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Chapter 2: The Philosophy of Chemistry: From Infancy Towards Maturity

Joachim Schummer
University of Karlsruhe

Section 1. Introduction

The time of complaining about the neglect of the philosophy of chemistry is over now. With more than 700 papers and about 40 monographs and collections since 1990, philosophy of chemistry is one of the most rapidly growing fields of philosophy.[1] Perhaps too rapidly, as it has become arduous for insiders to keep up-to-date, troublesome for newcomers to approach the field, and virtually impossible for outsiders to survey the main ideas. Being involved since the late 1980s, I think it appropriate to pause for a while and write a paper of the kind "Where do we come from?—Where are we now?—Where should we go to?"[2]

Thus, my paper is divided into three parts. We come from philosophical neglect—that is, virtually from nowhere—which I try to explain in the first part by recalling the disciplinary history of philosophy. We are now in a state of rapid growth, of prolific publishing, to which I provide some structure, in the second part, by pointing out the major trends and topics.[3] "Where should we go to?" is a question to which I can give only a personal answer, based on a pragmatist judgment of topics of infancy and topics of maturity that I try to justify in the third part.

Section 2. The philosophers' neglect of chemistry in context

Section 2.a A rule of thumb about the philosophers' interest in the sciences

Let me start with a look at the amount of literature published in the various sciences. Such data provides a good estimate of the relative size of the disciplines, in contrast to the coverage in the media and other talk about science. Figure 1 presents the number of new publications (books, papers, patents, etc.) as indexed by the major abstract journals in 2000 and 1979.

The most striking point is that chemistry is not only the biggest discipline, it is bigger than the total of all the other natural sciences, including all their related flourishing technologies. The *INSPEC* database (formerly, and strangely, called *Science Abstracts*) has besides physics also "electrical engineering, electronics, communications, control engineering, computers and computing, and information technology" and a "significant coverage in areas such as materials science, oceanography, nuclear engineering, geophysics, biomedical engineering and biophysics".[4] Yet, despite the rapid growth of computer sciences and information technology, all that now comes to less than 40% of the coverage of *Chemical Abstracts*. Also *Biological Abstracts* could greatly flourish in the past decade by covering besides biology also "biochemistry, biotechnology, pre-clinical and experimental medicine, pharmacology, agriculture, and veterinary science".[5] Despite the boom of the biomedical sciences and the overlap with chemistry, it is still only 40% of *Chemi-*

cal Abstracts. The earth sciences, less than a tenth of the size of chemistry, are even smaller than the social sciences and psychology.

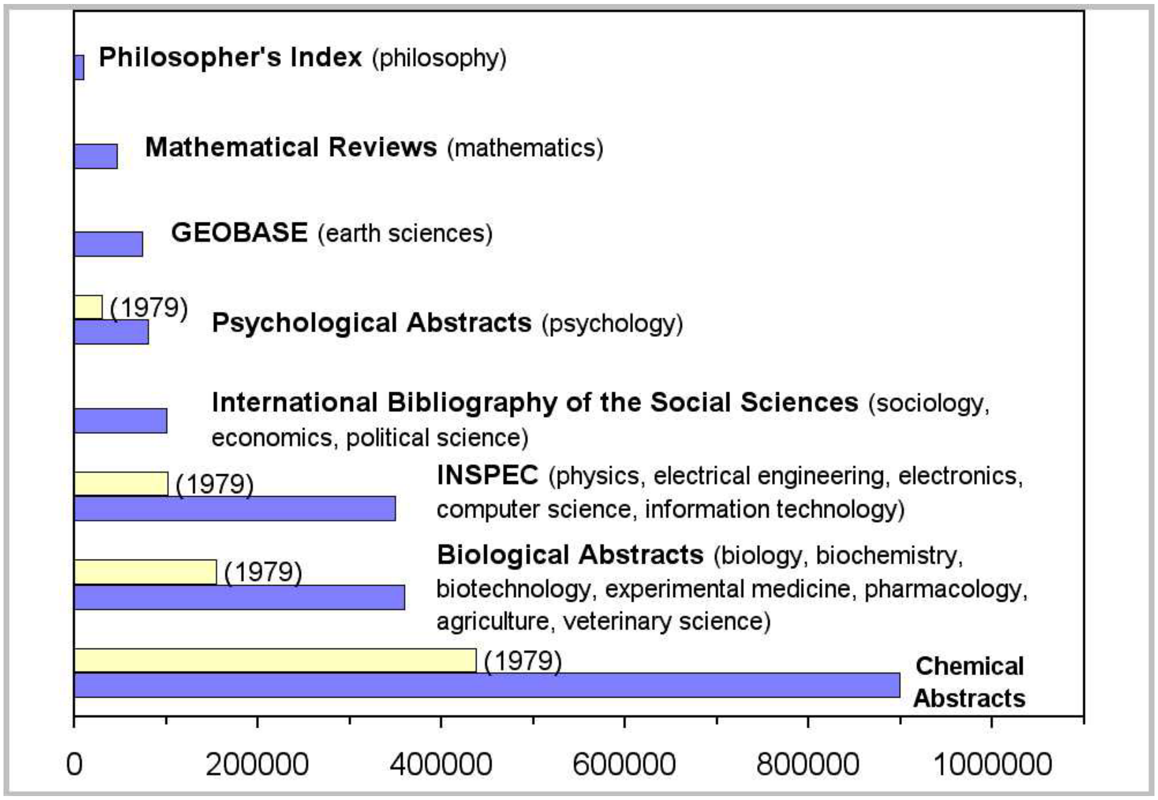

Figure 1: Number of new publications (papers, patent, books, etc.) indexed by the major abstract journals in 2000 and 1979. 2000 data are from the journals' web sites (in thousands: PI 10, MR 47, GB 74, PA 80, IBSS 100, INSPEC 350, BA 360, CA 899); 1979 data are from Tague et al. 1981.

