The Science of Materials: from Materials Discovered by Chance to Customized Materials

*Inaugural Lecture delivered on Thursday 17 January 2013*

Yves Bréchet

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Throughout the ages, humans have applied knowledge and know-how to master materials. They have gone from materials encountered by chance available in their environment to customized materials designed to meet multi-criteria specifications. Today, owing particularly to digital modelling on different scales, we are able to design high-performance materials, combining various classes of materials, in controlled geometries and dimensions. These innovation strategies – architectured or bio-inspired materials – have been integrated in many industrial sectors (cars, aeronautics, biomedical sciences, etc.).

YVES BRÉCHET

Yves Bréchet is a metallurgist and materials science professor at the Institut national polytechnique de Grenoble. He was appointed High Commissioner for Atomic Energy in 2012, and is a member of the French Academy of Sciences, the Academia Europaea and the European Academy of Sciences. He held the Liliane Bettencourt Annual Chair of Technological Innovation at the Collège de France for the year 2012-2013.
TABLE OF CONTENTS

Introducing Yves Bréchet
Serge Haroche

The Science of Materials: From Materials Encountered by Chance to Customized Materials
Inaugural Lecture delivered on Thursday 17 January 2013
Yves Bréchet

The world of materials
The historical trends
Technological innovation: from materials encountered by chance to customized materials
The strategies of development of high performance materials
The choice of materials
From architectured materials to bio-inspired materials
The science to make
EDITOR’S NOTE

The Collège de France Chair of Technological Innovation was created with the support of the Bettencourt Schueller Foundation.
The Liliane Bettencourt Chair of Technological Innovation is an Annual Chair that was created in 2007 by the Collège de France in collaboration with the Bettencourt Schueller Foundation. I would like to welcome Mrs Bettencourt Meyers and Mr Meyers who are with us today for this inaugural lecture.

Within the framework of this Chair, every year the Collège de France invites a scientific personality to give a series of lectures on a major aspect of technological innovation. This can be the development of new industrial processes based on fundamental research, the transfer of scientific knowledge to industrial applications, or the creation of companies or start-ups to commercialize these applications – to cite but a few examples of the crucial links developed between the elaboration of scientific knowledge and applications which have often revolutionized our everyday lives.

Previous holders of these Annual Chairs have spoken to us about research on medicines, the digital revolution, new medical and industrial diagnostic processes, nanotechnology and biomedical innovations. Today, Yves Bréchet is going to talk to us about the elaboration of materials as an introduction to his lecture series entitled “The Science of Materials: from Materials Discovered by Chance to Made-to-Measure Materials”. The importance, in our everyday lives, of the new materials that have appeared and been developed for the last century is obvious, be they essential semi-conductors for electronics, optical fibres and glasses, car and aeronautics components, metals used in nuclear plants, and nanometric objects developed for biomedical applications.

Developing a new material involves studying its properties, understanding its structure and developing efficient methods to prepare it. This is a domain where fundamental and applied research are clearly intimately intertwined. It is also a quintessentially interdisciplinary domain that requires the competences of physicists, chemists and even biologists at fundamental level, and then those of engineers to apply the research results.

At the Collège de France, an institution that inherently practices multi-disciplinarity, several recent Chairs have studied or are currently studying the properties of new materials from the perspective of fundamental research, in other words, they are seeking...

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to understand their properties purely out of curiosity. Let us recall that Pierre-Gilles de Gennes was a pioneer in the physics of liquid crystals and polymers. Jacques Livage is one of the founding fathers of soft chemistry aimed at making bio-inspired materials based on the model of those developed by nature at a low temperature, like marine animals’ shells. And Antoine Georges currently holds a Chair that is concerned with the structure of complex materials such as the famous ceramics with supra-conductive properties at a high temperature, which still raise unresolved theoretical questions for physicists. The Collège de France is the ideal place to host a Chair of technological innovation focused on the way in which fundamental research on these materials, so crucial to the development of our way of life, ultimately leads to concrete applications and uses.

