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Bionics and design: witnesses to the evolution of this approach

> Natural history research, even that which seems to be the fruit of pure and empty curiosity, can have very real uses...
>
> René-Antoine Ferchault de Réaumur
> *A History of Wasps* (1719)

Bionics is a relatively recent science, only defined in 1960 by Jack E. Steele of the US Air Force, after the congress held at Dayton, Ohio:

> Bionics is the science of systems that have functions copied from those of natural systems, or that present the specific characteristics of natural systems, or even those analogous with them (quoted in GÉRARDIN, 1968).

In other words, bionics is the science that searches in living beings, animal and vegetable, for system models with a view to technical achievements. This preocupation is very close to that of the designer.

However, bionics was practiced long before it was officially defined. A whole series of examples could be taken from art and technical history that attest to humanity's interest in natural models since ancient times. Some, like Daedalus and Icarus, to whom the invention of flight devices based on birds and the construction of robots have been attributed, have come to us only through myth.

Renaissance design and the renaissance of design

Unquestionably, the most concrete witness —and the most troubling— is that of Leonardo da Vinci, who contemplated at the same time both bionics, strictly speaking, and design.

The example of this Renaissance genius may seem too antique. But it is really quite up-to-date, as Leonardo carried out the elaboration of his works from the font of inspiration —nature— to the definitive material achievement. He was, simultaneously and successively, designer, painter, engineer, architect, sculptor, anatomist and naturalist in the widest sense of the word. He was a «designer», that is to say «draughtsman» in the literal sense of the word, and he did the analytic drawings as well as the syntheses of his projects.

Bionics evidently seems to have been, for Leonardo da Vinci, a creative practice. He analyzed, dissected and observed natural structures with a technician's eye, made innumerable anatomy sketches, and arrived at a transpositions of principles through different scales and different materials. His work is witness to the natural step from understanding to creation, from analysis to synthesis, from hypothesis to experiment.

During the last decade, it is clear that the profession of designer, considerably amplified, has become a general activity, more than ever «universal», resembling in this the role of artist-technician of the Renaissance.

It seems evident, therefore, that bionics should bring to today's designer this creative method, this verification of the validity of new constructions, this diversification of forms destined to precise functions.

Development of the concepts of bionics

When we consider the different intents of copying nature since the end of the last century, we would be tempted to recognize a succession of numerous periods, leading from artistic inspiration to technical analysis, to finally end up at theoretic developments.

«Kunstformen der Natur» (artforms in nature)

This collection, published by the German biologist Ernst Haeckel in 1893, had a great influence on the artists and engineers of its time. Besides his activities as a biologist, he tried to call attention to the remarkable diversity of forms that nature has to offer.

At the time of the first oceanographic expeditions, he began —among other things— the catalogue of microscopic plankton forms, drawing sketches of great precision and a rare elegance.

On growth and form

The work of Sir d'Arcy Thompson, *On Growth and Form* (1917), was a real best seller in its day, as it resumed and made accessible documents related to this theme. He showed that form and its proportions and mechanical behaviour could only be understood by understanding its genesis.

«Evolutionsstrategie» (strategies of evolution)

Beyond the imitation of the physical principles of natural systems, we owe to Ingo Rechenberg the opening of an original domain of reflection. The author proposes the application of «the method of innovation» of nature. The fusion of mutations carries out a true «brainstorming», by which the sieve of natural selection represents a «value analysis». We might remember that brainstorming comes from the terms of the ideas, with no previous censure or hierarchization. Rechenberg modified, in a random manner, the system parameters which he experimented with, and retained only those that contributed to the improvement of the system. These principles were recorded in his 1973 work, of which the title is explicit enough: *Strategies of evolution. Optimization of technical systems after the principles of biological evolution.* Rechenberg was the founder of one of the few bionics institutes: Bionics and Evolution Techniques, which is a department of the Technical University in Berlin.

Form and function

The relation between form and function is without doubt the aspect of bionics which touches most particularly on the designer. That is to say that other aspects, like the physical-chemical principles of the functioning of some sensory organs, do not concern their domain.

