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The Philosophy of Chemistry

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1. Introduction

It would seem that philosophy of chemistry emerged only recently. Since the early 1990s philosophers and chemists began to meet in many different countries to discuss philosophical issues of chemistry – at first in isolated national groups but soon cultivating international exchange through regular meetings and the publications of two journals (*Hyle* and *Foundations of Chemistry*) devoted to the philosophy of chemistry. While the social formation is indeed a recent phenomenon that is still in progress, the philosophical topics have a much longer history that in some cases predates chemistry. One could even argue that ancient Greek natural philosophy started with profoundly chemical questions about the elemental constitution of the world and about how to provide reason to the sheer unlimited material variety and its wondrous changes in which, for instance, water becomes solid or gaseous; wood turns into fire, smoke, and ashes; stones change into metals; food transforms into the human body; or certain materials convert a sick body into a healthy body.

In fact there is an almost continuous philosophical tradition focused on such questions. Because Aristotle's natural philosophy, which was centered on his theory of elements, was influential far into the 18th century, it provided the basis for much of chemical philosophy. The meticulous arts of performing desirable material changes in the laboratory, particularly alchemy and metallurgy, were deeply involved in pondering metaphysical and methodological issues, out of which not only modern chemistry but also the experimental method emerged, which influential figures like Francis Bacon popularized. Although the 17th century brought about a fundamental split into the mathematical and experimental sciences and many famous philosophers were inclined towards the mathematical tradition, philosophical discussions of chemical issues did not stop then. For instance, Kant, at least in his posthumous works, wrote extensively on chemistry, as did Hegel, Schelling, and particularly Engels, whose dialectical materialism later inspired 20th-century generations of philosophers in communist countries to reflect on chemistry. Outstanding 19th- and 20th-century chemists, from Liebig to Duhem, Ostwald, and Polanyi were heavily engaged in philosophical issues, although their influence gradually faded as philosophy of science established itself as an independent branch of philosophy in the 20th century. Particularly in German and English speaking countries professional philosophy of science became almost exclusively focused on the mathematical tradition, with favorite topics in statistics, mathematical logic, relativity theory, and quantum mechanics. While their work has without doubt been important to theoretical physics, they mistakenly consider this peculiar research field to be exemplary or representative of all the sciences. Apart from communist countries, the situation was different perhaps only in France, where two chemically trained philosophers, Émile Meyerson and Gaston Bachelard, were most influential in shaping French *épistémologie* and philosophy of science. In most countries, however, the gap left by philosophers of science was largely filled by chemists and historians of science, like Kuhn who developed his theory of paradigm changes on the model of the chemical revolution. The narrow focus of professional philosophers of science was only slowly opened, particularly through the philosophy of biology movement since the 1970s. Other philosophies of the special sciences followed soon, one of which is philosophy of chemistry.

In this chapter I will not try to review all the recent and past works in the philosophy of chemistry (for review articles see Schummer 2003a & 2006), because the topics are much too diverse and many require detailed chemical background knowledge. Instead, I discuss four issues that together might serve as an introduction to the philosophy of chemistry and at the same time give an idea of its scope. The four issues, which are chosen so that they build on each other and inspire further thinking and which are necessarily a personal selection, are: What is chemistry about? Is chemistry reducible to physics? Are there fundamental limits to chemical knowledge? Is chemical research ethically neutral?

2. What is chemistry about?

Philosophers, like children, tend to ask plain questions such as: what is chemistry about? What is its specific subject matter that distinguishes chemistry from other sciences? Dictionaries tell us that chemistry is about substances, chemical reactions, molecules, and atoms – but what are a substance, a chemical reaction, a molecule, and an atom, and how do these concepts relate to each other? Unlike substances in philosophy, a chemical substance is a piece of matter of any size, form, and state of aggregation with clearly defined and unique chemical properties that are qualitatively different from the chemical properties of other substances. A chemical property of a substance is its ability to change into other substances under certain conditions, and such changes from one substance to another are called chemical reactions. Because a substance is defined through its specific chemical reactions and a chemical reactions is defined through the specific substances involved, we end up in circular definitions: reactions define substances and substances define reactions. Can we escape the circle by giving priority to either substances or reactions?

