PREHISTORY OF PHILOSOPHY OF CHEMISTRY

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abstract

This article reviews the prehistory of the philosophy of chemistry up to the first half of the 1990s. Section titles: heritage of Kant; Hegel, Schelling, Peirce; Whewell, Mill, Broad; Ostwald, Cassirer, Paneth; French philosophy of chemistry; neglect of chemistry in English-language philosophy of science; philosophy of chemistry in Eastern Europe; resonance and politics; birth of philosophy of chemistry.

Key-words

Bachelard, Broad, Bunge, Cassirer, Duhem, Engels, Hegel, Kant, Kedrov, Meyerson, Mill, Ostwald, Paneth, Peirce, Polanyi, Schelling, Whewell.

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preliminary remarks

This article reviews the (pre-)history of the philosophy of chemistry,[1] from the time of Kant up to the first half of the 1990s, focusing on what philosophers had to say about chemistry, not on philosophical relevant remarks of chemists.[2] Rapid developments since then are covered in other articles in this volume.[3] There is an extensive literature on the concepts of substance and matter in the history of western metaphysics, in which numerous philosophers figure, including Aristotle, Averroës, Gassendi, Locke, and many more. However it is rare for these discussions to be related directly to chemistry. Düring's (1944) *Aristotle's Chemical Treatise: Meteorologica, Book IV* is a curiosity in using the word "chemical" in the title. It is only recently that the relevance of Aristotle's views on substances and "mixts" has been discussed in some detail, and has been referred to as first raising one of the fundamental issue of the philosophy of chemistry: Are the constituents present in the compound or not? (**See articles "Substance: Ancient views of Chemical Substance" and "Compound and Mixtures"**)

The extensive literature in the wake of influential publications of Kripke and Putnam on natural kinds, rigid designators and Twin Earth can perhaps be seen as a continuation of the remarks of Aristotle and Locke on (predecessors of chemical) substances. Locke already used the same examples of water and gold that were the prominent examples of Kripke and Putnam.[4]

> But if an *English-man*, bred in Jamaica, who, perhaps, had never seen nor heard of *Ice*, coming into *England* in the Winter, find, the Water put in his Bason at night, in a great part frozen in the morning; and not knowing any name it had, should call it harden'd Water; I ask, Whether this would be a new *Species* to him, different from Water? And, I think, it would be answered here, It would not to him be a new *Species*, no more than congealed Gelly, when it is cold, is a distinct *Species*, from the same Gelly fluid and warm; or that liquid Gold, in the Fornace, is a distinct *Species* from hard Gold in the Hands of a Workman.

Perhaps we should clearly distinguish between two separate issues: first, the ontology of *matter in general*; secondly, the ontology of *particular kinds of matter,* i.e. chemical kinds or substances. Explicit statements concerning this distinction, often in connection with statements concerning atomism and/or the autonomy of chemistry, can be found in the writings of numerous chemists and philosophers in the past few centuries: Lavoisier, Kant, Schelling, Mendeleev, Bachelard, Pauling, to

[1] References will be given using the year of first appearance of a work to facilitate situating a particular view. References to works more than a century old are given in notes, not in the list of references.
[2] **See articles on Boyle, Priestley, Lavoisier, Dalton, Mendeleev, Gibbs, Ostwald, GN Lewis, Prigogine.**
[3] A good survey of major developments until 2002 can be found in Schummer (2006).
[4] John Locke, *An Essay concerning Human Understanding*, Bk. III, ch. vi, §13.

name but a few. For example, in 1902, in "A Detailed Classification of the Sciences," Charles Sanders Peirce wrote: "Chemistry must here be understood as the science of the different kinds of matter (which is substantially the definition of Ostwald and of Mendeléef)." Pauling (1950, 109) emphasised that chemists "are interested in *different* kinds of matter{ XE "matter" }, not only in the *form* of substances" (emphasis added). Nevertheless, discussions in both the history of philosophy and the philosophy of science have been concerned mainly with the first issue, the ontology of matter in general; and similarly, historical research on atomism has usually focused on the physical side. As Paneth (1931, 113) noted: "the physical aspect (divisibility, mutual attraction and repulsion, and so on) has been discussed much more than the chemical (qualitative characteristics, valency, etc.)." While atomism and its preference of form over substance(s) is often seen as the metaphysical motor of western metaphysics (Schummer 2008, Ladyman and Ross 2006), varieties of anti-atomism are often encountered among philosophers interested in the chemistry of their times (see below).

the heritage of Kant

Though Kant (1727-1803) had made brief comments about science in his *Critique of Pure Reason*, his influential views can be found in the preface of his *Metaphysical Foundations of Natural Science*. The title already indicates that science is only possible because of certain metaphysical foundations. The use of mathematics introduces the pure part in science and at the highest level of abstraction there is the metaphysical *a priori* A natural science is genuine to the extent that mathematics is applied in it. Sciences like chemistry and psychology are rational (because they use logical reasoning), though not *proper* science,[5] because they miss the basis of the synthetic *a priori*. In the crucial passage Kant not only says that the chemistry of his time does not count as genuine science because it doesn't use mathematics, but that this requirement would be difficult *ever* to fulfil:

> So long, therefore, as there is for the chemical working of substances [chymischen Wirkungen der Materien] on one another, no concept which can be constructed [mathematically], i.e., no law for the approach or withdrawal of the parts [of substances] can be stated according to which (as, say, in proportion to their densities and suchlike) their movement together with consequences of these can be intuited and presented a priori in space (a demand that will be difficult ever to fulfil), so long chemistry can become nothing more than a systematic craft or experimental doctrine, but never science proper [*eigentlichen Wissenschaft*] ...

For a long time it was assumed that Kant could not have done any serious philosophy in his old age. Typically, Adicke, charged with editing the *Akademie Ausgabe* says in 1924 that in the 1790s Kant could not have been following the chemical literature seriously. However it is now well documented that from 1785 onwards Kant is following the developments in the theory of heat and chemistry in detail.[6] As a consequence, in the years 1796-1803 Kant was working on a draft of a work concerning

[5] Kant's phrase "eigentliche Wissenschaft" has been translated as genuine, real, proper, rigorous, or authentic science. For references to original sources for this section see van Brakel (2006).
[6] Friedman (1992) has shown that by 1785 Kant has become aware of the new discoveries in pneumatic chemistry; between 1785 and 1790 Kant has assimilated the developments in the science of heat; between 1790 and 1795 he

which he wrote to Christian Garve on 21 September 1798, "It must be completed, or else a gap will remain in the critical philosophy." Kant had become convinced that a new a priori science had to be added, lest the "pure doctrine of nature" remains incomplete. Not being able to give a philosophical account of the variety of substances Kant had started to see as a gap in his philosophy. If the synthetic a priori has to guarantee the possibility of all experience, much is missing if one is stuck with only physics (i.e. Newtonian{ XE "Newtonian" } mechanics). At the same time he noticed the progress by Lavoisier and others introducing accurate measurement into chemistry and hence the potential of mathematical reasoning. A systematic formulation of a dynamical theory of matter has to bridge the "gap" in Kant's philosophy of nature, which leads Kant to contemplate the central role of a "world aether" or "caloric aether".[7] Kant had always been against atomism.

