kay-Shuttleworth also explained that line-and-letter formulae offered a very convenient way of explaining the valence principle to students, stating: '[...] it is exceedingly desirable that the forms in which chemical formulae are for most purposes written should be such that it may be readily apparent how each unit of force of the several atoms is expended. [...] Graphic notation in the form invented by Dr. Crum Brown, effects this object most completely and satisfactorily.'[78] From this, we can posit that it was the didactic value of the new formulae which Kay-Shuttleworth had experienced first-hand in Frankland's RCC lectures and textbook that prompted him to adopt the notation in his own book.

Some of the other titles also betrayed direct links to Frankland. Attfield's *Chemistry* (1869), for instance, explained that the 'quadrivalent' nature of the aluminium atom is 'shown in the following formula for chloride of aluminium (Al_2Cl_6) from Frankland's "Lecture Notes for Chemical Students," which represents each aluminium atom as a body having four arms or bonds […]'[79] The diagram in question was reproduced from the 1866 edition of Frankland's textbook and featured the characteristic circles around the elemental symbols for aluminium and chloride (Figure 4.4). Buckmaster's *Elements of Inorganic Chemistry* (1869) and the third volume of the fourth edition of Miller's *Elements of Chemistry* (1869), too, featured several examples of line-and-letter formulae that closely resemble the diagrams in Frankland's *Lecture Notes* (Figures 4.5 & 4.6). In addition, Miller also made an explicit reference to Crum Brown and Frankland, saying that '[e]ach atom of every element is supposed to have a certain definite number of centres of attraction, or bonds as they have been called by Frankland [...]. To aid giving precision to our ideas, these bonds [...] may be represented graphically; and this has been done in various ways, the most convenient perhaps being that employed by Crum Brown.'[80] Buckmaster, too, explained that the term 'bonds' had been invented by Frankland.[81] In addition, Buckmaster's preface left absolutely no doubt that the new formulae had been adopted for the reason 'to make the work suitable for instruction in Chemistry, according to the Syllabus prepared by the Science and Art Department.'[82]

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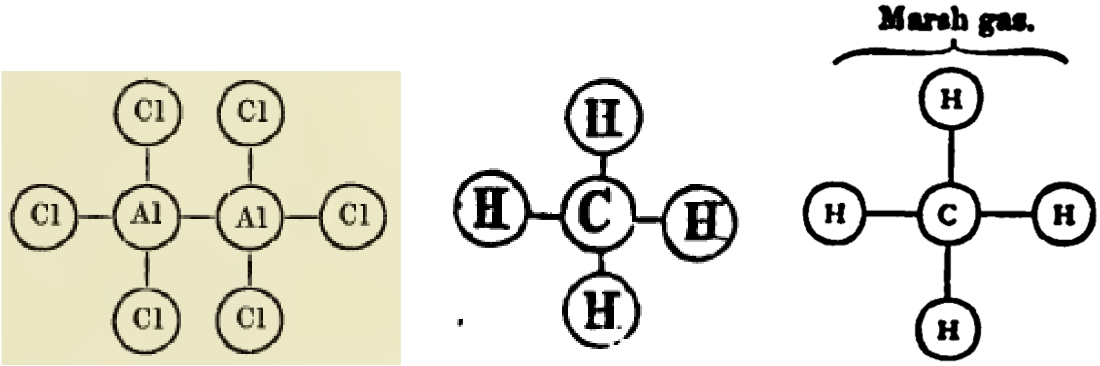
[76] Kay-Shuttleworth, *First Principles* (1868), p. iii.
[77] Ibid.
[78] Ibid, p. 64.
[79] Attfield, *Chemistry*, p. 103.
[80] Miller, *Elements*, III, pp. 58-59.
[81] Buckmaster, *Elements*, p. 19.
[82] Ibid, p. iii.



Figures 4.4 to 4.6: Line-and-letter formulae in Attfield's *Chemistry* (1869, left); Buckmaster' *Elements* (1869, centre); and Miller's *Elements* (1869, right).[83]

Bloxam's, Fownes', Gill's, and Roscoe's textbooks, on the other hand, did not exhibit any direct connection to Frankland or his teaching scheme. They did not mention Frankland by name when introducing and explaining line-and-letter formulae and did not state that the books followed the DSA syllabus. Furthermore, the diagrams in those books did not feature Crum Brown's and Frankland's characteristic circles. Yet each of these four titles could be found on the DSA's reading lists for 1869 and the following years.[84] Although it is not immediately apparent how the books found their way onto the reading lists, it is reasonable to presume that Frankland decided to include the titles exactly because they featured line-and-letter formulae similar to his own diagrams. By implication, it is also possible that some of the aforementioned authors decided to feature the new notation in their textbooks because they wanted to have a share of the textbook market, which in the late 1860s became increasingly dominated by Frankland's *Lecture Notes* as well as other books that employed the new formulae. After all, a place on the DSA reading lists was often a guarantee for a textbook's commercial success. As Josep Simon has pointed out in his study of the role of Adolphe Ganot's textbooks in the shaping of physical education in nineteenth-century Britain, most books that appeared on the DSA reading lists had a very good chance of being purchased and read by the large number of DSA students – a number which, as we saw, continued to rise throughout the second half of the nineteenth century.[85]

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[83] Attfield, *Chemistry*, p. 103; Buckmaster, *Elements*, p. 23; Miller, *Elements*, III, p. 60.
[84] Cf. DSA, *Directory: Revised to September 1869,* 20th edn (1869), pp. 92-93, 95; DSA, *Directory: Revised to September 1871,* 24th edn (1871), pp. 96-97, 100.
[85] By way of illustration, John Tyndall's (1820-1893) and Balfour Stewart's (1828-1887) physics textbooks entered the DSA reading lists for physics exams in the 1860s and remained on those lists for the following twenty years. As a result, the books reached several generations of readers and became a permanent fixture in English physics education. Balfour's *An Elementary Treatise on Heat* (1st edn 1866) went through six editions, whereas Tyndall's *Heat Considered as a Mode of Motion* (1st edn 1863) had as many as eleven editions during the nineteenth century (Simon, *Communicating Physics*, p. 52).

The growing demand and subsequent expansion of the British market for textbooks with line-and-letter formulae is reflected by the publication of a growing number of new editions as well as entirely new titles in the early 1870s. By way of illustration, new editions of Frankland's *Lecture Notes*, Kay-Shuttleworth's *First Principles*, and Miller's *Elements* were published between 1870 and 1872.[86] New titles included, among others, William G. Valentin's *Laboratory Text Book* (1871) and *Introduction to Inorganic Chemistry* (1872) as well as Josiah P. Cooke's *First Principles of Chemical Philosophy* (1870).[87] As a result, a relatively large number of textbooks with line-and-letter formulae were available on the British book market by the early 1870s, surpassing by far the number of comparable textbooks that were available in Germany during the same period. As the works of Warwick, Simon, Kaiser, and others have demonstrated, one of the main functions of textbooks was – and still is – to prepare students for examination.[88] By implication, this also means that textbooks played a major role in the propagation of the didactic practices and course syllabi which they embodied. The chemistry textbooks that I have listed in this chapter were no exception, as they often contained a number of exercises based on previous DSA exam papers.[89] As I demonstrate below, written DSA exams formed another integral part of Frankland's strategy to communicate line-and-letter formulae – and, through them, the concept of valence and the theory of structure – to as many students as possible. Serving as quintessential learning resources for all those students who intended to take RCC or DSA classes and to sit for the exams, those textbooks played a major role in the propagation and stabilisation of Frankland's syllabus.

Passing the DSA Exams

Printed exam papers for the May 1869 DSA examinations demonstrate that knowledge of line-and-letter formulae was absolutely indispensable if science students wanted to pass examinations in each of the three classes in organic and inorganic chemistry. By way of

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[86] Frankland, *Lecture Notes* (1870-72); Kay-Shuttleworth, *First Principles*, 2nd rev. edn (1870); Miller, *Elements*, 5th edn, 3 vols, rev. by Herbert McLeod ([1872-74]).

[87] Valentin, William George, *A Laboratory Text Book of Practical Chemistry: Or, Introduction to Qualitative Analysis. A Guide to the Course of Practical Instruction Given in the Laboratories of the Royal College of Chemistry* (London: Churchill, 1871); idem, *Introduction to Inorganic Chemistry* (London: Churchill, 1872); Cooke, Josiah P., *First Principles of Chemical Philosophy* (London: Macmillan, 1870).

[88] Warwick, *Masters of Theory*; Simon, *Communicating Physics*; Kaiser, *Drawing Theories Apart*; Lundgren and Bensaude-Vincent, eds., *Communicating Chemistry*.

[89] See, for instance, Buckmaster, *Elements*; Miller, *Introduction to the Study of Inorganic Chemistry*, 2nd ['new'] edn (London: Longmans, Green, and Co, 1871); and Snaith, William Abbotts, *Inorganic Chemistry for Elementary Classes: Designed Chiefly for Use in the Elementary Stage of Classes in Connection with the Science and Art Department, South Kensington* (London: Longmans, Green, and Co, 1871).

illustration, the ‘First Stage or Elementary Examination’ in organic chemistry required students to ‘[g]ive the symbolic and graphic formulas of the following compounds: — formic acid — acetic acid — oxalic acid — marsh gas — methyl — chloroform — ether.’[90] The ‘Second Stage or Advanced Examination’ in organic chemistry included a similar question, asking students to ‘[w]rite out the symbolic and graphic formulae of any member of each of the following families of organic bodies: —organic radicals — alcohols — ethers — haloid ethers — aldehydes — monobasic acids — anhydrides — ethereal salts — organo-metallic bodies.’[91] The pattern was also repeated in the ‘Honours Examination’ paper in organic chemistry, where students had to ‘[g]ive the constitutional formulae, both symbolic and graphic, of the following compounds: — Ethyl, trimethylamine, zincmethyl, sulphovinic acid, ethylene, isopropylic alcohol, allylic alcohol.’[92]

In the exams on inorganic chemistry, questions about graphic formulae were omitted from the elementary questions, but included in the advanced and honours examination papers. The advanced paper asked students to ‘[g]ive the names and formulae, symbolic and graphic, of the compounds of nitrogen with oxygen and hydrogen […]’, whereas the honours paper asked for ‘the symbolic and graphic formulae of the acids and anhydrides of phosphorus.’[93] DSA exam papers from later years show that Frankland continued to test students’ knowledge of line-and-letter formulae in the same rigorous manner, and that this approach was also continued by Frankland’s successors. By way of illustration, each of the organic and inorganic exam papers for the 1877 exams – produced collaboratively by Frankland and Henry Enfield Roscoe – contains at least one question requiring students to draw line-and-letter formulae.[94] This makes it very clear that each student who took the Department’s chemistry exams after 1869 was prompted to learn the new notation – ignoring or avoiding the formulae was not an option. The DSA syllabus and exam papers thus drove and facilitated the appropriation of line-and-letter formulae on a national scale.

To conclude, I have argued in this section that any student enrolled in one of the Department’s chemistry classes could not help but to learn how to handle the new graphic formulae, since using the new notation formed an integral part of the learning process. Even a student who attended just an elementary course in inorganic or organic chemistry had no choice but to learn

[90] Science and Art Department, *Examination Papers for Science Schools and Classes: May 1869* (London: [printed by Eyre & Spottiswoode], 1869), p. 46.
[91] Ibid, p. 47.
[92] Ibid, p. 48.
[93] Ibid, pp. 44-45.
[94] Cf. Science and Art Department, *Examination Papers for Science Schools and Classes: May 1877* (London: [printed by Eyre & Spottiswoode], 1877), pp. 51-57.

the formulae: attending one of the very first chemistry lessons, the student was introduced to the curious diagrams by a skilled teacher who had previously trained with Frankland in South Kensington during his summer vacation. Having witnessed his teacher explaining the formulae printed on a poster or drawn on the black board in the classroom, the student then returned home with homework to be prepared for the following lesson. Sitting at his desk, the student not only practiced how to write an accurate summary of his chemistry lesson, but also how to draw line-and-letter formulae of various chemical compounds, since this was one of the questions that he would most certainly find on his exam paper in the following May. In order to complete the task, the student was – fortunately enough – not left entirely to his own devices, since he had a number of suitable textbooks at his disposal. If he chose Frankland's *Lecture Notes* or any of the other books with line-and-letter formulae that had been published since the late 1860s, and if he followed the prescribed regime of writing and reading, the studious disciple was certain to learn how to "think" and to communicate chemistry by means of Frankland's lines and letters, be it on paper or in his own mind.

We have seen in this section that it is not always possible to explain with absolute certainty why authors, editors, or publishers chose to include line-and-letter formulae in their chemistry textbooks. However, in consideration of the evidence presented in this section, it is reasonable to posit that British authors, editors, and publishers decided to feature line-and-letter formulae because they were competing for a share in a textbook market that was entirely dominated by Frankland's education scheme. Yet, as we have seen in this section, textbooks were only one part of that scheme, which also consisted of personal instruction by skilled teachers, writing exercises, and preparation for annual exams. It was due to this centralised popular education system that over the course of the late 1860s and early 1870s, line-and-letter formulae reached a large number of vocational students in Britain.

4.3. Reception of the New Notation: Public Discourse in Popular Science Magazines

The impact of Frankland's scheme is confirmed by evidence from popular science magazines of that period. In this section, I demonstrate that popular science magazines such as the *English Mechanic* offered their readers a forum for discussing the content taught under Frankland's integrated education scheme. The section analyses the reception of the new line-and-letter diagrams during the period from 1869 to 1873 by following original contributions on the topic of recent development in organic and theoretical chemistry as well as the reaction of the magazine's readers to those contributions. We shall see that large parts of the coverage of the new chemical theories and the novel chemical notation centred on Frankland's education scheme, as was reflected in the frequent mentions of DSA classes and examinations as well as references to Frankland's *Lecture Notes* and other British textbooks that were published in the late 1860s. This, I argue, not only demonstrates that British popular science literature played a major part in the dissemination and appropriation of novel chemical theories and the new chemical formulae, but also that line-and-letter formulae reached indeed a very large and diverse audience through Britain's unique system of popular education under the DSA system.

The *English Mechanic* was a 'cheap mass-circulation science journal' that targeted predominantly working-class readers and covered a very broad range of scientific and technical topics. It was founded by the London-based printer George Maddick in 1865. The magazine was acquired by the journalist and philanthropist John Passmore Edwards in 1867 who, together with his editor Ebeneezer Job Kibblewhite, turned the periodical into a veritable commercial success. The magazine was published weekly and priced at 2d. Between 1866 and 1870, the periodical consisted of 24 tighly-set pages, but the length of the *English Mechanic* was extended to 32 pages in 1871. By that time, the magazine had acquired a large audience and sold over 30,000 copies a week.[95] The distinctive feature of the *English Mechanic* and the main reason for its commercial success was the active role of the readership in shaping the magazine's contents. By the end of the 1860s, six of the magazine's 24 pages were taken up with correspondence and another six pages were devoted to 'Queries' and 'Answers to Queries'. Original contributions – which usually appeared in the form of serial articles – took up between two and three pages of letterpress. The *English Mechanic* therefore relied almost entirely on content contributed by its loyal readers. According to Jim Mussell, the co-operative nature of the journal established the *English Mechanic* as a public space and redefined 'science as provisional, contemporaneous, and located in the dialogic exchange between contributors.'[96] In the late 1860s and early 1870s, the magazine became the place of a public discussion of the new chemical theories and novel chemical formulae that had been circulating in Britain since the mid-1860s.

The first serial article concerned with the new graphic formulae was written by the Manchester-based Swiss chemist Ferdinand Hurter and published between December 1869 and March 1870.[97] In response to the 'rapid progress' of '[s]cientific chemistry' and the subsequent

[95] Cf. Brock, 'Commercial Science Journals', pp. 111-15; and Mussell, James, *Science, Time and Space in the Late Nineteenth-Century Periodical Press: Movable Types* (Aldershot: Ashgate, 2007), pp. 29-36.
[96] Mussell, *Movable Types*, p. 31.
[97] Hurter, Ferdinand, 'Modern Chemical Notation', *English Mechanic*, 10 & 11 (1869-70), 344-45, 503-04, 524, 576-77, 602-03, 653-54 (vol 10), 9 (vol 11).

‘changes in its nomenclature, symbols, and notation’, Hurter’s article aimed to provide a ‘short account of these changes, and of the reasons for their adoption.’ The series opened with a brief discussion of the concepts of ‘equivalents’ and ‘atoms’, then proceeded to outline the history of alchemical and chemical symbols from obscure signs used in the early modern period to Kekulé’s sausage formulae and different variations of line-and-letter formulae.[98] Hurter concluded his series by saying that through providing an overview of the historical development as well as discussing some of the existing issues of modern chemical notation, he hoped to ‘have helped some of the readers of the ENGLISH MECHANIC to an understanding of the leading principles of the modern theory […].’[99] This concluding statements clearly indicates a strong presumed public interest in the profound theoretical changes which organic chemistry had been undergoing since the late 1850s. And indeed, Hurter’s contribution was soon followed by another set of articles on the same subject.

George E. Davis’ two-piece article ‘On Chemical Symbols’ was published just two weeks after the conclusion of Hurter’s series.[100] Similar to Hurter’s article, Davis’ articles focused on the state of the modern chemical notation and nomenclature which, as Davis lamented, ‘are at the present time woefully confused’, with ‘nearly every work taking a different view of matters.’[101] The serial article discussed the various sorts of formulae which populated chemical literature at that time, including ‘Empirical’, ‘Rational’, ‘Typical’, ‘Graphic’, and ‘Constitutional’ formulae, which we must once again see as a reflection of the strong public interest in the recent advances in organic and theoretical chemistry as well as the new formulae by means of which the ideas were represented.[102] Catering to this demand, the editors of the *English Mechanic* commissioned another series of instructive articles in the following year. Authored by the enigmatic science teacher Selimo Romeo Bottone, a new series of articles on chemistry was launched in December 1871 and concluded in November 1872. Comprising more than 240 thematic sections, Bottone’s ‘Lessons on Chemistry’ appeared in irregular intervals of two, three or four weeks, and covered between two and three full pages of the magazine.[103] The purpose of this series was to deliver an accessible yet comprehensive introduction to the fundamental principles of modern chemistry to those readers ‘who, though very anxious to become conversant with this beautiful science, are precluded from doing so, either by the expense attendant on procuring exhaustive works on the subject or by the fear that it is too difficult to

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[98] Idem, ‘Modern Chemical Notation’, *English Mechanic*, 10 (1869), pp. 344-45.
[99] Idem, ‘Modern Chemical Notation’, *English Mechanic*, 11 (1870), p. 9. Emphasis in original.
[100] Davis, George E., ‘On Chemical Symbols: Chapter I’, *English Mechanic* 11 (1870), 49-50; idem, ‘On Chemical Symbols: Chapter II’, *English Mechanic*, 11 (1870), 97-99.
[101] Idem, ‘Chemical Symbols: Chapter II’, p. 99.
[102] Ibid, p. 98.
[103] The first instalment of Bottone’s ‘Lessons’ appeared in *English Mechanic,* 14 (1871-72), 319-21. The last instalment was published in *English Mechanic,* 16 (1872-73), 213-14.

be mastered without very long and tiresome application [...].'[104] According to this agenda, Bottone's 'Lessons' covered every aspect of chemical science, including the most recent developments in chemical theory. As with Hurter's and Davis' contributions before, Bottone made use of line-and-letter diagrams when discussing the 'valency' of elements and the constitution of organic compounds to illustrate his ideas.[105]

Readers of the *English Mechanic* met Hurter's, Davis', and Bottone's works with great interest. Bottone's 'Lessons' in particular sparked a lively debate between contributors and readers of the magazine about the notion of valence and the prominent place which this concept occupied in DSA science classes and exams. Disagreeing with Frankland in one of his 'Lessons' in January 1872 and presenting his own interpretation of the valence of each known element in a separate table,[106] Bottone gave rise to a debate between readers of the *English Mechanic* that continued for several years. Readers and contributors who had written previously on chemistry began to quiz Bottone's as well as each other's ideas about possible constitutions of different chemical compounds. In a letter referring to Bottone's table of atomicities, for instance, Davis asked whether Bottone would be so kind to 'explain the constitution, and give in graphic formulas […] the following compounds: — Ferric chloride ($Fe_2 Cl_6$), platinum tetrachloride ($Pt Cl_4$ [sic], iron ammonia alum ($Fe_2 Am_2 2SO_4$), lead orthovanadate ($Pb_3 2VO_4$), lead ortho-phosphate ($Pb_3 2PO_4$), and chromic hexfluoride ($Ch F_6$).'[107] Another regular correspondent known by the pseudonym of 'Beacon Lough', too, employed graphic formulae to discuss and question Bottone's classification of nitrogen as a 'pentad' in one of the latter's contributions to the magazine.[108] To those letters, Bottone duly replied on a regular basis, often employing several of his own line-and-letter formulae to explain his theoretical position.[109] This debate between Bottone, Davis, Beacon Lough and other correspondents was accompanied by a considerable number of queries put forward by readers who requested more information on the subject matter at hand, thereby further adding to the lively exchange of opinions and ideas about the recent developments in organic and theoretical chemistry.

Those readers who were sending enquires about valence and chemical formulae often linked their questions directly to Frankland's education scheme, which shows that those readers did not seek clarification for purely intellectual reasons, but intended to solicit information that would help them to fare well in DSA exams. Concerns about examinations also led readers to

104 Idem, 'Lessons', *English Mechanic,* 14 (1871-72), 319-21 (p. 319).
105 See, for instance, idem, 'Lessons', *English Mechanic,* 15 (1872), 214-15 (p. 214).
106 Idem, 'Lessons', *English Mechanic*, 14 (1871-72), 395-96 (p. 396).
107 Davis, 'Equivalency of Iron and other Elements', *English Mechanic,* 14 (1871-72), 494.
108 Beacon Lough, 'Atomicities: To Mr. Bottone and "Sigma"', *English Mechanic*, 14 (1871-72), 640-41 (p. 641).
109 See, for instance, Bottone, 'Lessons on Chemistry', *English Mechanic,* 14 (1871-72), 589.

enquire about recent textbooks that could help to prepare for the exams by providing at least some guidance to the new DSA questions. And indeed, letters from numerous contributors make it very clear that understanding the concept of valence was vital to doing well in DSA classes and exams, since '[r]ight or wrong, Dr. Frankland's system of chemistry with his atomicities is taught in these classes […]', as Beacon Lough pointed out in his letter from 19 January 1872.[110] To this, George E. Davis added in another letter that graphic formulae are indeed taught in DSA science classes and that as an examined science teacher, he himself 'have found them of great use in teaching organic chemistry […].'[111] However, Davis also took care to explain that against common belief, graphic formulae were in fact not the only notation which was accepted as a correct answer to the DSA questions, assuring the readers of the *English Mechanic* that Frankland had personally told him '"that in the examinations an equal number of marks would be given for a correct answer upon any recognised system" […].'[112]

Davis' last comment about the free choice of notational systems, however, seem to have gone unnoticed, since more and more readers of the magazine began to send in requests for recommendations of books which could help to prepare for the exams. Expressing his concern that 'when I go up for examination (and I am told it has been the same the last few years) that there are two or three questions, out of about eight, which hinge more or less directly on this rational formulae, or on the graphic formulae […]', the correspondent with the pseudonym 'Dabbler' enquired whether he could receive 'some information about rational formulae, and the assumptions upon which it is based [...]', and he said that he would be therefore very 'glad to know what are the best books on graphic formulae.'[113] Bottone and another chemical writer, Alfred H. Allen, responded to this request. Bottone recommended 'Snaith's "Inorganic Chemistry for Elementary Classes," 1s. 6d.; Buckmaster's "Elements of Inorganic Chemistry," 3s.; Frankland's "Lecture notes," 12s.'[114] Allen, on the other hand, simply pointed out that 'it is a lamentable fact, that the Science and Art examinations in chemistry can scarcely be gone through without a special study of one of two or three books, the principal of which is that written by the examiner […]', thereby clearly pointing toward Frankland's *Lecture Notes*.[115] In the same spirit, the correspondent going by the name of A. Stone emphasised in his reply to a query by 'Home Student' that if the enquirer 'wants merely to lookup [sic] chemical theory for the Science and Art Department Examinations he had better read Frankland's "Lecture Notes for Chemical Students" (Van Voorst), or Valentin's "Practical Chemistry," or Buckmaster's.' He

[110] Beacon Lough, 'Lessons on Chemistry', *English Mechanic*, 14 (1871-72), 460.
[111] Davis, 'Examinations, Atomicities, &c.', *English Mechanic*, 15 (1872), 122-123 (p. 122).
[112] Ibid.
[113] Dabbler, 'Rational Formulae', *English Mechanic,* 17 (1873-74), 557.
[114] Bottone, 'Rational Formulae', *English Mechanic,* 17 (1873-74), 608.
[115] Allen, Alfred H., 'Rational Formulae', *English Mechanic,* 17 (1873-74), 608.

justified this selection by saying that the named books contain ‘everything likely to be asked for in the Examinations, and they will give him an advanced idea of the frantic and dazzling system (?) [sic] of notation now in vogue.’[116]

From the above examples, we can clearly see that all of the enquiries showed some familiarity with the revised DSA syllabus, which in turn demonstrates that a good knowledge of line-and-letter formulae was key to doing well in the DSA exams. The examples also show that it was notably in the context of Frankland’s education scheme that the readers had first encountered the concept of valence and the new graphic formulae. Furthermore, the examples make clear that British students learned how to use line-and-letter diagrams by attending DSA classes (or at least sitting for the exams) as well as by using textbooks as learning resources for their studies at home. Finally, we can infer from the frequent references to Frankland’s popular education scheme and the apparent absence of references to specialist journals that although a very large number of DSA students learned how to apply line-and-letter diagrams to solve formalised problems, it is very unlikely that those students regarded the formulae as anything else than learning tools that facilitated engagement with Frankland’s DSA syllabus. This, I believe, led to the rapid growth of a group of diagram users who appropriated the formulae in the context of “cramming” for Frankland’s formalised DSA exams, but who did not apply the formulae as paper tools in a research context.

4.4. Conclusion

This chapter has demonstrated how Edward Frankland strategically exploited Britain’s unique science education infrastructure to create a scheme through which he was able to communicate not only his new theoretical understanding of chemistry, but – most importantly – the new chemical notation to a large audience of British students. Introduced to Frankland’s graphic formulae by their science teachers and practicing the handling of those formulae with the help of suitable and widely available textbooks in the classroom as well as at home, a very large number of British students thus internalised the new symbols as part of their DSA education, although the majority of those students had no aspirations of using the formulae for research purposes. The directed and systematic communication of the new formulae to a mass audience, I conclude, was a feat unique to the British system of popular education which could not have been replicated in any other country in Europe.

[116] Stone, A., ‘Chemical’, *English Mechanic,* 15 (1872), 493-94.

By contrast, we have absolutely no reliable information about the communication mechanism responsible for the circulation and appropriation of the new formulae in Germany. Given the fact that neither the German Confederation nor the German Empire nor any of the individual German states had a system of mass education similar to the DSA, that Frankland's textbook was not translated into the German language,[117] and that only a very small number of textbooks with structural diagrams were available on the German print market prior to 1874, we must infer that German students as well as junior and senior researchers had encountered the formulae by other means that their counterparts in Britain. Yet as I demonstrate in the next chapter, there is irrefutable evidence that the new notation was appropriated very quickly, since from 1865 onwards the number of original research papers with line-and-letter formulae authored by German-educated chemists and published in German periodicals was rapidly increasing. Drawing on this evidence, the next chapter shows that it was predominantly German chemists who began to use the new diagrams as paper tools in specialist periodicals with confidence and in large numbers. Yet how did line-and-letter formulae reach those German chemists in the late 1860s and early 1870s, and which communication practices drove the appropriation of the formulae during when suitable textbooks were not yet readily available? The next chapter is therefore concerned with the dispersion and appropriation of line-and-letter formulae in Germany which, as I claim, occurred primarily by means of scientific periodicals.

[117] Frankland's textbook was neither translated into German, nor was it listed in the contemporary catalogues of German academic libraries, as I demonstrate in the next chapter.

CHAPTER 5

Learning by the Journal: The Important Role of Specialist Periodicals in the Communication of Line-and-Letter Formulae in Germany

The communication of line-and-letter diagrams to German chemists has not been investigated in detail, with the widespread assumption still being that the communication methods adopted by German chemists were similar to those used in the British case. This chapter will challenge and revise the existing account by undertaking an investigation of the communication practices through which line-and-letter diagrams reached German chemists in the late 1860s and early 1870s. In doing so, it aims to make a significant contribution to our current understanding of the development of science communication and chemical education in nineteenth-century Germany.[1] We shall see further below that David Kaiser's account of the dispersion of diagrams does not apply to the German context, and that the way in which line-and-letter formulae were circulated among German chemists was also significantly different from the way it occurred in Britain. Consequently, I propose a novel communication pattern to describe and explain the circulation and appropriation of line-and-letter diagrams in Germany. This explanation is based on the central claim of this chapter: that periodicals were important in the dissemination of new chemical formulae. This is because German chemistry students used specialist periodicals alongside textbooks as learning resources during the late 1860s and early 1870s. By providing this account, the chapter advances our historical understanding of the many different roles that periodicals had played in the transmission and the making of scientific knowledge.

The first section of the chapter outlines the communication practices and institutional arrangements that drove the circulation and appropriation of line-and-letter formulae in Germany. It begins by explaining the unique features of chemical education in Germany and shows that German chemistry students were not only required, but actively encouraged to use research journals in their studies. This stands in stark contrast to the accounts of the communication of new notation offered by Kaiser in respect of Feynman diagrams and Russell in regard to line-and-letter formulae in Britain, with communication in this case not hinging on individual actors, such as Freeman Dyson or Edward Frankland, but rather on the pedagogical

[1] In his 2003 monograph, Peter Ramberg calls attention to this under-researched episode in the history of chemistry when he says that the 'story of exactly how and why chemists in various countries quickly adopted [Crum] Brown's notation through the 1860s has yet to be written […].' (Ramberg, *Chemical Structure*, p. 28.) The current chapter represents the first ever attempt to tackle this problem.

practice of integrating research journals within classroom teaching. This was carried out by a number of early proponents of the structure theory, such as Emil Erlenmeyer, who held teaching positions at different locations in Germany. As a result, German chemistry students, unlike their British counterparts, used periodicals alongside textbooks as learning resources to become acquainted with the new line-and-letter formulae. The remainder of the first section demonstrates how Erlenmeyer, a popular university teacher and former student of Liebig, integrated periodical literature in his own lectures.