The seemingly innocent question of what is chemistry about prompts us to decide between two opposing metaphysical traditions, substance philosophy and process philosophy. Substance philosophers claim priority to entities, things, or substances and consider changes, like motion in space, to be only secondary attributes of entities. However in chemistry, change is essential rather than secondary; and it is radical because through chemical reactions all properties radically change. This suggests that process philosophy would be more suitable here, because it gives priority to processes and considers entities only as temporary states. Moreover, process philosophers can point to the fact that in the natural world there are no fixed and isolated chemical substances but only permanent chemical change of matter. However, in order to describe these changes precisely we need concepts that grasp the various states of change, for which the concept of chemical substances appears to be most suitable.

Chemists have solved the puzzle in a way that sheds light on the manifold uses of experimentation in science. Because, as process philosophy correctly says, there are no fixed and isolated chemical substances in the natural world, chemists make them in the laboratory and fill them in bottles, so that they are pure, isolated, and remain stable for further investigation. The material world is thus adjusted to the conceptual needs. However, the experimental trick works only through a quasi-operational definition of chemical substances, according to which a chemical substance is the result of perfect purification, which includes thermodynamic operations such as distillation. It happens that only the results of such purification procedures meet the definition of chemical substances, that only they have clearly defined and unique chemical properties that qualitatively differ from those of other substances.[1] The trick thus yields substances that are characterized through their chemical changeabilities, which combines both aspects of substance and process philosophies. Once such chemical substances are produced, they can also be characterized and later recognized by other properties, like optical and thermodynamic properties.

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[1] There are some exceptions, however, as always in the chemical world, particularly the so-called berthollides (for more details, see Schummer 1998). On the other hand, the quasi-operational approach allows solving the philosophical puzzle of natural kinds.

Chemists have used the same experimental strategy to develop an operational hierarchy of matter that formally resembles the metaphysical hierarchy known since Aristotle. Every technique that takes materials apart defines a part-whole relationship between the end products and the starting material. Thus, a material that can be taken apart by purification is, by definition, a mixture and the resultant materials are its component substances; a material that cannot be taken apart is, by definition, a chemical substance. There are two other sets of separation techniques that each defines a part-whole relation between materials. A mixture that can be taken apart into different materials by mechanical means, like sorting or cutting, is a heterogeneous mixture; otherwise it is a homogeneous mixture. A chemical substance that can be taken apart by chemical means, including electrochemical processes, is a compound; otherwise it is a chemical element. At the same time the chemical separation defines the elemental composition of a compound, which is an important chemical property. Overall this results in an operationally defined four-level hierarchy from chemical elements, to compounds, to homogeneous and heterogeneous mixtures. The hierarchy allows characterizing both a material and its changes through its composition on the lower levels. For instance, a compound is characterized by its elemental composition and a homogeneous mixture by its composition of substances.

Because chemistry is about radical change, it needs to deal with fundamental problems, as the following example illustrates: Assume you want to characterize something through its specific changes: as long as you do not perform the change, you have no certain idea about that; but once you have performed the change, the thing you want to characterize does no longer exist. Again, the logical puzzle is solved experimentally in chemistry. Because any material from homogeneous mixtures down in the hierarchy to elements cannot by definition be changed through mechanical separations, one can mechanically take small pieces from such a material and perform chemical test changes on these samples. The operational hierarchy guarantees that the chemical characteristics of all samples are exactly the same as that of the entire piece of material.

Thus far we have dealt only with substances and reactions. What about atoms and molecules? Because these are widely conceived as the true microscopic components of all materials, many argue that chemistry is ultimately about atoms and molecules rather than about substances. Investigating substances and chemical reactions is only a means to develop a better understanding of atoms and molecules and their dynamic behavior and reconfigurations that we perceive as chemical change. On the other hand, one could argue that all our knowledge about atoms and molecules is only a means to better understand and then explain and predict the chemical behavior of substances. While all chemical knowledge actually starts with the artificial creation of pure chemical substances and then continues with investigating them in the laboratory, the two positions differ only in what kind of knowledge they consider means and ends of chemistry.[2] The first position (which one might call theoreticism) takes the knowledge of substances as means for the knowledge of atoms and molecules to be considered an end in itself. For the second position (experimentalism) the knowledge of atoms and molecules is only a theoretical means for the proper end of understanding the behavior of substances. And because substances are artificially produced in the laboratory to suit our conceptual needs, one can also assume a third position, which one might call realism in the original sense because, unlike idealism, it acknowledges a fundamental difference between our concepts and the world. This position takes our knowledge of substances, whether reinforced by theoretical knowledge or not, only as a means to develop a better understanding of our messy material world, which includes both our natural environment and the chemical processes that happen in all kinds of industries.