On the contrary, innumerable works on biology dwell on the double aspect of the relationship between form and function. This is the domain of *functional morphology*.

Because of nature's often unexpected solutions, there is a hidden riches on which designers would be well advised to inspire themselves.

Models can offer similar solutions in front of a precise problem, as living creatures all share relations. Biologists call this *parallelism*.

It is thus that fish present two principal types of swimming fins: those of slow swimmers, and those of fast swimmers. For slow swimming, the fin is large and supple (Chinese carp). On the contrary, a sickle form characterizes fast swimmers like tuna and mackerel.

It is equally true that non-related living beings adopt a similar solution when faced with an important problem.

In this case, biologists speak of *convergence*.

The adoption, as well, of a fin system for in-water propulsion by mammals (dolphins, whales) and fish, is a sample of convergence.

The caudal fin: scull propulsion

Figure 1:

Nature does not know the movement of rotation around an axis. Propulsion by means of the oscillation of a fin, like that practiced by fish and whales, presents the inconvenience of the stopping of movement at each beat. However, technique has kept some of the solutions in the domain of the general shape of the fin and its suppleness, as well as the principle of propulsion by oscillations and the «pump» principle.

a) X-ray a trout fin and, superposed on its model, a supple scull for the propulsion of a boat (Ingo Rechenberg & Werner Voss, 1982).

b) Blue rorqual fin (seen foreshortened) and the prototype of a monopalm (FFNS, France, 1985).

c) Pump with rigid oscillating surface (Klaus Affeld & Heinrich Hertel, 1973).

Whatever it may be —whether a phenomenon of parallelism or of convergence— the selection of the same form for the same function underlines the interest of the system retained by nature.

The spindle form has been imposed on all rapid swimmers. But attention should be called to the fact that nature has gone beyond the advantage of mere form. She has retained many systems which improve gliding in the water, of which three have given bionic applications (fig. 2 and 3):

- The visco-elastic shock-absorbing skin of the dolphin: *Laminflo* covering for ship and submarine hulls.
- The mucus of fast fish, such as barracuda: *Polyox* (polyethilene oxide) for submarines, and additional «lubricant» in the water for fire-extinguishers.
- Microstructures from the surface of fast sharks: *3M/Minnesota microgroove covering* for ships and planes.

The limits of the form-function relationship

Biologists warn of the danger of an over-simplified interpretation which consists of attributing a form to a single function. As everyone knows, an organism must satisfy multiple functions whose requirements are often contradictory.

Let us take the case of fish: a fast swimmer, such as a trout, cannot offer an ideal hidrodynamic form which gives a quasi-laminary flow, allowing it to glide in the water without provoking turbulence. It must, to insure propulsion, possess fins in the first place, but must also have the possibility of nourishment, breathing, and sight. Fins, mouth, gills, eyes, all however contribute surfaces that disturb the glide.

But for the moment here we have the trout, apparently immobile, facing the current without the slightest movement!

The physicist Henri Coanda, of rumanian origin, while wondering about this curious phenomenon, formulated the hypothesis of the famous «Coanda effect»: water entering the mouth and going out through the gill fissures generates, around the body of the fish, a perfect laminary flow, provoking an aspiration effect which assures its stationary swimming. Actually, we do not know of a biological verification of this hypothesis, but Coanda was able to develop applications based on «the Coanda effect» in his first turbo-propeller plane (1910) as well as in «fluidic» control (fig. 4).

Escape tubes on London buses have since then had a «Coanda effect» design, assuring an almost total combustion and avoiding a contribution of smog to the city (cf. P. J. Grillo, 1960).

As can be seen, the observation of nature with a wide-awake spirit can call attention and lead to a technical innovation.

If we have chosen to illustrate this chapter on the form-function relationship with examples taken from the problems of propulsion in the water, it is because they seem highly symbolic of competition. We mean that competition leads to the selection of more competitive systems, those that present the best «price-quality» relationship.

