MATTER MATTERS by Manuel DeLanda

a series from DOMUS Magazine

Building with Bone and Muscle.

The field of biomimetics, a subfield of the science of materials, examines biological creatures in an attempt to derive design principles that may be utilized in an industrial context. The goal is not to simply replicate a specific material that is already used in nature. The silk produced by spiders as a structural foundation for their webs, for example, is a very desirable material with a tensile strength approximating that of Kevlar, the stuff used in bulletproof vests. Spiders, being predators, cannot be domesticated like silkworms, so their secret has to be literally extracted from them: the proteins that in long chains make a strand of silk are identified; the genes that code for the proteins are isolated and then inserted into a domesticated animal (a goat, in this case); and finally, the silk is recovered from the milk of the goat as a thick paste and extruded through small orifices to yield separate strands. As it happens, something like this is already taking place in some industrial settings. But it is not biomimetics, since no abstract principles are being learned that may be applied to other materials. On the other hand, if we studied vertebrates as load-bearing structures to learn from their unique combination of bone (bearing loads in compression) and muscle (bearing them in tension), in order to apply this combination in architectural structures using entirely different materials, this would constitute a valid example of biomimetics.

Bones are interesting for a variety of reasons. Like fiberglass and other composites, they are a hybrid of glue and grit, with collagen playing the role that epoxy resin plays in human-made composites, and tiny mineral crystals playing the role of the thin glass fibers. To the extent that humans have been using composites since they first used straw brick, the principle of combining glue and grit to get novel emergent properties was already known to us. But bones have other secrets to yield, particularly when considered in combination with cartilage, a material that also contains collagen and that may be converted to bone. The biomimetic principle here, combine two materials one of which may be transformed into the other, is simple but powerful. In biology it implies that the skeleton of embryos may be laid out with more flexible cartilage before it becomes rigidified into bone, with the exception of the external ear, the tip of the nose, and the ends of the ribs. Moreover, given that the bones of a new born infant are already articulated, the problem arises as to how to preserve these functioning joints while the bones grow in length several times their original size. Adding fresh cells and moving outwards at the edges, a solution used by other tissues, would destroy the articulations. The answer is to increase the length from within: the cartilage serving as interface between bones becomes the locus of growth, and it is later replaced by bone, thereby preserving the functionality of the articulations. Cartilage also helps bone be self-healing: after a fracture, a blood clot forms that seals bleeding vessels and holds together the broken ends; cartilage then replaces the clot, and it is, in turn, replaced by bone. Finally, the spongy nature of cartilage allows it to store an organic lubricating substance which is then squeezed out of it when one bone in the joint bears on the other. This allows bones to be self-lubricating.

Muscles are an even more interesting material. They are basically, ropes made out of jelly, but in which the rope is designed like a collapsible telescope, that is, in which layers of muscle can slide under each other (like the successive tubes of decreasing radius in a telescope) allowing the muscle to contract in size. The ability to contract, in turn, means that muscles can pull on external objects, in other words, that they can not only passively bear loads but they can actively exert their own loads. Since the bodies of animals must be able to push as well as to pull, many muscles in the body are used in pairs oriented in opposite directions. To say that muscles can exert loads is, in effect, to say that they are engines or motors, a typical human body having about six hundred of these engines. Material scientists have recently developed rudimentary forms of artificial muscle. There are, for example, “smart gels”, consisting of a liquid solvent mixed with solid chains of polymers that tangle with one another making the composite viscoelastic. A variety of stimuli (heat, electricity, chemicals) can be applied to these gels to make them contract or stretch. These smart gels are already replacing certain moving mechanical parts, such as valves.