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[2] In philosophy of science these two positions are sometimes called scientific realism and instrumentalism, which in my view is a misleading terminology, because both views are each instrumentalist with regard to the other kind of knowledge.

Of course the three positions express different views about the end of science in general, and they usually come from different areas of science, here, theoretical, experimental, and applied science. However, in chemistry the difference between theoreticism and experimentalism is more complicated than an introductory textbook of chemistry might suggest. That is because there is no one-to-one relationship between substances and molecules, such that each substance would consist of a single kind of molecules. Indeed, the concept of molecules works only for certain substances as a useful model approximation. If we assume that substances consist somehow of atoms, the molecular model singles out certain groups of atoms that on time average stick a bit closer together with each other than with others atoms. This model works quite well with many organic substances and gases but fails for instance with simple substances like water, metals, or salts for most purposes. In liquid water one can single out hundreds or thousands of different kinds of molecules, depending on one's accuracy and time average, such that pure water would be a complex molecular mixture. In metals and salts all atoms stick together in the same way such that each piece would consists of a single molecule. Hence, rather than talking of molecules, a more generic concept is that of interatomic structures of substances.

Interatomic structures of substances are dynamic entities, even if we disregard quantum mechanics for the sake of simplicity. To take water again as an example, the structure continuously changes on a time scale of less than a trillionth second. We might be able to identify some hundred kinds of preferred structures that recur on time average, but others appear if we only slightly change the temperature. Also for those organic substances where the molecular model works quite well, interatomic distances and angles change with temperature. Theoreticism is thus confronted with severe conceptual problems because the classical chemical concepts do longer work. If, in theoretical terms, a chemical reaction is defined by a change of the interatomic structure, pure substances would be complex mixtures that undergo permanent chemical reactions; and changes of temperature that do not change the substance identity would induce radical chemical reactions on interatomic structure. The problem of theoreticism is that it lacks useful concepts of kinds, both for entities and processes. If such concepts are introduced by virtue of model approximations, theoreticism would have to concede that chemistry is ultimately about its own models about the world rather than about the material world itself, i.e. only about what theoreticians are doing. Compare that with experimentalism that cannot only acknowledge such models as useful intellectual tools but can also claim that its own concepts perfectly fit at least a part of the material world, even if that part is artificially produced in the laboratory.

However also experimentalism smacks of self-satisfaction because it creates and focuses on the laboratory systems that best fit its conceptual framework. If the goal of science is to understand the world that we all live in, then realism is the only viable position, such that theoretical and experimental laboratory investigations are only useful means to that end.[3] That is even more important, if chemistry, as many think, is about developing an understanding of our material world in order to improve it according to human needs.

3. Is chemistry reducible to physics?

In recent philosophy of chemistry, the issue of whether chemistry is reducible to physics has been vividly debated. The debate was originally inspired by older bold claims like that of the

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[3] Note that theoreticism, experimentalism, and realism also differ with regard to our original question if entities or processes have ontological priority. Since ancient atomism, theoreticism has, at least before quantum mechanics, always favored substance philosophy and tried to reduce any change to motion in space. Experimentalism combines both substance philosophy and process philosophy and experimentally adjusts part of the material world to the conceptual needs of substance philosophy, whereas realism is forced to acknowledge the omnipresence of change.

mathematician Paul Dirac from 1929, according to whom the whole of chemistry would be reducible to quantum mechanics and thus would be part of physics. In so far as such claims express disciplinary chauvinism as a means to acquire social prestige and intellectual hegemony, or just the frequent disciplinary narrow-mindedness that ignores everything outside one's discipline, they should not much concern philosophy. On the other hand, in so far as such claims belong to the general position of physicalism, according to which physics would be fundamental to any science, including biology, the social sciences, and psychology, they express a metaphysical worldview that in its generality is beyond the scope of philosophy of chemistry, although philosophers of chemists can make specific and useful contributions to such debates. Furthermore, if the claim is about the explanatory and predictive scope of a specific theory, it is up to scientists rather than to philosophers to assess the exact limits of the theory by checking the thesis against experimental findings and rejecting unfounded claims according to established scientific standards. The remaining job of philosophers – both of chemistry and physics, because the reductionist claim is about the relation between chemistry and physics – largely consists in clarifying the underlying concepts and in checking for hidden assumptions and blind spots.

