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Technochemistry: One of the chemists' ways of knowing

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Abstract In this article, from the characterization of technoscience of the English historian J. Pickstone and the recognition of the importance of models and modelling in research and teaching of chemistry, the term technochemistry is introduced as a way of chemical knowledge. With the above new possibilities for rethinking the chemistry curriculum are opened.

Introduction

Although the history of chemistry has captured the interest of chemists and chemical educators, the philosophy of chemistry has not received as much attention (Scerri 2001). Nevertheless, the way in which chemistry is taught all around the world implies a unique philosophical position which can be characterized as logical positivism (Van Berkel et al. 2000; Erduran and Scerri 2002; Van Aalsvoort 2004). Chemistry education practice has not been driven to any great extent by educational, historical, or philosophical research findings. A few years ago J. Moore, as editor of the influential *Journal of Chemical Education* (Moore 2005a, b), indicated the poor impact of chemical education research on teaching and learning.[1] For example chemistry teachers generally ignored the fact that chemistry is the most productive among all of the sciences. The growth of chemical information in the

[1] That year was particularly interesting in *Journal of Chemical Education*. For example in another editorial Moore indicated (2005a): "There is clear evidence that the types of questions we ask also can influence our ability to assess students' knowledge accurately. Students who "solve" problems by memorizing and applying an algorithm often do not understand the concept underlying the problem solution". The same year witnessed a 'philosophical' debate between two well known chemists about what was chemistry (Sacks 2005): "The assertion that "Chemistry is the combination of principles and facts that caused the formation of the earth and its layering, that governs the ecosystem…" is bad enough, but, following the assertion that "Chemistry existed before… there was life", it implies that the "principles" and "facts" are properties as substantial as matter itself."

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last century has been outstanding. Thus, being up-to-date, being universally informed has become a mere fiction for many decades (Schummer 1999). However, the changes that have occurred in textbooks during the past four decades do not show any real recognition of the growth in chemical knowledge.

For the Canadian philosopher I. Hacking the activity of the experimental sciences is the result of *Representing and Intervening* (1983), as the name of his influential book so indicates. These two enterprises are not disjoint scientific activities but mutually reinforcing. In the laboratory, intervening by making use of apparatus and instruments increases awareness, and enables new performances. The American philosopher L. Laudan began his well-known book *Progress and its Problems* (1997) with the claim: *science is essentially a problem-solving activity*. For him and other science or technology philosophers (Toulmin 1972; Arthur 2009), problems and problem-solving are central to both scientific and engineering activities, in opposition to the traditional and positivistic view of science in science courses (McComas 1998). Particularly engineering philosophy is orientated toward the technological mode of 'being-in-the world', where design,[2] construction, implementation and manufacture are different steps towards the same aim: 'the designed world'. Design constitutes the cognitive bridge between the ideas and the products of technology existing in the real world. As can be seen in *Science for All Americans,* a long-term initiative devoted to reform K-12 education from the American Association for the Advancement of Science (1990, p. 107):

> The world we live in has been shaped in many important ways by human action. We have created technological options to prevent, eliminate, or lessen threats to life and the environment and to fulfil social needs. We have dammed rivers and cleared forests, made new materials and machines, covered vast areas with cities and highways, and decided –sometimes willy-nilly- the fate of many other living things. In a sense, then, many parts of our world are designed, shaped and controlled, largely through the use of technology-in light of what we take our interest to be. We have brought the earth to a point where our future well-being will depend heavily on how we develop and use and restrict technology. In turn, that will depend heavily on how well we understand the workings of technology and the social, cultural, economic, and ecological systems within which we live.

One way to embrace both the science and technology aspects of contemporary scientific activity is through technoscience, a term suggested originally by the Belgian philosopher G. Hottois (1984) and later generalized by the French philosopher B. Latour (1987). The main notion considered in the present work is that chemistry, as technoscience or technochemistry, must be incorporated in chemistry education.