The quantitative dominance of chemistry is no new phenomenon. To the contrary, many of the other abstract journals have grown more rapidly than *Chemical Abstracts* during the past three to four decades for various reasons. They could benefit from booming trends, as *Psychological Abstracts* from cognitive psychology; they absorbed new fields, as *Science Abstracts* did with computer science and information technology to become *INSPEC*; or they increased the overlap with chemistry, as *Biological Abstracts* did with biochemistry. By 1979, when no philosopher of science could even imagine the existence of philosophy of chemistry, *Chemical Abstracts* was more than four times as big as *Science Abstracts* (physics) and about three times as big as *Biological Abstracts*. Had those philosophers without prejudice gone into the laboratories then, they would have stumbled on chemistry almost everywhere.

Nowadays, philosophers overall write as many publications per year as chemists do in four days. Ironically, the figure suggests a rule of thumb about the philosophers' interest in the sciences: *the smaller the discipline, the more do philosophers write about it*, with the exception of the earth sciences. In the approximate order, philosophers write:

(1) about philosophy, as history of philosophy or, to be more correct, about what philosophical classics have published or left unpublished;
(2) about mathematics, as mathematical logic and philosophy of mathematical physics ('philosophy of science');
(3) about psychology, as philosophy of mind or naturalized epistemology;
(4) about the social sciences, as social and political philosophy and philosophy of social sciences;
(5) about experimental physics, as 'philosophy of science';
(6) about biology as philosophy of biology;
(7) and, to the smallest degree, about chemistry.

Thus, if philosophers produce general ideas about 'science', there are good reasons to be mistrustful. On the other hand, if one really wants to understand the natural sciences, there are good reasons to start with chemistry.

Section 2b. A history of philosophy explanation

Many explanations have been advanced for the fact that philosophers have so stubbornly neglected chemistry as if it were virtually non-existent. Is it the lack of 'big questions' in chemistry, its close relationship to technology, or the historically rooted pragmatism of chemists and their lack of interest in metaphysical issues? Or, is the alleged reduction of chemistry to physics (quantum mechanics) the main obstacle, so that, if chemistry were only an applied branch of physics, there would be no genuine philosophical issue of chemistry?

What all these approaches have in common is that they try to explain the neglect of philosophers by reference to chemistry, as if there were something wrong with chemistry. If there is only a bit of truth in our rule of thumb, however, it is the strange order of interest of philosophers that calls for explanation. In such an explanation, the neglect of chemistry would turn out to be only a special case, albeit an extreme one. I do not intend to provide a full explanation, but some hints from the *disciplinary* history of philosophy. Although we can in retrospect build a history of texts that we nowadays call philosophy, there is anything else than a continuous history of a discipline called philosophy, i.e. a history of a profession. The topical preferences of today's philosophers reflect the surprisingly young and awkward history of their discipline.

The relationship to mathematics goes back to a time, still at the turn to the 19th century, when 'philosophy' was just the generic term for all the arts and sciences collected in the philosophical faculties, among which the mathematical arts made up the largest part since medieval times. Thus professors in the philosophical faculties, i.e. professional 'philosophers', had to teach much mathematics, including applied mathematics such as mechanics and geometrical optics, which should become part of modern physics in mid-19th century. Other natural sciences like chemistry and biology (natural history) were mainly taught in the higher faculties of medicine, and therefore continued to be rather foreign to philosophers until today. When, during the 19th-century, most disciplines including modern physics grew out of philosophy in the generic sense, psychology and the social sciences ('moral philosophy') still remained under the label of philosophy. Their final separation was not much before the early 20th century. Roughly speaking, the later a discipline became independent from philosophy (in the generic sense), the smaller is it nowadays, and the better are its historical ties to today's philosophers, in accordance with our rule of thumb.

The separation of the disciplines caused a serious crisis about the question if there are any topics left over for philosophy as an own discipline. While most disciplines grew independent by defining their own subject matter to be investigated by empirical methods, the remaining philosophers refused to do so. Many picked up Kant's 18th-century ideas, proposed prior to the disciplinary formation of the modern sciences, who had reserved metaphysical and epistemological foundations of the mathematical sciences as genuine philosophical topics, besides ethics and aesthetics. That allowed them indeed to reconstruct a tradition that goes back to early modernity.

If we look at the tradition that modern philosophy of science considers as its own, it turns out that it is an extremely one-sided tradition, focused on mechanics that was formerly taught as 'mixed' or 'applied' mathematics in the philosophical faculties. A few points might illustrate that. First, the rise of early modern epistemology, both of the rationalist and the empiricist branch, with the exception of Francis Bacon, was closely connected to the rise of mechanical philosophy, which was strongly opposed to various kinds of chemical philosophies. Second, since modern physics has its theoretical roots in analytical or 'rational' mechanics, which did not belong to the physical sciences but to mathematics still in the early 19th-century, philosophical debates over 'the scientific method' were to a large part about establishing mechanics as a *physical* science. Kant's former dictum that, unlike the experimental sciences, only mechanics is a science proper because it has an a priori foundation in mathematics was an early and influential partisanship in these debates. That made it easy for Kantians to focus on mechanics and ignore the rest of the sciences. Finally, during the crucial phase of the professionalization of philosophy of science in the 20th century, it was first of all philosophically minded theoretical physicists who shaped the field with their numerous dissertations on the puzzles of quantum mechanics and relativity theory. They soon occupied most of the newly established chairs in philosophy of science—a situation that has not much changed since.