Yves Bréchet, you are certainly the ideal scientist for this Chair and for telling us about new materials from the different angles I have just mentioned. As a former student of the École polytechnique, you were steered towards materials science by Yves Quéré, and obtained your PhD from the Université Joseph Fourier in Grenoble where you became a professor, before joining the Institut universitaire de France. You specialised in the domain of materials modelling, particularly the modelling of metals and alloys, owing to a distinct taste for inter-disciplinarity and your desire to combine fundamental research with an engineering vision. Your work shares the common feature of drawing from industrial questions the key scientific issues that require fundamental research to further the development of increasingly high-performance materials. Though a theorist and specialist in digital modelling, you have always remained in close contact with experimenters and engineers. Your renown, which earned you the reputation of a sought-after scientific adviser for many private industrial companies and public research institutions, was recognised in 2010 with your election to the Académie des sciences.

Your studies on the ageing of materials, particularly on that of the materials used to build nuclear plants, are recognized and valued by the CEA. This is probably one of the reasons behind your nomination as High Commissioner for Atomic Energy. This is a position of great responsibility, which you attained after the Collège de France invited you to hold the Annual Chair of Technological Innovation. We are particularly grateful that you upheld your commitment to teach materials science at the Collège de France despite this very time-consuming responsibility. I now leave the floor to you.

AUTHORS

SERGE HAROCHE

Administrator of the Collège de France
The Science of Materials: From Materials Encountered by Chance to Customized Materials
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1 Mr Administrator, Fellow Professors, Dear Colleagues, Mr and Mrs Bettencourt-Meyers, Dear friends, Ladies and Gentlemen,

2 I am very grateful for the trust the Collège has put in me by appointing me to this Annual Chair of Technological Innovation. I am aware of what an honour this is, and I feel intimidated by the responsibility.

3 It is intimidating to have to teach everyone “science in the making”, irrespective of the discipline. The fact that, to my knowledge, I am the first metallurgist to be invited to do so since 1530 does nothing to comfort the fortunate man that I am. Doing so in front of some of my masters, who would have done it a thousand times better, worries me all the more.

4 The Liliane Bettencourt Chair of Technological Innovation is an audacious venture to bring science in the making closer to technology in the making.

5 When Pierre-Louis Lions put my name forward for this Chair, he added to this singularity in French academia by suggesting a materials scientist. Not only does this discipline not
exist as such in France, what is more, the materials in question are structural materials, which are so familiar that they are usually considered as a given of daily life and not a research object. And of all researchers, he proposed a researcher in metallurgy, a discipline that is more likely to be discussed when it comes to repainting the Florange blast furnaces in green. He must surely have been thinking of Bourdieu who, I believe, said that the Collège “sacralized heretics”. My task tonight is to convince you that structural materials in general, and alloys in particular, are a formidable source of technological innovation, and a treasure trove of profound scientific questions.

I feel particularly overwhelmed at having to deliver this inaugural lecture. It is rare, except in cases of advanced schizophrenia, to give a lecture to one’s library shelves. Yet that is the strange feeling I had looking at the list of my renowned colleagues gathered here this evening. Some either once lectured to me or taught me physics and chemistry through their books; this was the case of Philippe Nozières, Claude Cohen-Tannoudji and Jean-Marie Lehn. Others I met in evaluation committees, for example Pierre-Louis Lions and Jacques Livage. There are yet others whose work I deeply admire, particularly researchers from my generation like Marc Fontecave, Clément Sanchez, Stanislas Dehaene, Antoine Georges and Jean-Marie Tarascon. Finally, there are those whose books filled the hours of reading I added to the hours spent studying the so-called “hard” sciences as a teenager, without ever having met them in person: Jean Delumeau, Jacques Bouveresse, Paul Veyne, Jacques Gernet, Yves Bonnefoy, François Jacob, Jean-Pierre Changeux, Emmanuel Le Roy Ladurie, and so on. I would be happy if, by the end of this inaugural lecture, I had managed to convey to them some of the pleasure I derived from the company of their books by discussing a discipline outside of their own.

