Chemistry vs. Physics, the Reduction Myth, and the Unity of Science

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Zusammenfassung

Die Beziehung zwischen Chemie und Physik wird oft als ein Standardbeispiel für die Reduktion eines Teilbereiches der Wissenschaft auf einen anderen angeführt. Wir legen dar, daß von einer Vielfalt verschiedener Auffassungen von Reduktion keine wirklich auf jene Beziehung zutrifft. Die Gründe dafür können zumindest zum Teil in der Verschiedenheit der Vorgehensweisen von Physik und Chemie gefunden werden, die wir als bathogen bzw. phänomenologisch bezeichnen. In der Tat wird der im Prinzip nützliche Begriff der Reduktion zuweilen mißbraucht, um einen "Reduktionsmythos" aufzubauen, der die wissenschaftliche Forschung in einer bestimmten Richtung lähmen kann. Im Gegensatz dazu ist aber ein Miteinander der verschiedenen Teilbereiche im Sinne einer Einheit der Wissenschaften durchaus möglich und wird im tatsächlichen Wissenschaftsbetrieb auch praktiziert. Dies erfordert allerdings einen Standpunkt, wie er hier geschildert wird, der der Komplexität der Natur durch Zulassung verschiedener Vorgehensweisen zu ihrer Beschreibung gerecht wird.

1. INTRODUCTION: WHAT IS PHYSICAL IN CHEMISTRY?

Several studies have been devoted in recent years to the nature of the relationship between chemistry and physics [1–5]. Those studies have been centered around the legitimacy and exact meaning of the statement that chemistry is entirely reducible to physics.

Until some time ago, the physicalists view, which granted chemistry an autonomous status only on the experimental level, was accepted without discussion. The theories of physics were assumed to be a complete and satisfactory explanation of chemical facts; the only role of a theoretician in chemistry was seen in the overcoming of the computational difficulties arising in the application of those theories to specific predictions. For example, the preface to one of the standard textbooks of quantum chemistry (1944) starts: 'In so far as quantum mechanics is correct, chemical questions are problems in applied mathematics. In spite of this, chemistry because of its complexity, will not cease to be in large measure an experimental science, . . .' [23]; Oppenheim and Putnam write (1958): 'Only in the twentieth century has it been possible to micro-reduce to the atomic and in some case directly to the subatomic level most of the macrophysical aspects of matter (e. g. the high fluidity of water, the elasticity of rubber, and the hardness of diamond) as well as the chemical phenomena of the elements, i. e. those changes of the pheripheral electrons which leave the nucleus unaffected. In particular, electronic theories explain, e. g. the laws governing valence, the various types of bonds, and the 'resonance' of molecules between several equivalent electronic structures" [6].

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A more moderate and critical attitude seems to be now emerging: significantly, even Mario A. Bunge, well-known for his work on the foundations of physics, is inclined to deny that theoretical chemistry is just a chapter of physics [3]. Theobald [1] stresses the existence of specifically chemical concepts, as well as the differences in interpretations provided by chemistry and by physics. Lévy [2] points out that the classical concept of reduction does not apply to the relationship between chemistry and physics: she introduces the new notion of reduction by synthesis to describe that relation. Primas [4] emphasizes that "most theoretical concepts of chemistry have not yet been successfully reduced to quantum mechanics, and it is an open question whether such a reduction can ever be achieved". Finally, we have pointed out elsewhere [5] that the *explanation* of observations sought and provided by chemistry is essentially different from that of physics, and "even the extension of physics to include more concepts would not suffice to reduce chemistry to it".

At the level of motivation, it may be argued that the above analyses are at least in part the result of the collapse of physicalism after the emergence of molecular biology and of cybernetics. This is transparent in the very choice of the terms (components, system, emergence) in the following fundamental statement by Bunge: "What is physical about a chemical system is its components rather than the system itself, which possesses emergent (though explainable) properties in addition to physical properties" [3].

At the logical level, many points remain unsettled. The three major ones are: the definitions of the two sciences in question; the distinction between explanation and prediction; the very meaning of the term 'reduction' in connection with the chemistry-physics relation.

The three points are interrelated: for instance, if nuclear physics is taken as representative of physics proper, then the statement by Bunge quoted above might be taken as a statement bearing on different chapters of physics, because the relation between a nucleus and its nucleons is similar (though not so rich) to the relation between a molecule and its constituent atoms. Bunge himself has been led by considerations of this kind to base his study on a detailed formal analysis of the concept of 'field of inquiry'.