[2] As Flusser indicated (Flusser 1999, pp 17–18): In English the word *design* is both a noun and a verb… As a noun, it means—among other things- 'intention', 'plan', 'intent', 'aim', 'scheme', 'plot', 'motif', 'basic structure' all these (and other meanings) being connected with 'cunning' and 'deception'. As a verb ('to design') meanings include 'to concoct something', 'to simulate', 'to draft', 'to sketch', to fashion', 'to have designs on something'. The word is derived from the Latin *signum*, meaning 'sign' and shares the same ancient root… Falling into the same category are other very significant words: in particular *mechanics* and *machine*… Another word used in the same context is 'technology'. The Greek *techne* means 'art' and is related to *tekton*, a 'carpenter'. The basic idea here is that wood (*hyle* in Greek) is a shapeless material to which the artist, the technician, gives form, thereby causing the form to appear in the first place… Such considerations in themselves constitute a sufficient explanation of why the world *design* occupies the position it does in contemporary discourse. The words *design, machine, technology* and *art* are closely related to one another, one term being unthinkable without the others, and they all derive from the same existential view of the world.

Technoscience

During the Cold War, a philosophy of science which defended science's superior analytical purity and focused on science methodology and the reduction of various scientific disciplines to physics was enthroned in most of the Anglo-Saxon intellectual world (Echeverria 2003). Since 1938, when Reichenbach's book *Experience and Prediction, an Analysis of the Foundations and the Structure of Knowledge* was published, the distinction between contexts of discovery and justification occupied a prominent place in the philosophy of science. Since then, at its most known version,[3] logical positivism, presenting science as a linear succession of successful discoveries and placing the emphasis on factual recall with confirmatory experiments, contributed to identifying what kinds of research questions and issues were adequate. As indicated by Reish (2009, p. 458):

> Had these mechanisms that transformed philosophy of science been somehow diverted, displayed or counteracted, if the profession had not only allowed but also encouraged its brightest lights to complete its technical work in philosophy, with analysis of the issues and public debates, one can only wonder if the plans of scientific philosophy to help realize a more informed public scientifically and epistemologically, and maybe a more peaceful, economically stable and just world, would not have seemed so naive and deluded as they appear today.

But in the 1960′s, several philosophers of science started to question the lack of historicity of logical positivism, which was based mainly in the context of justification (Reichenbach 1938) and proposed alternative ways of conceiving the philosophy of science based on historical ideas such as change, progress, or revolution (Toulmin 1961, 1972; Kuhn 1969). More recently several philosophers have also questioned other traditional assumptions of logical positivism such as reductionism and verificationism (Popper 1969; Hacking 1983; Laudan 1997; Harré 2004). This indicates that the philosophy of science has escaped the constraints imposed by the context of justification without losing sight of the question of rationality. New and different ways of approaching the philosophy of science have emerged, for example Giere (1999) considers that science does not need laws because: *science does not deliver to us universal truths underlying all natural phenomena; but it does provide models of reality possessing various degrees of scope and accuracy* (p. 6). A different modern approach to the philosophy of sciences is based on the concept of technoscience, conceived as a way of knowing and acting, and not just simply as research done using apparatus and instruments, as an expression of the primacy of 'utilitarian' technology over pure and disinterested science, or as a neutral term used to describe the current regime of scientific research (Bensaude-Vincent and Simon 2010).

In this paper, rather than follow the evolutionary approach of Toulmin (1972),[4] or the philosophical ideas of Hacking (2004) or the sociological ones of Latour (1987, 1999,

[3] This was the 'logical' part of logical positivism. O. Neurath, one of the Vienna Circle founders, had another sociological agenda. He promoted, for example, Isotypes as an International Picture Language. With strong Marxism influence he died before the logical part became the only one.

[4] However it is important to remember his rationalistic approach to science and technology. For him (1972 p. 370): "What marks a scientist's as rational is not his competence in the formal manipulation of established concepts and arguments: rather, it is his readiness to think up, explore and criticize new concepts, arguments and techniques of representation, as ways of tackling the outstanding problem of his science. So, in both science and technology, the operative question of rationality arise over the justification of procedural changes; and they arise in similar ways, whether the procedures in question are 'scientific', i.e. explanatory or representational, or 'technological', i.e. practical or technical."

