Chemists and the School of nature

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The term biomimicry first appeared in 1962 as a generic term including both cybernetics and bionics[1]. It referred to all sorts of imitation of one form of life by another one while the term "bionics" defined as "an attempt to understand sufficiently well the tricks that nature actually uses to solve her problems"[2] is closer to the meaning of "biomimicry" as it has been used by material scientists since the 1980s. Biomimetism is an umbrella covering a variety of research fields ranging from the chemistry of natural products to nanocomposites, via biomaterials and supramolecular chemistry. . It is an informal movement and the concept itself is so loose that one can wonder whether biomimetism is more than a slogan forged by chemists in order to hop on the "green" bandwagon. Or could it bring a revolution into chemistry with a profound transformation of its practices? It is too early to judge, but a historical perspective helps pointing out some trends and tendencies.

A Promethean Project?

Attempting to of the image of chemists in popular culture. Since Faust and Frankenstein, the ambition to emulate imitate living things is certainly not new to chemistry—indeed it is one of the most constant features nature, particularly by creating life, is associated with the idea of obscure practices in the den of the laboratory. This image was inspired by accusations against Medieval and Renaissance alchemists. It became more honorable in the nineteenth century, when the synthesis of dozens of organic compounds awakened the ambition to recreate biological susbtances in the laboratory. "To reproduce, using only the elements and the range of molecular forces, all the compounds defined as natural and the chemical metamorphoses that matter undergoes within living beings,"[3] was the dream of Marcellin Berthelot. No more magic or witchcraft: by starting from the four basic elements—carbon, hydrogen, oxygen, and nitrogen—and proceeding methodically from the simplest to the most complex, the chemist should be able to synthesize the most complex of compounds. Exalters of synthesis, such as Berthelot or William Odling were tormented by the hope of removing the frontier between the inert and the living, and dissipating the mystery of life.[4]

This attitude induced reactions in defense of the specificity of life. Louis Pasteur, for instance, stated that there was a characteristic asymmetry in life structures that could not be reproduced by chemical operations alone.[5] Claude Bernard, on the other hand, underlined that synthesizing a product starting from first principles does not mean that one has synthesized the properties of living beings.[6] Moreover, the synthetic agents used by chemists in their laboratories were, he maintained, very different from those created by organisms.[7] To the arrogant chemists who pretended reducing life to physics and chemistry, Bernard replied by considering chemistry as an auxiliary science to physiology and medicine..

Is biomimicry the twentieth-century resurrection of the Promethean ambitions of alchemists and synthetic chemists? The aim of today's chemists seem to be totally different. Firstly, biomimicry, as its name implies, aims to mimic life, not to reproduce it. 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, contemporary chemists accept and emphasize the differences between the strategies used in the evolution of life and those invented by the laboratory chemist. The culture of chemistry emphasizes the purity and homogeneity of substances, the stability of their composition, and the control of the reactions carried out at the bench, where one can limit the number of parameters involved. These are the requirements impressed on chemists during their training; nature was never taught such laws. Living beings owe their existence to a blind evolution that is not afraid of impurities, defaults, mixtures, and composites.[8] In contrast to chemical products, biological products have characteristics that are eminently temperamental and still successful—

so long as we don't damage nature too much. Finally, the living being synthesizes only a few products out of all the possibilities offered by the laws of chemistry. In particular, nature never uses metals as structural materials. It operates along lines that are unorthodox in the eyes of the ordinary chemist: ambient or slightly raised temperatures, and in the presence of a whole range of perturbations. And yet nature creates complex hierarchical structures that integrate multiple functions. While chemical engineering operates at the molecular or macromolecular scale and fixes groups with a well-determined function, nature creates on all scales, from molecular to macroscopic. Decidedly, the "tinkering of the evolutionary process", to cite François Jacob,[9] has no reason to be envious of human invention. We are a long way from the arrogance of the nineteenth-century chemists!

The chemist's idea of nature is more humble: the game is no longer metaphysical, but technological. The controversy on the specificity of living beings has been suppressed by molecular biology—at least for a while—and is no longer on the agenda. Biomimetism cannot be described in terms of a gradual closure of the gap between nature and human art, as 19th-century chemists used to do. There is no general plan to challenge and overtake nature. The internal evolution of material science and technologies engineering toward composite, or even hybrid,[10-16] structures favors the comparison with natural materials, such as wood, bone, and mollusk shells. The chemists and physical chemists who examine nature are motivated by the desire to produce new and more efficient materials. They are looking for answers to some of their questions in nature. They are content with picking up local models as solutions to their current technological problems. "We can be encouraged by the knowledge that a set of solutions has been worked out in the biological domain" wrote Stephen Mann.[17]

Biologists, chemists, physical chemists, and engineers are reunited around a common problem: how can we create, develop, maintain and, eventually, recycle a functional structure with optimal properties? They started to consider nature as an artist, an incomparable engineer from which we can learn many lessons. After celebrating the synthetic as unnatural during the "Plastic Age," ours is a time of fascination for the wonders of nature and the beauty of life[18]. Indeed, not all chemists have renounced the ambition to emulate, or even surpass, the limits of nature; the difference is that their ideas arise from careful studies of the materials created by life.

