The New Identity of Chemistry as Biomimetic and Nanoscience

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This paper aims at characterising the distinct features of the recent trends of biomimetic chemistry within the long tradition of chemistry challenging nature through the artificial creation of life. Through a survey of various strategies for mimicking biological materials and biological processes it will be argued that nanotechnology is revitalising the chemists' ambitions to answer the big questions about the origin of life and the universe.

Introduction

The question of the disciplinary identity of chemistry has emerged as a major focus from several recent historical accounts. A number of historians describe the emergence of the autonomous discipline of chemistry through the eighteenth century before presenting the chemistry of nineteenth century as a "mature science". The biological metaphor so frequent in history of science conveys the image of a natural process, the smooth and unproblematic development of a positive science. The image of chemistry as a maturing discipline was shaped by chemists themselves. From Thomas Thomson in the early nineteenth to J.R. Partington in the twentieth century, via Hermann Kopp, Adolphe Wurtz, Albert Ladenburg, and Marcelin Berthelot, Edward Thorpe, Pierre Duhem, Ida Freund, Wilhelm Ostwald, and Ahron Idhe, to name only a few, chemist-historians have shaped an image of their discipline as a stable and powerful branch of natural sciences. So confident they were in the success of their discipline, that they never realized that the biological metaphor of the growth and maturity of disciplines would necessarily imply the question of its decay. If the analogy of disciplines with living beings is pushed one then should admit that disciplines are bound to die after their golden age.

Who would dare say that chemistry is an old, decaying discipline close to its death, because it no longer attracts students and suffers from a bad public image? However there are many visible symptoms of decay: chemical theory has been

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subjected to aggressive attempts at reduction in the twentieth century after Paul Dirac had claimed that the whole of chemistry could be deduced from the laws of quantum physics. Chemical technologies are now challenged by biotechnology in pharmaceutical industry, and will presumably be increasingly replaced by bio-processes and bio-products in the future. The golden age of chemistry is far behind us. Synthetic products are viewed as poisonous and chemical manufactures as nuisances.

Today chemists are struggling with what they view as a crisis of the public trust in chemistry. They complain about their low prestige, the lack of public recognition of their achievements, and the misguided popular associations of chemistry, with poison, pollution, hazards, death and sorcery. So deep is the depression among chemists today that they are ready to give up their chemical identity by eagerly embracing new labels for their activities, such as ‘molecular science’, ‘materials science’, or ‘nanotechnology’. Is it the death of chemistry?

What can we do as historians of chemistry in the face of this situation?

Two decades of science studies have taught many to avoid the essentialist pitfall. Chemistry is not like a living organism with a trajectory predetermined by nature. Like most sciences, chemistry has been socially and culturally constructed, its current profile is the result of negotiations with the scholastic culture that shaped universities in the early modern period, of repeated battles with the mechanistic paradigm, which came to prevail in the modern period, of repeated tensions with medicine, pharmacy and life sciences. The long-term perspective suggests that the current distrust of chemistry is nothing like a sudden fit, a kind of pathology in the life of the chemical discipline. In the socio-constructionist perspective, the present state of chemistry can be characterised as a new phase of long lasting struggles between chemists and the neighbour sciences, especially physics and the life sciences.

This paper will focus on the tensions between chemistry and life science in order to examine how negotiations at this interface can reconfigure the practice and the ambitions of chemistry.

Two faces of chemistry with regard to life sciences

A glimpse at the *longue durée* suffices to reveal two contrasted postures of chemistry in its relation with medicine and biology, the modest attitude and the arrogant one.

1) Chemistry as a service science

The modest attitude can be illustrated in the 18th century when chemistry emerged as an academic discipline. It is clear that the urgency of chemistry for pharmaceutical and medical training was the foundation of the establishment of Chemistry Chairs in many European Universities. In addition, dozens of chemistry courses, public or private, free or charged were delivered for training medical students and apothecaries among others. In an age when training practitioners and enlightening the public were not two separate activities, public experimental demonstrations constructed chemistry as a fashionable and legitimate science. Chemistry enjoyed high prestige and was integral part of the *philosophes*' culture.[1] Moreover the medical and pharmaceutical audiences deeply determined the agenda of chemical research. For instance plant chemistry was one of the first research programs ever conducted, at the Paris Royal Academy of Science in the eighteenth century mainly for studying the medical virtues of plants. For this purpose new analytical techniques – solvent analysis – had to be developed and a new notion of constituent element – as proximate principle - was developed.[2] Medical and pharmaceutical applications fostered the advancement of both chemical science and chemical technologies. Pharmaceutical applications played a key role in the emergence of synthetic industries as well as in understanding biochemical processes. Thus it is clear that the modest attitude, servant of liberal arts such as medicine, was not an obstacle to the advancement of chemical knowledge.