Because there are many different versions of reductionism, conceptual distinctions are necessary. *Metaphysical or ontological reductionism* claims that the supposed objects of chemistry are actually nothing else than the objects of quantum mechanics and that quantum-mechanical laws govern their relations. In its strong, eliminative*,* version, metaphysical reductionism even states that there are no chemical objects proper. Microstructural essentialism reformulates eliminative metaphysical reductionism in semantic terms by employing a certain theory of meaning and reference to claim that the proper meaning of chemical substance terms, such as 'water', is nothing else than the (quantum-mechanical) microstructure of the substance. However, as was shown above, it makes a difference if the objects of chemistry are substances or interatomic structures, such that giving up substances, as eliminative reductionism and its semantic twin claim, would be giving up chemistry as we know it. Even if substances have an interatomic structure, the fact that a theory can be used to describe the structure and to develop useful explanations does not mean that it 'owns' interatomic structures. There are other important theories to describe interatomic structures, like classical chemical structure theory that is much more useful to explain chemical properties, as we will see below. Moreover, anti-reductionists argue that theoretical entities are determined by their corresponding theory, such that theoretical entities of different theories cannot simply be identified. For instance, from the different meanings of the term "electron" in quantum electrodynamics and in chemical reaction mechanisms one might conclude that the term "electron" has different references, which rules out ontological reductionism.

Epistemological or theory reductionism claims that all theories, laws, and fundamental concepts of chemistry can be derived from first principle quantum mechanics as the more basic and more comprehensive theory. That claim has prompted many technical studies on the difficulties of quantum mechanics to derive the classical concept of molecular structure and the chemical law that underlies the periodic system of elements. Moreover, because most of the successful applications of quantum mechanics to chemical problems include model assumptions and concepts taken from chemistry rather than only first principles, their success can hardly support epistemological reductionism. Apart from such technical matters, quantum mechanics cannot derive chemistry's classificatory concepts of substances and reactions, and it cannot explain, not even compete with, chemical structure theory, which has been developed since the mid-19th century in organic chemistry to classify, explain, predict, and synthesize substances.

Methodological reductionism, while acknowledging the current failure of epistemological reductionism, recommends applying quantum mechanical methods to all chemical problems, because that would be the most successful approach in the long run (approximate reductionism). However, the mere promise of future success is hardly convincing unless a comparative assessment of different methods is provided.

By modifying the popular notion that "the whole is nothing but the sum of its parts" two further versions of reductionism have been developed. *Emergentism* acknowledges that new properties of wholes (say, of water) emerge when the parts (say, oxygen and hydrogen) are combined, but concedes that the properties of the whole can be explained or derived from the relations between the parts, i.e. epistemological reductionism. *Supervenience*, in a simple version, means that, although epistemological reductionism might be wrong, the properties of a whole asymmetrically depend on the properties of the parts, such that every change of the properties of the whole is based on changes of the properties of or the relations between the parts, but not the other way round. If applied to the reduction of chemistry to quantum mechanics, i.e. to chemical entities as wholes and quantum mechanical entities as parts, emergentism and supervenience presuppose elements of epistemological or ontological reductionism, such that the criticism of these positions applies accordingly.

The discussion of reductionism distracts from the fact that chemistry and physics have historically closely developed with many fruitful interdisciplinary exchanges without giving up their specific disciplinary foci. For instance, chemistry greatly benefits from quantum mechanics, because that is the only theory we have to explain electromagnetic, mechanical, and thermodynamic properties of materials. However, when it comes to chemical properties, the properties that define chemical substances and which chemists are mostly interested in, quantum mechanics is extremely poor such that chemists here rely almost exclusively on chemical structure theory. Rather than focusing on reductionism, with its underlying notion of a Theory of Everything, it seems more useful to discuss the strengths and weaknesses of different theories for different purposes. For instance, quantum mechanics helps analyze the optical properties that chemists routinely use in all kinds of spectroscopies to understand the kind of time averaged interatomic structures that chemists are interested in. If these structures can successfully be translated into chemical structure theory, however, it is chemical structure theory rather than quantum mechanics that provides information about chemical properties.

Chemical structure theory, which has been continuously developed since the mid-19th century, is more like a rich sign language than a depiction of individual physical structures. It is one of the hidden assumptions of reductionism, that both kinds of structures are the same. However, chemical structure theory encodes types of chemical reactivities according chemical similarities in characteristic groups of atoms, and it has numerous general rules for how these groups can interact and be reconfigured to describe chemical reactions. The important difference to physical structures, which are described in terms of individual space coordinates, is that it describes both the structures and their reconfigurations in general concepts that are chemically meaningful. Despite its recourse to general concepts, the language is rich enough to distinguish clearly between hundreds of millions of substances and their chemical properties. Once the chemical structure of a substance is known, chemical structure theory allows both identifying the substance and predicting its chemical properties. Moreover, because chemical properties describe radical change of substances, these predictions enable one to make new, unknown substances in the laboratory, such that predictions guide the production of novelty. This is nowadays successfully performed several million times per year, which makes chemical structure theory one of the most powerful predictive tools of science.