The long but historically contingent affinity to theoretical physics made 'philosophers of science' neglect not only chemistry but also every other branch of the natural sciences, including experimental physics until recently. Relicts of the older meaning of 'physics', as the generic term for the natural sciences still in the early 19th century, and the ambiguity of the English term 'physical' contributed to the confusion of philosophy of physics with philosophy of science. It was not before the early 1970s that biologists first reacted to the narrow focus and established their own groups together with biology-minded philosophers. It took another two decades that a similar movement occurred with respect to chemistry. In some sense, philosophy of science now lately repeats the 19th-century process of the ramification and professionalization of the natural sciences.

Section 2c. Philosophy of chemistry before the 1990s[6]

Although western mainstream philosophy of science has neglected chemistry, it is not true that there was no philosophy of chemistry before the 1990s. In Section II.2 we will see that mainstream historiography of philosophy has simply ignored what philosophical classics had said about chemistry. Second, other scholars, particularly chemists and historians of chemistry, filled the gap left by professional philosophers. Third, philosophy of science in communist countries was broad enough to include chemistry, particularly in the period from the late 1950s to 1990.[7]

Section 2c.i. Dialectical philosophy of chemistry

Philosophy of chemistry in communist countries drew on Engels' dialectical materialism, where chemistry featured prominently as a case against what he called vulgar or French materialism, i.e. mechanical philosophy. Like Comte a few decades earlier but with reference to Hegel's distinction between 'mechanism', 'chemism', and 'organism', Engels suggested a nonreductive hierarchy of the sciences. For the mechanical, chemical, and physiological level, he postulated different 'forms of movement' each with own laws as well as general 'dialectical laws' for the transformation from lower to higher levels.

While Engels' own treatment of chemistry remained fragmentary, 20th-century philosophers expanded on his ideas. They soon recognized that chemical phenomena could serve to illustrate universal laws of Engels' doctrine. For instance, acid-base-reactions were used to exemplify his 'law of contradictions' about counter-acting forces in nature. In addition, acid-base-reactions, when performed by titration with indicators, could colorfully visualize his general 'law of the change from the quantitative into the qualitative'. Philosophers of science in communist countries had an established role in tertiary science education and were officially committed to interpret particular scientific facts, problems, and developments within the general framework of dialectical and historical materialism. Because Engels had reserved an own 'form of movement' for chemistry, they were free to deal with chemistry as an autonomous field. Indeed, they produced a wealth of studies on modern chemical phenomena, laws, theories, theory dynamics, and sub-discipline formation. It is impossible to review the literature here, as there are studies on almost every philosophical issue, albeit of differing quality. At least it might be said that Engels' 19th-century framework was liberal enough to elaborate on such sophisticated topics as the relation between quantum chemistry and quantum mechanics, but epistemologically too naive to deal with quantum chemical concepts such as Pauling's resonance structures.[8]

The case of dialectical philosophy of chemistry proves that post-Kantian philosophy of science needed not have chemistry on its blind spot if it relied on later authorities. Engels published in the 1870s when the formation of modern scientific discipline was almost complete, with mechanics being only a subdiscipline of modern physics. Kant published a century earlier, before the modern discipline formation, in a premodern attitude to establish rational mechanics as the only real science and to discredit the then growing experimental sciences. Although both have been made ahistorical authorities of eternal validity in different philosophical ideologies, their views of science are only of historical significance nowadays, with Kant's view being surely much more anachronistic than Engels'. Yet, the Kantian legacy is still dominating in philosophy of science. For instance, when the eastern part of Germany was united to the western part in 1990, dialectical philosophy of chemistry immediately vanished in favor of the uninspired Kantianism that has pervaded the western part. Thus, the neglect of chemistry also results from the arbitrary choice of anachronistic authorities. In Part II, I will argue for an understanding of philosophy that gets rid of both anachronism and authorities.

Section 2c.ii. Philosophy of chemistry without philosophers

As long as professional philosophers in the Western countries did not care about chemistry, scholars from various disciplines approached the field, each from their own perspective and with specific questions. Particularly scholars of chemistry education have always recognized the need to reflect on methods and to work on the clarification of concepts, such that most of their journals are still a rich source for philosophers. Working chemists usually stumbled on philosophical issues when their own research challenged them to reflect on received notions or methodological ideas. Earlier prominent examples include Benjamin Brodie, Frantisek Wald, Wilhelm Ostwald, and Pierre Duhem. However, the series of philosophizing chemists did not stop in the early 20th century.[9] For instance, Friedrich Paneth's work on isotopy made him think on the concept of chemical elements (Paneth 1962). Alwin Mittasch's reflection on the notion of causation in chemistry arose from his studies on chemical catalysis (Mittasch 1948). Faced with the reluctance by contemporary scientists to accept his own theories and based on his detailed experience in laboratory practice, Michael Polanyi challenged received rationalist methodologies of science by calling for social factors and the role of tacit knowledge (Polanyi 1958). Edward T. Caldin, who as any other chemist primarily worked in the laboratory, argued that the then prevailing Popperian methodology simply failed to grasp the role of experiments in the experimental sciences and the way scientists deal with theories (Caldin 1959; 1961).

Since the late 1970s also theoretical chemists, who worked hard on the development of quantum chemical *models* for chemical purposes, began to question the naive reductionist view, albeit common among western philosophers of science, according to which chemical concepts and laws could simply be derived from quantum mechanical principles.[10] Guy Woolley, in a seminal paper (Woolley 1978), argued that the concept of chemical structure cannot be deduced from quantum mechanics. Hans Primas devoted a whole book on the issue of reductionism, arguing that quantum mechanical holism does not allow to derive statements about chemical objects without further assumptions (Primas 1981; 1985). Giuseppe Del Re and Christoph Liegener (1987a/b; Del Re 1987) considered chemical phenomena lying on a higher level of complexity that emerges from but does not reduce to the quantum mechanical level. Others began to question naive reductionism too (e.g., Theobald 1976; Lévy 1979; Bunge 1982; Weininger 1984).

