Sci & Educ (2009) 18:443–455
DOI 10.1007/s11191-008-9156-4

Physical Construction of the Chemical Atom: Is it Convenient to Go All the Way Back?

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Abstract In this paper we present an analysis of chemistry texts (mainly textbooks) published during the first half of the 20th century. We show the evolution of the explanations therein in terms of atoms and of atomic structure, when scientists were interpreting phenomena as evidence of the discontinuous, corpuscular structure of matter. In this process of evidence construction, new contributions from physicists and physical chemists that were incorporated to chemical research acquired 'chemical' meaning, since they were related to research questions that genuinely came from chemistry. Conversely, the core ideas of 19th-century chemical atomism, among which we must highlight valence and Mendeleev's periodic system, provided 'clues' for imagining an atom in terms of the elements adjusted to their chemical behaviour, which changed periodically as a function of atomic mass. With this, chemistry ceased to be a descriptive science and began to be a 'law-based', *theoretical* science. Little by little, chemistry teaching became the teaching of the internal structure of atoms, which were arranged in the Periodic Table according to criteria and 'construction rules' related to quantum mechanics. We pose the question: 'how can we now teach general chemistry in a way that does not disregard current knowledge about the structure of the atom yet, at the same time, gives priority to *chemical* criteria, thus making such structure useful to interpret chemical change?'.

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1 Didactics of Science, Science, and the History of Science: Presentation of Our Research Focus

Science is a human activity in which many factors intervene, since it develops in various *contexts* (justification, innovation, teaching, evaluation: Echeverría 1995). These contexts finally converge, resulting in a very special scientific 'product', the textbook, which is used—among many other things—to introduce young people to the most *conceptual* aspects of scientific activity. It is often assumed that they will learn the *practical* aspects of the scientific profession when they are themselves performing the activity for which they are being prepared. But, as it is usually accepted nowadays, it is not possible to introduce chemical entities in a meaningful way without understanding adequately why they are necessary, i.e., to what kind of experimental intervention they correspond and how they relate to the chemical behaviour of materials.

1.1 A New Perspective for Chemistry Teaching is Emerging

Until recently, becoming a science teacher required, in the first place, being able to logically reconstruct a particular space of phenomena and to present the set of theory and examples in an *apodictic* (i.e., expository) way; in order to achieve this, the mastery of scientific theories was unavoidable. All other science-teaching activities (experimental practices, problem solving, debates, text writing…) were subordinated to the presentation of content in a rather axiomatic approach. But teaching paradigms have now changed due to many different causes that we will not analyse here; such causes are related both to what we currently know about science teaching and learning (thanks to the contributions of didactics of science and the cognitive sciences), and to the aims that society pursues regarding scientific literacy in citizens (seeking higher efficacy). Current science teaching aims at generating scientific activity in those who learn in order to make them 'competent', that is, *capable of acting, later, as citizens*. To achieve this, science teaching today should provide understanding of the complexity of the situations in which scientific entities were generated and achieved their meaning. Such entities usually seem logical but lifeless in textbooks, and this should change nowadays.

For future citizens, who will need to know how to apply scientific content and will have to make sense of what they learn, we must design chemistry teaching that is more ambitious, that cannot be limited to transmitting ideas without meaning for students. We should design chemistry classes committed to the language networks, theoretical representations and value-laden practices that belong to science. Our school chemistry must take into account how our students will live, and therefore it needs to have a future and, consequently, also a past.

Scientific vocations (without which science would have no future) should be planned for in this new teaching culture. This is why we think science needs didactics of science (i.e., science education as an academic discipline: Adúriz-Bravo and Izquierdo-Aymerich 2005) in order to provide the foundations for new pedagogies. Didactics of science should generate a school science that, just as with scientists' science, develops over time—each person's social and cultural time. Thus, the history of science becomes an unavoidable reference for didacticians of science (i.e., researchers in science education) for different reasons. The main reason is to give science a 'time' dimension. But history also provides resources to 'narrate' the science that has been lived in each particular context, so that students can 'enter history' and understand that they also can live their own 'history of science' as they acquire specific competencies.