From the point of view of learning from vertebrate technology, the principle here is that the variety of mobile load-bearing structures may be increased by linking a passive composite (bone) with an active one. This yields structures that are dynamic, capable, for example, of switching from one gait to another (from walking, to trotting, to galloping, in the case of quadrupeds) each gait involving different sets of muscles, the transitions from one gait to another occurring at specific critical points in speed. But just as in the case of bone a key role was played by the interface material in joints (cartilage) the interface between bone and muscle itself is also crucial. If soft muscles were linked directly with hard bone, the combination would be clumsy and imprecise. Muscles have to control bones at a distance, via a material of intermediate stiffness: tendon. The muscles operating our hands, for example, are located up our arms, connected to our hand bones through long and thin tendon cords. Thus, the final biomimetic lesson for structural engineering is that special materials must be used for the interface between passive and active materials. Apparently, the human body and its vertebrate kin are full of lessons for today’s builders of load-bearing structures.

One Dimension Lower.

Some of the most interesting material phenomena occur at critical points of intensity. The familiar sequence of states of matter, Gas-Liquid-Solid, illustrates in its own humble way the spontaneous micro-architectural changes that matter undergoes at these critical points. These sequences of so-called “phase transitions” exemplify matter’s capacities for autonomous change, capacities that may lay dormant as long as a critical point is not reached. But why should these phase transitions take place at a point? The answer is that they do not always do. Water will change from liquid to solid at a specific point in temperature (at exactly zero degrees centigrade) as long as we keep other parameters (such as pressure or volume) constant. If we change pressure as well as temperature, the critical values at which this phase transition takes place will now form a line, and if we in addition change the volume of water, these critical values will form a surface.

One way of describing the situation is to say that the spontaneous changes that animate matter from within always take place one dimension lower than the space formed by the parameters triggering the changes. The variable “N” is traditionally used in mathematics to designate the number of dimensions of a given space. In these terms we can say that critical phenomena always take place at N-1 dimensions. Although in the case of phase transitions the N-1 rule refers to the dimensions of the abstract mathematical space formed by the values of some parameter, similar ideas apply to physical space. Since our familiar spatial surroundings are three dimensional, the rule would make us expect that exotic material behavior should occur in two dimensions, that is, in all physical surfaces, and this is indeed the case. That all physical surfaces are special places is clear from the fact that the physics and chemistry of the monomolecular layers binding a piece of matter are different that those that govern the bulk material contained within those exterior layers.

The reason for this difference derives from the special situation in which molecules at the surface find themselves. Those in the interior of a piece of matter are surrounded on all sides by similar molecules, while those at the surface are only bound to similar molecules on one side, the other side being exposed to another material, such as air. In this sense the surface of any material object is the site at which one type of matter interfaces with another, and therefore the place where interfacial phenomena, such as rusting and corrosion, take place. Surfaces also tend to possess a certain amount of free energy (referred to as “surface tension”) that is absent from the material in bulk. The same asymmetry that makes surfaces into interfaces is at work here: the forces acting on the molecules by other molecules inside a piece of material tend to cancel each other out; those same forces, however, affect the molecules at the surface in some directions but not in others, so that unlike those inside, surface molecules are not at equilibrium. In liquids this free energy manifests itself by forcing droplets to adopt a quasi-spherical form, the form that will minimize surface energy. The surfaces of solid objects also possess this free energy but the bonds among their component molecules are too strong for the energy at the surface to bend them into a droplet. Nevertheless, the free energy is there sometimes in quantities surpassing that of liquid surfaces.

For builders of load-bearing structures the free energy of solid surfaces is important because the cracks or fractures whose uncontrolled propagation can endanger the structural integrity of a building are in fact nothing but surface. Cracks are prototypical N-1 entities. To say that the surface of a liquid has free energy means that work has to be performed, or outside energy spent, to move molecules from the interior of the liquid to the surface. To put this differently, work must be performed to enlarge the surface. Similarly for solids. The expansion of a crack in a structure under tension, for example, demands the creation of fresh surface, indeed of two new surfaces since a fracture always has two sides. The minimum amount of energy needed to cause a tensile fracture in a given structure is therefore twice the surface energy of the material of which the structure is made. Where does the energy needed for crack propagation come from?

