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Bernadette Bensaude-Vincent

Reconfiguring Nature Through Syntheses :

From Plastics to Biomimetics

in B. Bensaude-Vincent, W.R. Newman eds, *The Natural and the Artificial. An Ever-Evolving Polarity* Cambridge MA, MIT Press, 2007, pp. 293-312.

As Maurice Merleau Ponty noticed in 1956: «We cannot think about nature without realizing that our idea of nature is impregnated with artifacts».¹ Each age tends to interpret nature through models derived from one of its most advanced technologies. Nature was a clock in the context of seventeenth-century mechanism, then it was described as a laboratory by eighteenth-century chemists. The breeders' activity was behind Darwin's natural selection and computers are behind the notions of genetic code and program.

Does this mean that we should reverse Aristotle's view and say that «nature is a copy of art»? Such a statement would immediately raise the question: Where does the concept of «artifact» itself come from ? Art is always preceded by nature whether it be considered as an imitation of nature, as a transformation or as an improvement of nature. So we would be quickly trapped in a circle, if we discuss the question *in abstracto*.

The present paper is an attempt to disentangle this circle through a review of various strategies of chemical synthesis in the twentieth century. In characterizing the various concepts of nature involved in three different practices of synthesis - polymer chemistry, combinatorial chemistry and biomimetic chemistry - I will argue that the representations of

¹ Maurice Merleau-Ponty, *La nature*, Cours 1956-57 p. 120 « Nous ne pouvons penser la nature sans nous rendre compte que notre idée de nature est imprégnée d'artifice » .

nature and artifacts are mutually constructed. Like prey and predator defining their own identities through their relation, nature and artifact are continuously reconfigured through their changing relations. It is one and the same process that builds up the meaning of «natural» and the meaning of «artificial».

Plastic artifacts and rigid nature.

In contrast to wood or metals, synthetic polymers are molded. They are polymerized and shaped simultaneously. In more philosophical terms, matter and form are generated in one single gesture. This specific process undoubtedly increases the potential uses of such materials. However the triumph of synthetic polymers originated in commercial strategies as much as in their intrinsic properties. Their history is extremely important for determining how “synthetic” became a synonym of “artificial” and how the plasticity of synthetic polymers deeply transformed the perception of nature².

Celluloid is always referred to as the first artificial plastic although it was made from cotton treated with nitric acid, mixed with camphor and subjected to heat and pressure. Its artificiality derived from the function assigned to this new material rather than from its composition. Celluloid was initially designed and manufactured by John Wesley Hyatt in 1870 as an imitation of ivory for billiard balls. As Robert Friedel has rightly pointed out, this was a marketing strategy rather than a representation of the intrinsic value of the material because celluloid could only have the appearance of ivory without offering its density and elasticity, two properties that matter for billiard balls³. In fact, celluloid, like the parkesine presented by Alexander Parkes at the London Exhibition in 1862, was an invention with no specific purpose. Unlike natural materials it was not attached to one specific function. Instead it could be used for many things, such as combs, buttons, collars and cuffs. It was a "chameleon material" which could imitate tortoise-shell, amber, coral, marble, jade, onyx, or other materials, according to the color. Far from being an advantage, this enormous potential raised an uncertainty among celluloid manufacturers as to the proper image and function of

² For a cultural history of plastics in the American context see Meikle, Jeffrey L., *American Plastic. A Cultural History*, New Brunswick, Rutgers University Press, 1995); for an overview of plastics in the British context Mossman Susan T.I., Morris Peter.J.T.(eds), *The Development of Plastics*, London, The Science Museum, 1994.

³ Robert Friedel, *Pioneer Plastic: The Making and Selling of Celluloid* (Madison: University of Wisconsin Press, 1983).

their product. Although it was a better material than the natural products that it replaced for certain uses, celluloid was viewed as being a cheap, nasty, deceptive imitation of the natural⁴. A manual of household taste considered it as "inartistic and vulgar" because the authenticity and sincerity of natural materials were based on their limited potential for shapes and colors⁵. The superiority of nature lay in its rigid order. In the same manner as Aristotle claimed that the art of Delphi knife-makers was inferior to nature because their product was multifunctional and not exclusively suited for one function, the "good taste" condemned the multifunctionality of artificial materials⁶. Thus in the late nineteenth-century, imitation of natural materials was still the key for the invention and the acceptance of new materials. Their enormous potential of uses was an obstacle rather than a key to their success. In fact, the early plastic materials raised the question: what are these artifacts good for?

Leo Baekeland, drawing lessons from the celluloid case, quickly recognized that he should not manufacture his "bakelite" - a synthetic material made from phenol and formaldehyde - as an imitative substitute but as an invention which would rearrange nature in new and imaginative ways. In a best-seller telling *The Story of Bakelite*, published in 1924, the journalist John Kimberly Mumford inscribed the invention of bakelite within the big picture of a cosmogony. From the dawn of the world, nature had stored up the wastes of dead creatures from which the chemists would later derive wonderstuffs⁷. The "thousand uses" of bakelite – for electric appliances, radios sets, automobiles... – were no longer a weakness. They signaled its "Protean adaptability". This proved to be a key for Baekeland's success although new natural polymers – like cellophane for instance- were still successfully launched on the market in the 1920s.