One of the blind spots of reductionism, or physicalism for that matter, is that sciences other than physics deal with different issues and subject matters that require entirely different kinds of methodologies, concepts, and theories. In chemistry, which deals with substances and radical change, classification and synthesis are at least as important as analysis, or its physics counterpart of a quantitatively accurate and true description of the world as it is. Classification is not only a matter of building useful empirical or operational concepts. It also requires theoretical approaches that include or can deal with classificatory concepts and substantial change, otherwise the theories cannot address the issues that are to be explained or predicted. Chemical theories need to deal with hundreds of millions of different substances and hundreds of thousands of kinds of reactions. Theoretical physics, on the other hand, stands out among the sciences because, apart from particle physics, it intentionally lacks classificatory concepts.

Furthermore, because radical change is essential to chemistry, synthesis is an integral part of chemistry both on the experimental and theoretical level. That is not simply because synthesis can provide useful compounds, although this option has historically shaped much of chemistry. Chemical properties are revealed only through synthesis, i.e. by chemical reactions that change one substance into another under controlled laboratory conditions. Accordingly, a chemical theory that is expected to make predictions must be able to predict syntheses, and the only way to test the predictions is of course by way of synthesis. Again, synthesis is not part of the methodology of physics, at least as mainstream philosophers of physics conceive it, so that the model of physics would miss a central part of chemical concepts, theories, and methods. However, since many physicists along with chemists engage in materials science to produce new useful materials, the methodology of experimental physics might approach that of chemistry.

4. Are there fundamental limits to chemical knowledge?

An important epistemological task of philosophy of science consists in understanding the limits of scientific knowledge on a general level. Again, it is up to scientists to check the limits of a specific theory or model in order to avoid unjustified scientific claims that lead people astray by unfounded promises. Unfortunately, such promises increasingly appear with the public struggle for funding and public attention, in popularizations of science, and sometimes even in the disguise of philosophy. The epistemological task consists in scrutinizing a scientific approach, its concepts and methods, for implicit assumptions that limit the scope or validity of its epistemic results. Such an analysis may provide not only an epistemological assessment of the scientific approach but also answers to the more ambitious question of whether complete and perfect knowledge is ever possible or not. In the following I discuss three issues that each shed light on the limits of chemical knowledge: the concept of pure substances, methodological pluralism, and the proliferation of chemical objects.

As has been discussed in the previous Sections, chemistry rests on the concept of chemical substances, experimentally in characterizing, classifying, and producing materials and in describing chemical change as well as theoretically in explaining, classifying, and predicting materials and chemical change through structure theory. However, chemical substances are idealizations in two regards that each pose limits to chemical knowledge. First, although chemical substances are experimentally produced through purification techniques and as such are real entities, perfect purity is a conceptual ideal that can never be fully reached in practice. Thus, any real substance as an object of experimental investigation contains impurities, whereas any conceptual description needs to assume perfect purity or a well-defined mixture of pure substances. Because even very small amounts of impurities can drastically change chemical properties, through catalytic activity, there is always the risk that the gap between concepts and objects leads to misconceptions and wrong conclusions. On the other hand, because chemists know well about the problem, they can take particular care about possible impurities that they assume are relevant in each case.

Secondly, and more importantly, the pure substances that chemists produce and put in bottles for chemical investigations do not exist outside the laboratory. Instead, the materials outside the laboratory are messy and mostly under continuous transformations and flux. Any material sample of, say, a soil, a plant, or even sea water, can be analyzed into hundreds or thousands of substances of different amounts, depending on one’s analytic accuracy. And before it became a sample, the piece of matter was in continuous flux and interaction with its environment and hardly a perfect homogeneous mixture. The problem is not to describe all that; rather the problem is that any accurate description of material phenomena outside the laboratory turns into an endless list of facts. Moreover, if a mixture contains more than five or ten substances, the theoretical reasoning of chemistry fails because of over-complexity. Hence, the conceptual framework of chemistry is not very suitable to describe the real material world, but still it is the best we have for that purpose. The way chemists deal with such real world issues is, again, by making assumption about what is relevant and what not by focusing on specific questions for which the relevance of factors can be estimated or controlled.