Any structure carrying a load is for that very reason a reservoir of energy, of strain energy to be exact. When structures bearing loads in tension have a small crack the probability that it will propagate will depend on an energy budget: as a crack grows it releases some of the strain energy stored in the structure, this being the “credit” side of its budget, while at the same time it will have to spend energy creating fresh surface, this being the “debit” side of the budget. There is, for any given material, a critical crack length below which the credit side is lower than the debit side so the fracture does not grow. But if the critical length is exceeded, the credit side will now show an energy surplus that will allow the crack to propagate spontaneously, sometimes explosively. Interestingly, the critical length is independent of scale: in a structure made of mild steel, for example, bearing a load of 11,000 pounds per square inch, the critical length is about six feet, regardless of the size of a structure. This means that for relatively small objects (swords, machine parts) there is not enough space for the critical length to be reached; small cracks will form but they will never get to the point where they can wildly propagate. Mild steel is, therefore, a safe material for their construction. But in larger load-bearing structures there is plenty of space for accidental fractures to reach the critical length and, more importantly, many deliberate discontinuities (doors, hatchways, panels) will from the start be larger than the critical size. These discontinuities, from the point of view of fracture dynamics, are nothing but incipient cracks. Thus, it is not only necessary to go one dimension lower (from volumes to surfaces) to understand what cracks are, we need to go one even lower (to critical lengths) to understand their behavior. Either way, it would seem, it pays to think to the N-1.

The Importance of Imperfections.

In the ancient craft of metallurgy the distinction between being hard and being tough has long been understood. A blacksmith manufacturing a sword in classical times, for example, knew that the edge and body of the weapon had to have distinct properties. The edge, if it is to stay sharp, must be able to preserve its pointy, triangular shape for as long as possible, that is, it must be hard. But the sword's body, the part that must perform a load-bearing role, must be tough: rather than trying to hold on to a particular form it must be able to change shape, that is, it must yield without breaking under the blows of another sword. If instead of tough the swords's body was hard it would be brittle and hence incapable of bearing the loads placed on it during hand to hand combat. A similar point applies to metallic armor: it must yield without breaking under the impact of an arrow or other projectile, and the more it yields, the more it allows the arrow to dent it, the more it robs the arrow of its kinetic energy as the latter exhausts itself trying to penetrate it. Hardness and toughness are distinct but complementary properties in metallurgy.

Ancient blacksmiths also knew the kinds of operations or transformations that human beings can apply to metals in order to get these properties. They knew that cold working a piece of metal, by repeatedly hammering it, for example, would yield a hard edge. They also knew that the brittleness that inevitably accompanies hardness could be eliminated by annealing the metal piece, that is, heating it to a high temperature below its melting point, then allowing it to cool down slowly. Annealing restores the ductility, hence the toughness, of a cold worked piece of metal. Yet, despite this ability to successfully match physical operations to desired metallic properties, the actual microscopic mechanisms unleashed by the operations and responsible for the properties remained a mystery. Today we know the main characters in this hidden drama and they turn out to be imperfections.

A piece of metal is typically crystalline. When molten metal undergoes the critical transition to the solid state, crystallization may begin at several points in the liquid simultaneously, with different crystals growing at different angles from each other. When two such growing crystals eventually meet a boundary forms, a layer that may be more or less deformed depending on how different the angles of growth were to begin with. These are two-dimensional defects, surfaces dividing the piece of metal into separate grains. Within these grains another type of imperfection exists, a one-dimensional defect called a "dislocation". Given that crystals are nothing but geometrically packed atoms, and that we can arrange many of these atoms into mathematically perfect arrays, it is tempting to picture a crystal's internal structure as consisting of rows of atoms placed precisely on top of one another. But here and there we can find extra rows of atoms that disrupt the perfection of the array, introducing a distortion in neighboring rows.

Moreover, these extra rows can, in a sense, move through the crystal. Because the chemical bonds that join metallic atoms together, when broken by the application of a force, can easily reconstitute themselves, the atoms in an extra row can, one at a time, break and become bonded to those in a neighboring row. These atoms will now become part of a non-defective row but will leave behind another defect displaced relative to the first. Although strictly speaking this is a process in which one defect disappears as a new one is born next to it, for all practical purposes it all happens as if the original dislocation had actually moved in position. For this reason dislocations are considered mobile line defects, and they exist in more or less numerous populations in most crystalline materials.