Hence we might say that in later life Kant allotted chemistry a central place in his metaphysics. However, it is the early view of Kant that has had an enormous impact, his later views still being a matter of research and unknown to writers in the nineteenth and twentieth century.[8] Kant's *Opus postumum* appeared in German (in the Academy edition) after more than a century of problems delaying its publication. And what was published is generally considered a mess, printing piles of papers in random order without any editing. The first abridged English edition only appeared in 1993.[9]

In the English speaking world Kant's view that chemistry is not a genuine science is "exemplified by its place in William Paley's *Natural Theology*, the mandatory textbook read by every Cambridge gentleman throughout the nineteenth century" (Nye 1993: 5). There was some opposition to Kant's towering view, but with little impact. Paneth (1931) argued that Kant's definition results in an extremely narrow and inappropriate conception of science and declares "chemistry, too, to be a true science, even in those branches where it contains little or no mathematics", claiming that Boyle also recognised that chemistry demands "principles different from the mathematising ones of physics" (117) and reminding us "that it was the analytic chemist, unhampered by mathematics or indeed almost any theory, who discovered the majority of all chemical elements" (118). But such occasional opposition to Kant's views never caught on. There are traces of Kant's criterion for genuine science up to the present day.[10] If anything, the conviction that chemistry could only become a genuine science if mathematised, only took stronger hold after the emergence of quantum chemistry.

Hegel, Schelling, Peirce

Kant set the scene for subsequent writings in German *Naturphilosophie*, including Schelling (1775-1854) and Hegel (1839-1914).[11] Also the philosophical interest of the German chemists von Liebig,

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has completed the conversion to Lavoisier's system of chemistry.

[7] Note that Kant didn't presuppose a separate chemical force (in addition to contact-dynamical, attractive and repulsive forces).

[8] For arguments supporting this reading of Kant's *Opus postumum* and its significance for the philosophy of chemistry see Vasconi (1999), Lequan (2000), van Brakel (2006).

[9] For a detailed discussion of the *Opus* see Friedman (1992, 213-341).

[10] Recent examples of references to Kant's influential view include Hunger (2006: 151) and Mainzer, who writes: "Chemistry is involved in a growing *network of mathematical methodologies and computer-assisted technologies* with increasing complexity. Thus chemistry, is a *science* in the sense of Kant, ..." (1998: 49, emphasis in original).

[11] For an excellent brief statement of the relations between Kant's, Hegel's, and Schelling's philosophy of chemistry see Burbidge (1996, 15-24).

Ostwald, Mittasch, and Paneth can be placed in this tradition. In Schelling's early work on the philosophy of nature, the philosophy of chemistry takes a central place. He begins the first chapter of his *Ideas for a Philosophy of Nature* with a discussion of the new combustion theory and writes:[12] "The new system of chemistry … spreads its influence ever more widely over the other branches of natural science, and employed over its whole range may very well develop into the universal system of Nature." The purpose of chemistry is to investigate the qualitative variation of matter. Mechanics is altogether formal; chemistry provides content (substance). In his later work the philosophy of chemistry more or less disappeared from his natural philosophy and was taken over by a philosophy of life.

Schelling agreed with Kant that only natural science mathematised is genuine, and, like Kant and Hegel, he argued against mechanical chemistry because of the (according to them) false atomic hypothesis. However, according to Schelling Kant's formal account of synthesis leaves the substances out of the world. For Kant only the basic laws of physics (mechanics) could be deduced from a priori principles, the realm of demonstrable, authentic science. Schelling's aim was to achieve the transcendental deduction also for chemistry, biology, and eventually medicine.[13] Chemistry is a genuine science, because Schelling claims to provide justification not only for mechanical motion but also for the chemical composition of bodies.

Instead of a mechanistic, atomistic physics (mechanics) setting itself the impossible task of constructing the different kinds of matter from the extrinsic relations of homogenous "atoms", Schelling proposed a dynamic chemistry of forces, which would explain our experience with diverse kinds of matter in terms of specific (dis)equilibria of attraction and repulsion. Attractive and repulsive forces constitute the *essence* of matter itself. Dynamic chemistry does not postulate any original matter such that out of its synthesis all other phenomena can arise. Rather, since it considers all matter to be originally a product of opposing forces, the greatest diversity of matter is nothing else than differences in the relationship of these forces.

Only in recent decades has the role of chemistry in Hegel's philosophical system been studied in some detail. Hegel scholars had simply passed over Hegel's philosophy of nature and the difficult chapters on "Real Measure" and "Chemism" in his *Science of Logic*, assuming that whatever he might have said would have become obsolete by scientific progress. Hegel's working life coincided with the emergence of modern chemistry. He displayed familiarity with the work of Lavoisier and Berthollet wrote at length on Bergman's affinity notion, engaged in an extensive debate with Berzelius; and discussed in particular everything that showed the possibility of more accurate measurements allowing precise calculation. Like other *Naturphilosophen* he referred to the work of Richter (1762-1807).[14] Hegel presented his own formulation of chemical affinity around 1803. As Burbidge (1996, 6) remarks, Hegel "delighted in informing his students of what was current in the world of chemistry," which

[12] Friedrich Wilhelm Joseph Schelling, *Ideen zu einer Philosophie der Natur als Einleitung in das Studium dieser Wirssenschaft*, 2. Auflage, 1803.

[13] Schelling's view on the potential scientific status of medicine is said to have had direct impact on German university politics of his time.

[14] J.B. Richter, allegedly one of Kant's students and, allegedly, the first chemist who took the mathematisation of chemistry seriously, being the author of *De usu mathesos in chemia* (Königsberg 1789), had shown that accurate measurements could determine the standard proportions of an acid and a base that combine to form a salt; i.e. chemistry as finding a way of measuring real bodies.

cannot be said of many philosophers today.

For Hegel chemistry was essentially a matter of process, not components. Substances are the product of “real processes”. A “chemical object” (not restricted to ordinary chemical objects in his *Chemismus*) is an independent totality that is (nevertheless) determined by its relation to other objects through its reactions with other stuffs; i.e. it inherently refers to something else. The essential flaw of mechanism and atomism is that complete or comprehensive explanation is never possible. Each entity or event requires reference to other entities to explain its own existence, a “real reciprocal relatedness”. Affinity draws “opposite” bodies into a union so close that it transforms their qualities; and chemical reduction separates substances out of such unions and reconstitutes them as independent. Compared with a quantity in mechanics such as velocity, density constitutes a thing’s reality, its “real measure”, at least as a first step. **I**n a strictly logical way he reasoned from density to stoichiometric masses to elective affinity (which might be considered to correspond to Gibbs energy in modern terminology) to the nodal lines characterising chemical space, to the conclusion that chemistry is a genuine science.[15]

At a more abstract level chemism played an ineliminable role in Hegel’s system. The term “chemism (Chemismus)” was first used by Schelling and refers to the relations of affinities, a category of relatedness distinct from mechanism.[16] Developments in chemistry seemed to have shown that properties of classical matter seemed to be subject to what nowadays is called downward causation, subordinate to the properties of an overarching chemical process. From the perspective of twentieth century chemistry Hegel’s requirement of a special category of explanation might seem superfluous, but his writings may be said to address a real issue before the general acceptance of atomic theory.