The marketing of synthetic polymers relied on two major arguments. On the one hand, the image of cheapness was re-evaluated. Promoters of synthetic polymers in America presented chemical synthesis as a cornucopia of cheap products within everyone's reach. Chemistry was envisioned as a driving force towards the democratization of material goods⁸. Chemical substitutes were also presented as pillars of stability : "one plastic a day keeps depression

⁴ The only domain where celluloid was uniquely suited and eclipsed all rivals - the films for photography and cinematography – both caused its triumph and its defeat. While celluloid generated a new technological concept –roll film – less flammable substitutes were actively sought out. (R. Friedel, *Pioneer Plastic*)

⁵ See Charles Eastlake, *Hints on Household Taste* (1872) quoted by Robert Friedel, *Pioneer Plastic*, 88.

⁶ Aristotle, *Politics*, I, 2, 1252 b.

⁷ John K Mumford, *The Story of Bakelite* (New York: Robert L. Stillson, 1924).

⁸ Edwin E Slosson, "Chemistry in everyday life", *Mentor*, 10, (April 1922): 3-4 ; 11-12, quoted by Meikle, « Plastic, Material of a Thousand Uses » in Joseph J. Corn, *Imagining Tomorrow. History, Technology, and the American Future* (Cambridge: The MIT Press, 1986), 77-96.

away". They were said to provide jobs and feed the market economy thanks to the rapid obsolescence of the mass products.

On the other hand, Williams Haynes promoted chemical substitutes as a way to spare natural resources. "Modern civilization", he argued, was making unprecedented demands upon the world's stock of wood, iron, coal, copper, rubber, and petroleum. "The use of chemical substitutes releases land or some natural raw material for other more appropriate or necessary employment"⁹. Chemically manufactured substitutes would thus contribute to the conservation and protection of nature. At the same time, in breaking the traditional alliance between one material and one specific function – which was considered as the main characteristic of natural materials - the invention of substitutes opened up a broad field of potential innovations and came to epitomize the abstract notion of progress.

The campaign orchestrated in the 1930s to promote nylon, the new polyamid synthetic fiber 6-6 invented by William Carothers in Du Pont's laboratories, was an attempt to break with the image of synthetics as cheap substitutes for natural materials. The term nylon was selected after months of debate because it avoided all connotations of an artificial substitute for silk.¹⁰ The promoters of synthetic polymers went further in claiming the superiority of synthetic materials over those provided by nature. The argument was based on two rather antithetical characters of synthetics. First, because of their invariable chemical composition, they offer uniform properties and a strict control of quality whereas natural products, being always variable and mixed with impurities, must be submitted to repeated analyses and assays. This argument could apply to all manufactured products, to metals as opposed to wood, for instance. The second argument is more specific: synthetic polymers allow a large variability of forms, of uses and tastes, because they are molded. Plasticity which had been seen as a weakness, an inferiority of the artificial as compared to the natural, became the most positive value of synthetics in the mid-century.

However it was only a few decades after World War II that plastics got rid of their early connotation of cheap substitutes for natural materials. When they were used by sculptors, architects and couturiers for artistic creation they became noble materials, highly praised

⁹ Williams Haynes, *Men money and Molecules* (New York: Doubleday, Donan & Company, 1936) 155. In Williams Haynes' view, the Cassandras who, considering the limits of natural resources, announced the collapse of industrial revolution ignore the coming of the "chemical revolution". Chemical power would displace mechanical power and restore stable relations between modern culture and nature.

¹⁰ Susannah Handley, *Nylon The Story of a Fashion Revolution*, (Baltimore: The Johns Hopkins University Press, 1999). In order to create a popular euphoria, a gigantic 2-ton model of a woman's leg was exhibited. On the chemist's crusade and the creation of the slogan "Better things, for better living...through chemistry", see David J. Rhees, *The Chemists' Crusade, The Rise of an Industrial Science in Modern America, 1907-1922* (Ph.D. dissertation, University of Pennsylvania, 1987); "Corporate Advertising, Public Relations and Popular Exhibits : The Case of Du Pont" in B. Schroeder-Gudehus ed. *Industrial Society and its Museums 1890-1990* (London: Harwood Academic Publishers, 1993), 67-76.

for their lightness, their mobility and plasticity. This changing image has to do with the processes used for manufacturing plastics. As Jeffrey Meikle pointed out, in the 1930s and 1940s, thermosetting plastics had encouraged the image of a static, eternally perfect future society ; in the fifties, when thermoplastic plastics, infinitely capable of being melted and reshaped, proliferated in daily uses, plastics connoted disposability and impermanence. With curved shapes and pneumatic architecture, synthetic materials created an aesthetic of their own in which artificiality became synonymous with plastic change, contrasting with the rigidity of nature. In 1971, the French philosopher Roland Barthes devoted a few pages to plastics in his review of the mythologies of modernity. "Plastics," he wrote, "are like a wonderful molecule indefinitely changing."¹¹ They meant potential change, pure movement. They connoted the magic of indefinite metamorphoses to such a degree that they lost their substance, their materiality, to become pure virtualities. In turn, Jean Baudrillard used plastics to describe a paradox inherent in consumerist society: the increasing mass-production of items requires more and more ephemeral products. "In a world of plenty, fragility replaces rarity as the dimension of absence"¹² Thus plastics exemplify the "culture of the disposable" characteristic of the second half of the twentieth century.