Because the border between philosophy and history of science has never been sharply drawn, not surprisingly many historians of chemistry approached the field by dealing with philosophical issues of the past, of which two for some time ranked so high among historical topics of chemistry that it is impossible to review the literature here. These are the metaphysical issue of atomism and the methodological issue of conceptual change and theoretical progress as exemplified by Thomas Kuhn's treatment of the 'chemical revolution'.[11] Of course, both topics attracted many philosophers as well. Particularly the second topic caused for a while much fruitful collaboration and competition, and a flood of case studies. Challenged by the historiographic rigor of their colleagues, the philosophers' case studies frequently did not much differ from historical work, except by their greater ambition to make them a case for or against a general methodological position, such as pro or con Popper, Kuhn, Lakatos, and so on. Yet, picking-up chemical stories as evidence for one or the other general methodology in science overall is hardly a conclusive argument, nor can it count as philosophy of chemistry proper. This has never been better criticized than by chemist-philosopher Elisabeth Ströker in one of the most detailed historical account of the 'chemical revolution' (Ströker 1982).

More than in other historical branches, historians of chemistry approached philosophical issues in a wealth of fine studies on the history of ideas, theories, and methods and the mutual impact between chemistry, on the one hand, and its neighboring disciplines, philosophy, humanities, religion, and the general society, on the other.[12] Insofar as they did that with the aim of a better understanding of our present intellectual culture and the role of chemistry therein, they did a job that professional philosophers refused to do. Interestingly, the few western philosophers who dealt at book-length with chemistry, e.g. Gaston Bachelard (1932; 1953), Elisabeth Ströker (1963; 1982), and François Dagonet (1969), were strongly historically minded. I will come back to this point which is by no means pure chance (Section 3e).

The case of the pre-1990 history in Western countries illustrates that there is a need for philosophical reflections on chemistry, whether professional philosophers take notice of that or not. The need comprises both the analysis of chemical details as well as integrating perspectives to locate chemistry in the overall culture and the history of ideas. Through their education, philosophers usually have particular skills to meet these needs, if accompanied by some understanding of and interest in chemistry. Both were lacking, however, with the exception of a few individuals who found themselves outside the established circles.

Section 3. Recent trends and topics in the philosophy of chemistry

Section 3a. Establishing socially

The most obvious distinction of the emergence of the philosophy of chemistry in the 1990s to the previous period was its social establishment. Had former scholars worked in relative isolation, the new generation sought contact with each other and the exchange of ideas. Since the late 1980s, chemists, philosophers, and historians of chemistry began to gather in more or less formal working groups with regular meetings in many countries, such as the *Werkgroep Filosofie van de Chemie* in the Netherlands, the *Gruppo Nazionale di Storia e Fondamenti della Chimica* in Italy, and the *Arbeitskreis Philosophie und Chemie* in Germany. In addition, there was a call from the chemical industries for building bridges between chemistry and the humanities as an effort to improve the bad public image of chemistry.[13] In 1994, national meetings happened to grow to a series of international conferences in London (March), Karlsruhe (April), Marburg (November), and Rome (December). By 1997, international ties enabled the formal establishment of an *International Society for the Philosophy of Chemistry* with annual summer symposia. Two journals were launched, *HYLE: International Journal for Philosophy of Chemistry* (since 1995, edited by the author) and *Foundations of Chemistry* (since 1999, edited by Eric Scerri). The parallel rise of internet technologies, which were soon employed for many purposes (e-journal, e-mail discussion forum, regularly updated bibliography, information boards for conferences, syllabi, and so on), essentially helped establish a community and attract a wider audience.

Section 3b. Rediscovering the philosophical classics

The historical neglect of chemistry mentioned above is in part also an artifact by historians of philosophy who simply ignored what philosophical classics had said about chemistry. This has been brought to light in a growing number of recent studies. A prominent example is Kant's *opus postumum* that was not published before the early 20th century (with an English translation as late as 1993), though it contained a complete revision of his former theoretical philosophy against the background of the new Lavoisian chemistry.[14] Also Hegel's extensive writing on chemistry, albeit placed in his most famous books, became subject to scholarly investigations only recently.[15] And while Duhem's *La théorie physique. Son objet—sa structure* (1905-6) has long been a classic in the philosophy of science and translated into many languages, his *Le mixte et la combinaison chimique* (1902) was translated into English not before 2002. Who would have thought that even Rousseau had written a book on chemistry (Bensaude-Vincent & Bernardi 1999)? It is up to historians of philosophy to explore further writings on chemistry in philosophical classics such as Leibniz, Schelling, Schopenhauer, Herschel, Comte, Peirce, Broad, Alexander, Mill, Cassirer, Bachelard, to mention only a few who immediately spring to mind.