Although Hegel and Schelling both can be said to claim the status of *eigentliche Wissenschaft* for chemistry, Kant’s view remained dominant, primarily because the natural philosophy of Schelling and Hegel was not well received. Influential chemists such as Berzelius and von Liebig made strongly dismissive statements concerning Hegel’s and Schelling’s philosophy of chemistry, a response that was subsequently shared by philosophers of all stripes (including Hegelians).[17] Although most contemporary commentators agree that both Schelling and Hegel were well-informed about the science of their time and, notwithstanding recent meticulous scholarship bringing Hegel’s and Schelling’s philosophy of chemistry to the reader, it is still an open question whether this is of more than purely historical (side-)interest.

The founder of American pragmatism Charles Sanders Peirce, at one time a consulting chemical engineer, often drew on his experience as a working scientist,[18] not only in his philosophy of science, but also in his abstract logical and metaphysical speculations. Just as Kant was impressed by the work of Lavoisier, Peirce was impressed by the work of Mendeleev. Like Hegel, Peirce too believed that the

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[15] By assimilating the laws of constant and multiple proportions in his system, Hegel resolved Kant’s doubts about giving a priori treatment of the “chymischen Wirkungen der Materien” (Ruschig 2001, 12, 21). According to Burbidge (1996), Hegel’s “development of measure” replaces Kant’s “concept of matter at all” as the basis for constructing concepts in “pure intuition.”

[16] It has been suggested that the Hegelian concept of chemism anticipates the logical structue of the acid-base definition by Brønsted.

[17] For the early reception of Hegel and Schelling’s philosophy of chemistry see Meyerson (1921, 576-582), who, notwithstanding his positive attitude towards their general philosophy, spoke of their “altogether bizarre attitude toward chemical theory” (581).

[18] On the possible lasting effect on his philosophy of him being presented as a young boy with “Liebig’s 100 bottles” see Seibert (2001).

notion of valency was one of the most important ideas in the history of science. He based his phenomenology or phaneroscopy, which he also called "phanerochémy", chemistry of appearances, or chemistry of thought, on an analogy with chemical elements and compounds.[19] Phanerochemistry is the science of the phaneron - "a proper name to denote the total content of any one consciousness." The structure of the phaneron is quite like that of a chemical compound. Just as chemical elements (basic substances) are characterized by their valency, conceptual elements are also characterized by the number of their possible bonds with other elements. His search for the "indecomposable elements" of thought Peirce saw as analogous to Mendeleev finding the periodic classification of chemical elements. Moreover, for Peirce this wasn't just a heuristic analogy:[20]

> [I]t is certainly true that all physical science involves … the postulate of a resemblance between nature's law and what it is natural for a man to think … and consequently, sound logic does distinctly recommend that the hypothesis of the indecomposable elements of the Phaneron being in their general constitution like the chemical atoms be taken up as a hypothesis ...

Still it cannot be said that Peirce gave a central place to chemistry in the scheme of things because, as he remarked in his "Views of Chemistry: sketched for Young Ladies" of 1861 (reflecting Kant's early view): "We must be satisfied with the Natural History of the chemical Elementary bodies without as yet explaining their physics."

Whewell, Mill, Broad

Whewell was a contemporary of Schelling and Hegel, but, although he was equally unimpressed by atomistic theories, was not impressed by their metaphysical speculations. He wrote that it "was not indeed without some reason that certain of the German philosophers were accused of dealing in doctrines vast and profound in their aspect, but, in reality, indefinite, ambiguous, and inapplicable," followed by a detailed critique of a couple of passages in Schelling's *Ideas* of 1803. In his *The Philosophy of the Inductive Sciences*, Book VI "Philosophy of Chemistry," he focused on chemical affinity and the idea of substance (including element, atom, composition). Following Berzelius he took "polarity" to be the most basic concept of chemistry. However, he didn't think the fundamental concepts of chemistry were satisfactory in terms of clarity and consistency, whereas "nothing less than the most thoroughly luminous and transparent condition of the idea will suffice". Therefore (agreeing with the early Kant): "at present chemistry cannot with any advantage, form a portion of the general intellectual education."[21]

According to Mill every science is originally experimental and thus has an inductive aspect. It is deductive to the extent that it has been mathematised reducing complex and specific cases to "the

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[19] Citations in this section are from Peirce's "The Basis of Pragmaticism in Phaneroscopy" (1906). For the relation of Peirce's "phanerochemistry" with his semiotics and his three categories see Tursman (1989).

[20] Drawing on analogies with chemical concepts was still quite common among philosophers around 1900. Frege also studied chemistry and borrowed the chemical terminology of saturated and unsaturated bonds in his famous *Begriffsschrift*.

[21] William Whewell, *The Philosophy of the Inductive Sciences* (1840, 1847). Citations in this paragraph from Part One, Bk I, § 12 and Part Two, Bk XIII, § 9.

fewest and simplest possible inductions." Newton's mechanics is the greatest example, but smaller examples are taking place continually, for example Liebig's observation that all blue colouring matters which are reddened by acids contain nitrogen and this may well lead one day to an even more general account of acids and alkalies. Chemistry has already "one great generalization", viz. Dalton's atomic theory. However chemistry "is still in the main an experimental science; and is likely so to continue unless some comprehensive induction should be hereafter arrived at, which like Newton's, shall connect a vast number of the smaller known inductions together." However, he envisaged a possible future in which chemical truths might be deducible from the laws or properties of "simple substances or elementary agents." If this were to happen it might "furnish the premises by which [this] science is perhaps destined one day to be rendered deductive." [22]

Mill doesn't expect chemical laws to be reducible to mechanical laws: "entirely new set of effects are either added to, or take the place of, those which arise from the separate agency of the same causes". The product of a chemical reaction is in no sense the sum of the effects of the individual reactants, say an acid and a base; the joint action of multiple causes acting in the chemical mode is not the sum of effects of the causes had they been acting individually. The properties of the reactants Mill dubbed "hetereopathic," which figured in hetereopathic laws. It is because of his (brief) remarks on hetereopathic laws that Mill is usually considered the first of the British emergentists.

Like the German *Naturphilosophen*, the British emergentists reacted against mechanistic philosophies. The view of the latter is characterised by Broad (1925, 76) as:

> All the apparently different kinds of stuff are just differently arranged groups of different numbers of the one kind of elementary particle; and all the apparently peculiar laws of behaviour are simply special cases which could be deduced in theory from the structure of the whole under consideration, the one elementary law of behaviour for isolated particles, and the one universal law of composition. There is really only one science, and the various 'special sciences" are just particular cases of it.

However, says Broad (like Mill and Hegel), this picture is wrong. There are many "special sciences" because { XE "Broad" } (1925, 58f):

> There need not be any peculiar *component* which is present in all things that behave in a certain way. The characteristic behaviour of the whole *could* not, even in theory, be deduced from the most complete knowledge of the behaviour of its components taken separately or in other combinations, and of their proportions and arrangements of this whole.

Broad distinguished between intra-ordinal and trans-ordinal laws (52), the latter introducing emergent properties, corresponding to Mill's hetereopathic laws, except that Broad's trans-ordinal laws are not causal. Although Broad is often cited saying that the situation "with which we are faced in chemistry … seems to offer the most plausible example of emergent behaviour" (65), and chemistry

[22] Citations in this paragraph are from John Stuart Mill, *A System of Logic: Ratiocinative and Inductive*, Bk. II, ch. iv, § 5-6. Apparently in the last citation the word 'perhaps' occurs in some manuscripts, but not in others. Citations in the next paragraph are from Bk III ch. vi, § 1-2.

figures prominently when he explains his emergentism and trans-ordinal laws (1925, 59-71), on the whole he didn't give much attention to chemistry in his theory of science and knowledge. For example, in his *Scientific Thought* (1923), there isn't one word about chemistry.