The fast fish: the hydrodynamic fuselage

Figure 2:

a) Fast fish like this Loo mackerel, present biconvex profiles which characterize a good penetration in the water.

b) The same form can be equally applied to another «fluid» such as air. V. Tatin & L. Paulhan's (engineers) *Aérotorpille* plane, from 1919, has a fuselage which remind us of a fish form, with a propeller mounted «on the tail».

c) Mechanical pilot fish for guiding ships, patented in 1905 by the Norwegian Cornelius Lie.

The dolphin: a hydrodynamic fuselage

Figure 3:

a) Classic airplane with cylindrical fuselage, a DC8.

b) Silicone mock-up of a dolphin for hydrodynamic studies.

c) Project of a plane with a so-called *laminary* profile, inspired by that of the dolphin (H. Hertel, P. Thiède, K. Affeld, G. Clauss of the Aeronautic Institute, Berlin, ILTUB, 1966-1969).

d) A depression below the pilots' cockpit of a plane can correct the glide disturbance caused by the extruding element. Project by Heinrich Hertel after observations on the form of a melon and on the airing of dolphins (1969).

The immobile trout in the stream: a «Coanda effect»?

Figure 4:

The first turbo-propeller plane in aviation history, built by Henri Coanda, exhibited at the Aeronautics Salon in Paris, 1910. According to the engineer's friend, the designer Jacques-Paul Grillo, this would be a bionic invention. Coanda could have formulated the theory of the effect named after him by observing fast fish at sea and trouts in rivers and reflecting on the hydrodynamic role of the gill fissures.

Parallel to our purpose, we must quote testimonies from authors who are renowned in design and bionics.

On the utility of research in natural history

> [...] Natural history research, even that which seems to be no more than the fruit of pure and empty curiosity, can have very real uses, which would be enough to justify it even to those who only want research into useful things, if before condemning we could have the patience to wait for time to show the use we could make of its [...] (René-Antoine Ferchault de Réaumur, *A History of Wasps* [1719]).

We owe to Réaumur the reinvention of wood-fiber paper, a technique practiced in China more than a thousand five hundred years ago, but unknown in Europe. The observation of wasps building their nest with a paste of wood fiber inspired Réaumur with the idea of replacing cloth by less costly vegetable matter. It was not till 135 years after the publication of his proposal that the first wood fiber plant became a reality (Gottlieb Keller, Germany).

The «design» of the living world

> Time out of mind it has been by way of the «final cause», by the teleological concept of end, of purpose or of «design» in one of its many forms (for its moods are many), that man has been chiefly wont to explain phenomena of the living world.
>
> [...] To seek not for ends but for antecedents is the way of the physicist, who finds «causes» in what he has learned to recognize as fundamental properties, or inseparable concomitants, or unchanging laws, of matter and energy (D'Arcy Thompson, 1917, vol. I, pp. 5-6).

The burdock: an attachment system

Figure 5:

The burdock, *Arctium lappa*, photographed in Autumn *(a)*. The Swiss Georges de Mestral patented in 1951 the *Velcro* ribbon (*vel*ours «velvet» + *cro*chets «hooks»), inspired by the attachment system of the fruits of this plant. One side of the ribbon has shaved curls which serve as hooks, similar to the supple hooks of the plant, while the other side has fine curls similar to the curls of an animal's fur, into which the hooks attach. First adopted by NASA, this bionic invention has in time conquered every sector of our every-day life: the system does not need a special installation *(b)*.

Angled paddles: wing-tip «jet stream»

Figure 6:

The «Berwian» windmill by Ingo Rechenberg takes advantage of the complex eddy effect. Active paddle tips are turned towards the centre, where the turbine is placed. The windmill was optimized by the method of «evolution strategy» at many levels (number and position of the blades, profiles, etc.).

Figure 7:

Ingo Rechenberg, of the Bionics Institute, Berlin, has shown that paddles, the great feathers at the wing-tips of large birds such as predators, reduce energy loss.