Thus bestowed with an "unbearable lightness of being", plastics were clearly praised as unnatural. The bright colors and shiny surfaces of vinyl and formica were praised for their surface, for their superficiality, their inauthenticity. According to Meikle, they expressed "a faith in technology's capacity for transmuting nature's imperfections so as to arrive at the dazzling perfection of the artificial. »"¹³ "Dazzling perfection" sounds like the right word : the plastic age did not mean to improve on nature but to construct fake utopic worlds by accumulation of light and disposable artifacts. Thus the traditional connotation of forgery attached to artifacts turned to be a positive value.

This brief survey of a success story shows how the distinction between artifact and nature has been reconfigured by the contrast between plasticity and rigidity. The manufacture of chemical substitutes was initially justified by a very specific view of nature as a rigid economy. First, each natural material was presented as rigidly assigned to a specific function – wood for construction, cotton for clothing, for instance. By contrast, synthetics were meant to be flexible and multifunctional. Second, nature was considered as a strictly limited stock of

¹¹ Roland Barthes, *Mythologies*, (Paris: Denoel-Gonthier, 1971), 171-73.

¹² Jean Baudrillard, *Le système des objets*, (Paris: Gallimard, 1968), p. 204 in the 2000 edition

¹³ J.L.Meikle, "Beyond Plastics : Postmodernity and the Culture of Synthesis", Working paper N°5 in David E. Nye, Charlotte Granly (eds), *Odense American Studies International Series*, (Odense : Odense University, 1993), 1-15, quot. p. 12.

resources by contrast with the promise of welfare out of the chemical laboratory. Nature was presented as a finite collection of products rather than as a continuous process of generation. No *natura naturans*, it was a *natura naturata*. It seems plausible that these various connotations of rigidity deeply influenced the adoption of the word “plastics” for all the family of synthetic polymers and subsequently favored the positive value attached to the artificial.

Artifacts as *êtres-de raison* vs stupid nature

Most of the synthetic polymers which became commodities in the twentieth century were designed by trial and error. Although big investments were made by chemical companies such as Du Pont or by rival nations in the case of synthetic rubber, the synthetic techniques were labor-intensive, and often based on serendipity. Like many other domains, the practices of synthesis have been deeply transformed by the use of computers. For designing molecules with interesting medical, magnetic, optical, or electronic properties 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 past¹⁴. Many algorithms are now available to design molecules, using computation, combination, randomization..... Rather than trying to survey them all, I will focus on two of them: computational chemistry and combinatorial chemistry.

How can one dispense with the painstaking and expensive process of synthesizing new molecules without even knowing if their properties will meet one's requirements? This is obviously a pressing question for all kinds of companies. Computational chemistry is a way of avoiding the cost of synthesis by modelling the chemical behavior on a computer from three different perspectives: thermodynamic features, electronic properties and the spatial, molecular conformation.¹⁵ The technique was initiated in the early 1970s by Cyrus Lewenthal in the context of the Multiple Access Computer (MAC) Program at MIT based on x-ray crystallographic models. By visualizing the 3-D structure of a compound and rotating it, one can predict how a small molecule could interact with a protein. Molecular graphics are not

¹⁴ Al Globus, John Lawton, and Todd Wipke, "Automatic molecular design using evolutionary technique" *Nanotechnology* 10 (1999): 290-299. David E. Clark (ed.), *Evolutionary Algorithms in Molecular Design*, (Weinheim: Wiley-VCH, 2000).

¹⁵ A.J. Hopfinger "Computational Chemistry, Molecular Graphics and Drug Design", *Pharmacy International*, ? (September 1984): 224- 228.

only visualized but also manipulated. Of particular importance is the conformational analysis which associates a relative energy to each conformation of a molecule.

The guiding principle is expressed in this advertisement of Molecular Design Ltd: "Now you can find out how well a new compound works before it does". Here is a way of producing artifacts without putting material properties to work. The creative process is no longer an interaction between physical molecules and human bodies or machines – with the pressure of money. Rather it is an interaction between an algorithm and a virtual reality.

Computational design of molecules deeply transformed the status of the artifact. First, it banished the craft dimension from the making of artifacts in the interest of rationality and efficiency. An artificial material is basically the answer to a well-defined question, whatever the question: how to bind a molecule to the receptor of a specific protein for new medicines or how to make a light, stiff and tough material for airplanes. Modern "virtual alchemists" no longer teased the fire in dark laboratories but did not renounce the Promethean ambitions of ancient alchemists. Beyond the objective of calculating the properties and reactivity of different structures, the ambition of computational methods is to "model the real world by computer in a reasonable amount of time" as Uzi Landman, director of the Georgia Tech Center puts it¹⁶. They are intended to subdue the messiness of nature to the logic of computation.

The supreme achievement would be to build up a material *ab initio*, using computer calculations and starting with the most fundamental information about the atoms and from the basic rules of physics. Nanotechnologies, in particular, rest on the assumption that it is possible to control the construction of a material from bottom-up. By placing atoms and molecules at selected positions, it is possible to build structures suited to a particular design atom by atom. Eric Drexler, who devoted a number of popular writings to nanotechnologies in the 1980s, announced prophetically that "nanotechnology would bring changes as profound as the industrial revolution"¹⁷. Drexler depicted atoms and molecules as nanomachines. They are "universal assemblers" that could be used as machine tools by engineers in order to create molecular machines performing better. Improving on nature is the main objective and there is no limit to the power of those handling the "universal assemblers". They handle "the engines of creation".