2003) I share the techoscientific approach proposed by the English historian J. Pickstone (2000) in his book *Ways of Knowing*.

Pickstone (2000, 2005, 2007) addresses the history of science and technology originally from four ways of knowing (WoK), which then he links with four WoW. Knowing is not just a mental operation, it is also a mode of doing. For him:

> As western society has grown more complex, so ways of knowing and doing have been built up. These 'ways' or projects interact in various ways and their 'coverages' vary over time… history of science and technology is not a matter of successions, or the replacement of one kind of knowledge by another; rather it is a matter of complex cumulation and of simultaneous variety, contested over time (2000, p. 9)

He divides the four ways of knowing-working in two groups. The first group concerns only one way of working-knowing, and it is world-reading, *i.e.* hermeneutics and rhetoric related with religion and eternal truths, which will not be not considered here. The second group considers three ways of knowing-working: natural history-craft; analysis-rationalization and synthesis-invention.

Natural history and craft[5] deals with kinds. Natural history refers to a first classification of the different components of the world, i.e. the variety of all things, whether human or natural, "normal" or "pathological." *It is about the 'notebook' cultures of men and women who loved to 'take note' of their surroundings- not chiefly for meaning, nor necessarily for use, but for the wonder of it or from a compulsion to identify and collect* (2000, p. 60). Crafts allowed humans to transform animal, plant or inorganic materials into food, clothes, housing, weapons or implements. Natural history is the space of taxonomies: celestial, geological or biological and the place where they become public, botanical gardens, zoos and science museums.

Analysis and rationalization deal with "components" or elements. If natural history recognizes the variety and change in the world, analysis, as a way of knowing, seeks order by dissection. In analysis objects can be seen as composed of "elements" or "processes". Analysis happens in the public space of laboratories (anatomy, chemistry, physics and engineering) in schools, colleges, polytechnics, hospitals and universities. It is important to recognize that the activities carried out in laboratories, spaces dedicated to practical work rather than to theoretical research, have been considered traditionally of less intellectual value. The Latin word *laborare* remind us of manual labour conducted by slaves in both the Roman Empire and the Greek cities. However, even since that time the most important feature of a laboratory was recognized to be its isolation from everyday life. Chemical laboratories that predated physics labs by almost two centuries first accomplished this (Crosland 2005). In laboratories chemistry becomes a profession *and in all these roles—improving production, assessing pollution, devising regulations,* etc.—*chemist functioned chiefly as analysts; and for the most part that is what was taught in institutions of chemical education* (Pickstone 2000, p. 104). Analysis as a knowledge practice may be associated with the technical practice of rationalization particularly of manufacturing production.

Synthesis and systematic invention creates systems. If analysis is to separate the "elements" that make up the world, synthesis is to put them together. In this way one can have control over them and create new phenomena. Synthesis is based on the systematic production of novelty. It is the "private" space of control either for military or economic purposes (in biomedical, new

[5] The word craft in English language refers to art or cunning. As indicated at the end of the seventeenth century in John Oxon' book *The Mechanical Exercises of the Doctrine of Handy-Workers*, Handycraft signifies Cunning or Sleight or Craft of the Hand which cannot be taught by words but is only gained by Practice or Exercise (cited in Vega 2010, p. 170).

Table 1 Ways of knowing and working (second group only)

Production of		
Knowledge		Commodities
Ways of knowing	*Act on/with "objects" as*	Ways of working
Natural history	Kinds	Craft
Analysis	Compounds	Rationalization
Synthesis	Control(led) systems	Invention

materials or nuclear physics laboratories), and its products become public in the industrial techno-scientific complex. Synthetic chemistry, through experimental work is a key example. Synthetic chemists not only prepare experiments, and design and construct devices (there is an important tradition within chemistry in this sense, Knight 1995); they also create phenomena as well. As Cerruti (1998) indicated: *phenomena are generally accepted, and philosophically discussed, as the aims and the result of experiment in physics; in general, substances are the aims and the results of the most important experimental practices in chemistry* .[6]