What can be the consequences for chemistry of this new perspective on nature? One possibility is to borrow products directly from the biosphere and adapt them for industrial production. This is certainly an efficient route to reconciling chemical technology and the environment. However, learning, not extracting, from nature—is a more subversive attitude for chemical science itself.[17,19-25]

Borrowing from the biosphere

In response to ecological concerns, which increasingly demand materials to be recyclable or biodegradable, natural materials represent a huge potential of useful resources. Some, such as wood and flint, have been used since the beginning of mankind. Curiously, it is always overlooked that the idea of using wood as a material dates back to prehistoric times, and we speak only of the Stone Age. At first, wood was used as such, to make tools or construct shelters, but later, like other vegetable materials, it was exploited to extract a very important polymer found in plant cell walls, namely cellulose. The domestic (cotton fabric) and biomedical (cotton wool) uses of cellulose date from ancient times, but new applications continue to appear, for example, in construction industry (composite materials reinforced with cellulose fibers).

The most widespread animal biopolymer of the biosphere is collagen, which has multiple applications.[26] However, due to the epidemic of "mad cow" disease, the use of its denatured form to make gelatin is becoming highly compromised, as are its biomedical applications. For example, reconstituted collagen can serve as a covering for burns, prior to skin grafting, but this involves direct contact with the internal tissues and so the risk of contamination is high. We must therefore search for substitutes. One of the candidate substitutes is chitin. This is the essential component of the carapaces of insects and arthropods in general, but it can be found in many other invertebrates and fungi, notably molds, yeast, and diverse microorganisms. Chitin is a polymer of acetylglucosamine, which is deacetylated here and there. Over the

past twenty years, this familiar substance suddenly proved to offer a host of medical applications[27] : as a hemostatic agent, as covering for burns, as suture material in vascular and dental surgery, as compatible matrices in drug delivery, as a substrate for cellular or organotypic cultures, as a material for contact lenses...Its use as a texturing agent in foodstuff is being considered; and carboxymethyl-chitin is used in cosmetology. Most of these biopolymers are currently being studied with the aim of applications such as films for fruit and vegetables, and encapsulation for seeds or, on much smaller scale, for pharmacological ingredients, which can lengthen their bio-availability.

No doubt these biomaterials can be exploited without an in-depth understanding of their properties. However, if one day we want to be able to manufacture materials with a similar performance to those of nature, then we must attempt to understand why wood is an unrivalled composite material and why chitin is such a good healing substance. And that's where research in biomimetics begins.

The challenge is to elucidate how life creates complex hierarchical structures, integrating many functions, to understand biological strategies in order to apply them, with suitable modifications, to the field of technological design.

A school of design

To the extent that nature is regarded as a model, biomimicry can be conceived of as a technology transfer from nature to human technologies. This view, first shaped by scientists working in biomechanics,[28] has been developed by material chemists such as Julian Vincent. He insists in considering life as one technology among others: "We routinely fail to recognize the similarities between our technical problems and the solutions to similar problems in other technologies. In particular we routinely fail to tap into the four billion years worth of R&D in the natural world".[29] The notion of "natural technology" ignores the great divide between nature and artefact inherited from scholastics. Is it possible to overcome a fundamental dichotomy, that is deeply rooted in our culture and reinvigorated in the current public debates about genetically modified food? The idea of producing in vitro, and in the absence of living cells, structures similar to those found in organisms is an impossible feat, since life is the result of evolutionary processes lasting millions of years. Even if today's chemists worked day and night in their laboratories with a passion similar to that of Balthazar Claes, the hero of Balzac's *In Quest of the Absolute*, they would never have enough time to reproduce such syntheses. Moreover, the structures that we find in nature arise more from serendipity than from an intelligent planning. Nature designs its materials by generating variability through mutation and recombination and then selecting those structures that are the fittest.

Is it reasonable to try to copy life? Indeed there are a number of well-known examples of inventions made by copying nature such as the chain saw cutters inspired by a wood beetle, the Velcro inspired by the hooked burs of a plant. However, as Stephen Vogel emphasized, successful copying is rare[30]. In attempting to imitate the light-weight structures found in the wings of birds, the flying machines of many generations of inventors ended in disaster. The history of aerodynamic techniques is full of aborted trials due to this mimicry. Could chemists be exposing themselves to the same dangers?