The second and third sections of this chapter provide further evidence for my claim that German students used scientific journals along with textbooks to learn how to read and use the new notation. The second section is concerned with the limited availability of Germanophone textbooks containing line-and-letter formulae during the late 1860s and early 1870s. The section demonstrates that only a small number of suitable textbooks were available on the German market for didactic literature, and that in many cases, they were also not available from academic libraries. The third section is concerned with the German print market and library provision of chemistry journals. It begins by explaining why many German and international authors chose to publish their contribution on organic chemistry in German journals, which in the 1860s resulted in the dramatic increase of research articles using line-and-letter formulae. The second part of the section shows that German students had little trouble in accessing periodicals in academic libraries, whereas it was harder for them to access to textbooks because of restrictive library regulations. I conclude that German periodicals constituted more readily accessible learning resources that German students used next to textbooks in order to become familiar with the new formulae in the late 1860s and early 1870s.

5.1. Learning Lines and Letters in Nineteenth-Century Germany

As I mentioned in the introductory chapter, both Kaiser's account of the adoption of Feynman diagrams and Russell's account of the communication of line-and-letter diagrams in Britain, developed further in the preceding chapter, are centred on individual communicators – Freeman Dyson and Edward Frankland, respectively.[2] In the German case, the distribution pattern was more complex. Two reasons are worth highlighting for consideration here: first, the pluricentric nature of the German pedagogical landscape characterised by the absence of national curricula for schools and universities and, secondly, the relatively large number of academic positions

[2] Cf. Kaiser, *Drawing Theories Apart,* Chapter 3; Russell, *Frankland*, Chapter 10.

available at Germany's chemical teaching and research institutes.[3] The number of individuals who took an active part in the promotion of line-and-letter formulae during the 1860s was consequently much higher than in Britain, where chemical education remained almost exclusively in Frankland's hands from the mid-1860s to the late 1880s. Drawing on my list of early diagram users (Appendix) as well as published biographical accounts, I have identified a number of diagrammatic pioneers who played a leading role in the communication of line-and-letter formulae to German chemistry students during the late 1860s. I argue in this section that instead of one leading figure, there were a number of German pioneers who began introducing university students to the new notation through personal instruction at different locations. Furthermore, I claim that the students who were introduced to the formulae in the 1860s often used specialist periodicals along with textbooks, which was the result of the unique German model of research-based learning that required university students to use current research literature alongside other learning resources in their studies.

Among the German diagrammatic pioneers, Emil Erlenmeyer was without any doubt one of the most influential promoters of the new chemical notation, as we shall see further below.[4] Erlenmeyer studied with Justus Liebig and Heinrich Will in Giessen, and was awarded a PhD in 1850. He completed his Habilitation under Bunsen in Heidelberg in 1857 and continued to work there as a Privatdocent (untenured university lecturer) until he was awarded a full professorship at the newly founded Polytechnische Schule München (Munich Polytechnic School) in 1868.[5] My biographical survey of the names of early diagram users listed in the Appendix indicates that a number of students were most likely introduced to the notation by Erlenmeyer in person.

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[3] For an introduction to the history of chemical education in the German lands, see Homburg, Ernst, 'Two Factions, One Profession: The Chemical Profession in German Society, 1780-1870', in *The Making of the Chemist*, pp. 39-76.

[4] However, it is not clear where pioneers such as Erlenmeyer and Baeyer had first encountered line-and-letter formulae before they began using the diagrams in their own teaching and research.

[5] For more biographical details, see Rocke's most recent publication 'Theory versus Practice in German Chemistry: Erlenmeyer beyond the Flask', *Isis*, 109.2 (2018), 254-75. The most comprehensive account of Erlenmeyer's scientific work is Meyer's doctoral thesis 'Erlenmeyer'. The position of Privatdocent (also spelled Privatdozent) is a teaching position that was created in the eighteenth century, and which still exists at German universities today. Privatdocenten are untenured university lecturers who have completed a post-doctoral dissertation ('Habilitationsschrift') and were given the authorisation to teach at university level ('venia legendi'). Privatdocenten often find themselves in precarious positions because their lectureship carries 'prestige but no salary or corporate rights.' (Charles McClelland, *State, Society, and University in Germany: 1700-1914* (Cambridge: Cambridge University Press, 1980), p. 165.) For an overview of the history of the former Polytechnische Schule München, now Technische Universität München, see Hermann, Wolfgang A., ed, *Technische Universität München: Die Geschichte eines Wissenschaftsunternehmens*, 2 vols (Berlin: Metropol, 2006). For an overview of the devopment of technical education in Germany, see König, Wolfgang, 'Zwischen Verwaltung und Industriegesellschaft: Die Gründung höherer technischer Bildungsstätten in Deutschland in den ersten Jahrzehnten des 19. Jahrhunderts', *Berichte zur Wissenschaftsgeschichte*, 21 (1998), 115–22.

Ludwig Darmstaedter (1846-1927) and Albert Ladenburg (1842-1911), for example, started publishing research articles that featured line-and-letter formulae only a very short time after they came in contact with Erlenmeyer.[6] Similarly, the biographies of Carl Graebe and Carl Liebermann strongly suggest that these two chemists were introduced to line-and-letter formulae by the prolific researcher and future Nobel Prize laureate Adolf Baeyer during their stay in Berlin. Baeyer had acted as Liebermann's PhD advisor between 1862 and 1865, whereas Graebe worked on his Habilitation project in Baeyer's laboratory at Königliches Gewerbe-Institut (renamed Königliche Gewerbeakademie in 1866) between 1865 and 1868.[7] In 1867 and 1868, Liebermann and Graebe were working together in Baeyer's laboratory on synthetic dyes before becoming industrial researchers at the Badische Anilin- und Sodafabrik (BASF) in 1868. The two chemists began publishing papers with line-and-letter formulae in 1867.[8] In addition, diagrammatic pioneers were teaching at locations such as the University of Göttingen (Heinrich Ludwig Buff and Rudolf Fittig) and the University of Tübingen (Adolf Strecker), and they served as active promoters of the new formulae. Although evidence to confirm every individual case from primary sources is scarce, it is reasonable to posit that there were a number of teachers who made use of the new formulae in their lectures and classes at different university locations throughout Germany.[9]

Diagrammatic pioneers such as Erlenmeyer and Baeyer were working as academic researchers and educators at chemical institutes that shared a number of characteristic features. Jeffrey Johnson's foundational paper 'Academic Chemistry in Imperial Germany' (1985) establishes a number of these features: 1) the first generation of chemical institutes had been established before 1866; 2) they were predominantly state-funded; 3) they provided training in

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[6] Ladenburg first used the diagrams in a research paper that he co-authored together with Charles Friedel (1832-1899) in 1867, and Darmstaedter published his first paper with line-and-letter formulae in 1868. Cf. Friedel, Charles, and Albert Ladenburg, 'Ueber die Synthese eines Kohlenwasserstoffs und dessen Constitution', *Annalen der Chemie*, 142 (1867), 310-22; and Darmstaedter, Ludwig, 'Ueber die relative Constitution und einige Metamorphosen des Epichlorhydrins', *Annalen der Chemie*, 148 (1868), 119-31.

[7] For an overview of the history of the former Gewerbeakademie, now Technische Universität Berlin, see Bruch, Rüdiger vom, 'Von der Bergakademie zur Technischen Universität Berlin', in *Von der Phlogistik zur modernen Chemie*, ed. by Michael Engel (Berlin: Engel, 1994), pp. 260–74.

[8] Graebe, Carl, and Carl Liebermann, 'Ueber Alizarin und Anthracen', *Zeitschrift für Chemie*, 11 (1868), 279-81; idem, 'Ueber Farbstoffe aus der Anthracengruppe', *Berichte*, 1 (1868), 104-06; idem, 'Ueber den Zusammenhang zwischen Molecularconstitution und Farbe bei organischen Verbindungen', *Berichte*, 1 (1868), 106-08; idem, 'Ueber Anthracenderivate', *Berichte*, 1 (1868), 186-89.

[9] However, the Appendix also lists a number of formulae users without any apparent affiliations with structural pioneers such as Erlenmeyer, Baeyer, and others. The majority of individuals in this group are senior researchers in advanced academic positions, for instance Adolf Claus (1838-1900) at the University of Freiburg, or Heinrich Limpricht (1827-1909), Hugo Schwanert (1828-1902), and Robert Otto (1837-1907) at the University of Greifswald. By way of illustration, Claus held the position of associate professor (außerordentlicher Professor) in 1868 when he started using line-and-letter formulae in his research publications, yet it is not clear who had pitched the new diagrams to him. Similarly, Limpricht, Schwanert, and Otto held senior positions when they began using the formulae in 1868.

practical and theoretical research skills; and 4) these chemical institutes offered advanced students the opportunity to participate in research programmes that were overseen by each institute's director. Johnson's lists identifies a total of eight first-generation institutes that were partly or fully associated with the universities of Breslau, Erlangen, Giessen, Göttingen, Halle, Heidelberg, Königsberg, and Marburg.[10] These were but the first generation of chemical institutes: many more institutes were established between 1866 and 1895. The vast majority of these second-generation institutes had teaching and research agendas with a very strong focus on organic chemistry.[11] In addition, the second generation of institutes usually featured huge buildings designed to accommodate a large growing number of students and academic members of staff.[12] The new institutes functioned as centres of training as well as research, and in this capacity 'provided the new [chemical] industry with most of the trained organic chemists and marketable synthetic compounds it needed […].'[13] As a result, we can see that the last third of the nineteenth century witnessed the expansion of teaching and research institutions across the whole of the German Confederation and the wider German Empire that not only attracted a growing number of students, but also offered new teaching positions for academic chemists.[14]

The idea that chemistry students should be trained in research methods and undertake research projects as part of their formal training is commonly as associated with Justus Liebig's 'Giessen School', 'Giessen Model', or 'Giessen System' of chemical education. Liebig had gradually developed his pedagogical agenda and research programme over the course of the 1830s and 1840s. In the following decades, the Giessen Model was appropriated by other educational establishments in Germany and abroad.[15] Consequently, the majority of the diagrammatic pioneers who were teaching at German institutions in the 1860s and 1870s had been trained under Liebig's scheme, which in turn means that the pioneers were likely to replicate Liebig's research-based approach to chemical training in their own syllabi.

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[10] Johnson, 'Academic Chemistry', Table 1, p. 502.

[11] The only chemical institute with an explicit focus on inorganic and physical chemistry at that time was Robert Wilhelm Bunsen's laboratory at the University of Heidelberg (f. 1855). See Nawa, Christine, 'A Refuge for Inorganic Chemistry: Bunsen's Heidelberg Laboratory', *Ambix*, 61.2 (2014), 115-40.

[12] Catherine Jackson has recently demonstrated that the design of those new laboratory buildings reflected the institutes' purpose of training students in organic research methods on a mass scale. Cf. Jackson, 'Chemistry as the Defining Science: Discipline and Training in Nineteenth-Century Chemical Laboratories', *Endeavour*, 35 (2011), 55-62.

[13] The following second-generation institutes were established in the 1860s and 1870s: Berlin, Bonn, Kiel, Leipzig, München, Strassburg, Tübingen, and Würzburg (Johnson, 'Academic Chemistry', Table 1, p. 502).

[14] In addition, university graduates found new career opportunities at the growing number of polytechnic schools that were being established in the German states during the second half of the nineteenth century (Homburg, 'Two Factions', pp. 70-71).

[15] Cf. Fruton, *Contrasts*, pp. 17-20; and Rocke, 'Origins and Spread of the "Giessen Model" in University Science', *Ambix*, 50.1 (2003), 90–115 (pp. 100-01).

Characteristic Features and Impact of the Giessen Model on Teaching and Learning Practices in German Chemical Education

Beyond developing a model of chemical education that established research as a part of the chemical curriculum, the broader contributions of Liebig to the making of modern chemistry is well documented. Studies by Jack Morrell (1972), Frederic L. Holmes (1989), Regine Zott and Emil Heuser (1992), Brock (1997, 2003), Rocke (2003), and Jackson (2006), among others, have demonstrated that Liebig's research school not only reformed chemical education, but also laid the foundation for the gradual professionalisation and institutionalisation of chemistry as an independent academic discipline during the first half of the nineteenth century. While Liebig's Giessen institute was not the first facility in the German lands to provide a chemical laboratory where students could train their experimental skills, Liebig was the first one to introduce a systematic research-based training scheme. The scheme combined rigorous practical exercises with lectures and regular examinations, in which the practical and theoretical parts were designed to complement each other. After acquiring basic knowledge, Liebig's students were trained in research methods before they were given research projects at the end of their studies, on which they worked together with Liebig. Although Holmes' 1989 study has shown that only a minority of students who had attended the Giessen institute eventually became independent research chemists, historians agree that Liebig's systematic laboratory training played a key part in making successful researchers.[16] However, testimonies of Liebig's students make it very clear that examinations and engagement with recent scholarship in the form of journal literature also played an equally important part in this process. It was, in fact, Justus Liebig and his elaborate Giessen Model of chemical research and education that resulted in the systematic use of periodicals as learning resources.

The most comprehensive collection of close-up descriptions of Liebig's teaching style and everyday laboratory life are found in Jacob Volhard's seminal two-volume biography *Justus von Liebig* from 1909.[17] In his description of what Liebig expected from his more advanced

[16] Seminal works on the Giessen Model include Morrell, 'Chemist Breeders'; Holmes, Frederic L., 'The Complementarity of Teaching and Research in Liebig's Laboratory', *Osiris*, 2nd ser., 5 (1989), 121–64; Fruton, *Contrasts*, Chapter 2; Brock, 'Breeding Chemists in Giessen', *Ambix*, 50.1 (2003), 25–70; idem, *Liebig*; and Rocke, 'Origins and Spread'. The Giessen Model is also discussed in Zott, Regine, and Emil Heuser, eds., *Die streitbaren Gelehrten: Justus Liebig und die preußischen Universitäten* (Berlin: ERS-Verlag, 1992); A critical revision of the history and historiography of research schools in chemistry is provided in Jackson, 'Research School'. On Liebig's international network of former students, see Schwedt, Georg, *Liebig und seine Schüler: Die neue Schule der Chemie* (Berlin: Springer, 2002); and Busse, Neill, *Der Meister und seine Schüler: Das Netzwerk Justus Liebigs und seiner Studenten* (Hildesheim: Georg Olms Verlag, 2015).

[17] Volhard, Jacob, *Justus von Liebig*, 2 vols (Leipzig: Barth, 1909), I, pp. 86-99.

students, Volhard not only says that the students were to be able to work independently on their assigned research projects, but also that students were to be capable of 'finding their way around chemical literature' ('sich in der chemischen Literatur zurechtzufinden').[18] Furthermore, Volhard explains that Liebig developed many of the research projects for his advanced students from his own 'literary activity' ('literarische Tätigkeit'), which strongly implies that Liebig assigned to his students worthwhile research questions that he had found in specialist publications. This also implies that the students were expected to engage with the said literature in order to follow up on the most recent scholarship that was related to their research assignment.[19] Finally, Liebig strongly encouraged his advanced students to publish their experimental results in his own *Annalen der Chemie*, which meant that students became proficient with the culture of specialist communication during their studies. In conclusion, the student testimonies and autobiographical notes collected in Volhard's book reveal that Liebig's students were not only required to engage in original research, but also to engage with periodical research literature as part of their training programme in Giessen. In consideration of the lasting impact of the Giessen Model on chemical education in Germany, it is therefore reasonable to posit that other educators followed Liebig's lead and actively promoted the use of specialist periodicals as an integral part of chemical training.

Drawing on Emil Erlenmeyer's teaching practices as a case study, we shall see that the use of periodical literature was in fact part and parcel of how chemistry was learnt in German universities. Indeed, evidence from primary sources demonstrates how Erlenmeyer, as a former Giessen student, went on to make frequent references to periodical literature in his own lectures. Erlenmeyer was an experienced teacher and prolific researcher who made significant contributions to the theory of chemical structure.[20] After completing his doctoral studies under Liebig and Will in Giessen in 1850,[21] and having worked for five years as a pharmacist in a small town in the Duchy of Nassau, Erlenmeyer decided to continue his research career at Heidelberg, a university town in the Grand Duchy of Baden, which in the late 1850s became one of the early breeding grounds for the emerging theory of chemical structure.[22] In Heidelberg, Erlenmeyer joined August Kekulé's private laboratory at some point between winter 1856 and spring 1857. He completed his Habilitation and became Privatdocent in 1857. From spring 1857 to Kekulé's relocation to Ghent in November 1858, the two Privatdocenten Kekulé and Erlenmeyer had

[18] Ibid, p. 88.
[19] Ibid, p. 94. Cf. also Volhard, 'Justus v. Liebig sein Leben und Wirken', *Annalen der Chemie: Supplementband*, 328 (1903), 1-40 (p. 16).
[20] Rocke, 'Theory versus Practice'.
[21] Fruton, *Contrasts*, p. 30; Brock, *Liebig*, p. 62.
[22] Cf. Rocke, *Image and Reality*, pp. 109-17.

been sharing facilities and working side by side in the same building.[23] From the late 1850s onwards, Erlenmeyer was also closely associated with other structural pioneers, such as Alexander Crum Brown, Alexandr Butlerov, and Adolf Baeyer, on a professional as well as a personal level.[24]

Erlenmeyer became associate professor (außerordentlicher Professor) at the University of Heidelberg in 1863, where he remained until receiving and accepting a call to the Polytechnische Schule München in 1868. Printed biannual records of lectures and classes held at the University of Heidelberg indicate that Erlenmeyer began his teaching career with lectures on 'technological chemistry' ('Technische Chemie') before shifting his pedagogical profile to organic chemistry. Erlenmeyer taught his first class on organic chemistry – a 'Repititorium', or examination review course – in the winter semester of 1859-60, while his first proper university lecture with emphasis on organic chemistry ('Organische Experimentalchemie') followed in the winter semester of 1860-61. He continued to give this lecture each semester until relocating to München in autumn 1868.

The archive of the Deutsche Museum in München preserves a number of Erlenmeyer's lecture notes from his time as Privatdocent in Heidelberg and as professor in München. Indexed as 'Lecture manuscripts: organic chemistry' ('Vorlesungsmanuskripte: organische Chemie') in the museum's Erlenmeyer Collection, the majority of handwritten sheets are unfortunately undated.[25] However, Erlenmeyer's historic lecture notes leave no doubt that the lectures included a significant number of bibliographic references to research articles published in German and foreign periodicals. It is also important to point out that many of the references refer to line-and-letter formulae included in the notes. By way of illustration, one specific structural diagram bears the references 'Plöchl.BB.16.2817' (Figure 5.1), which is Erlenmeyer's shorthand notation for J. Plöchl's paper 'Ueber Phenylglycidasäure (Phenyloxacrylsäure)' published in volume 16 of the *Berichte der Deutschen Chemischen Gesellschaft* in 1883 (Figure 5.2).[26] The two examples below illustrate that this system of referencing allowed students to follow the diagrams from Erlenmeyer's chemistry lecture to the exact page of the journal in which the diagram had originally appeared. This, I conclude, is good evidence for the integral

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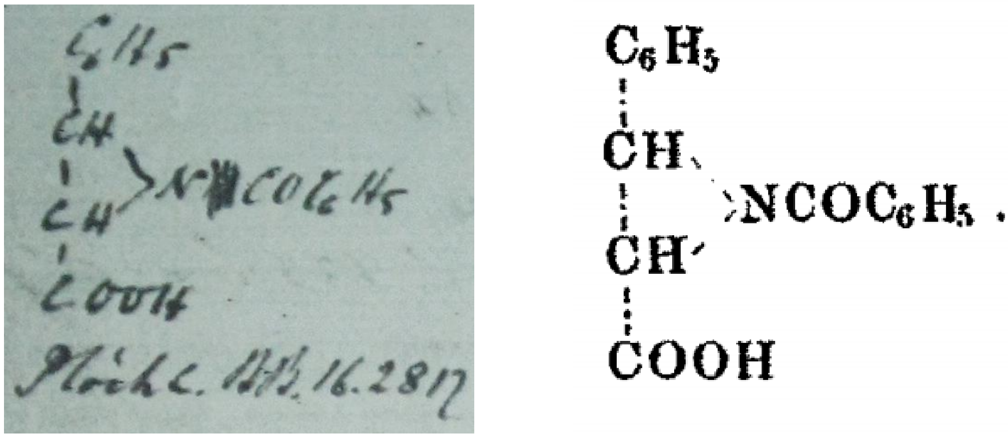
[23] Kekulé's modest establishment was located at the heart of Heidelberg and included two small laboratory spaces as well as a tiny lecture room. Cf. Anschütz, *August Kekulé*, 2 vols (Berlin: Verlag Chemie, 1929), I, p. 66.
[24] We cannot exclude the possibility that Erlenmeyer was introduced to line-and-letter diagrams through written correspondence with Crum Brown. However, my survey of the correspondence between the two researchers did not produce any evidence to support this hypothesis. The eight letters in question are located in ADM, Handschriften-Sammlung, Signatur HS 1967-77/1-8.
[25] ADM, HS 1968-589/1-6.
[26] Plöchl, J., 'Ueber Phenylglycidasäure (Phenyloxacrylsäure)', *Berichte*, 16 (1883), 2815-25 (p. 2817).

part that periodical literature played in chemical education at German universities in the nineteenth century.



Figures 5.1 & 5.2: Handwritten diagram for ‘Anhydrid einer Benzoylimidozimmtsäure’ in Erlenmeyer’s lecture notes with bibliographic reference (left) and the same diagram in the referenced paper (right).[27]

The evidence presented in this section gives us very good reason to believe that German chemistry students made frequent and systematic use of specialist periodicals during their studies because this was strongly encouraged by Liebig’s pedagogical agenda. Furthermore, Erlenmeyer lecture notes show clearly that chemistry teachers who had been educated according to the Giessen Model were very likely to continue Liebig’s tradition of research-based learning by integrating periodical literature in their everyday teaching. Given that a relatively large number of line-and-letter diagrams were published in German specialist periodicals during the late 1860s (see, again, Appendix), I conclude that research journals had played an integral part in the learning process of German students who were studying organic chemistry during that period. I provide further evidence for this argument in the following two sections of this chapter, where I explore and contrast the availability of Germanophone textbooks to specialist periodicals. The next section investigates the German print market and library provision for suitable didactic literature. The third section does the same for German chemistry journals. Taken together, the two sections demonstrate that periodicals came to function as the primary learning resources involved in introducing students to line-and-letter formulae, at least in part because they were more readily available and accessible to students than textbooks.

[27] ADM, HS 1968-589/6 (left); Plöchl, ‘Ueber Phenylglycidasäure’, p. 2817 (right).

5.2. German Chemistry Textbooks and the 'Wide Gap' Between Research and Instruction in the Late 1860s and Early 1870s

This section is concerned with the German print market and library provision for textbooks in the late 1860s and early 1870s. Drawing on historic library catalogues as well as booksellers' lists, I demonstrate in the first part that the availability of Germanophone chemistry textbooks with line-and-letter formulae was very limited. We shall see that, in contrast to the comparatively large number of textbooks that were available in Britain by the late 1860s, only a small number of suitable textbooks had appeared in Germany during the same period. The second part of the section demonstrates that academic libraries were slow to procure relevant didactic literature, and that there were significant local differences between libraries regarding the number of available textbooks titles, thereby adding more substantial evidence to the argument that German chemistry students used periodicals next to textbooks to learn how to interpret and use the new chemical notation.

Chemistry in the Marketplace: German Textbook with Line-and-Letter Diagrams in the Late 1860s and Early 1870s

> In the field of academic chemistry a powerful change has taken place in the last decades, yet most textbooks on this subject still speak a language untouched [by this development]; [the textbooks] ignore, to a greater or lesser extent, those facts and standpoints that are being attested great importance in scientific research. And so a wide gap separates scientific research from scientific instruction.
>
> – Heinrich Ludwig Buff, 1868.[28]

As I explained at the beginning of this chapter, new evidence indicates that textbooks played a less important role in the communication of the new structural notation in Germany than was

[28] 'Auf dem Gebiet der wissenschaftlichen Chemie hat sich in den letzten Jahrzehnten ein mächtiger Umschwung vollzogen, aber noch reden die meisten Lehrbücher dieser Wissennschaft eine davon unberührte Sprache; sie lassen Thatsachen und Gesichtspunkte, denen man in der forschenden Wissenschaft eine hervorragende Bedeutung zu erkennt, mehr oder weniger unberücksichtigt. Und so trenn eine weite Kluft die forschende Wissenschaft von der lehrenden.' (Buff, Heinrich Ludwig, 'Kurzes Lehrbuch der anorganischen Chemie entsprechend den neueren Ansichten von H. L. Buff, Dr. ph., Privatdocent der Chemie an der Universität zu Göttingen. Erlangen, Verlag von Ferdinand Enke. 1868. XXVII und 436 Seiten gross Octav', in *Göttingische Gelehrten-Anzeiger*, 129 (1868), 326-37 (pp. 326-27).

the case in Britain, where Frankland's educational scheme facilitated the wide circulation of his *Lecture Notes* as well as comparable textbooks. In Germany, no such system was in place, and copies of Frankland's *Lecture Notes* were not available on the German market for educational literature, as the following survey of German catalogues and booksellers' lists demonstrates. An exhaustive review of the cumulative bibliography *Vierteljahrs-Katalog aller neuen Erscheinungen im Felde der Literatur in Deutschland* (*Quarterly Catalogue of New Literature Published in Germany*) for the period from 1866 to 1874 has revealed that neither the 1866 nor the 1870-72 edition of Frankland's *Lecture Notes* was ever appropriated for the German market. The *Vierteljahrs-Katalog* was the most comprehensive booksellers' bibliography of Germanophone literature in the nineteenth century. The bibliography was published quarterly and listed new titles of books, periodicals, maps, and atlases that had been published by German publishers and booksellers in the preceding three months. In addition, the bibliography also listed reprints of foreign titles that had previously appeared in another country, but were then reissued by German publishers for the German market.[29] The fact that Frankland's *Lecture Notes* was not listed in the *Vierteljahrs-Katalog* also indicates that the textbook was never translated into the German language. The results of this search suggests that *Lecture Notes* was not routinely stocked by German booksellers. Thus, the *Lecture Notes* never had a strong pedagogical impact in the German lands as it did in Britain. So which other textbooks might German students have used to familiarise themselves with the new line-and-letter formulae?

Due to the lack of systematic studies into the history of German chemistry textbooks from the second half of the nineteenth century, we do not have a complete list of didactic works with line-and-letter diagrams that were published in that period.[30] There are, however, inventory lists of historic book collections that provide a very good first overview of the main textbooks from that period, most important of which is the inventory list of the Hofmann Library in Berlin.[31] My survey of the list revealed that the overall number of late-1860s Germanophone

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[29] *Vierteljahrs-Katalog aller neuen Erscheinungen im Felde der Literatur in Deutschland: Nach den Wissenschaften geordnet*, 43 vols (Leipzig: J. C. Hinrichs'sche Buchhandlung, 1846-88). The bibliographical information was collected and compiled by the publisher and wholesaler Hinrich'sche Verlagsbuchhandlung in Leipzig, and the whole project was subsidised by the Börsenverein des Deutschen Buchhandels. For more details, see Kastner, Barbara, 'Statistik und Topographie des Verlagswesens', in *Geschichte des deutschen Buchhandels im 19. und 20. Jahrhundert*, ed. by Historische Kommission des Börsenvereins des Deutschen Buchhandels, 3 vols in 6 parts ([Frankfurt am Main: Buchhändler-Vereinigung], 2001-15), I.2: *Das Kaiserreich 1871-1918*, ed. by Georg Jäger (2003), pp. 300–67.

[30] Bettina Haupt's aforementioned survey extends only to 1850. Cf. Haupt, *Chemielehrbücher*. Future historians would therefore greatly benefit from detailed studies in the history of German chemistry textbooks during the second half of the nineteenth century.

[31] Covering monographs in chemistry and related areas, the library was established and curated by August W. Hofmann as his own private book collection before it was incorporated into the official library of Deutsche Chemische Gesellschaft (DCG) in 1893. To my knowledge, the inventory list is the most comprehensive list of the historic chemical literature of Germany in existence. However, the early

textbooks with line-and-letter formulae was surprisingly low. Consequently, none of the textbooks published in the German lands prior to 1868 made use of line-and-letter formulae in the same way as the *Lecture Notes* and other English textbooks did, and it was only after 1868 that Germanophone textbooks featured the new diagrams in greater numbers. Yet, as I have mentioned on several occasions before, German researchers had been making systematic use of the new notation in their research articles since 1864 (see, again, Appendix). The production of suitable textbooks thus lagged behind the state of chemical research, just as Heinrich Ludwig Buff pointed out in the epigraph above. As we shall see below, only five German titles with line-and-letter formulae were published in the late 1860s, thereby indicating that the market for Germanophone chemistry textbooks with line-and-letter diagrams was not as well developed and dynamic as the British market, where students were able to choose between nine different textbooks by 1869.

