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Kant and the tradition of axiomatic chemistry

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ABSTRACT

In the *Metaphysical Foundations of Natural Science*, Kant famously argues that chemistry is not a proper science because chemistry does not allow for the application of mathematics. Although existing work on Kant and chemistry has greatly clarified many aspects of Kant's views on chemistry, a contextualized account of Kant's views on chemistry in relation to the chemistry books of his day is still a desideratum of Kant scholarship. In this article, I relate Kant's views on chemistry to the views of Stahl (1659-1734), Wiegleb (1732-1800), Erxleben (1744-1777), Weigel (1748-1831), Lavoisier (1743-1794), and Gren (1760-1798). I will highlight the structure and method of chemistry in Kant's time, arguing that chemistry was construed as ideally an axiomatic science in which non-fundamental judgments are deductively derived from fundamental judgments. Kant's denial that chemistry is a proper science can be fruitfully understood as a denial that chemistry has attained a proper axiomatic form. In line with this interpretation, I argue that it is not the case, as McNulty claims, that for Kant there are chemical laws.

1. Introduction

In this article I will provide a new reading of Kant's claim that chemistry is not a proper science, as Kant argued in the *Metaphysical Foundations of Natural Science* (1786).[1] Kant famously denies that chemistry is a proper science, even though it is a systematic rational science, because its principles are empirical and it does not allow for the application of mathematics. The status of chemistry in Kant's work has been analyzed in detail by McNulty (2014, 2015, 2017) and Blomme (2015. See also Garcia, 2024; Carrier, 1990). In this article, I expand on these important articles, by noting that standard readings of Kant's views on chemistry have missed one important aspect of the history of chemical thought, namely: the fact that many chemists during the eighteenth century, ranging from Stahl (1659-1734) to Gren (1760-1798), thought of chemistry as ideally an axiomatic science. I show, expanding on the interpretation of Van den Berg and Demarest (2020) of biology during the eighteenth century and the interpretation of Van den Berg (2023) of eighteenth-century medicine, that many chemists thought of chemistry as both an experimental science and as a science that must be axiomatically ordered. Moreover, Kant's conception of proper science can itself be understood in terms of the ideal of an axiomatic science, modelled by the Classical Model of Science (De Jong & Betti, 2010; Van den Berg, 2014). Kant's denial that chemistry is a proper science can then fruitfully be interpreted as a denial that chemistry has attained a proper axiomatic form.

Through relating discussions of eighteenth-century chemistry with the ideal of axiomatic science (De Jong & Betti, 2010), I provide a new perspective on the history of chemistry and Kant's views on chemistry. That chemistry was viewed by its practitioners as ideally an axiomatic science is seldom noted, especially not by Kant scholars. The reason for this is probably that chemistry is widely viewed as an experimental science, and commentators have difficulty in seeing how an experimental science can be an axiomatic science. Van den Berg and Demarest (2020), have, however, with reference to eighteenth-century biology and the philosopher Christian Wolff, showed that many philosophers in the eighteenth century viewed empirical sciences as both experimental and axiomatic. The idea is that in the analytic phase of a science, judgments are discovered empirically and experimentally, which subsequently function as principles from which other truths are logically deduced in the synthetic phase of a science. This conception of axiomatic empirical science, I argue, was also applied to chemistry. I will further show that the ideal of axiomatic science informed every facet of Kant's

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[1] I refer to the *Akademie Ausgabe* (AA) (Kant, 1902), which refers to *Kant's gesammelte Schriften*. Eds. Royal Prussian Academy of Sciences et al. Berlin 1902-. [Translations are from *The Cambridge Edition of the Works of Immanuel Kant*. In particular, I use Kant, 1992, Kant, 1998; Kant, 2004]. References to the *Critique of Pure Reason* are per usual to the A/B edition. See for bibliographic details the reference section.

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views on chemistry, something that has not yet been noted by commentators.

My argument will be as follows. I argue that (i) Kant accepts a conception of axiomatic science, modelled by the Classical Model of Science of De Jong and Betti (2010), according to which a proper axiomatic science is deductively ordered and we have *knowledge* of all judgments of a science. Kant's denial that we have knowledge in the strict sense of chemical judgments is thus based on his axiomatic conception of science. (ii) Kant's denial that chemistry is a proper science must be related to a discussion of what constitute proper fundamental principles of an axiomatic science such as chemistry. Kant argues that the merely empirical principles of chemistry do not ground a proper science, since only a priori principles make knowledge possible. Such a priori principles of a natural science are supplied, among others, by mathematics, which is needed to ground knowledge of determinate individual natural things (which is not supplied my metaphysics). Hence mathematics makes knowledge possible in natural science. Since chemistry does not allow for the application of mathematics, it does not produce knowledge and is not a proper axiomatic science.

Moreover, I further argue that (iii) Kant's denial that chemistry allows for the application of mathematics means that he did not think we could reason deductively about phenomena in nature as Newton had done with the help of mathematics in physics. For Kant, mathematics is one way (though not the only way) to establish deductive order in a science, and this route is not available to chemistry which hampers its becoming a proper natural science. So, to summarize, mathematics makes (a) knowledge in natural science possible and (b) provides a privileged way (though not the only way) to deductively order natural science. Because of (a), containing mathematics is a precondition for a natural science discipline being a proper axiomatic natural science (De Jong & Betti, 2010), which chemistry is not. Finally, I argue, opposing McNulty (2015), that in line with the idea that chemistry is ideally an axiomatic science, Kant did not assign the status of laws to chemical regularities.

My argument expands on the important analyses of Van den Berg (2014) and McNulty (2014). McNulty (2014) analyzes Kant's claim that chemistry does not allow for the application of mathematics as involving two distinct claims: (x) we "must think of the application of mathematics to a proper natural science as requiring a coordination of the mathematical and natural" (2014, p. 399) and (y) this coordination must be a priori grounded by a priori (metaphysical) principles (2014, p. 405). Claim (x) has been made by Van den Berg, 2014. See for a less complete earlier account, Van den Berg, 2011). Influenced by Friedman's (1992) account of Newton's use of mathematics in the deduction of the law of gravitation, as well as Harper's (2002) account of Newton's mathematics, van den Berg argued that Kant thought, following Newton, that mathematics provides a priori models of physical phenomena (thus, mathematics is coordinated with nature, in McNulty's terms. On Newton, see Cohen, 1980, 1999). Moreover, mathematics fulfills an epistemic function for Kant in natural science, Van den Berg (2014) argues, insofar as mathematics allows Newton to reason deductively about nature and insofar as mathematics provides a priori principles of natural science. These last aspects of the use of mathematics have not been stressed by McNulty but they will be central to my current paper.

McNulty (2014) correctly stresses that van den Berg does not adequately stress that (y) mathematical constructs must also be a priori grounded by a correct metaphysics. Blomme (2015, p. 491, p. 499) likewise argues that chemistry misses a correct metaphysics of corporeal nature. I will, inspired by McNulty (2014) and Blomme (2015), argue in this paper that the chemistry of Kant's time during the writing of the *Metaphysical Foundations* (1786), is to a large extent Stahlian chemistry which comprises a combination of the chemistry of principles and the corpuscular mechanical chemistry (Carrier, 1986, pp. 1–17). This provides a historical argument for Kant to deny chemistry the status of proper science. Kant believed that the mechanical natural philosophy does allow of mathematization, but is based on a faulty metaphysics, which implies that the mathematization of mechanical chemistry will also be faulty. Hence, chemistry in the Stahlian sense cannot be a proper science. Finally, I will argue, opposing McNulty (2015), that Kant does not believe that there are chemical laws.