It must be admitted that in the specific domain of structural materials, biomimetics is not always a technological dead end. There are a few spectacular successes. One of the first was the creation of a material inspired by the abalone mollusk. Although it contains very ordinary components, the shell of this mollusk has a high toughness. Its structure, which was determined by marine biologists, caught the attention of a chemical engineer, Ilian Aksay, who had been working for a few years on a light-weight shield financed by the US army.[31] After having patented shields made of composite ceramic–metal materials, he had the idea of making a more resistant material inspired by the laminated microstructure of the abalone, in which there are alternative layers of calcium carbonate and proteins, like bricks and mortar. Other fruitful research fields examined the iridescent tissue of butterfly wings and the hexagonal structure of their eyes[32,19] (and attempted to reproduce the forms found on the upper surface of water lily leaves, which make the leaves so impossible to wet[19,33]

However, other attempts at imitation have been less conclusive, such as the dolphin skin[19,34] Biomimicry is no guarantee of success. On the one hand, nature can only be used as a structural model

when the structure–properties relationship has been thoroughly elucidated. On the other hand, we cannot simply transpose the structures invented by nature. Even when they appear to have been optimized, they still suffer from very different constraints from those of technology. Because they are too complex and too temperamental for industrial production, we cannot simply transfer a solution found in nature to a technological problem.

Mother nature as a top model

In which sense can nature be considered as a model for material design? As a tentative identification of the main lines of material science underlying the ideals of biomimicry, we could use the traditional distinction between structural and functional materials and put forward the idea that biomimetics aims to imitate either the supporting structure of living matter, or its various functions. However, this scheme does not stand up to a close examination of the organization of living material. Let's consider the plasma membrane, which separates the interior of cells from the extracellular matrix. This material— for that is what it is — is clearly structural; the phospholipid bilayer constitutes a sort of cellular exoskeleton. At the same time, it is also functional, due to the various proteins that ensure exchange of material and energy from the interior to the exterior of the cell. Thus the classic distinction between structural and functional materials is not relevant for biological materials.

In this respect, materials science follows the same line. Without trying to imitate life, material science has brought to the fore the question of the distinction between functional and structural. It is remarkable that plastic materials, which were designed to replace traditional structural materials, are today being investigated for purely functional applications: transportation of electricity, emission of light, or transformation under the influence of an electric field. It is also remarkable that the most emblematic functional material of the twentieth century, silicon, has been reconsidered as a potential structural material for micromechanics.

Rather than providing models for either structural or functional materials, nature is a model for designing smart materials. In the 1980s, research was reoriented toward reactive and multifunctional materials. We now have a whole range of materials capable of reacting to optical, electric, thermal, mechanical, or magnetic stimuli, leading to a change in properties. Some of these are now widely used, such as piezoelectric crystals, which transform a mechanic constraint into an electric field to produce the spark that lights the gas or, inversely, does mechanical work upon the action of a voltage, which can be used to control mechanical movements with great precision. Photochromic lenses, which darken under the effects of bright sunlight, are another application. Among all these reactive materials, some have acquired a particular status: those that lead to an electric response or respond to an electric stimulus. Since today's information processors only manipulate electricity, the former are used as sensors and the latter as actuators. By linking end to end a sensor, a processor, and an actuator, we obtain an automated chain. In biomimetics, we also say that this occurs in living systems: the eye is a sensor, the brain is a processor, and the muscle is an actuator.

These functions are so similar to those of humans that we use the phrase "intelligent materials". However, at this stage, this is a very poor notion of intelligence and, moreover, a false notion of the material. In fact, all the examples of "intelligent materials" that we have today result from the assembly of different materials into a single system: one material acts as a sensor; another one as an actuator; and a third one—generally silicon—is the processor. What should be added in order to get truly intelligent materials? The system should be a single and unique piece of material integrating all these functions.

The smaller the scale of this integration, the more we will be dealing with, properly speaking, a material. The limit could well be the molecular scale. We can envisage a material in which one molecule plays the role of a sensor, the next a processor, and a third an actuator. Nanomaterials—or nanostructured materials—are therefore a *passage obligé* on the road to truly intelligent materials.

What else could we ask of such a material? Without doubt, a little autonomy. Ordinary materials age, their properties degrade with time, some oxidize and others decompose or disintegrate. An ideal material would have self-diagnostic, self-maintenance, and even self-reparative properties. It would also be able to

self-destruct or self-degrade, and leave no inconvenient trace of its fleeting existence. However, before doing so, and to complete its list of properties, it should have self-replicated—or produced an improved version of itself due to a process of internal learning and regulation. Finally, all these feats should be performed with minimal cost in terms of energy and primary materials.