¹⁶ See the web site of Georgia Tech Center for Computational Materials Center.

¹⁷ K. Eric Drexler, *Engines of creation*, (New York, Anchor Press /Doubleday, 1986); see also "The coming era of nanotechnology" in Tom Forester (ed) *Materials Revolution. Superconductors, New Materials and the Japanese Challenge*, (Cambridge, Mass. : The MIT Press, 1988). *Unbounding the Future: The Nanotechnology Revolution* (New York: Morrow, 1991). *Nanosystems: Molecular Machinery, Manufacturing, and Computation* (New York: Wiley, 1992).

The revival of such archaic fantasies is not the ineluctable consequence of the rational design of molecules. Combinatorial chemistry – a computer-assisted method of discovering drugs developed in the 1990s- leads to quite different views of art and nature. It consists in reacting a set of starting materials in all possible combinations. Instead of using the computer in order to avoid the contact with physical molecules, like computational chemistry, this method amplifies it, while trying to eliminate all serendipity in the process of synthesis¹⁸. Once a the route for synthesis has been selected and optimized, in a few steps and a few months thousands of compounds are synthesized with no other purpose than being systematically stored. The idea is to obtain a "library" of substances¹⁹. Many of them are messy mixtures and prove useless when they are tested against proteins. However they are stored since the library should contain molecules for every possible protein target, embracing the maximum diversity without redundancy. Then with the help of computer "evolutionary algorithms", a fittest structure will be selected.

It is "rational" design because of the application of the rules of combinatorials and algorithms of selection. But it is no longer intentional. The combinatorial chemist is like the monkey randomly typing letters with the expectation that a verse of the *Iliad* will come out of these meaningless sequences of characters. It is assumed that all technological or medical questions will find an answer in a library of billions of structures designed by combining and recombining the letters provided by nature. While the Ancient Greek metaphor of the letters of the alphabet is often used to describe combinatorial chemistry, the analogy with the military seems more adequate for describing the second step of this technique. Thousands of the molecules stored in the library are shot on a target protein. Both the random manipulation of letters and the blind shooting deeply differ from the traditional strategies of chemical synthesis in which each move is carefully planned and oriented towards an end. Not surprisingly, for a number of chemists combinatorial chemistry is a despicable method of fabricating substances. Pierre Laszlo, for instance, refers to it as "the moronic travesty of scientific research known as combinatorial chemistry". It is a "perversion of the latter" whose unique goal is "the proliferation of chemicals".²⁰

Combinatorial chemistry is certainly a cheap and fast way of designing drugs or other interesting molecules for industrial and commercial aims. However making and storing

¹⁸ X.-D. Xiang et al. *Science*, 268 (1995), 1738 ; Xiang, *Annual Review of Materials Science*, 29 (1999), 149.

¹⁹ The relevance of the term "library" for the storage of molecules is questioned by Roald Hoffmann in "Not a library", *Angewandte Chemie, International Edition* (abbreviated as *Angew. Chem. Int. Ed.*) 20001, 40(18): 3337-3340.

²⁰ PierreLaszlo, «Handling proliferation», *Hyle*, 7 N°2 (2001) 125-140, on p. 128.

unnatural and improbable molecules can also be a cognitive enterprise. As pathology is useful for advancing physiology, similarly designing monstrous artifacts may be a way to better understand nature.²¹ To a certain extent combinatorial chemistry is an exploratory method analogous to that of eighteenth-century chemists who performed hundreds and hundreds of reactions in order to build up affinity tables²². Affinity tables served as instruments of prediction like the libraries of molecules. For eighteenth-century chemists and for combinatorial chemists, knowing through making, is the most reasonable investigative strategy. The underlying assumption is that we cannot predict exactly where to find the correct solution to any demand without making all the reactions and testing all possible structures. This means enlarging the potential of natural resources in order to be able to make use of part of them. "The Lord is subtle...", too subtle for the understanding of contemporary chemists. They are ready to play dice, provided they have gathered in their library all the possible structures in order to sort out the optimal combination in a few steps. As pointed out by Roald Hoffmann, this recent branch of chemistry has revived the old tradition of the *Ars combinatoria* illustrated by the catalan alchemist Ramon Lull and later by Leibniz²³. Combinatorial chemistry can be considered as a special way of mimicking nature by simulating the blind processes of selection at work in the evolution of living organisms. It is nothing like copying natural structures because they are smart and well designed for specific purposes. Rather it is copying the non-teleological mechanisms of repetition and massive production of substances with imprecise shooting of the target that seems to be the rule in the molecular processes of replication²⁴. Here we find the Bergsonian view of life as a spontaneous, aimless movement with no direction, no intention. Generating variability through combinations and recombinations and then selecting those variants that are useful is a blind and stupid process. The contrast with conventional chemical synthesis is striking. Because it is a creation without design, combinatorial chemistry is hardly an "art" if we agree that all human arts are characterized by purposes or intentions.