There is the question of whether Kant denied that chemistry could not even in principle become a proper natural science or merely that the chemistry of his day could not do so. (mostly taken to be Stahlian chemistry even though Kant did adopt Lavoisier's chemistry toward the end of his life). I will not give a detailed answer to this question (see for discussion McNulty, 2014, 2016; Blomme, 2015) but am inclined to read Kant as mainly targeting the chemistry of his day. In the *Metaphysical Foundations*, Kant articulates, as Breitenbach (2022) has shown, a normative conception of proper science that should be achievable for sciences that are not yet proper sciences and he makes clear that the lack of proper mathematicization of chemistry is a feature of the chemistry of his day. All of this suggests that eventually chemistry can adopt the status of a proper natural science.

The structure of the paper will be as follows. In the second section, I will more precisely explain my use of the concept of axiomatic science, explaining that I use the concept of axiomatic science to refer to de Jong and Betti's Classical Model of Science (2010). I will stress that the concept of axiomatic science involves a concept of a science that is deductively ordered and a concept of science in which we have *knowledge* of all fundamental and non-fundamental chemical judgments. In section three, I will provide an overview of methodological views of chemists during the eighteenth century, ranging from Stahl (1659-1734) to Gren (1760-1798). I will argue that many of these chemists viewed chemistry as ideally an axiomatic science. In the fourth section, I will argue that Kant followed Newton in taking mathematics to provide a priori principles of natural science and that mathematics enables deductive reasoning concerning natural phenomena. Since chemistry does not allow of the application of mathematics, it follows that chemistry lacks a priori mathematical principles and that one way to deductively order the contents of chemistry is unavailable. I will further argue that Stahlian chemistry, which as a species of mechanical philosophy is partly mathematizable, is based on faulty metaphysical assumptions and that hence any mathematization of Stahlian chemistry is faulty. Finally, in the fifth section, I will discuss the nature of chemical principles, the empirical principles of chemistry, and the status of chemical elements as Kantian ideas of reason, and argue that Kant does not believe in the existence of chemical laws (contra McNulty).

2. Axiomatics and the Classical Model of science

In this paper, when I refer to the concept of axiomatic science, I will always refer to a traditionally Aristotelian conception of proper science modelled by De Jong and Betti (2010) as the Classical Model of Science. According to the Classical Model, a proper science is a system *S* satisfying the following conditions:

(1) All propositions and all concepts (or terms) of *S* concern a *specific set of objects* or are about a *certain domain of being*(*s*).
(2a) There are in *S* a number of so-called *fundamental concepts* (or terms).
(2b) All other concepts (or terms) occurring in *S* are *composed of* (or are *definable from*) these fundamental concepts (or terms).
(3a) There are in *S* a number of so-called *fundamental propositions.*
(3b) All other propositions of *S follow from* or *are grounded in* (or *are provable* or *demonstrable from*) these fundamental propositions.
(4) All propositions of *S* are *true.*
(5) All propositions of *S* are *universal* and *necessary* in some sense or another.
(6) All propositions of *S* are *known to be true.* A non-fundamental proposition is known to be true through its *proof* in *S.*

(7) All concepts or terms of *S* are *adequately known*. A non-fundamental concept is adequately known through its composition (or definition) (De Jong & Betti, 2010, p. 186).

De Jong and Betti do not, of course, claim that sciences should follow these conditions. Rather, they claim that this normative conception of proper science has been widely influential throughout history through its wide-spread adoption by philosophers and scientists. The Model has been abstracted from the conceptions of science found in Aristotle's *Posterior Analytics*, the *Port-Royal Logic* of Arnauld and Nicole, and the *Wissenschaftslehre* of Bolzano (De Jong & Betti, 2010, p. 187. Van den Berg, 2021, p. 264). According to De Jong and Betti (2010), the model was also adopted by Wolff, Kant, and Frege, and was only widely abandoned after Frege (see on Kant's endorsement of the Classical Model (Van den Berg (2014)). Note that according to de Jong and Betti although the Classical Model was widely adopted before Frege, it was not universally adopted. As Van den Berg and Demarest (2024) make clear, philosophers such as Crusius and philosophers standing in the tradition of Crusius thought that sciences such as physics (like many other sciences) are predominantly *probable* sciences, and thus did not think that physics provides *knowledge* in the strict sense, i.e., certain cognition that is true and known to be true (conditions 4 and 6 of the Model). This led Crusius to frame alternative conceptions of science (note that one can also, of course, accept the Model as an ideal and claim that many sciences are still probable or hypothetical, and thus fall short of the ideal).

A few remarks on the Model are in order. Note that, first of all, the Classical Model is stronger than modern conceptions of axiomatics. Conditions (4)-(6) are not required by modern conceptions of axiomatics, where people postulate syntactic or semantic consistency. However, conditions (4)-(6) were typically endorsed by (early) modern followers of the Aristotelian conception of science, such as Wolff and Kant (Van den Berg, 2021, p. 265). Note also that different followers of the Model can have different conceptions of how to construe the principles of a science. In a Kantian understanding of the Model, the fundamental principles of a science are synthetic a priori judgments or principles, and this is allowed for by the Model. Thus, it is not the case that fundamental principles are self-evident truths (this is *one* understanding of the term axiom, but the Model is broader than this understanding and accommodates multiple conceptions of fundamental principles).[2] Finally, I am aware, as one referee noted, that Kant reserves the term axiom for intuitive principles of mathematics. However, this does not mean he does not accept the Model, for as Van den Berg (2014, chapter 2. See also Van den Berg, 2021) has persuasively argued, he does accept the idea that sciences (including non-mathematical sciences) have fundamental principles and that non-fundamental judgments are derived from these fundamental principles (condition 3 of the Model).

Now, I am arguing for the claim that when Kant denies chemistry the status of proper natural science, he is in effect arguing for the claim that the chemistry of his day does not satisfy the conditions of proper axiomatic science of the Classical Model. More precisely, my claim will be that when chemists in the eighteenth century described an ideal of proper science that chemistry should satisfy, they had in mind something like the Classical (axiomatic) Model. This is a novel claim since many commentators on eighteenth-century chemistry, and especially the scholars dealing with Kant and chemistry, have not related chemistry to an axiomatic ideal of science. This is probably because chemistry is an empirical experimental science, and commentators have difficulties in seeing how an empirical and experimental science can also be axiomatic. However, if we consider the chemists of Kant's day, we will clearly see that they endorsed the idea that chemistry should have fundamental principles and that non-fundamental judgments are deductively derived from these fundamental principles (condition 3 of the Model). The fact that chemistry is an experimental discipline does not pose a problem for conceptualizing chemistry as an axiomatic science. As Van den Berg and Demarest (2020) have shown for biology in the eighteenth century, another empirical and experimental science, sciences could incorporate experiments (often in the analytic part of the method of the science), while subsequently demanding that the results of experiments were presented in a deductive fashion (often in the synthetic part of the method of a science). Moreover, Van den Berg and Demarest (2020) show that such conceptualizations of experimental science were common among followers of axiomatic science, i.e., the Classical Model, such as Christian Wolff, who explicitly combined an empiricist outlook on empirical science with an axiomatic normative ideal.