2) Promethean chemistry

The alternative attitude of chemists playing God or at least mimicking life and improving on nature is more familiar because it has deeply influenced the public image of chemists. Most historical examples became legendary. Paracelsus is said to have tried to make an *homunculus* by maceration of sperm in manure over forty nights. The legend of Faust (the scholar who signed a pact with the Evil) originated from a true 16th century character, a German alchemist and astrologist named Johann Faust, who boasted his achievements in magic and necromancy. Mary Shelley's *Frankenstein* revived the image of the chemist playing God in the nineteenth century before chemists themselves revived their Faustian ambitions with the emergence of synthetic chemistry. The legend of the synthesis of urea in 1828 as the death sentence of "vital forces" was forged and propagated by chemists such as Hermann Kolbe, Wilhelm August Hofmann and Berthelot.[3] They claimed that the metaphysical belief in a vital force was destroyed by the synthesis of an organic compound previously synthesised by living organisms.

Wohler's synthesis was presented as an epoch-making discovery, the dawn of a new era, where chemists would be able to create organisms.

In reality, the vital force concept was not swept away by the synthesis of urea. As John Hedley Brooke argued, this is a biased interpretation of this synthesis[4]. First the claim is non acceptable since Wohler's synthesis was not a direct synthesis from elements but only a partial synthesis from a cyanate. Second, the anti-metaphysical claim rests on confusion between products and process. Urea is an organic substance but not an organism; it is a product of life but it was not synthesised through the same process in the organism. It was thus easy for physiologists such as Claude Bernard to state that chemists could certainly imitate the products of life but could not imitate the ways of nature. Nevertheless it is clear that the ambition to rival nature and to improve on it has encouraged the advancement of chemical science.

Despite the strong contrast here outlined, modest and arrogant chemists share at least one common attitude. While nineteenth century chemists made efforts to expand the territory of chemistry to physiology they were less inclined to provide a chemical explanation of life processes than eager to interface with physiology and agriculture. In short their ambition was less representing than intervening. Paraphrasing Ian Hacking‘s words, I would like to emphasise a major and constant feature of the identity of chemistry, "Chemists are laboratory workers, they are learning about matter through making materials". As Gaston Bachelard noticed they rely on facticity to understand nature. This is how he interpreted Berthelot's famous statement: "Chemistry creates its object".[5] Knowing through making, making things and making them pure, as artefacts, is the chemist's approach to nature.

The Nanotechnology Challenge

1*) What is new with nanotechnology*

Nanotechnology is minimally defined by, design at the nanoscale (1-100 nanometers).

"Working at the atomic, molecular, supra-molecular levels, in the length scale of approximately 1-100 nm range, in order to understand, create and use materials, devices and systems with fundamentally new properties and functions because of their small structure".[6]

I will retain three major features:

- At this scale it is possible to visualise and address a single molecule rather than N (Avogadro number) of molecules.
- At this scale the boundary between inorganic and organic matter no longer makes sense. DNA is a molecule rather than “the secret of life”. Nano and biotechnology work together.

Molecules, macromolecules as well as genes and proteins, all building blocks of matter and life are viewed as machines performing specific tasks.

This domain instantiates what science policy advisers name the new regime of knowledge production.[7] A regime characterised by the dogma of inter-disciplinarity and networks of research including academe and industrial companies. Research in nanobiotechnology blurs the boundaries between academic disciplines such as physics, chemistry, and biology as well as chemical electrical mechanical engineering. Various combinations are being developed from molecular genetics to synthetic biology that may deeply affect the identity of chemistry and even bring about the end of chemistry as a discipline of its own. What historians of chemistry do have to say about the future of chemistry?

2) The death of chemistry

In 1986, the Nobel Prize for Chemistry was awarded by two IBM researchers Binnig and Rohrer for the Scanning Tunelling Microscope, an instrument emblematic of a new approach to materials synthesis. With STM and AFM scientists cannot only visualise individual atoms but also manipulate them. It opened up a new avenue of research, portrayed in the US National NanoIntitiative in 2000 as, “shaping the world atom by atom”.