²¹ In a paper entitled "unnatural acts" Roald Hoffmann reported the case of a chemist who created a slightly different structure of DNA, with hexoses instead of pentoses as the sugar building blocks of nucleic acids. In doing "what nature chose not to do", he created "an alternative universe", which did not work but could help understand why "normal" DNA works. Roald Hoffmann, "Unnatural Acts", *Discover* (August 1993) : 21-24.

²² On affinity tables see Isabelle Stengers, "Ambiguous Affinity: The Newtonian Dream of Chemistry in the Eighteenth-Century" in Michel Serres ed. *A History of Scientific Thought* (.Oxford, Blackwell, 1995), 372-400. Lissa Roberts, Setting the Table: the Disciplinary Development of Eighteenth-Century Chemistry as read through the Changing Structure of its Tables", in Peter Dear ed., *The Literary Structure of Scientific Argument* (Philadelphia: University of Pennsylvania Press, 1991), 99-132.

²³ Roald Hoffmann, "Not a library" *Angewandte Chemie, International Edition*, 40, N°18 (2001)3337-3340.

²⁴ Miroslav Radman, « Fidelity and infidelity », *Nature*, 413 (13 September 2001) 115.

Both computational chemistry and combinatorial chemistry are total syntheses since they proceed from the basic units. They are both rational in the sense that they follow strict rules of design rather than the *ingenium* and the skills that are usually characteristic of art. The craft dimension of the artifact disappears. Whether it be a virtual macromolecule on the screen of a computer or a physical unnatural compound stored in the library of combinatorial chemists, the artifact is above all an *être-de-raison*. Both methods face the making of artifacts as a problem of calculus. Computation and combinatorics are agents of production. However the meaning of production is quite different. In computational chemistry producing is a demiurgic creation of virtual realities. In combinatorial chemistry production is proliferation in an attempt to exhaust all the possible combinations of elements provided by nature.

While the boundary between science and technology seems to fade away, so does the boundary between nature and art. Art is deprived of most of its traditional attributes: intentionality, skills and ingenuity, crafts. Nonetheless the boundary between nature and art is restored by the conventions governing the patenting systems. The molecules made by rational design are considered as inventions rather than as discoveries ; hence they are patentable. They are designed as potential market goods in a close alliance between researchers and venture capitals.

Biomimesis : nature is technology

Traditionnally a material was extracted from nature then processed for human purposes. Its structure and properties constrained the making of artifacts and determined the performance of the end-product. The quality of a violin for instance is dependent on the quality of the wood used to make it, among other factors. By contrast the advanced materials manufactured over the past three decades are no longer preconditions of the production process. They are designed as the optimal solution to a specific problem. Given a set of desired functions or performances, let us find the properties required and then design the structure combining them. This approach presided over the development of materials science and engineering in response to very specific demands raised by military and space programs in the 1960s. Rockets, nuclear reactors, space flight, created the need for materials which were not currently available

Within a few decades of R&D on such high performance materials, however, materials scientists and engineers realized that they had to forget about the linear scheme – structure, properties, performance - in favor of a systems approach. Structure, properties, functions and

process have to be mutually adjusted in a continuous feed-back process. They are like the four summits of a tetrahedron which holds together the creative process of any artifact²⁵. It is the search for optimization of artifacts that requires a synergy between structure, properties, functions and process.

Moreover, these high performance materials are generally made of several materials in order to obtain the best compromise between properties such as the lightness provided by plastics, the toughness of metals, and the resistance to high temperature of ceramics. Most of them are composite structures: they are made of a matrix reinforced by fibers. The concept of the composite emerged out of the fiber reinforced plastics manufactured in the 1950s but gradually composites became something different from reinforced plastics.²⁶ The use of long, high-modulus fibers like carbon or Kevlar®, allowed chemical engineers to design new materials with never before seen properties. In contrast to conventional plastics which are mass-produced, high performance composites or more recently hybrid materials associating organic and inorganic components at the molecular level, are designed for a specific task under specific conditions. Materials by design are mapped with anisotropic structures and a specific chemical composition adjusted to specific efforts in the use of the end-product. Thus each one offers a landscape of its own. Each one is unique.

At first glance, these materials as light as plastic with the toughness of steel and the stiffness or heat-resistance of ceramics are a veritable paradigm of ingenuity, and most definitely unnatural. Like the chimeras invented by the Ancients, they associate different species into one body. The modern centaurs incorporate multiple species in the inner matter rather than in their external appearance.

Ironically, the search for ever more artificial materials has drawn the attention of scientists towards natural materials. Suddenly in the 1980s and 1990s, journals of materials sciences began filling up with beautiful pictures of molluscs and insects. Like the old popular books entitled *The Marvels of Nature*, they enthusiastically describe the details of sea-urchins and abalone shells, spider silk, penguin feathers and dolphin skin,