Once relevance aspects shape the kind of facts one considers and the kind of knowledge one pursues, the abstract ideal of complete and perfect knowledge is given up. The fragmentation into different knowledge domains according to different relevance aspects then seems unavoidable, and new domains grow as new questions become relevant. While that might to some degree be true of all the experimental sciences, in contrast to theoretical physics, it is characteristic of chemistry as the prototype of experimental laboratory sciences and as by far the biggest discipline.[4] In contrast to the ideal of a universal Theory of Everything, which has been important in theoretical physics, chemistry is guided by a pragmatist pluralism of methods. Not only does each subdiscpline of chemistry develop its own kinds of methods, concepts, and models tailored to specific substance classes and types of chemical change, also within each particular research field there is, even for the same experimental system, a variety of different models at hand that serve different purposes. One might argue that this is because the right universal approach has not yet been found. However, methodological pluralism seems to be rather a characteristic of chemistry that allows flexibly dealing with complexity by splitting up approaches according to what matters in each case. Rather than being a surrogate of universal theories, methodological pluralism is an epistemological approach in its own right. It requires that the quality of a model is not judged by standards of truth and universality but, instead, by its usefulness and the precision by which its scope of applications is limited. A model in chemistry is a theoretical tool to address specific questions, which is useless if you do not know for which kind of systems and research questions is can reasonably be used.

Methodological pluralism produces a kind of patchwork knowledge rather than universal knowledge. The advantage is that it allows incorporating new kinds of knowledge without fundamental crisis by extending the patchwork. Moreover, it can deal with relevance aspects, which the claim to universal knowledge cannot. Because patchwork knowledge can always be extended, by including new kinds of knowledge and new relevance aspects, the scientific endeavor is open-ended in both dimensions. Therefore, the idea of complete and perfect knowledge, and all its derived epistemological concepts that might be useful to apply to the notion of universal knowledge, are meaningless in chemistry.

Further support for the last conclusion, that chemical knowledge can never be perfect and complete, comes from an analysis of the concept of chemical properties, i.e. from the specific subject matter of chemistry. All material properties are dispositions, i.e. they describe the behavior of materials under certain contextual conditions, such as mechanical forces, heat, pressure, electromagnetic fields, chemical substances, biological organism, ecological systems, and so on. Because a property is defined by both the behavior and the contextual conditions, we can freely invent new properties by varying the contextual conditions to increase the scope of possible knowledge almost at will. Chemical properties stand out because the important contextual factor is of the same kind as the object of investigation, both being chemical substances, such that chemical properties are strictly speaking dispositional relations. A chemical property of a substance is defined by how it behaves together with one or more other substances, and the important behaviors are those of chemical transformation – although the

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[4] Note that, in quantitative terms of publications, chemistry is almost as big as all the other sciences together (Schummer 2006).

lack of transformation, i.e. chemical inertness, is sometimes also important. If a new, hitherto unknown substance results from the transformation, it can be made subject to further investigations, by studying its reactivity with all known substances, which in turn may result in many hitherto unknown substances to be studied, and so on. The procedure results in exponential growth of substances, not just in theory but also historically over the past two centuries, and there is no fundamental limit to an endless proliferation in the future. Because each substance increases the scope of possible chemical knowledge, chemical knowledge can never be complete.

Even worse, one can argue that the synthesis of new substances increases the scope of possible knowledge (the number of undetermined properties) much faster than the scope of actual knowledge (the number of known properties). If we call the difference between possible knowledge and actual knowledge non-knowledge, chemistry produces through synthesis much more nonknowledge than knowledge, as the following simplified calculation illustrates. Assume we have a system of n different substances, then the number of all possible chemical properties corresponds to the number of all combinations from pairs to n-tuples (times the variations in concentration and other contextual conditions, which will be neglected here). While the synthesis of a new substance increases the scope of actual knowledge only by a single property (the reaction from which the substance resulted), it increases the scope of possible knowledge or undetermined chemical properties according to simple combinatorics by

$$\sum_{k=2}^{n+1} \frac{(n+1)!}{k!(n+1-k)!} - \sum_{k=2}^{n} \frac{n!}{k!(n-k)!} .$$

For instance, if the original system consists of 10 substances, which corresponds to 1013 possible properties, the synthesis of a single new substance creates 1023 new possible properties. Thus, while the actual knowledge increases only by one property, nonknowledge grows by 1022 undetermined properties. If the system consists of 100 substances, a single new substance increases nonknowledge by 10^{30} undetermined properties, and so on. One might criticize the calculation as being too simplistic, but a more precise calculation, which additionally considers variations in concentration and other contextual conditions, would bring about even much faster growth of nonknowledge.