In 1986, Eric Drexler from MIT described the coming new era in a popular book *Engines of Creation*. He advocated a radically new technology that will handle individual atoms and molecules to be clumped together like the elements of Lego construction sets. Molecular manufacture will make clean and efficient products. By contrast, current organic synthesis is described as an awkward manner of making complex molecular chains by putting molecules together in a vessel, then stirring and hoping that the molecules will fall in the right place to make the desired product.

“Chemists have no direct control over the tumbling motions of molecules in a liquid, and so the molecules are free to react in any way they can, depending on how they bump together. Yet chemists nonetheless coax reacting molecules to form regular structures such as cubic and dodecahedral molecules, and to form unlikely-seeming structures such as molecular rings with highly strained bonds. Molecular machines will have greater versatility in bond making, because they can use molecular motions to make bonds, but can guide these motions in ways that chemists cannot".[8]

To the champion of molecular manufacture chemical synthesis is a primitive technology. It belongs to the ancient tradition of bulk technology handling billions of atoms that was initiated by flint chipping and is still used for making microcircuits. Chemical synthesis operating on billions of molecules is described as a messy, dirty and hazardous way of manufacturing artefacts. Whereas in Drexler's ideal molecular manufacture nano-robots pick and place individual atoms to make molecules, chemists rely on the haphazard motions of crowds of molecules in a liquid. Whereas nanotechnologists, just as genetic engineers program molecular machines to perform specific tasks, synthetic chemists cannot control the assembly process of chemical reagents in their vats according to specific plans. Whereas molecular manufactures will be clean and environment-friendly, chemical plants are dirty and polluting. They always expose people to hazards and dangers, while molecular manufactures will be safe. So striking is the contrast between the old and the new styles of synthesis, between top down and bottom up approaches that Drexler wondered: "It is amazing that chemists are able to do anything at all, and in fact, they have impressive and growing accomplishments".[9]

This depreciative evaluation of chemical synthesis prompted strong reactions in the chemical community. First Drexler's concept of molecular manufacture has been submitted to merciless criticisms from chemists. Richard Smalley, George Whitesides, and other chemists argued that it was a chemical non-sense.[10] Drexler thinks of molecules as rigid building blocks, that can be assembled like the parts of toys to perform mechanical functions. Drexler's machines are non feasible because they are not adapted to the special features of the nano-world. As Whitesides emphasised a nanoscale submarine would be impracticable because of Brownian motion, which would make useless all efforts to guide the submarine. For most chemists Drexler is a visionary who knows nothing about molecules. Chemists are the true experts in the molecular world, they have been doing molecular assemblies for centuries and they know that atoms cannot be handled as Lego set constructions. For most of them Drexler's depreciative description of chemical synthesis emphasises the skills and genius required for making a successful synthesis. They read his statement as a eulogy, in praise of synthetic chemists, who like to portray themselves as artists.[11] Thus in response to the revolutionary claims of the champions of nanotechnology chemists revive the conventional image of the chemist-artist, which was fashionable in the 18th century, for instance in the entry 'chemistry' written in Diderot's *Encyclopédie*.

Changing Practices of synthesis

What can we do with such rhetorical claims on both sides? We have to check them against the real practices of design at the molecular level. Over the past decades how did chemists meet the challenges of nanotechnology and biotechnology?

1 Rational design

New design techniques have been developed that change the self-representation of chemists as artists. The use of computers deeply transformed chemical synthesis as many other activities. Twentieth-century chemists, material scientists and pharmaceutical chemists have developed a variety of computer-assisted methods often referred to as "rational design" by contrast with the empirical, serendipitous processes of synthesis used in the past.· Many algorithms are now available for designing molecules with interesting medical, magnetic, optical, or electronic properties., using computation, combination, randomisation.

Computational chemistry is a kind of bottom-up technology based on quantum theory and computers. It was initially basic research close to physics. It was aimed at building up a material *ab initio*, using computer calculations and starting with the most fundamental information about the atoms and the basic rules of physics. But computers can also be used to make molecular mechanics models of large systems for industrial purposes.[12] The technique is a way of avoiding the cost of synthesis. The idea is to find out how well a new compound works before it has been made by modelling its chemical behaviour on a computer. Three different perspectives are used: thermodynamic features, electronic properties and the spatial, molecular conformation. By visualizing the 3-D structure of a compound and rotating it, one can predict how a given molecule interacts with a protein.