1.2 Chemistry Teachers and Chemistry Textbooks

The contexts in which science is generated are diverse and their interactions are quite complex; in this paper, we will deal with one particular context of science—*teachers'* and *students'* science—that is reflected in textbooks; one in which the scientific knowledge to be taught and learnt is portrayed. Such knowledge configures the accepted disciplinary content, to enable students to become professional chemists. The study of this content may show us how authors—chemists *and* chemistry teachers at the same time—select some particular elements of the research that is being produced and published in specialised journals and transform and combine such elements to offer convincing explanations to their readers: the students. We are especially interested in highlighting the agreements that were made when constructing a 'physical atom' that behaved just as the chemical atom should. We will refer to two excellent chemistry teachers—Mendeleev and Pauling—and, by comparing their teaching proposals, examine the changes produced in the way chemistry was taught, with the aim of arriving at some conclusions that may help us teach chemistry nowadays in a better way.

In his 1868–1870 *Principles of Chemistry*, Dmitri Mendeleev elaborated his Periodic Table as an effort to show his own students a comprehensible overview of the chemistry of their time. To serve this aim, he proposed a chemical law—the *periodic law*—that is different in many aspects to physical laws but that, like these, proposes a regularity relating a large number of chemical facts and, in doing so, explaining them. In the sixth edition of Mendeleev's book (1900), physical and chemical properties of substances already appear arranged according to the Periodic Table of Elements, which thus presents students with a 'system of chemistry', which enables them to approach it in a 'reasoned, chemical' way giving an account of why certain substances react with one another and why others do not.

Back in those times, the existence of the atom as a physical reality was not a generally accepted idea, although many chemists did accept it as a plausible working *hypothesis*. The symbols with which chemistry was written allowed imagining an underlying material structure for substances, formed by bound particles, but no-one would yet dare to represent such a structure by means of 'balls' (corresponding to real atoms of the elements in the Table) and 'links' (chemical bonds between these atoms of the elements, corresponding to their valences) as Pauling finally did, and as is currently done in the first stages of chemistry teaching. The problem of such a representation is that it 'forgets' that 'atoms' are different *kinds* of matter, irreducible to one another, and that, by appeal to them, explanation of real, *specific* chemical changes is intended.

As chemistry texts provided evidence of the physical existence of the atom, and at the same time, of other material particles smaller than it, scientists began to imagine an atom formed by electrons, neutrons and protons. Since these particles were the same in all atoms, it was necessary to attribute the 'irreducibility' of the atoms of the elements to their special inner structure. Linus Pauling (1901–1994), in his book *General Chemistry: An Introduction to Descriptive Chemistry and Modern Chemical Theory* (1947), presented recent research on atoms, molecules and electrons by means of images that introduced students to the physical evidence for the atom that chemists had *imagined* to account for chemical facts (Nye 2000). The Periodic Table had to be radically transformed and, since then and until now, has so well adapted to the structures of atoms that it has turned, for students, from a chemical system into a 'system of electrons'. This may worry us as teachers, since where does *chemistry* appear for these students?

The intellectual journey from Mendeleev to Pauling was long and difficult, but also enlightening. When teaching, should we take into account this adventure of imagination and creativity implied in combining new discoveries (radiations and their interactions, quantisation of energy, electrically charged particles, movement of electrical charges…) with chemistry (that already had its own law, the periodic law)? Should we also realise the difficulty implied in explaining *chemical* characteristics of elements by means of atoms, that are all constructed in the same fashion and with the same 'blocks', as a necessary step to going beyond this kind of explanation? Our answer to both of these questions is: 'yes'; *how* to do it is the main goal of our research.

1.3 Our Research Focus: Atomic Theory in Current Chemistry Teaching

In order to approach the two questions stated above, we have analysed a selection of chemistry textbooks from the first half of the 20th century and popularisation books written by the scientific researchers themselves[1]. We want to better understand the function that the Periodic Table had in this process of construction of views as to the structure of the physical atom, since, in spite of its profound transformation during more than one hundred years, the Table's teaching role has remained intact[2]. Mendeleev never accepted the internal structure of the atoms of elements, since this meant to him that atoms could transform into one another, contradicting in this way the very *meaning* of 'chemical element', on which the whole of chemistry was founded. What can we say about this apparent contradiction?

When chemistry is taught at school, teachers and textbooks usually begin by interpreting chemical change as a rearrangement of atoms. Symbols of the elements are taught for use as 'atoms' and students are shown how they can apply this formalism to *write* chemistry. Nevertheless, it is usually taken for granted that students already know how to recognise, and intervene on, the chemical changes to which such abstract languages make reference… when this is, we think, precisely *what should be taught in the chemistry classes*. Because of this situation—and here lies, we think, the problem—the Periodic Table is not perceived by students as a system arranging and ordering the elements from the point of view of their interactions, since students are not acquainted with the latter; they are just confronted with a system that arranges and orders the *electrons* in the atoms.