The world of materials

A material is matter that fulfils a function. The most basic classification therefore concerns function. When the function of an object is to transmit forces (like the side frame of a car or the beams that make up a frame), the materials used are called structural materials. When the object’s function is to transmit or store information (in the form of power, light or heat transmission), they are called functional materials. Simplistic as it may be, this is an efficient classification for describing the evolution of materials: until the twentieth century, materials essentially had structural functions, and the command of mechanical properties and the capacity to give them the required form were the yardsticks of a civilization’s technical performance. A good part of what follows concerns structural materials, as their historical evolution extends over a longer period of time.

Materials can conveniently be classified according to their composition and to the nature of the chemical bonds between atoms. This classification is used not only in physics but also in engineering, as it groups together materials with similar properties. There are organic materials and inorganic materials. In organic materials, and particularly polymers, the carbon skeleton plays a crucial role and the interchain bonds are relatively weak. Inorganic materials, on the other hand, correspond to strong interatomic bonds. Depending on the role of the electrons in these bonds, a distinction is made between metals in which electrons move without difficulty, and ceramics in which electrons remain “attached” to atoms. Metals, polymers and minerals have rather different usage properties, as a result of the diverse nature of the bonds between atoms. Metals are malleable, their properties are highly dependent on the temperature in use and the
thermo-mechanical treatments they have undergone; they are good heat and electricity conductors, and are quite vulnerable to corrosion. While ceramics are much stiffer than metals and retain their properties at a high temperature, they are fragile, have little damage tolerance, are difficult to shape, and are formed through processes similar to pottery, involving particle suspensions followed by consolidation. Polymers are much lighter than metals and ceramics, and far less stiff. Their properties drop very quickly as the temperature increases and they are very easy to shape. Metals, ceramics and polymers are thus the main basic families of materials. Mixing these materials leads to a new class, composites. Natural organic materials are composites that are particularly well suited to their functions; I shall revert to this later. In terms of their use, materials’ origin is as important as their properties. Metals and ceramics exist in multiple forms in nature. Polymers exist in natural organic matter, though most of the time in a composite form – natural rubber being the exception. “Artificial” polymers only made their appearance very late in time, with the development of the oil industry.

The historical trends

Let us now examine historical trends. Given our limited knowledge, the outline I am now going to provide is a fundamentally Western perspective on history, and essentially focuses on structural materials. Historians have customarily named the different ages of humanity after the materials that prevailed in those periods: the Stone Age, the Copper Age, the Bronze Age, the Iron Age, etc. The nineteenth century can be seen as the steel age, the twentieth century as the age of polymers and then silicon. This habit is telling: the successive stages of our material civilizations are facilitated by the development of materials and energy resources.

While the materials used by human beings have continuously evolved, this has happened at very different speeds over the course of history, and has accelerated considerably in recent decades. In pre-historical times, around 50,000 BCE, the only materials our ancestors used were natural ones, be they mineral or organic. The choice of materials was essentially limited by their proximity. By around 50 BCE, the diversity of available materials had grown substantially. The Romans had excellent knowledge of ceramics and glass, they used both stone and mortar, and their work with metals, silver, gold, tin, lead, bronze and planished iron demonstrated a sound working knowledge of metallurgy, albeit not as great as that found much earlier in Far Eastern civilizations. Between the Roman Empire and the end of the Middle Ages, the world of materials evolved relatively little. While the engineers of the Middle Ages learnt to use civil engineering materials, as witnessed in the powerful religious architecture of the time, they did so with local raw materials: limestone in Reims, volcanic stone in Clermont-Ferrand and wood in Norway. The nineteenth century was unquestionably the century of metals, particularly ferrous materials. Cast iron and steel allowed for bridges, ships, trains, and later cars to be built. The industrial revolution was as much that of steel as it was that of the steam engine. The twentieth century saw two revolutions: metals and ceramics, which prevailed. Artificial polymers emerged, made from petroleum, with the fascinating variability of their properties, and the capacity to “build” matter on an atomic level, by playing with the chain arrangements. The second twentieth century revolution was the forceful appearance of functional materials, in much smaller quantities, but with very high added values. The electrical energy revolution was made possible by materials that already
existed. The microelectronics revolution required the manufacturing of very pure silicon, and the optic fibre revolution could not have occurred without the ability to use highly pure glasses with a gradient index.