Table 1 summarizes the relation between WoKs and WoWs. It is important to recognize that both are used like elements in modern chemistry instead of taxonomic boxes, it means, they can be combined. Pikstone exemplifies this in chemistry as (2005, p. 270):

> Analysis in academic chemistry c 1800 was built on the natural history of stuffs, and also worked with the newly systematized chemical elements of Lavoisier. Chemists who wished to improve the yield of chemical processes based on crafts were sometimes able to use this "elementary" analysis to elucidate and refine the process; in other words, chemical technics could sometimes draw on the same kind of analysis and elements which passed muster as good chemical science. But improvers of technical processes often had to work through a kind of practical natural history (such as knowing where good ingredients could be found and how they might be judged by eye), or by suggesting refinements to the craft process, or by what we might call technical analysis (such as dividing obscure processes into component parts and systematically varying the conditions in order to increase yields).

So according to Pickstone taking into consideration the different ways of chemists' work, which of course change in intensity over our own history, chemistry can be seen as a craft, as a rationalization or as an invention. Or in a particular historical time, as the overlap of any two of them, or of all three.

Chemists' ways of knowing

In Aristotle's *Nicomachean Ethics, techne* is defined as a capacity acquired by habit or practice that is accompanied by reasoning and whose objective is the production of novelty. Later he

[6] Cerruti also indicated the importance of solvents like instruments: "A fundamental use of certain solvents is to permit reactions between other substances that—under different conditions—would not be able to react, or would react in a different way. Thus, in many cases, solvents provide reaction media, tailored on chemist's synthetic needs: on a single laboratory bench, in otherwise equal vessels, different solvents furnish distinct environments in which the same substances have unlike interactions". The author's own chemistry research experience, with air-sensitive compounds, that can be isolated and characterized only in an argon atmosphere fully agrees with Cerruti's ideas.

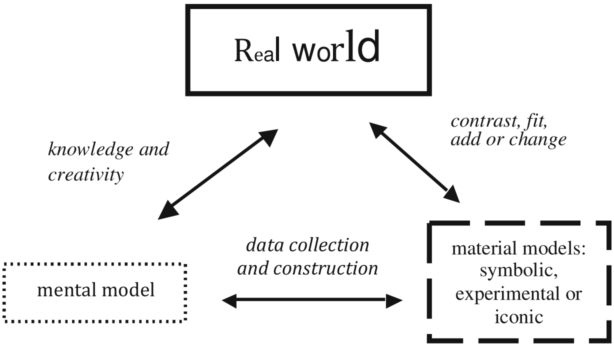

Fig. 1 The relationship between the real world, the two types of models and modelling (*in arrows*)

notes that decision is also relevant as an appropriate means, because an incorrect account of the media employed would make the action not only technically but morally inadequate. Reasoning could grow if the chances of thinking about the results of technical development are allowed. Here are deployed skills to identify possible targets and overcome risks discussed in search for successful solutions. Many years later, in 2003, the Committee on Challenges for the Chemical Sciences in the 21st Century of the National Research Council published the report *Beyond the Molecular Frontier* (Breslowet al. 2003). It states, conclusively, the importance the design and synthesis of new substances and its analytic counterpart will have. Besides Pickstone suggests *that crafts are generally inherited rather than novel, and that rationalized production in some sense reconstitutes existing processes, but that (synthetic) invention like (synthetic) experimentalist creates novelties –things and processes that did not exist before* (2000, p .158). To do this is necessary, as the German philosopher H. Arendt[7] recognized years ago as 'the guidance of a model' something that Suckling et al. (1978) widely exemplified in chemistry (such as quantum mechanics, functional groups, linear free energy relationships, hard and soft acids and bases).

Models (m) are representations, usually based on analogies, which are built contextualizing certain portion of the world (**M**), with a specific goal (Chamizo 2011). In chemistry, models are also mediators between the real world and us. It means they function not only as representations but also as means of intervention (Hacking 1983). *It is when we manipulate the model that these combined features enable us to learn how and why our interventions work (*Morgan and Morrison 1999, p. 12). As can be seen in Fig. 1 in their relation with the real world not only models can be altered but also the real world becomes altered.