Combinatorial chemistry is a different strategy. It consists in reacting a set of starting materials in all possible combinations. The computer eliminates all serendipity in the process of synthesis.[13] Once a the route for synthesis has been selected and optimised, in a few steps and a few months thousands of compounds are synthesised with no other purpose than being systematically stored in a "library" of substances. Then with the help of computer "evolutionary algorithms", a fittest structure for specific targets will be selected.

2) Bio-inspired chemistry

Another possible response to the nanotechnology challenge is to be found in bio-inspiration.

Whereas 19th and 20th century chemists challenged natural products with their synthetic products, by the end of the 20th century, living creatures were reconsidered either as a source of raw materials desirable for environmental concern or as a source of inspiration for synthetic chemists.[14] Materials scientists aiming at designing composite structures or materials by design (for specific applications) realized that biomaterials present optimal combination of properties and adaptive structures. Sea-urchin or abalone shells are wonderful bio-mineral structures made out of a common raw material calcium carbonate. They present a complex morphology and assume a variety of functions. Similarly, the spider's silk is a fiber extremely thin and robust that offers an unchallenged high strength-to-weight ratio. Wood which originally was the archetype of material is now redefined not only as a composite material made out of long, orientated fibers immersed in a light ligneous matrix but also as a complex structure with different levels of organization at different scales. Nature seems to provide elegant solutions to the problems tackled by modern chemists.

Biomimetic strategies thus prompted new collaborations between biologists and chemists, sometimes under the umbrella of a new discipline Materials Science and Engineering.[15] Biomaterials taught many lessons to chemists: first, most of them are multifunctionnal and offer a good compromise between various functions. Second, biomaterials unlike chemical products are not afraid of impurities, defaults, mixtures, and composites. Third, access to their fine structure reveals that biomaterials present a complex hierarchy of structures with structural features occurring on different size scales.

However bio-inspired chemistry is not confined to attempts at mimicking the exquisite hybrid structures of biomaterials. Nanotechnology prompted a new chemical challenge: how to self-assemble molecules? For designing at the nanoscale, human hands and tools are helpless.[16] Biomaterials rely on a more elegant solution since the building blocks self-assemble without the mediation of assembling tools. Self-assembly is ubiquitous in living systems, and it is extremely advantageous from a technological point of view because it is a spontaneous and reversible process with little or no waste and a wide domain of applications. Two very different strategies –hybridization or mimicry– are being developed to get the self-assembling of molecules.

Using the building blocks of living systems for making devices and machines is just taking advantage of the devices selected by biological evolution. Given that there is little chance that we can emulate nature, who spent billions of years for designing and perfecting high-performance structures, it seems more reasonable to start from the building blocks provided by nature in order to achieve our own goals. For instance, it is not too difficult to take advantage of the potentials of DNA to make structures at the nanoscale. It is routine practice today in a number of laboratories to use complementary DNA strands for making nanotransistors, or other circuits. In this strategy, chemistry gives way to genetic engineering. By re-combining DNA, bio-engineers use it as a program to make new structures that they control with Atomic Force Microscopy. Steven Boxer, a chemist from Stanford who uses proteins as transistors in electronic circuits, thus describes his strategy: “We’ve decided that since we can’t beat them (biomolecular systems), we should join them”.[17] This hybrid strategy of design uses the building blocks of biosystems –DNA, proteins, bacteria, micelles or colloids– as molecular machines that are re-engineered for technological purposes. Does it mean that nanobiotechnology will bring about the death of chemistry?

The alternative strategy is to mimic the biological processes of self-assembly by using thermodynamics and chemical properties. The challenge that contemporary chemists have to face is to dispense with the information of the genetic code in order to self-assemble the components and to control morphogenesis. To meet this challenge chemists call all the resources of physics and chemistry: chemical transformations in spatially restricted reaction fields, external solicitations like gravity, electric or magnetic fields, mechanical stress, gradients and flux of reagents during the synthesis. They are also playing with a wide spectrum of weak bonds –Hydrogen bonds, Van der Waals forces–, etc. –instead of making and breaking covalent bonds between atoms.

3) Chemistry at the school of nature

Chemists are learning many lessons at the school of nature. In fact, a whole range of novel chemical practices are being developed by biomimetic chemists.