Section 3c. Struggling with reductionism

Still an important topic in today's philosophy of chemistry is reduction—not of biology to chemistry but of chemistry to physics. Criticism of reductionism plays different roles. First, it provides a more precise and technical understanding of the limits of quantum mechanical approaches to chemistry, and thereby defines independent areas for the philosophy of chemistry. For instance, in a series of papers Eric Scerri (e.g. 1991, 1994) has convincingly argued that quantum mechanical approaches are not able to calculate the exact electronic configurations of the atoms. Because that has been, since Bohr's early atomic theory, taken as the quantum mechanical explanation and reduction of the periodic system of the chemical elements, the latter is open to new philosophical analysis (see Section II.5). Similar arguments can be found with regard to the concept of molecular structure, following-up the issues raised by Woolley (see Section I.3.2). Second, the criticism of reductionism at the 'lowest' level of chemistry to quantum mechanics challenges microreductionism as a general metaphysical, epistemological, or methodological position and thus contributes to general philosophy. In the most detailed philosophical study on various forms of reductionism (incl. supervenience and microstructural essentialism à la Putnam and Kripke), Jaap van Brakel (2000) has made chemistry a case to argue for a kind of pragmatism in which the 'manifest image' of common sense and empirical sciences has primacy over the 'scientific image' of microphysics. For Nikos Psarros (1999), rejection of reductionism is even a necessary presupposition of his extensive work on the culturalist foundation of chemical concepts, laws, and theories which he seeks in pre-scientific cultural practices, norms, and values. For many others, including myself, it supports a pragmatist and pluralist position about methods that distinguish clearly between fields of research where quantum mechanical approaches are poor or even useless as compared to other approaches, and those where they are strong and even indispensable. Third, once reductionism has lost its credit to secure the unity of the sciences, new relationships between autonomous sciences, like structural similarities and interdisciplinarity, have become subject to both philosophical and historical investigations.[16]

Section 3d. Adapting philosophical concepts

Because of their narrow focus on theoretical physics, concepts of mainstream philosophy of science frequently require considerable revision before they help shed some light on chemistry. It is the gap between what Thomas Kuhn (1976) has called the 'mathematical' and the 'Baconian sciences' that philosophers of chemistry must bridge, because modern chemistry comprises both. Since chemistry is by far the largest scientific discipline, with enormous impact on every other experimental science, philosophers of chemistry also make valuable contributions to our philosophical understanding of the sciences when they adapt classical concepts for an understanding of chemistry. Examples, which are scattered around in the two journals and in numerous general anthologies and collections,[17] include the concepts of experiment, law, model, prediction, explanation, natural kinds, substance, and process; the scientific approaches to concept building, model building and classification; the treatment of competing theories; methods of research in the sense of exploring the new; the role of instruments in research; the distinction and relationship between science and technology; and so on. Also the topic of scientific realism, sometimes misused to distinguish theoretical physics from the rest of the sciences that are thereby discredited as 'immature sciences', appears in new light if applied to chemistry, and even becomes a research methodological concept if applied to synthetic chemistry (Schummer 1996a). While philosophers of mathematical physics have confined methodology to the 'context of justification', if not to proof theory, philosophers of experimental sciences like chemistry put more emphasis on the 'context of discovery', i.e. on scientific research methodology.

Section 3e. Analysing the structure of chemistry

Since each scientific discipline has its own fundamental concepts, methods, and theories, philosophy of chemistry reaches a state of maturity, in my view (see Part III), when it focuses on peculiarities of chemistry. This not only requires a double competence in chemistry and philosophy but also a deep understanding of the history of chemistry because our present scientific disciplines, with all their peculiarities, are historical entities, snapshots in a process of development. Thus, unlike general philosophers of science, with their eternal, albeit sometimes personal, ideas of 'general science', many philosophers of chemistry do merge with historians of chemistry to analyze fundamental concepts, methods, and theories in modern chemistry. It is in these areas where a great many works have been done in the past decade, such that I can give only a brief list of the most important topics.

As to fundamental concepts, philosophical and historical analyses include chemical concepts such as element, pure substance, chemical species, compound, affinity, chemical reaction, atom, molecular structure, and aromaticity.[18] Recent interest in chemical methods has focused both on practical methods, such as experimentation and instrumentation and chemical synthesis,[19] and on cognitive methods, such as the pictorial language of chemistry and the various forms of model building and representation.[20] Still neglected are methods of classification—probably a legacy of the traditional focus on the 'classification-free' modern physics before the rise of the particle era—although recent studies on the periodic system combine classificatory and theoretical aspects.[21] With respect to chemical theories, the axiomatic mathematical structures of physics with their apparently universal validity made philosophers reluctant to accept what chemists, virtually without any difference in meaning, call theories, models, or laws. Thus, save the aforementioned studies on models in chemistry, most of the present work on chemical theories is strongly historically orientated or about quantum chemistry and physical chemistry.[22]

Section 3f. Transcending boundaries

Ironically, philosophy of chemistry emerged at a time when scientific activities increasingly transcended disciplinary boundaries towards problem-orientated research. From environmental science to nanotechnology (Schummer 2004c), chemists are heavily involved in these activities, such that philosophers of chemistry are challenged to take them seriously. Three recent books, which each of their own combine philosophical and historical analyses of transdisciplinary research, have taken up this challenge. Hans-Jörg Rheinberger (1997) has analyzed the experimental settings, epistemological conditions, and the transdisciplinary culture in which cancer research moved in the 1950s towards protein synthesis as the biochemical background of molecular biology. Applying ideas from ancient philosophy of nature and technology, Bernadette Bensaude-Vincent (1998) has investigated modern materials science which has shifted from pure materials to composites that are individually designed for various technological purposes. With a critical view on classical approaches in the philosophy of science, Maureen Christie (2001) has examined the methodological basis on which theories of ozone depletion have actually been accepted in the atmospheric sciences since the 1970s.