Ostwald, Cassirer, Paneth

In his anti-atomism{ XE "atomism" }, philosopher-chemist Ostwald{ XE "Ostwald" } aimed, first, to distinguish between what is given in experience and what is postulated by the mind: nothing *compels* us to affirm that mercury{ XE "mercury" } oxide "contains" mercury and oxygen{ XE "oxygen" } { XE "Mach" }. Second, he aimed to show that energy is the most general concept of the physical sciences.[23]

In his Faraday lecture of 1904 he still argued vehemently against the atomic theory and, acknowledging his debt to Franz Wald,[24] stressed that the deduction of the laws governing the nature of substances must start from the conception of "phase," a concept far more general than that of substance. Ostwald was one of the first physical chemists to give reasonably precise empirical (macroscopic, thermodynamic) definitions of chemical substances. In his terminology, if the properties of two co-existing phases{ XE "phases" } remain invariant during a phase{ XE "phase" } change, the system is called hylotropic. If it is hylotropic over a range of temperatures as the pressure varies{ XE "temperature" }, it is a pure chemical substance{ XE "substance" }. If it is not, it is a mixture. If it is hylotropic over all pressures and temperatures{ XE "temperatures" } except the most extreme ones, it is a simple substance.

In 1907, while addressing metamerism, polymerism, and the role of valence{ XE "valence" } in structure theory{ XE "structure theory" }, [25] he acknowledges that when compared with "structure theory," his account in terms of differences in energy content "predicts, however, nothing whatever about the chemical reactions{ XE "chemical reactions" } which are to be expected." He further acknowledges "the spatial arrangement of elements" to be{ XE "elements" }" to be' "a very important aid." When the results of the experiments of Thomson on ions in the gas phase and Perrin{ XE "Perrin" } on Brownian motion{ XE "Brownian motion" } became available Ostwald finally surrendered in November 1908:[26]

> I have convinced myself that a short while ago we arrived at the possession of experimental proof for the discrete or particulate [körnige] nature of substances [Stoffe], which the atomic hypothesis has vainly sought for a hundred years, even a thousand years.

Referring to publications by Duhem, Ostwald, and Meyer, the neo-Kantian Ernst Cassirer included 17 pages of his *Substanzbegriff und Funktionsbegrif* (1910) on chemical concepts. Cassirer associated the progress of science with the change from "purely empirical" descriptions of their subject matter,

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[23] For Ostwald's energeticism see **article Ostwald**.

[24] The Czech chemist František Wald (1861-1930) resisted the atomic theory until the end of his life. For the relation of Wald and Ostwald see Ruthenberg (2008).

[25] Ostwald (1907, 326-329); preface German edition dated September 1907.

[26] Emphasised text in the Preface dated November 1908 of his *Grundriss der allgemeine Chemie*, 4. Auflage (1909).

toward the rational stage of "constructive concepts" and wrote: "The conceptual construction of exact natural science is incomplete on the logical side as long as it does not take into consideration the fundamental concepts of chemistry" (203). Constructive concepts (which lend themselves to mathematical treatment) were realised in theoretical physics from the very beginning (Galileo, Newton), but were only slowly developed in chemistry, first examples being Richter's law of definite proportions, Dalton's law of multiple proportions, Gibbs's phase rule, the chemical atom characterised by atomic number, and the theory of composite radicals. Like many before him Cassirer stressed the relational aspect of chemical concepts and argues that the concept of a (chemical) atom{ XE "atom" } is (since Dalton{ XE "Dalton" }'s law of multiple proportions{ XE "multiple proportions" }) a relational, regulative ideal concept, "a mere relative resting point." The concept of the atom is (merely) a mediator; therefore, "we may abstract from all metaphysical assertions regarding the existence of atoms" (208).

The chemist Paneth, already cited twice, is of importance for the philosophy of chemistry because of his engagement in the debate with Fajans and von Hevesy concerning chemical identity in view of the discovery of isotopes (van der Vet 1979) and because of a thoroughly researched lecture he gave in 1931.[27] It addresses the familiar question how "elements" persist in compounds. According to Paneth the apparent contradictions which arise can be dissolved by distinguishing clearly the double meaning or different aspects of the chemical concept of element, which are defined referring to one another. The *Grundstoff* or basic substance is *"the indestructible stuff present in compounds and simple substances"*; the *einfacher Stoff* or simple substance is "*that form of occurrence in which an isolated basic substance uncombined with any other appears to our senses*" (129-30, emphasis original). The latter is a chemical substance like others, except that it cannot be decomposed (further) by chemical means.[28] The former provides the basis for the systematic ordering of the elements in the periodic system. Although the atomic theory contributes enormously to our understanding, "the concept of basic substance as such does not in itself contain any idea of atomism", as Lavoisier acknowledged (133). Paneth extended his distinction to the radicals of organic chemistry (usually unobservable), compounds of higher order (such as $SO_3.H_2O$), as well as (forms of occurrence of) simple substances (because of different phases, allotropy, etc.). [29]

French philosophy of chemistry

As Bensaude-Vincent (2005) has shown, among French philosophers of science in the twentieth century, chemistry was never neglected as much as it was in English language literature. History of science was considered necessary for the understanding of science; hence the "chemical revolution" or "Stahl or Lavoisier?",[30] was a continuing issue of debate long before Kuhn used it as a case study in the *Structure of Scientific Revolutions*.[31] Important philosophers with a background in chemistry, in

[27] For a thorough discussion and contextualisation of this lecture see Ruthenberg (2009).
[28] Paneth writes "*chemical* means", because he wants to exclude differing isotopes giving rise to different simple/basic substances.
[29] One simple substance may occur in different (allotropic) forms (Paneth 1931: 131, 143n51).
[30] Bachelard and the French historian of science Metzger tended to minimise the role of Lavoisier in the history of chemistry.
[31] Kuhn has acknowledged the influence on his thinking of Koyré, Meyerson, and Metzger.

particular Duhem, Meyerson, and Bachelard, shaped their philosophical theories in relation to matter theories in general and the atomic theory in particular, revising the metaphysical notion of substance in various ways. Their metaphysical views differed, but in each case "the prodigious variety of the changes [devenirs] of matter" (Bachelard 1932, 192) was of central concern.

Duhem criticised the indefiniteness of the atomic hypotheses, favouring the integration of mechanics and thermodynamics into a broader theory.[32] For example he did not accept that van 't Hoff's stereochemical representations should be understood as a fully fledged geometric picture of something real. Molecular structures do not have to be understood in terms of atoms, but can equally well be understood in terms of the chemical properties of the compounds. The importance of Duhem for the philosophy of chemistry is now well documented (see article on **Duhem** in this volume).

Meyerson wrote at length about (the history of) chemistry, in particular in relation to theories of matter, but always while writing on a more general metaphysical or epistemological theme. In his 600 page *De l'explication dans les sciences* (1921), philosophy of chemistry themes are scattered throughout most chapters, but often difficult to identify; e.g. in the chapter entitled "Forms of Spatial Explanation" more than half is on the concept of the chemical element, stereochemistry, affinity, etc. In one of the most central chapters of the book on "The Irrational" again the "chemical irrational" takes up half. Meyerson's familiarity with the history of chemistry and philosophy was truly impressive. His extensive discussion and evaluation of Hegel's and Schelling's philosophy of chemistry and its reception was already mentioned. When he criticises Kant arguing that "there can be no *pure* science" (1921, 402), he refers in support to Whewell. He discusses Perrin's publications in great detail. When he has reason to mention Broad's writings on emergence (in Meyerson 1931, 500), he comments that Broad's definition of mechanism (cited above) can already be found in the writings of Diderot.