In this definition all the words are important: the representations are essentially ideas, but not necessarily as they can also be material objects, phenomena or systems (all of them constitute a certain part of the world **M**). Representations have no meaning by themselves; they come from someone (either an individual or a group, usually the latter) that identifies them as such. The development of an analogy that is made up of those features or properties that we know are similar between (m) and (M) is often the first step of modelling. That are built contextualizing certain portion of the world **M**, refers to a historically defined time and place it also frames the representation. A model is usually one in a

[7] Arendt (1958, p.140–141) stated: "The actual work of fabrication is performed under the guidance of a model in accordance with which the object is constructed. This model can be an image beheld by the eye of the mind or a blueprint in which the image has already found a tentative materialization through work. In either case, what guides the work of fabrication is outside the fabricator and precedes the actual work process".

historical sequence in a particular area of knowledge. Is the result of previous historic decisions of the institutionalization of successful solutions. Some portion of the world indicates its limited nature; models (m) are partial for the world (M). A specific goal, establishes its own purpose, here a way of knowing and working.

There are only two types of models: mental and material.

Mental models are reflected representations built by us to account for a situation. Material models are the ones that we have empirical access to and have been built to communicate with other individuals. Material models are expressed mental models and can be further: symbolic, experimental or iconic.

Symbolic material models correspond to the languages of sciences, such as mathematics or chemistry. So those constructed mathematical equations to describe precisely the portion of the world being modelled (Malvern 2000; Mehrtens 2004) are symbolic material models. These models represent the regularities that different scientific communities at various times in its history identified with some portion of the world (M). Other example of symbolic material model is the one used by chemists to represent elements, compounds and reactions (Crosland 1962; Hoffmann and Lazlo 1991). The chemical knowledge obtained through symbolic models long time ago (Vollmer 2006) and devoted both to rationalization and invention has been well identified by Klein (1999, 2001, 2003) and Morgan and Morrison (1999, p. 18):

> …In 1853 Dumas used his formula equation to introduce the notion of substitution, something he would later develop into a new theory about the unitary structure of organic compounds. This notion of substitution is an example of the construction of a chemical conception that was constrained by formulas and formulas equations. Acting as models these chemical formulas were not only the referents of the new conception but also the tools for producing it. Through these models the conception of a substitution linked, for the first time, the theory of proportion to the notions of compound and reaction. We see then how the formulas (models) served as the basis for developing the concept of a substitution, which in turn enabled nineteenth-century chemists to provide a theoretical representation for empirical knowledge of organic transformations.

In addition to symbolic material models are experimental material models and iconic material models. Examples of experimental material models (Harré 2009) are male Sprague–Dawley rats used in a standardized way in biomedical research or disease modelling action for possible future remedies. Experimental material models are also devices or apparatus (Harré 2004), such as the famous Urey-Miller (recreating the atmosphere's original conditions that allowed the generation of amino acids) or the Tokomak (used to study the fission reactions that occur in stars), carrying out experiments to simulate a particular aspect of the world (**M**). Iconic material models correspond to images, diagrams, or scale-models, like a map (Tversky 2005) or the so-called 'molecular models' and also simulations and animations (Kozma and Russell 2005). Stereochemistry (Ramsay 1981) was constructed with iconic material models in three dimensions (De Chadarevian and Hopwood 2004). For example, in the early years of nineteenth century, in England, Dalton constructed wooden models of atoms and Hofmann his croquet ball molecular models.[8] As Pickstone (2000, p 142) indicated about Hofmann:

[8] In the same direction as Morgan and Morrison before (Meinel 2004 p. 269) indicated: "In all the cases the models have a life of their own. They are neither mere representations of scientific theories or data, nor are they purely practical tools. This partial autonomy, which is partly embedded in their physical structure, is a tricky thing, for it may give birth to developments not intended by those who made these models. At the same time—and this seems to be peculiar to chemistry—they provide a material link between theoretical notions, chemical reactions, and the body and gestures of the chemist."