Importantly, the fact that chemistry is deductively ordered is not sufficient for it to be an axiomatic science, for as we have seen the Model is much broader. If chemistry is to satisfy the conditions of the Model it is also required that the propositions or judgments of a science are in some sense necessary (condition 5) and that we *know* the propositions of a science (condition 6). It is here, I submit as a novel claim, that Kant himself, even though he accepted the Model as an ideal of science, thought that chemistry was not yet a proper science (hence the Model is an ideal not yet satisfied). The chemists, we shall see, often did not explicitly mention condition 5 and 6 of the Model but recounted the fact that chemistry was a proper and fully empirical or experimental science. The fact that chemistry was fully empirical and experimental was tied, as we shall see, to Stahl's belief that we do not have knowledge of the ultimate (a priori) principles of chemical phenomena. Hence, Stahl accepted the full conception of axiomatic science, including the claim that we must have knowledge of all judgments of chemistry, and denied that the knowledge postulate of the Classical Model (condition 6) is satisfied for chemistry.[3] Hence, chemistry is not a proper science. Similarly, Kant defines knowledge in natural science as involving *apodictic certainty*, which implies that we are justified in asserting the necessary truth of a judgment (AA 4: 468. Van den Berg, 2021, p. 266). This condition is only met for empirical sciences, Kant argues, if empirical judgments are partly proven on the basis of a priori principles (Ibid. See also Van den Berg, 2014, p. pp. 35-37). However, since chemistry lacks a priori principles, we do not have knowledge of chemical judgments in the strict sense. Hence, like Stahl, Kant argued that the knowledge postulate of the Model is not satisfied and chemistry is not a proper science. We thus clearly see that Kant's denial of chemistry as a proper science follows from his axiomatic conception of science. Note that I argue that Kant's denouncement of chemistry as an improper science follows from its fully empirical and experimental status, which was acknowledged by both Kant and the chemists of his day. Thus, to a certain extent Kant was merely summarizing well known conceptions of chemistry. Finally, note that in this paper I argue for the novel claim that Kant's claims that chemistry lacks a priori mathematical and metaphysical principles, and that subsequently chemistry is not a proper science, must also be related to the ideal that a proper natural

[2] Betti and Van den Berg (2014) make clear that the Model describes a core conception of proper science, shared by many authors, but accommodates many different *varieties* of this core conception (differing among different authors). Thus, while the Model describes the *core conception* that a science must have fundamental principles, the question whether these principles are synthetic a priori judgments or self-evident (analytic or identical) judgments is one where followers of the Model might have *different opinions*.

[3] In this article, I will thus mainly focus on conditions (3) and (6) of the Classical Model. A full evaluation of all the conditions of the Classical Model in relation to the views of the chemists of Kant's day is beyond the scope of this paper. I suspect, however, that while several chemists accepted the model as an ideal of proper science, it could be the case that many chemists thought that chemistry contains a lot of hypothetical cognition and therefore does not (yet) satisfy conditions (4)-(6) of the Model However, further research will have to corroborate this suspicion.

science is an axiomatic science. As such, the ideal of axiomatic science is shown to be essential to all facets of Kant's views on chemistry.

3. Chemistry and axiomatics in the eighteenth century: an overview

In this section I will discuss the conception of chemistry of the chemists of Kant's day. This historical context has been previously discussed, in part, by McNulty (2017). McNulty, 2017 discusses the dominant conception of chemistry as a science of the dissolution and decomposition of substances (p. 89), and shows how many of Kant's contemporary chemists define chemistry in terms of the methodological distinction between analysis and synthesis. In addition, he mentions the debate among chemists on whether chemistry was a practical or theoretical doctrine, arguing that Kant took chemistry to be a theoretical doctrine, and that Kant followed the chemists of his day by viewing chemistry as an experimental science. What McNulty does not do, however, is consider the logical structure of the science of chemistry by relating the eighteenth-century conception of chemistry to views on axiomatics. This will precisely be my main aim in what follows. I will argue that chemists of Kant's day viewed chemistry as an axiomatic science, in which non-fundamental judgments are deductively derived from fundamental principles (in a propositional sense), and as a science that produces knowledge. This conception was maintained even though these chemists also viewed chemistry as an experiential science. Chemistry was both deductive and experimental, with experimental results incorporated in a deductive system (see Van den Berg & Demarest, 2020). Finally, a note on the term principle. When I talk of 'principles' in axiomatics, I have in mind fundamental judgments of a propositional form that stand at the basis of a deductive system. The chemists of Kant's time, as a referee has stressed, also had an ontological meaning of the concept of principle, referring to principles as fundamental substances. It is important to remember that these two senses of principle are not clearly distinguished in the modern period. But, importantly, the two senses of principles are thought to correspond to each other: fundamental principles in the propositional sense express fundamental principles in the ontological sense. In what follows, I will make clear in different contexts in what sense I take the term 'principle'.

In his instructive 1983 article on the distinction between theory and practice in the history of chemistry, Christoph Meinel notes that the eighteenth century was a period in which the scientific status of chemistry was actively discussed. This discussion was closely related to debates on the nature and method of chemistry. According to Meinel (1983, p. 121), Robert Boyle (1627-1691) had influentially defined chemistry as an experimental science in the seventeenth century and thought that the theory of chemistry should proceed experimentally. This gave rise to conceptions of chemistry in which the theoretical and practical parts of chemistry were closely connected. According to Pierre Macquer (1718-1784), as Meinel explains (1983, p. 122), theoretical chemistry adopted a logical, systematic, and synthetic axiomatic presentation from simple to complex, whereas practical chemistry opposed systematic exposition. In this context, there was also debate on whether chemistry constitutes a proper science or *scientia*, with Daniel Sennert already proclaiming in the seventeenth century that chemistry was not *scientia* since it did not provide insight into ultimate causes, a proclamation that led to a great deal of debate of which Kant was to become a part. Later in the eighteenth century, Meinel argues (p. 126), the common distinction between theory and practice of chemistry became replaced by a distinction between pure and applied chemistry, a distinction we will also encounter in our eighteenth-century textbooks.

If we turn to the content of eighteenth century philosophy, we can, following the insightful Carrier (2001), note that many chemists in the period preceding Lavoisier followed the chemistry of principles (in the ontological sense). Carrier describes this chemistry as follows:

> The idea was to explain the properties of substances by assuming a number of abstract elements or principles. These principles were supposed to bear properties such as hardness, combustibility, or volatility. Ordinary substances gain their properties by incorporating the corresponding principles, and it is the presence of these principles in the substances that accounts for the properties of the latter (Carrier, 2001, p. 216)

Carrier notes that it was, of course, not the idea to introduce one principle for one property. Rather, the number of principles was restricted and the idea was to explain as much as possible concerning chemical properties in turns of the combination of a limited number of elements (Carrier, 2001, p. 217). The famous chemist Stahl, who Kant largely followed in his critical period, accepted the chemistry of principles and introduced, for example, phlogiston as the principle of combustion, salt as a principle for solidity, density, and weight, and mercury as the principle of metallic properties. In addition, Stahl postulated chemical *instruments*, fire and air, that contribute to initiating and stopping chemical processes (p. 218). Note that I take the chemistry of principles to correspond with an axiomatic conception of science in which science is built on fundamental propositional principles, which correspond to ontological principles. Both reality and science are hierarchically structured, and the axiomatic conception of science is meant to capture an ontological hierarchy in nature.

Carrier (1986, p. 2) makes clear that a counterpart to the chemistry of principles in the modern period was the corpuscular tradition that one can find in Boyle and, combined with the chemistry of principles, in Newton. According to the corpuscular tradition, one should adopt a reductionistic approach according to which all the chemical processes are reduced to the form and motion of the parts of matter. Stahl, as Carrier (1986, p. 5) explains, adopts the chemistry of principles because one can be empirically certain of the nature of chemical principles (in the ontological sense), in contrast to corpuscular parts of matter, which go beyond experience. Thus, the principle of salt is operationalized as, for example, a quantity with weight, density, and solidity, and other empirically accessible qualities. Hence, the chemistry of principles is suited to making an empirical science out of chemistry. Nevertheless, Stahl also adopts aspects of the corpuscular tradition. He takes matter to be composed out of corpuscles and the chemical principles are composed out of atoms with a specific figure and it is the figure of these atoms that determines chemical reactions (1986, p. 6). More specifically (Carrier, 1986, p. 7), Stahl distinguishes principles, mixta, composita, and aggregata. Mixta consist immediately of chemical principles, while composita comprise a higher level of complexity, comprising connections of multiple mixta but also connections of mixta and principles. Next and independently to mixta exist aggregates, which consist of mechanically mixed materials. In aggregates, chemical properties do not play a role. In this way, Stahl integrated corpuscularism and the chemistry of principles.