Anyway, the epistemological problem or paradox is ultimately rooted in the peculiarities of the chemical subject matter, i.e. in radical change, and therefore unknown in other sciences. Rather than depicting the world as it is, chemistry develops an understanding of the world by changing the world. Because the changes are radical in that they create new entities, any such step of understanding increases the complexity of the world and thus makes understanding more difficult. We will see below that this paradox of understanding also poses specific ethical issues.

5. Is chemical research ethically neutral?

Chemical knowledge has always been mysterious and suspicious in Western societies because it is knowledge of radical change. Christian mythology, particularly the apocryphal Book of Henoch, identifies chemical knowledge with the secret knowledge of primordial Creation that the Fallen Angles had once betrayed to humans. Up to the 18th century, performing chemical changes was routinely accused of modifying divine Creation against God's will, and some people think so even today. On the other hand, the prospects of radical change has always fueled fantasies of changing the material world at will according to human needs or specific economic interests, from alchemy to the chemical industry and current visions of nanotechnology. Since thoughtless industrial chemical production has caused severe environmental issues, through pollution, accidents, and unsafe products, anything related to chemistry is publicly considered with suspicion. Many consider the archetypical mad scientist, the chemist

Victor Frankenstein in Mary Shelley's novel, emblematic of the modern academic-industrial endeavor of chemistry.

It would be wrong to disregard the specific cultural embedding of chemistry from a philosophical point of view, because it has essentially shaped ethical views of chemistry. After all, ethics is a branch of philosophy, such that ethics of chemistry is a natural branch of philosophy of chemistry. From the fact that for instance mathematics is rather poor in ethical issues but rich in logical issues, it would be mistaken to conclude that the focus of all philosophy of science is on logic. Each discipline has its own variety of issues that call for philosophical treatment. Although this chapter does not include an ethical analysis of chemistry for the sake of brevity (see Schummer 2001), it prepares such an analysis by some conceptual clarifications that are focused on the issue of whether chemical synthesis is ethically neutral or not, i.e., if it can be made subject to justified moral judgments.

At first it is useful to point out the distinction between the academic discipline of chemistry and the chemical industry, of which only the former concerns us here. The chemical industry, as any industry, is definitely not ethically neutral because it deliberately acts according to (non-epistemic) values, and its actions have direct positive and negative consequences for human beings. The important question is if chemical research that synthesizes new chemical substances is ethically neutral. Strictly speaking no scientific research is ethically neutral in so far as it produces knowledge about the world that could enable people to perform ethically relevant actions. That can be either actions to prevent harm, such as when understanding the causes of stratospheric ozone depletion by clorofluorocarbons enables one to take effective measures against the depletion; or actions to cause harm, such as when understanding the biochemical metabolism of human beings allows one to choose a more effective poison. On this general level, because scientific knowledge enables effective actions, scientists have a particular responsibility for the kind of knowledge they pursue. Apart from and above that, is there anything that makes the synthesis of new substances ethically relevant?

We are used to make a distinction between science and technology, including technological research or engineering sciences. In this view science describes the natural world and makes true discoveries of the world, whereas technology changes the world by producing artifacts and makes useful invention for change. In this view, technology is, unlike science, ethically relevant above the general level because, like industry, it deliberately acts according values of usefulness and directs its actions accordingly. Because chemical synthesis meets that definition of technology, it would seem that chemical synthesis is essentially a technology rather than a science and therefore ethically relevant above the general level.

However, the distinction between science and technology includes two related problematic assumptions, which incidentally have their roots in the cultural background mentioned at the beginning of this section. First, it assumes that science cannot, by definition, be about understanding radical change, because that is the domain of technology. However, if the goal of science is describing and understanding nature, the assumption is equivalent to the thesis that there are no radical changes in nature so that there is no place for such a science. The underlying philosophical view is known since antiquity as the opposite of process philosophy, and its Christian counterpart is the notion of nature as the perfect divine creation. As has been argued above, chemistry is all about understanding radical change, about transformations of substances into one another. If one acknowledges that there are radical changes in nature, understanding and discovering such changes is clearly a scientific endeavor. And because chemical synthesis is the best experimental way we have to study such radical change, it meets all requirements of scientific methods.