Their cascade placement leads to the formation of marginal eddies that auto-organize into a helicoidal plait in the interior of which the axial air column is accelerated. What follows is a «jet» effect at the tips of the wings.

a) Andes condor.

b) «The Stork», experimental glider by Otto Lilienthal (1894).

c) Simple marginal eddy at a truncated wing-tip, responsible for a great energy loss.

d) Complex eddy showing the role of the multiple winglets, analogous to the paddles (feathers) of birds.

Physical principles of flight

> Man has made thousands of attempts to emulate birds. The human species has made and tested an infinite number of wings —all to reject them immediately. All, all has been in vain and no utility has arrived for this long-awaited feat.
>
> True free flight has remained, till this day, a problem for humanity, as it has for thousands of years.
>
> There is no help but to renounce wholly from means of sustentation based on lighter than air gases and we must therefore renounce from the use of inflated balons, and to rely on the grand effects of the flight of the animal world; we can only use one method of flight, where we use only not very thick wing bodies, those which offer very little resistance when penetrating the air in a horizontal direction.
>
> Flying animals are capable, while maintaining this principle, of rising and rapidly propelling themselves through the air. If we wish, therefore, to profit equally by the advantages of this principle, we should find the correct explanation of this effect of flight. The reduction of such an effect to its cause is carried out by the true knowledge of mechanical processes; and it is mechanics, the science of the effects of forces, which will give us the means to explain these mechanisms.
>
> The art of flight is therefore a problem whose scientific treatment depends essentially on a knowledge of mechanics. The reflections needed are, however, of a relatively simple nature and it is worth the effort of giving a glance at the relationship between the art of flight and mechanics (LILIENTHAL, 1889 : 6-7).

Principles of morphology

> When we first hear a biologist say in clear language that under the form of an animal we must always see the function, or when he insists, in a precise manner, on the relationship that links the body form to its functional activity, we can be a little disoriented by the multiplicity of images evoked.
>
> Let us look at: skeletons, rotation movements, liquid waves, gravity, wind, surface tension, warping, parallel expansion or contraction, varied growth, eddies, pressure, etc. To each of the forms that we have seen, there is associated an effect, something that functions, a *function* [...]
>
> With *chainettes*, we have gravity, that is a regime of constant and parallel forces; and with a billowing sail, which also has a *chainette* profile, we also have a regime of constant and parallel forces, those of a regular wind [...]
>
> With *logarithmic* and *surface spirals* we have a self-renewing phenomenon which always resembles itself.
>
> From which we draw the second point: when two or more forms are of the same species, there *may* be *something* in common in regard to their respective corresponding function [...]
>
> Actually, all forecasts are impossible, and it is necessary, in the presence of two functions that have something in common, to specify this something, if it exists, and to determine rigorous limits.
>
> After which one may doubt how simple «resemblance» can be even more dangerous (MONOD-HERZEN,

1956 : 144-145. See fig. 8, which illustrates some examples cited).

Analogies between physical phenomena or technical achievements and organisms

Figure 8:

(a-b) Medusa *Polycanna germanica* (Haeckel) and the evolution of an eddy in a liquid (K. Mack). *(c-d)* System of crossed geodes on the wall of a vorticel, a microscopic unicellular aquatic animal (Schaefer), and on Japanese basketwork.

Figures taken from the work of É. Monod-Herzen (1956).

On the riches of natural forms

The observation of natural forms offers us a marvelous support: an inexhaustible fount of combinations serving life are to be found there. In the admirable work of d'Arcy Thompson, *Growth and Form*, an extraordinary richness of natural forms and the study of their growth is found. We must also mention the works of Monod-Herzen, who first pointed out the problem posed by those strange and delicate organisms called radiolaria.

No architect can afford to ignore the work of the zoologist Ernst Haeckel, a prodigious repertoire of forms and constructive themes, from multiple arborescence to the most complicated networks. I am convinced that the future of structures is enclosed in these mysterious arrangements.

Nature offers us a range of secrets that will not be revealed except with much patience and love [...] (Le Ricolais, 1935-1969).