Let us now turn to the manner in which chemists construed the method of chemistry during the eighteenth century. Stahl (1659-1734), in his *Philosophical Principles of Universal Chemistry* (1730), illustrates the method of chemistry in terms of the combined method of analysis and synthesis: "Universal chemistry is the Art of resolving *mixt*, *compound*, or *aggregate* Bodies into their *Principles*; and of composing *such Bodies* from those *principles*." (Stahl, 1730, p. 1). Next to describing the method of chemistry in terms of the combined method of analysis and synthesis, Stahl clearly argues that the theory of chemistry should be treated axiomatically, even though it is also based on a posteriori experiment and analysis: "Its *Theory*, in *general*, is acquired by *Information*, axiomatically and demonstratively delivered in the synthetical manner." (Stahl, 1730, p. 2). Hence, even though chemistry is an experimental science, it should also be treated axiomatically (on experimental axiomatic science and its possibility in eighteenth-century Germany, see Van den Berg & Demarest, 2020). Finally, it is noteworthy that Stahl defines principles, a posteriori, as those principles (in the ontological

sense) of bodies that we reach in the final stage of analysis. Thus, he writes: "A *Principle* is defined, a priori, that in mix'd matter which *first existed*; and a posteriori, that into which it is *at last resolved*. (Stahl, 1730, p. 4). Principles of chemistry, and here I am referring to principles in the propositional sense corresponding to ontological principles, are always principles discovered empirically by analysis. Consequently, Stahl defines chemical principles as those principles "into which all Bodies are found reducible by the chemical operations hitherto known" (Stahl, 1730, p. 4). For Stahl, then, chemical principles in the propositional sense are empirical, and it was precisely the empirical status of the principles of chemistry (in the propositional sense) that led Kant to deny chemistry the status of proper science.

If we turn to the *Encyclopedia of Diderot and D'Alembert* and consider the article on chemistry from Gabriel-François Venel published in 1753, we find many considerations concerning the nature and method of chemistry that are familiar. First of all, chemistry is defined as an empirical and experimental science that, as yet, lacks a mathematical treatment, an objection that Kant would later also formulate. Thus, Venel writes that calculations done in mathematical physics that we so admire "do not however make it possible to calculate chemical effects, or at least have not led so far to such calculations" (Venel, 1753). In addition Venel takes the combined method of analysis and synthesis to be the true method of chemistry, and notes that true demonstrations in chemistry boil down to decomposing or analyzing a body by means of analysis and then synthesizing or recomposing this body again by synthesis.

> If a Chemist manages to gather back together in an orderly fashion all those principles that he has separated in the same fashion, and if he manages to recompose a body that he has broken down, he has attained a true demonstration of Chemistry. And indeed, the art of Chemistry has reached this level of perfection in several essential areas (Venel, 1753).

Similar to the anonymous author of the dictionary, the German textbook author Christian Weigel (1748-1831), in his *Grundriß der reinen und angewandten Chemie* (Weigel, 1777), took the combined analytic-synthetic method to be the basis of chemistry, and, similar to Stahl, took the principles of bodies (in the propositional sense corresponding to an ontological principle) to be found empirically through the analysis of bodies (1777, p. 2, p. 3). Pure chemistry deals with the (primary) components of bodies, whereas applied chemistry looks at the use of chemistry for specific sciences, arts, and products (1777, pp. 6-7). A very similar conception of chemistry, its nature and its methods was articulated by Johann Christian Wiegleb (1732-1800), in his *Handbuch der allgemeinen Chemie* (1781) (Wiegleb, 1781).

Johann Christian Polycarp Erxleben (1744-1777), known by Kant scholars because he wrote a textbook on physics which Kant used for his lectures, wrote his *Anfangsgründe der Chemie* in 1785 (Erxleben, 1785), and stressed both the fact that chemistry was an experimental science and that it was deductively ordered. Hence, Erxleben attempted to show that chemistry was an axiomatic experimental science. He states that chemistry is based on observations and experiments, from which the chemist deduces through strict logical deductions (*Folgerungen und Schlüsse*) the manner in which bodies are mixed, which knowledge is then again confirmed by new experiments (1785, p. 5). Hence, again, chemistry is both an experimental science and an axiomatic science ordered by deduction. This method is aptly and succinctly described, according to Erxleben, by saying that chemistry adopts the combined analytic and synthetic method (p. 5). Similarly, Friedrich Albrecht Carl Gren (1760-1798), in his *Systematisches handbuch der gesammten Chemie* (1794) (Gren, 1794), described the method of chemistry in terms of analysis and synthesis and also described chemistry, in its theoretical part, as a *science* (*Wissenschaft*) in which we *deduce* truths from *general principles* (in the propositional sense) which truths are based on experience, consequences, and syllogistic inferences (1794, p. 1). Hence, Gren, like his predecessors, stressed that chemistry is a deductive axiomatic science and an experimental science. As Gren also explains, the basis of chemistry is observation and experiment, from which the *theory* is derived through correct (syllogistic) inferences (*Vernunftschlüsse*) (p. 2). Thus, experiment provides empirical truths from which further consequences are derived by means of logical deductions.

Note that the adoption of an axiomatic model of science by chemists is independent of the actual scientific theories that the chemists propounded. Thus, the state of chemical theory adopted by Gren, who published his textbook on chemistry in 1794, is fundamentally different from that of say Stahl and Erxleben, who worked earlier, with many new developments occurring in chemistry during the course of the eighteenth century. Nevertheless, all saw chemistry or chemical theory as an axiomatic science. The same is true for Lavoisier (1743-1794), who, according to a traditional account, caused a revolution in science and chemistry. Lavoisier's rejection of the phlogistic chemistry (of, among others, Stahl) at the end of the eighteenth century has been viewed as a chemical revolution, even though many now take issue with the conceptualization of this revolution (see, for a small sample, Siegfried, 1988; Perrin, 1988; Hoyningen-Huene, 2008; Chang, 2015). I will not enter this debate in this paper. However, what I do want to stress is that, in spite of the dissimilarities between Lavoisier and his predecessors, Lavoisier can also be argued to adopt an axiomatic conception of science.

In his memoirs submitted to the academy (1777), Lavoisier argues that explanations of many chemical phenomena are all *deduced* from a simple principle (in an ontological sense, to which however there corresponds a principle in a propositional sense from which truths are deduced: he posits a principle in the propositional sense as a that clause as a basis for deduction, and within this that clause he names the ontological principle), namely the oxygen principle combined with the matter of heat. The idea of an axiomatic science which deduces many facts from a single principle (in the propositional sense) was adopted by Condillac (Condillac & Bonnot, 1982 [1749], p. 1), who Lavoisier cites approvingly many times in his *Elements of* Chemistry (1802). As Lavoisier puts it in his memoirs:

> In the continuation of the Memoirs that I have just communicated to the Academy, I have reviewed the main phenomena of Chemistry; I have insisted on those that accompany combustion, the calcination of metals, & in general all operations where there is air absorption & fixation. *I have deduced all the explanations from a simple principle*, namely that clean air, vital air, is composed of a particular principle that is specific to it, that forms its basis, & that I have named the *oxygen principle*, *combined with the matter of fire & heat*. Once this principle was accepted, the main difficulties of Chemistry seemed to disappear & dissipate […] (Lavoisier, 1777, 1; Translated by Blomme and quoted in Blomme, 2023, p. 18. Italics are also from Blomme, although he does not relate this quote to an axiomatic conception of chemistry).