The first Germanophone textbook with line-and-letter formulae was Buff's short introductory work *Grundlehren der theoretischen Chemie* (1866).[32] However, this book did not elaborate on the function of the new formulae – it simply depicted the formulae as one possible notation to express ideas about chemical constitution according to the principles of valence and structure. Furthermore, Buff provided no systematic introduction to the new notation, and the formulae were employed only sporadically throughout the book. More German textbooks with line-and-letter formulae appeared two years later. These were Buff's *Kurzes Lehrbuch der anorganischen Chemie* (1868), Roscoe's and Schorlemmer's aforementioned *Kurzes Lehrbuch der Chemie* (1868), and Adolf Strecker's *Kurzes Lehrbuch der organischen Chemie* (1868).[33] Yet, again, these books did not employ the formulae systematically to classify compounds or to explain their chemical properties in the way Frankland did in his *Lecture Notes*. In addition, the books also frequently included other notational systems such as type formulae so that the number of line-and-letter formulae in those books remained comparatively low. The first German textbook to systematically employ a large number of visual formulae in the discussion of organic compounds was Erlenmeyer's *Lehrbuch der organischen* Chemie (1868-69).[34] Two

history of the Hofmann Library collection is not well documented, and it remains unclear which of the books in the collection originally belonged to Hofmann and which titles were added later. Between 1901 and 1944 the library was located in the Hofmann Haus, the DCG's headquarters in Berlin. The library stock reached approximately 8000 titles by 1944. In 1945, the library was confiscated by Soviet troops and taken to Moscow. After the fall of the Soviet Bloc, Humboldt University's Science Library took charge of the remaining 5500 titles of the Hofmann Library collection. For details, see Fontius, Julia, and Bernd Fichte, 'Sammlung mit wechselnden Standorten: Hofmann-Bibliothek', <https://www.ub.hu-berlin.de/de/standorte/erwin-schroedinger-zentrum-zwbib-nawi/standort-informationen/besondere-sammlungen-2/hoffmann-bibliothek-1.html> [accessed 18 August 2018]. I would also like to thank head librarian Ida-Maria Mäder for providing additional information and access to the library catalogue.

[32] Buff, *Grundlehren*.

[33] Idem, *Kurzes Lehrbuch*; Roscoe, *Kurzes* Lehrbuch (1868); Strecker, *Kurzes Lehrbuch* (1868).

[34] Erlenmeyer, *Lehrbuch*.

more textbooks followed in the early 1870s.[35] However, compared to the large number of titles with line-and-letter diagrams that were available to British chemistry students by the mid-1870s, the number of Germanophone textbooks on the German market remained small.

To conclude, we have seen in the first part of this section that the German market for didactic literature did not offer as much variety in terms of suitable textbooks as the British market. However, the number of different titles alone is not a good indicator for the way in which textbooks were used. James Secord's foundational study of reading practices and readers' responses to the *Vestiges of the Natural History of Creation*, along with Josep Simon's study of the production, circulation, and appropriation of physics textbooks in France and Britain, made it clear that different groups of readers had different means of accessing and reading books.[36] Above all, these two studies show that libraries were popular reading locations. In addition, Simon's study has demonstrated that in the context of formal education, students often chose to consult textbooks in school and university libraries, especially when studying intensively for an examination.[37] So is it not possible that libraries stocked some of the textbooks that I have mentioned above? With regard to the circulation and appropriation of textbooks that were not widely available on the market, it might seem reasonable to presume that those textbooks were stocked by libraries that were regularly frequented by students. However, we shall see in the second part of this section that the early German textbooks with line-and-letter diagrams were not evenly distributed and were not widely available at academic libraries, which once again indicates that those textbooks were not read by a large audience in the 1860s.

New Textbooks and Where to Find Them: German Library Provisions for Chemistry Textbooks in the Late Nineteenth Century

University libraries, along with the two national libraries of Austria and Prussia, were the largest and most frequented libraries in the German lands. The increase in the number and size of those libraries was a direct result of the far-reaching higher education reforms undertaken by Prussia and other German states during the first half of the nineteenth century. The number of German universities experienced a drastic decline over the course of the eighteenth century and during

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[35] Schorlemmer, *Kurzes Lehrbuch der Kohlenstoffverbindungen oder organischen Chemie. Zugleich als zweiter Band von Roscoe's Kurzem Lehrbuch der Chemie* (Braunschweig: Vieweg, 1871); Wislicenus, *Adolf Streckers kurzes Lehrbuch der organischen Chemie*, 6th edn (Braunschweig: Vieweg, 1874).
[36] Secord, *Victorian Sensation: The Extraordinary Publication, Reception, and Secret Authorship of Vestiges of the Natural History of Creation* (Chicago, IL: University of Chicago Press, 2000); Simon, *Communicating Physics*.
[37] Cf. Simon, *Communicating Physics*, Chapter 7.

the Napoleonic Wars. As part of its effort to rebuild and strengthen the nation, Prussia began to establish new universities and to reform existing institutions at the beginning of the nineteenth century. Prussia's reforms of its universities and other segments of its educational system were based on an educational ideology that was developed by Wilhelm von Humboldt (1767-1835), Friedrich Schleiermacher (1768-1834), and Johann Gottlieb Fichte (1762-1814). At the core of this neo-humanistic ideology was the concept of the university as a research institution where professors would not merely reproduce knowledge, but also engage in research to produce new knowledge, and to communicate this new knowledge directly to their students. These reforms had a profound impact on the development, status, organisation, and funding of university libraries because the libraries were assigned a central role in implementing the neo-humanistic ideology by providing the universities the necessary knowledge resources to fulfil their role as institutions of integrated teaching and research. For this purpose, university libraries were allocated state funds that allowed them to gradually increase the number and breadth of their stocks.[38]

Consequently, these libraries experienced an increasing influx of users from academic and non-academic backgrounds, among whom members of academic staff as well as students of higher education institutions formed the two largest groups. By way of illustration, the administration of the Royal Library of Berlin recorded a total of 667 individuals who borrowed books for out-of-library use over the period from March 1828 to March 1829. Out of this total number, 48 individuals identified as 'professors of the Friedrich Wilhelm University' and 10 as professors of other institutions, while 9 individuals identified as Privatdocenten. In addition, the record lists 6 'members of the Academy of Science' and 3 'members of the Academy of Liberal Arts' as well as 38 'Doctors of Philosophy'.[39] The total number of professional scholars thus amounts to 114 individuals. This group of academics is pitted against a total of 331 students of the university, divided into 160 students from the faculty of theology, 46 from the faculty of law, 59 from the faculty of medicine, and 66 from the faculty of philosophy (which included the natural sciences).[40] Another administrative report lists a total of 2300 borrowers in 1863, amongst whom university students formed yet again the largest group with 558 individual users

[38] Cf. Buzás, Ladislaus, *Deutsche Bibliotheksgeschichte der Neuesten Zeit*, 1800-1945 (Wiesbaden: Reichert, 1978), pp. 31-33. Further reference works on the history of German libraries are Weimann, Karl-Heinz, *Bibliotheksgeschichte: Lehrburch zur Entwicklung und Topographie des Bibliothekswesen* (München: Dokumentation Saur KG, 1975); and Schmitz, Wolfgang, *Deutsche Bibliotheksgeschichte* (Bern: Peter Lang, 1984).

[39] Cf. Paunel, Eugen, *Die Staatsbibliothek zu Berlin: Ihre Geschichte und Organisation während der ersten zwei Jahrhunderte seit ihrer Eröffnung 1661-1871* (Berlin: de Gruyter, 1965), p. 205.

[40] Ibid.

for that year.[41] Julius Petzholdt's comprehensive *Addressbuch* for 1875 indicates that the library's main reading room was frequented daily by 200-300 readers.[42]

University students thus represented the single largest group of library users. However, primary sources from the second half of the nineteenth century show that the provisions of libraries did not always match the demands of their users. The availability of textbooks with line-and-letter formulae at academic libraries was very limited for the most part of the nineteenth century. Data taken from historic library catalogues demonstrate that even though five textbooks had been published by 1869, these works were not necessarily acquired by academic libraries.[43] For instance, neither Buff's *Grundlehren* (1866) nor his *Kurzes Lehrbuch* (1868) are recorded in the alphabetical catalogue of the University Library Heidelberg (Universitätsbibliothek Heidelberg). Roscoe's and Schorlemmer's *Kurzes Lehrbuch* (1868), as well as Strecker's *Kurzes Lehrbuch* (1868), are also missing from the pages of the catalogue. And although there is a record of Erlenmeyer's *Lehrbuch*, the information in the catalogue indicates that it was not the 1868-69 edition, but only the later 1883-94 edition that was acquired by the library (Figure 5.3).[44] The information in the catalogues thus indicates that none of the five early textbooks with line-and-letter formulae had ever been held by the University Library Heidelberg.

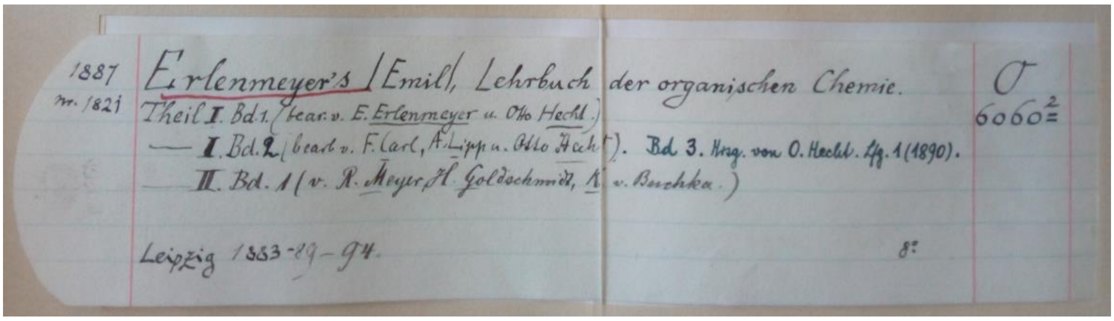
1887
Nr. 1821
Erlenmeyer's (Emil), Lehrbuch der organischen Chemie. O
Theil I. Bd. 1. (bearb. v. E. Erlenmeyer u. Otto Hecht.) 6060²
— I. Bd. 2. (bearb. v. F. Carl, A. Lipp u. Otto Hecht). Bd 3. Hrsg. von O. Hecht. Lfg. 1 (1890).
— II. Bd. 1 (v. R. Meyer, H. Goldschmidt, K. v. Buchka.)
Leipzig 1883-89-94. 8°

Figure 5.3: Extract from University Library Heidelberg's historic alphabetical catalogue.[45]

[41] Ibid, pp. 307-308.
[42] Petzholdt, Julius, *Adressbuch der Bibliotheken Deutschlands mit Einschluss von Oesterreich-Ungarn und der Schweiz*, 2nd ['new'] edn (Dresden: G. Schönfeld, 1875), p. 36.
[43] Paul Kaegbein's edited volume *Deutsche Bibliothekskataloge im 19. Jahrhundert: Analytisches Repertorium*, 2 vols (München: K. G. Saur) provides a very helpful resource for locating historic library catalogues from nineteenth-century Germany.
[44] Erlenmeyer, *E. Erlenmeyer's Lehrbuch der organischen Chemie*, 2nd edn, ed. by Otto Hecht, 2 vols (Leipzig: C. F. Winter, 1883-94).
[45] Heidelberg, Universitätsbibliothek Heidelberg (UBHD), *Catalogus Alphabeticus Bibl. Acad. Heidelberg*, vol 185 (n.d.). The alphabetical catalogue comprises more than 300 volumes. Each volume is composed of sheets of thick paper with pockets for filing cards with detailed bibliographic references. Some, albeit not all, filing cards also include information concerning the date when the recorded item entered the library. In the case of Erlenmeyer's *Lehrbuch*, the information on the filing card indicates that the library began purchasing some individual volumes of the second edition of Erlenmeyer's textbook only in 1887. On the history of the Univeristy Library Heidelberg, see Mittler, Elmar, 'Bibliothek und Universität:

The situation was no better in other parts of Germany. For instance, the first printed library catalogue of the Königliche Technische Hochschule zu Berlin (KTHB) of 1885 records the 1868 editions of Buff's *Kurzes Lehrbuch* and Strecker's *Kurzes Lehrbuch* as well as the 1868-69 edition of Erlenmeyer's *Lehrbuch*, but does list the 1866 edition of Buff's *Grundlehren* or the 1868 edition of Roscoe's and Schorlemmer's *Kurzes Lehrbuch*, thus indicating that the last two books were never procured by that institution.[46] Many of the 1866-68 textbooks are also missing from the library catalogues of the Königliche Technische Hochschule zu München (KTHM) and the catalogue of the reference library ('Handbibliothek') of the University Library Berlin (Universitätsbibliothek Berlin).[47] The largest and most frequented academic library in the German lands was the Royal Library of Berlin (Königliche Bibliothek zu Berlin). However, not even this library stocked textbooks with line-and-letter diagrams during the 1860s, as the library's accession catalogues indicate.[48]

In conclusion, we have seen in this section that there was a shortage of German textbooks with line-and-letter diagrams in the late 1860s and early 1870s. This, in turn, strongly suggests that those German students who were introduced to the new chemical notation by diagrammatic pioneers during that period could not rely on textbooks alone to complement their studies.[49] On the one hand, as we have seen in the case of British students in the previous chapter, classroom teaching was not enough to become proficient in interpreting and

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Skizzen zu ihrer Wechselbeziehung', in *Semper Apertus: Sechshundert Jahre Ruprecht-Karls-Universität Heidelberg 1386-1986*, ed. by Wilhelm Doerr, 6 vols (Berlin: Springer, 1985), IV: *Übergreifende Beiträge*, ed. by Wilhelm Doerr, pp. 1–20.

[46] Cf. *Katalog der Bibliothek der Königlichen Technischen Hochschule zu Berlin* (Berlin: [Buchdruckerei von Denter & Nicolas], 1885), pp. 168-82.

[47] *Katalog der Bibliothek der Königlichen Technischen Hochschule zu München* (München: [M. Pössenbacher'sche Buchdruckerei (Eigentümer Max Franz)], 1881); *Universitäts-Bibliothek zu Berlin: Verzeichnis der Lesesaal- und Handbibliothek* (Berlin: [Berliner Druckerei Actien-Gesellschaft], 1891).

[48] Berlin, Staatsbibliothek zu Berlin – Preußischer Kulturbesitz, Akzessionsjournale Kauf, 1866-1870. So-called accession catalogues, sometimes also termed accession lists, are a continuous record of 'accession numbers' ('Akzessionsnummern') that are assigned to books and journals when the titles become part of the library. Each items is given an individual accession number through which it can be identified. I have reviewed the relevant accession catalogues for the period 1866 to 1870, and I have found that none of the above textbooks with line-and-letter formulae are listed in those catalogues, meaning that those textbooks were not held by the library during that period. On the history of the Königliche Bibliothek zu Berlin in the nineteenth century, see Pertz, Georg H., *Die Königliche Bibliothek zu Berlin in den Jahren 1842 bis 1867* (Berlin: Gustav Schade, 1867); and Paunel, Eugen, *Die Staatsbibliothek zu Berlin: Ihre Geschichte und Organisation während der ersten zwei Jahrhunderte seit ihrer Eröffnung 1661-1871* (Berlin: de Gruyter, 1965).

[49] There is circumstantial evidence that textbook provisions gradually improved when local branch libraries – so-called Institutsbibliotheken and Seminarbibliotheken – were introduced as the second pillar of the university library system towards the end of the nineteenth century (Cf. Schmitz, *Deutsche Bibliotheksgeschichte*, pp. 136-37). Christoph Meinel and Christine Nawa mentioned in a private conversation during the 11th International Conference on the History of Chemistry 2017 in Trondheim that a relatively large number of second-generation chemical institutes featured separate rooms for small library collections. See, for instance, construction plans reproduced in Kolbe, Hermann, ed., *Das chemische Laboratorium der Universität Leipzig* (Braunschweig: Vieweg, 1872). I would like to thank Meinel and Nawa for their instructive comments on this subject.

understanding line-and-letter formulae. In order to continue their studies at home and to prepare for exams, British students could choose from a comparatively large number of suitable textbooks. German students, on the other hand, did not have access to the same resources and were therefore likely to draw on other forms of reading material to familiarise themselves with the new diagrams. We have already seen in the first section of this chapter that the German research-based approach to chemical education required students to engage with periodical literature. The next section provides further evidence for my hypothesis that German chemistry students did not rely on didactic literature alone, but also made frequent use of research journals when studying line-and-letter diagrams in the late 1860s and early 1870s.

5.3. The Significance of Chemistry Periodicals in German Line-and-Letter Pedagogy

I argued in the first section of this chapter that the use of periodical literature was an integral part of chemical education in Germany because chemistry students were not only expected, but actively encouraged, to consult research journals during their studies. In the 1860s, German periodicals featured line-and-letter diagrams in large numbers, which turned those periodicals into an excellent learning resource for chemistry students during a period when suitable textbooks were not widely available. Yet we might wonder how chemical periodicals featuring the new notation came to be so successful in the German print market during the 1860s and over the course of the following decades. In what follows, I explain why German chemistry periodicals became the internationally leading research outlets to feature line-and-letter formulae in large numbers. I do this by outlining the history of the specialist chemistry journal from the late-eighteenth to the late-nineteenth century. I demonstrate that the number of line-and-letter formulae in German periodicals increased drastically in the late 1860s due to a number of factors, including the size and dynamic of the German market for commercial science journals, the establishment and the proliferation of chemical institutes with a strong focus on organic chemistry, and the integral role that periodical literature played in German chemical education.

Chemistry, Competition, and Commerce: Origins of the Chemical Research Journal in Nineteenth-Century Germany

In his seminal work, the *Fontana History of Chemistry* (1992), Bill Brock asserts that the 'home of specialized journals was Germany' because 'there was a flourishing book trade and many distinguished publishing houses.'[50] As we shall see further below, the foundation of a relatively large number of commercial academic publishers during the late eighteenth and early nineteenth centuries does indeed represent one of the main reasons for the early emergence of commercial specialist chemistry journals in the German lands. One of the very first commercially successful periodicals specialising in one specific area of science was Lorenz Crell's *Chemische Annalen* (1784-1803).[51] Crell's *Annalen* was not only a commercially successful specialist journal edited by a university professor of medicine and published by a commercial academic publishing house; it was also one that acquired an international reputation, serving as a model for other scientific journals such as the French *Annales de Chimie*. Equally important, the *Chemische Annalen* played a major role in the development of chemistry as a scientific discipline in its own right by providing a publication platform that brought chemists from different German states together to form a scientific community.[52] In this section, we shall see that specialist commercial science journals developed in Germany due to a very specific combination of unique conditions not present anywhere else in Europe. The following outline of these unique conditions will enable us to understand the commercial success and growing international reputation of German chemical periodicals, such as Liebig's *Annalen der Chemie und Pharmacie* and *Berichte der Deutschen Chemischen Gesellschaft* in the second half of the nineteenth century.

The development of the German market for specialist scientific journals differed significantly from the print markets in Britain or France, which was a result of the pluricentric nature of the political, economic, and educational landscape of the German lands prior to the foundation of the German Empire in 1871. One of the main reasons for the early emergence of commercial specialist journals was the lack of publically-sponsored publications such as *Philosophical Transactions* or *Comptes Rendus*, due to the absence of a national learned society such as the Royal Society in London or the Académie des Science in Paris. Although small societies and academies had existed in a number of German states since the seventeenth

[50] Brock, *Fontana History*, p. 447.
[51] Cf. Kirchner, *Zeitschriftenwesen*, I: *Von den Anfängen bis zum Zeitalter der Romantik* (1958), p. 160; and Crosland, *Annales*, pp. 64-68. On Crell's professional background and his early editorial activities, see Gielas, 'Editorial Beginnings'.
[52] Hufbauer, Karl, *The Formation of the German Chemical Community, 1720-1795* (Berkeley, CA: University of California Press, 1982), p. 94.

century, and although some of these institutions were involved in publishing proceedings, academic transactions, and other miscellaneous content, the readership and the circulation of those publications were very restricted.[53] As a result, commercial publishers entered the market to supply the growing academic audience with relevant scientific information.[54] These independent commercial academic publishers were closely associated with the local university, academy, or learned society.[55] The companies often bore the name 'Universitätsverlag' (university publishing house) and adjusted their publishing portfolios according to the demand of the local academic institutions. Members of the university published their research communications almost exclusively with the Universitätsverlag. As university publishers usually accounted for the majority of the intellectual output of the affiliated institution, their lists usually lacked a thematic focus and covered several subjects ranging from theology and cameralism to medicine and natural philosophy.[56]

From the middle of the eighteenth until well into the second half of the nineteenth century, scientific publishing was thus in the hands of commercial publishing houses located in the university towns of the German states. Reacting to the changing structure of universities and the nascent specialisation of scientific disciplines around the middle of the nineteenth century, some of the larger university publishers began to consolidate their portfolios during the 1850s and 1860s. However, prior to the 1860s, the majority of German publishers had not made any serious attempts at pursuing specialisation in the natural sciences.[57] Among the names of the largest and most successful university publishing houses during the first half of the nineteenth century were Johann Ambrosius Barth (f. 1780 in Leipzig), Vandenhoeck & Ruprecht (f. 1735 in Göttingen), and Carl Winter (f. 1805 in Heidelberg). The wide geographical dispersal of these publishing houses resulted in a growing output of scientific print as well as in a strong competition between the enterprises which, as Meinel puts it, 'required efficiency and

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[53] Cf. Meinel, 'Structural Changes', p. 48.

[54] By way of illustration, the very first learned journal identified by book historian Joachim Kirchner was a society publication, but the second title was a commercial journal. The first of these two publications is the *Miscellanea Curiosa Medico-Physica* published between 1670 and 1706 in Schweinfurt, Bavaria. The journal was entirely in Latin and published annually by the Academia Naturae Curiosum, a learned society dedicated to studies in natural philosophy and medicine, established in 1652. The second learned journal was the *Acta Eruditorum* (1682-1782) established by university professor Otto Mencke (1644-1707). Cf. Kirchner, *Zeitschriftenwesen*, I, pp. 18-22.

[55] Driven by the ideas of the Enlightenment and the increasing competition between German states, the eighteenth and nineteenth centuries saw a strong increase in the number of universities and technical colleges. By way of illustration, in 1840 Prussia alone had six universities in Berlin, Bonn, Breslau, Greifswald, Halle, and Königsberg. Cf. Anderson, Robert D., *European Universities from the Enlightenment to 1914* (Oxford: Oxford University Press, 2004), Chapter 4.

[56] Jäger, Georg, 'Der Universal-, Fakultäten-, und Universitätsverlag', in *Geschichte des deutschen Buchhandels*, I.1: Das Kaiserreich 1871-1918, ed. by Georg Jäger (2001), pp. 406-22 (406-7, 417).

[57] Estermann, Monika, and Ute Schneider, 'Wissenschaft und Buchhandel - Wechselwirkungen', in *Wissenschaftsverlage zwischen Professionalisierung und Popularisierung*, ed. by Monika Estermann and Ute Schneider (Wiesbaden: Harrassowitz, 2007), pp. 7–12 (p. 8).

diversification,' but also led to the stabilisation of a 'few market leaders' such as Gilbert's *Annalen der Physik* and Liebig's *Annalen der Pharmacie* (later renamed to *Annalen der Chemie und Pharmacie*) in the 1830s.[58]

Commercial chemistry journals were among the most successful publishing enterprises in nineteenth-century Germany. As early as the 1800s there was already a large customer base for chemical periodicals that consisted of university researchers, doctors, and practising pharmacists, as the case of Crell's *Annalen* demonstrates.[59] The readership further increased over the course of the nineteenth century due to the institutionalisation of chemical research and education in the form of chemical institutes and rise of organic chemistry in Germany. In the middle decades of the nineteenth century and up until approximately 1870, the *Annalen der Chemie* under Liebig's and Wöhler's editorship became the undisputed flagship journal and global 'leader in the field of organic chemistry.'[60] Liebig became editor of the *Annalen* in 1832 and was joined by Wöhler as co-editor in 1838.[61] The commercial success of the *Annalen* was based on a number of factors. First, it resulted from the unique conditions on the German print market that I have outlined above. Secondly, it was due to the aforementioned institutionalisation of chemical research and education that resulted in constantly growing number of readers as well as research contributions. Thirdly, Liebig's international reputation and his expertise as a skilled and experienced editor guaranteed the journal's lasting success. Finally, it was also a consequence of the Giessen Model of chemical education. As we have seen in the previous section, Liebig encouraged his advanced students to publish their results in his *Annalen* as part of their training. This strategy not only promoted the reputation of the Giessen institute as a leading centre of research and learning, but also contributed 'to establish the *Annalen* as a potentially international journal', since a large proportion of Liebig's students came from abroad.[62] Under Liebig's and Wöhler's editorship, stretching from the late 1830s to the early 1870s, 'the *Annalen* became the most important journal of chemical communication in the world', as Bill Brock fittingly explains in his seminal textbook.[63] Whatever forms of chemical knowledge and notation the *Annalen* promoted thus received a large and ready audience.

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[58] Meinel, 'Structural Changes', p. 50.
[59] Cf. Gielas, 'Editorial Beginnings'.
[60] Ihde, *Modern Chemistry*, p. 272. As I have mentioned in the introductory chapter, our understanding of the history of the *Annalen* is still very patchy due to the lack of primary sources, especially with regard to the second half of the nineteenth century. However, there is a number of cursory studies that offer a first approach to the subject. Cf. Van Klooster, H. S., 'The History of Liebig's Annalen der Chemie', *Journal of Chemical Education*, 34 (1957), 27–30; Kirchner, *Zeitschriftenwesen*, II: *Vom Wiener Kongress bis zum Ausgange des 19. Jahrhunderts* (1962), pp. 114-15; Crosland, *Annales*, pp. 264-5; and Phillips, J. P., 'Liebig and Kolbe, Critical Editors', *Chymia*, 11 (1966), 89-97.
[61] Crosland, *Annales*, p. 264.
[62] Ibid. Italics in original.
[63] Brock, *Fontana History*, p. 447.

Yet the *Annalen* was not the only German periodical with a wide circulation, an international audience, and a strong focus on organic chemistry. In the late 1860s, the position of the *Annalen* was challenged by the *Berichte der Deutschen Chemischen Gesellschaft*, which emerged as a new competitor on the market for chemical journals in 1867. The emergence of the *Berichte* reflected the need for a reform of chemical publishing that was driven – once again – by the increase in organic research. The journal was conceived by members of the German Chemical Society (Deutsche Chemische Gesellschaft) as a means to increase publication rate by publishing short research papers as quickly as possible – something which the *Annalen* was not able to provide due to its slow publication rate. The problem was that *Annalen* issues appeared monthly and there was often a gap of several months before a submitted paper was printed in the *Annalen* so that cutting-edge research papers were often delayed.[64] Alternatively, the *Berichte* were published biweekly and contained much shorter papers so that research could be communicated much faster. Although editors of the *Annalen* initially regarded the new *Berichte* as a direct competitor and a real threat to their own franchise, it soon became clear that the two journals served different functions and thus complemented each other. Authors published short research papers in the *Berichte* and more extensive papers on the same subject in the *Annalen*. The two thus served as alternative publication outlets serving the different needs of the chemical community at a time of intensified research activity in the area of organic chemistry. The launch of the *Berichte* resulted in the diversification of the German market for chemical research journals around 1870 and the *Annalen* and the *Berichte* became established as the leading chemistry journals in the second half of the nineteenth century. Due to the strong focus of the German chemical institutes on organic research, both journals published predominantly papers on organic chemistry, and it was these two journals that contained the largest number of research articles with line-and-letter formulae in the late 1860s and throughout the 1870s.

To summarise, we saw in the preceding section that only a small number of Germanophone textbooks with line-and-letter diagrams were published in the 1860s, which strongly implies that German chemistry students could not rely on textbooks alone to interpret and apply line the new notation during the course of their studies. Yet as I have explained in the first part of this section, a comparatively large number of research articles with line-and-letter formulae began to appear in German chemistry journals during the same period, which was due to a number of economic and institutional reasons that were unique to the development of chemical education and the market for periodical print in Germany. This, I conclude, provides

[64] Cf. Van Klooster, 'Liebig's Annalen', p. 27; and Hückel, Walter, '100 Jahre Geschichte der Berichte', *Chemische Berichte*, 100.1 (1967), i–liii (p. iii).

very strong evidence for my claim that German chemistry students employed chemistry journals alongside other resources to advance and strengthen their knowledge of line-and-letter diagrams. With these premises, it is reasonable to posit that periodicals played a key role in the circulation and appropriation of line-and-letter formulae in Germany. But were periodicals accessible to those students who wished to consult them? As we shall see in the second part of this section, library provisions were significantly improved during the second half of the nineteenth century so that students were able to make good use of those journals.

The Role of German Libraries in the Circulation of Chemical Knowledge

In this part of the section, I assess the availability and accessibility of different forms of literature in German academic libraries by drawing on the official terms and conditions of usage specified in printed library catalogues from the 1870s and 1880s. In what follows, we shall see that the libraries' regulations made access to textbooks rather difficult for the reason that the books had to be ordered from the stack room in advance, and that only a limited number of books could be issued at a time. Students and, to some degree, members of academic staff, had to overcome several bureaucratic hurdles before they were able to consult textbooks inside the library or at home. In the case of periodicals, the situation was quite different, since German as well as foreign research periodicals were usually available in the library reading rooms and could be accessed by academic staff as well as regular students with very little effort.[65] In the second part of this section, I argue that the library regulations must be seen as evidence for the claim that a large number of university students in Germany had been using not only lecture notes and textbooks, but also specialised periodicals as learning resources since at least the second half of the nineteenth century.

In academic libraries, books were often more difficult to access than journals. The peculiar discrepancy regarding the access to textbooks and serial literature was the consequence of a structural feature that all German academic libraries had in common, namely the spatial separation between the reading room (usually called 'Lesesaal'), with a small number of open access holdings, on the one hand, and the stack room (termed 'Magazin' or 'Büchersaal') as the central repository for the majority of printed material, on the other hand.[66] Access to the

[65] Periodical literature on chemistry and related disciplines usually include *Annalen der Chemie und Pharmacie*, *Annalen der Physik und Chemie*, *Berichte der Deutschen Chemischen Gesellschaft*, *Journal für praktische Chemie*, and *Zeitschrift für analytische Chemie*. Foreign titles usually include *Journal of the Chemical Society*, and *Bulletin mensuel de la société chimique de Paris*.
[66] Mittler, 'Bibliothek und Universität', p. 10.

stack room was limited to members of library staff, so all items that were not on display in the reading room had to be ordered in advance.[67] As a general rule, frequently used reference works, such as encyclopaedias and dictionaries, as well as major titles of serial literature were made available on open shelfs in the reading room and could therefore be consulted without prior notice. All other items had to be looked up in the catalogues and ordered with a paper slip at the service counter.