The ductility of metals, their ability to yield without breaking, is mostly derived from the fact that the mobility of dislocations allows entire layers of atoms to slide over one another when subjected to a force. For this effect to happen without the assistance of mobile defects all the bonds in a given layer of atoms would have to break and reconstitute simultaneously, a relatively unlikely event. But with dislocations this process can take place by repeatedly breaking only a few bonds at a time. The existence of populations of mobile defects implies that this ability of atom layers to slide can be present throughout a piece of metal. On the other hand, too many dislocations may have the opposite effect: with less room to maneuver defects start getting into each others way, eventually becoming immobilized, caught in complex tangles. This, in turn, reduces the sliding capacity of the non-defective atom layers. In other words, the metal becomes hard.

Hammering (and other types of cold working) produces large numbers of dislocations with limited mobility, and it is thus the appropriate operation to produce the cutting edge of a weapon or tool. But if the load-bearing body is to remain tough it must be annealed, a process that erases many dislocations allowing the surviving ones to break away from their tangles and recover their mobility. Two-dimensional defects, that is, grain boundaries, may also participate in the generation of ductility. Although the movement of dislocations is constrained by these boundaries, impurities accumulating along surface defects may sometimes act as lubricants allowing grains to slide over one another. The key role played by both one and two dimensional defects in the emergence of large-scale metallic properties is the reason why the practice of metallurgists today is aimed in large part at the control of grain and dislocation structure and distribution. Evidently, the descendants of the ancient blacksmiths have become aware of the importance of imperfections.

Events Producing Events.

In the material world there is hardly a more important relation than that between causes and their effects. Nevertheless, our understanding of just what causes and effects are is strangely primitive. Part of the blame for this state of affairs should go to philosophers, at least to those who have traditionally confused an analysis of how the link between causes and effects is perceived by us humans with an analysis of what the causal link itself is. The philosopher David Hume, for example, argued long ago that all that our senses reveal about causality is that there is a constant conjunction between an event acting as a cause, such as a collision between billiard balls, and an event acting as an effect, a change in the state of motion of the balls. Many of his followers took this to mean that objective causality can indeed be reduced to the subjective perception of this constant conjunction.

The problem is that our senses can reveal only the existence of an invariable coincidence between two events, but not of any process through which one event may be regularly produced by another. Two successive events may always be experienced in association, but no necessary genetic link between the two is ever directly sensed, and it is precisely this genetic link, this production of one event by another event, that constitutes the objectivity of causality. There is, of course, no question that in order to study some causal relations we must use the constant conjunction or regular succession of events as evidence for the possible existence of a causal link. But to reduce the objective production of one event by another to their observed invariable correlation is to confuse causation with the tests used to establish its existence.

Another problem with the traditional view is that while constant conjunction may sometimes be evidence of causality, this criterion works only for linear causes, the simplest and most mechanistic form of causality. The formula for linear causality is “Same cause, same effect, always.” The impoverished view of causal productivity that linearity implies has, in turn, made a perfect target for critics who argue that such a simple relation cannot account for the richness of pattern we observe in the material world. We can imagine two different ways in which this formula may enriched, one by breaking with the “same” part, the other by challenging the “always” part. The first departure yields nonlinear causality, at least when the word “same” is taken to refer to the intensity of the cause. Let me give an example relevant to builders of load-bearing structures, that is, an example in which the event “changing the amount of weight supported by a structure” is the cause, while the event “becoming deformed” is the resulting effect.