Lavoisier's comment perfectly fits an axiomatic conception of science: we explain phenomena in chemistry by *deducing* them from fundamental principles, such as the oxygen principle coupled with the matter of heat (here again principle is taken in the ontological sense to which there corresponds a principle in a propositional sense from which truths are deduced).

We have seen that many chemists throughout the eighteenth century conceived of chemistry as both an experimental and an axiomatic science.[4] Although the principles of chemistry were taken to be empirical,

[4] In written communication, Henny Blomme told me that the axiomatic ideal of chemistry was probably also adopted outside of German speaking countries in the works of for example Boerhaave, Geoffroy and Bergmann. In a future article, I would like to investigate these traditions more fully. In this paper, I restrict myself to giving an analysis of the chemical writers that constituted the immediate context for Kant's works.

discovered by analysis, chemistry was conceived of as a deductive axiomatic science with fundamental propositions from which non-fundamental propositions were deduced by strict logical means. In the next sections, we will see that Kant's denial that chemistry is a proper science is informed by this axiomatic conception of science. At this point, we can, however, ask whether chemists also accepted the idea that chemistry should provide scientific knowledge, capturing condition 6 of the Classical Model and the wide conception of axiomatic science adopted in the modern period. We have seen that chemists affirmed that chemistry is deductively ordered, but what about chemical knowledge? To answer this question we can follow Blomme's (2023) discussion of principles in Stahl, which shows that Stahl viewed chemistry as an incomplete science in which we lack full knowledge. This anticipates, as we shall see, the view of Kant.

Blomme (2023, p. 12) notes that Stahl distinguishes physical principles from chemical principles (here the term principle is primarily taken in its ontological sense, although again these principles correspond to principles in the propositional sense). Physical principles are, according to Stahl, known a priori and express the *essence* of composed bodies (ibid). The empirical, chemical principles are the principles we have talked about so far, functioning as principles of chemistry. As Blomme notes, Stahl argued that physical principles are, at the time when he wrote his tracts, uncertain and unknown. Hence, the idea is that chemistry is an incomplete science. Although we know empirically the chemical principles of chemical phenomena, we do not know the physical principles expressing the essence of matter that ultimately ground the chemical phenomena. In his writings, Stahl limited himself to discussion of chemical principles, although the goal of chemistry was finally to arrive at essential, physical principles (ibid.). The conclusion we can draw from this is that Stahl argued that the knowledge postulate of the Classical Model of Science was not fully satisfied. After all, Stahl said that chemistry is incomplete and that our knowledge is not complete and resolvable to absolutely fundamental principles. Thus, for Stahl, the axiomatic conception of science we have discussed in this paper remains an ideal for chemistry, one of which the chemistry of his day fell short. Blomme rightly notes the strong parallels between Kant and Stahl. I add to Blomme by noting that like Stahl, Kant viewed chemistry as not yet fulfilling the axiomatic ideal of science. Moreover, in the *Metaphysical Foundations* Kant viewed the a priori demonstrable forces of attraction and repulsion of matter as explicating the essence of matter, but he also argued, like Stahl, that these forces do not fully account for chemical phenomena because there is an explanatory gap between the fundamental principles of his dynamics and the specific variety of forces accounting for the specific variety of matter in chemistry (on this gap, see Friedman, 1992; McNulty, 2017 argues that physical laws can never explain chemical phenomena). To conclude: both Stahl and Kant argued that chemistry did not yet satisfy the classical axiomatic ideal of science, and because of this we see that the axiomatic ideal of science played a role in Kant's views on chemistry. In the next section, we will further see how the axiomatic ideal of science shaped Kant's ideas of the role of mathematics in science and chemistry.

4. Mathematics and chemistry

In this section, I will provide an account of Kant's claim that proper science should contain mathematics, on the basis of which he denies that chemistry is a proper science, that is based on state of the art interpretations of Kant of Van den Berg (2014) and McNulty (2014), the latter providing an important improvement on van den Berg's work. Kant's claim that proper science should contain mathematics has, however, been interpreted by earlier commentators, so we shall discuss these earlier commentators first (here I follow the lead of McNulty, 2014).

Körner (1955, p. 81) discusses the anticipations of perceptions and notes that it ensures the applicability of mathematics to psychometrics and econometrics, closely associating mathematization with making measurement possible. Similarly, Brittan (1978) does not very deeply engage with the question of why a proper science requires mathematics, but holds that the axioms of intuition guarantee the applicability of mathematics to objects, and that the phoronomy of the *Metaphysical Foundations* shows how to construct a composition to motions, so that a magnitude can be assigned to them (1978, p. 103). Hence, as McNulty states (2014, n8), Brittan seems to view mathematicization of a concept as the assignment of a metric to a concept, a problematically minimal claim (see on this topic also Nayak & Sotnak, 1995). By contrast, Friedman (2013and 1992) stresses, as McNulty (2014) also notes, the role of construction in mathematics and notes that mathematical constructs represent nature. This reading has influenced Van den Berg (2014) and McNulty (2014) who think that mathematicization requires the coordination of mathematical constructs with natural phenomena, as achieved for example by Newton, as Van den Berg (2014) stresses. However, McNulty rightly notes that van den Berg underplays the fact that mathematical constructs must be based on adequate metaphysical presuppositions. In the following, we will start from Van den Berg (2014) and McNulty's (2014) reading of Kant's claim that proper sciences contain mathematics, to provide a novel reading of Kant's view that chemistry is an improper science.

4.1. Mathematical modelling following Newton

Newton's use of mathematics in natural philosophy has been described as the Newtonian Style by Cohen (1980, 1999). According to this style, Newton starts the *Principia* by considering simplified mathematical constructs, derived from nature simplified. After this, he modifies this simplified construct by continuously comparing the construct with the external world, so that the construct matches the world better. Finally, Newton, in the final stage in book III, applies his constructs to the physical world. (Cohen, 1999, pp. 148-155). See also Van den Berg & Demarest, 2024).

We can illustrate this last stage of the Newtonian Style by looking at a derivation or proof of Newton from Book III of the *Principia*, the book in which he provides his famous deduction of the law of gravitation (here, I follow van den Berg's 2014 analysis of Newton and Kant. See also van den berg, 2025; Van den Berg & Demarest, 2024). In proposition 1 of Book III, Newton wants to prove the proposition:

> The forces by which the circumjovial planets [or satellites of Jupiter] are continually drawn away from rectilinear motions and are maintained in their respective orbits are directed to the center of Jupiter and are inversely as the squares of the distances of their places from that center (Newton 1999, p. 802)

In order to prove the first part of the proposition, Newton refers to phenomenon 1, an empirical proposition, established by astronomical observation, according to which

> The circumjovial planets [or satellites of Jupiter], by radii drawn to the center of Jupiter, describe areas proportional to the times, and their periodic times—the fixed stars being at rest—are as the 3/2 powers of their distances from that center (Newton 1999, p. 797)

Phenomenon 1, together with proposition 2 of book 1, a mathematical or kinematical a priori proposition, provides Newton with his proof for the fact that the satellites of Jupiter are centripetally directed to the center of Jupiter. The kinematical Proposition 2 of book 1 reads:

> Every body that moves in some curved line described in a plane and, by a radius drawn to a point, either unmoving or moving uniformly forward with a rectilinear motion, describes areas around that point proportional to the times, is urged by a centripetal force tending toward that same point (Newton 1999, p. 446).