All readers had to complete registration before they were allowed to use the library. For example, the 1876 regulations of the Library of Königliche Geologische Landesanstalt und Bergakademie in Berlin (KGLB) required all users to obtain an authorisation certificate ('Erlaubniskarte') from the head of the library before they were allowed to enter and use the reading room.[68] Once the certificate was obtained, different sets of rules applied to students and scholars when it came to the borrowing of books. Undergraduates were subject to much stronger restrictions than doctoral candidates ('Doktoranden'), Privatdocenten, and professors when taking items out of the library for home use. For instance, each of the libraries' terms and conditions that I have examined included a section that required students to have their request forms signed by a professor before they could take items home.[69] In this way, the request form ('Verlangzettel') doubled as an official deposit document ('Empfangsschein'), which ensured that the item was returned on time. Each item had to be requested and signed off on a separate request form. In addition, the maximum number of items that could be borrowed was limited, ranging between one and three titles, and never exceeding five volumes.[70] Senior academic staff were allowed to borrow more books and, in some cases, even periodicals, with the maximum number of items ranging between twenty (KGLB) and as many as fifty titles in the case of the

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[67] Although regulations were changed toward the end of the century to allow academic staff to enter the stack room and retrieve books without authorisation from library officials, access remained highly restricted for the most part of the nineteenth century. Cf. Laude, Jules, *Les bibliothèques universitaires allemandes et leur organisation* (Paris: Librairie Émile Boullion, 1900), p. 60. Laude quotes from the most recent regulations to illustrate that point.

[68] '§ I.2. Wer das Lesezimmer zu benutzen wünscht, muß mit einer von dem Direktor der Anstalt ausgestellten Erlaubniskarte versehen sein, welche auf Verlangen dem Custos vorzuzeigen ist.' (*Katalog der Bibliothek der Königlichen Geologischen Landesanstalt und Bergakademie zu Berlin* (Berlin: [A. W. Schade's Buchdruckerei], 1876), p. vii.)

[69] The outline of the general terms and conditions of usage in this section is based on a crtical and careful review of historic sources, including UBHD, *Die Benutzung der Universitätsbibliothek betreffend* (c. 1866), Signatur F 8698 2-6; UBHD, *Vorschriften über die Benützung der Universitätsbibliothek durch die Studierenden* (c. 1893), Signatur F 8698 2-10; Rektor und Senat der Königlichen Technischen Hochschule zu Berlin, 'Bestimmungen über die Benutzung der Bibliothek', in *Katalog der Bibliothek der Königlichen Technischen Hochschule zu Berlin,* pp. 1-6; Directorium der königlichen polytechnischen Schule, 'Bibliothek-Ordnung', in *Katalog der Bibliothek der Königlichen Technischen Hochschule zu München*, pp. iii-vi; Direktor der Königlichen Geologischen Landes-Anstalt und Bergakademie, 'Vorschriften für die Benutzung der Bibliothek', in *Katalog der Bibliothek der Königlichen Geologischen Landesanstalt und Bergakademie zu Berlin* (Berlin: [A. W. Schade's Buchdruckerei], 1876), pp. vii–x; and Paunel, *Staatsbibliothek*, pp. 385-89.

[70] Rektor und Senat der Königlichen Technischen Hochschule zu Berlin, 'Bestimmungen', p. 4.

Library of Königliche Technische Hochschule zu München (KTHM). Finally, in most cases members of academic staff were allowed to keep the items for one semester, or just two months in the case of the Library of Königliche Technische Hochschule zu Berlin (KTHB), while the maximum loan period for students varied between only eight days (KTHB) and six weeks (KTHM). From this, we can clearly see that the regulations and restrictions made it very difficult for students borrow textbooks from the library.

When it came to the use of journals inside the library, by contrast, students and scholars were accorded the same rights, which ultimately made using periodical literature in the vast majority of cases more convenient than working with books. The terms and conditions of the KGLB Library state that, after being admitted to the reading room, users were free to work with 'periodicals displayed [in the reading room] as well as all works and maps in the library.'[71] Similar regulations were in place at the KTHM Library, where periodicals were displayed in the reading room and were thus easily accessible to every authorised user of the library.[72] The regulations stated explicitly that users were allowed to take the journals from their shelves, but also stipulated: 'displayed periodicals are to be returned to their designated place each time after use.'[73] Very similar rules are also outlined in the 1885 library catalogue of the KTHB Library.[74]

In conclusion, the library regulations make it very clear that textbooks were in most cases not very accessible to students because of the need to obtain signatures from professors, as well as the comparatively short loan periods and the limited number of books that could be taken home. And even if a student decided to consult a specific textbook inside the library's reading room, he had to fill out a request form and order the book from the service desk, which in some cases was followed by a waiting period of one entire day before the item was delivered. Also, only one item was issued at a time, and the student had to return one textbook before he was handed another one. Periodicals, on the other hand, were usually found in the reading room and could therefore be consulted at short notice – the student could easily walk over to the designated self-service shelfs and take the relevant volume back to his reading desk. All this suggests that periodicals were more readily accessible than textbooks for the reason that serial literature was usually displayed in the reading room and could be consulted on the spot without

[71] '§ I.1. In demselben [Lesezimmer] können die ausgelegten Zeitschriften und alle in der Bibliothek enthaltenen Werke und Karten benutzt werden.' (Direktor der Königlichen Geologischen Landes-Anstalt und Bergakademie, 'Vorschriften', p. vii.)
[72] Directorium der königlichen polytechnischen Schule, 'Bibliothek-Ordnung', p. v.
[73] 'Die aufliegenden Zeitschriften sind jedesmal nach dem Gebrauche an ihren festgetzten Platz zu legen.' (Ibid.)
[74] '§. 16. Zeitschriften liegen zur freien Benutzung aus; sie dürfen nicht aus den Mappen herausgenommen werden. Die Mappen sind nach der Benutzung sofort wieder in das gehörige Fach zurückzulegen.' (Rektor und Senat der Königlichen Technischen Hochschule zu Berlin, 'Bestimmungen', p. 6.)

prior notice, thus providing further evidence for my claim that German chemistry students consulted periodicals at least as often as textbooks.

5.4. Conclusion

This chapter undertook a pioneering and much-needed investigation of the patterns and institutional arrangements through which line-and-letter diagrams were circulated in Germany and appropriated by German students in the late 1860s and early 1870s. In this chapter, I have demonstrated that the process by which German students encountered and appropriated the new diagrams was fundamentally different from the way in which the formulae were communicated in Britain. Conversely to British students, who relied predominantly on textbooks, German chemistry students used scientific journals alongside textbooks to learn how to read and use the new notation. By undertaking a comparative study of the ways in which line-and-letter diagrams were disseminated in Britain and Germany, Chapters 4 and 5 have demonstrated that the circulation and appropriation of the new chemical notation was a gradual and non-uniform process that was shaped by local didactic practices, and which was highly contingent on the local educational arrangements and the availability of different printed learning resources such as textbooks and periodicals. This, I conclude, calls for a critical reassessment of our current historical understanding of the function of specialist periodicals by acknowledging that the readership of science journals was not limited to researchers, but often included students who consulted this literature in the context of learning.

Finally, Chapters 4 and 5 have also demonstrated that over the course of the 1860s and 1870s, line-and-letter formulae became a fixture in chemical education. As we saw in the previous chapter, the communication of the new notation in Britain was further supported by new textbooks that featured line-and-letter formulae. Although the production of Germanophone chemistry textbooks in the 1870s requires further study, a cursory review of bibliographic sources indicates that new textbooks with line-and-letter formulae were also published in Germany.[75] Consequently, the number of British and German students who became proficient in interpreting and using the formulae in their capacity as heuristic devices and communication tools continued to increase. Although only a fraction of those students became

[75] German textbooks with line-and-letter formulae published in the 1870s include Schorlemmer, *Kurzes Lehrbuch der Kohlenstoffverbindungen oder organischen Chemie. Zugleich als zweiter Band von Roscoe's Kurzem Lehrbuch der Chemie* (Braunschweig: Vieweg, 1871); Pinner, Adolf, *Repetitorium der organischen Chemie* (Berlin: Robert Openheim, 1872); and Wislicenus, *Adolf Streckers kurzes Lehrbuch der organischen Chemie*, 6th edn (Braunschweig: Vieweg, 1874).

academic or industrial researchers with professional interests in organic chemistry, evidence from specialist journals makes it clear that more and more chemists began to use the new notation in their research contributions to specialist journals from the late 1860s onward. As we shall see in Part III of this thesis, the rising number of new diagram users went hand in hand with an increase in the iconographic diversity of line-and-letter formulae, since many users employed the diagrams as they saw fit. Yet from the early 1880s to the early 1890s, line-and-letter formulae underwent a transformation that eventually resulted in a reduction of iconographic diversity and acquired a much more uniform appearance on the printed page. I argue in the following chapter that the standardisation and internalisation of the formulae's iconography was the result of a tacit convention that was established not so much by scientists, as by the editors and publishers of chemistry journals who were responding to the economic pressures of a competitive print market.

PART III

Standardisation and Internalisation

I argue in the final part of this thesis that the processes which led toward a more uniform and standardised appearance of the formulae were not driven by official agreements between members of the scientific community, but rather by market forces governing the production and distribution of scientific print. The chapter explains these processes by illustrating how the rise in research activity in organic chemistry from the 1860s onwards resulted in a significant increase in the number of research papers published in German scientific periodicals. The growing amount of space taken up by the new formulae obliged editors and publishers of abstract journals – whose prime objective was to cover as much periodical literature as quickly as possible – to introduce editorial measures for fitting more abstracts on the page of their journals in order to secure their journals' commercial success in the highly competitive markets for periodical literature. Taken together, the editorial measures introduced by leading German and British abstract journals finally resulted in a noticeable reduction of the iconographic variety of the formulae and thereby contributed to a more uniform appearance of the new notation on the printed page.

CHAPTER 6

Tacit Conventions and the Making of the Modern Chemical Notation: How Editors, Publishers, and Printers of Scientific Journals Shaped Line-and-Letter Formulae in the 1870s and 1880s

The present chapter explains how the communication of initially rather space-consuming line-and-letter diagrams by means of periodical literature resulted in a gradual reduction of their iconographic diversity and a contraction in their expansiveness. By offering this account, the chapter pursues two objectives. First, the chapter demonstrates that abstract journals such as *Journal of the Chemical Society Abstracts* and *Chemisches Zentralblatt* played a central role in the international circulation of line-and-letter formulae and thus drove the constant increase of the number of diagrams on the pages of scientific journals. Secondly, the chapter shows that the different editorial strategies for the management of line-and-letter formulae were contingent on the specific position of those periodicals in their respective markets.

The first section of this chapter demonstrates that the growing iconographic diversity as well as the space taken up by line-and-letter formulae during the 1860s and 1870s was driven by the large number of research papers with the new notation published in German periodicals. The section provides bibliometric data to demonstrate that the number of research articles published in German periodicals superseded the number of papers published in British or French journals, and that a large proportion of the German research articles contained line-and-letter formulae. In addition, the section demonstrates that the flood of the space-consuming formulae soon became a veritable problem for a specific kind of journal, namely the chemical abstract journal. Since the economic success of those journals on the market for scientific print depended on the journals' ability to cover as many chemical publications as possible, space-consuming formulae soon became a major economic concern: the more formulae, the higher the printing costs. The editor of *Chemisches Zentralblatt*, the leading abstract journal of its time, consequently decided to reduce the amount of space consumed by the formulae by leaving as many formulae out as possible. It was the first journal to introduce editorial measures to deal with the flood of the new diagrams.

The second section explains the origins of the 1879 editorial guidelines that were devised by Henry Watts to deal with the large amount of space that line-and-letter formulae – reproduced from German periodicals – were taking up in his abstract journal, the *Journal of the*

Chemical Society Abstracts. The purpose of the section is to demonstrate that it was again an abstract journal that suffered most from the influx of the new formulae, and whose editor consequently chose to introduce editorial measures due to the economic pressure resulting from rising printing costs. The section does this by comparing the *Journal of the Chemical Society Abstracts* to other British science journals that covered organic chemistry. The comparison reveals that the editorial strategy of each periodical was highly contingent on its unique position in the print market. This comparison makes it very clear that abstract journals faced economic pressures that did not apply to other journals. As a result, other journals did not implement such drastic editorial measures as Watts' 'Instructions'. In doing this, the section also shows that it was abstract journals which were driving the establishment of a tacit iconographic convention during the 1880s and early 1890s.

The third section is concerned with the gradual emergence, spread, and implementation of a tacit notational convention over the course of the 1880s and early 1890s. It argues that Watts' 'Instructions' played a major role in the establishment of the iconographic convention, since evidence from British as well as French and German periodicals demonstrates that line-and-letter formulae printed in those journals during the 1880s began to look more uniform and to display the features that Laszlo identified in his seminal paper. Watts' 'Instructions' played a major role in the process, since a number of Anglophone periodicals appropriated Watts' editorial guidelines in the 1880s. However, we have also strong evidence that the convention was spreading regardless of whether formal notational rules were enforced, as the example of Edward Frankland's manuscript in this last section demonstrates. The comparison between the original version of a formula in Frankland's handwritten submission to the Royal Society and the final printed version of the same formula demonstrates that scientific printers began to implement the iconographic convention even without having received any formal instructions to do so.

As a whole, the chapter thus demonstrates the key role that journal editors and printers played in the standardisation of the appearance of line-and-letter formulae. With a strong financial incentive to reduce the space occupied by such formulae, editors of abstract journals in particular were concerned to regularize the formulae in a way that protected their commercial interests, offering explicit and detailed advice to authors. Authors' manuscripts and practices became increasingly disciplined through such interventions from editors, and through the growing conventions among chemical typesetters, leading to the gradual establishment of an international iconographic convention.

6.1. Size, Space, and Symmetry: Development of Line-and-Letter Formulae from the late 1860s to the early 1890s

As already briefly mentioned in the introductory chapter, the appearance of line-and-letter formulae underwent a gradual transformation from the late 1860s to the early 1890s. During the 1860s and 1870s, the iconographic diversity as well as the number and size of the new structural notation increased significantly. In the following two decades, however, this development was followed by a noticeable reduction in the variety of different styles of line-and-letter formulae as well as in the space which individual diagrams occupied the printed page. As a result, the 1890s saw the emergence of a tacit iconographic convention that persists to the present day. In this section I examine the transformation of the formulae in great historical detail by comparing different structural diagrams that were published in British, German, and – occasionally – French periodicals from the late 1860s to the early 1890s.[1] In providing this detailed account, the first part of the section sets the scene for the remainder of the chapter, where I explain the transformation of line-and-letter formulae by referring to different editorial strategies employed by editors and publishers of scientific journals in order to harness the growing number and size of the new formulae.

Textbooks and, notably, periodicals published in the late 1860s and throughout the 1870s experienced an unprecedented and rapid increase in the number as well as the size of line-and-letter diagrams. During those years, structural diagrams displayed a high degree of iconographic diversity. By way of illustration, the examples on the following pages are taken from different British and German sources published between the late 1860s and the late 1870s, and we can see that the formulae differ significantly from each other in terms of size as well as in number and type of typographic elements employed (Figures 6.1 to 6.7). However, another glance at the formulae below reveals that the majority of diagrams occupy a relatively large amount of space on the printed page due the vertical orientation of the molecule's carbon chains which extend over several lines of type (Figures 6.1, 6.2, 6.4, 6.5). The other specimens, too, consume a considerable amount of space due to additional elements such as extremely large type (Figure 6.3), curved hyphenated lines (Figure 6.6), and large parentheses (Figure 6.7). Apart from that, however, the formulae have very little in common. It was notably the large number of diagrams that began to appear in German periodicals (Figure 6.6 to 6.9) during the period that displayed the highest degree of iconographic diversity. From this, it becomes

[1] As I have explained in the introductory chapter, up until the late 1880s and early 1890s representations of the structure theory made only very rare appearances in French journals due to the strong opposition to atomistic and structural ideas.

apparent that many different styles and forms of the new notation were populating the pages of textbooks and periodicals in the 1860s and 1870s.

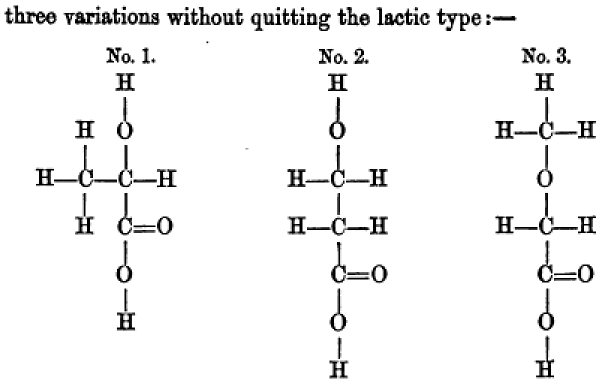


Figure 6.1: Formulae in the second volume of the second edition of *Lecture Notes* (1872).[2]

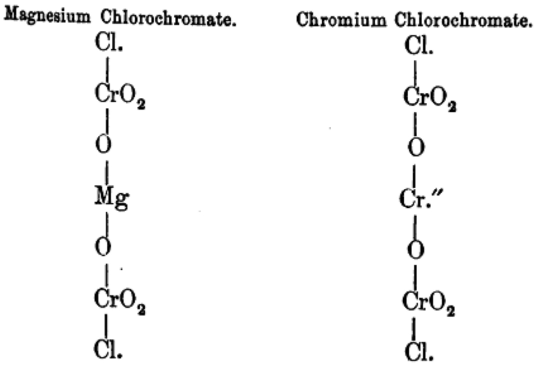
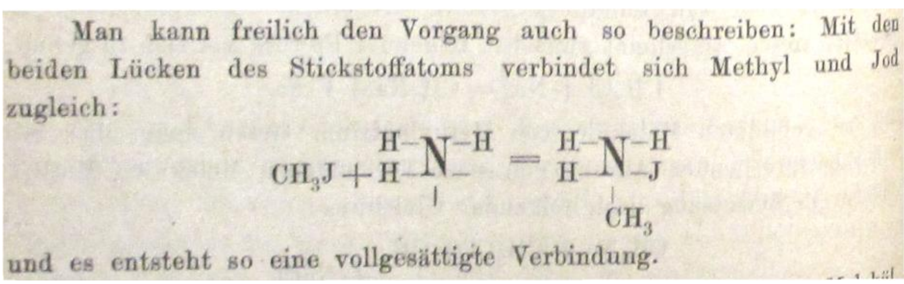


Figure 6.2: Formulae in *Journal of the Chemical Society*, 23 (1870).[3]



Man kann freilich den Vorgang auch so beschreiben: Mit den beiden Lücken des Stickstoffatoms verbindet sich Methyl und Jod zugleich:

$$CH_3J + \begin{matrix}H-\\H-\end{matrix}\overset{\;}{N}\begin{matrix}-H\\-\end{matrix} = \begin{matrix}H-\\H-\end{matrix}N\begin{matrix}-H\\-J\end{matrix}\underset{CH_3}{}$$

und es entsteht so eine vollgesättigte Verbindung.

Figure 6.3: Formulae in Erlenmeyer's *Lehrbuch* (1868-69).[4]

[2] Frankland, *Lecture Notes* (1870-72), II: *Organic Chemistry* (1872), p. 145.
[3] Thorpe, Thomas Edward, 'On a New Chromium Oxychloride', *J. Chem. Soc.*, 23 (1870), 31-35 (p. 35).
[4] Erlenmeyer, *Lehrbuch*, p. 222.

Figure 6.4: Formula in *Zeitschrift für Chemie*, 9 (1866).[5]

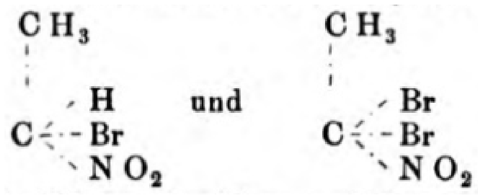


Figure 6.5: Formulae in *Berichte*, 6 (1873).[6]

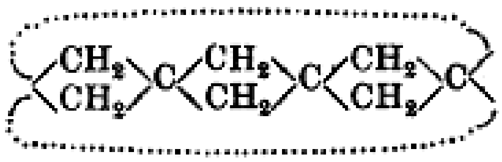


Figure 6.6: Formula in *Annalen,* 140 (1866).[7]

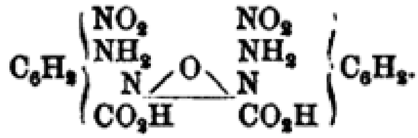


Figure 6.7: Formula in *Annalen*, 163 (1872).[8]

The expansion of iconographic diversity of line-and-letter formulae continued well into the 1870s. From the beginning of the 1880s onwards, however, the formulae began to resemble each other more and iconographic differences began to disappear. The comparison of line-and-letter formulae from the 1890s reveals that the majority of diagrams published in British, French, and German publications shared a number of distinct features that made their appearance much more uniform than was the case in the 1860s and 1870s. This development was first described by Pierre Laszlo in the aforementioned paper ‘Conventionalities in Formula Writing’ in 2001.[9] Laszlo claims that between 1865 and 1905 a new convention was gradually established that resulted in the emergence of a standardised – or, as Laszlo calls it, ‘stereotyped’ – form of structural formulae.[10] Laszlo’s pioneering study presents a catalogue of the distinct features that made up the convention, and which are still shared by all structural diagrams today. However, the study is limited in so far as it remains on a descriptive level, meaning that Laszlo does not explain by which processes the convention was established and maintained. In what follows, I shall therefore draw on Laszlo’s study to flesh out the transformation of line-and-letter formulae

5 Hlasiwetz, Heinrich, ‘Ueber die Basicität der Ferulasäure’, *Zeitschrift für Chemie*, 9 (1866), 603-04 (p. 604).
6 Meyer, Victor, and Casimir Wurster, ‘Ueber die Nitroverbindungen der Fettreihe: Fünfte Mittheilung’, *Berichte*, 6 (1873), 94-96 (p. 96).
7 Baeyer, ‘Ueber die Condensations-producte des Acetons’, *Annalen der Chemie*, 140 (1866), 297-306 (p. 304).
8 Salkowski, H., ‘Ueber die Chryanissäure’, *Annalen der Chemie*, 163 (1872), 1-64 (p. 61).
9 Laszlo, ‘Conventionalities’.
10 Ibid, p. 47.

to describe the new features of those diagrams. In the second and third sections of this chapter, I go on to explain the different processes that led to the formation of this convention by looking at the different strategies which editors and publishers of chemical periodicals had developed to manage the growth in number and size of structural diagrams on the printed page.

The first of these features concerns the accentuation and spatial orientation of atoms other than carbon or hydrogen (called heteroatoms) within large organic molecules. The first example below illustrates two formulae following this convention by stressing the nitrogen and hydrogen atoms that make up the functional group of secondary amines (Figure 6.8). The second feature addresses the use of connectors within visual formulae. Representing a direct chemical relation – usually chemical binding forces of some sorts – centred dots (e.g. 'C · C'), hyphenated lines (e.g. 'C - - - C') and predominantly solid lines (e.g. 'C — C') all came to be used as connectors in structural diagrams from approximately 1865 onwards. Parentheses such as those used in type formulae, on the other hand, began to disappear during the same period and by the early 1890s were no longer employed to represent chemical bonds. The two corresponding examples below demonstrate the application of parantheses in L. Dossios' formula for 'Milchsäure' (lactic acid) from 1866 (Figure 6.9) and Theodor Zincke's of the same compound from 1883, in which the parentheses are replaced by solid lines as representations of chemical bonds (Figure 6.10). Finally, the third convention established the abbreviation and demarcation of frequently occurring chemical groups by means of shorthand notations, for instance 'C_2H_5 –' for an ethyl or 'C_6H_5 –' for a carbonyl group, as represented in the third example below (Figure 6.11). Looking at the examples of formulae below (Figures 6.8, 6.10, 6.11), we can clearly see that diagrams all look very similar and more uniform than line-and-letter formulae from the 1860s and 1870s. This demonstrates that by the late 1880s and early 1890s, the formulae began to follow the same iconographic convention.

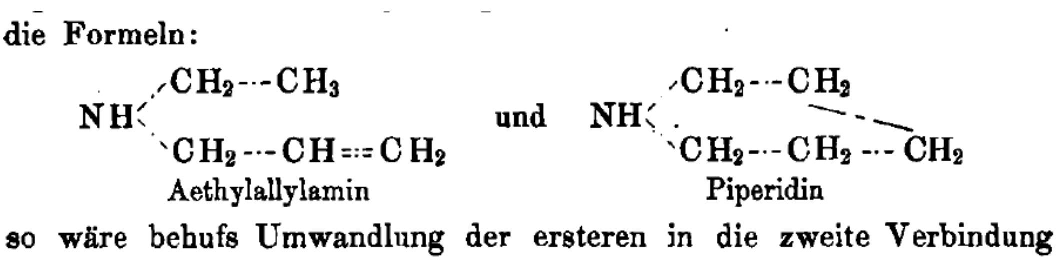
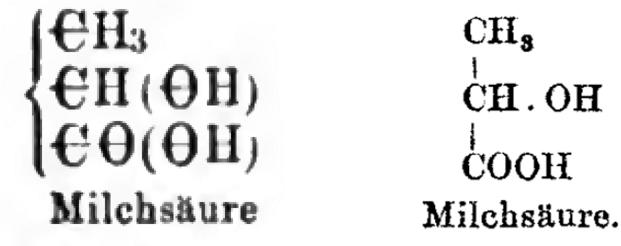


Figure 6.8: Two formulae arranged horizontally and oriented toward the nitrogen and hydrogen atoms on the left-hand side. In *Berichte*, 16 (1883).[11]

[11] Liebermann and Carl Paal, 'Ueber Derivate des Allylamins', *Berichte*, 16 (1883), 523-34 (p. 523).



Figures 6.9 & 6.10: Dossios' formula for 'Milchäure' from 1866 (left) and Zincke's formula for 'Milchäure' from 1883 (right).[12]

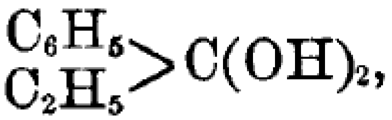


Figure 6.11: Formula in *Journal of the Chemical Society Transactions*, 47 (1885).[13]

It is important to note that a small number of – predominantly German – formulae had been displaying some of the described features since the 1860s. By way of illustration, research papers from this period published in *Annalen der Chemie* and *Zeitschrift für Chemie* occasionally featured formulae that accentuated heteroatoms, or which abbreviated carbon chains by means of shorthand notations similar to those described by Laszlo's third feature. Looking back at what we have learned about the process of typesetting and printing in the third chapter of this dissertation, the early appearance of diagrams with those features hardly comes as a surprise, as each of the three characteristic features outlined by Laszlo represents an effective way to reduce the work of composing space-consuming formalisms. By way of illustration, replacing lengthy carbon chains with shorthand notations allowed for a reduction of the justification work that would have been otherwise required to represent a carbon compound in its extended form with bonds expanding into both dimensions of the printed page. In addition, condensing carbon chains in the described manner also allowed the reduction of the amount of type required to typeset the formula, which in the case of large molecules could easily result in savings of several dozen pieces of type.

Bearing in mind that the composition of space-consuming formalism required a significant amount of justification work and was therefore a laborious and very costly enterprise, it is reasonable to surmise that printers or publishers made early attempts either to reduce the size of the formulae or to make the process of composing line-and-letter formulae more efficient.

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[12] Left: Dossios, L., 'Theoretische und empirische Beiträge zur Constitution der Glycole und der ihnen entsprechenden Formeln', *Zeitschrift für Chemie*, 9 (1866), 449-52 (p. 449). Right: Zincke, Theodor, 'Beiträge zur Kenntniss der Styrolderivate', *Annalen der Chemie*, 216.3 (1883), 286-323 (p. 320).

[13] Forster Morley, Henry, and Arthur G. Green, 'Action of Zinc Ethide on the Benzoate of Propylene Chlorhydrin', *J. Chem. Soc. Trans.*, 47 (1885), 134-38 (p. 134).

For instance, it is possible that printers developed a number of labour-saving conventions in their workshops, and it is also possible that budget-conscious publishers actively encouraged the application of such conventions in order to reduce or cap the costs of printing extensive formalisms. Although we have very little first-hand evidence of publishers or printers doing that due to the lack of reliable sources,[14] this scenario is highly plausible. We have a number of documented cases where nineteenth-century printers and publishers collaborated very closely with editors and authors of scientific works, which sometimes included discussions of technical details related to the typesetting and printing of scientific illustrations and formalisms.[15]

To summarise, it is highly probable that the hidden work of specialised compositors and undocumented arrangements between editors, publishers, and printers contributed to the development of a tacit iconographic convention during the 1860s and 1870s. For this reason, more research on typesetting practices and printers' conventions is required to achieve a better understanding of the different factors which resulted in the formulae's modern appearance, as I explain in more detail in the next chapter. Yet we have also very strong evidence from printed sources that formalised typographic rules such as Henry Watt's 'Instructions to Abstractors' played a crucial part in that story. The following two sections are therefore concerned with the documented reasons that led editors and publishers of chemical journals to introduce editorial measures aimed at managing the number and size of the new formulae. The next section argues that it was chemical abstract journals that were most affected by the economic pressure that resulted from the rapidly growing number of German research articles with line-and-letter formulae during the late 1860s and 1870s.

[14] Laszlo suggests that accentuating the heteroatom, for instance, might have facilitated pattern recognition, thereby not only assisting readers, but also allowing the compositor to place and arrange large formula on the page in a standardised and efficient manner. Laszlo claims that is therefore only reasonable to surmise that compositors of different printing houses developed in-house rules for the efficient handling of chemical diagrams and other scientific and mathematical formalisms (cf. Laszlo, 'Conventionalities', p. 54).

[15] One of those cases is the close collaboration between Vieweg, Schorlemmer, Roscoe, and Macmillan which that we have seen in Chapter 3. Another prominent example is the new mathematical notation for vector analysis developed and employed by Oliver Heaveside (1850-1925). As Graeme Gooday explains in his forthcoming chapter, the printers of the commercial journal *Electrician* had no apparent difficulties to accommodate Heaveside's unusual mathematical formulae. However, this was not the case with the printers of the Royal Society: before one of Heaveside's papers could be published in the *Philosophical Transactions*, the printing firm Harrison & Sons had to cut a new set of type, which required a significant amount of negotiation and collaboration between Heaveside, the Society's Assistant Secretary Herbert Rix (1850-1906), and Harrison & Sons. Cf. Gooday, 'Periodical Physics in Britain: Institutional and Industrial Contexts, 1870-1900', in *Constructing Scientific Communities*.