Some materials, such as the mild steel so often used in modern buildings, do behave linearly under loads, a fact that was already established in the seventeenth century by Robert Hooke. These materials will stretch or contract by a given amount which is always proportional to the load. Hooke’s law may be presented in graphic form as a plot of load versus deformation, a plot that has the form of a straight line (explaining one source of the term “linear”). On the other hand, many organic materials display a J-shaped curve when load is plotted against deformation. A slight tug of one’s lip, for example, produces considerable extension, but once the straight part of the “J” is reached any additional pull results in relatively little additional extension, although it may indeed cause quite a bit of pain. This exemplifies a nonlinear relation between the intensity of the cause and the intensity of the effect: a cause of low intensity produces a relatively high intensity effect up to a point (the inflection point of the “J”) after which increasing the intensity of the cause produces only a low intensity effect. Other materials, such as rubber, display a S-shaped curve, which translates into a more complex relation between intensities. If we imagine trying to deform an automobile’s tires, pulling very hard produces at first almost no effect at all. As the intensity increases, however, a threshold is reached at which the rubber-made structure does stretch but only up to a second point (the second arc of the “S” shape) at which it again stops responding to the load. Neither one of these two examples exhibits a constant conjunction relative to intensity.

The second challenge to linearity comes from the fact that causes seldom act in isolation, but are usually accompanied by other causes that may interfere with them. In some cases this interference may lead the cancellation of the effect which is supposed to “always” occur. But even if the interference is not so drastic, it may still reduce the probability that the effect will be produced to less than a 100%. In other words, causality becomes statistical, as when one says that “Smoking causes cancer in 70% of smokers”. In statistical causality one event simply increases the probability that another event may be produced. Much as in the case of cancer it is events internal to a person, such as metabolic events related to inherited predispositions, that interfere with the primary cause, so in the case of materials under load, it is events related to their internal microstructure that make their deforming behavior less than a 100% predictable. Dissolved gases, nonmetallic intrusions, variations of chemical composition, even details of their process history (such as the shaping process), make materials not isotropic, that is, not likely to exhibit identical properties in all directions. In these conditions observing a constant conjunction of cause and effect is not possible. Manufacturers of materials, for example, must deal with questions of quality control in a statistical way, testing entire populations of samples of a material to arrive at the average probability that a given deformation event will take place. Designers of load bearing structures must, in turn, take into account not only the magnitude of the load but its direction, since the material may respond in different ways depending on orientation.

Nonlinear and statistical causality bring back to the philosophical conception of the causal link some of the complexity that was taken away by the notion of constant conjunction. Additional complexity may come from an analysis of catalysis, and extreme form of nonlinear causality in which an external cause produces an event that acts merely as a trigger for an entire sequence of further events. But while restoring the richness of causal relations does make them more likely to explain complex material behavior, it is a restoration of their objectivity that will have more profound philosophical consequences: material events producing other material events in ever more intricate series, whether there are humans around to observe them or not.

Evolvable Materials.

The term "nanotechnology" today evokes images of carbon nanotubes, cylindrically rolled sheets of graphite that are one hundred times stronger than steel, and could one day replace this metal in the production of cables to bear loads in tension. However, the creator of this and other novel forms of carbon, the late Richard Smalley, was not always at the center of the nanouniverse. The inventor of the term, Richard Drexler, once occupied this place and had a very different idea of what the technology should be: not just a matter of small scale, 1000 times smaller than micro, but an entirely different assembly process for materials. Drexler dreamt of materials put together one molecule at a time, the way a protein is assembled inside a living cell. Instead of ribosomes, the specialized organelles that perform this feat in the natural world, he proposed using nanobots, miniature versions of the programmable universal computers that populate the desktop today. As was proven decades ago, such universal computers, whether in their familiar electronic variety or in the mechanical version needed for nanobots, can self-reproduce if correctly programed. This was a crucial feature for any realistic application of nanotechnology in the industrial production of materials, since assembling them molecule by molecule would take centuries unless large armies of nanobots were simultaneously involved, and creating large populations of them would be greatly facilitated if they could reproduce themselves. On the other hand, this capacity could also make nanobots as dangerous as viruses or bacteria, a nightmarish possibility that Drexler responsibly envisioned from the start but which turned out to be his downfall: Smalley stole the leading role from him by denouncing this paranoid view as an obstacle for the public acceptance of the new technology.