**Technological innovation: from materials encountered by chance to customized materials**

11 The historical trend I have just outlined reflects the evolution not only of available materials, but also of the way humans relate to materials, successively moving from the “materials encountered by chance” to the “optimized material”, then to “competition between optimized materials” and finally to the “construction of customized materials”. This trend, which will be the common theme of these lectures, also reflects the shift from know-how to a science, then to a body of sciences, called the *engineering sciences*.

12 This is effectively technological innovation. Today, we are faced with what some have called “the hyper-choice of materials”. There are about 100,000 materials available to engineers, with a wide variety of processes to apply them. Every day new materials are discovered, though only a limited number of them make it out of the laboratory. A material is used not for a single property, or rarely so, but for a combination of properties, and for the possibilities of implementation. And despite the variety of materials available, in each domain of application, a limited number of families prevail: in the building industry, glasses, steels and concretes; in the car industry, steels, aluminium alloys and polymer composites; and in microelectronics, silicon remains the largely prevalent semi-conductor. But here innovation is far more than the extension of a catalogue of options. The three pillars of the modern science of materials, the optimization of materials, of choices between materials, and finally the design of customized materials, mark a profound evolution of our ways of using matter.

13 The optimization of materials, as the result of a scientific process, is relatively recent. It was born with modern metallurgy, whose founding concepts, dislocations and theory of phase transformations date back to the thirties, forties and fifties. A few key ideas should be remembered: however important the chemical bond may be, it provides neither the full story nor the microstructure; the sequence of phases resulting from the material’s lived history is a crucial component for understanding its behaviour. Macroscopic properties are at least as dependent on the deviations from the periodicity of perfect crystal, and defects play a crucial role in this behaviour. These notions that emerged from metallurgy spread to the study of other classes of materials, and the need for adopting a comparative approach then gradually led to the development of materials science. The latter is the daughter of physics, chemistry and mechanics, though not reducible to any of them; it lies at the crossroads between the fundamental disciplines and engineering sciences, structural mechanics, process engineering, and design.

14 This is the setting of technological innovation. The driving force of innovation is the evolution of applicative requirements, leading to the need for materials jointly to fulfil increasingly complex functions, which is called “multi-functionality”. To a growing extent, the innovation strategies that have led to the development of high performance materials involve modelling and digital simulation. Finally, with the ultimate request to develop customized materials, associations of materials and geometries are being
considered which may draw inspiration from the observation of natural solutions. This series of lectures looks at this whole landscape.

The strategies of development of high performance materials

The scientific development of high-performance materials began with physical metallurgy. Certainly, Benvenuto Cellini “knew” that by throwing his silverware into the furnace where he sought to cast his *Perseus*, he was improving the castability of the bronzes, and the organ builders “knew” that adding antimony to the tin-lead alloy of the 32 feet prevented them from creeping under their own weight. But the microstructural cause of these phenomena was only discovered much later. Fine characterization experimental techniques, as well as modelling and simulation tools, made it possible to understand and control basic mechanisms. This fundamental knowledge constitutes a set of “basic bricks”, in a sense, that allows us to build integrated optimizing tools for the use of materials. High-performance alloys are now developed through a joint experimentation and modelling approach, knowing that performance should be understood as both a combination of interesting properties and an operational implementation capacity (assembly, surface treatments, etc.). But a “high-performance” material must also maintain its performance over time. It must be able to resist the aggressions of chemistry and temperature, which ruin the material all the more insidiously in that their impact is deferred. The durability of materials is a crucial aspect of their performance, which is poorly understood because it often results from combined phenomena (such as stress corrosion). This resistance to aggressions is exacerbated in cases of “extreme conditions” that follow from system performance requirements beyond the materials’ capacities. Meeting these requirements may involve design solutions, such as the development of cooling circuits and thermal barriers for aeronautical engine turbine blades. But understanding the behaviour of materials in these extreme conditions is sometimes necessary to ensure the adequate functioning of industrial systems over time. The nuclear materials domain is a particularly demanding case of extreme conditions, as irradiation attacks the three pillars of materials' behaviour: chemistry (as an effect of transmutations), the crystalline order (as a consequence of radiation-induced defects) and the transport of species. The expected developments in the command of controlled fusion relate not only to the difficult problem of the stability of hot confined plasmas, but also, and in a limiting way, to that of materials able to resist irradiation by 13 MeV neutrons, at temperatures of several hundred degrees that are possible only if heat can be efficiently extracted.