The leaves of the giant water-lily: nervated architecture

Figure 9:

Internal view of the Crystal Palace, London, built by Paxton in 1851 to house the Universal Exposition. Note the multiple supports corresponding as well to the static principle of the floating leaf of *Victoria amazonica*, on whose structure this construction is based: the leaf is not a structure which planes over its stalk, but rather the whole nervated structure rests on the water.

Figure 10:

a) The floating leaf of the giant water-lily *Victoria amazonica* can reach a diameter of 2 metres. It owes its rigidity to the radial nervatures and concentric nervatures on the underside, as well as to the up-curled edges.

b) The water-lily photographed in the greenhouse of the famous Kew Gardens near London.

c) Greenhouse with pleated roofing, entirely constructed in glass by the gardener and amateur architect Sir Joseph Paxton at Chatsworth in 1849. This greenhouse, whose construction principles are based on the leaf of *Victoria amazonica*, opened the way to the industrialization of light constructions, and constituted the prefiguration of the London Crystal Palace.

Bony frames: the optimal arrangement of matter

Figure 11:

a) Schematic representation of the distribution of bony matter in a human femur.

b) Section of a femur, with the fine fibers named *trabeculae* of the spongy bone.

c) This matter, capable of reacting to real mechanical contraction (weight of the body in oblique position, muscle traction, etc.), redistributes itself constantly, orienting the elements of its frame along the median lines of force (by deposit, by matter reduction).

d) Design of nervatures, called *isostatic*, of a panel of reinforced concrete in the auditorium of the Biology Department at Freiburg im Breisgau University, Germany. The static principle retakes a technique which applies this principle to the «natural» distribution of matter that was patented by the italian architect Pier Luigi Nervi in 1950.

e) The Eiffel Tower (1889) in Paris owes its wise «design» to a pupil of Culman, the alsatian engineer Maurice Koechlin. An ideal distribution of matter guarantees the mechanical efficiency of the 300 metre high tower: its 7.000 tons of steel would fit in a cube measuring only 10 × 10 × 10 metre!

Minimum, maximum, optimum

The notion of «structure» invades our field of knowledge. In fact, more than structure itself, the structure of structures, if I may be allowed the pleonasm, is more important. We see a kind of intellectual evolution developing, where ***quality*** overcomes ***quantity***, and with the emergence of the ***mathematical idea of variation***.

It has quite justly been remarked that the nature itself of the objects that we consider matters less than their arrangement. Beyond a poetic analogy, forms, substances, life itself, are no more than the result of these arrangements...

The constant of our universe is change. Our only hope is to understand it: to study what remains invariable in the course of change. Through the ages, the desire of the constructor is always the same: *to liberate enormous spaces with imponderable materials.* (LE RICOLAIS, 1935-1969. Somewhere else —«The desire of the constructor»— expressed himself in an even more poignant manner: *infinite space, weightless.*)

[...] the authors Stefan Hildebrandt & Anthony Tromba give us a thoughtful account of the symmetry and regularity of nature's forms and patterns. Although often easily seen, these forms and patterns are not always easily explained. Are there simple universal laws that allow us to comprehend them? [...]

It is the story of the development of the branch of mathematics called the calculus of variations, which concerns questions of optimization —finding forms or patterns that maximize or minimize a particular quantity. Is the igloo the optimal housing form for minimal heat loss to the outside? Do bees really use the least possible ammount of wax in constructing their hexagonal cells?

Moreover, is there an underlying principle that describes the infinite variety of forms in our world?

These questions have no final answers, but scientists continue to explore the notion that nature is governed by the principle of the economy of means —that nature proceeds in the simplest, most efficient way [...] (HILDEBRANDT & TROMBA, 1985. Introductory-jacket-text).