In this paper we shall try to probe further into the third point of above list: this will also throw further light on the first two points (for the second one cf. also ref. 5).

2. RADICAL AND MODERATE REDUCTIONISM

A standard definition is: "Reduction, in the sense in which the word is here employed, is the explanation of a theory or a set of experimental laws established in one area of inquiry, by a theory usually though not invariably formulated for some other domain." [7]

Actually, in the everyday practice of science as well as in the mental attitudes of scientists, several different kinds of reduction occur.

The most immediate kind might be called *reduction by subsumption*. By this we mean the radical view that some discipline A is included in some other B in the sense that the whole theoretical body (language) of A can be completely mapped (translated) onto a subset of the language of B. This view, which is often expressed by slogans such as "chemistry is nothing but physics" is actually seriously suspect; for it ignores the fact that different languages in science may have emerged and remained different because there were different aims ('programmes') and problems. Although cases of possible equivalence of languages are known – e. g. in solid-state physics and quantum chemistry – it should be expected in general that the sections of reality or worlds of objects described by the two languages are different, and thus no satisfactory mapping is possible. For instance, terms like catalysis and organism are not included in the vocabulary of theoretical physics. The very possibility of language equivalence mentioned above is such only in so far as both solid-state physics and quantum chemistry treat collections of nuclei and electrons by quantum-mechanical methods: but the two languages originate from the need to treat very large periodic systems with weak atom-atom bonds (like metal crystals) on one side, and comparatively small non-periodic systems with a number of strong atom-atom bonds on the other.

In short, it seems almost trivial that any attempt to translate a term from one scientific language into some other language will involve a change in meaning, inasmuch as the meaning of a concept depends on the context in which it is used, viz. on the field of science to which it applies. 'Local' or 'partial' mappings may be possible: but soon at least some relations will be found that cannot be translated without changes in meaning.

Reduction by subsumption may be qualified as radical, in contrast to Monique Levy's moderate reduction by synthesis. What she did was essentially to study the relations between chemistry and physics and to conclude that the asymmetric connection and overlapping of those disciplines could lead to formation of an interdisciplinary field dominated as it were by the more extended partner. *This process could be called per definitionem reduction, but would correspond to inclusion in physics of new concepts coming from the reduced science.* It is a moderate, indeed peaceful form of reduction, because it hurts reality in the least possible way. It is often practiced by theoretical physicists: for example Prigogine's work on dissipative structures, which arose in the process of treating the problems of physical chemistry, is now claimed by many to belong to the body of 'theoretical physics'.

What is least satisfying with the moderate point of view is that the term 'reduction' applied in this way looses its sharpness; and the statement that theory A has been reduced to the theory B becomes more or less a purely historical remark. Therefore, reduction by synthesis is already rather far off from what common sense would understand by reduction.

3. EPISTEMOLOGICAL MODELS OF REDUCTION

One possible way to bring more clarity to the concept of reduction is the construction of epistemological models of reduction. It will not be attempted and is not our purpose here to give a complete review of all the epistemological models od reduction which have been suggested at one or the other time. We rather refer for details to the literature [9–17], and only mention here some main lines of thinking.

The best-known model goes back to Nagel [7]. In Nagel's model a theory A is considered to be reduced to a theory B if A can be obtained as the logical consequence of B (or B plus some additional assumptions) while the language of the two theories may, but need not be equivalent (in the latter case the scientific terms of the reduced theory must be translatable to terms which are well-defined in the vocabulary of the reducing theory).

On the other hand, Feyerabend stresses the "existence of pairs of theories that may be regarded as competitors and yet do not share any element of meaning" [9]. In such cases the attempt to translate one theory into another will involve a drastic change of the meaning of the scientific terms [9, 10]. Now, it may happen that two theories, which in Nagel's view are connected by a reduction relation, form such an incompatible pair; if so, Nagel's model must be rejected, and one should speak of 'transitions between theories' rather than of 'reduction'.

Finally, there are intermediate positions [11–17] which imply modifications of Nagel's model, but still maintain the concept of reduction. The applicability of the intermediate models in question to the relation between physics and chemistry has been discussed in the above mentioned study be Lévy [2], who has grouped together the models in the following manner: Models relying primarily on the criterion of definability [11, 12], models giving priority to the criterion of derivability [13], logico-formal models [14, 15], and models admitting different types of reduction [16–18].

Thus, each of the epistemological models of reduction stresses some particular aspect of intertheoretic relations and neglects other aspects. This idealization of intellectual history is a natural (and necessary) feature of epistemological models. However, as Nickles observes, "unfortunately, philosophers almost inveterately forget the limitations of these models and, in time, come to misuse them" [16].