Clearly, the development of high-performance materials needed to meet increasingly stringent specifications does not only involve developing appropriate microstructures and ensuring their stability over time and their robustness to implementation processes, but also the possibility of meeting specifications through a “system” strategy, such as, for example, surface treatments. The hyperbolic case of extreme conditions, the development of technological solutions for controlled fusion, will certainly stem from this joint material/system approach. While it is not sure that this is achievable, the material alone obviously cannot be a solution for systems that must extract heat, confine the field and resist irradiation. What I am describing for an exceptionally stringent case also holds true for more common domains like the design of materials for car bodies or
sparking drink cans: the time when materials were designed independently of implementation conditions has definitively passed and, more and more, technological innovation requires close collaboration between materials and design sciences.

The choice of materials

This necessary link between materials science and industrial design naturally appeared with the huge range of materials and the need to develop algorithms to rationally choose materials and processes. For this vast range of options also came fierce competition: simply think of the competition between steels, aluminium alloys and polymer matrix composites for car bodies, between carbon-epoxy composites and high-performance aluminium alloys for aerofoils or, more prosaically, the variety of materials used for drinks packaging (glass, cardboard, steel, aluminium, plastics). The competition between materials and the variety of possible solutions required objective, simple and efficient comparison tools with which to react rapidly to changing specifications contingent on technical, economic or legal conditions. Michael Ashby first raised this problem during the nineties in Cambridge. Basically, it called for a “comparative” state of mind. Tools for measuring a material’s adequacy against certain specifications, the “performance indexes”, first had to be set up. The equivalent then had to be done for selecting processes with a simple cost estimate tool. The problems associated with the coupling of materials, forms and processes required new strategies inspired by expert systems. The issues of multi-criteria, multi-constraint or multi-objective choices mobilized all the value analysis techniques, the Pareto front concept and, sometimes, artificial intelligence techniques such as fuzzy logic. Over the last ten years, choice methods have emerged that are currently used in multiple industrial sectors. These methods’ operational character is linked to their application in the form of software programmes, with “material” or “process” databases structured and ranked into families and sub-families. The tools developed in the public domain are merely the tip of the iceberg: all the large, highly efficient companies in the materials domain produce or use their own tools, which are simultaneously an expertise archiving tool, an engineer training method and a competitive technology watch tool. But the most significant point to remember from this work is that materials should be compared to one another as early as possible in the design process. Never will a cast aluminium wheel be designed in the same way as a welded rolled steel wheel, and it is only possible to benefit from the advantages of composite materials in a bicycle if we forget about the sacro-saint diamond structure frame, highly suited to metallic tubular structures. The systematic procedure for choosing materials, assisted by software using structured databases, requires an in-depth functional analysis of the relevant component. Finally, it must in itself be iterative and hierarchical.