According to Meyerson the driving force of science is the search for a hidden fundamental identity of identification or individuation: the astonishing variety is only apparent; hence the title of one of his books: *Identité et réalité* (1908). For example, throughout the history of the physical sciences, the unity of matter underlies material diversity. However, this process of rationalisation comes to a (temporary?) stop when it encounters "irrationals", for example the variety of chemical elements or when material properties cannot be reduced to geometrical features. The "existence of the irrational" is encountered at every stage. He opposed a priori speculations in/concerning science. Such deductive effort (such as that of Kant, Hegel, Schelling) fails because reason cannot "draw from itself the diversity of nature" (1908, 399). Furthermore, against Kant, chemistry "unquestionably presents all the characteristics of a distinct science" (1921, 167f).

Although there is a "closer and closer union of chemistry and atomism" (1921, 164), Meyerson stresses that Lavoisier's elements are hypothetical entities. To speak of chlorine in the salt of the sea and in the yellow chlorine gas "literally makes no senses at all" and he distinguishes elements taken in their atomic state and taken in their molecular state (1931, 83; 1936, 123), a view somewhat similar to Paneth's distinction of basic substances and simple substances. The existence of the silver-element is

[32] In a series of articles, Needham (2002) has shown that Duhem developed what he regarded as an essentially Aristotelian view of substances or matter, as an alternative to the corpuscular view (**see article Duhem)**

only a hypothesis which is obtained after many deductions; and pure silver, like the mathematical lever, the ideal gas, or the perfect crystal are abstractions created by a theory (1908, 31).

Bachelard, initially a chemistry teacher at a provincial French college, later became a philosopher of science with a strong influence in France. However, in English publications on Bachelard's philosophy of science, chemistry is never mentioned. Typically, in Tiles' (1985) book on Bachelard's philosophy of science, his book with "chemistry" in the title, *Le pluralisme cohérent de la chimie moderne*, isn't mentioned once.[33] As Bensaude (2005) reports, even in France Bachelard's disciples and commentators overlooked the part played by chemistry in his works. Perhaps the accessibility of Bachelard's chemistry orientated views has suffered from his sometimes idiosyncratic views and terminology. He saw the promise of a reduction of chemistry to numbers and came to support energeticism 50 years out of date.[34]

According to Bachelard the notion of (chemical) substance "operates effectively as a *category*".[35] In daily life and pre-modern chemistry substances are treated in a naïve realistic sense. The chemist still does this when she says the density of gold is 19.5. This stage is followed by rational interpretation. The description of substances by synthesis is the foundation of chemical rationalism. In modern organic chemistry substances "only get to be truly defined at the moment of their construction." Similarly, in the early history of the discovery of the chemical elements, one cannot "fail to be struck by the success of realism". But when Mendeleev proposed his system for the organization of elementary substances, "the *order* of substances imposes itself as a rationality." In the third stage, which he labels "non-Lavoisian chemistry" or metachemistry,[36] substance becomes "ex-stance" or "surstance" (with reference to Whitehead), revealing "the really essential dynamisation of substance." In a reaction the chemical substance looses its status of stable and well-defined matter: becoming defines itself underneath being. When substances are in (catalytic) reaction words like "presence" or "co-existence" are not very clear anymore. Furthermore, speaking of "absolutely pure substance" cannot be taken for granted, because it is obtained by a sort of induction along different (operational) trajectories and dependent on the definition of neighbouring substances. The notion of "chemical trajectories" (which has some similarity to Whewell's consilience) represents a new type of coherent pluralism, as the title of one of his books indicates. Each chemical substance refers to all the others – knowing about a chemical substance includes knowing how it is located among other substances and how it behaves in all chemical reactions in which it can take part.

Although at times tempted to excessive speculation in view of the rapid developments in the sciences of his time (relativity theory, photochemistry, catalytic reaction mechanisms), Bachelard is perhaps the best candidate to be considered the first philosopher of chemistry properly speaking. His major views can be summed up in one citation (1940, 45):

> Metaphysics could have only one possible notion of substance because the elementary conception of physical phenomena was content to study a geometrical solid

[33] Theobald published an article on Bachelard's philosophy of chemistry in French (1982), but in his English language publication on the philosophy of chemistry (1976) he goes along with mainstream logical empiricism.
[34] "Energy is a real substance and substance is not more real than energy" (Bachelard 1940, 56).
[35] Citations in this paragraph from Bachelard (1940), chapter III.
[36] See on the metachemistry of Bachelard and Latour: Nordmann (2006).

> characterised by general properties. Metachemistry will benefit by the chemical knowledge of various substantial activities. It will also benefit by the fact that true chemical substances are the products of technique rather than bodies found in reality. This is as much as to show that the real in chemistry is a realization.

Traces of Bachelard's views can be seen in current philosophy of chemistry in the work of Joachim Schummer when he emphasises the stuff and technique distinct feature of chemistry.[37] Bachelard's influence (via Foucault and Latour) can also be discerned at the basis of the "materialist turn" in the history of science and the history of chemistry in particular (Bensaude-Vincent 1998, Klein 2008), now also referred to as "historical epistemology".[38]

neglect of chemistry in English-language philosophy of science

Until about 1960, English-language dominated philosophy of science mainly consisted of philosophy of physics. In the eighteen parts of the *Foundations of the Unity of Science: Toward an International Encyclopedia of Unified Science*, published between 1938 and 1970, the only references to chemistry can be found in Kuhn's (1962) *The Structure of Scientific Revolutions* and, significantly, a few pages on chemical bonding in Frank's (1946) contribution on the foundation of physics. In the two main philosophy of science journals, *The British Journal for the Philosophy of Science* (since 1949) and *Philosophy of Science* (since 1933) there have been about ten articles in total on the philosophy of chemistry before the 1960s, including a perhaps neglected paper of Margenau (1944) on Pauli's exclusion principle.[39]

By now there is an extensive literature discussing the possible causes of the neglect of chemistry in the philosophy of science and there may be some truth in every suggestion made. Here we list some of the factors that may have played a role, most of which can be seen as stage-set by Kant's pronouncements on the status of chemistry. First of all, pre-1960 interest in the philosophy of science was almost exclusively in *theoretical* science.[40] That chemistry is not a theoretical science in the sense of theoretical physics tends to be supported by chemists themselves who, in the words of the chemist Polanyi (1958: 156), have always been wary of theoretical speculation unsupported by detailed experimental observations – a recurrent theme in public lectures of well-known chemists.

Putting the emphasis slightly differently, physics and chemistry were lumped together as *exact* natural sciences with focus on studying its *logical* structure. This meant that the interest was in laws in the sense of mathematical equations stating relations between magnitudes and theories that were axiomatisable, at least in principle.[41] In that sense there are few laws and theories in chemistry and the

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37 See Schummer (2008) and (1996, 180, 182, 226).

38 See **article on Bachelard** for a more extended and somewhat different presentation of Bachelard as a philosopher of chemistry.