> He promoted this pioneering institution (Royal College of Chemistry founded in 1845) not just by training analyst, but by pointing to the possibilities of synthesizing new materials. Interestingly, atomic models were central to his demonstrations; wooden balls joined by sticks allowed chemists to envisage how atoms might be arranged in compounds. If you could model natural compounds, you might extend your models to new compounds and then try to make them. Models encouraged ideas of 'building' new molecules.

Today, there are several million chemists all over the world writing about one million documents (papers, books and patents) a year (Schummer 2006). They rationalize, invent and intervene in the world producing new forms of matter (Hall 2000). As noted Bertholet, about 150 years ago: *they create its object*. This means, and in agreement with Arendt, that chemists usually produce in their laboratories (sometimes through experimental material models), using symbolic material models or helped by iconic material models, a large variety of new substances.[9] This is technoscience, deeply rooted in chemistry' history and practice.[10] Pickstone indicated again (2000, pp. 163–164):

> Technoscience is a way of knowing and a way of making… Synthetic technoscience is when academics and industrialist work on model systems that are philosophically and commercially interesting, and when synthetic experiments/inventions are developed in networks of universities, research institutions and industrial research laboratories.

The biological version of technoscience is called synthetic biology. Remembering what Pickstone said, unlike analysis that seeks to recognize the 'elements' which constitute the world, synthesis addresses the problem of putting them together. This is a design issue. Bensaude-Vincet recognized it recently (2010, p. 228):

> Synthetic biologists have developed an approach in which they break production processes down into their constitutive elements in order to identify the 'unit operations' in the synthetic process. In this respect, they seem to have adopted the method invented by chemical engineers for chemical synthesis a century earlier… Thus in adopting the

9 Schummer stated (Schummer 2004, p. 399): "…however, the great majority of chemists actually produce new substances. That is by far the largest scientific enterprise—roughly estimated, a third of all scientists worldwide are involved in this project. Surprisingly, no philosopher of science seems to have ever been aware of it." Related to this and the importance of models see also Pagliaro (2010).

10 For example about the difference between chemistry and physics, Toulmin indicated (1972 p. 149): "If we mark sciences off from one another by their respective 'domains', even these 'domains' have to be identified, not by the types of objects with which they deal, but rather by the questions which arise about them." More recently Talanquer recognized (2011): "The symbiosis between the science and the industry has given a unique character to chemistry, its practice, and its institutions. Let us compare, for example, the current employment distribution for chemists and physicists in the US. According to the US Bureau of Labor Statistics (US BLS 2010), close to 48 % of all physicists in the country work in post-secondary educational institutions versus 52 % who hold jobs in other areas. In this latter group, only 4 % of these professionals work in manufacturing while around 77 % of them are involved in research or educational activities in a variety of governmental agencies (e.g., national labs and observatories, NASA). In contrast, only 21 % of all chemists hold jobs as post secondary faculty versus 79 % employed in other areas. Of these latter professionals, close to 42 % work in manufacturing while only 23 % are involved in research or educational activities. As we can see, while close to 88 % of all physicists in the US are involved in research or education, only 39 % of chemical scientists participate in those types of activities. Although, this disparity in the types of activities in which working chemists and physicist are involved may vary from country to country, analysis of available labour data from other industrialized countries such as the UK (HESA 2002) suggests that similar divergences in the landscapes of physics and chemistry as professions can be seen throughout the developed world. While physics as a practice can be well characterized as a scientific enterprise, chemistry should be better conceived as a hybrid of academic and industrial endeavours."

program of synthetic chemist, synthetic biologist have reopened the offensive against vitalism, breaking down any remaining barriers between the living and the inanimate.