²⁵ Voir 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,

²⁶ Originally the term "composite" was used in conjunction with "reinforced plastics". The U.S Society for Plastic Industries had a Reinforced Plastics Division which was renamed Reinforced Plastics and Composites Division, in 1967. In France, a bi-monthly magazine entitled *Plastique renforcé/Verre textile* published by the professional organization bearing the same name, started in 1963 and was rechristened in 1983 *Composites* with *Plastique renforcé/verre textile* as a subtitle. See Bryan Parkyn « Fibre reinforced Composites », in Mossman Susan T.I., Morris Peter.J.T.(eds), *The Development of Plastics*, (London : The Science Museum, 1994), pp. 105-114 and Bernadette Bensaude-Vincent, "The New Science of Materials : A Composite Field of Research" , in Carsten Reinhardt, ed. , *Chemical Sciences in the 20th Century Bridging Boundaries*, (Wiley-VCH, 2001) pp. 258-270

the hedgehog spine and the porcupine quill, the beautiful colors of *Urinadae* and *Morphidae* butterflies and even single cell marine algae like coccolithophores. Why did nature thrown out the door by the triumph of plastics return through the window? It is the quest for high performance and multifunctional materials that prompted this shift back to nature. Living organisms provide models of high-performance materials. In living creatures around them, and in their own bodies, scientists and engineers found inspiring models of structure, models of integration of functions and models of processes. The spider's silk is a fiber extremely thin and robust that offers an unchallenged strength-to-weight ratio. Though mollusk shells are made out of a common raw material - calcium carbonate - they present a variety of structures – layered, tubular, porous, foam-like structures – with elaborated shapes and they assume a variety of functions²⁷. The remarkable properties of bulk materials are the result of a complex arrangement at different levels, with each level controlling the next one. The hierarchy of structures with multiple levels of organizations from the molecular scale up to the macroscopic scale, exemplified in bones and wood, very much impressed materials scientists. It is viewed as a key for the reliability of a material because the structure can respond to chemical or physical stress at different scales. It is the key for such desirable functions as growth, self-repair and recycling.

How could those efficient, smart and highly reliable structures be designed? The processes used by nature are no less admirable and marvelous to a chemist. Organisms synthesize these materials at ambient temperature, without high pressures. The various components are simultaneously synthesized and self-assembled, with a controlled orientation. The ingenuity of nature confounds the skill of contemporary engineers. Nature is an unrivaled master who teaches lessons to humans. For dealing with this new master, most chemists and materials scientists have started collaborations with biologists.

Interdisciplinary collaborations may use various strategies. To a number of chemists it seems hopeless to improve on nature, or even to compete with nature. As Steven Boxer, a chemist from Stanford put it: “We’ve decided that since we can’t beat them (biomolecular systems), we should join them.”²⁸ Let's start from the building blocks provided by life - whether they be proteins, bacteria, genes - in order to achieve our own technological goals. An example is the spider silk. After it has been demonstrated that

²⁷ Lowenstam, H.A. ; Weiner, S., *On Biomineralization* (Oxford University Press, Oxford, New York, 1989).

²⁸ Boxer Steven quoted in “Exploiting the Nanotechnology of Life”, *Science*, 254, 29 November 1991, p. 1308-09.

the main thread of a variety of spider was composed of two proteins, named spiderine 1 and spiderine 2, some chemists isolated the spider's gene which encodes these two proteins, and inserted it into the mammal glands of goats. When the first yield of silk comes, then these chemists will have to learn how to spin it order to obtain mechanical properties similar to the spider's silk²⁹. Using biotechnologies in order to manufacture materials for industrial purposes is a very attractive pathway: on the one hand, proteins like spiderine are beyond the reach of organic synthesis; on the other hand, for large scale production polymers produced by genetically-modified plants would be easily recyclable. However, this strategy meets the same difficulty that was pointed out by the promoters of synthetics in the 1930s : nature is too versatile, too impure to meet the requirements and standards of industrial production.

In stark contrast with chemists who jump onto the bandwagon of biotechnologies, a number of chemical engineers found in biomineral structures model solutions to their own problems. For instance, Ilian Aksay from Princeton University had designed a material for a light US-Army shield and had already patented a ceramics-metal composite, when he realized that he could make a far-better material in imitating the layered structure of the abalone shell.³⁰ Similar efforts have been made to imitate the iridescent wings of butterflies in order to design similar fabrics and the hexagonal structures of moth-eyes have inspired new anti-reflection structures for industrial emitting cathodes or photothermic absorbers³¹.

Models, inspiration, imitation...what exactly is the meaning of "mimesis" in the current expression "biomimetics"? It does not invite such attempts as Hyatt's efforts to imitate natural ivory. The goal is neither to produce an indistinguishable copy, nor to reproduce the appearance of the biological model. Biomimetism is by no means orientated toward artificial replicas of products generated by life. Would it rather be a renewed attempt to challenge nature like nineteenth-century apostles of chemical synthesis did? No one claims to destroy the boundary between the realm of physico-chemical phenomena and life. All the metaphysical debates and ambitions that inspired the legend surrounding

²⁹ J.P. O'Brien, S.R. Fanhenstock, Y. Termonia and K.H. Gardner, "Nylons from Nature : Synthetic analogs to spider silk", *Advanced Materials* 10 (1998) 1185; A Seidel, O. Liivak and L.W. Jelinski, "Artificial spinning of the spider silk", *Macromolecules*, 31 (1998) 6733; H. Arribart, "Du biomimétisme à l'ingénierie génétique : la production du fil 'araignée par voie laitière à faible coût", in C. Sanchez (ed) *Biomimétisme et matériaux*, (Observatoire français des techniques avancées, vol. 25, 2001), p. 139-143.

³⁰ M. Sarikaya, I. Aksay eds, *Biomimetics : Design and Processing of Materials* (Woodbury, AIP Press, 1995).