Problems relating to environmental safety have added themselves to design issues with all the subtlety of any fashion trend: right at the forefront! Ecodesign requires method and rigour. Even if we limit ourselves to simple issues of energy impact and carbon footprints, it is crucial to fully understand that life cycle analysis must bear upon the industrial object and not the material, and that energy or chemical balance sheets must clearly distinguish between the manufacturing and functioning phases of the object. This is fundamental to any rational ecodesign approach. A particularly relevant case with regard to these issues concerns the thermal regulation of buildings, be it by developing
high-performance insulators, or implementing systems that contribute to smoothing out the early evening electricity consumption hike. These are two fundamental challenges for materials science. But at the other end of the matter/energy duality lies the question of recycling and of reusing materials. There again, a comprehensive perspective is needed: steel from cars has been efficiently recycled only when electrical circuits have been integrated in such a way as to allow for easy removal of the copper wires that caused lamination defects in recycled steels; and the strain on rare earths, which is a major concern in the press, could perhaps be partly resolved by using the “urban mine” that the magnets already in place in our electric engines constitute.

From architectured materials to bio-inspired materials

Increasingly stringent specifications are leading to physically contradictory requirements regarding materials: a high yield strength and a high deformability; strong thermal conductivity coupled with great inertia; very good behaviour at a very high temperature and great tolerance to damage and to the propagation of pre-existing cracks. These intrinsic contradictions may be avoided by means of a strategy known as architectured materials. These materials consist of one or several materials coupled together, with a controlled geometry allowing for the matter and properties to be distributed over length scales that match the dimensions of the component (Fig. 1). While the name architectured materials and the process of developing this strategy to bypass contradictions are innovative, there are many examples of such solutions: cables that couple axial rigidity and flexibility; sandwich structures which couple lightness and flexural stiffness; the metal polymer multilayers used to package airtight insulators combining perforation resistance, airtightness and low thermal conductivity; the self-blocking materials made from ceramics that couple tolerance to damage and heat resistance. While the strategies described above rely on the command of geometries, it is also possible to leverage gradients of microstructures, such as surface treatments, and composition gradients.
These two major classes of architectured materials considerably expand the range of available materials, combining discrete degrees of optimization (the choice of materials) and continuous geometric variables (for example cables’ angles of torsion, the dimensions of sandwiches’ skin and core). This new wealth cannot be exploited through a “trial and error” process: the relations between the constitutive variables of architectured materials and their properties must be clarified through modelling (whether analytical or digital), and this modelling tool can then be used to design optimized materials to meet complex specifications. While cables and sandwich structures are rather trivial examples, customized materials can also be designed for more “targeted” applications. For example, the development of sound-absorbing materials for aeroplane engines requires not only open porosity – so that the pressure wave can penetrate and be dissipated – but also good mechanical resistance – without which the material would have to be combined with structures causing excess weight. One possible solution is to develop a family of materials with double porosities formed through the random stacking of brazed hollow spheres. The geometry of the channels between the spheres controls the fluid shear, and therefore the acoustic absorption. The nature of the constitutive material and the thickness of the shells and of the brazing neck control the mechanical properties of the stacking. Resistance to chemical aggression is obtained through a surface treatment. A literally “customized” material is thus developed, which is able to ensure the acoustic absorption of a given noise spectrum.

This new strategy of architectured materials, which is expected to allow for innovative and customized materials to be developed to meet increasingly stringent specifications, affords a new outlook on the very same natural materials that were accessible to our ancestors in prehistoric times. But this outlook is neither nostalgic nor blindly admiring of “Mother Nature’s” creations. It is an engineering perspective which, faced with
troubling contradictions, analyses the solutions found in the domain of the living: being solid and tolerant to damage, having structures which gradually stiffen with use. We have long known that seashells are both hard and resistant, that tendons have evolving stiffness, and that our teeth resist wear and thermal shock relatively well. But analyzing the reasons behind the efficiency of natural materials is itself recent. In view of the limitations imposed on them, life forms use only a limited number of “basic bricks”, those involving polymers or ionic solutions, which do not require high-temperature processes – those which, by nature, fall under the soft chemistry that is dear to Jacques Livage and Clément Sanchez. Engineers, on the other hand, have access to Mendeleev’s entire table, which they sometimes take the liberty of expanding. But nature makes up for this limited number of “basic bricks” through virtually infinite ways of organizing them. Dentin and enamel are formed, in different proportions, by the same organic and inorganic components, affording both wear resistance and the blunting of cracks before they reach a critical state. The cortical bone and the trabecular bone, both formed of collagen and hydroxyapatite, differ in the organization of these two materials’ porous structure. And wood, formed of a lignite and cellulose cellular structure, develops different combinations of flexibility and solidity within the same tree, depending on the filament winding of the cellulose. We can naturally see where the source of architectured materials’ biomimetic inspiration lies: associating a variety of materials with a diversity of architectures to magnify the possibilities for developing customized materials (Fig. 2). Not by slavishly imitating nature – I am ready to bet that the best material to make a tree remains wood – but by drawing inspiration from its principles – reducing the size of fragile phases, hierarchical architectures, self-healing processes, etc. – to produce materials suited to new requirements.