39 For selected references see Table 1-6 in van Brakel (2000, 19).

40 For other possible causes for the neglect of a philosophy of chemistry see Paneth (1931, 113-115) and more recently publications of Bensaude-Vincent (2008, 13-21), Del Re, Janich, Ruthenberg, Scerri & McIntyre, Schummer, and many others (references in van Brakel 2000, 18n59).

41 Mulckhuyse (1961) is an early attempt to do philosophy of chemistry that meets the formalistic standards of traditional philosophy of science. He presents an axiomatisation in first order logic of the classical (van 't Hoff type) theory of chemical structure. But this had no further impact. For a critique of the limited scope of his project see Schummer (1996, 248f, 255).

numbers chemists manipulate are usually values of physical magnitudes. Mainstream philosophy of science simply regarded chemistry as part of physics and an unimportant part at that, the general impression being that with the quantum mechanical interpretation of the chemical bond, chemistry had been reduced to physics. If there might have been some philosophy of chemistry in the pre-quantum era, it became irrelevant in one fell swoop. This applied in particular to the German *Naturphilosophen* and the British emergentists.

Chemical examples might be used in the philosophy of science or even in other parts of philosophy, for example in discussing the status of dispositional properties; not forgetting that such dispositional properties only become respectable by becoming obsolete in our "rise from savagery" as Quine (1969, 134-6) put it (following a suggestion of Russell). But usually such examples had little if anything to do with what might be considered typically chemical (as distinct from physical). Still, in the 1960s a few isolated publications focusing more specifically on the philosophy of chemistry appeared. Most of them can be seen as reporting falsifications of universal features of "the" method of science. For example, it was reported that received views on theory and explanation and their relation to experimental data were not confirmed by chemical practice.[42] This development continued when the relevance of (historical) case studies became an important part of the (historicised) philosophy of science (see below). However, if an occasional paper on the philosophy of chemistry was published in philosophy of science journals, it had no further impact. For example, in 1962 the *British Journal for the Philosophy of Science* published in two instalments a translation of Paneth's 1931 paper on the epistemological status of the chemical concept of element (republished again in *Foundations of Chemistry* in 2003). There were only two extremely brief responses to Paneth's paper, disputing historical details concerning Locke and Lavoisier. Neither the republication of Paneth's article, nor an earlier exchange between Caldin and MacDonald on *chemical* theories (in the same journal), had any further impact, until philosophy of chemistry emerged with its own journals.

There was only one (potentially) inherently chemistry-related subject, emergence, which was discussed in some detail by logical empiricists until the historical and social turn of the 1960s. In the "final statements" of logical empiricism by Nagel and Hempel, the doctrine of emergence was given its proper place. A precise definition of emergence can be given in terms of non-deducibility of statements of different theories or discourses. An emergent trait is defined relative to some given theory, whereas the latter is "subject to indefinite modifications in the light of macroscopic evidence." The doctrine of emergence is essentially correct, but rather trivial. What might be emergent at one time, may not be emergent at another time. Further, emergence is not restricted to the special sciences; the mass of a Helium atom is also emergent (from the mass of protons and neutrons). Nagel (1969, 369) comes close to identifying Broad's transordinal laws with his own bridge laws and "assumptions adjoined to the theory when it is applied to specialised circumstances".

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[42] For example Caldin (1959), Churchman and Buchanan (1969), Theobald (1976). Caldin (1961) also published a short book, *The Structure of Chemistry in relation to the philosophy of science* (reprinted in *Hyle* 2002), in which he criticised the prevailing Popperian methodology for failing to grasp the role of experiments. However, as to physics and chemistry as experimental sciences, "it is hard to see that there is any fundamental difference" (104).

philosophy of chemistry in Eastern Europe

Independently of developments elsewhere, in the period 1949 to 1986, quite a number of publications on the philosophy of chemistry, primarily in German and Russian, appeared in Eastern Europe.[43] This included a range of books devoted solely to the subject. According to Vihalemm (2004, 8) in the period 1960-1980 two "all-union" philosophical conferences focusing on chemistry took place in the USSR and a bibliography listed 565 publications (all in Russian), including 60 monographs. The number of philosophy of chemistry articles published in the *Deutsche Zeitschrift für Philosophie* was larger than the number of articles appearing in the same period in *all* English language philosophy journals. The number appearing in the major Russian journal *Voprosy filosofii* [*Problems of Philosophy*] was about the same.

Chemistry was seen as a prototypical domain that illustrates the dialectic of quantity and quality; already Hegel used the acid/base "dialectic" as one of his major case studies.[44] Hegel's point of the dialectics of quantity and quality had been taken up by Engels in his *Dialectics of Nature*. This book consists of unfinished notes. The important historian of science B.M. Kedrov used extensive texts from Engels' *Nachlass* and added parts from Engels's other publications and from the Marx-Engels correspondence, as well as brief connecting texts, so that the whole became unified.[45] Engels had been strongly influenced in his view on the natural sciences by Carl Schorlemmer, the first professor of organic chemistry in Britain, elected FRS in 1871, and also the first well-known Marxist natural scientist, friend of Marx and Engels. This explains the significant presence of chemistry in the *Dialectics of Nature*, even more so in the extended "Kedrov"-version. This "historical" aspect of the connection between dialectical materialism and chemistry was stressed by Kedrov in numerous publications. Kedrov opposed any form of strict reductionism; physics and chemistry are "both separate and together". This is the principle of subordination and objectivity. The irreducibly macroscopic character of typical chemical phenomena was stressed; e.g. reaction velocity only makes macroscopic sense. That chemical laws had a higher "specificity, complexity, and individuality" was also used to argue against reductionism. Kedrov and his associates rationalised the history and theory of chemistry into a number of stages (somewhat similar to the views of Bachelard mentioned above). Starting from the premise that chemistry is simultaneously a science and a production technology, properties of substances are associated with (1) only elemental composition, to which are added in the course of time (2) molecular structure, (3) thermodynamic and kinetic reaction conditions, (4) capacity of self-organisation (Kuznetsov 2006).

In the GDR much was written on the relation between physics and chemistry.[46] In the terminology

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[43] For original sources for this section see van Brakel (2000, 22-27).

[44] For the present purpose dialectical materialism can be taken as the view that [i] everything that exists consists of matter-energy, [ii] this matter-energy develops in accordance with universal laws, [iii] knowledge is the result of a complex interaction between human(s) and their 'external' world (but both humans and their external world are part of the same material world).

[45] Kedrov's many source books on Mendeleev (in Russian) are required reading for any historical research on Mendeleev's discovery of the periodic law. For an overview of Kedrov's work in the history of chemistry and his active role in bringing large delegations of Russian philosophers of science to meetings of the ICLMPS see contributions to special issue of *Russian Studies in Philosophy*, 44 (3) (2005/6).

[46] For a detailed insider's overview of the institutional rise of philosophy of chemistry in the GDR see Laitko (1996). A bibliography of several hundred items has been prepared by Joachim Schummer (see *Hyle* webpage). See also Schummer (2006: 23-24).

of Engels and Kedrov the question was: what is specific to the chemical form of movement? In brief the conclusion reached was that the subject of chemistry is a set of laws, governing "chemical forms of movement" and the transformation of chemical matter. Each chemical transformation corresponds to a chemical law. It was argued that (chemical) "transformation of matter" includes polymorphous transformations and radioactive decomposition, leading to an extensive discussion on the precise definition of chemistry, rephrasing Engels' definition of chemistry as the science of the qualitative changes of bodies that occur under the influence of changes in their quantitative composition and structure.