Note that this is a deductive proof proceeding from one a priori premise (the kinematical proposition 2 of Book 1) and one empirical premise (phenomenon 1) to the conclusion. The proof states (semi-formally) that (i) for all bodies a, it holds that if Aa then Ba (kinematical proposition 2

of Book 1), (ii) for the satellites of Jupiter, A holds (phenomenon 1), hence (iii) for the satellites of Jupiter, B holds (conclusion, first part of proposition 1 of Book III). Here, we thus see how Newton, using an a priori mathematical construct of bodies describing areas proportional to the times, allows scientists to reason deductively concerning phenomena such as the orbits and forces or accelerations governing the satellites of Jupiter. In short: mathematics makes possible deductive reasoning in natural science concerning individual determinate natural objects.

It is important to note that mathematics (which I take to include kinematics) provides a twofold epistemic function in natural science. First, mathematics provides a priori *principles* of proofs in natural science (note that here the term principle is meant in its propositional sense), which also, to be sure, employ empirical propositions. Such an a priori principle is, for example, the mathematical or kinematical Proposition 2 of Book 1 of Newton's *Principia* mentioned above. Second, through providing a priori models of natural phenomena, mathematics enables deductive and quantitative reasoning concerning individual determinate objects. The fact that mathematics, together with metaphysics we might add, provides a priori principles through which we justify cognition in natural science, as Newton's proof above illustrates, secures that we can have *knowledge* in natural science, since empirical knowledge, Kant argues, must be based on a pure or a priori part that justifies the apodictic certainty of physics. As Kant explains this in the *Preface* to the *Metaphysical Foundations*:

> What can be called proper science is only that whose certainty is apodictic; cognition that can contain mere empirical certainty is only knowledge improperly so-called. Any whole of cognition that is systematic can, for this reason, already be called science, and, if the connection of cognition in this system is an interconnection of grounds and consequences, even rational science. If, however, the grounds or principles themselves are still in the end merely empirical, as in chemistry, for example, and the laws from which the given facts are explained through reason are mere laws of experience, then they carry with them no consciousness of their necessity (they are not apodictally certain), and thus the whole of cognition does not deserve the name of a science in the strict sense; chemistry should therefore be called a systematic art rather than a science (AA 4: 468)

Here, Kant argues that proper natural science must be based on a pure a priori part and refers to the fact that the principles of chemistry are empirical to deny chemistry the status of a proper science (with the term principle again meant in its propositional sense). That the principles of chemistry were empirical was commonly acknowledged within eighteenth century Stahlian chemistry, as we have seen in the previous section, since the principles of chemistry were taken to be discovered empirically through analysis. Note that if chemistry also had mathematical principles, such as, as we have seen, Newtonian physics has, then chemistry could justify its cognition on the basis of a priori principles as in physics and we could thus properly speak of chemical knowledge. However, since chemistry lacks mathematical principles, it lacks a priori principles concerning determinate things, and thus there is not chemical knowledge properly speaking.

In order to understand this last point it is important to remark that for Kant, the pure a priori part of natural science is given by *both* metaphysics and mathematics. Now, to be sure, Kant provides a priori *metaphysical* and dynamical foundations for physics, matter theory, and chemistry in the *Metaphysical Foundations*. What is lacking, however, are mathematical a priori principles of chemistry, and this leads Kant to deny the possibility of chemical knowledge. Why natural science must, besides metaphysics, have mathematical a priori principles, is because mathematics, as we have seen in the Newton example, provides through its constructions a priori quantitative principles or models of *determinate individual natural objects*, such as the orbits of the satellites of Jupiter, something which metaphysics cannot deliver since it is concerned with general concepts. It is only mathematics, we might say, that provides a priori models that can be applied to individual determinate natural objects. Natural science, Kant argues, requires such a priori principles of determinate individual objects, and thus requires mathematics. As Kant again puts it in the Preface to the *Metaphysical Foundations*:

> I assert, however, that in any special doctrine of nature there can be only as much proper science as there is mathematics therein. For, according to the preceding, proper science, and above all proper natural science, requires a pure part lying at the basis of the empirical part, and resting on a priori cognition of natural things. Now to cognize something a priori means to cognize it from its mere possibility. But the possibility of determinate natural things cannot be cognized from their mere concepts; for from these the possibility of the thought (that it does not contradict itself) can certainly be cognized, but not the possibility of the object, as a natural thing that can be given outside the thought (as existing). Hence, in order to cognize the possibility of determinate natural things, and thus to cognize them a priori, it is still required that the intuition corresponding to the concept be given a priori, that is, that the concept be constructed. Now rational cognition through construction of concepts is mathematical. Hence, although a pure philosophy of nature in general, that is, that which investigates only what constitutes the concept of a nature in general, may indeed be possible even without mathematics, a pure doctrine of nature concerning determinate natural things (doctrine of body or doctrine of soul) is only possible by means of mathematics (AA 4: 470)

To summarize Kant's first argument for denying chemistry the status of a proper science. All proper natural science must have mathematical a priori principles (in the propositional sense) of determinate individual objects that justify *knowledge* in natural science, for empirical principles do not justify knowledge properly so-called, which is apodictically certain and thus requires a priori justification. Hence, since chemistry does not contain mathematics it is an improper natural science.

We must note that in the Newtonian derivation given as an example above we reason from both a priori and empirical principles. Hence, the conclusion is empirical, but can, according to Van den Berg (2014, p. 37), nevertheless qualify as certain knowledge, because it is proven on the basis of some a priori principles. Kant, van den Berg submits, acknowledges this possibility in the Jäsche Logik when he says:

> […] our cognitions can concern objects of experience and the certainty concerning them can still be both empirical and rational at the same time, namely, insofar as we cognize an empirically certain proposition from principles a priori (AA 9: 71. See also Falkenburg, 2000 who stresses this quote in her analysis of knowledge in the appendix)

Thus, we can take the following conception to be articulated in this quote: "A judgment A is cognized on the basis of (proven from) a priori principles if A is derivable from a collection of judgments which contains both a priori principles and empirical judgments" (Van den Berg, 2014, p. 37). Michael Friedman, in his famous analysis of Kant's interpretation of Newton's deduction of the law of gravitation, which is also proven on the basis of both a priori and empirical premises, also acknowledges this type of justification, noting that the law of gravitation is a mixed law that we can assign material necessity and certainly qualifies as knowledge (Friedman, 1992, p. 167)

Kant's second argument for denying chemistry the status of a proper science is that through mathematics, as we have once again seen in the Newton example, we can reason *deductively* in natural science concerning natural phenomena. Hence, the deductive form of a natural science can be established by using mathematics. Now, (Van den Berg (2014) has convincingly argued that Kant took proper science to be axiomatic science, and in this paper we have seen that many chemists in the eighteenth century agreed: proper chemical science is axiomatic chemistry. Hence, the fact that chemistry was a non-mathematical science was a problem for establishing chemistry axiomatically. Although, it must be stressed, it is possible to arrange chemistry in a deductive

fashion without the help of mathematics, we cannot give, as Newton did, deductive demonstrations concerning natural phenomena, and thus our capacity to reason deductively is hampered by the fact that chemistry is a non-mathematical science. This is another problem for viewing chemistry as a proper science. Note that in this context, Kant provides precisely the fact that chemistry does not have Newtonian mathematical laws that determine the intensity of a force or motion relative to distance and other variables such as mass or density as a reason for denying chemistry the status of a proper science. As Kant puts it:

> So long, therefore, as there is still for chemical actions of matters on one another no concept to be discovered that can be constructed, that is, no law of the approach or withdrawal of the parts of matter can be specified according to which, perhaps in proportion to their density or the like, their motions and all the consequences thereof can be made intuitive and presented a priori in space (a demand that will only with great difficulty ever be fulfilled), then chemistry can be nothing more than a systematic art or experimental doctrine, but never a proper science, because its principles are merely empirical, and allow of no a priori presentation in intuition (AA 4: 470-471).