6.2. The Rising Flood of Diagrams and Its Consequences: The Leading Role of German Periodicals in the Communication of Line-and-Letter Formulae during the 1860s and 1870s

The growth in diversity of line-and-letter formulae that we have observed in the first section of this chapter was in fact a result of the rising number and size of the structural diagrams which were published in German chemistry journals throughout the 1860s and 1870s. I have already explained in the previous chapter that the rising output of academic and industrial research in organic chemistry, together with the landscape of academic publishing in Germany, meant that chemical periodicals from the German lands assumed a leading role in international print communication in chemistry. As a result, German periodicals were not only the main driving force in the communication of the new notation, but also the first to be affected by the rising number and size of the new formulae as more and more of the new diagrams began to appear on their pages. In what follows, we shall see that by the early 1870s the growing space which line-and-letter formulae occupied on the printed page presented editors and publishers of abstract journals with serious economic problems, since those journals occupied a very specific niche in the print market which offered the journal makers only very little flexibility to navigate the problems. The following case of the world-leading abstract journal *Chemisches Zentralblatt* makes it clear that editors and publishers of abstract journals played an active and essential part in the reduction of the described iconographic diversity by introducing measures which were primarily motivated by concerns about their journal's commercial viability.

The Leading Role of German Chemistry Journals in the Dissemination of the New Formulae

The high degree of iconographic diversity in German periodicals is no surprise, as it was a direct consequence of the growing amount of research in organic chemistry that was published in those journals from the mid-1860s. For reasons explained in the previous chapter, by the second half of the nineteenth century German specialist journals became the leading publication outlets for chemical research worldwide. Among the large number of titles on the market, it was notably *Annalen*, *Berichte*, and *Zeitschrift für Chemie* (f. 1858) that became the world-leading publications for research in organic chemistry.[16] It was in those journals that there was a strong increase in the number of the new formulae. By way of illustration, while only 4 out of 38 contributions (10.5 %) to volume 147 (1868) of the *Annalen der Chemie* made use of line-and-

[16] Hückel, '100 Jahre', p. ii.

letter formulae, the number rose to 7 out of 21 contributions ($33.\overline{3}$ %) in volume 153 (1870), and further to 13 out of 33 contributions (39.4 %) in volume 171 (1874). We can observe similar patterns of growth for the other two journal titles for the same period. At the same time, the sources leave no doubt that the formulae continued to grow in size and complexity.

The largest increase in the number of research papers published in German chemistry journals occurred between c. 1856 and c. 1870, as statistical data compiled by Christoph Meinel demonstrates. In his seminal paper 'Structural Changes in International Scientific Communication' (1993), Meinel compares the number of chemical papers published in British, French, and German research journals between 1801 and 1875. The results of this pioneering and highly enlightening bibliometric analysis are visualised in the three bar charts below. The charts show chemical papers published in German (Figure 6.12), French (Figure 6.13), and British journals (Figure 6.14), respectively. Each bar chart represents the absolute number of papers published within the indicated five-year periods, starting with the period 1801 to 1805. In each chart the rear bar in dark grey represents the number of original papers in the respective language, whereas the front white and shaded bars represent their translations into other languages.[17]

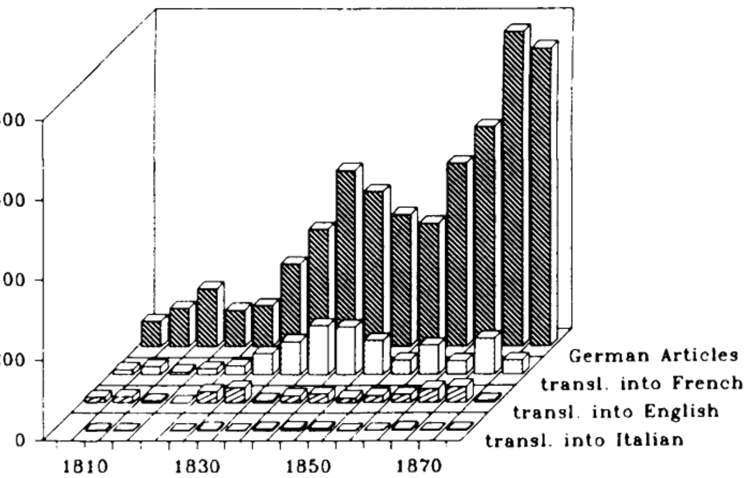

Figure 6.12: Number of articles published in German periodicals, 1801-75.

[17] Figs. 6.12 to 6.14 are reproduced from Meinel, 'Structural Changes', p. 53. Meinel's bibliometric analysis 'is based on the total of chemical papers by the 200 nineteenth-century chemists included in the Dictionary of Scientific Biography (New York, 1970-1990), and the subsequent translations of these papers into other languages. The papers are those listed in the Royal Society Catalogue of Scientific Papers (London, 1867-1925) which covers a fairly complete choice of journals.' (Ibid, p. 52.) It is important to note that 'due to the great number of German papers, the respective vertical scale [in Figure 6.12] has been reduced, and multiple translations of the same paper into one language are counted but once.' (Ibid, p. 54.)

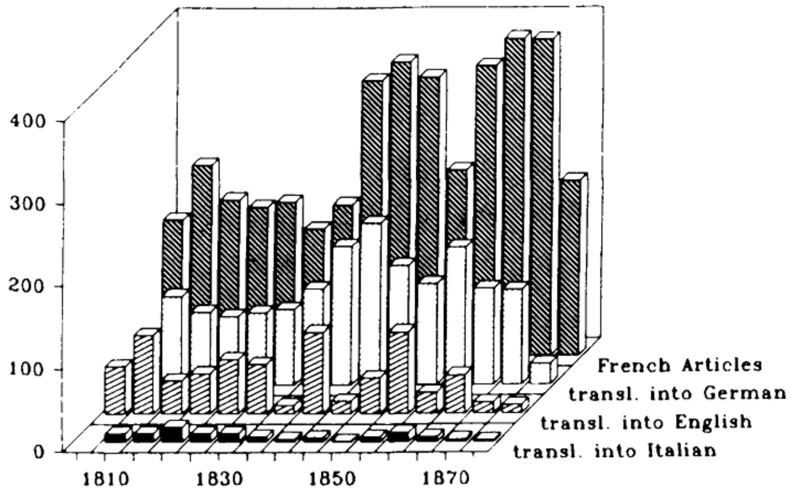

Figure 6.13: Number of articles published in French periodicals, 1801-75.

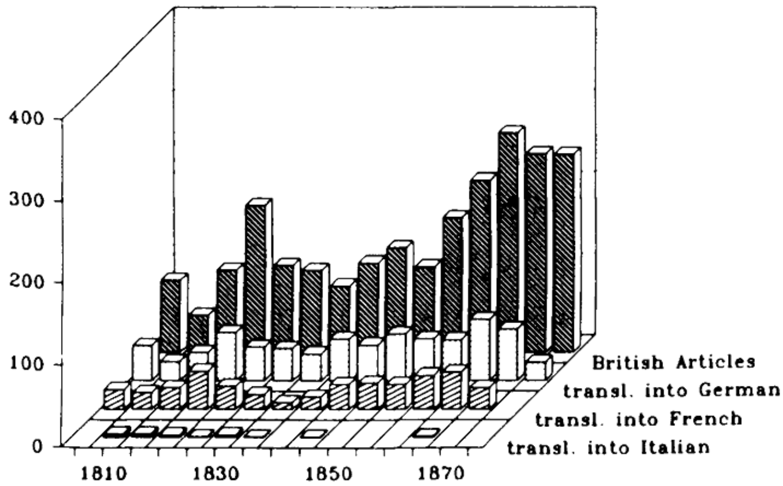

Figure 6.14: Number of articles published in British periodicals, 1801-75.

Meinel's results show that the number of German papers published in German periodicals (rear bar in Figure 6.12) as well as the number of foreign papers translated into the German language (white bars in Figures 6.13 & 6.14) increased dramatically in the period between c. 1856 and c. 1875. By way of illustration, a comparison of the charts shows clearly that during the period 1866 to 1870 almost 800 papers appeared in German periodicals (Figure 6.12), but approximately only half that number in French journals (Figure 6.13), and fewer than 300 papers in British publications (Figure 6.14). For the whole period 1801-1875, Meinel found that 'an average of 30-50% of all English and French papers included in our sample were soon available in German.'[18] These findings make it very clear that throughout the first three quarters of the nineteenth century, and especially for the years after 1856, a very large proportion of German, French, and British researchers selected German periodicals as the preferred publication outlets for their original research. In addition, Meinel also points out that researchers from the European periphery such as chemists from Russia or Scandinavia frequently submitted papers to German periodicals in order to 'make themselves known to the rest of Europe'.[19] From this, we can see that for the most part of the nineteenth century German specialist chemistry journals functioned as the leading means of print communication for chemical research that was produced anywhere in the world. This being the case, it becomes obvious why those journals experienced such a dramatic increase in the number of line-and-letter formulae during the 1860s and 1870s.

The above figures make clear that German periodicals were the driving force behind the dissemination of the new formulae during the 1860s and 1870s. In communicating papers on organic chemistry that featured the new structural diagrams to a large international audience, the journals ultimately contributed to the increase in the number and size of line-and-letter formulae in print. The case of abstract journal *Chemisches Zentralblatt* demonstrates in the next part of this section how rising printing costs and the increase in chemical information forced the publisher and editor of the *Zentralblatt* to introduce a number of editorial measures, which included the reduction of the number of line-and-letter formulae printed on the pages of this periodical. The case of the *Zentralblatt* thus demonstrates that by 1870 line-and-letter formulae had already become an economic concern to some journal makers, which required editorial intervention. The publisher thus resorted to making several changes to the layout of the journal, on the one hand, and to cutting the length of the abstracts, on the other. The latter was partly achieved by printing fewer line-and-letter formulae in the *Zentralblatt*.

The Modern Abstract Journal and the Rise of Organic Chemistry: How Publishers and Editors Handled the Flood of Chemical Information in the 1870s

Specialised abstract journals emerged as a separate 'synthetic' genre, as Alex Csiszar calls it, in the second half of the nineteenth century.[20] In his seminal study of the emergence and gradual

[18] Ibid, p. 54.
[19] Ibid.
[20] Csiszar, 'Seriality', p. 405. The seminal work on the history of abstract journals is Manzer, Bruce M., *The Abstract Journal, 1790-1920: Origin, Development and Diffusion* (Metuchen, NJ: Scarecrow Press, 1977). An overview of the history of abstract journals in Britain is found in Meadows, 'Access to the

establishment of the specialist science journal as the 'principal locus for demarcating scientific authority',[21] Csiszar explains that commercial abstract journals were the first kind of serial publications to serve the purpose of providing a 'systematic digest of periodical literature' in various branches of science. The new genre of the abstract journal began to emerge when more and more scientific communications were published in commercial journals in rapid succession during the second half of the century, which resulted in a rapidly growing number of research articles on different scientific subjects. This increase in the quantity of specialist research articles resulted in two major challenges to the organisation of scientific knowledge. Firstly, as the number of new journals began to rise, readers of scientific literature found that the landscape of scientific publishing was becoming increasingly eclectic, disorganised, and confusing.[22] Secondly, a large number of research contributions were published in small and often obscure journals that were very difficult to locate and access. Specialised abstract journals catering to a small number of disciplines or research areas emerged as a remedy to those problems and thus stepped in to a new market driven by the growing demand for comprehensive coverage of international periodical literature.[23] One of the very first abstract journals was *Chemisches Zentralblatt*, established by the prolific publisher Leopold Voss as *Pharmaceutisches Central-Blatt* on 14 January 1830 in Leipzig. [24] Targeted primarily at practising pharmacologists, the journal was published weekly from September 1830 and covered a wide range of Germanophone and international periodicals. The growing significance of chemical research and the subsequent increase in the number of readers trained in chemistry rather than pharmacy led the editor Wilhelm Knop (1817-91) to put a stronger emphasis on chemical publications and to change the journal's title to *Chemisches Central-Blatt* in 1856. Knop was succeeded as editor by his assistant Rudolf Arendt (1828-1902) in 1862.[25]

Results of Scientific Research: Developments in Victorian Britain', in *The Development of Science Publishing*, 43–62. Abstract journals are also briefly discussed in Brock, 'Science', in *Victorian Periodicals and Victorian Society*, ed. by Jerry Don Vann and Rosemary van Arsdel (Toronto: University of Toronto Press, 1994), pp. 81-96.

[21] Csiszar, 'Seriality', p. 426.

[22] Ibid, p. 408.

[23] Cf. Brock, 'Science', pp. 86-87.

[24] Seminal works on the history of this influential journal include Weiske, Christian, 'Das Chemische Zentralblatt - ein Nachruf', *Chemische Berichte* 106.4 (1973), i–xvi; Pflücke, Maximilian, 'Hundert Jahre Chemisches Zentralblatt', *Berichte der Deutschen Chemischen Gesellschaft A*, 62 (1929), 132–44; idem, 'Das Chemische Zentralblatt 125 Jahre alt', *Angewandte Chemie*, 66.17-18 (1954), 537–41; Schneider, Wolfgang, 'Historische Betrachtungen über das Chemische Zentralblatt', *Die Pharmazeutische Industrie*, 16 (1954), 52–54. It is striking that the *Zentralblatt* is completely omitted from Crosland's comparison of European chemical journals in Crosland, *Annales,* pp. 245-73.

[25] Cf. Weiske, 'Das Chemische Zentralblatt', pp. i-ii. The journal title changed from *Pharmaceutisches Central*-Blatt to *Chemisch-Pharmaceutisches Central-Blatt* in 1850 and then again to *Chemisches Central-Blatt* in 1856. The spelling was changed to *Chemisches Zentralblatt* in 1907 (fifth series, volume 11).

Abstract journals served two main purposes. On the one hand, the journals' readers expected to be provided with a comprehensive coverage of as much periodical literature as possible. On the other hand, the readers also expected to stay up to date with the most recent serial publications in their field, which meant that the time period between the publication of an original research article and the publication of the abstract of that article had to be kept as short as possible. In other words, since timeliness was one of the selling points of an abstract journal, any kind of backlog or delay had to be avoided. As commercial publishing enterprises, abstract journals also had to remain affordable in order to maintain or expand their customer base of paying subscribers, which meant that, as in the case of other commercial periodicals, retail prices had to be kept in check. The journals' commercial success thus depended on the ability to provide a comprehensive overview as quickly as possible while remaining competitive by keeping their prices down. Just like other specialist abstract journals,[26] the *Zentralblatt* struggled to find a balance between timely publication, comprehensive coverage, and affordable pricing when faced with the flood of research articles in organic chemistry during the second half of the nineteenth century. As we shall see in the remainder of this section, it was especially the rapidly increasing printing costs that put the *Zentralblatt* under enormous pressure and eventually resulted in the editor's decision to shorten abstracts by leaving out as many chemical formulae as possible.

And, indeed, the retail price of the *Zentralblatt* experienced a drastic increase over the course of ten years for the period 1864-74, and it was concerns about further price rises that eventually led Arendt to introduce several measures to cap the rising costs of the journal, as we shall see further below. To be more precise, the retail price rose from 3 ½ Thaler in 1864 to 5 Thaler in 1865 (43% increase),[27] and then again from 5 Thaler in 1870 to 7 Thaler in 1871 (40% increase) to 7 ⅔ Thaler in 1872 (10% increase), and finally from 7 ⅔ Thaler in 1873 to 9 Thaler in 1874 (17% increase). For the whole period from 1864 to 1874, the price of the *Chemische Zentralblatt* thus rose by approximately 257%. Although not every single increase was accompanied by an official statement from the journal's editor or Leopold Voss, the journal's Leipzig-based publisher, we have good evidence from two printed statements in which Voss

[26] Cf. Gooday, 'Periodical Physics'.
[27] The Thaler was legal tender in the Kindgom of Saxony (Königreich Sachsen) between 1838 and 1873. There were 30 Neugroschen in one Thaler and 10 Pfennige in one Neugroschen. Hermann Junghans' recent work on the different currency unions formed between German states in the nineteenth century provides handy convergence tables for all currencies in circulation between 1806 and 1873. See Junghans, Hermann, *Entwicklungen und Konvergenzen in der Münzprägung der deutschen Staaten zwischen 1806 und 1873 unter besonderer Berücksichtigung der Kleinmünzen* (Stuttgart: Franz Steiner, 2017).

decided to explain the renewed increase. In a note on the very last page of the last *Zentralblatt* issue of 1871, Voss announced the upcoming increase with the following words:

> As a result of the significant increase in the costs of printing and typesetting that has taken place since November of this year, and due to the simultaneous increase in the cost of paper, I am forced to raise the retail price of the Chemisches Zentralblatt again […], albeit by the small amount of 20 [Neugroschen] for the year.[28]

The new price, however, did not last long, as production costs continued to climb. The publisher was therefore forced to announce the next increase of the journal's retail price only two years later, explaining that as 'a result of the repeated increase in paper and especially printing costs, […] which amounted to 33 ⅓ p[er] c[cent] in May of this year, we are forced to raise the price of the Centralblatt again from next year onward […].'[29] This statement thus leaves no doubt that the publisher was faced with a sudden and unexpected increase in production costs which was not anticipated in their business plan. This strong increase was a result of the overall increase in printing costs in Germany, which was caused by a number of local trade agreements achieved by print workers' unions (Buchdrucker-Vereine) in several German states around 1870, and which were consolidated in a nationwide trade agreement (Allgemeiner Deutscher Buchdruckertarifvertrag) for the whole territory of the newly-founded German Empire in 1873.[30] At the same time, the cost of paper, too, was on the rise.[31]

In addition to the sharp increase in retail price imposed by the publisher of the *Zentralblatt*, additional substantial measures were introduced by the journal's editor Rudolf Arendt (1828-1902). Explaining the new editorial approach in the preface ('Vorwort') inserted at the beginning of the bound volume for the year 1870, Arendt made it clear that the

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[28] 'Durch die seit November d. J. eingetretene bedeutende Erhöhung der Preise für Satz und Druck, sowie durch gleichzeitige Steigerung der Papierpreise, bin ich leider gezwungen, mit Beginn des nächsten Jahrganges den Ladenpreis des Chemischen Centralblattes nochmals zu erhöhen, um den, wenn auch geringen Betrag von 20 Ngr. für den Jahrgang.' ('Zur Nachricht', *Chemisches Zentralblatt,* 3rd ser., 3 (1871), 832.)

[29] 'Durch die wiederholt eingetretene Erhöhung der Papier- und namentlich Druckpreise, deren letzte Steigerung im Mai d. J. 33 ⅓ p. c. beträgt, sind wir gezwungen, den Preis des Centralblattes vom nächsten Jahr an wieder zu erhöhen und haben denselben auf 9 Thlr. festgesetzt.' ('Zur Nachricht', *Chemisches Zentralblatt,* 3rd ser., 5 (1873), 832.)

[30] Cf. Kuczynski, *Arbeitslohn,* p. 565. The struggle of the German printers unions against their employers is treated at length in Kirchner, Hans-Martin, 'Wirtschaftliche Grundlagen des Zeitschriftenverlages im 19. Jahrhundert', in Kirchner, *Zeitschriftenwesen*, II, pp. 379-476 (pp. 452-57); and Heller, Alfred, *Das Buchdruckgewerbe: Die wirtschaftliche Bedeutung seiner technischen Entwicklung* (München: Verlag der Buchhandlung Nationalverein, 1911).

[31] Cf. Kirchner, 'Wirtschaftliche Grundlagen', pp. 436-39.

‘continuous growth of the chemical literature made [those changes] necessary, since under the previous arrangements it became more and more impossible each year for abstract to keep up with recent phenomena [‘Erscheinungen’] […].’[32] In the same preface, Arendt named three measures that he had introduced at the beginning of the same year in order to speed up the publication of abstracts and thus to avoid lengthy delays. According to Arendt, each of these served the purpose of fitting more abstracts on the printed page.[33] The three measures are the introduction of a combined essay review – called ‘Wochenbericht’ – to be published weekly; changes to writing style, journal size, and typography; and changes to the journal’s extensive index.[34]

Taken together, the three changes were meant to reduce the number of delayed abstracts from 80 to zero in the volume of the following year. Confident that the measures would prove effective, Arendt suggested in the aforementioned preface that ‘in the future all the literature of each year will have been fully abstracted only a few weeks’ after the end of that year.[35] The following comparison of the number of abstracts published in the *Zentralblatt* before and after the introduction of the said measures clearly shows that the measures were taking effect, which can be seen from the improved ratio of abstracts per printed page, increasing from close to 1.5 abstracts in 1870 to more than three abstracts in 1879 (Table 1).

Volume (year)	**No. of abstracts**	**No. of pages**	**Abstracts per page**
1st ser., vol 1 (1830)	403	544	0.74
1st ser., vol 21 (1850)	507	912	0.55
3rd ser., vol 2 (1870)	1200	832	1.45
3rd ser., vol 11 (1879)	2556	832	3.07

Table 1: Development of *Chemisches Zentralblatt*, 1830-79.[36]

[32] Arendt, Rudolf, ‘Vorwort’, *Chemisches Zentralblatt*, 3rd ser., 1 (1870), iii-iv (p. iii).
[33] Ibid.
[34] The purpose of the Wochenbericht section was to provide essay reviews of the ‘most recent publications in all areas of pure and applied chemistry’ (Arendt, ‘Vorwort’, p. iii). In practice the new essay review included short abstracts of journal articles which ranged from just one sentence to a whole paragraph occupying one third of the printed page in the *Zentralblatt*. The approximate mean length abstracts in the essay review was somewhere between three to five sentences, and formulae were included only on very rare occasions. Changes to typography and size of the journal concerned the omission of illustrations and the reduction of the font size. The issues of the third series dropped all wood engraving and condensed the text, which was achieved by reducing the font size in the extended abstracts by approximately one point, and that of the Wochenberichte by approximately two points.
[35] ‘[...] ja es darf jetzt zuversichtlich in Aussicht gestellt werden, dass in Zukunft über die ganze Literatur eines jeden Jahres immer schon wenige Wochen nach Schluss desselben vollständig wird referirt worden sein.’ (Arendt, ‘Vorwort’, p. iii.)
[36] Adapted from Weiske, ‘Das Chemische Zentralblatt’, Table 1, p. iii.

Although Arendt did not address chemical formulae directly in his 1870 preface, there is very strong evidence that his editorial measures affected the way in which the formulae were employed in the *Zentralblatt* after 1870. Above all, a comparison between the last volumes of the second series (1856-69) and the first volumes of the third series (1870-88) reveals a clear reduction in the number of line-and-letter formula on the pages of the periodical.[37] There are two ways in which space-consuming diagrams were treated after 1870: formulae were either reproduced in full and without any alteration so that the diagrams in the *Zentralblatt* look almost identical to those in the original journal paper from which the abstract is taken. Alternatively, space-consuming diagrams were intentionally left out and thus did not feature in the abstract at all. Although none of these two measures impinged on the appearance of line-and-letter formulae, Arendt's decision to introduce such measures makes it very clear that the diagrams posed a serious economic threat to the commercial viability of the abstract journal. The exclusion of line-and-letter formulae was therefore a necessary and effective measure to cap printing costs, on the one hand, and to guarantee the timely production of a constantly growing number of abstracts, on the other.

In this section, we have seen how the increase in organic research papers published in the *Annalen* and the *Berichte* posed a serious problem to the abstract journal *Chemisches Zentralblatt.* In order to deal with the influx of chemical information and to secure the journal's economic standing, the editor of the *Zentralblatt* introduced measures which were aimed at increasing the number of abstracts on the printed page. These measures included printing fewer line-and-letter formulae so that the number of the new diagrams was drastically reduced. This, I argue, indicates that to abstract journals such as the *Zentralblatt*, the new notation became an economic problem and thus called for the intervention of publishers and printers of serial print. In the next section, we shall see that British periodicals concerned with publication of abstracts faced the same problem. However, unlike the *Zentralblatt*, the editor of Britain's only chemical abstract journal *Journal of the Chemical Society Abstracts* did not decide to avoid the new formulae, but rather to introduce editorial measures aimed at implementing a new notational convention. As we shall see at the end of this chapter, it was partly through those 'Instructions' that iconographic diversity of printed line-and-letter formulae was noticeably reduced by the end of the 1880s.

[37] First series 1830-1855, second series 1856-1869, third series 1870-1888, fourth series 1889-1896, fifth series 1897-1918, sixth series 1919-1924, seventh and final series 1925-1969. Discontinued in 1969.

6.3. Dealing with the German Fallout: The Case of British Science Journals

The present section draws on the existing scholarship in the history of British science journals that I outlined in the thesis introduction. In particular, it deals with the different approaches with which editors of major British science journals approached line-and-letter formulae in the 1870s and 1880s. The periodicals under investigation are the journals of the Chemical Society, the *Philosophical Transactions* and *Proceedings* of the Royal Society, and William Crooke's (1832-1919) *Chemical News*. Apart from drawing on the original results produced by Aileen Fyfe and her *Philosophical Transactions* research team, the section builds on Bill Brock's historical studies of the *Chemical News*, on the one hand, and Edgar G. Watchurst's pioneering study in the history of the publications of the Chemical Society, on the other.[38] In addition, the section draws on original insights from my investigation of primary sources held at the archives of the Royal Society and the Royal Society of Chemistry in London.

Henry Watts and the Journal(s) of the Chemical Society

Out of the four British periodicals under consideration, it was the *Journal of the Chemical Society* that was most heavily influenced by this development. Unlike the *Proceedings*, the abstract section of the *Journal of the Chemical Society*, established in 1848, did not provide accounts of the research submitted to the Chemical Society for publication, but rather featured notices on chemical papers published in British and foreign scientific journals.[39] Due to its international scope – covering 15 journals in 1848, 32 journals in 1871, and 60 journals in 1891[40] – the abstract section had to accommodate an incessantly growing corpus of chemical publications from the early years of its existence. The *Journal* had constantly struggled to control the rising number of pages which the abstracts occupied. Yet from the 1860s onwards, it was especially the rising number of abstracts from German sources that posed a serious challenge to the *Journal.* Not only was the preparation and publication of abstracts under a constant threat of being delayed, but the rising number of pages would also have resulted in an increase in the already high price of the periodical. While the abstracts covered less than 20% of all pages in 1848 and only 29% in 1856, the overall proportion of abstracts rose very quickly to

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[38] Brock, 'The Making of an Editor'; idem, *William Crookes (1832-1919) and the Commerzialisation of Science* (Aldershot: Ashgate, 2008); Watchurst, 'Journal'.

[39] As early as 1862, the Council of the Chemical Society had officially acknowledged and emphasised the importance of abstracts from domestic and notably foreign sources as a means to increase the sales figures of the journal. Cf. 'Proceedings at the Meetings of the Chemical Society', *J. Chem. Soc.*, 16 (1863), 430-53 (p. 443).

[40] Watchurst, 'Journal', pp. 201-08.

approximately 60% in 1875.[41] The abstracts were temporarily suspended in 1862 in order to make more space for original research papers. Due to popular demand, however, the section was re-instituted in 1871, but the growing number of papers, on the one hand, and the growing length of those papers, on the other, forced the Society's Council and Publication Committee to publish the abstracts in a separate journal from 1878 onwards (*Journal of the Chemical Society Abstracts*). Original research papers were published in the Society’s *Journal of the Chemical Society Transactions.*

Evidence shows, however, that this measure was not sufficient to reduce the size of the new abstract journal. In May 1878 the Publication Committee finally acknowledged that the growing number and size of visual formulae represented a major part of this problem.[42] Faced with an increasing number of international publication on organic chemistry,[43] the recently founded *Abstracts* finally introduced its ‘Instructions to Abstractors’ in 1879. These guidelines required the journal's abstractors to use a specific kind of notation in order to reduce the space covered by chemical diagrams, thereby altering the notation of the original paper. The ‘Instructions’ were laid out in the Society's proceedings of 1879. John H. Gladstone, President of the Chemical Society between 1877 and 1879, not only explained the rationale behind these regulations, but also officially acknowledged the great significance of abstracts in his Presidential Address of the same year:

> The importance of the abstracts which we now publish is universally recognised. In order to facilitate the publication of them, to economise space, and especially to reduce the confusion which arises from different kinds of nomenclature, a new series of instructions to abstractors has been drawn up; and it is hoped that the suggestions adopted, after much consideration, by the Council of our Society, may not, be without their influence upon the practice of authors themselves.[44]

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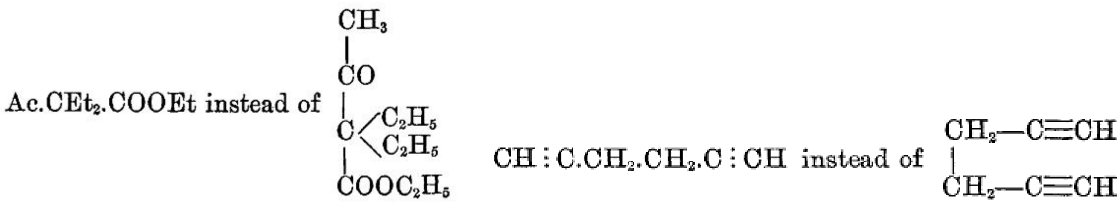
[41] Ibid, Table III, pp. 86-88.

[42] One of the main objectives of the ‘Instructions to Abstractors’, published in 1879, was to ‘economise space’ in order to facilitate and accelerate the production of abstracts. Cf. Watts, Henry, ‘Instructions to Abstractors’, *Journal of the Chemical Society Transactions,* 35 (1879), 276-81 (p. 276). These ‘Instructions’ were elaborated by subcommittee of the Publication Committee, officially appointed on 9 May 1878, and the results laid before the Council of the Chemical Society on 19 December 1878 (London, Historical Collection of the Royal Society of Chemistry, Minutes of the Publication Committee, vol I: 1854-1879).

[43] The number of reports published on organic chemistry made up 37,8% of all abstracts published in 1871, 40,8% in 1877, and 46,3% in 1891 (Watchurst, ‘Journal’, Table III, pp. 86-88).