A brief excursion into the history of chemistry shows us that its specific concepts (element, molecule, simple and compound substance, bond, structure…) and the magnitude that permits 'measuring' in chemistry (the 'quantity of substance') do not derive from the 'real' (physical) atom, but this instead needs to adapt to such ideas in order to provide genuine chemical explanations. The concept 'element' is, in fact, a *chemical* concept, and hence there are as many kinds of chemical atoms (and of symbols) as of elements. Elements were themselves established as a hypothesis of chemistry long before there was physical evidence available (Furió et al. 2002). Understanding this and making it evident in our teaching will allow differentiating more clearly between the physical and the chemical atom; the latter *supports* the 'chemical thinking' that we should develop in chemistry classes.

In previous papers, we have commented on the absence of authentic processes of 'theoretical modelling' in chemistry teaching: chemical facts are explained as examples of an atomic theory of which the main entity is a physical atom (cf., Izquierdo-Aymerich 2006) and no relations are established between different facts, or between facts and abstract

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[1] We have also analysed papers published in the *Journal of Chemical Education* from 1923 (the year in which it was established) until 1950 (cf., Linares and Izquierdo-Aymerich 2004).

[2] In Eric Scerri's recent book (2007), all of the stages of such a process are very well documented.

ideas, that require introducing chemical entities to explain them. The distance between what is being explained in the classroom (chemical phenomena and ways of controlling them) and a robust explanation (a simple, *surrogate* 'world' of atoms related to one another thanks to the Periodic Table and bound together according to simple rules) is so big that very few students can go through it (unless they continue studying science, and even in this case, many of them still have great difficulties). We feel that chemistry that is taught from atomic structures can easily lead to this reductionism, in which chemical facts are practically absent.

In the following sections, we want to present partial results of our research into the teaching of the atomic theory, a brief overview of the landmarks in the process of construction of a chemical atom as a physical entity. We want to insist on the necessary subordination of the physical atom to the chemical atom in chemistry teaching, since otherwise, chemistry could be reduced to physics and would thus no longer have sense as an independent discipline. We think this is a lesson that we can draw from the history of chemistry and profitably use to reflect on chemistry at school and university (Izquierdo-Aymerich 2006; Linares and Izquierdo-Aymerich 2004).

2 The Chemical Atom: Starting Point

Let us consider again what we have discussed above. If we explain chemistry by appeal to the properties of the atoms of the elements, two crucial questions remain unanswered: how can these atoms be 'seen' when we do chemistry? How were these atoms discovered or invented and why? If students never pose such questions, they will always miss a link between real chemical processes and their explanations through atoms. And if they formulate the questions, most current textbooks do not offer them satisfactory answers; students see chemistry as a rather formal endeavour and escape from it when they have the opportunity.

What kind of answers to these questions are we imagining? We think we can find one fruitful answer in 19th century stoichiometry, which gave emergence to an authentic *chemical* atomic theory after a long process that lasted for almost sixty years (from the publication of the first part of J. Dalton's *A New System of Chemical Philosophy* in 1808 until the Karlsruhe Conference in 1860, in which the masses for all known chemical elements were agreed on and the difference between atom, molecule and chemical equivalent was systematised).

2.1 Atoms for Chemistry

We can locate the beginning at Dalton's hypothesis of maximum simplicity, which permitted assigning atomic masses to simple substances, or 'elements', from the stoichiometric laws that were known at the moment, thus initiating the atomic theory… of chemistry! Berzelius (1779–1848) developed this particular atomic theory in a brilliant way, addressing some chemical regularities—such as Gay-Lussac's law of reaction volumes of gases (1811) and the 'atomic' interpretation of specific heats in metals from Dulong and Petit's law (1819). He assigned a relative value to 'chemical portions', or atomic masses, with a scale in which hydrogen had the value 1. He gave a symbol to each portion; with this, he was able to write down formulas for each chemical substance, ones in which the quantities of the elements involved were multiples of that atomic mass. These symbols, with their associated masses, could easily be interpreted as atoms.