Besides disciplinary boundaries of the sciences, there are also disciplinary boundaries within philosophy which philosophers of chemistry are about to transcend. If 'philosophy of science' means philosophical reflection on science, there is no need to restrict that to epistemological, methodological, and metaphysical reasoning, as philosophers of physics have done. Philosophy is a much richer field, and sciences like chemistry have many more interesting, sometimes even more pressing, aspects that philosophers can deal with. Thus recent and forthcoming work include special issues on *Ethics of Chemistry* (by *HYLE*), on *Green Chemistry* (by *Foundations of Chemistry*), and on *Aes-*

thetics and Visualization in Chemistry (by *HYLE*). Once the full scope of philosophy is acknowledged, topics in the philosophy of chemistry spring up abundantly (see 4d). This might go at the expense of simple paradigms of the field, but the intellectual profit is incomparably richer.

Section 4. From infancy towards maturity: a pragmatist point of view

Since every historical account orders the material according to certain preferences and values, also my review of the recent development of philosophy of chemistry in Section 3 is a personal one. It is based on certain ideas of what philosophy can and should do in my view to meet general societal needs and to avoid the shortcomings of stagnancy and ossification of which we have ample evidence in other fields of philosophy. In this part, which addresses the normative question "where should we go to?" I will now argue for these ideas by distinguishing between topics of infancy and topics of maturity from a pragmatist point of view.

Section 4a. Topics of infancy

To avoid misunderstandings, I emphasize that topics of infancy are very important topics and should not be neglected. They are important, however, only during an state of self-defining and structuring a field, and for preparing topics of maturity. I believe that philosophy of chemistry is to a large part just in that state.

Rediscovering the philosophical classics for a certain field is a typical topic of infancy or crisis (in the original Greek meaning of separation). It belongs to the general topic of disciplinary history writing. Instead of coming from nowhere, the new field is shown to be rooted in an old tradition, from which it receives authority and importance. Classical examples are Priestley's history of electricity from 1767, and Ostwald's history of electrochemistry from 1896. Similarly, complaining about or analyzing the previous neglect of a field are topics of infancy, as everything I do in the present paper. On the other hand, rediscovering the classics can be an inspiring enterprise in that it shows us long forgotten perspectives to be followed-up in future philosophical research.

Second, struggling with reductionism is for the most part, but not always, a topic of infancy regarding chemistry, albeit a topic of maturity for the philosophy of physics. Once more, I emphasize, it is important for the philosophy of chemistry. It prepares the grounds for more relaxed and deeper studies of subjects whose logical independence have been proven before, and thus moves towards topics of maturity. Furthermore, it places the philosophy of chemistry in the context of general philosophy and thus contributes to its broader acceptance. And it helps us develop a better understanding of the much more complex relationships between the sciences, both historical and logical.

Third, adapting classical philosophical concepts to an analysis of chemistry are preliminary topics too, whereas the analysis itself is not. For philosophers, concepts are tools like spectrometers are for chemists. If they use the wrong tools, the results are at best irrelevant. For instance, in the received philosophy of science view, an experiment is something to test, improve, or develop a theory. We can find this notion in chemistry too, and we even find instances for all the roles philosophers have ever assigned to experiments. Yet, if we look at what chemists mean by 'experiment', it turns out that the great majority use the term ‘experiment’ in a sense that philosophers are hardly aware of (Schummer 2004a).

Section 4b. A pragmatist definition of topics of maturity

The topics I have mentioned so far are topics of infancy only with respect to what I consider topics of maturity. I claim that a philosophical field reaches a state of maturity only if it defines its own issues with respect to the peculiarities of its object. In our case that means that topics of maturity are those which derive from peculiarities of chemistry. This is by no means a truism in philosophy. Indeed many philosophers reject the idea and claim to the contrary that philosophical issues are prior to or independent of any particular objects, that true philosophical issues are only so-called perennial or general problems. For them, chemistry would be interesting only if and insofar as it provides examples or illustrations of their general problems. If the perennial view were right, there would never be a particular philosophy of chemistry, nor of biology and so on, because the philosophical interest in such fields would be only instrumental to solving perennial issues. As I have indicated with my historical remarks on philosophy in Part I, there are good reasons to doubt such perennial problems of philosophy. They rather result from an arbitrary historiography of philosophy with references to favorite authorities. Instead, I would defend a kind of pragmatism according to which philosophical issues should always derive from the specific objects (the *pragmata* in Greek).

Unlike the perennial view, the pragmatist view requires a detailed understanding of chemistry, not only in its present form but also in its historical development. That is why philosophy of chemistry needs to be closely linked to the history of chemistry. Moreover, because of the incredible size of contemporary chemistry (about one million publications per year), there is a need for new methods to grasp what chemists are actually doing. It does not help much to ask a chemist or two what their four million colleagues are doing. That is simply beyond the intellectual scope of individuals (Schummer 1999). Instead, one needs empirical methods for qualified statements. For instance, most people would not believe that much more than half of the chemists are synthesizing new substances on a regular basis; yet, that is what qualified statistical analysis says (Schummer 1997b). Last but not least, philosophical issues of chemistry should be related to the problems chemists are actually confronted with.

Once we have a better understanding of what chemists are really doing and concerned with, we can do the philosophical analyses that I consider topics of maturity. These include the conceptual, metaphysical, and methodological investigations mentioned earlier. However, it also includes topics beyond conventional philosophy of science.

Section 4c. An eye on the philosophy of biology

It is instructive to see what philosophers of biology consider as the major topics of their field nowadays, in a state of maturity as we can assume. For instance, take the table of contents of the recent anthology *The Philosophy of Biology*, ed. by David L. Hull and Michael Ruse, published by Oxford University Press in 1998 (see Table 1). It is a collection of 36 previous articles divided into ten thematic sections. The first four sections are about metaphysical, methodological, and conceptual issues of evolutionary theory; section V is devoted to ontological issues in taxonomy. The second half of the book relates various topics of biology to different branches of philosophy, beyond received philosophy of science, such as anthropology, ethical theory, applied ethics, philosophy of history, and philosophy of religion. There is no general scheme of how scientific topics are related to philosophical issues, such that we could simply transfer them to philosophical issues of chemistry. Instead, the philosophical issues derive from the peculiarities of the biological topics.