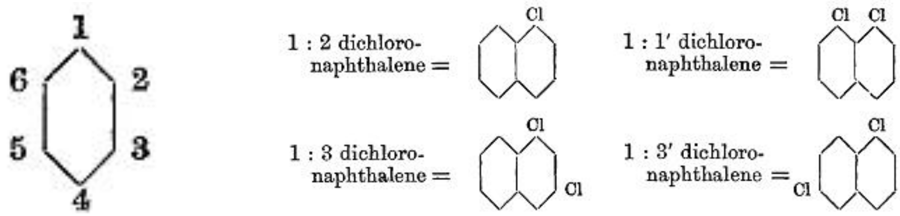
[44] ‘Anniversary Meeting’, *J. Chem. Soc. Trans.,* 35 (1879), 257-75 (p. 263).

According to these principles, the 'Instructions' outlined the need to 'economise space' by shortening the formulae and writing them 'in one line whenever this can be done without obscuring their meaning.'[45] In order to achieve this, 'dots should be used instead of dashes' to represent bonds and functional groups substituted by selected 'symbols' (e.g. 'Me' for 'CH_3'), thus reducing the two-dimensional iconography of extended line-and-letter formulae to a linear notation suitable to be printed as part of the written text (Figures 6.15 & 6.16).



Figures 6.15 & 6.16: Guidelines for reducing the two-dimensional iconography of line-and-letter formulae to a linear notation.[46]

To reduce the amount of space taken up by extensive ring formulae, Watts introduced a new form of systematic nomenclature that would be able to communicate all essential details of the molecule's arrangement by means of a specialised 'names'.[47] Thus, hexagonal benzene rings could be avoided altogether. The nomenclature would indicate the position of the functional groups ('radicles') attached to the ring by a numeric code based on a universal template (Figure 6.17).[48] In the case of more complex ring systems, this nomenclature would be implemented in the manner outlined in the second example below (Figure 6.18).



Figures 6.17 & 6.18: Special nomenclature for ring formulae.[49]

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[45] Watts, 'Instructions', p. 276.
[46] Ibid, p. 277.
[47] As Evan Hepler-Smith points out in his paper, German chemists often followed the same approach to naming new compounds by inventing their own nomenclatural rules based on the iconography of line-and-letter formulae (Hepler-Smith, '"Structural Formula"', pp. 10-11). Consequently, Watts' strategy to use specially devised names based on the appearance and arrangement of ring formula is not an isolated case and reflects a broader trend in the practice of late-nineteenth century organic chemistry. However, it is important to note it was only at the Geneva Conference in 1892 that chemists finally achieve an international agreement on one specific set of nomenclatural rules to replace all other conflicting systems of nomenclature (ibid, pp. 25-27).
[48] Watts, 'Instructions', p. 278.
[49] Ibid, pp. 278-79.

The above examples clearly demonstrate that Watts' 'Instructions' followed the same rationale as the measures introduced by Arendt, namely that economising space made publication more rapid and allowed for more abstracts to be fitted on the pages of the Society's abstract journal. Comparing Watts' editorial guidelines to the characteristic features of modern formulae that Laszlo describes in his 2001 paper, we can see that although they were not completely identical, the two conventions have much in common. Although the accentuation of heteroatoms, for example, is not covered in the Instructions, we can see that Laszlo's and Watts' conventions both cover the use of shorthand expressions for recurring chemical groups. In addition, both conventions aim to avoid vertically arranged line-and-letter formulae that occupy a large amount of white space on the page. Despite the differences between the two systems, is it therefore reasonable to posit that Watts' 'Instructions' played an essential part in shaping the conventions that govern the iconography of the modern line-and-letter formulae today. I elaborate on this point in the following paragraph.

One of the major historiographical challenges of explaining how specific conventions and standards are shaped and established over time is the lack of reliable primary sources that may offer direct insights into those processes. This certainly applies to the gradual emergence of the modern convention for the appearance of line-and-letter formulae. Although we shall see in the remainder of the chapter that Watts' guidelines were appropriated by a number of chemistry journals in the 1880s, Laszlo's convention also began to take hold in journals that did not introduce Watts' formalised instructions. What, then, was the reason behind that? We can find the answer to this question in the practical and economic rationale laid out in the 'Instructions'. Watts' own explanation of his guidelines makes it clear that the main purpose of the 'Instructions' was to economise space and to reduce the cost of printing. We can therefore reasonably posit that even where there is no evidence that editors and publishers of other journals embraced the 'Instructions' directly, similar reasons to those outlined by Watts pertained. After all, both Laszlo's convention and Watts' 'Instructions' represented excellent strategies not only to economise space, but also to make the process of typesetting more efficient and therefore less costly. Yet, as I have mentioned before, in the case of the Chemical Society's *Abstracts*, there can be no doubt that the 'Instructions' changed the number as well as the appearance of the formulae appearing on the journal's pages after 1879.

Evidence from the printed sources shows clearly that Watts' editorial guidelines had a significant impact on the number of formulae as well as the number of abstracts that were printed in *Abstracts* over the following years. While there was still a considerable number of visual representations in the volume of 1881, the number was significantly reduced by 1883. While not all of the Society's abstractors chose to adhere to the guidelines, so that unabbreviated formulae can still be found throughout the 1880s, it becomes apparent that more abstracts could be accommodated on the pages of the *Abstracts.* Thus, while only 1347 abstracts could be accommodated on 843 abstract pages before the separation of the journals in 1875, the total number of abstracts rose to 1980 in the year 1883, occupying 1180 pages, and finally reached 2179 abstracts on 1252 pages in 1889.[50] The ratio of abstracts per printed page consequently increased from approx. 1.6 in 1875 to approx. 1.68 in 1883 and further to approx. 1.74 abstracts in 1889 (Table 2).

Year	**No. of abstracts**	**No. of pages**	**Abstracts per page**
1875	1347	843	1.6
1883	1980	1180	1.68
1889	2179	1252	1.74

Table 2: Development of *Journal of the Chemical Society Abstracts*, 1875-89.[51]

We have thus seen how the need to economise space had prompted the Council and Publication Committee of the Chemical Society to take action to regulate the use and form of chemical formulae in its journals. The *Transactions* and *Abstracts* were the first and only journals to introduce such drastic measures. Yet it was also mentioned earlier that these two titles were by no degree the only scientific periodicals in Britain to cover organic chemistry. Why were similar measures not considered by the *Chemical News* and the *Proceedings* and *Philosophical Transactions of the Royal Society*? A quick comparison shows that, in fact, only a very small number of visual formulae appeared on the pages of those journals throughout the 1870s and 1880s. But what was the main reason for this, and why were there so many more visual representations in the *Transactions* and *Abstracts of the Chemical Society*, in the first place? The next part of this section demonstrates that the different historical backgrounds of the periodicals gave rise to distinctive editorial strategies which, in turn, accounted to a significant extent for the attitude of the responsible editors and publishers toward visual formulae in chemistry.

[50] Watchurst, 'Journal', Table III, pp. 86-88.
[51] Adapted from Watchurst, 'Journal', Table iii, pp. 86-88.

Philosophical Transactions and *Proceedings of the Royal Society*

Compared to the titles of the Chemical Society, both the *Philosophical Transactions* and the *Proceedings of the Royal Society* included a relatively small number of visual representations in abstracts and papers on chemistry, but still exceeded the *Chemical News* in this matter. No strategies were adopted to reduce the number of visual formulae featured in a paper, and no efforts were undertaken to change or crop the symbols, as in the case of the *Journal of the Chemical Society*.

The fact that the Royal Society had no need for such alterations can be explained not only by the sporadic appearance of research papers featuring those formulae, but also by the option to publish research in either the *Proceedings* or the *Philosophical Transactions* in various forms, and the generous publication budget that the Society had at its disposal. Being mainly financed by membership fees, the journals were not forced to generate profit in order to survive, and never since the *Philosophical Transactions* had become the official journal of the Royal Society in 1752 had its value and significance been contested. Although in the eighteenth and nineteenth centuries the Royal Society had to devise different strategies to cover the production costs of the journal, the *Philosophical Transactions* had never faced the threat of bankruptcy and immediate extinction. As Aileen Fyfe points out in her recent paper, although the publication of the *Philosophical Transactions* had never been a profitable enterprise and incurred major costs to the Royal Society, 'the publication finances were not expected to balance: they were considered part of the general finances of the Society.'[52] Furthermore, the choice between two distinctive, but interrelated publication formats enabled the Royal Society's Committee of Papers to select the most appropriate title according to the quality and relevance of the manuscript, and to publish submitted material either as a short notice in the *Proceedings*, as a full-length paper in the same journal, or as an extensive research article in the *Philosophical Transactions* (with an abstract thereof being communicated in the *Proceedings* beforehand). For these reasons, the journals of the Royal Society were in a much safer financial position than their commercial counterparts.

By way of illustration, the monthly *Proceedings* were used for abstracts or papers whose results were not considered relevant enough to appear in the prestigious *Transactions*, while the latter were chosen as a biannual repository for more substantial research.[53] By alternating

[52] Fyfe, 'Journals, Learned Societies and Money', p. 278.
[53] From 1870 onwards, however, shorter publication intervals became increasingly relevant. Consequently, the *Proceedings* were mostly used as a vehicle for research which had to be published and disseminated rapidly (i.e. before the publication of the biannual *Transactions*).

between the two publication outlets, the Royal Society acquired a high degree of editorial flexibility which allowed it to publish an unusually high proportion of submissions without making extensive changes to the original paper. Sloan Despeaux's survey of editorial and refereeing practices for mathematical papers demonstrates that in fact, less than 15% of all submissions to the Royal Society remained unpublished during the last three decades of the nineteenth century. According to the minutes of the Committee of Papers, approximately 3500 paper submission were rejected for publication in the *Philosophical Transactions* between 1832 and 1900. Yet while the overall number of submitted manuscripts kept rising during the last three decades of the nineteenth century, the number of archived (i.e. rejected) papers remained constant at around 100 submission per decade. These figures are explained by the fact that papers rejected for publication in the *Philosophical Transactions* still retained a good chance of being published – in extenso or in a slightly shortened form – in the Society's *Proceedings*.[54] In the case of those submissions on organic chemistry that were printed in both journals (i.e. first as an abstract in the *Proceedings*, followed by a research paper in the *Transactions* later), it can be observed that while the amount of text was significantly reduced in the abstract, the number of visual formulae remained the same in both publications, with the same number of representations included in the *Proceedings* as in the *Transactions*. Thus, while the text could be subjected to substantial editing, formulae usually stayed untouched.

The Society's editorial strategies are best explained by relating them to the journals' audience, print runs and budget. Being lavishly financed by the subscription fees of the members of the Royal Society and not being dependent on commercial success, the *Philosophical Transactions* and *Proceedings* had no need to economise on the number of printed pages, to avoid illustrations in order to save printing costs or to boost sales figures by keeping the price as low as possible. In fact, there were no official instructions or guidelines for referees to consider the omission of illustrations due to pending costs. Quite to the contrary, the Society was ready to pay for illustrations in the majority of cases and would rather renegotiate the contract with its printer than consider placing any restrictions on the use of images, graphs and formalisms.[55] As a consequence, it was primarily the referees' assessment – based on scientific expertise – and not financial considerations upon which the Committee of Papers based their decisions regarding the use of illustrations in forthcoming papers, with the Royal Society subsequently

[54] Despeaux, Sloan Evans, 'Fit to Print? Referee Reports on Mathematics for the Nineteenth-Century Journals of the Royal Society of London', *Notes and Records*, 65.3 (2011), 233–52 (p. 242).

[55] Like other learned societies at that time, the Royal Society too was becoming more aware of its rising printing costs and considered to renegotiate the contract with its designated printer Taylor & Francis, eventually leading to the termination of this contract and the appointment of Harrison & Sons in 1877 instead. Cf. Brock and Meadows, *Lamp of Learning*, pp. 48-49.

paying for their production and printing.[56] The minutes of the Committee of Papers contain numerous records showing that the quality rather than the cost of illustrations constituted the primary concern of editors, and cases can be found where illustrations were ordered to be reproduced or improved in the case of unsatisfactory first results.[57] Yet the archives show no records of any special regulations concerning the handling of chemical formulae. Overall, the Royal Society placed very few restrictions on the length of scientific papers and the application of illustrations. Chemical formulae were not cropped, but reproduced in full. From this, it follows that formulae could be employed freely both in the *Proceedings* and the *Philosophical Transactions*, and that any changes in the iconography and use of those representations were not imposed by editors and referees, but rather reflected authors' personal preferences.[58]

Chemical News

Compared to the number of visual formulae in the periodicals of the Chemical and the Royal Society, the apparent lack of chemical representations in the *Chemical News* is striking. As in the case of the *Proceedings* and *Philosophical Transactions*, this characteristic is best explained by the specific background of William Crookes' long-running chemistry journal (published in London from 1859 to 1932). Being the only commercial periodical among the titles studied in the current section, the *Chemical News* depended to a much higher degree on commercial success than the periodicals issued by learned societies. By 1869, approximately 10,000 copies of the journal were circulated each week and by 1900, Crookes was making an income of £400 p.a. from the sales of the *Chemical News* alone.[59]

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[56] Correspondence between the Secretary and members of the Committee of Papers suggests that it was a common procedure to get an estimate from the Society's printer for the production costs of illustrations once the referees have recommended the respective paper for publication. See, for instance, a letter by Warren De la Rue to Stokes with an estimation of the cost for having an astronomical paper by Prof B. Stewart printed together with tables and illustrations (London, Library and Archives of the Royal Society (LARS), RR, Referees' Reports, ref. no. RR/7/169, 23 November 1872).
[57] See, for instance, a letter from Herbert Rix, Associate Secretary, to Harrison & Sons. In this letter, Rix urges the printer to go ahead and produce an improved version of mathematical formulae after the first copy proved to be faulty (LARS, New Letter Book, ref. no. NLB/1/438, 4 April 1887).
[58] Yet data from the archives of the Royal Society indicates that referees considered the *Philosophical Transactions* to be more suitable for the publication of illustrations than the Society's *Proceedings*. Thus, Sir Michael Foster states in his referee report on W. N. Hartley's and A. K. Huntington's paper 'On the Action of Organic Substances on the Ultra-Violet Rays of the Spectrum', *Philosophical Transactions*, 170 (1879), 257-74 that 'the numerous diagrams, which are an essential part of the paper, could not be conveniently given in the "Proceedings" and my recommendation therefore is that the paper be published in the Transactions.' (LARS, RR, Referees' Reports, ref. no. RR/8/225, n.d.)
[59] Brock, *Fontana History*, p. 456.

The journal's extraordinary success was based on its rapid publication, low price and wide circulation. In times when chemical research was mostly published in specialist periodicals issued by learned societies and professional organisations, Crookes' weekly journal provided an essential source of information for all those readers who were interested in various fields of chemistry, but could not afford such costly publications as the *Journal of the Chemical Society* or foreign journals such as *Annalen der Chemie*. It also provided its audience with up-to-date information on the meetings of learned societies that most readers would have been unable to attend, often being faster in publication than the original proceedings and often produced from or supplemented by Crookes' own shorthand notes.[60] Indeed, rapidness of publication had been one of the biggest advantages of the *Chemical News* over its British competitors since its foundation in the late 1850s.[61] One of the most effective strategies to maintain a high publication rate and to avoid high printing costs was to avoid illustrations wherever it was feasible. Moreover, due to the fact that the *Chemical News* appeared at weekly and not at monthly or biannual intervals, the available number of pages was highly restricted, usually comprising no more than twelve pages per issue (excluding advertisements).

Operating under such strong limitations, Crookes faced the challenge of including as much information as possible on the printed page while catering for a highly diverse and generalist audience. As this eclectic readership demanded rather an overview of relevant developments in all fields of chemical research and application than highly specialised and technical information, it was the 'Chemical Notices from Foreign Sources' that occupied the most pages in the periodical. Serving as a medium for the rapid dissemination of chemical information in the broadest sense, these 'Notices' usually provided only short summaries of the contents of published papers, in some cases mentioning as little as the title of the relevant communication, and did obviously not require the reproduction of chemical formulae to fulfil the audience's needs. The omission of formulae and illustrations also allowed the *Chemical News* to meet its tight publication deadlines. Ironically, these deadlines were also the reason for the rare appearance of visual formulae in some of the more extensive research papers that were occasionally reproduced in full, since including unaltered copies of research papers allowed the editor to avoid the labour-intensive editorial work of cropping both text and illustrations, and to forward the original article directly to his printers. In general, however, the relatively low number of visual formulae was a direct consequence of Crookes' editorial strategy of offering concise notices, the more infrequent reproduction of complete research papers, and the

[60] Ibid, p. 455.
[61] Ibid, pp. 455-56; Brock, 'Making of an Editor', p. 190.

avoidance of as much editorial work as possible. This editorial strategy remained unchanged even after the editorship was effectively handed over to Gardiner in 1906.

Through the comparison between *Journal of the Chemical Society Abstracts* and other major science journals from Britain, this section has demonstrated that abstract journals faced different economic pressures than titles such as the journals of the Royal Society and the *Chemical News* due to their unique position on the British and German markets for scientific print. The Royal Society's generous budget, on the other hand, allowed *Philosophical Transactions* and *Proceedings* to grow in size without being threatened by imminent financial hardship and decline. It was thus for distinctive economic reasons that editors of abstract journals such as *Chemisches Zentralblatt* and *Journal of the Chemical Society Abstracts* developed strategies to reduce the number and size of line-and-letter formulae on the page. In the next section, we will see how editorial measures based on Watts' 'Instructions' were adopted by a number of other chemical journals in the 1880s and thus led to the gradual establishment of the iconographic convention described at the beginning of this chapter.

6.3. How the Economics of Printing Led to the Standardisation of Structural Diagrams in the 1880s and 1890s

The previous two sections of the chapter have demonstrated that editors and publishers of *Chemisches Zentralblatt* and *Journal of the Chemical Society Abstracts* introduced different measures to reduce the space occupied by the formulae on the printed page in order to minimise the economic threat to their journals posed by the rapidly growing number of pages as well as the increasing printing costs.[62] As I have explained on several occasions, in addition to making expensive demands on paper, line-and-letter formulae were expensive to typeset, since the composition costs of those formulae could be two or three times higher than the costs of plain text. It is mainly for these economic reasons that Rudolf Arendt decided to omit line-and-letter formulae wherever that was possible and the Chemical Society introduced Watts' Instructions to Abstractors in 1879. Although the measures applied by the *Zentralblatt* were different from those implemented in the *Abstracts*, there is very good evidence that those measures gradually led to a more uniform and standardised appearance of line-and-letter formulae during the 1880s

[62] Further evidence for this is provided by Aileen Fyfe, who states that 'complex typesetting required for tables and algebra' very often raised the production costs of commercial as well as society-funded scientific journals to such a degree that those expenses made the whole publication enterprise unprofitable. Cf. Fyfe, 'Journals, Learned Societies and Money', pp. 277-78.

and 1890s. In fact, the examples presented in the first section of this chapter make it very clear that line-and-letter formulae published in British, German – and, for that matter, French – periodicals in the last two decades of the nineteenth century clearly exhibited a set of common features, as Laszlo points out in his seminal paper of 2001.

But can we be really sure that it was exactly those editorial measures that led to the standardisation of line-and-letter formulae in the said period? The present section argues that this was indeed the case, as the appropriation of Watts' 'Instructions' by a number of other Anglophone journals over the course of the 1880s clearly demonstrates. Focusing on the decision made by the Committee on Nomenclature and Notation of the American Chemical Society in 1886, I show that American chemists decided to implement the 'Instructions' in their own journals because they considered them an effective way of dealing with the growing number as well as diversity of structural diagrams. This, I claim, represents very strong evidence of the ongoing importance of the 'Instructions' in regulating the growth of line-and-letter formulae. More particularly, the case of the American Chemical Society demonstrates that the Americans regarded Watts' 'Instructions' as a suitable means of introducing more uniformity to the confusing plethora of diagrams flooding their journals. In providing this account, I show that soon after the Instructions were first published in 1879, chemists came to implement the guidelines not only as tool to curb the printing costs of chemical periodicals, but also as a directed measure to standardise chemical notation.

The section concludes by arguing that although the notational rules of the Chemical Society were adopted by only a small number of chemical journals directly, the conventions were still spreading. I do this by comparing the formula in one of Frankland's handwritten manuscripts, dating from 1889, with the final version of the same formula that appeared in the *Proceedings of the Royal Society* in the same year. Like the journals of the Royal Society, the majority of editors of Anglophone science journals did not openly adopt the 'Instructions' of 1879. Yet the case of Frankland's formula clearly shows that some of the conventions described in the first chapter of my dissertation were enacted by the printers of those journals during the process of printing. This example therefore also provides strong evidence that by the end of the 1880s, a tacit convention was already in place so that formal notational rules were no longer required to ensure that the formulae adhered to the current conventions. And, although there is no indication that any of the French or German periodicals made use of Watts' Instructions, I claim that the case of Frankland's formulae provides sufficient evidence to surmise that printers of non-Anglophone journals were acting in a similar way by making alterations to line-and-letter formulae wherever the authors did not adhere to emerging conventions themselves. As a result, we can see that the conventions described by Laszlo were indeed taking hold over the course of the 1880s. This, finally, strongly suggests that by the early 1890s the majority of chemists publishing in international journals were sufficiently familiar with the conventions that a uniform appearance of line-and-letter formulae was achieved by that time.

The Appropriation of Watts' Instructions in Anglophone Publications

We have already established in the previous section that Watts devised the 'Instructions to Abstractors' primarily for the purpose of reducing the space consumed by line-and-letter formulae on the printed page. Yet in his aforementioned Presidential Address of 1879, the Chemical Society's President John Gladstone additionally stated that 'it is hoped that the suggestions adopted, […] by the Council of our Society, may not be without their influence upon the practice of authors themselves.'[63] In saying this, Gladstone clearly suggested that authors of original research papers submitted to the Society's *Transactions* might also use the guidelines to achieve a more consistent appearance of the formulae that they use in their manuscripts. When the American Chemical Society adopted Watts' Instructions in 1886, the members of its recently established Committee on Nomenclature and Notation made very clear that achieving a more uniform coherent system of nomenclature and notation was at the core of their decision.[64] From this, we can see that the Instructions' main purpose changed from merely reducing the costs of printing to transforming the face of the structural diagrams that began to populate chemical periodicals in large numbers, but which, as we saw in the first section of this chapter, still displayed a large degree of iconographic diversity throughout the 1870s and early 1880s.

The *Journal of the American Chemical Society (JACS)* was established in 1879 as the official publication outlet of the American Chemical Society (ACS) that was founded in New York in 1876.[65] Rivalled only by the *American Chemical Journal* (f. 1879), the *JACS* was one of the most influential and widely-read American chemical journals during the last decades of the nineteenth century. So what was the reasoning behind the decision to appropriate and popularise Watt's 'Instructions' in that journal? As the official journal of a national society whose mission it was to represent the entirety of the American chemical community, *JACS* reflected

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[63] 'Anniversary Meeting', p. 263.

[64] Cf. Breneman, A. A., G. E. Moore, A. R. Leeds, and others, 'Report of the Committee on Nomenclature and Notation', *JACS*, 8 (1886), 116-18 (pp. 116-17).

[65] For a brief historical overview of the development of chemical journals in the United States, see Ihde, *Development*, pp. 270-73; and Crosland, *Annales*, pp. 267-78. For a detailed history of the American Chemical Society, see Skolnik, H., and K. M. Reese, *A Century of Chemistry: The Role of Chemists and the American Chemical Society* (Washington, DC: American Chemical Society, 1976).

the ACS's agenda to bring order to chemical nomenclature and notation to American chemistry. In doing so, the ACS followed a global trend: as Evan Hepler-Smith explains in his dissertation, in the 1880s chemists across the world became increasingly concerned about the confusion stemming from different nomenclatural systems, and a number of the recently established national societies to standardise and regulate nomenclature, often together with attempts to do the same for chemical notation. Yet during that time the efforts to regulate nomenclature and notation did not extend to international agreements, but were restricted to the national level.[66] Although each society had its own specific reasons for seeking standardization, we have very good first-hand evidence to explain why the ACS was pursuing that agenda. Announcing the introduction of Watts' rules in 1886, the Committee on Nomenclature and Notation stated that, although the 'principles' were 'merely for general guidance' and authors should therefore be 'allowed the widest liberty that is consistent with clearness of expression [...], the demands of teaching and the needs of those engaged in related branches of science, or in commerce, direct that chemical nomenclature should be sufficiently fixed and definite to render the subject of chemistry accessible to those who are less acquainted with its technical details.'[67] This indicates that it was mainly pedagogical concerns – and not economic concerns about printing costs – that stood behind the appropriation and popularisation of Watt's 'Instructions' by the American Chemical Society.

Watts' Instructions also found their way to the other side of the Pacific, where they were appropriated – 'to a considerable extent', in Watt's own words – by the Royal Society of New South Wales in the 1880s.[68] These instances thus provide sufficient evidence of the instructions' utility in regulating chemical nomenclature and notion, thereby attesting to their lasting impact and success. Yet the evidence presented in this subsection also makes it very clear that only a small number of exclusively Anglophone society journals chose to implement the rules. Evidence presented at the beginning of this chapter nevertheless demonstrates that formulae published in other Anglophone journals as well as in French and German periodicals from the 1880s onwards, also began to follow the characteristic features identified by Laszlo. This suggests that

[66] Those national efforts eventually culminated in the first international Conference on Chemical Nomenclature in Geneva in 1892. For details, see my introductory chapter and Hepler-Smith, 'Nominally Rational'. The leading role of national chemical societies reflects the growing nationalisation of chemistry described in Meinel, 'Structural Changes'; idem, 'Nationalismus und Internationalismus in der Chemie des 19. Jahrhunderts', in *Perspektiven der Pharmaziegeschichte: Festschrift für Rudolf Schmitz zum 65. Geburtstag*, ed. by Peter Dilg (Graz: Akademische Druck- und Verlagsanstalt, 1983), pp. 225-42; and Rocke, *Nationalizing Science.*
[67] Breneman and others, 'Report', p. 117.
[68] Watts to Armstrong, 13 Sept 1881, quoted in Traynham, James, 'Organic Nomenclature: The Geneva Conference 1892 and the Following Fifty Years,' in *Organic Chemistry: Its Language and Its State of the Art*, ed. by M. Volkan Kisakürek (Basel: VHCA, 1993), pp. 1-7 (p. 3). See also Hepler-Smith, 'Nominally Rational', pp. 126-27.

the convention was spreading, regardless of whether formal notational rules were enforced. This might have been the case because authors chose to follow the conventions that they had previously encountered in Anglophone research or abstract journals. Yet we also have strong evidence that printers began to implement the convention regardless of authors, as the next section demonstrates.

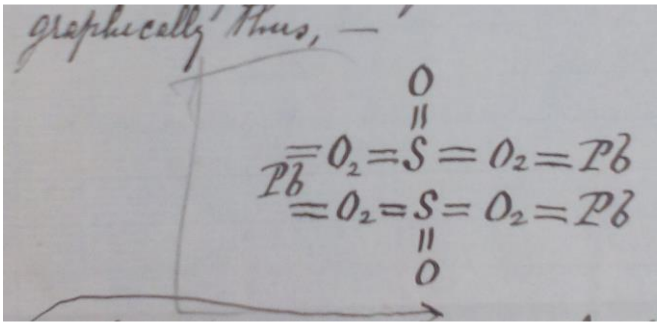
Aligning Lines and Arranging Letters: How Printers Enforced the Notational Convention

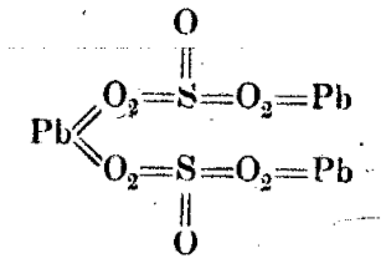
This last part of the present section deals with the role of printers in the making of the new notational convention. The following comparison between the original version of a formula in Edward Frankland's manuscript submission to the Royal Society and the final printed version of the same formula demonstrates that scientific printers played a decisive part in the implementation of the more uniform and standardised form of line-and-letter formulae. In doing this, the following example also provides rare first-hand evidence of the power that printers held over the form in which readers of printed works encountered scientific knowledge such as chemical formalisms. The relevant document is dated 1889 and is located in the archives of the Royal Society in London.[69]

The comparison between Frankland's handwritten manuscript and the published paper reveals minute but significant differences between line-and-letter formulae in the manuscripts and those which eventually appeared in print in the journals of the Royal Society. In the specific case of Frankland's paper 'Contributions to the Chemistry of Storage Batteries. No. 2' published in the *Proceedings* volume 46 in 1889,[70] it becomes evident that the author had initially arranged the double bonds of his diagram for 'red lead salt' in a different way than they later appeared on the printed page. From the manuscript, we can see that Frankland exclusively used angles of ninety degrees in his line-and-letter formula for the given compound (Figure 6.19). Yet, by comparing Frankland's handwritten line-and-letter diagram to the final product on the page of the *Proceedings* (Figure 6.20), we can clearly see that the angle of the two double bonds joining the lead atom (Pb) to the oxygen atoms (O_2) was altered. Since there are no proof marks on the manuscript related to the arrangement of the bonds or the orientation of the formula on the

[69] This work was made possible by the New Scholar Award 2015 of the Society for the History of Alchemy and Chemistry (SHAC). I would like to thank the Society for the generous support of this project. For a full report, see Kiprijanov, Konstantin S., 'Report. SHAC New Scholar Awards 2015', *Chemical Intelligence*, 15 (January 2016), 20–21 <http://www.ambix.org/wp-content/uploads/2016/01/ChemIntelJan2016.pdf> [accessed 16 July 2018].
[70] Frankland, 'Contributions to the Chemistry of Storage Batteries. No. 2', *Proceedings of the Royal Society*, 46 (1889), 304-08.

printed page, we must assume that it was not the editors', but the printers' decision to change the appearance of the formula. Consequently, the printed formula for 'red lead salt' below allows us to witness how the journal's printers realigned two of the bonds to a forty-five degrees angle, thus employing them simultaneously to stress the position of the lead atom and to emphasise the compound's horizontal axis of symmetry. In doing so, the printers clearly adhered to the convention of emphasising the position of the heteroatom as the chemically most important part of the represented compound.