Helicoid bone of the python and the tree-branch junction: very resistent elastic profiles

Figure 12:

a-c) The danish designers Rud Thygesen and Johnny Sørensen have managed to give this wood chair lightness, solidity and sobriety, all economic, while taking particular care of the detail of the insertion of the back support into the horizontal ring of the seat. They imitated the detail of the junction of a branch and the trunk of a tree, where «nature resolves this problem by the wise arrangement of fibers and true proportions» (1981, in J. BERNSEN, 1983).

d) The pterigoid bone at the rear of the upper mandible of the python constitutes, with the square bone, a very special double joint which allows the snake to swallow whole prey of a considerable volume.

e) Geometric plane of this triple branched helicoid.

f) Project of glass fiber and polyester chairs by Fabrice Vanden Broeck (1984). Certain details notably the foot-seat and the foot-seat-back junctions are inspired by the pterigoid bone, where similar forces are exercised.

Bee hive: a minimum of material, optimum mechanical resistance

Figure 13:

Prototype of an alveolar fasciculus for the refrigeration system of a thermal station (1989). Designer Norbert Linke of General Electric Plastics, Holland, had just attended a conference where one of us (B. Kresling) had made a demonstration of the evolution of the art of construction by bees, from juxtaposed cells of single bees to group cells of social bees.

Figure 14:

a) Assembly principle of the alveoles of social bees. The common background is goffered. This solution guarantees an excellent «material economy - ensemble stability» relationship.

b) Sandwich structure technique with flat adornments.

c) Sandwich structure of a water ski with beehive interlining (*Reflex*, Zodiac Group, France).

Bat wing: beating flight or planing flight?

Figure 15:

In spite of the flight stability problems that this contraption posed, the «Bat» (plane number 3), by Clément ADER (1893-1897), is a master work of ingenuity. Constructed with hollow «bones», wood and cork, the plane weighed no more than 450 kilos, despite its imposing wing-span of 15 metres...

The perfection of shells

Figure 16:

The oldest shells in the universe are the crusts of the cooling stars... We can compare them to an egg-shell: they are formed on the surface of moving liquid drops. In long-ago prehistory, about 400 million years ago, living nature took advantage of the fact that a curved structure is 50 to 100 times stronger than a flat structure of the same thickness. This means that the protecting envelope around fragile micro-organisms can as much reduce the expense of material and weight as obtain a greater degree of protection. This brought a literal explosion of the difusion of shell structures [...] Concreted, they constitute the numerous mountain chains of our planet. The sediment beds can reach 1.000 metres thickness and stretch for hundreds of kilometres.

In the whole of living nature, shells are present everywhere: in the egg-shell, the chitinous scales of coleopters and other insects, the vaulted cranial cavity, the protecting carapace of turtles, birds' beaks; the greater part of bones are tubular structures, and are shells, as well as wheat, maize, and bamboo stalks. Seed grains are protected by thin-walled capsules, nuts are wrapped in coriaceous shells, and as the saying goes, to have a skull as thick as a nut-shell.

The most astonishing observation I have been able to make is that practically all flower petals or calyces are shells. Whether it be the simple petal of a cherry blossom, the bell of a fox-glove, the calyx of a lily, a tulip or a jonquil, the complex form of a lady's slipper or of all the marvellous variants of an orchid, all these flowers are thin-walled shells with a double curve. From a *static* point of view, they are extremely refined and can resist strong winds with a mininum of material expense. What is more, they have no more than one support, something our engineering techniques can not yet imitate. Their design shows a relief or a planing of the edge of the shell, the simplest way of reinforcing the edge (and of avoiding the placing of a havy supporting beam).

I believe that flowers —vivacious or woody plants— not only present the most frequent type of shell, but that they are also those of the greatest beauty. They offer a complementary perfection: they are *kinetic structures*. According to need, they can vary their form to open or close the flower, or even to aid the process of pollinization. Thus we see that an insect penetrating a flower, such as a snapdragon, triggers a whole mechanism by the simple change of the depth curve of the corolla. This idea has not yet found an application in the construction field. But the possibility is real, and the transformation of the form could be done without damage: it would be enough to displace the support points. Interesting innovations await us [...] (ISLER, 1989 : 135-136).