Hence, in his denial that chemistry is a proper science, Kant again took the Newtonian mathematical style as a paradigm for proper natural science.

Note that Kant's claim that chemistry is not proper science is not based on the idea that the chemistry of his time lacked mathematical or quantitative treatment of its phenomena altogether. As McNulty has noted, Kant was exposed to developments in quantitative chemistry. For this reason, Kant must have believed that quantitative treatments are insufficient for chemistry to become a proper science. Rather, what is required for chemistry to become a proper science is, according to McNulty (2014, p. 395), *mathematical construction* of chemical concepts. As Blomme (2015) similarly argues, a metaphysics of nature must provide concepts that are mathematically constructible, and it is motion that is the most fundamental determination of matter, hence we must be able to construct a priori (representations of) motions. I agree with both McNulty and Blomme and would argue that this supports my reading of mathematization in Kant as Newtonian mathematical modelling. After all, Newton provided a priori models (constructions) that a priori represent motions of natural objects, and hence when Kant laments the lack of mathematization in chemistry, he probably had in mind the lack of a priori Newtonian mathematical models of nature, which makes chemistry an improper natural science.

4.2. The metaphysical presuppositions of mathematical natural science

McNulty argues that mathematics in natural science must be based on correct metaphysical assumptions, and takes issue with Van den Berg (2014) for not developing this idea sufficiently. On the basis of this insight, we can formulate an additional historical argument for why chemistry is not a proper natural science, an argument that builds on and extends the argument of McNulty (2014). McNulty argues that according to Kant a mechanical or corpuscular chemistry could be mathematically constructed but is metaphysically incoherent. I will argue the same, but relate this to the fact, not discussed by McNulty, that Stahl combined corpuscular mechanical philosophy with the chemistry of principles (discussed by Carrier, 1986, pp. 1–17). Hence, Kant's argument that a mathematical chemistry is based on an incoherent metaphysics is a critique of the chemistry accepted in his day.

In the *Metaphysical Foundations*, Kant addresses different metaphysical interpretations underlying physics, and in particular his matter theory, when he distinguishes between the mechanical and dynamical model of explanation in physics. Kant favours the dynamical mode of explaining natural phenomena in terms of dynamical forces, as is clear from the following statement:

> The general principle of the dynamics of material nature is that everything real in the objects of the outer senses, which is not merely a determination of space (place, extension, and figure), must be viewed as moving force. So by this principle the so-called solid or absolute impenetrability is banished from natural science, as an empty concept, and repulsive force is posited in its stead (AA 4: 523).

In line with this dynamical conception of physics and matter, Kant also tries to develop a dynamical chemistry, through what Carrier (2001) has called a continualist account of chemical compounds where compounds are not conceived as constituted by corpuscles. This dynamical chemistry was, as far as Kant was concerned, the proper chemistry of the future (McNulty, 2014 argues that even this chemistry cannot be mathematicized, and hence cannot be a proper science. I cannot enter this discussion here). Nevertheless, the posits of traditional mechanical natural philosophers (such as geometric shapes of corpuscles) can be mathematically represented, a fact that leads Kant in the *Metaphysical Foundations* to argue that in some respects there are epistemic advantages of the mechanical mode of explanation over the dynamical mode of explanation, whereas Kant seems to argue that we cannot mathematically represent matter constituted dynamically by dynamic fundamental forces. As Kant himself puts the point:

> And here the mathematical-mechanical mode of explanation has an advantage over the metaphysical-dynamical [mode], which cannot be wrested from it, namely, that of generating from a thoroughly homogeneous material a great specific variety of matters, which vary both in density and (if foreign forces are added) mode of action, through the varying shape of the parts and the empty interstices interspersed among them. For the possibility of both the shapes and the empty interstices can be verified with mathematical evidence. By contrast, if the material itself is transformed into fundamental forces (whose laws we cannot determine a priori, and are even less capable of enumerating reliably a manifold of such forces sufficient for explaining the specific variety of matter), we lack all means for constructing this concept of matter, and presenting what we thought universally as possible in intuition. (AA 4: 524-525).

Thus, Kant is quite clear that we can mathematically represent or model the fundamental metaphysical posits of a mechanical natural philosophy, such as corpuscles with a particular geometric shape and the empty interstices between them, to explain for example density. The same is true of the mechanical and corpuscularian chemistry of Kant's time, which was partly adopted by Stahl, who Kant followed in his critical period. As we have seen, Stahl combined corpuscular mechanical philosophy with the chemistry of principles (see section 2). Recall that Stahl took matter to be constituted by corpuscles and that chemical principles are composed out of atoms with a specific figure, and that it is the figure of these atoms that determines chemical reactions (Carrier, 1986, pp. 1–17, p. 6). Carrier, 2001 adds that Stahl criticized chemical explanations cast in corpuscles, arguing that they are vague, but that he inconsistently maintained corpuscles at the level of ontology.

By arguing that the mechanical natural philosophy can be mathematized, Kant seems to adopt the position with respect to his contemporary chemistry, articulated by some chemist of his day (see section 2 on the Encyclopedia of Diderot and d'Alembert), that although chemistry has as a matter of fact not yet incorporated mathematics in the way Newton has, it may be possible in the future to mathematize chemistry. Indeed, in the *Metaphysical Foundations* Kant says that mathematizing chemistry is a great difficulty, but he does not seem to deny its possibility altogether. However, were we to model the chemistry of Stahl mathematically it would still not make chemistry into a proper science, because the resulting mathematical chemistry would be based on faulty metaphysical (mechanical) assumptions, and hence the mathematical models employed in chemistry would be void of meaning. As Kant puts this point:

> Conversely, however, a merely mathematical physics pays doubly for this advantage on the other side. First, it must take an empty concept (of absolute impenetrability) as basis; and second, it must give up all forces inherent in matter; and beyond this, further, with its original configurations of the fundamental material and its interspersing of empty spaces, as the need for explanation requires them, such a physics must allow more freedom, and indeed rightful claims, to the imagination in the field of philosophy than is truly consistent with the caution of the latter. (AA 4: 525).

Thus, although we may ultimately be able to mathematicize Stahlian chemistry, it would not make chemistry into a proper science since Stahlian chemistry rests on faulty (non-dynamical) metaphysical foundations and is inconsistent. This is another historical argument for Kant's claim that chemistry is not a proper science, related to the chemistry of his day. To what extent Kant's dynamical chemistry of the future can be mathematicized and become a proper science, something McNulty, 2014 denies, remains for me an open question.

5. Chemical elements and their status as ideas of reason

As we have seen throughout this paper, Kant takes the ontological principles of chemistry, such as salt and mercury, to be empirical, insofar as chemists of his time took these principles to be discovered empirically by analysis. However, according to Carrier (2001), taking such principles to be empirical leads to a circularity in the deductive structure of chemical theory, since principles are supposed to explain the (chemical) properties of substances they cannot be ordinary substances themselves. Hence, according to Carrier, Kant reconceptualizes chemical principles as ideas of reason, fictitious objects that we use to systematize our knowledge that lie beyond the bounds of experience (see on this topic also Frketich, 2025).

I am not sure Kant really acknowledged this circularity in chemical theory. Rather, he mentions chemical principles as empirical principles throughout the *Metaphysical Foundations*, and seems to hold, with his contemporary chemists, that principles have a clear empirical meaning (being associated with empirically observable properties of substances). In the *Danziger Physik* (AA: 29: 162-163, quoted in Carrier, 2001), Kant mentions the supposed purity of chemical elements or principles as a reason to view them as ideas of reason. This argument can also be found in chemical textbooks of Kant's time. Thus, Weigel (1777), in his *Grundriß der reinen und angewandten Chemie*, mentions fundamental principles (*UrAnfange*) as the most simple materials from which bodies are composed, and argues that they are only knowable through their effects and cannot be empirically apprehended in their purity (1777, p. 38). Gren (1994 p. 34) later remarks explicitly that elements of bodies exceed the domain of experience. Hence, Kant could have followed a similar train of thought, holding on the one hand that chemical principles are empirical, being found by analysis and being correlated with observable properties of bodies, while these elements in their purity exceed the domain of experience.