³¹ S.J. Wilson, M.C. Hutley, « The Optical Properties of Moth-Eye anti-reflection surfaces », *Optical Acta*, 29 (1982), 993. see also Serge Berthier, "Biomimétisme et structure des lépidoptères" in C. Sanchez (ed) *Biomimétisme et matériaux*, (Observatoire français des Techniques avancées, vol. 25, 2001), p. 117-126.

Wöhler's urea synthesis are gone. Contemporary materials scientists are content with picking up local models as solutions to their current technological problems, related to integration, miniaturization, and recycling.

Is biomimetics one more expression of the back-to-nature movement that characterized the *fin-de-siècle*? Beyond the arrogance of synthetic chemists is it a humble worshipping of nature? Such questions require us to disentangle our assumptions about nature.

First, material scientists look at nature through engineers's eyes with a non-dissimulated anthropomorphism. "We can be encouraged by the knowledge that a set of solutions have been worked out in the biological domain," writes Stephen Mann, a natural scientist who entered the field of materials science. "The challenge then is to elucidate these biological strategies, test them *in vitro*, and to apply them with suitable modification, to relevant fields of academic and technological inquiry."³² Biomimetics is grounded on the working hypothesis that nature is a designer who had to face specific problems. In fact, the proximity between nature and artifact results less from a naturalization of engineering practices than from a technicization of nature. Contemporary biomimetics denies the ancient distinction between *physis* and *technê*: it is grounded on comparative studies of human technologies and the "technologies of nature" conducted by scientists working in biomechanics. Steven Vogel, for instance, contrasted "two school of design"³³. Julian Vincent, a chemist professor at the University of Reading, insists in considering life as one technology among others and seeks to promote biomimesis as a case of "technology transfer".

"Over three-quarters of all inventions emerge from closely related technology. We routinely fail to take advantage of the solutions and practices of other sciences and technologies. 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."³⁴

The idea is to improve the Theory of Inventive Problem Solving (TRIZ from the Russian acronym of this methodology of invention) by including the sophisticated systems

³² Stephen Mann, "Crystallochemical Strategies" in Stephen Mann, John Werbb, Robert JP Williams (eds) *Biomineralization, Chemical and Biological Perspectives*, (Weinheim, VCH, 1989), p. 35-62. Quot. p. 35.

³³ Steven Vogel, *Cat's paws and catapults. Mechanical worlds of nature and people* (New York, London, W. Norton & Company, 1998).

³⁴ Julian Vincent, "Structural biomaterials and biomimetic strategies", in C. Sanchez (ed) *Biomimétisme et matériaux*, p. 313-324.

designed by nature in the data base so that inventors can more easily find useful information for their specific problems.

A second assumption is that Nature is teleological. Nature's objective was the optimization of functions in an organism in order to ensure the survival and reproduction of this organism in a particular environment. Optimization has to be evaluated in terms of the best possible compromise between the necessary functions but also in terms of cost. "Since money and energy are directly equatable," Vincent writes, "it makes sense to see how natural systems apportion their energy between various functions, and how they design materials, mechanisms and structures".³⁵ Nature works with minimal energy, at low temperature, with cheap common raw materials. But the cost includes time. Nature has spent billions of years for designing and perfecting high performance structures capable of sustaining life, a length of time that no human, whatever his or her genius, can afford!

Despite this huge gap of time scale between nature and artifacts, it is assumed that there is a formal similarity in human and natural design strategies: given a set of functions to be achieved nature searched for the optimal compromise between those functions at minimal energy cost. This view of nature as a collection of optimally adapted organisms has been challenged by a number of evolutionary biologists. Stephen G. Gould and Richard Lewontin, for instance, castigated it as "the Panglossian paradigm", a remake of the "everything is made for the best purpose" of Dr Pangloss, Voltaire's famous hero³⁶. Natural selection can be viewed as an optimizing agent only by focusing exclusively on the immediate adaptation of organisms to local conditions. This fragmented view ignores the constraints imposed by the overall architecture, by the phyletic heritage that delimits pathways of development. Every organism and a fortiori every organ in an organism is not optimally designed for its functions because nature must follow an inherited plan. Borrowing from nature local solutions to a specific set of technological problems may be misleading. Materials scientists who consider only the functions to be performed overlook other variables, notably the general constraints that determined the

³⁵ Julian Vincent, "Structural biomaterials and biomimetic strategies" in C. Sanchez (ed) *Biomimétisme et matériaux*, p. 313-324, on p. 315.

³⁶ S.J. Gould, R.C. Lewontin, "The spandrels of San Marco and the Panglossian Paradigm : A critique of the adaptationist programme", *Proceedings of the Royal Society of London, Series B*, vol. 205, issue 1161,(sept 21 1979), 581-598.

inner organization of each material. Biomimetism should therefore rely on a more integrative and holist view of its models.³⁷

The view of nature as a technology is fruitful as long as the analogy between nature and human technology is established at a global level, considering both of them as "technological systems". Each system – nature and human art – is a distinct entity with a coherence of its own rather than a collection of models and copies. Instead of a simple importation of notions taken from materials science into biomechanics, instead of a simple transfer of models taken from nature into technological contexts, the analogy between nature and technology emulates new promising perspectives and inventive practices of science such as the ecological systemic approach of the exchange between nature and humans or the soft chemistry ("chimie douce") whose object is the study of chemical reactions at ambient temperature in open reactors, much like the chemical reactions that occur in living organisms³⁸. Finally as pointed out by Vogel, we should evaluate the benefits of biomimetism. There is a long tradition of inspiration taken from nature in technology. "The tendency to view nature as the golden standard for the design and as a great source of technological breakthroughs" rests on a number of legends forged by inventors themselves who emphasized their debt to nature³⁹.