Secondly, the distinction between science and technology assumes that the world can clearly be divided up into natural entities and artifacts, which in the Christian (and Platonic) tradition is equivalent to the distinction between entities made by God in the primordial Creation and entities made by humans. In this view science is about the natural world whereas technology is about producing artifacts from the resources of the natural world. However, also pure substances isolated from natural resources are artifacts because they always result from purification techniques, such as any experimental setting in the experimental sciences would have to count as an artifact. Moreover, a substance that can be isolated from natural resources through purification can, as a rule, also be synthesized in the laboratory from different compounds, such that there is no scientific way to distinguish between natural and artificial substances, in contrast to artifacts in technologies that can usually be clearly recognized as artifacts. Furthermore, if chemical changes are natural and if nature is essentially process-like, there is no reason to question that the outcomes of such changes are natural, regardless of whether the changes have been experimentally directed or not and whether the outcomes have been known before or not. In sum, the distinction rest on an archaic notion of nature, as something given and static without changeabilities, whereas all modern experimental sciences focus on the study of the dynamics of nature (Schummer 2003b).

When we therefore can reject the idea that chemical synthesis per se is a kind of technology rather than science, that does not mean that chemical synthesis is always performed as science. It all depends on the research questions in each case. If the research is performed to study chemical changeabilities, it rather belongs to science. If the synthetic research aims at useful products, it would rather be counted as technological research. However, modern science, in chemistry as well as elsewhere, is a collaborative enterprise that is driven by a variety of motives and intentions that no philosopher is able to identify. One can pursue a specific scientific research question that is also important for a technological goal and integrated in a broader project. And one can pursue at the same time scientific and technological knowledge without much compromising, which some philosophers have recently discovered as the latest move towards “technoscience”, although that is known in chemistry since centuries.

Finally, if we ignore all these complications and take chemical synthesis in the purest sense of science: is it apart from the general level ethically neutral because it is science rather than technology? The answer is no, and the main reason lies again in the fact that chemistry is about radical change. Synthetic chemistry does not only produce knowledge but also actively changes the world which may affect anybody living in that world. Assume that in the course of scientific studies on chemical reactivities a chemist has produced a new substance that happens to be extremely toxic and that, by some incidents, leaves the laboratory and cause severe human poisoning or environmental disasters. We would rightly hold the chemist responsible for that harm, not only because of the lack of security measures, but also because the chemist was the original creator of the agent that caused the harm. In such a case, the chemist might insist that he had no intention to cause the harm, which would hardly excuse him because the lack of intentions might just be negligence. Also the argument that he could not foresee the toxic properties of his creation would not count much, because chemists know well that any new substance is unique and has infinitely many properties which, by all scientific standards, bear surprises, such that harmful effects are not unlikely. After all, that is expected from radical change unlike from gradual or marginal change. In sum, even if chemical synthesis is not technology but science, it is beyond the general level ethically relevant because it performs radical changes on the world.

Conclusion

Although each of the issues discussed above branches out into various specific issues, there are two running threads throughout this chapter, which are radical change and dealing with real world complexity. First, chemistry is essentially about radical change that cannot adequately be captured by physics; and radical change enables synthesis, which makes chemical knowledge fundamentally incomplete and chemical research ethically relevant. Second, chemistry deals with real world complexity by adjusting the material world in the laboratory to its classificatory concepts, which are not reducible to physics, and by following methodological pluralism, both of which pose limits to understanding the world outside the laboratory, including predictions of how its synthetic products behave in that world.

The two running threads, composed in this chapter for introductory reasons, might give a too homogeneous impression of current philosophy of chemistry, though. Indeed the field is extremely rich in topics that cover all branches of philosophy, including epistemology, methodology, metaphysics, ontology, ethics, aesthetics, and semiotics. Moreover, there are many important philosophical studies that analyze specific chemical concepts and issues in their particular historical and cultural contexts. From that diversity one might conclude that philosophy of chemistry hardly exists yet as a clearly defined and homogenous field, because it lacks paradigmatic issues and a focused methodology and borrows instead as much from philosophy as from history of science and science studies.

It is certainly true that much of current philosophy of chemistry is still in a process of defining itself anew and that the contemporary zeitgeist is not without impact on that process. However, there are other, perhaps more important, reasons for the diversity. Remember that chemistry follows methodological pluralism rather than universalism, which produces a kind of patchwork knowledge diversified by relevance aspects. Because most of today's philosophers of chemistry have a background, if not a former career, in chemistry, it is likely that their philosophical work is influenced by the epistemological style of chemistry, which deeply distrusts the big pictures and simplifications of universalism. If chemistry also in this way inspires philosophy, the better for philosophy.

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