A major lesson retained from nature is that living organisms conjugate inorganics and organics in the making of biomaterials and use templates, i.e. scaffolds that direct the inorganic structure formation. The use of soft moulds to shape hard materials is a key to achieve the synthesis of inorganic materials with all sorts of curved shapes. This branch of chemistry has been recently renamed “nanochemistry” because biomimetic processes are bottom-up syntheses performed at a few nanometres length-scale.[18]

In stark contrast with conventional organic chemistry, which operates at high temperatures, in high vacuum and with organic solvents, a new style of chemistry operates at room temperature, in rather messy and aqueous environments, just as nature does. This chemistry, named “chimie douce” (soft chemistry) by Jacques

Livage in 1977, aims at synthesizing original materials by performing reactions under quasi-physiological conditions, with biodegradable and renewable by-products and with an economy similar to that of nature.

Another branch of chemistry, no longer confined to the interactions between atoms and molecules using strong covalent bonds, is named “supramolecular chemistry” by Jean-Marie Lehn in 1978, and consists in using building blocks such as macromolecules, aggregates and colloids. According to Lehn, its objective is to reproduce the selectivity of the interaction between receptors and substrates in biology, with the help of hydrogen bonds and stereochemistry.

A more recent branch, dynamic combinatorial chemistry –also developed by Lehn– relies on the collective behavior of molecules for getting self-assembly. Lehn summarizes his credo in a simple formula: a glass of water has properties different from a water molecule. The components mixed in a solution explore the possibilities of binding and this dynamics ends up with the correct double helix. Unlike the lock and key static model of recognition, which presupposes that the correct target has been identified, in this process the lock and the key select each other, through a random process of interactions. The basic concepts are “from static to dynamics, from real to virtual, and from prefabricated to adaptive”.[19]

New Ambitions for Chemistry

Self-assembly seems to open a new path for emulating nature’s processes. Are we witnessing a resurrection of the Faustian ambitions of alchemists and synthetic chemists? Nineteenth-century chemists could certainly synthesise the products of life but they failed to imitate the ways of nature in their vessels and furnaces. By contrast, today chemists are working hard to reproduce nature’s processes. The current intensive trend of research on self-assembly could thus bring a landmark in the longstanding rivalry between chemists and biologists.

Indeed, mimicking does not mean reproducing life. For most chemists, it is no longer a question of competing with nature to prove that life can be reduced to the interplay of chemical forces. On the contrary, many contemporary chemists acknowledge and emphasize the differences between the strategies used in the evolution of life and those invented by the laboratory chemist.

However, self-assembly has revived the chemists’ ambition to access the “essence of life”. They hope to self-organize complex metastable structures instead of wellordered materials, and thus maybe to shed a new light on the old problem of the origin of life.

For Lehn, controlling the basic forces of self-organisation is the ultimate aim of chemistry. His program of "Constitutional Dynamical Bionanotechnology" revives the greatest ambitions for chemistry as he assumes that something emerges from the collective behaviour of molecules, which results from coupling processes rather than just expressing information contained in the components. As Philip Ball rightly points out, chemists are now addressing the "big questions" about the Big Bang and the origin of life. Some of them are even ready to go further and even attempt to unveil the secret of the emergence of consciousness. For instance, George Whitesides assumes that chemical language can decipher the most complex phenomena: "The nature of the cells is an entirely molecular problem. It has nothing to do with biology".[20] And since neurons also use chemical mediators, chemists should also be able to contribute to merge silicon electronics with the brain.

In conclusion, although it is risky for historians of science to predict the future, let me venture some remarks on the possible future of chemistry. The current trans-disciplinary regime of scientific research will not bring about the death of chemistry. Far from losing their identity, today chemists are responding to the new challenge of nanobiotechnology by developing new synthetic practices and novel styles of chemistry. Some of them are even reviving the most arrogant attitude as they expand their territory and want to address the big metaphysical questions.

Moreover, as a technoscience, a science combining knowing and making, a science focused on performance and productivity, a science networking a variety of different actors, chemistry could well become THE model science for the twenty-first century.

Notes

[1] See Christine Lehman, "Between commerce and philanthropy: Chemistry courses in eighteenth-century Paris". in B. Bensaude-Vincent, C. Blondel eds, *Science and Spectacle in the European Enlightenment*, Adelshot, Ashgate, 2008, pp. 103-116.