The performance scale of this program is represented on the figure above (where each criterion is marked on the 0 to 100 scale). Is this a utopian dream? Certainly, if we consider the present state of the science and material engineering, and their predicted evolutions. On the other hand, no, if we consider the state of living materials. In the figure, living material is at the summit of the cube, i.e. a "top model" with the measurements 100,100,100, represented here by an asterisk. With sensors, actuators, and processors, nature is completely integrated and autonomous by definition. It is not surprising that it is used as a model for advanced materials. It remains for chemists to find out how to emulate it on all fronts, and, if possible, to create and organize materials on a time scale that is acceptable for industrial production.

The challenges of complexity

It is already clear that biomimetic thinking has overturned materials science. But more specifically what changes does it bring in chemical sciences? The first lesson that chemists retained from nature was that they had to synthesize composite and hybrid microstructures associating organic (or biological) and mineral components. Historically it was the first incentive that turned the attention of chemists towards biomimetism. Stephen Mann's work on biomineralization[17,35], Paul Calvert's articles on biomimetic composites[20,36] and Sarikaya and Aksay's 1995 book[37] paved the way to the hybridization of chemistry with biology and mechanics. Such collaborations may benefit from the recent evolution of solid state chemistry and polymer science towards nanostructures. More specifically, the know-how in intercalation processes accumulated by solid state chemists[38,39] is a major resource for the design and the rearrangement of hybrid structures[40]. The synthetic skills of polymer chemists, their experience in the design of composites and multiphase systems using polymer blends, copolymers, liquid crystal polymers, ... offer a huge potential for the biomimetic approach[41-44]. However, chemists from these various specialties have to learn the language of other disciplines instead of defending their own territories.

Moreover chemists have realized that the complexity of biological materials with their hierarchical structures requires very specific procedures of crafting the materials. They want to imitate nature's processes as well as mimicking the product to which they lead. They eventually meet the challenge that Claude Bernard addressed to those chemists who pretended to emulate life while it was clear that the procedures that they employed to reproduce living substances differed from those used by nature itself. Concerning the imitation of nature's processes, contemporary chemists face two new challenges. How can they control the kinetics of reactions in order to get complex metastable structures instead of well-ordered materials? How are they going to dispense with the information of the genetic code in order to self-assemble the components and to control morphogenesis?

The first problem is clearly the agenda of a new style of chemistry, named "chimie douce" (soft chemistry) by Jacques Livage in 1977[45]. Performing chemical reactions under quasi-physiological conditions, with biodegradable and renewable by-products and with an economy similar to that of nature, requires the use of sol-gel route and molecular precursors[46-51]. In order to obtain original materials whose structures and textures are determined by local energy minima rather than one global energy minimum, soft chemistry uses the significant kinetic effects that occur at mild temperatures conditions. Over the past decades, soft chemistry has expanded to larger scales by using more complex building blocks such as macromolecules, aggregates and colloids.[24,52-55]

To meet the second challenge - how to obtain self-assembly in the absence of genetic information - chemists developed two different routes. First, they play with intermolecular bonds instead of making and breaking covalent bonds between atoms. Thus was created a new branch of chemistry, named "supramolecular chemistry" by Jean-Marie Lehn in 1978.[56] Supramolecular chemistry is often presented as a way to design chemical processes that mimic the coding of biological processes.[57,58] 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.[57,59] Thanks to molecular recognition the building blocks self-assemble to form supramolecular structures, and even materials.[57,60-63]

In contrast to the first one, the second route did not lead to the creation of a new branch of chemistry. Rather it consists in astute combinations of tricks intended to obtain complex systems . All the resources of physics and chemistry are put at work : 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.[25,64-67] Working in open reactors is the most innovative lesson that academic chemists are learning from nature.[68] Although they could as well have learnt it from industrial practices, it is certainly one of the major changes that biomimetism will bring into the practices of chemistry.

To conclude, biomimicry is not just a new vogue taken up by chemists to regain prestige. Nor is it a new paradigm, in the sense that it would impose a unique model. Rather it should be regarded more as a scientific style inspired by technological considerations and a fresh look at nature. Biomimetism is not adequately described in terms of technology transfer. It is more a question of inspiration in the poetic sense, i.e. the invention of original forms or processes starting from a natural motif that solves a similar problem. The various strategies presented here - either borrowing directly from living things, or mimicking nature's structures, functions and processes- are certainly not exhaustive. However they are part of a new culture that encourages the chemist to work outside his or her niche. After having learnt the virtues of defects and impurities from physicists and metallurgists in the mid-twentieth century, chemists are learning the virtues of complexity and self-assembly from nature. A new and hybrid science is coming into being, that crosses the disciplinary boundaries between biology and chemistry. That science calls for a rejection of the comfortable practices of purity, control and measurement which have ensured the success and glory of chemistry for the past two hundred years. It is time for chemists to shake their routine practices and to "open" their laboratories to the complex environment where biomaterials have been generated by nature.

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