To what extent can any recent advance in materials technologies really be attributed to biomimetism? To be sure, biomimetism has been fruitful, especially in the domain of biomaterials for drug delivery or artificial organs. It has inspired new ways of synthesis using all possible resources of chemistry and physico-chemistry to self-assemble elements or to obtain the rich morphologies of many natural structures. Unlike the products of computational or combinatorial techniques, these products require a lot of craft, of skill, ingenuity, imagination and a dose of indiscipline. But most of them are local prowesses whose utility is still disputable given the gap between the molecular scale and the bulk material.

³⁷ Advocates of evolutionary models in technology and economics develop more integrative approaches to technological products. Their holist perspective leads to question the idea that the winning technologies are always the optimal ones because of the « path-dependency ». See Paul David, "Understanding the economics of QWERTY. The necessity of history" *Economic History and the Modern Economist*, (Blackwell: Oxford, 1986). John Ziman ed. *Technological Innovation as an Evolutionary Process*, (Cambridge: Cambridge University Press, 2000).

³⁸ Bensaude-Vincent, B., Arribart, H., Bouligand, Y., Sanchez, C., "Chemists at the School of Nature", *New Journal of Chemistry*, 26 (2002) 1-5.

³⁹ S. Vogel, *Cats' paws and catapults*, p, 249-75. Among the most famous examples of successful copies are the Crystal Palace designed by Joseph Paxton whose roof allegedly copied a giant water lily; the spinneret for extruding textile fibers inspired by the organ of silkworms; barbed wire; and the velcro invented by the Swiss engineer Georges Mestral on the model of the hooked burs that clung to his socks.

In conclusion, the three cases studies here presented witness the complexity of the interplays between nature and artifact. First, there is no straightforward diachronic evolution of the representations of nature and artifact over the twentieth century. Certainly the contrast is striking between the rigidity of nature generated by the emphasis on the plasticity conferred to synthetics during the plastic age and the plasticity or flexibility of nature that biomimetic strategies confer to nature. However it would be oversimplistic to state that the cult of artificialism prevailing in the mid-century has prompted a *fin-de-siècle* back-to-nature movement. In the same cultural context one can find several coexisting notions of nature and artifact. Combinatorial chemistry suggests a stupid nature while at the same time biomimetics conveys the image of nature as an insuperable engineer. Over the twentieth century the concepts of nature and artifact have been continuously reshaped. To a certain extent the arrogance of the plastic era and the ambition of computational chemists revived the Promethean mythology attached to chemistry since early alchemy. Similarly the current trends in biomimetics seem to revive Aristotle's notion of art as a copy of nature. The interplay between nature and artifact sounds pretty repetitive. Like a classic theatre play performed in modern costumes, advanced technologies seem to re-enact old cultural patterns in the language of modern physics and chemistry with atomic and molecular structures replacing the four principles and substantial forms.

Does this mean that our concepts of nature and artifacts are cultural entities more or less independent from the actual practices of syntheses? To be sure, the representations of technological items are heavily constrained by cultural models. This does not mean they are culturally or socially constructed rather than shaped by the actual processes of design and manufactures. In view of the various synthetic practices here examined the dilemma between cultural and material determinisms seems extremely reductionist. In referring both the concepts of nature and the concepts of artifact to external factors, one would overlook the creative power of their interplay. Rather than a one way influence of culture upon nature and artifact these case studies suggest that technological choices are shaped by the kind of relation they engage in with nature. Early synthetic materials, like celluloid and bakelite, were aimed at substituting for natural materials. Nevertheless they became successful substitutes not through a servile imitation of nature but rather by marking their distance from nature. The image of plastics was shaped by contrast with a rigid nature. Symmetrically when materials technologies were aimed at the production of

artifacts totally different from those of nature, at new materials with never before seen properties that supposedly epitomize the domination of mankind over nature, of spirit over matter, the most successful strategy proved to be the imitation of the most modest natural materials like parts of insects and sea-shells. Nature and artifact are like a couple of infernal twins playing tricks on the people around them. They are mutually defined by an ambivalent relationship of connivance and rivalry.

Whatever the images attached to the notions of nature and artifacts their polarity is what defines the two terms. It thus seems impossible to escape the circle mentioned in the introduction of this paper. The circle however is not necessarily “vicious”. Rather it illustrates the complex status of the great dichotomies that shape our culture. Our perception of nature being determined not only by the art/nature couple but also by the other ancient divide between nature and society. The great divide between nature and artifact is operational at two levels. The views of nature as a clock, as a laboratory, as a computer program or as an engineer belong to the nebulous domain of mentalities, or uncontrolled mental representations underlying technological or social practices. At the same time, they act as consciously controlled and highly sophisticated heuristic models, contributing both to the understanding of nature and to technological innovation.