Against the common idea that technique is the answer to a need, the Spanish philosopher J. Ortega y Gasset (1982) characterized it as "the production of the superfluous", with emphasis on human capacity, that now and in the Paleolithic era human life itself is created. It means it is "artificial" as opposed to the life of animals that only "exists".[11] Hence, as Bhushan (2006) and also Bensaude-Vincent recognized (2010), the boundary between the natural and the artificial is unclear. This difficulty in chemistry's history reminds us of the discussion on vitalism (Benfey 1975). However, in terms of technoscience, once it is explicitly recognized that there are particular targets, the priority seems to be the actions performed rather than the substances created. There are no substances without action and without design. They are not only the result of intentional human action but they also make sense embedded in a specific historical context. The main way that chemists' know is by doing and this action increases the complexity of the world.[12] In this way, chemistry is a technoscience, particularly Pickstone' synthetic technoscience, which can then be characterized or defined[13] as technochemistry.

Learning chemistry as technochemistry

We learn about the world mainly learning about how to intervene in it. The know-how involves learning processes of the practice whose explanation lies not only in the internalization of declarative statements and facts.[14] This is not commonly accepted in schools and universities. For example, after he had analyzed current and post-war textbooks and syllabi representative of secondary chemistry education in most Western countries trying to find why they are so remarkably similar, Van Berkel et al. (2000) recognized that the structure of the currently dominant school curriculum *is accurately described as a rigid combination of a specific substantive structure, based on corpuscular theory, a specific philosophical structure, educational positivism, and a specific pedagogical structure, initiatory and preparatory training of future chemists.* Furthermore (Gilbert et al. 2000) emphasizes:

> The major purposes of chemical education in the 21st century will be to introduce all young people to the implications of chemical technologies and to provide the basis for the advanced study of chemistry by only some of those young people. In order to

[11] "Under this perspective, human life, the existence of man appears formally consisting essentially of a problem. For other entities in the universe there is not a problem, because existence means effective, conducting an essence" (Ortega y Gasset 1982 p. 51).

[12] About this Schummer recently stated (2010): "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."

[13] There are a general agreement that a definition should be in positive terms, not be too broad or narrow, nor circular and neither use figurative language.

[14] Here it is important to recognize the narrow characterization of technology as only applied science. A wider and consensual approach indicated that technology is: "The application of scientific or other knowledge to practical tasks by ordered systems that involve people and organizations, productive skills, living things and machines" (Dusek 2006 p. 35). Related to this simple approach to technology as applied science is the recognized fact that many chemical discoveries have been result of accidents (serendipity, Roberts 1989).

address both these purposes adequately, the future curriculum at all levels will have to reflect, to a far greater degree than is currently the case, trends in chemistry itself.

Learning in the real world is a product of problem solving. Students who are actively engaged in the educational process make substantial connections with course content. Hence it is necessary to construct and relate personal knowledge to problem solving.[15] These connections promote a deep level of processing (Knowlton 2003). Recognizing the enormous variety in types of problems Watts (1991) divided problem-solving in two different categories that can be roughly characterized like: PS1 as a purely intellectual process and PS2 as an implementation task –translating concepts into practical outcomes. Problems in the PS1 category are usually presented at the end of scientific textbooks. This is a clue that they are all somehow related and require for their solution the same kind of mathematical manipulation or repertoires. On the other hand problems in the PS2 category are real world rooted problems, with different possible solutions. Related to these ideas research results from the dichotomy *successful/unsuccessful problem solvers* showed (Herron and Greenbowe 1986) that successful problem solvers have among other characteristics a good command of basic facts and principles. They have general reasoning strategies and construct appropriate representations, that is are capable of inventing and using models. They can apply a number of verification strategies. Many of the technical activities are carried out by solving problems. Here is the exercise of cunning, which is able to harness the resources it has to reach the target, the dominating aim. Cunning[16] in technoscience is rational because it relies on knowledge of the discipline and makes available ways to reach the resolution of the problem. Such availability is not mindless.[17]

The designer considers the actions at an abstract level (mental model) and defines its pragmatic possibilities through a material model which as a result will be successful or not depending on the previously established objectives and/or the technical capacity of individuals involved in producing what is required. This process is called modelling (Fig. 1), and it is not a stranger to scientific or technical learning, or to those who have to do with the historical context and social responsibilities.[18] The incorporation of technoscience in the teaching of chemistry begins with ensuring that students move from using models to

[15] Related to problem solving see for example Chamizo (2007).