Many publications appeared drawing negative conclusions concerning the reduction of chemistry to quantum mechanics (via quantum chemistry). It was argued that the chemical and quantum mechanical structure of molecules should be distinguished. The connection between the valence-structure method and classical chemical formulae is discussed, as too is the underlying issue of "model." Because quantum mechanics in its standard Copenhagen interpretation was seen as undermining materialistic principles, chemistry became the "first science" to deal with the material properties of the world. In this literature *both* the idea that chemistry was qualitatively different from physics in some absolute sense *and* the idea that chemistry could be reduced to physics via quantum chemistry, was regarded as a fetish. The relation has to be understood dialectically as two things that can be unified and in contrast at the same time.

resonance and politics

An extra stimulus for the interest that developed in Eastern Europe in the philosophy of chemistry may have been an article in *Voprosy filosofii* in 1949 by Tatevskii and Shakhparanov.[47] They argued that "the physical theory of resonance is erroneous and the philosophical setting of its authors and propagandists is Machistic" and "hostile to the Marxist view".[48] Around the same time (1946-1949) Chelintsev, a professor of chemical warfare at the Voroshilov Military Academy and a mediocre chemist, attacked Pauling's resonance theory of aromatic organic compounds and proposed an anti-resonance benzene theory. Apparently Chelintsev had Lysenkoistic aspirations–though he was not successful in this respect. Also in 1949 Y. Zhdanov published a review of Butlerov's Collected Works,[49] in which he criticised the most influential supporters of the theory of resonance in the USSR, Syrkin and Dyatkina, of ignoring "the best achievements of Russian and Soviet science." There is no consensus as to the relative importance of these events for what is not under dispute: a hectic period of two years during which the political correctness of resonance theory was discussed by both chemists and philosophers in the USSR.[50]

The theory of resonance presents a possible problem for materialism in the following sense. How could something ("resonance") that has no material base in a particular molecular structure be the cause

[47] For original sources for this section (including citations) see van Brakel (2000, 27-34).
[48] 'Machistic': referring to Lenin's crititicism of Mach in his chief philosophical work *Materialism and Empirio-Criticism* (1st Russian edition 1909).
[49] Zhdanov was chemist and head of the Department of Science of the Central Committee of the Communist Party.
[50] Pechenkin (1995) describes the episode as (merely) a "religious rite" in science. For again another view see Vermeeren (1986).

of anything? Quotations from publications of Pauling and in particular Wheland, who had spoken of "merely intellectual constructions," and "does not correspond to any intrinsic property of the molecule itself" in connection with resonance, were reiterated over and over again in discussions among chemists in Moscow that reached their height in 1951.[51]

The issue fell on fertile ground, not so much because of the principles of dialectical materialism,[52] but because there had been priority disputes since 1863 about the originators of the theory of chemical structure (Butlerov, Couper and Kekulé), in particular between German and Russian historians. That in English publications the name of Kekulé dominates, Couper may be mentioned briefly and Butlerov often not at all seems to be an obvious bias. On the other hand, it is equally wrong to claim that Butlerov is the true creator of the theory of chemical structure.[53] Probably it is fair to say that Butlerov, Couper, and Kekulé between them made all the important contributions but, because they knew each others work and met one another on their journeys, a ranking in terms of priority doesn't make much sense. It might be added that Butlerov and Kekulé were personal friends and as far as is known did not quarell about priorities.

In Moscow two conferences were held in 1950 and 1951 at the Institute of Organic Chemistry of the USSR Academy of Sciences. At both conferences, Chelintsev's "new structural theory", was decisively, and with little discussion, rejected as worthless. At the level of chemical research the difference between "bourgeois" resonance theory and the continuation of the "great tradition of Butlerov" amounted to no more than substituting "mutual influences" for "resonance". When Stalin died in 1953 the rhetoric disappeared. In 1958 Pauling was elected honorary member of the Academy of Science of the USSR. (Pauling had also written on "life and death in the atomic era".) In November 1961 Pauling gave a lecture entitled "The theory of resonance in chemistry" at the Institute of Organic Chemistry of the Academy of Science in Moscow to an audience of about twelve hundred people. The lecture was translated and published in a Russian journal, after which Pauling became the most admired Western chemist in the Soviet bloc.

That this example of the politicisation of science had more to do with nationalism than with dialectical materialism is confirmed by the fact that in the GDR, the general issue of the significance of the development of quantum chemistry was often discussed, but the Russian hype about Butlerov and "resonance" had little impact – after all, Kekulé was considered German.[54]

Stork (1963) completely rejects the Russian accusation that resonance theory as developed by Pauling, Wheland, and Ingold fails both empirically and philosophically. However, it should be noted that these criticisms (in the GDR) of the events in Moscow appeared well after the hype was over in the USSR. Furthermore, as Brush (1999: 268) correctly remarks: "For chemists in the West, the apparent

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[51] The debate in Russia could be followed by readers of the *Journal of Chemical Education*, 29 (1952) 2-15; 31 (1954) 504-514. The journal also published an article of the Russian historian of science G.V. Bykov on the importance of Butlerov (39, 1962, 220-224).

[52] The British marxist Haldane (1938, 91-92) had referred to "resonance energy" and "the phenomenon of tautomerism" as "a beautiful example of dialectical thinking, of the refusal to admit that two alternatives ... are necessarily quite exclusive."

[53] On the ignis fatuus of Butlerov's theory of chemical structure see Weininger (2000).

[54] In the GDR one was more concerned with highlighting the significant contributions of German chemists; for example heralding J.B. Richter as the pioneer of modern stoichiometry. An earlier conflict with nationalistic overtones was that between Duhem and Ostwald concerning the relative importance of Stahl and Lavoisier (Bensaude-Vincent 2005, 631).

absurdity of the Marxist ideological critique obscured a significant difference between VB and MO." According to Brush the molecular orbital theory permits a more realistic interpretation than the valence bond (or resonance) theory. However that may be, reflection on resonance hybrids, tautomerism, the "riddle of benzene," and such like is still a relatively neglected theme in the philosophy of chemistry.

With the decline of dialectical materialism as a political force, discussions on the philosophy of chemistry in Eastern Europe disappeared.[55] While philosophy of science in the tradition of logical empiricism was interested in what Kant called proper science, i.e. exact (mathematised, if possible axiomatised) science, under dialectial materialism in Eastern Europe there was more room for the philosophy of the science(s) of different kinds of matter (though still not very much).

birth of philosophy of chemistry

Since the 1960s many different strands of philosophy of science have emerged in mainstream analytic philosophy of science. First, interest arose in historical case studies to provide arguments for and against the rationality of scientific progress or development, both within philosophy of science "proper" and in the sociology (or anthropology) of science. At the same time the number of papers in the history of chemistry that included philosophical considerations increased considerably. As a result, philosophical reflection on chemistry increased, roughly in proportion to the number of "major events" in the history of chemistry. Typically in Kuhn's *The Structure of Scientific Revolutions* (1962), Boyle, Dalton, Lavoisier, and Priestley figure prominently. As a consequence of the increased interest in case studies, but also for other reasons, an interest developed in the experimental side of natural science, as a reaction against the bias within philosophy of science towards (formal) theory. This also favoured the appearance of more chemical case studies. In Hacking's *Representing and Intervening* (1983) there are discussions of Boyle, Dalton, Davy and Lavoisier, as well as references to Berzelius, Brønsted, Kekulé, Lewis, Pasteur, Prout, and von Liebig. In Latour's *Science in Action* (1987) there are more references to Crick, Mendeleev, and Pasteur than to Einstein, Newton and Copernicus. Altogether, in the period 1960-1994 there were about forty publications concerning chemical case studies in main stream journals.[56] About half of them were on oxygen replacing phlogiston.[57] The chemical revolution takes on extra significance in this development because it has been argued that it should not be seen as "an empirical confirmation of Kuhn's theory, but rather as an indication that the chemical revolution is a constitutive part of it" Hoyningen-Huene (2008: 101).