Figures 6.19 & 6.20: Frankland's handwritten formula for 'red lead salt' and typeset formula for the same substance published in 1889.[71]

6.4. Conclusion

This chapter has demonstrated how the flood of chemical research articles coming from German periodicals drove the rapid increase in iconographic diversity as well as space consumption of line-and-letter formulae during the 1860s and 1870s. The chapter has made it clear that it was the abstract journals that were most affected by the negative economic consequences of the said increase in the number and size of the formulae. We have seen that editors of chemical abstracts journals consequently introduced different editorial measures to cap printing costs and thereby to secure their journals' commercial success on the competitive market for scientific print. Those editorial measures had in common that they served the purpose of reducing the space consumed by the formulae. In 1870, Rudolf Arendt, the editor of *Chemisches Zentralblatt* at that time, decided to reduce the number of line-and-letter formulae by omitting the diagrams wherever that was possible. Following the recommendations of the Chemical Society's Publication Committee, Henry Watts went further and introduced a number of formalised rules

[71] Left: LARS, PP, Proceeding Papers for Procs 46, 1889, MS no. 27, pp. 1-6 (p. 3). Right: Frankland, 'Storage Batteries', p. 307.

known as ‘Instructions to Abstractors’ in 1879. The chapter argued that those guidelines played a key role in establishing a tacit convention for the appearance of line-and-letter formulae over the course of the 1880s and 1890s, resulting in a more uniform and standardised iconography that formed the necessary condition for the first official international agreement on systematic organic nomenclature achieved at the Geneva Conference in 1892.

The chapter also discussed possible factors that led to the gradual emergence of the said iconographic convention in during the 1880s and 1890s. On the one hand, we have seen that learned societies such as the American Chemical Society and the Royal Society of New South Wales adopted Watt’s ‘Instructions’ in their journals as means of regulating and standardising chemical nomenclature and notation. On the other hand, I have explained that even where we lack first-hand evidence that editors and publishers of other journals embraced the ‘Instructions’ directly, it is reasonable to posit that practical, economic, or pedagogical considerations similar to those outlined by Watts and the ACS nomenclatural committee pertained. Finally, the chapter also demonstrated that printers, too, contributed to the shaping of the tacit convention by changing the appearance of diagrams without being instructed to do so by the editors of the journal. In providing this account, the chapter has demonstrated that the economics of print as well as communicative practices played an absolutely crucial part in bringing about the modern notation of organic chemistry.

Yet just how important were those economic and practical aspects of printing and publishing as casual factors of the emergence of the organic notation in its modern form? After all, we must not forget that practising scientists, too, had specific requirements in relation to the notation. In addition, it we can imagine that some of the characteristic features described by Pierre Laszlo above were developed and applied in the context of teaching, because they facilitated pattern recognition and therefore made it easier to write and memorise the formulae. Unfortunately, the lack of relevant sources makes it very difficult to assess the part that those considerations played in shaping the iconography of the formulae. So just how much agency can we assign to those researchers who were using chemical diagrams in their laboratory journals, private notebooks, research paper manuscripts, and on the blackboard in the classroom? Was the appearance of line-and-letter formulae really a direct consequence of the economic and practical side of science communication which I have described in this thesis, or were there also epistemic factors involved? I will address these and other questions in the concluding chapter of my dissertation.

CHAPTER 7

Conclusion

> When I draw a molecule in China or in Argentina, it is the same molecule. People understand immediately without knowing Spanish or Chinese. That is beautiful. Our common goal is not about power or borders of the country, it is about bringing forward human knowledge.
>
> — Ben Feringa, 2016 Nobel Laureate in Chemistry.[1]

Drawing on a large number of published and unpublished sources from Britain, Germany, and other countries, my thesis has challenged the existing account of the making of the modern chemical notation during the second half of the nineteenth century. Although chemical notation and nomenclature underwent further transformations over the course of the twentieth century, and although new ways to represent chemical substances were developed from existing line-and-letter formulae in the same period, present-day notation still bears a very close resemblance to its late nineteenth-century counterpart. It is notably this iconographic uniformity of line-and-letter formulae that enables the diagrams to function as universal communication tools between different research communities across the globe, and it is exactly this unique feature of the formulae that is captured in Nobel Laureate Ben Feringa's enthusiastic statement quoted above.

This thesis has raised two main questions. First, why do line-and-letter formulae look the way they do? And secondly, how did the diagrams become the standard notation of organic chemistry? The first two sections of this chapter evaluate my findings in relation to these questions. The first section is concerned with my account of the success of line-and-letter formulae. The section discusses an important historiographical question that I have raised on several occasions in my thesis, namely whether it was predominantly epistemic considerations or practical and economic concerns that were the main reason for the emergence of line-and-letter formulae in their current form. The second section underlines and reflects on the methodological advantages of studying the circulation of scientific knowledge from a transnational and interdisciplinary perspective. The third and final section elaborates on how

[1] Official Twitter Feed of the Nobel Prize, '"When I draw a molecule in China or in Argentina, it is the same molecule. People understand immediately without knowing Spanish or Chinese. That is beautiful. Our common goal is not about power or borders of the country, it is about bringing forward human knowledge." Ben Feringa', [Twitter post] (@NobelPrize, 29 January 2018).

further studies into the history of chemical communication might produce new and important insights into the making of chemistry as a modern scientific discipline.

7.1. The Role of Communication Practices in the Making of Modern Chemistry: Knowledge in Transit

The thesis has demonstrated the essential contribution that communication practices such as teaching, writing, editing, printing, and publishing played in the inception, proliferation, appropriation, and standardisation of structural formulae over a prolonged period of more than thirty years. Yet as I have mentioned in Chapter 2 as well as at the end of Chapter 6, this does not imply that theoretical considerations, such as the specific heuristic requirements of structural chemists, had no role to play in the making of line-and-letter formulae. Drawing on the results of my research, this section reflects on the importance and changing roles that heuristic and epistemic as well as economic and practical factors played in the making of the modern chemical notation.

Structural chemists such as Archibald Scott Couper, August Kekulé, and Josef Loschmidt devised different forms of chemical diagrams that all served the main heuristic purpose, namely to represent the hypothetical constitution of chemical compounds according to the principles of the structure theory. Line-and-letter formulae, Kekulé's sausages, and Loschmidt's circles were all designed to visualise the connections between atoms that, according to the structure theory, account for the chemical behaviour of the resulting molecule.[2] From this, we can see that theoretical considerations were the driving force behind the inception of new sets of formulae that were designed to visualise what other types of formulae could not. In other words, this means that it was heuristic requirements posed by the emerging theory of chemical structure that led to the inception of new chemical representations.

However, we also saw that by the beginning of the 1870s neither Kekulé's nor Loschmidt's formulae were any longer in use. By comparing the practical and economic aspects of different printing techniques in Chapter 3, I demonstrated that the reason for this was not the epistemic "inferiority" of those formulae, but the very practical challenges of reproducing Kekulé's and Loschmidt's diagrams on the printed page. Consequently, typeset line-and-letter formulae proved to be the kind of constitutional representation that offered the most cost-

[2] I have already explained in Chapter 2 that line-and-letter formulae represented the links between atoms and radicles by means of typographic connectors such as solid or dotted lines, or sometimes also punctuation marks. Kekulé's diagrams achieved the same by means of touching "bulbs", and Loschmidt's diagrams depicted the links as the intersection between circles.

efficient and speedy way of communicating structural ideas. Furthermore, we saw in Chapter 6 that economic and practical concerns also played a very important part in the establishment of a tacit iconographic convention and the resulting standardisation of an internationally recognised appearance of line-and-letter formulae prior to the Geneva Conference of 1892. Drawing on the findings of Chapters 2, 3, and 6, I conclude that, although heuristic requirements were instrumental in the design of new diagrams in the 1850s and 1860s, theoretical considerations played only a minor part in the proliferation and consolidation of the new line-and-line formulae in the following three decades. Consequently, it was predominantly through the various processes of communication that the new diagrams acquired their modern appearance and became established as the default symbolic notation of organic chemistry.

Yet communication practices must not be viewed as being distinct from other tasks such as handling laboratory equipment or calculating chemical equations. Chemists have relied on a wide range of practices to develop, circulate, debate, and assert their arguments about the behaviour, composition, or constitution of chemical substances, combining experimenting and imaginative visual thinking with the manipulation of diagrams on paper as well as reading, note taking, data processing, teaching, and publishing. Each of those practices was – and still is – of real importance and played a crucial part in the making of new chemical knowledge about the unobservable microworld. In other words, each of the tasks carried out by chemists inside and outside of the laboratory constituted a part of the continuum of practices that served chemists as a highly versatile toolkit for their work. This, I conclude, demonstrates that chemical representations, as well as the means by which they were communicated, must not be understood as being secondary to chemical theories or laboratory work, but were in fact situated in the very midst of the knowledge-making process.

There is more to be gained from studying the making of scientific knowledge from comparative and communication-centred perspective. First, the approach developed in this thesis will enable historians to shed new light on the minute details and tacit aspects of the day-to-day work of researchers and, in doing so, also to avoid the pitfalls of theory-focused as well as laboratory-centered accounts of what constitutes ‘scientific work’. Secondly, historians will be able to develop a more nuanced and less narrow understanding of the scientific profession as well as the social role of scientists within a given historical context, thereby also gaining new insights into the complex relations between the sciences, education, and society, as I explain in more detail in the following section.

7.2. Rethinking the Geographical and Social Landscapes of Nineteenth-Century Science

Engaging a comparative approach and focusing on the role that different kinds of print media played in the circulation and appropriation of line-and-letter formulae in Britain and Germany during the 1860s and 1870s, Chapters 4 and 5 explained how print markets and, notably, institutional arrangements impinged on the circulation of chemical knowledge in the two countries. The comparative analysis revealed major differences between the means of circulation and appropriation of the new line-and-letter formulae in Britain and Germany. We have seen that in Germany, the formulae reached student readers predominantly by means of specialist periodicals, whereas in Britain students encountered the diagrams by means of textbooks that catered predominantly for the DSA classes. By elucidating these differences in the communication of line-and-letter diagrams, the thesis has made an important contribution to challenge and supplement Britain-centred accounts of the formulae's success. In addition, the close investigation of the use of printed matter in chemical education made it clear that we need to broaden our historiographical perspective on didactic practices by including other possible learning resources and techniques in future studies into the role of communication practices in the making of scientific knowledge.

More importantly, the communication-centred approach exercised in this thesis allows us to take a fresh look at the professional identity as well as the social role of nineteenth-century scientists. Studies in the history of chemistry, for instance, describe the identity of chemists predominantly in terms of their theoretical and practical research skills – acquired through education and training – as well as their affiliations with localised institutions and research schools. Yet it is noticeable that the vast majority of those studies pay little to no attention to the central role of communication practices in the identity of a chemist;[3] and although there exists a small body of literature that portrays various forms of communication activities as part of a chemist's everyday work, those activities are presented as something that chemists "just did" as a necessary part of their work. In other words, communication practices are usually not listed among the core skills of the professional chemist.[4] My thesis has made an important

[3] See, for instance, Bud and Roberts, *Science versus Practice*; Knight and Kragh, eds., *The Making of the Chemist*; and Homburg, *Van beroep 'Chemiker': De opkomst van de industriële chemicus en het polytechnische onderwijs in Duitsland, 1790-1850* (Delft: Delftse Universitaire Pers, 1993).

[4] Notable exceptions are Hepler-Smith, 'Nominally Rational'; and Golinski, Jan*, Science as Public Culture: Chemistry and Enlightenment in Britain, 1760-1820* (Cambridge: Cambridge University Press, 1992). Publication strategies of nineteenth-century chemists are also discussed in Gordin, *Scientific Babel: How Science Was Done Before and After Global English* (Chicago, IL: University of Chicago Press, 2015); and Langfeld, 'Umsetzung'.

contribution to reconceptualising what it meant to be a (successful) scientist in the nineteenth century by stressing the importance of communication skills and expertise to the work of Berzelius, Liebig, Roscoe, and others.

To be more precise, we have seen that Berzelius made strategic use of letterpress technology to maximise the circulation and impact of his notation, and that Liebig employed his journal – *Annalen der Chemie* – to disseminate the research output of his Giessen School to a diverse international audience. Similarly, Roscoe was very particular about using only the highest quality of illustrations and typesetting in his highly successful textbook franchises, which he achieved through long-term strategic partnerships with leading scientific publishers such as Macmillan and Vieweg. All this, I believe, makes it explicit that researchers played an important and active role in the national and international book trade by collaborating very closely with editors, printers, and publishers throughout their careers. I therefore conclude that we must view print-market expertise as being at the very heart of the skill set of nineteenth-century scientists: researchers not only possessed in-depth knowledge of the technical aspects of book production and the economics of national and international print markets, but also used that expertise strategically to improve their social standing and to advance their scientific careers.

7.3. Future Avenues of Research

As Jenny Rampling has recently stressed in her editorial of a special anniversary issue of *Ambix* on the 'Future of the History of Chemistry', the discipline is constantly 'on the move.'[5] One of the recent trends in the history of alchemy, chemistry, and the molecular sciences is the growing interest in the role of scientific media and chemical education in the making of chemical knowledge, as special journal issues, conference sessions, and workshops clearly demonstrate.[6]

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[5] Rampling, Jennifer M., 'The Future of the History of Chemistry', *Ambix*, 64.4 (2017), 295-300 (p. 295).
[6] See, for instance, Nye and Stephen Weininger, eds., 'Paper Tools from the 1780s to 1960s: Special Issue in Honor of Ursula Klein', *Ambix*, 65.1 (2018). Several sessions of the 11th International Conference on the History of Chemistry (ICHC) 2017 were concerned with chemical education as well as the proliferation, reception, and use of various forms of didactic literature. Furthermore, the Spring Meeting 2018 of the Society for the History of Alchemy and Chemistry (SHAC) was concerned with 'Alchemy and Print Culture', and the Society's 9th Annual Postgraduate Workshop 2018 featured papers on the 'Experience and Experiment: Materiality of (Al)chemical Texts and Objects'. For a report of the ICHC proceedings, see Lykknes, Annette, '11th International Conference on History of Chemistry (11th ICHC), Trondheim, Norway 2017', *Chemical Intelligence*, 19 (February 2018), 32-34 <http://www.ambix.org/wp-content/uploads/2018/02/Chemical-Intelligence-February-2018.pdf> [accessed 16 July 2018]. My participation of this conference was made possible through SHAC's generous support in the form of the New Scholar Award 2017 grant. Cf. Kiprijanov, 'SHAC New Scholar Awards 2017', *Chemical Intelligence*, 19 (February 2018), 28-29. This issue of *Chemical Intelligence* also contains information on SHAC's Spring Meeting and the Annual Postgraduate Workshop 2018.

Current and future scholars engaged in this kind of research will therefore greatly benefit from the approach and findings presented in this thesis. It is the purpose of this last section to reflect on how my approach can be fruitfully applied to a number of areas that require further investigation. First, I outline the benefits of investigating the day-to-day work of nineteenth-century scientific printers. Secondly, I reflect on the situation in France by explaining how future historical studies can shed new light on the processes which drove the appropriation of the new formulae there. Thirdly, I explain what can be gained from studying the history of stereochemical formulae from a communication-centred perspective. Finally, I elaborate on how further studies into the history of specialist libraries and library use will advance our understanding of the information requirements and reading patters of students and researchers in Germany and elsewhere.

As I have mentioned at the end of Chapter 6, it is not implausible that some characteristic features of line-and-letter formulae identified by Laszlo had originally been introduced in the context of teaching, which in turn means that didactic requirements might have played a more important role in the shaping of the formulae's iconography than previously assumed. However, we can answer this question only by studying handwritten lecture notes and manuscripts of influential university teachers in comparative perspective. This kind of research requires additional and extensive archival work and therefore lies beyond the scope of this thesis. In addition, my thesis has made it clear that even if certain conventions were coined by teachers or researchers on the blackboard in the classroom or on the pages of the laboratory journal, it is plausible that scientific printers adopted and thereby implemented those conventions as strategies to economise space and therefore save printing costs. The answer to this question, again, requires additional research into the mostly undocumented work and tacit knowledge of scientific printers, which I will leave to future generations of historians who are interested in this project.

I also explained in the introductory chapter that line-and-letter formulae practically did not appear in French publications until the vindication of the structure theory that followed the gradual implementation of the new system of international nomenclature after the Geneva Conference in 1892. Thus, it was only during the 1890s that an increasing number of French chemists began to employ line-and-letter formulae in their publications. However, it has to be emphasised that we still lack a detailed understanding of the exact processes that drove the circulation and appropriation of the diagrams before and after the implementation of the Geneva rules. Where, for instance, did French chemists first learn about the formulae, and which resources did they have at their disposal? Although French chemists were reluctant to use the structural notation in Francophone publications prior to 1892, there can be little doubt that a significant proportion of French researchers had already seen the formulae on the pages of leading British or German periodicals before. This, in turn, implies that foreign publications played an important role in advocating structural formulae and the structure theory in France, thereby bringing about a change in attitude towards atomistic ideas in French chemistry.

In order to investigate the impact of foreign publications on the chemical community in France, it would be necessary to study the number of British and German publications in French academic libraries, as well as to undertake a thorough bibliometric analysis of the number of British and German abstracts that were published in French abstract journals during the last decades of the nineteenth century. Furthermore, a close examination of the role of editors and publishers as well as student reading patterns would shed new light on how Marcellin Bertholet and other prominent antiatomists managed to maintain their influence over the French chemical community for such a long time. What, for example, were the commercial relations between Bertholet and the editors and publishers of influential periodicals and textbooks? Who was in charge of compiling the reading list for the official chemical curriculum at the École Polytechnique and other leading teaching institutions? And to what degree had French students access to recent research papers published in foreign periodicals? Pursuing these and similar questions will produce a more accurate historical picture of the appropriation of atomist and structural ideas in France.

As mentioned in Chapter 2, line-and-letter acquired a new theoretical meaning by the end of the 1880s when chemists began to use the diagrams not only as representations of structural, but also of stereochemical ideas. A third area deserving of future research is thus the evolution of stereochemical formulae. While historians such as Peter Ramberg have studied stereochemical formulae before, the resulting account has once again a very strong focus on theoretical and experimental work carried out by individual scientists inside the laboratory.[7] Yet as this thesis has demonstrated, this is not enough to capture and explain the processes through which the formulae acquired new meanings and epistemic functions. For instance, the new mode of representing the spatial arrangement of physical atoms within a three-dimensional molecule was accompanied by a new convention for “reading” stereochemical formulae that was developed by Emil Fischer (1852-1919) in 1891. Consisting of a set of simple rules and commonly known as ‘Fischer projection’ today, the convention allowed line-and-letter formulae to be inscribed with stereochemical meaning so that three-dimensional structures could be represented on a two-dimensional surface. But why did Fischer chose to rely on line-and-letter diagrams instead of developing a new form of diagrams to contemplate and represent

[7] Ramberg, *Chemical Structure*. See also Ramsay, *Stereochemistry*.

stereochemical ideas?[8] And in which context and by which means, exactly, did other chemists learn to interpret and use Fischer's convention? I believe that these questions can be explored productively by following the circulation and appropriation of stereochemical formulae in the context of teaching and research across different international communities. The communication-centred approach developed in this thesis will also shed new light on the fundamental role that the stereochemical diagrams had in identifying and investigating new experimental and theoretical research questions, thereby contributing to the further advancement of chemistry as a scientific discipline.

Finally, a fourth area deserving of future research concerns the availability and accessibility of various kinds of scientific literature for different groups of library users in Germany. I showed in Chapter 5 that the study of library provisions and regulations can offer new and exciting insights into the circulation and appropriation of scientific knowledge in a localised context. By way of illustration, the close investigation of a number of historic library catalogues has revealed that, on the one hand, Frankland's textbook *Lecture Notes* was not available at those libraries, which strongly implies that *Lecture Notes* was not used by German chemistry students and therefore did not play any role in the circulation and appropriation of line-and-letter formulae in the German lands. On the other hand, the evidence presented in the chapter suggests that students routinely used periodicals next to textbooks as learning resources due to the gradual improvements in student access to journal literature that were achieved during the last decades of the nineteenth century. The fifth chapter challenged and revised the received narrative by making it evident that the circulation and appropriation of line-and-letter diagrams in Germany followed a different path than in Britain. In providing this alternative account, the chapter also clarified that an accurate historical understanding of the circulation and transmission of scientific knowledge can only be achieved if future studies of reading and learning practices also include publications that were not originally designed for didactic purposes. Yet in order to do that, more detailed studies of local library provisions are required.

As mentioned in Chapter 5, chemical institutes in Germany began to establish specialised departmental libraries ('Institutsbibliotheken') during the final two decades of the nineteenth century. There can be no doubt that detailed studies of available sources related to the history of individual departmental libraries would provide new insights into how specialised knowledge was procured, organised, distributed, and received in a local context. A close

[8] The chemist C. S. Hudson carried out a preliminary study of Fischer's notation. Cf. Hudson, C. S., 'Historical Aspects of Emil Fischer's Fundamental Conventions for Writing Stereo-Formulas in a Plane', *Advances in Carbohydrate Chemistry*, 3 (1948), 1-22 (pp. 3-4).

investigation of departmental libraries would also offer a new understanding of how different forms of scientific literature was used by different groups of readers, as well as of the practical challenges faced by members of administrative staff to meet the different information needs of their library users. With regard to the specific case of line-and-letter formulae, an investigation of specialist libraries will also shed new light on the British and French context, and should therefore be conducted in comparative perspective. While this lies beyond the scope of my thesis, I have demonstrated that such a comparative, interdisciplinary historical approach to science communication can be fruitfully applied to similar research questions in the future. This, ultimately, will make clearer the historical importance of communication practices such as reading, publishing, editing, and printing to the making of scientific knowledge outside the laboratory.

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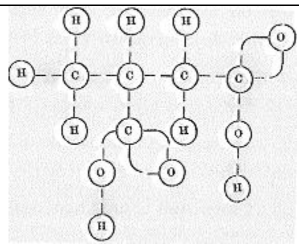
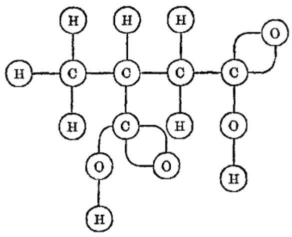
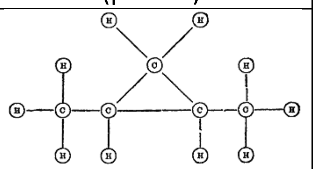
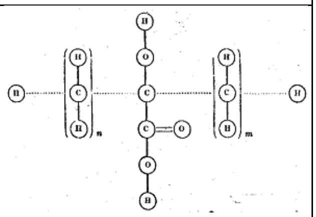
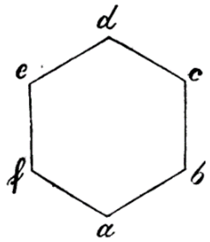
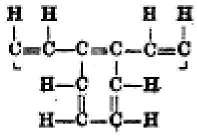
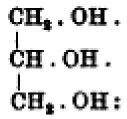
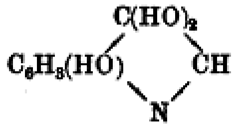
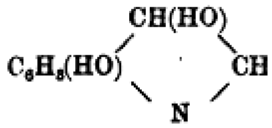
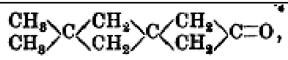
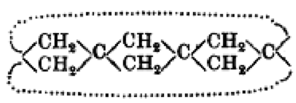
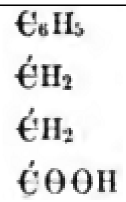
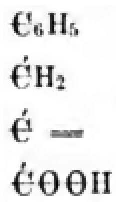
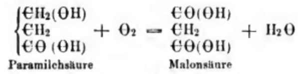
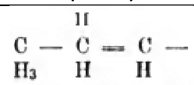
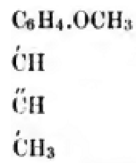
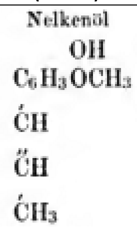
APPENDIX

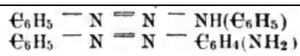
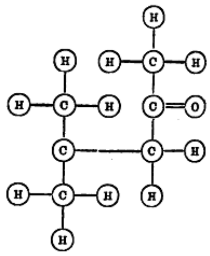
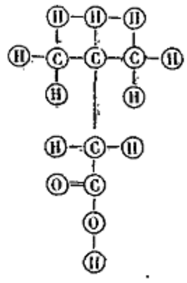
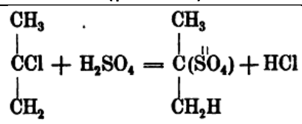
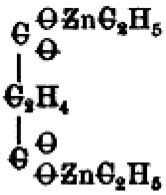
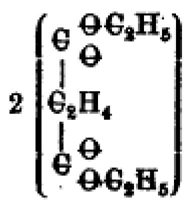
Journal Articles with Line-and-Letter Formulae, 1864-68

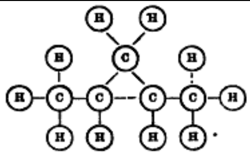
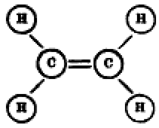
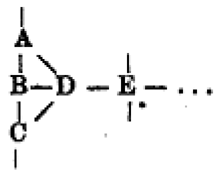
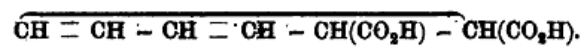
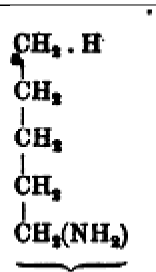
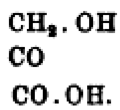
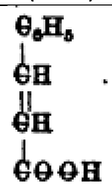
This Appendix is a near-complete compilation of original research articles with line-and-letter formulae that appeared in major British, French, and German specialist journals between 1864 and 1868. The compilation records research articles published in *Berichte der Deutschen Chemischen Gesellschaft*, *Annalen der Chemie*, *Zeitschrift für Chemie*, *Journal für praktische Chemie*, *Transactions of the Royal Society of Edinburg, Journal of the Chemical Society*, *Philosophical Transactions* and *Proceedings of the Royal Society, Annales de Chimie,* and *Bulletin de la Société Chimique.* The compilation excludes line-and-letter diagrams that appeared in abstracts.

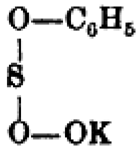
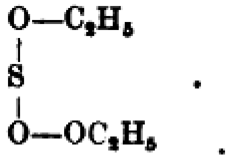
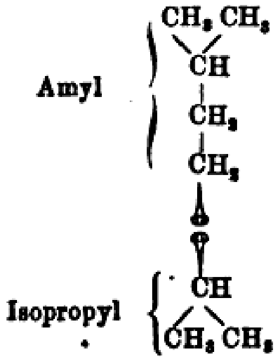
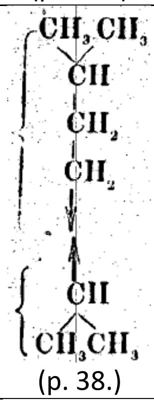
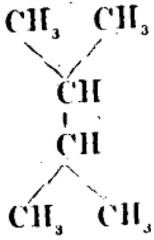
Date	Author	Title	Journal	Formulae in Article
1864	Alexander Crum Brown	'On the Theory of Isomeric Compounds'.	*Proceedings of the Royal Society of Edinburgh*, 5 (1864), pp. 707-19.	 (p. 710.)
1865	Alexander Crum Brown	'On the Theory of Isomeric Compounds'.	*J. Chem. Soc.*, 18 (1864), 230-45.	 (p. 234.)
1866	Ernest T. Chapman and William Thorp	'The Relation between the Products of Gradual Oxidation and the Molecular Constitution of the Bodies Oxidised'.	*J. Chem. Soc.*, 19 (1866), 477-99.	 (p. 494.)
1866	Edward Frankland and Baldwin F. Duppa	'Researches on Acids of the Lactic Series. No. I. Synthesis of Acids of the Lactic Series'.	*Philosophical Transaction*, 156 (1866), 309-59.	 (p. 346.)

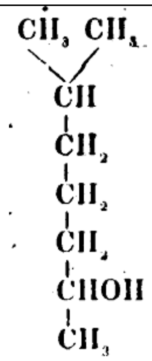
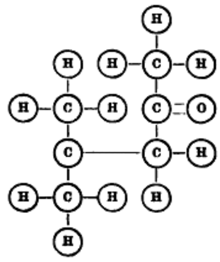
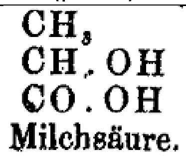
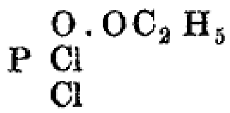
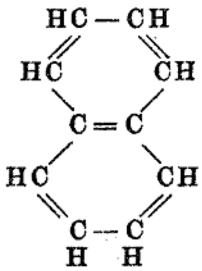
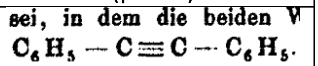
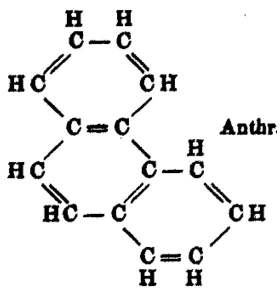
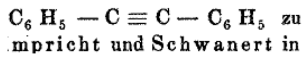
1866	August Kekulé	'Untersuchungen über aromatische Verbindungen'.	*Annalen der Chemie*, 137 (1866), 129-96.	 (p. 158.)
1866	Emil Erlenmeyer	'Studien über die s. g. aromatischen Säuren'.	*Annalen der Chemie*, 137 (1866), 327-59.	 (p. 346.)
1866	Emil Erlenmeyer	'Studien über den Process der Einwirkung von Jodwasserstoff auf Glycerin'.	*Annalen der Chemie*, 139 (1866), 211-34.	 (p. 216.)  (p. 225.)
1866	Adolf Baeyer and & C. A. Knop	'Untersuchungen über die Gruppe des Indigblaus', pp. 1-38.	*Annalen der Chemie,* 140 (1866), 1-38.	 (p. 8.)  (Ibid.)
1866	Heinrich L. Buff	'Ueber die Einwirkung von Brom auf Propionsäure', pp. 156-166.	*Annalen der Chemie,* 140 (1866), 156-66.	Formel CH_3-CO-OH und (p. 165.) CH_3-CH_2-OH Essigsäure (Ibid.) C_6H_5-CH_2-CH_3 und nicht (Ibid.)
1866	Adolf Baeyer	'Ueber die Condensations-producte des Acetons'.	*Annalen der Chemie,* 140 (1866), 297-306.	 (p. 304.)  (Ibid.) C_8H_{14}=C=C_8H_{12}=C=O. (p. 305.)