Section Headings		**Related Philosophical Branches**
I.	*Adaptation*	Metaphysical, methodological, and conceptual issues of evolutionary theory
II.	*Development*	
III.	*Units of Selection*	
IV.	*Function*	
V.	*Species*	Ontology, Classification
VI.	*Human Nature*	Anthropology
VII.	*Altruism*	Ethical Theory
VIII.	*The Human Genome Project*	Applied Ethics
IX.	*Progress*	Philosophy of History, Epistemology
X.	*Creationism*	Philosophy of Religion

Table 1: Table of Contents of *The Philosophy of Biology*, ed. by David L. Hull & Michael Ruse, Oxford University Press 1998; 36 articles grouped in 10 thematic sections.

Section 4d. Discovering topics in the philosophy of chemistry: some examples

What philosophers of chemistry can learn, and in my view should learn, from the philosophy of biology is the discovery of philosophical issues that derive from the peculiarities of chemistry. There is no simple rule or recipe to do that, as philosophy is a creative enterprise. However, one can take the branches of philosophy as guides, as analytical instruments rather than as sets of perennial issues. To illustrate that, I finally provide a few examples from my own recent work, arranged according to different branches of philosophy and each with reference to, in my view, obvious peculiarities of chemistry.[23]

(1) *Logic*: Prior to formal or symbolic logic, philosophical logic explores conceptual structures that we use in representing and reflecting the world. If we look at the conceptual structure of chemistry, it turns out that it is built on a peculiar kind of relations (Schummer 1997c, 1998a). For instance, a chemical property describes a complex dynamic and context dependent relation between various substances, and not something that is proper to an isolated thing. Some philosophical classics, like Hegel, Cassirer, and Bachelard, recognized the peculiar relational structure of chemistry earlier, which is also deeply rooted on our common sense, for instance, when we use metaphors from chemistry to describe social relations. However, with the exception of philosopher-chemist Peirce and his followers, logicians have badly neglected relations, such that we have only little understanding of how the complex conceptual structures of chemistry are built out of basic chemical relations (Schummer 1996, 1998a).

(2) *Ontology*: When conceptual structures are used to frame the world, we are entering the field of ontology. For its twenty million and more substances, chemistry has built the most advanced classification system of all science, for which there is no model

in other fields. Taking chemistry as a classificatory science seriously, from an ontological point of view, requires the investigation of very abstract notions, such as chemical entity, species identity, similarity, class membership, distinctions, and hierarchies. Again, we are only at the beginning of an understanding that shows that the ontological structure of chemistry is presently in state of change (Schummer 2002a). For instance, while classical chemical classification has been based on a strict correspondence between pure substances and molecules, recent trends to include also quasi-molecular species challenges the traditional system and causes deep ontological issues about the criteria of species identity.

(3) *Methodology*: While philosophers of science have been telling us that scientists aim at a true theoretical description of the natural world, the great majority of chemists (which also means the great majority of scientists, see Sect. I.1) have actually been engaged in synthesizing new substances, i.e. changing the natural world. Chemical synthesis is, to be sure, the most obvious peculiarity of chemistry, albeit the most neglected one because it is foreign to any received idea of philosophy of science. Since methodology is concerned with scientific methods, a methodological understanding of synthetic chemistry requires an analysis of the goals, procedure, techniques, and dynamics of that endeavor (Schummer 1997a/b). In particular, we need a better understanding of the theoretical concepts of chemistry which, unlike quantum mechanical concepts, not only predict natural phenomena but also serve as guidance for the production of new substances a million times per year.

(4) *Philosophy of language & semiotics*: Chemists have their own sign language of structural formulas and reaction mechanism which calls for semiotic analysis (Schummer 1996c). Rather than being only a set of iconic, symbolic, or index signs (according to the classical semiotics of Peirce and Morris), it is a particular language system endowed with elements of theoreticity that allows chemists not only to communicate with each other in a concise and precise manner about chemical entities and relations; it is also the major theoretical device for predicting and producing new chemical substances (Schummer 1998a). As compared to its extraordinary success, we still have little philosophical understanding of how theory is encoded in the language and if the system is a new type of theory, different from what we know from other sciences.

(5) *Philosophy of technology*: Although synthetic chemistry stands out because of its productivity, that does not entail as such being a kind of technology. Indeed, synthetic chemistry is a good case to evaluate various standard distinctions between science and technology according to their underlying ideas of science (Schummer 1997d). It turns out that all these ideas are hardly in agreement with contemporary experimental science. The case of synthetic chemistry may help sharpen the concepts of science and technology for a better understanding of their relations. For instance, historians of technology now consider the chemical industry the only real science-based industry. If that is true, philosophers are challenged to explain the peculiar epistemological relation between chemical knowledge and technology without mixing them up.

(6) *Philosophy of nature*: While in all the other natural sciences nature is, by definition, the object of their study, chemistry breaks the rule by the strange opposition of ‘natural versus chemical’, held by both chemists and nonchemists. Here, philosophers are

required to analyze on which peculiar notion of nature the opposition rests and whether such an opposition is well grounded or not. Historical analyses reveal that the opposition came up only after ancient Greek philosophy and has pervaded the Christian era from the earliest times up to the present (Schummer 2001a, 2003b, 2004b). Systematical analyses show that the opposition, while being descriptively meaningless, serves normative ends in implicit quasi-moral judgments (Schummer 2003b). Again, here is a task for philosophers to prepare the grounds for a normative discourse by making the implicit explicit.