These changes in mainstream analytic philosophy of science started to have some impact in restoring the balance between chemistry and physics in philosophical discourse. However the more influential contributions to the debate remain focused on physical case studies. Moreover, many chemical case studies are not concerned with what might be specific for chemistry. Usually they "test" positions in general philosophy of science ("models" of Popper, Lakatos, Laudan, Hacking, Latour, etc.). Polany's *Personal Knowledge* (1958) is one of the influential books instigating this historical and experimental turn, but it contains surprisingly few comments on chemistry, although he considered

[55] In the 1980s cooperation between German philosophers from the west and the east became possible, leading to joint publications; an example is the contribution of Pälike (1984) on Schelling's philosophy of chemistry.
[56] For selected references to case studies in this period see Table 1-11 in van Brakel (2000, 36).
[57] For references see McEvoy (2000).

chemistry and physics "two forms of existence". Bunge is a rare exception of a philosopher of science in this period who made explicit (though exceptionally little) room for chemistry in his philosophy of science.[58]

In retrospect, a number of more or less independent developments (and individuals) can be seen as having provided the right context for the eventual emergence of the (sub)discipline of philosophy of chemistry in the mid 1990s. Without claiming to be complete, the following can be mentioned.[59]

In the period 1986-1993, publications on themes in the philosophy of chemistry started to appear with some regularity in main stream philosophy of science journals (with contributions of Akeroyd, Christie, Ramsey, Scerri, van Brakel, and others). Perhaps the first journal in which papers on the philosophy of chemistry were published with some regularity was the Italian journal *Epistemologia* (Del Re, Lévy, Liegener, Mosini, Villani).

Independently from developments in philosophy (of science) and reflections on quantum chemistry by philosophers in the GDR (Buttker, Fuchs, Haberditzl, Laitko) and elsewhere (Bogaard, García-Sucre & Bunge, Lévy), publications of theoretical chemists appeared raising issues concerning the complexity of quantum chemistry, which from a philosophical point of view could be seen as undermining simplistic reduction models (Aquilanti, Claverie & Diner, Del Re, Hartmann, Primas, Sutcliffe, Woolley). The issues raised in these publications are still in the process of being sorted out.

The materialist turn in the history of science already mentioned led to philosophically relevant studies of the history of chemistry as the prototypical material science (Bensaude-Vincent, Klein, Nye, Stengers).

In journals such as *Journal of Chemical Education* occasionally brief articles appeared touching on philosophical themes (Benfey, Pauling, Scerri, Weininger), for example a discussion in the early 1990s on the reality of orbitals involving many participants.[60]

In addition to names mentioned above and in previous sections a few miscellanea still need to be added; contributions from the side of process philosophy (Earley), phenomenology (Ströker), structuralism in the philosophy of science (Balzer et al., Hettema & Kuipers, Lauth) and, rather independently from all other developments, publications on the language of chemistry and aesthetic features of molecules (Dagognet, Hoffmann, Laszlo).

In the Netherlands there were attempts to "start" philosophy of chemistry in 1981.[61] Although a couple of publications resulted (van der Vet, Zandvoort), including contributions to a 1986 Symposium issue of *Synthese* (van Brakel, Vermeeren), there was however little follow up.

Early interest in the philosophy of chemistry in various countries was often tied to meetings with a predominantly historical orientation. In Italy, the first meeting of the *Convegno Nazionale di Storia e Fondamenti della Chimica* took place in 1985. By 1993, more or less regularly, there were meetings on the history and philosophy of chemistry in several countries

Interest at various places in Germany was brought together in the establishment of the *Arbeitskreis*

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[58] See Bunge (1982) and two brief chapters on "chemism" in volume 4 and 7 of his *Treatise on Basic Philosophy* (1985).

[59] In the list below only names are given of the authors of relevant publications. Most references can be found in van Brakel (2000) or in the bibliography on the *Hyle* webpage. See also Schummer (2006) for discussion.

[60] See citations and references in Table 5-9 of van Brakel (2000, 137).

[61] See *Chemisch Magazine* (The Hague), October 1981, pp. 591-598.

Philosophie und Chemie, which was founded at a meeting in Coburg (Germany) in June 1993. At the same time the first *Erlenmeyer-Kolloquium der Philosophie der Chemie* took place in November 1993. Before the year 2000 three monographs on the philosophy of chemistry appeared in German (Schummer, Hanekamp, Psarros).

There seems little doubt that the break through towards the emergence of a philosophy of chemistry took place in the mid-1990s, underscored by a range of "facts". At conferences such as the International Congress of Logic, Methodology and Philosophy of Science occasional philosophy of chemistry already appeared on the program in the 1970s, but only in the 1990s would there be more than one paper on philosophy of chemistry appearing on each program.[62]

Passing over the first meetings on "philosophical problems in chemistry" in the GDR and USSR, which took place in the 1960s,[63] and meetings on the history of chemistry in numerous countries, in March 1994 the *First International Conference on Philosophy of Chemistry* took place in London, followed a month later in Karlsruhe by *Tagung Philosophie der Chemie: Bestandsaufnahme und Ausblick*. In October of that year the American *Philosophy of Science Association*, organised for the first time in its history a colloquium on the philosophy of chemistry during its biannual congress. In November the *Second Erlenmeyer Kolloquium* on the philosophy of chemistry took place at Marburg. In December 1994 the meeting *Riflessioni Epistemologiche e Metodologiche sulla Chimica* was held in Rome. Contributions to the last four conferences mentioned were published in Proceedings appearing in the period 1994-1996.

In 1995 the journal *Hyle: An international Journal for the Philosophy of Chemistry* published its first volume (in electronic form) and in 1997 it also appeared in printed form (editor: Joachim Schummer). The *International Society for the Philosophy of Chemistry* was formally established at an international symposium on the philosophy of chemistry and biochemistry held at Ilkley (U.K.) in July 1997. Again in 1997 a special issue of *Synthese* on the philosophy of chemistry came out. In 1999 the first issue of *Foundations of Chemistry* appeared (editor: Eric Scerri).

As to the future, it remains to be seen whether present philosophy of chemistry will narrow down to becoming a proper part of mainstream "analytic" philosophy of science or whether it will further broaden its present scope of incorporating all philosophical traditions, both present and past, which claim to have something to say about chemistry or the transformation of substances.[64]

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[62] As Vihalemm (2004, 9n) has pointed out, contributions to the 8th ICLMPS are missing from Table 1-13 in van Brakel (2000, 38).

[63] For early work on philosophy of chemistry in Estonia during this period see Vihalemm (2004).

[64] For some interesting proposals concerning which themes to include in the infancy and maturity of the philosophy of chemistry see Schummer (2006: 26-34).

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