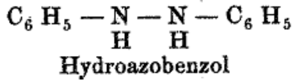
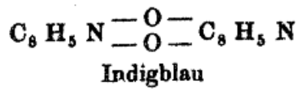
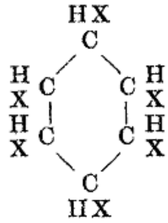
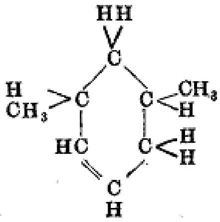
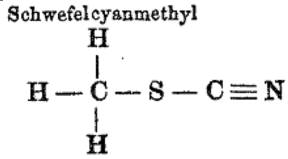
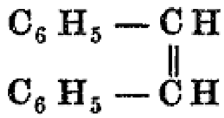
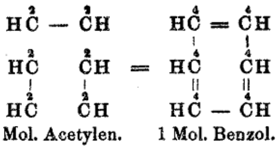
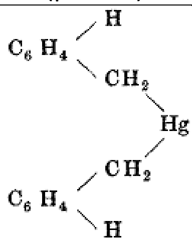
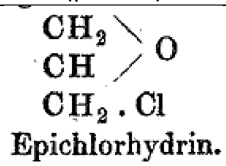
1866	Emil Erlenmeyer	‘Studien über die sogenannten aromatischen Säuren’.	*Zeitschrift für Chemie*, 9 (1866), 206-09.	 (p. 209.)  (Ibid.)
1866	L. Dossios	‘Theoretische und empirische Beiträge zur Constitution der Glycole und der ihnen entsprechenden Formeln’.	*Zeitschrift für Chemie*, 9 (1866), 449-52.	 (p. 449.)  (Ibid.)
1866	Emil Erlenmeyer	‘Ueber die Constitution des Anisöls (Anethols)’.	*Zeitschrift für Chemie*, 9 (1866), 472-74.	 (p. 474.)  (Ibid.)
1866	Emil Erlenmeyer	‘Ueber die Constitution des Nelkenöls (Eugenols)’.	*Zeitschrift für Chemie*, 9 (1866), 475-76.	 (p. 476.)
1866	Heinrich Hlasiwetz	‘Ueber die Basicität der Ferulasäure‘.	*Zeitschrift für Chemie*, 9 (1866), 603-04.	 (p. 604.)

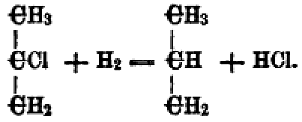
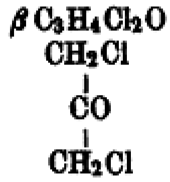
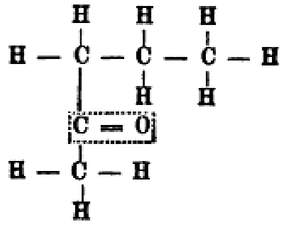
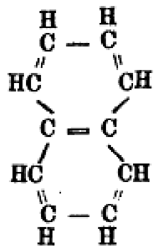
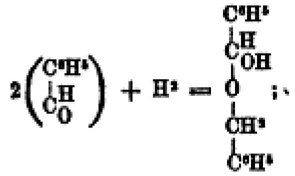
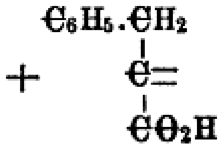
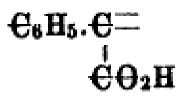
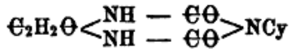
1866	August Kekulé	‘Beziehungen zwischen den Diazoverbindungen und den Azoverbindungen, und Umwandlung des Diazoamidobenzols in Amido-azobenzol‘.	*Zeitschrift für Chemie*, 9 (1866), 689-93.	 (p. 690.)  (Ibid.)
1867	Edward Frankland and Baldwin F. Duppa	‘Synthetical Researches on Ethers. No. 2. Action of Sodium and Isopropylic Iodide upon Ethylic Acetate’.	*J. Chem. Soc.,* 20 (1867), 102-16.	 (p. 112.)
1867	Edward Frankland and Baldwin F. Duppa	‘Recherche synthétiques sur les éthers’.	*Annales de Chimie*, 4th ser., 11 (1867), 487-92.	 Acide isopropacétique. (p. 491.)
1867	A. Oppenheim	‘Neue Untersuchungen über die Isomerie des Chlor-Aethyls und des gechlorten Propylens’.	*Journal für praktische Chemie*, 102 (1867), 338-42.	 (p. 339.)
1867	Adolf Claus	‘Beiträge zur Kenntniss [sic] der zweibasischen Säuren’.	*Annalen der Chemie*, 141 (1867), 49-79.	 (p. 61.)  (Ibid.)

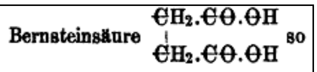
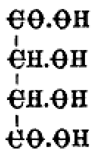
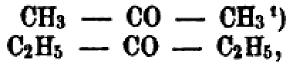
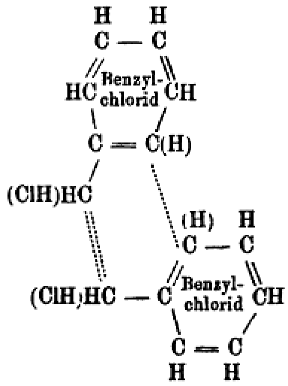
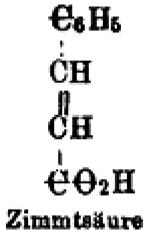
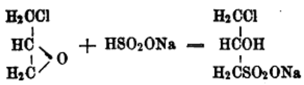
1867	Ernest T. Chapman and William Thorp	‘Ueber die Beziehung zwischen den Producten stufenweiser Oxidation und der Molecularconstitution der oxydirten Körper‘.	*Annalen der Chemie*, 142 (1867), pp. 162-91.	 β Hexylen C_6H_{12} : (p. 184.) Aethylen C_2H_4 :  (Ibid.)
1867	Charles Friedel and Albert Ladenburg	‘Ueber die Synthese eines Kohlenwasserstoffs und dessen Constitution’.	*Annalen der Chemie*, 142 (1867), pp. 310-22.	 (p. 312.)  (p. 313.)
1867	Carl Graebe and O. Born	‘Ueber Hydrophtalsäure’.	*Annalen der Chemie*, 142 (1867), 330-45.	 (p. 333.)
1867	Adolphe Wurtz	‘Ueber eine neue Klasse zusammengesetzer Ammoniake’.	*Annalen der Chemie*, 142 (1867), 359-64.	 Isoamyl-amin. (p. 364.)
1867	H. Wichelhaus	‘Ueber Constitution und Zusammensetzung der organischen Säuren, die neben O und H 3 Atome C enthalten’.	*Annalen der Chemie,* 143 (1867), 1-22.	CH_2-OH, andererseits (p. 8.)  Carbacetoxylsäure. (Ibid.)
1867	Carl Glaser	‘Untersuchungen über einige Derivate der Zimmtsäure’.	*Annalen der Chemie,* 143 (1867), 325-46.	 (p. 328.)

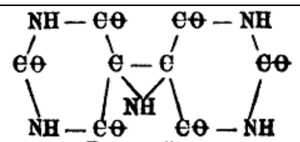
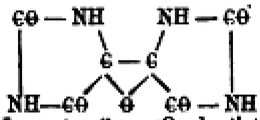
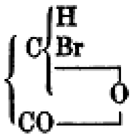
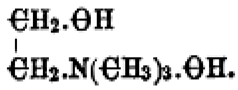
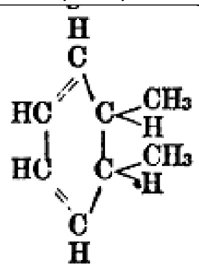
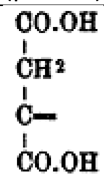
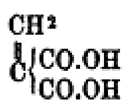
1867	Adolphe Wurtz	'Umwandlung der aromatischen Kohlenwasserstoffe in Phenole'.	*Annalen der Chemie,* 144 (1867), 121-24.	 (p. 123.)  (p. 124.)
1867	Carl Schor-lemmer	'Zur Kenntniss [sic] der Kohlenwasserstoffe der Reihe C_nH_{2n+2}'.	*Annalen der Chemie,* 144 (1867), 184-91.	 (p. 189.)
1867	H. Wichelhaus	'Ueber Constitution und Zusammenhang der organischen Säuren von 3 At. Kohlenstoff'.	*Annalen der Chemie,* 144 (1867), 351-57.	$CH_2 . OH$ CH_2 $CO . OH$ Fleischmilchsäure $CH_2 . OH$ $CH . OH$ $CO . OH$ Glycerinsäure $CH_2 . OH$ CO $CO . OH$ Carbacetoxylsäure (p. 356.)
1867 -68	Carl Schor-lemmer	'Researches on the Hydrocarbons of the Series $C^n H^{2n+2}$. No. III', pp. 34-39.	*Proceedings*, 16 (1867-68), 34-39.	 (p. 38.)
1867 -68	Carl Schor-lemmer	'Researches on the Hydrocarbons of the Series $C_n H_{2n+2}$. No. IV'.	*Proceedings*, 16 (1867-68), 367-72.	 (p. 368.)

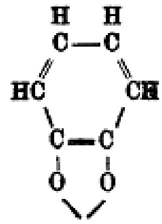
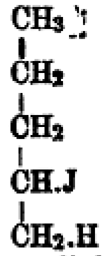
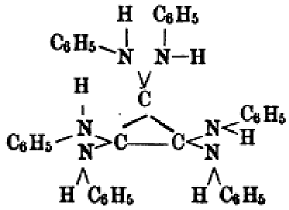
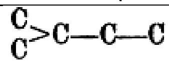
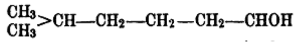
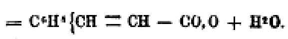
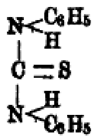
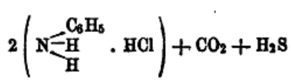
1867-68	Carl Schor-lemmer	'On the Constitution of Capryl Alcohol from Castor-Oil'.	*Proceedings*, 16 (1867-68), 376-81.	 (p. 381.)
1868	Edward Frankland and Baldwin F. Duppa	'Synthetische Untersuchungen über Aether. II. Einwirkung von Natrium und Isopropyljodür auf Essigsäureäther'.	*Annalen der Chemie,* 145 (1868), 78-93.	 (p. 88.)
1868	H. Wichelhaus	'Ueber organische Säuren von 3. At. Kohlenstoff'.	*Berichte*, 1 (1868), 23-25.	 (p. 24.)
1868	H. Wichelhaus	'Ueber Phosphor-verbindungen'.	*Berichte*, 1 (1868), 77-81.	 (p. 79.)
1868	Carl Graebe	'Ueber Naphtalin'.	*Berichte*, 1 (1868), 36-38.	 (p. 37.)
1868	Carl Graebe and Carl Liebermann	'Ueber Alizarin und Anthracen'.	*Berichte*, 1 (1868), 49-51.	 (p. 50.)  (Ibid.)
1868	Carl Graebe and Carl Liebermann	'Ueber Farbstoffe aus der Anthracengruppe'.	*Berichte*, 1 (1868), 104-06.	 (p. 106.)

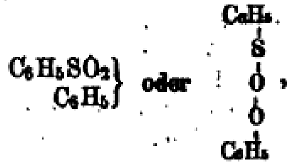
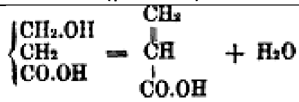
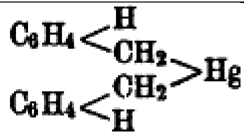
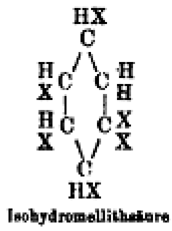
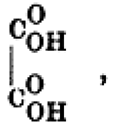
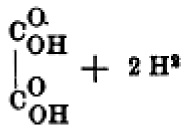
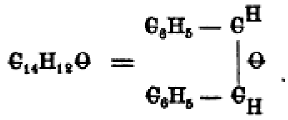
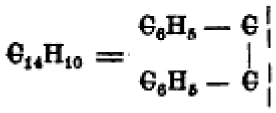
1868	Carl Graebe and Carl Liebermann	'Ueber den Zusammenhang zwischen Molecularconstitution und Farbe bei organischen Verbindungen'.	*Berichte*, 1 (1868), 106-08.	 (p. 107.)  (p. 108.)
1868	Adolf Baeyer	'Ueber die Umlagerung im Moleküle'.	*Berichte*, 1 (1868), 119-21.	 (p. 120.)
1868	Adolf Baeyer	'Ueber die Reduction aromatischer Kohlenwasser-stoffe'.	*Berichte*, 1 (1868), 127-29.	 (p. 129.)
1868	August W. Hofmann	'Ueber die dem Senföl entsprechenden Isomeren der Schwefelcyanwasserstoffäther'.	*Berichte*, 1 (1868), 169-84.	 (p. 175.)
1868	Carl Graebe and Carl Liebermann	'Ueber Anthracen-derivate'.	*Berichte*, 1 (1868), 186-89.	 (p. 188.)
1868	Heinrich L. Buff	'Ueber Alphahexylen und Alphaamylen'.	*Berichte*, 1 (1868), 206-10.	 (p. 208.)
1868	R. Otto & E. Dreher	'Ueber Quecksilberphenyl und Quecksilbertolyl'.	*Berichte*, 1 (1868), 234-35.	 (p. 235.)
1868	H. Wichelhaus	'Ueber die Ketonsäure'.	*Berichte*, 1 (1868), 263-67.	 (p. 266.) $CH_3 - CBr . OBr - CO . OH$ (Ibid.)

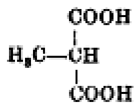
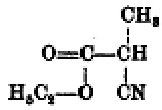
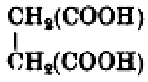
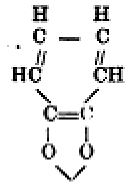
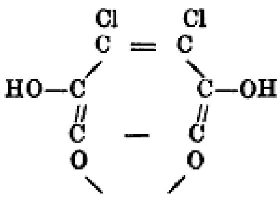
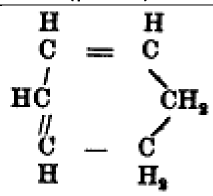
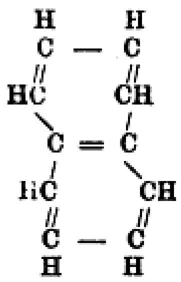
1868	Charles Friedel and Albert Ladenburg	'Ueber ein vom Aceton abgeleitetes Propylenbromür'.	*Zeitschrift für Chemie*, 11 (1868), 47-49.	 (p. 49.)
1868	E. Mulder	'Ueber einige vom Aceton abgeleitete Körper'.	*Zeitschrift für Chemie*, 11 (1868), 51-53.	 (p. 53.)
1868	Edward Frankland and Baldwin F. Duppa	'Synthetische Untersuchungen über Aether', pp. 60-64.	*Zeitschrift für Chemie*, 11 (1868), 60-64.	 (p. 63.)
1868	Carl Graebe	'Ueber die Constitution des Naphtalins und der Naphtochinone'.	*Zeitschrift für Chemie*, 11 (1868), 114-18.	 (p. 117.)
1868	Adolf Claus	'Ueber den aus Bittermandelöl bei Einwirkung von Natriumamalgam entstehenden Körper'.	*Zeitschrift für Chemie*, 11 (1868), 127-28.	 (p. 128.)
1868	Carl Glaser and B. Rad-ziszewski	'Ueber einige Umwandlungen der Mandelsäure'.	*Zeitschrift für Chemie*, 11 (1868), 140-43.	 (Phenylacrylsäure). (p. 141.)  (Ibid.)
1868	Adolf Strecker	'Bildung von Glycocoll aus Harnsäure'.	*Zeitschrift für Chemie*, 11 (1868), 215-16.	 (p. 216.)

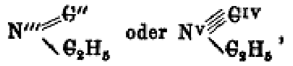
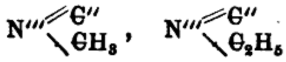
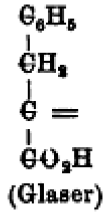
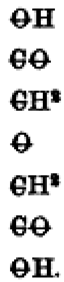
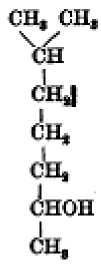
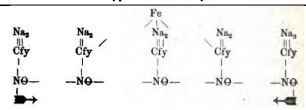
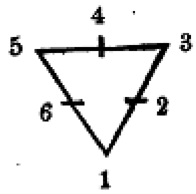
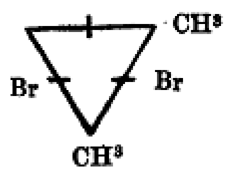
1868	Adolf Strecker	‘Ueber eine neue Bildungsweise und die Constitution der Traubensäure’.	*Zeitschrift für Chemie*, 11 (1868), 216-18.	 (p. 217.)  (p. 218.)
1868	Th. Swarts	‘Ueber die Umwandlung der gesättigten Verbindungen in wasserstoff-ärmere’.	*Zeitschrift für Chemie*, 11 (1868), 257-60.	 (p. 259.)  (Ibid.)
1868	E. Mulder	‘Das Keton der Ameisensäure’.	*Zeitschrift für Chemie*, 11 (1868), 265-66.	 (p. 265.)
1868	Carl Graebe and Carl Liebermann	‘Ueber Alizarin und Anthracen’, pp. 279-281.	*Zeitschrift für Chemie*, 11 (1868), 279-81.	 (p. 280.)
1868	Carl Glaser	‘Untersuchungen über einige Derivate der Zimmtsäure’.	*Zeitschrift für Chemie*, 11 (1868), 228-42.	 (p. 342.)
1868	Emil Erlenmeyer	‘Notizen aus den Studien über die kohlenstoffhaltigen Sauerstoff-verbindungen’.	*Zeitschrift für Chemie*, 11 (1868), 342-43.	 (p. 343.)

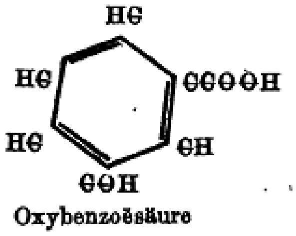
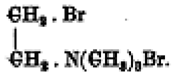
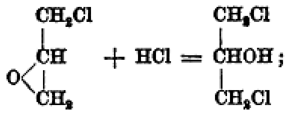
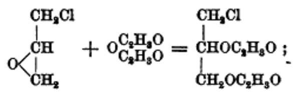
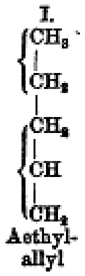
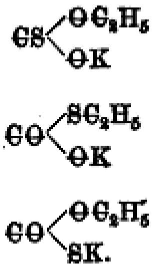
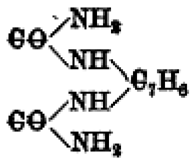
1868	Adolf Strecker	'Ueber die Constitution der Harnsäure und ihrer Derivate'.	*Zeitschrift für Chemie*, 11 (1868), 363-67.	 Purpursäure (p. 365.)  Leucotursäure (Oxalantin) (p. 366.)
1868	V. Merz	'Ueber die Monosulfosäuren des Naphtalins'.	*Zeitschrift für Chemie*, 11 (1868), 393-99.	$\frac{C_{10}H_7SO_3}{C_{10}H_7SO_3}>Pb + 3H_2O.$ (p. 396.)
1868	William H. Perkin and Baldwin F. Duppa	'Ueber die Constitution der Glyoxylsäure'.	*Zeitschrift für Chemie*, 11 (1868), 424-27.	 Bromglycollid (p. 425.)
1868	Adolf Strecker	'Ueber das Lecithin'.	*Zeitschrift für Chemie*, 11 (1868), 437-40.	$NH_2 - CH_2 - CO.OH$ (p. 439.)  (Ibid.)
1868	Adolf Baeyer	'Reduction aromatischer Kohlenwasser-stoffe'.	*Zeitschrift für Chemie*, 11 (1868), 445.	 (p. 445.)
1868	V. von Richter	'Ueber die Constitution von Isojodpropion-säure'.	*Zeitschrift für Chemie*, 11 (1868), 449-54.	 (p. 453.)  Maleinsäure (Ibid.) $\frac{C^4H^3O^4}{C^4H^3O^4}>Zn''.2H^2O.$ (p. 454.)

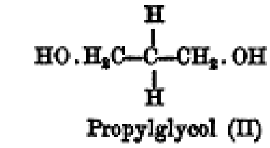
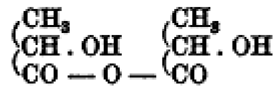
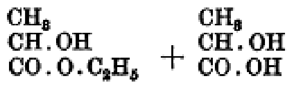
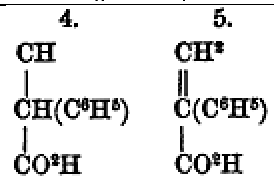
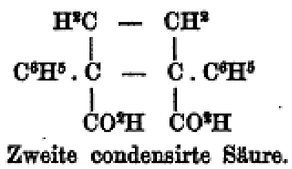
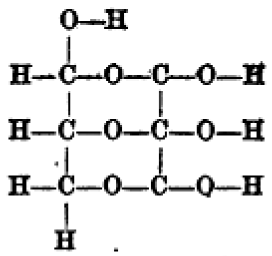
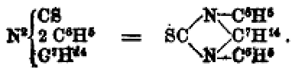
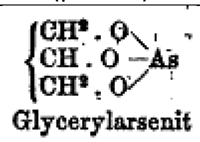
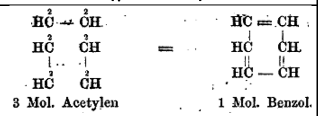
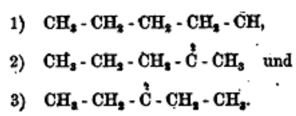
1868	Carl Graebe	'Untersuchungen über die Chinongruppe'.	*Zeitschrift für Chemie*, 11 (1868), 464-79.	 Chinon. (p. 478.)
1868	Adolphe Wurtz	'Ueber einen neuen mit dem Amylalkohol isomeren Alkohol'.	*Zeitschrift für Chemie*, 11 (1868), 490-92.	 Isoamyljodür (p. 492.)
1868	V. .Merz and W. Weith	'Ueber die Entschwefelung chemischer Verbindungen'.	*Zeitschrift für Chemie*, 11 (1868), 513-14.	 (p. 513.)
1868	F. Hallwachs	'Ueber Dicyanamidsäure'.	*Zeitschrift für Chemie*, 11 (1868), 515-18.	 (p. 517.) Cyanamid,  (Ibid.)
1868	Carl Schor-lemmer	'Ueber die Constitution des Caprylalcohols aus Ricinusöl'.	*Zeitschrift für Chemie*, 11 (1868), 521-22.	 gruppirt (p. 522.)  (Ibid.)
1868	Rudolf Fittig	'Ueber die Constitution des Cumarins, der Cumarsäure und der Melilotsäure'.	*Zeitschrift für Chemie*, 11 (1868), 595-97.	 Cumarsäure (p. 595.)  Cumarin (p. 596.)
1868	V. Merz and W. Weith	'Ueber die Entschwefelung chemischer Verbindungen'.	*Zeitschrift für Chemie*, 11 (1868), 609-13.	 (p. 613.)  (Ibid.)

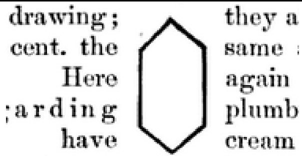
1868	R. Otto and A. Gruber	'Ueber Sulfobenzid und zwei isomere Bichlor-sulfobenzids'.	*Zeitschrift für Chemie*, 11 (1868), 630-33.	 (p. 632.)
1868	Johannes Wislicenus	'Ueber die aus β-Jodpropionsäure entstehende Oxysäure'.	*Zeitschrift für Chemie*, 11 (1868), 683-84.	 (p. 684.)
1868	E. Dreher and R. Otto	'Ueber Quecksilberphenyl und Quecksilbertolyl'.	*Zeitschrift für Chemie*, 11 (1868), 685-86.	 (p. 686.)
1868	Adolf Baeyer	'Ueber die Umlagerung im Molecüle'.	*Zeitschrift für Chemie*, 11 (1868), 720.	 (p. 720.)
1868	Charles Friedel and Albert Ladenburg	'Beiträge zur Kenntniss [sic] der Propylen-verbindungen'.	*Annalen der Chemie,* 145 (1868), 190-96.	 (p. 190.)  (p. 193.)
1868	Adolf Claus	'Ueber die Reduction der Oxalsäure'.	*Annalen der Chemie,* 145 (1868), 253-56.	 (p. 255.)  (Ibid.)
1868	Heinrich Limpricht and Hugo Schwanert	'Ueber einige Verbindungen der Toluolgruppe'.	*Annalen der Chemie,* 145 (1868), 330-50.	 (p. 331.)  (Ibid.)

1868	Emil Erlenmeyer	‘Ueber die Dicarbonsäure aus dem Aethylidenchlorür’.	*Annalen der Chemie,* 145 (1868), 365-73.	II.  (p. 365.)  Cyanpropionsäure-Aethyl (p. 366.)
1868	M. Simpson	‘Ueber die Bildung der Bernsteinsäure von dem Aethylidenchlorür aus’.	*Annalen der Chemie,* 145 (1868), 373-76.	 Gewöhnliche Bernsteinsäure. (p. 374.)
1868	Carl Graebe	‘Untersuchungen über die Chinongruppe’.	*Annalen der Chemie,* 146 (1868), 1-65.	 Chinon (p. 62.)  Chloranilsäure. (p. 65.)
1868	Carl Graebe	‘Ueber die s. g. Additionsproducte der aromatischen Verbindungen’.	*Annalen der Chemie,* 146 (1868), 65-73.	 Benzolon. (p. 71.)  Naphtalin (p. 73.)

1868	A. Gautier	'Ueber eine neue Reihe von Verbindungen, welch emit den Cyanwasserstoffsäure-Aethern isomer sind'.	*Annalen der Chemie,* 146 (1868), 119-24.	 (p. 123.)
1868	A. Gautier	'Ueber die neuen Nitrile der Reihe der fetten Säuren'.	*Annalen der Chemie,* 146 (1868), 124-30.	 (p. 126.)
1868	Carl Glaser	'Untersuchungen über einige Derivate der Zimmtsäure. Zweite Abhandlung'.	*Annalen der Chemie,* 147 (1868), 78-107.	 (p. 104.)
1868	W. Heintz	'Ueber die Constitution der Diglycolsäure und eine neue Bildungsweise des Diglycolsäure-äthers'.	*Annalen der Chemie,* 147 (1868), 188-213.	 (p. 199.)
1868	Carl Schorlemmer	'Ueber das Caprylalkohol aus Ricinusöl'.	*Annalen der Chemie,* 147 (1868), 222-28.	 (p. 227.)
1868	W. Weith	'Ueber die Nitroprussid-verbindungen'.	*Annalen der Chemie,* 147 (1868), 312-39.	 (p. 339.)
1868	Rudolf Fittig and J. Velguth	'Ueber das Isoxylol, einen neuen, mit dem Xylol isomerischen Kohlenwasserstoff'.	*Annalen der Chemie,* 148 (1868), 1-23.	 (p. 22.)  Dibrom-Xylol (Ibid.)

1868	L. Barth	‘Untersuchungen über die Oxybenzoësäure’.	*Annalen der Chemie,* 148 (1868), 30-49.	 (p. 45.)
1868	Adolf Strecker	‘Ueber das Lecithin’.	*Annalen der Chemie,* 148 (1868), 77-90.	 (p. 89.)  (Ibid.)
1868	Ludwig Darmstaedter	‘Ueber die relative Constitution und einige Metamorphosen des Epichlorhydrins’.	*Annalen der Chemie,* 148 (1868), 119-31.	 (p. 121.)  (Ibid.)
1868	Adolphe Wurtz	‘Ueber ein neues Isomeres des Amylalkohols’.	*Annalen der Chemie,* 148 (1868), 131-36.	 (p. 136.)
1868	C. Bender	‘Ueber das Verhalten des Kohlenoxysulfids gegen alkoholische Kalilösungen’.	*Annalen der Chemie,* 148 (1868), 137-43.	 (p. 141.)
1868	E. G. Strauss	‘Ueber Toluylenharnstoff’.	*Annalen der Chemie,* 148 (1868), 157-60.	 (p. 160.)  (Ibid.)

1868	J. Y. Buchanan	'Ueber die Chlorpropion-säure'.	*Annalen der Chemie,* 148 (1868), 169-74.	 (p. 173.)
1868	N. von der Brüggen	'Ueber den Diäthyläther einer Dimilchsäure'.	*Annalen der Chemie,* 148 (1868), 224-35.	 (p. 225.)  (p. 227.)
1868	K. Kraut	'Ueber die Zimmtsäure und die mit ihr isomeren Atropasäure'.	*Annalen der Chemie,* 148 (1868), 242-48.	 (p. 245.)  (p. 248.)
1868	H. Kämmerer	'Beiträge zur Kenntniss [sic] der Citronsäure'.	*Annalen der Chemie,* 148 (1868), 294-325.	 (p. 323.)
1868	Hugo Schiff	'Aldehydderivate einiger Amide'.	*Annalen der Chemie,* 148 (1868), 330-38.	 (p. 335.)
1868	Hugo Schiff	'Ueber Glycerylarsenit'.	*Annalen der Chemie,* 148 (1868), 339-41.	 (p. 341.)
1868	Heinrich L. Buff	'Alphahexylen und Alphaamylen'.	*Annalen der Chemie,* 148 (1868), 341-51.	 (p. 345.)  (p. 346.)

1868	C. Bell	'On the Solubility and Crystallisation of Plumbic Chloride in Water, and in Water Containing Various Percentages of Hydrochloric Acid, Specific Gravity 1.162'.	*J. Chem. Soc,* 21 (1868), 350-55.	 (p. 354.)