(7) *Philosophy of literature*: Another important field for making the implicit explicit is the literature insofar as they mediate the public image of scientists. There are many complaints about the gap between the 'two cultures' and about the bad image of scientists, expressed in such figures as the 'mad scientist'. It is also well known that scientists in the media frequently appear as a mixture of the medieval alchemist and the modern chemist. Yet, little is known why writers shaped these figures. Investigations of the 19th-century literature reveal that writers indeed began pillorying chemistry of all sciences because of metaphysical, theological, and moral concerns (Schummer 2005b). Again, it is up to philosophers of chemistry to analyze those accusations of particularism, materialism, atheism, and hubris, which historically form the philosophical background of the public image of science nowadays.

(8) *Ethics*: Although applied ethics is now a flourishing field of philosophy, chemistry is almost neglected. That is more than surprising because many major moral issues, from environmental issues to pharmacological issues to chemical weapon research, are strongly related to chemistry. The fact that synthetic chemists do not only produce knowledge but also change our material world has caused public concerns since at least two centuries. It requires sober ethical analyses that separates moral issues proper from quasi-moral concerns as mediated through the literature or normative notions of nature in order to prepare an ethical framework for a moral discourse (Schummer 2001b, 2001-2002, 2005a).

(9) *Aesthetics*: More than any other scientists, chemists make heavy use of all kinds of means of visualization, from simple drawings to virtual reality. In addition, chemists have increasingly made claims to the beauty of their synthetic products, and there is clear empirical evidence that this is also an actual research motivation. Both call for systematic investigations of the role of aesthetics in chemical research (Schummer 1995, 2003a, Spector & Schummer 2003). In particular, aesthetic analysis may help understand crucial issues of research creativity and innovation. If beauty is an accepted research value, we need to understand on what aesthetic theory that notion of beauty is based and how aesthetic values relate to other research values, both epistemological and moral.

The list of topics could be easily extended further. Yet, I do not want to put my own research into the focus. If the paper has a message, then it is to encourage philosophers of chemistry to think for their own, be skeptical about perennial problems, and discover new philosophical issues of chemistry. There are plenty of them waiting for discovery.

Let me finally come back to Figure 1. If one compares the size of philosophy with that of chemistry, it is evident that the philosophy of chemistry will never be even visible on such a figure. However, the sheer mass of chemistry and its omnipresence does make the philosophy of chemistry one of the most important and difficult fields of philosophy.

Note

1 Interested readers may find a regularly updated online bibliography maintained by the author at http://www.hyle.org/service/biblio.htm .

2 A first draft of this paper was presented as the opening lecture of the *Sixth Summer Symposium on the Philosophy of Chemistry, Washington, DC, 4-8 August 2002.*

3 Earlier review articles include van Brakel & Vermeeren 1981, van Brakel 1996, 1999, 2000, chap. 1, Ramsay 1998, Brock 2002, Schummer 2003c.

4 Quoted from the *INSPEC* web site.

5 Quoted from the web site of *Biological Abstracts.*

6 This section and Part II borrows from Schummer 2003c. For brevity reason, references are largely confined to monographs and collections; more references may be found in the online bibliography quoted in Note 1

7 Unfortunately, the philosophy of chemistry literature in communist countries is not reviewed yet, except for the German Democratic Republic, see Laitko 1996. For a bibliography, see Schummer 1996b.

8 For the historical background of the debates on resonance structures, see Rocke 1981. For philosophical analyses, see Laitko & Sprung 1970, pp. 80-109; Vermeeren 1986; Schummer 1996a, sect. 6.5.2.

9 Interested readers may find more on the chemists mentioned in this section in the *HYLE* series "Short Biographies of Philosophizing Chemists."

10 An earlier paper by a theoretical chemist that includes many later critical ideas is Hartmann 1965.

11 Paul Hoyningen-Huene (1998) has argued that the chemical revolution was even Kuhn's paradigm case for his notion of scientific revolutions.

12 To name but a few historians with obvious philosophical interests: J.H. Brooke, W. Brock, M.P. Crosland, A.G. Debus, E. Farber, R. Hooykaas, D. Knight, T.H. Levere, A.N. Meldrum, H. Metzger, M.J. Nye, A. Rocke, and many more.

13 Two valuable publications from these initiatives are Mittelstraß & Stock 1992 and Mauskopf 1993.

14 Carrier 1990; Vasconi 1999; van Brakel 2000, chap. 1.2.

15 Engelhardt 1976; Burbidge 1996; Ruschig 1997.

16 E.g. Danaher 1988, Janich & Psarros 1998, Reinhardt 2001.

[17] In addition to the ones mentioned elsewhere, these include Janich 1994, Psarros, Ruthenberg & Schummer 1996, Mosini 1996, McIntyre & Scerri 1997, Psarros & Gavroglu 1999, Sobczynska & Zeidler 1999, Bhushan & Rosenfeld 2000, Earley 2003, Sobczynska, Zeidler & Zielonacka-Lis 2004.

[18] Book-long philosophical or historical studies on chemical concepts include Klein 1994, Schummer 1996a, Psarros 1999, Görs 1999, Brush 1999, van Brakel 2000, Neus 2002.

[19] Baird 1993, Rothbart & Slayden 1994, Schummer 1996a, 1997a/b 2002a, Holmes & Levere 2000, Morris 2002, Baird 2004.

[20] Laszlo 1993, Janich & Psarros 1996, Francoeur 1998, Schummer 1999-2000, van Brakel 2000, Klein 2001.

[21] Scerri 1998, 2001, forthcoming; Cahn 2002.

[22] E.g., Nye 1993, Schummer 1998b, Gavroglu 2000.

[23] A comprehensive treatment of such topics will be Schummer 2005c.

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