4. MATHEMATICAL FORMALIZATION OF REDUCTION

Mathematical formalisms are even apter to seduce the user into overestimating their power than epistemological models. Fomalized descriptions of reduction have also been given in connection with most epistemological models, but must be considered with caution. For example, in the framework of W*-logics one characterizes theories by W*-algebras of observables and W*-logics dealing with propositions about the observables.

A W*-algebra is a commutative Banach algebra with involution (C*-algebra) which is the dual space of some Banach space. W*-logics are logics whose lattice of propositions is given by the projection lattice of a W*-algebra. In the framework of such logics one can make the hypothesis that every consistent phenomenological theory is a subtheory of some universal theory in the sense that the W*-algebra of the subtheory is a subalgebra of the W*-algebra of the universal theory. It is claimed that this thesis 'includes all successful reductions so far, and can account for the emergence of properties of wholes not possessed by their parts' [4].

It should be noted that every formalized description of reduction relies on a formalized definition of the *reducendum*: in our example it was a "W*-theory". Actually, preconceived structures come into play when primitive concepts like the notions of property, observable, and proposition are used. This situation is unavoidable, but after a long formal analysis one may tend to forget it. Very often in modern mathematics theorems are made to look almost like trivialities by sufficiently sophisticated definitions, the work being thus shifted from proving to defining. In other words, instead of describing complicated relations between simple concepts, the mathematician describes simple relations between complicated concepts, the so-called proof-generated concepts [19]. It must be kept in mind, therefore, that although formalization is legitimate and possibly important, it does not suppress the need of investigating concepts and their relations to physical reality: in other words, it does not eliminate the necessity of justifying the approach to reduction used.

In the case of chemistry, for instance, doubts could arise whether a science based on operations (as Berthelot put it, chemistry is the science of analysis and synthesis) can be squeezed into a framework which deals mainly with observables and propositions about observables, and thus places emphasis on the measuring aspects of science. In short, the question is not whether a formalization can be found, but whether such a formalization brings a solution to the problem of reducibility.

5. THE BATHOGENOUS AND THE HORIZONTAL APPROACH

The concept of reduction can also be analysed with respect to the approach to scientific explanation characteristic of the disciplines under consideration. Theoretical physics, for instance, is dominated by the 'bathogenous' approach: the ultimate goal is to proceed to 'deeper' and 'deeper' levels of reality, so as to show that all phenomena are the result of the interaction of a few elementary particles, indeed are manifestations of a single unified field.

The adjective 'deep' is used here in connection with the idea of levels of complexity: from the world directly accessible to our senses to biological tissues, enzymes, molecules, atoms, 'elementary' particles, quarks. By going deeper one looses complexity: the physicist goes to the deeper level by resolving the entities of any given level into simpler constituents; so that he plunges deeper and deeper along a hierarchical scale of theories.

In short, *the concept of bathogenous reduction refers in general to the process of treating the* (or at least some) *fundamental concepts of one theory as the explananda of another deeper-lying theory*, even (indeed normally) at the cost of some loss of details. The associated model of explanation will be usually, although not necessarily always, the nomological-deductive one [8].

One possible way to characterize chemistry is to state that it explores reality at a certain level of deepness (or complexity). This level of deepness can be identified in the bathogenous hierarchy of theoretical physics as that of entities in general not smaller than atoms and molecules.

Of course, atoms and molecules also accur on the physicist's hierarchical scale; therefore, from his bathogenous point of view he may consider that he has 'solved' the problems of chemistry because he can account for the *possibility of existence* of those smaller entities in the language of the next deeper level. In this way, however, the physicist has actually reduced to physics just those concepts of chemistry which fit into his bathogenous scheme. For instance, the magnetic properties of a substance are explainable in terms of the magnetic momenta of its molecules and the magnetic momentum of a molecule is explainable in terms of its electronic structure. This is because the concept in question always sees the given particle as a point, and applies as such to an electron as well as to the whole molecule. Evidently, a similar approach would fail to explain the reactivity, acidity or aromaticity of a substance.

For the sake of the argument, let us assume nevertheless that reduction can be understood in this one-sided manner (i. e. rejecting concepts which are difficult to explain in terms of physics). Unfortunately, even then the concept would not easily apply to the relation between physics and chemistry. Physics itself is not always capable of resolving a system into separate parts, but has to allow for holistic effects, as is illustrated by Einstein-Podolsky-Rosen correlations or, more generally, by the existence of 'entangled systems' – systems that have interacted in the past and have then been separated. In this way "spatially separated parts of an isolated system are in general correlated, even if they no longer interact" [4].