Formulas were part of chemists' work; chemists used them as 'paper tools' (cf., Klein 2001) with which they interpreted mass and volume relations. Some important problems needed to be solved in order to accept Avogadro's hypothesis (using it directly, the substance formulas derived were barely credible!). Due to these problems, chemists used one-, two- or four-volume formulas for organic substances according to different criteria, which made it difficult to relate the substance formulas with their properties.

2.2 Molecules

Around 1850, Laurent (1807–1853) and Gerhardt (1816–1856) unified formulas to two volumes. These new formulas reflected regularities that could be interpreted in terms of similar structures for similar substances; they provided criteria to classify substances and processes and to establish 'chemical families'. Structural formulas began to be designed (e.g., carbon tetravalence was established by Kekulé (1829–1896) in 1857…) (Hiebert 1959).

If symbols represented 'elementary portions', then formulas represented the *quantity* of substance. Could a physical entity be imagined to represent such a quantity? For Laurent, such an entity was the *molecule*, that is, the minimum quantity of a substance participating in a process represented by an equation; this led to differentiating between the concepts: 'chemical atom' and 'chemical molecule'.

In 1858, Cannizzaro had published 'Sunto di un Corso di Filosofia Chimica Fato nella Reale Università di Genova' in the journal *Nuovo Cimento*. This paper is an excellent example of the contribution of chemistry teaching to research, since, in it, the author provides students with different entry points to arrive at a sole value of atomic mass for each known element. For this purpose, Cannizzaro uses justifications coming both from physics and from chemistry. Indeed, two-volume formulas were those obtained from Avogadro's hypothesis, which also had empirical backing from physicists' works on specific heats of gases; these works showed that 'chemical molecules' existed as physical entities. Finally, at the Conference in Karlsruhe (1860), Cannizzaro's contribution was crucial (Laurent and Gerhardt had already died); with it, a unified table of atomic masses was elaborated and became accepted by all chemists.

Combination of chemical explanations (regarding chemical transformation of materials) and physical explanations (related to the behaviour of materials in situations in which there is chemical change), as proposed by Cannizzaro, was very fertile, but its consequences did not convince all chemists. When van't Hoff (1852–1911) proposes the tetrahedral orientation of carbon bonds in 1874 to explain optical isomers, these 'three-dimensional molecules' caused anger in some chemists. This is the case with Hermann Kolbe, who, in his short text 'Sign of Times', despises van't Hoff's proposal and qualifies it as imprudent and ignorant of chemical research:

> Whoever thinks this worry seems exaggerated should read, if he is capable of it, the recent phantasmagorically frivolous puffery (…) 'La Chimie dans l'Éspace'. (…) It is typical of these uncritical and anticritical times that (…) virtually unknown chemists (…) pursue an attempt to answer the deepest problems of chemistry which probably will never be resolved (especially the question of the spatial arrangement of atoms). (Kolbe, in Rocke 1993, p. 329)

The atomic hypothesis seemed to some important chemists to be too speculative, but chemistry nevertheless possessed a powerful language of symbols that could be interpreted as real atoms, with their own masses… or not.

2.3 The Periodic Law of Elements

Chemists had agreed on the value of the mass that accompanied elements in their chemical combinations. This ‘atomic mass’, together with a thorough study of the physical and chemical properties of substances, allowed Mendeleev to arrange the elements and enunciate the periodic law (in his *Principes de Chimie*, volume 2, page 351). With this, the crucial concept of a chemical element emerges (Bensaude-Vincent 1979). Such a concept points at the atom, as long as it is a chemical atom, and hence is different for every element. Mendeleev manifests his adherence to the (chemical) atomic theory by insisting on the difference between a simple body and an element, stating that the term ‘element’ *suggests* the idea of atom (Bensaude-Vincent 1994).

The construction of a physical atom had to be done from this chemical atom, whose physical reality was not at all evident, nor even necessary, for many chemists, even if chemical language (formulas, entities) was already unified in atomic terms, using valences and structures, and allowed the writing of chemical equations and the classification and characterisation of chemical processes.