[2] F.L. Holmes, *Eighteenth-Century Chemistry as an Investigative Enterprise*, Berkeley, Office for the history of science, 1989. Mi Gyung Kim, *Affinity, That Elusive Dream,* Cambridge, MA: MIT Press, 2003.

[3] Brooke, J.H. 1968, "Wöhler's Urea and its Vital Force—A Verdict from the Chemists." *Ambix* 15 (1968):84-114. Ramberg, P., 2000: 'The Death of Vitalism and the Birth of Organic Chemistry: Wöhler's Urea Synthesis and the Disciplinary Identity of Organic Chemistry', *Ambix* 47: 170-95.

[4] Brooke, John Hedley, "Wohler's urea – a verdict from the chemists", *Ambix*, 15, 1968, reprint in *Thinking about Matter. Studies in the History of Chemical Philosophy,* (Aldershot, Variorum, 1995), pp. 84-114.

[5] Marcellin Berthelot, *La synthèse chimique*, Paris, G. Baillère, 1876, quoted from the 8th edition Paris, Félix Alcan, 1897, p. 275.

[6] Roco, M.C. Williams R.S., Alivisastos P. *Nanotechnology. Research Directions IWGN Interagency Working Group on Nanoscience Workshop Report,* Dordrecht, Boston, Kluwer, 2000.

[7] M.Gibbons, C.Limoges, H.Nowotny, S.Schwartzman, P.Scott….*The New Production of Knowledge: the Dynamics of Science and Research in Contemporary Societies*, Sage, 1994. H.Nowotny, M.Gibbons, P.Scott, *Re-thinking Science: Knowledge and the Public in an Age of Uncertainty*, Polity Press & Blackwell Pub, 2001.

[8] Eric K. Drexler, *Engines of Creation*, *The Coming Era of Nanotechnology*, New York, Anchor Books, 1986, p. 13.

[9] Drexler, Eric K. "Introduction to nanotechnology" in Markus Krummenacker, James Lewis (eds) *Prospects in Nanotechology. Proceedings of the 1st general conference on nanotechnology:* developments, applications, and opportunities nov 11-14, 1992, Palo-Alto, John Wiley & Sons 1995, p. 2.

[10] See Smalley, Richard, " Of Chemistry, Love and Nanorobots". *Scientific American*, Sept. 2001, 76. Whitesides, George M., "The Once and Future Nanomachine", *Scientific American*, Sept. 2001, 78-83. See also Jones, Richard, L., *Soft Machines*, Oxford, New-York, Oxford University Press, 2004.

[11] See Roald Hoffmann, "In praise of synthesis" in *The Same and Note the Same*, New York, Columbia University Press, 1995, pp. 94-100.

[12] On computational chemistry see Francoeur, Eric, "Cyrus Leventhal, the Kluge and the origin of interactive molecular graphics", *Endeavour*, 26 (1) 2002, 127-131.

[13] X.-D. Xiang et al. *Science*, 268 (1995), 1738 ; Xiang, *Annual Review of Materials Science*, 29 (1999), 149.

[14] M. Sarikaya, I. Aksay (eds.), *Biomimetics : Design and Processing of Materials* (Woodbury, AIP Press, 1995. C. Sanchez (ed.) *Biomimétisme et matériaux*,, Paris, Observatoire français des techniques avancées, vol. 25, 2001, pp. 139-143.

[15] B. Bensaude-Vincent, "The construction of a discipline: materials science in the USA", *Historical Studies in the Physical and Biological Sciences*, 31, Part 2 (2001) 223-248,

[16] It is to circumvent this obstacle that Drexler imagined "universal assemblers" for his molecular manufacture. The contrast between this mechanosynthetic strategy and the self-assembly in living matter has been emphasized by Richar Jones op. cit. supra.

[17] Steven Boxer "Exploiting the Nanotechnology of Life", *Science*, 254, 29 November 1991, 1308-09.

[18] See Geoffrey Ozin, André C. Arsenault, *Nanochemistry: A Chemical Approach to Nanomaterials,* London, Royal Society of Chemistry, 2005, p. 10.

[19] Lehn Jean-Marie, "Dynamic combinatorial and virtual combinatorial libraries", E*uropean Journal of Chemistry*, 5, N°9, 1999, 2455-2463. "Toward self-organisation and complex matter", *Science*, 295, 29 March 2002, 2400-2402.

[20] Whitesides quoted by Ball, Philip "What chemists want to know", *Nature*, 442/3, August 2006, 500-502, on p. 501.