There is another approach in science which may be called the 'horizontal' one. This is the Aristotelian approach to phenomena, which consists in the ordering of facts into categories, omission of irrelevant concepts and introduction of operative ones, emerging from the classification process and defined "*per genus proximum et differentiam specificam*". This way of processing the information on complex entities and events in nature based on suitable simple concepts is the approach prevailing in (or should we say specific of) chemistry as well as biology. The typical mark of this approach is just the stopping at a certain level of deepness as suggested by Theobald [1], who cites Aristotle's Nichomachean Ethics: "It is the mark of an educated man to look for precision in each class of things just so far as the nature of the subject admits".

If the approach of physics is addressed as a bathogenous plunge [5], the approach of chemistry could be described as a horizontal floating at a certain level. Connected with this approach is the mode of explanation characteristic of chemistry [5], whereby phenomena are explained by indicating the substances (molecules) responsible for them.

Let us consider typical chemical concepts such as valency, functional group etc. Those concepts are associated to the rules governing the transformations of molecular structures into one another ('chemical reactions'). It is outside the scope of physics to deal with such concepts just because they refer to a scientific approach other than that of physics.

In fact, so different are the approaches of chemistry and physics (and the methods used in those fields of science) that mathematical methods, while being essential in physics, play only a minor role in chemistry. Let us recall here Comte's view, which went so far as to state: "Every attempt to employ mathematical methods in the study of chemical questions must be considered profoundly irrational and contrary to the spirit of chemistry. If mathematical analysis should ever hold a prominent place in chemistry – an aberration which is fortunately almost impossible – it would occassion a rapid and widespread degeneration of that science" (Philosophie Positive, 1830). This is thought-provoking even today: especially to those who know chemistry enough to appreciate the sound part of such an apparently paradoxical statement.

6. THE HISTORICAL PROCESS OF REDUCTION

Once it is clear that the statement that one theory is reducible to some other is strongly context-dependent and has sometimes even been rejected altogether, one may inquire why such ideas (or should one say myths?) came into being.

The answer to this question becomes apparent if the historical processes connected with theory reduction are examined. This can be done, for instance, by trying to apply the "reduction relation to theory-pairs in which one member at some time replaced the other as the accepted basis for research" [20]; in which case the 'new theory must be such that the old theory reduces to (a special case of) the new theory" [14].

However, we can easily persuade ourselves that we do not need to cling to concepts like theory-replacement or scientific revolution for the present purpose. Let us take arbitrary standard examples: the reduction of phenomenological thermodynamics to statistical mechanics, the reduction of the Mendelian theory of heredity to molecular biology, the reduction of physical optics to Maxwell's theory of electromagnetism, the reduction of classical mechanics to relativistic mechanics. In all cases it turns out that the *reducens* is historically younger than the *reducendum*. This remark suggests that the emergence of a "reduction myth" is often (if not always) a symptom of the emergence of a new field or subfield of science. Quite possibly it reflected originally the ambitions and prospects of the new discipline struggling for a place in science, but remained more or less alive as long as the discipline itself. Actually, in all the cases mentioned above, and in spite of the apparent success of the reduction process, the reduced field of science also remained active, although with a somewhat different role than before the arising of a reducing discipline.

This also holds for the relation between chemistry and physics, if it is taken into account that in speaking of the reduction of chemistry to physics one usually refers to physics after the rise of quantum mechanics (which is considered the tool for explaining chemical binding). For instance, Dirac's well-known statement [21], that "the underlying physical laws necessary for the mathematical theory of a larger part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the application of these laws leads to equations much too complicated to be soluble", appeared shortly after the rise of quantum mechanics.

The actual historical process in this case can be described as a kind of merging of some subfields of physics and chemistry, as discussed e. g. in the paper by Lévy [2] mentioned above. In this sense, quantum theory is not only part of physics, but part of chemistry as well (although not embracing all of either science).

At least some of the founding fathers of quantum theory seem to have been quite aware of this situation. In fact, Heisenberg even took the point of view that physics and chemistry have been completely unified by quantum theory: "Actually through quantum theory these two sciences have come to a complete union" [22]. This is quite a radical statement, and in this form raises several doubts about the reductionist thesis: it is perhaps easier to appreciate it by keeping in mind that Heisenberg apparently misunderstood chemistry as being the science of atoms, not of molecules. At any rate, the implication that quantum theory "has its roots just as much in chemistry as in atomic physics" [22] must be considered as recording a historical fact.