2.4 Disputes and Agreements

At the end of the 19th century, the huge difficulties that chemical atomism faced when trying to explain organic chemistry ‘on paper’ with formulas and equations were overcome by means of *praxiological* and *epistemological* agreements. Among the first kind of agreements, we want to highlight some contributions from physics: evidence that it provided on the corpuscular nature of gases, the properties of solutions and the conductivity of some materials. Among epistemological agreements, we think that discussions on the nature of chemical theories and hypotheses were important; such discussions put chemists from different generations in confrontation with one another. Finally, young chemists (Kekulé’s generation, born after 1820) imposed their point of view: chemical theories and hypotheses became more conventional and chemical language more sophisticated and abstract.

3 From the Chemical Atom to the Physical Atom: Main Hallmarks in a Restless Period

Lavoisier is generally regarded as the creator of a New Chemistry that worked using *instruments* that allowed measuring and reasoning from the results obtained. This new quantitative chemistry, oriented towards the analysis of substances in order to know their composition and to characterise chemical change, had to establish its own ‘territory’, one apart from physics as to questions, methods, hypotheses, entities and so on. But chemistry finally needed physics to decide between the quantities that should represent substances; with this, the real, physical existence of chemical atoms and molecules began to be established. In order to identify new properties in substances, chemists increasingly used new instruments from physics. A new ‘speciality’ in chemistry emerged and became consolidated: *physical* chemistry; this soon evolved into ‘general chemistry’.

In the period spanning from 1890 to 1945, important changes arose: scientific changes (radiations, quantisation, relativity…), political changes (the First World War, the Russian Revolution, the Spanish Civil War…) and social changes (a new social order derived from the wars and from the Russian revolution). We can consider this to be a ‘turbulent’ period and at the same time recognise and admire the creativity of young scientists who shared their knowledge and intuitions in order to 'create a new entity', the physical atom of elements, bearing immense possibilities both for peace and for war.

During this period, different 'models' for matter were under scrutiny. Is what is detected in vacuum tubes a 'fourth state' of matter, showing its ultimate components? What is ether and how does it relate to matter and its chemical properties? Is matter formed out of inert particles? Can mechanics be reduced to energy, which does not require atoms? (Moreno 2006).

Physical chemistry provided the space of confluence between chemical and physical contributions before the First World War; for instance: spectra, interactions between materials and electricity (with the introduction of ions), electron oscillations and light emission, and charge- and mass-relations between protons and electrons.

In spite of all this, towards 1900 atomism lost some supporters when it faced the emergent thermodynamics. Mach and Duhem considered atoms to be 'obsolete'. Ostwald, in a lecture in 1904 at the Chemical Society in London, stated that the laws supporting chemical atomism could be deduced from thermodynamics… and that hence atomic theories had failed. Boltzmann, a defender of atoms, considered himself to be, in 1906 (just before his suicide), a 'loser' against the anti-materialistic spirit around, in which 'real' atoms had no place.

But, in the same period, new evidence appeared. This evidence was accepted enthusiastically by young scientists, such as Marie and Pierre Curie and Jean Baptiste Perrin, who saw in the experiments conducted the culmination of positivism (Wolke 1988). Mendeleev was appalled by these proposals that broke the unity of atoms, which were previously identified with elements. He died in 1907, strongly opposing these ideas, which, contrary to what he thought, would maintain the Periodic Table as a major *didactical* device (Scerri 2007).

From Rutherford to Heisenberg and Schrödinger many other things happened; but still the Periodic Table conserved its place of privilege as an organising heuristic in the formation of new generations of chemists. Niels Bohr's (1858–1928) contributions in Copenhagen managed to explain the stability of the new physical atom that was emerging from incipient quantum mechanics.

Thus, theory at this time favoured the 'construction' of a physical atom, formed by particles and electric charges… but, as Urbain writes in his book (1922), this atom must also be an *element* (Pacault 1994)!

Once the physical reality of the atom, its internal structure, and its relationship with the Periodic Table were accepted, chemists moved to the construction of a theory of chemical bonds, one that should be useful and 'teachable'. And the 'good' teaching of chemistry became of the utmost importance in the consolidation of research at institutions. Quantum theory was introduced in chemistry when interpreting valence, structures and bonds, providing an explanation to the chemical behaviour of matter… As counterpart, chemistry provided quantum mechanics with concrete experimental situations to account for, ones in which quantum equations were required to provide approximate solutions.

In all the cases, an important question arose: 'How should scientific explanations be—realistic and 'visualisable', or abstract and mathematical?'. Occasions to wonder whether the scientific explanation needs to be either 'visualisable' or 'abstract' multiplied (Fernández-Rañada 2004).