[16] Cunning as a metaphor is the catalyst, which is a shortcut and gets the desired objective. Toulmin concludes his *Human Understanding* with a chapter entitled 'The Cunning of Reason' where he said (p. 478): "In science as much as in ethics the historical and cultural diversity of our concepts gives rise to intractable problems, only so long as we continue to think of 'rationality' as a character of particular systems of propositions or concepts, rather than in terms of procedures by which men change from one set of concepts and beliefs to another."

[17] Related to this Tala (2011) in her research work about enculturation into technoscience recently recognized: "This study has revealed how technoscientific ideas quite naturally also arise in discussions with practicing scientist and how they find support in actual scientific practices in nanoscience, a technoscientific field of research. Indeed, the ideas of technoscience quite naturally guide understanding of how novices learn the practical epistemology and methodology of modelling and simulations which are closely connected to the advancement of technology".

[18] About this Schummer stated (2010): "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 artefacts 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".

building models, i.e. modelling (Justi et al. 2011). There are neither rules nor methods to learn how to construct models but analogy is a good start (Hesse 1966). Certainly three conditions are required for modelling:

- Knowledge (to know as much as possible the characteristics of that portion of the world);
- Choosing and integrating a set of items considered important for a particular goal (like analogies);
- Imagination and creativity (to design the mental model compatible with that portion of the world settled on as the target)

This student-centred modelling approach is a progressive learning process which is analogous to scientists' work and in the case of chemistry must be devoted particularly as was discussed above to design materials[19] with specific properties.

The incorporation into the world of new substances, the result of the work of synthetic chemists, makes the world much more complex and this also requires the teaching of technochemistry to consider a second aspect, which refers to the responsibility of those who do it. When considering chemistry as technochemistry, ethics should not be absent from its teaching.[20]

Conclusions

Technochemistry then, refers to the activities derived from the chemical experiment, which in a fundamental way and based on a specific set of values, transform the reality in which we live. About its teaching Talanquer considers (2011):

> Given the technoscientific nature of chemistry, education research in the area should also expand its horizons to go beyond the investigation of the teaching and learning of scientific practices. In particular, it would be desirable to pay more attention to how students and teachers engage and what they learn from productively participating in ''chemical design'' activities in realistic contexts.

Hence in considering chemistry as technochemistry we open a myriad of issues that should be expanded methodically. Taking into account technochemistry as one of the chemists' ways of knowing new and different questions emerge to be resolved not only in its teaching, but also in its public understanding.[21] Some of the key issues to consider are: the use of models and modelling in the resolution of both theoretical and practical problems (Izquierdo and Aliberas 2004) and also the issues of social responsability that arise in relation to their solutions.

[19] A material is a substance or compound that is used for a purpose… is a piece of matter to which we give an intentional utility (Martínez 2011 p. 9).

[20] Many years ago Toulmin (1950) wrote this in the epilogue of his book entitled *An Examination of the place of Reason in Ethics*: "is not right to accept uncritically current institutions, they must evolve as situations to which they apply. There is therefore always a place in society for 'moralist' one who criticizes the morality and institutions of the moment and stands closer to a practical ideal. The ideal must be kept facing is a society where is not tolerated neither poverty and frustration. Scientists are those who have to find ways to reduce the extent of poverty in the world, providing new channels of satisfaction and fulfilment, but the testimony of science continues to be about what is practicable, that is on facts: what is or could be, not what it should be."

[21] For example Pickstone indicated (Pickstone 2000, p 201): "Through patenting and the many forms of sponsorship, the tradition of public research is now seriously endangered by commercialization of university science. Perhaps our need now is less for public understanding of science than for a much wider and strong understanding of science for the public."

Finally it is worth to remember Chemistry' Nobel Laureate J. M. Lehn approach to chemistry (Lehn 1995 p. 206) or perhaps technochemistry:

> The essence of chemistry is not only to discover but to invent and, above all, to create. The book of chemistry is not only to be read but to be written! The score of chemistry is not only to be played but to be composed!

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