7. CONCLUSIONS

The relationship between chemistry and physics has often been regarded as a standard example of reduction of one field of science to another. Actually, as is shown by the above discussion, none of a variety of conceptions of reduction and reductionism is really applicable to that relationship. The reasons for this can be found at least in part in the *difference of the approaches of physics and chemistry*, which have been referred to as the bathogenous and the phenomenological approach.

Construction of epistemological models and/or setting up mathematical formalisms to describe the process of reduction is of no help: proper definitions may well make it possible to prove (even in a mathematically rigorous way) the reducibility of one discipline to another, but then the real task becomes to demonstrate the adequacy of the definitions. Reduction and explanation are concepts which may be perfectly clear in specific contexts: but their application to whole fields of science requires extreme caution, given their inherent limitations. Moreover, a real danger of misleading philosophical and scientific thinking is connected with calling 'reduction' procedures which actually recognize the autonomy and the specificity of a given discipline, and simply amount to attempts to define it as a new chapter of some other discipline. This would be legitimate only if the name of the 'reducing' discipline did not carry with it a specific approach, paradigm, programme, and body of concepts unsuitable or unsufficient for the 'reduced' discipline.

Indeed, the history of science suggests that the concept of reduction is often misused to establish a 'reduction myth' whose practical effect may be to paralyze research in given directions. In the case of physics and chemistry, in contrast to the reduction myth, the real historical process appears as a piecewise merging of some subfields of those two sciences with the formation of new domains (and new sets of *ad hoc* concepts) which are rooted in both the two formerly separated fields of science. This has taken place also at the interface between biology and other sciences, and should be viewed as a perfectly healthy process of formation of interdisciplinary fields of inquiry. The latter are in a sense the cement needed to hold together the edifice of science.

It seems to us that the case for reductionism taken in the sense of mechanism or physicalism is lost without appeal. As always happens, however, this just means that we have to make a fresh start in an old direction. In fact, if Science is neither just physics, nor just chemistry, nor just biology, nor just the general theory of systems, what is it? And what is the profound reason for the success of the beautiful studies of most outstanding contemporary philosophers of science, who based most of their theories and models on the assumption that physics equals the whole body of science? An attempt to answer these questions is out of the scope of this article. But a few remarks may suggest some lines of reflection.

First of all, there is one legitimate use of a reductionist approach, which was already pointed out by the great master Aristotle: understanding requires the formulation of a minimal number of principles or rules, and the identification of the 'elements'. However, Aristotle also insisted that the 'programme' of science should be aimed at grasping the *essence* of a thing as well as (in modern language) the *mechanism* of a phenomenon. Both require a degree of reduction. The central difference between this type of reduction and the one currently advocated until recent years lies in the refusal of 'nothing-but'-ism. That concepts not applying to the parts may be necessary to explain the whole sounds like a truism, but is precisely what was neglected by modern reductionism, and led to myths such as the reduction of chemistry to physics.

In short, science appears to have a much wider scope than the programme of physics implies. The latter is rightly given the title of Queen of the Sciences, since she passes to deeper and deeper levels of reality by applying a systematic reductionism, i. e. by systematically dropping concepts and problems proper of a descending scale of levels of complexity; and thus reaches the very roots of sensible reality. Nevertheless, its approach does not exhaust physical reality: indeed, that very approach would be completely pointless if at the same time there were no attempts to understand entities and events at the various levels of complexity; for the indispensable connection with sensible reality would then be impossible.

As concerns the edifice of science, we could perhaps agree – although just in a formal sense – with the "anything goes" of Paul Feyerabend. There are many ways to answer questions opened by "why?" and/or "how?" in connection with Nature. Each way may require a different type of methodology and even different criteria of truth (confutability, internal consistency, etc.): and thus there may be sciences and theories differing by their natures as well as by their approaches, programmes, and paradigms. The point is that, even if we confine ourselves to physical reality, we are faced with an inexhaustible object of study: there are many, perhaps infinitely many ways of looking at it, and the only criterion for the validity of a given type of approach or of explanation is that we really feel that the representation of the physical reality it brings about in our minds is more satisfactory than otherwise in helping us to gain a richer and richer rational picture of the physical world and a fuller and fuller grasp of the order reigning in it.

The real unity of Science is not to be found by reducing it to a single model of scientific explanation, but by looking at it in the way of the Ancients: as the Philosophy of Nature.

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