In the following section, we will highlight the teaching orientations of the proposals around 'chemical bond', as a result of which the physical atom became part of the explanations used by chemists to justify and represent chemical change, and we will give more consideration of US scientists.

4 A New Way of Teaching Chemistry

Chemists continued to practise chemistry, paying attention to those contributions by physical chemists that helped them to interpret their findings. The physical atom that interested chemists was expected to be able to ‘react’, that is, to form bonds with other atoms in the way in which chemistry had established. Big molecules and their structures now posed a challenge that the incipient ideas concerning a physical atom needed to face.

4.1 Bonds and Reactivity: Static or Dynamic Electrons?

Towards 1900, Gilbert N. Lewis (1875–1946) left Harvard and travelled to Europe; he worked with Nerst in Göttingen and with Ostwald en Leipzig. He came back to the US in 1901. There, when faced with the task of explaining the laws of valence to his students, he figured out the idea of representing the atom as a series of concentric cubes with electrons at each corner; such cubes explained the eight-element periods in the Periodic Table and were in accordance with the electrochemical theory that chemical bonds were formed when electrons were transferred. Such a proposal was initially not very well received, but constituted the basis for Lewis’s 1916 paper, in which the bond is modelled as two shared electrons.

Lewis’s model permitted representation of a vast number of molecules, but did not match with the ‘physical atom’ based on spectroscopy, which required moving electrons; it also clashed with Bohr’s atom. The dispute was not over until 1923, when Lewis publishes his book *Valence and the Structure of Atoms and Molecules*. Irving Langmuir (1881–1957) was right in defending and developing this incipient model (now known as Lewis-Langmuir’s), and he introduced two kinds of bonds, which he labelled as ‘covalent’ and ‘electrovalent’.

4.2 Adaptation of Quantum Mechanics to Chemistry

The ‘electron pair’ turned out to be useful in explaining reaction mechanisms, such as displacement, and was the basis for the new quantum chemistry of London, Schrödinger and Pauling. Along this process, work by chemists, such as R. Robinson (in Oxford) and C. Ingold and his wife Edith, was paramount in configuring the characteristics of the ‘real’ chemical atom.

Theories coming from physics and chemistry—and often impelled by their teaching—intertwined and advanced together. W. Heitler (1904–1981) and F. London (1900–1954) explained the molecule of hydrogen with the ‘new mechanics’, and F. Hund proposed a completely different approach, which he named ‘molecular orbitals’. Linus Pauling adhered to the first view, which he considered to be more ‘visualisable’ and more adequate for teaching purposes. He therefore developed his theory of hybridisation, which he had advanced when teaching (Nye 1996).

4.3 Chemistry Textbooks

During these years, chemistry textbooks had continued the traditional teaching proposal: chapters devoted to the properties of substances, ordered according to Mendeleev’s Table, which systematised them. From Bohr and Lewis onwards, chemistry could become more theoretical and less descriptive: it had obtained a *justification* for its main law, the periodic law, even if such justification was not what

Mendeleev himself would have liked. By the 1920s, it was more or less accepted that the chemical atom had a real physical existence and that it was formed out of electrically charged particles. These new ideas began to appear in chemistry textbooks, as annexes or as specific chapters (e.g., in Spain, in Vitoria's books, in their successive editions from 1916, the atomic theory therein constitutes an annex that became more and more extensive).

The French translation of Nerst's *Treatise of General de Chemistry* (in 1921) included: the new theories of thermodynamics and relativity, atomic theory (the chapter devoted to it discusses stoichiometric laws and Avogadro's hypothesis, the periodic system, the constitution of atoms, spectra of the elements and atomic numbers as *net* positive charge in nuclei), X-ray spectroscopy and radioactivity.

We have seen the importance of Pauling's ideas in explaining chemical bonds with quantum mechanics. His labour as a teacher was of no less importance. Since his return from Europe, in 1927, he taught chemistry at the California Institute of Technology (Caltech), in Pasadena. Pauling had already been educated in the modern chemistry of atoms, but could not find suitable books to teach it to his own students. Again, as we have discussed in many other cases, *teaching needs* impelled new ideas: it was difficult to explain the equivalence between carbon bonds, and Pauling did so by introducing a new idea of the mixture, or 'hybridisation', of *s* and *p* orbitals.

Nevertheless, his didactical constructions did not completely coincide with proposals from some other great teachers: J. Hildebrandt (University of California at Berkeley) or A. Noyes.