Be that as it may, Kant reconceptualizes pure elements as a priori ideas of reason that systematize chemical knowledge. McNulty (2015) has argued on the basis of this fact, and against a standard reading that there are no chemical laws according to Kant (Friedman, 1992; van den berg, 2025), that since chemical laws must be grounded in a priori principles, they must be grounded in a priori ideas of reason, and that this fact allows us to interpret Kant as holding that there are chemical laws. As McNulty puts the point:

> […] I develop an alternative, 'ideational' account of natural laws, according to which ideas of reason necessitate the laws of some non-physical sciences. Chemical laws, for instance, are grounded on ideas of the elements, and the chemist aims to reduce her phenomena to these elements via experimentation. Although such ideas are beyond the possibility of experience, their postulation is necessary for the achievement of reason's theoretical ends: the unification and explanation of the cognitions of science (McNulty, 2015, p. 1).

A consequence of this reading is that chemistry, since it is based on principles that go beyond experience, provides belief and not knowledge in the strict sense. According to McNulty (2015), a theoretical belief is hypothetically necessary for the achievement of some theoretical end (p. 7). In this way for example, the "principle that phlogiston is the bearer of inflammability makes possible chemical laws of combustion and calcinability, and so belief in this principle is thereby warranted for the achievement of the ends of chemistry" (p. 8). McNulty sees the fact that chemistry is based on belief and not knowledge as a consequence of his interpretation, and as to be expected since Kant does not take chemistry to be a proper science.

To evaluate McNulty's argument it is important to note that Kant typically describes the principles of a science as certain judgments. In the *Logic*, for example, he distinguishes intuitive principles (axioms) and discursive principles (in the propositional sense), and writes.

> Immediately certain judgments a priori can be called principles/ insofar as other judgments are proved from them, but they themselves cannot be subordinated to any other. On this account they are also called principles' (beginnings'). (AA 9: 110)

Thus, principles are tied to certainty, and importantly certainty is a feature of knowledge, not of belief. This becomes clear in Kant's definition of knowledge, when he notes that certainty is an objective sufficient ground for taking something to be true:

> Finally, when taking something to be true is both subjectively and objectively sufficient it is called knowing. Subjective sufficiency is called conviction (for myself), objective sufficiency, certainty (for everyone).(A822/B850)

Thus, in Kant's conception of science, we know and do not believe principles, and this is a problem for McNulty's reading, since on his account we believe and do not know the principles of chemistry. That Kant thinks we know the principles of a science aligns with his conception of science, for on a traditional conception of axiomatic science, which we attribute to Kant, we know the principles and what is derived from them (De Jong & Betti, 2010).

Now McNulty might object that Kant's comments on principles in the *Logic* are geared towards his conception of proper science, but that his point is precisely that chemistry is not a proper science. I remain hesitant, however, to attribute laws to chemistry adopting McNulty's account. In the *Metaphysical Foundations*, Kant takes the fact that chemistry has no a priori principles to show that chemistry is not a proper science and he argues that chemical laws are based on empirical principles and thus carry with them no consciousness of necessity (AA 4: 468), which means that chemical laws are not proper laws in the strict sense, since proper laws require necessity, as Kant stresses throughout his work and has been stressed multiple times by Watkins (2019). Hence, the upshot of my analysis is that, in line with Friedman, 1992, proper empirical laws must be grounded by *constitutive* (and not regulative) a priori principles, as is the case, as Friedman (1992) has shown, for Newton's law of gravitation, which is grounded in mathematical a priori principles, as well as metaphysical synthetic a priori principles. Since this does not hold for chemistry, there are no proper chemical laws. Real laws require a constitutive metaphysical basis and it is precisely this which is lacking in the case of chemistry.

McNulty has two counterarguments to his disposal, with which I will end. First, McNulty (2015) repeatedly stresses that Kant often states that chemistry has empirical laws, even in the *Metaphysical Foundations*. This is true and could be taken as a problem for my reading, where it not for the fact that Kant also makes clear in the *Metaphysical Foundations* that chemical laws are merely contingent (AA 4: 469). This is strictly speaking impossible, since laws must possess some form of necessity. In the same vein, Kant speaks of chemistry as an improper science based on

empirical principles. Hence, my reply to McNulty's claim that Kant often speaks of chemical laws is that the expression chemical laws uses the term 'law' improperly (or in a loose sense). Laws in the strict sense are necessary in some sense and require a priori grounding by a priori constitutive principles, something which chemistry lacks.

McNulty could also argue that in insisting that laws must be grounded in a priori principles, my account does not allow for the possibility of properly *empirical* laws, which Kant clearly thinks there are. But as is clear throughout this paper, I take empirical laws to be deduced from both a priori principles, which provide them with their nomological character, and empirical principles, which provide them with empirical content. The necessity of empirical laws is wat Friedman has called *mixed material necessity* (see section 4,1). According to Friedman's (1992) derivation account, which I endorse, the prototypical empirical law of nature for Kant is Newton's law of gravitation. Now Kant believes that we have knowledge of the law of gravitation, but also correctly acknowledges that this law is derived from empirical principles (Newton's phenomena) and a priori constitutive principles (of mathematics and metaphysics). Hence, Kant accepts that we have knowledge of empirical laws, such as the law of gravity, but denies that the chemistry of his time provides such knowledge.

6. Conclusion

In this article, I provide a new perspective on Kant's infamous claim that chemistry is not a proper science because it does not allow for the application of mathematics. Starting from the idea that Kant accepted an axiomatic ideal of science, I have provided novel historical research on the history of chemistry that shows that many chemists during the eighteenth century saw chemistry as both an experimental and axiomatic science. Kant's claim that chemistry is not a proper science can be fruitfully interpreted as the claim that chemistry has not yet attained proper axiomatic form. In particular, I take Kant and several chemists of his day to follow the axiomatic conception of science as modelled by De Jong and Betti's Classical Model of Science (2010). I read Kant's argument that chemistry does not allow for the application of mathematics as involving two separate arguments: (i) mathematics in the Newtonian tradition provides a priori models of natural phenomena and as such provides a priori principles for proofs in natural science, which consist of a mix of a priori and empirical premises. As such, mathematics secures knowledge in physics. Since chemistry does not contain mathematics, it is not based, as physics is, on a priori mathematical principles concerning individual determinate natural objects, and hence chemical cognition does not qualify as chemical knowledge (*Wissen*) in the strict sense. Providing knowledge is, however, a prerequisite for being a proper axiomatic science. (ii) Through providing a priori models of natural phenomena, Newton was able to use mathematics to reason deductively concerning individual natural objects, such as the orbits of planetary bodies. As such, mathematics is a privileged way (though not the only way) to obtain deductive structure in natural science. Since chemistry does not contain mathematics, an important route to deductively organizing the contents of this science, namely via mathematics, was not available to chemistry. This constitutes an obstacle for chemistry to become a proper science. I have also argued that Stahlian chemistry in Kant's time, which he adopted during the critical period, was partly based on corpuscular assumptions, and that *if* this chemistry had been mathematicized it would have been pointless since the chemistry was based on faulty metaphysical assumptions. Finally, I argued that since chemistry is ideally an axiomatic science based on principles we *know* (and do not *believe*), chemical laws must be based on constitutive a priori principles, which they are not, and cannot be based on regulative ideas, which McNulty (2015) has argued for.

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