Figure 2. Parallel between nature’s materials and engineers’ materials

<table>
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<tr>
<th>BIOLOGICAL MATERIALS</th>
<th>ENGINEERED MATERIALS</th>
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<tr>
<td>Light elements are prevalent C, N, O, H, Ca, P, S, Si</td>
<td>Very wide variety of chemical elements</td>
</tr>
<tr>
<td>Growth in temperature ranges limited by self-assembly processes</td>
<td>Manufactured from poorly condensed phases (liquids, gases, powders, etc.) and processes for all temperature ranges</td>
</tr>
<tr>
<td>Ranked architecture found on all scales from the nanometre to the millimetre</td>
<td>Formatting of the component and control of the microstructure at scales far below those of the component</td>
</tr>
<tr>
<td>Adaptation at tissue level or material level to fulfil the function, and adaptation to the slow evolution of surrounding conditions</td>
<td>Optimal selection of the material, form and process to fulfil the function</td>
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<tr>
<td>Self-healing</td>
<td>Designed with security margins</td>
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Hence, the important question of elaboration processes arises: whereas soft chemistry builds them with great elegance through bottom-up processes, our aim is to produce
them fast, in large quantities and at a low cost, as should be the case for structural materials, through top-down processes.

**The science to make**

From this perspective of materials innovation strategies, I have deliberately adopted an “engineering science” bias or, basically, one of “understanding in order to do”. I am certainly not trying to suggest that the science needed to develop these innovative strategies is complete. A great number of fundamental questions still remain open and, in a way that is characteristic of materials science, they articulate concepts and competences drawn from other fundamental disciplines. The command of microstructures requires a quantitative understanding of couplings in thermodynamics and kinetics, particularly at the level of interfaces. It requires an understanding of morphogenesis that we are still far from having achieved. Materials’ durability, however important it may be, especially in extreme conditions, is only partially understood, particularly when external stresses interfere jointly, as in the case of stress corrosion. The development of architectured materials through a top-down elaboration strategy can become systematic and reliable only by drawing on an in-depth understanding of the physical chemistry of metal/oxide/polymer interfaces. And, very importantly, the return of geometry in the design of materials with internal architectures raises many issues that remain unresolved, from the mechanics of entangled materials to the difficult question of the mechanics of the continuous environments needed for materials involving intermediary scales. Finally, if the goal is to develop materials that optimally meet contradictory specifications, optimization methods within semi-continuous spaces, which associate the choice of materials, the optimization of forms, and multi-scale modelling, will have to be spread from applied mathematics to materials science.

**Figure 3. The innovation strategies for structural materials and the evolution from materials encountered by chance to customized materials**
I would like to conclude with an overview of the technological innovation lectures I will give this year at the Collège de France in the field of structural materials – or at least of materials which partly fulfil a structural function (Fig. 3). Each lecture will have a corresponding seminar that will explore pathways of application for the ideas developed in the lecture, so as to provide everyone with an idea of the variety of industrial domains concerned by this substantive reflection on innovation in the materials field. Together these will serve as a foundation for this Chair’s final symposium, the subject of which is as simple to state as it is difficult to define: “How can the holes within the space of materials be filled?”

BIBLIOGRAPHY

On the selection of materials


On architectured materials


On structural biomimetism


AUTHORS

YVES BRÉCHET

Guest Professor, Liliane Bettencourt Annual Chair of Technological Innovation