Pauling realised that two different perspectives were in competition, corresponding to two diverse sets of foundations: one giving priority to thermodynamics and another one giving priority to atomic structure; he opted for the second, while Hildebrandt attempted to combine them in his own book.

Pauling wanted to transform chemistry teaching starting from the new principles of quantum mechanics applied to chemical reactions. He was convinced that, in order to motivate students, they should be presented with concrete images of the molecules, from which chemical properties could be derived; he thought that the application of mathematics to chemistry was not deemed important by students. Under his direction, plastic and wood molecular models were elaborated. In this way, Pauling aligned with the tradition of Dalton and Kekulé; perhaps Kolbe would have criticised him as he did with van't Hoff.

In 1947, Pauling got his *General Chemistry* published. The book was a great editorial success. Atomic theory and bonds were the core of the book, but descriptive chemistry was also important. The Periodic Table continued to play a central role in his didactical proposal, but the periodic law had turned into a 'rule' to construct atoms from protons and electrons.

Pauling's book has provided the 'cast' for many textbooks that followed, even until now. The 'usual' current textbook begins with an exposition of the atomic theory, from which descriptive chemistry is derived. Authors have almost always opted for images to make the world of atoms more 'real' than the world of substances.

Textbooks explain the construction of the physical atom as the discovery of something that was unknown, whose structure is progressively revealed. But the 'dialectic' of this atom with real chemical phenomena is in many cases lost; students do not become acquainted with such phenomena and therefore fail to understand the atomic theory, as they cannot 'see' what it comes to explain.

5 Concluding Remarks

The process of 'construction' of the physical atom that we have 'narrated' in this paper would not have been possible if there had not been a pre-existing idea of the chemical atom that could not be left aside since the whole of chemistry was based on it. The physical atom was constructed not only from physics, but also from hypotheses that chemists had elaborated about its existence and properties; but the structure of this atom is not in itself 'chemical'. Our historical review has permitted us to assess the paramount intellectual adventure thanks to which quantum mechanics was configured. We have also suggested that the 'refined' product of this quest—the idea of the physical atom—could be of little use when learning chemistry if historical aspects are disregarded (Linares and Izquierdo-Aymerich 2004).

The physical atom has acquired a central role in current chemistry teaching; but we think that, in order for it to have genuine chemical meaning, it must be able to function as a *chemical entity*. In our opinion, it is only in this way that electrons and structures are meaningful within the framework of chemistry. That is, even if the idea of the physical atom was 'logically' constructed *from* that of the chemical atom in scientists' science, students cannot equally well derive the ideas of chemistry from those of the physical atom: the process is—in this sense—not 'reversible'.

The chemistry-on-paper that is derived from the behaviour of quantum atoms, represented through formulas and equations, with heavily stylised semiotic devices such as dots and arrows, might be much simpler than experimental chemistry and could perhaps be taught more easily. But it might not make sense for its audience: atomic theory with its symbols and representations are needed… *to support chemical thinking*, but they cannot substitute for it. We surmise that Pauling would probably agree with our last comments and he wouldn't provide structural answers without chemical questions that made those answers necessary.

Chemistry cannot be introduced *only* via physical entities; the *praxis* of chemistry is irreducible to that of physics. This reflection leads us to consider that, nowadays, we would need to help students to 'decode' the Periodic Table so that it continues to contribute to chemistry teaching and to understanding the concept of a chemical element.

All current chemistry textbooks consider Dalton to be the 'father of the atomic theory', as if his theory were to be the one accepted nowadays. This linear simplicity when reconstructing the process of 'doing science' is a 'history' provided by textbook authors, which can be analysed from a *didactical* perspective, since it is laden with instructional intentionalities. But we could also argue that such a biased reconstruction of chemistry could be confronted as well when trying to capture the complexities of scientific thinking and to value the contribution of teaching to the development of chemistry.

We must also state in a most conclusive way that we think chemistry *cannot go* 'all the way back' to being a descriptive science, centred on the physical and chemical properties of substances. Being finally able to establish *relations* between the internal structure of materials and the chemical interactions between them is a major achievement that we do not want to give up in any way. However, it should remain clear that what we want to manage and understand in chemistry classes is *chemical change*.

Acknowledgements We thank the editor, reviewers and language advisor provided by *Science & Education* for their help with our manuscript

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