Scallops: superposed waves

Figure 17:

a) Design by the french engineer Robert Le Ricolais of a scallop *Pecten jacobeus*. To the curved valve waves, delicate channels are added, whose number increases with the scallop's growth.

b-c) Le Ricolais applied the static principle of this scallop —opposing curves and crossed waves— to cylindrical forms like nave supports and compound panels (1935). The *Isoflex* panel, a system of crossed wave plates, assembled by soldering, is seven times stronger to warping than a flat waved plate.

The computer in the school of nature

Whoever wished nowadays to develop a new model of automobile would not begin by seeking to penetrate all the secrets of the design of postal buggies to remake, internally, all the essential models of the history of the automobile, and finally arrive, with a notable delay, at the problem itself. He would more likely examine the best types on the market and try to find in what way they could be improved: an improvement he would introduce into his own model, to bring hope. He would begin from the best known design and compare the performance of his to this. It is therefore all the more astonishing that, till a few years ago, so much money and man-power were so hesitatingly invested in the study of nature's design, to which hardly any improvement can be added. Of course, whoever wishes to obtain, for example, a drill of optimum form, ultralight, and very durable, could burrow around a long time in piles of bones or tree elements before finding —if he ever does— something worth taking home. The doubt about whether the function to which the biological element is now adapted correspond to the conditions to which the drill will be put under normal service, as foreseen, darkened the brow of the most notorious optimist and made him uneasy.

The problem is thus that a singular (biologic) construction element cannot be copied and is not a «ready to wear»; beginning from here, the problem is posed in quite another manner: what is needed is the creation of a *method* capable of furnishing components with qualities of lightness and durability comparable to those of the biologic design. With this method, it is not obligatory to arrive at a dog's femur, a tiger's claw, or a bird's wing, but that would help to design a drill which offers all the qualities characteristic of a biological design. This problem was solved at the KfK (Centre for Nuclear Research, Karlsruhe) with the development of a CAO (Computer Aided Optimization) method. To furnish proof that this method really established the optimum of a biologic configuration by computer-simulated creative methods, it was verified by applying it to a number of biologic examples. It was shown that effective simulation by CAO was perfectly possible, from the scar left by a branch on a tree-trunk to the configuration of a particular root or even the configuration of the insertions of branches on a tree; equally perfectly, the form of a tiger's or bear's claw can be simulated, or the form of plant thorns, the process of healing of a bone fracture, etc. Thus, we can know that the CAO method is suitable for the development of machine components towards a biologic optimum (MATTHECK, 1992 : 14).

Trees: models for industry

Figure 18:

a) Accidental formation of a trellis on a chestnut by one branch which solders the two main branches.

b-d) The physicist Claus Mattheck gave the CAO logician «homework» to optimize a similar detail where two cylinders are joined by a crosspiece and which receive the same necessities as the tree in nature. The thickening zones of the growth rings correspond to an apparatus that impedes the appearance of excessive constraints. The accumulation of material through the years is only sensitive to the free area of the trunk and to the junction itself. The logician, having learned from trees to optimize structures, can thus foresee the phenomena in other cases: the efficiency of the CAO method is verified and the gaze of the designer refined...

e-i) Optimization of a chain link by the same CAO method (C. Mattheck, 1992. FEM: Susanne Burkhardt, Jürgen Schäfer).

Figure 19:

The «biodesign» in *Art Nouveau* introduced «vegetation» forms into industrial production, to give elegance and an appearance of lightness. From the technical point of view, constructions like the «quioscs» of the Paris underground stations (1909) or furniture by Hector Guimard are of the «rod and knot» type. Thanks to the careful joints and the systematic triangulation of elements, these structures are mechanically better than those drawn with a compass. But the forms do not really translate those of plants, which only accidentally have a like triangulation (the photograph shows the branch of a large plane tree in the Avenue Foch, Paris). The detail of the emu basin is no doubt closer to Guimard's metallic structures. The imitation of these biological forms is not always justified, except in the measure where the mechanical environment of the natural structure is taken into account (muscles, support points...). The CAO can intervene in these approaches.

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