Given that nanobots are still science fiction worrying about their possible risks may indeed seem premature. But reflecting on the potential menace forced Drexler to think about other subjects that are interesting in their own right. Specifically, the dangers posed by self-reproducing nanobots are directly linked to their capacity to evolve out of our control. If they could mutate the way viruses or bacteria do then they could become as dangerous to humans as ordinary germs. Hence a crucial aspect of nanobot design is to deny them the very capacity to evolve, and this led Drexler to consider the question of evolvability in general: what properties of materials, and more generally, of material assembly processes, allow living creatures to change in ways that keep them adapted to their environment? One such property is, of course, the capacity to transmit genetic information from one generation to the next, but this is a capacity that nanobots must also have. There are other properties of the biological cell, however, that are also crucial in allowing evolution. Many materials within living systems, such as proteins acting as catalysts for chemical processes, operate through a lock-and-key mechanism: a protrusion in one protein must geometrically match a corresponding hole in another protein. However, no precise positioning of the two proteins is needed for the key to fit the lock. Bumping more or less randomly is usually enough for the protrusion to find its matching hole. By contrast, in a typical assembly-line factory, two components that must be fit together must not only have matching parts, a screw and a hole, for example, they must be carefully positioned for the match to succeed. This means that, unlike proteins, a change in size or shape in the not matching parts of a factory component can affect the insertion position of a screw or the hole causing the assembly to fail.

Similarly, while in a living cell the components of a complex object just float or diffuse to the assembly site, in a factory they must be transported by a special channel, such as a moving belt for solids, tubes for liquids, and wires for electricity. The significance of these differences is this: in an assembly process depending on precise positioning and channeled transport any changes in the size or shape of one component must be accompanied by exactly corresponding changes in the other component and, moreover, these changes may necessitate further adjustments in the transportation channels. The problem with this is that in evolution most changes are random, and the probability that a random mutation in one component will be accompanied by exactly matching changes in other components and their channels is almost zero. In a living cell, on the other hand, the lock and key mechanism does involve spatial fit but only in the relevant portion of the two molecules, the rest of the shape being largely unimportant. Any mutation affecting the non-relevant parts does not disturb the fit. And given that the components find each other by floating inside the cell and then bumping more or less randomly, no additional mutations are needed in the transportation mechanism. In short, assembly processes in the cell can accommodate random mutations in a way those in a factory cannot. To this it must be added that in a factory the materials of which the parts are made are typically rigid, and the design of the whole assemblage based on fixed lengths and areas. This means that adding a new part involves changing the positions of many other parts. In a cell, parts are more flexible and the overall topological connectivity of the assemblage is more important than its metric properties, so that a new component appearing by random mutation can be more easily accommodated.

To Drexler the lesson of this analysis is straightforward: if you do not want nanobots to be able to evolve beyond human control, design them so that their assembly, and the assembly of the materials they build, involves channeled transport, precise positioning, geometric specification of overall design, and rigid, non-adaptive materials. But to a materialist philosopher the lessons have a broader significance. Adult multicellular organisms, for example, while still using diffusion as a transport mechanism also possess many tubes and other fixed channels. Similarly, many components of their bodies, such as bone articulations, must maintain precise positions relative to one another, and these components acquire more or less fixed lengths, areas, and volumes as the organism stops growing. This implies that if these organisms reproduced by cloning their adult features their capacity to evolve would be greatly diminished. On the other hand, if their reproduction is performed by single cells which unfold into the adult shape through complex embryological processes, and if a substantial amount of this unfolding retains diffusive transport, non-exact matching, adaptive parts and topological specification of the assemblage, then they can take advantage of random mutations to produce viable alterations of the final form. Having the capacity to profit from randomness is thus a crucial mark of evolvable materials, and this is a lesson that users of simulated evolution in computers, such as architects or urbanists breeding new designs using Genetic Algorithms, must always keep in mind.

Extensive and Intensive.

Architects must constantly deal with certain properties of material objects that physicists refer to as “extensive”, properties such as length, area, and volume. The main characteristic of these properties is their divisibility – a ruler one meter long divided into two halves yields two half meter rulers – a characteristic well suited to the architectural practice of organizing space by functional subdivision. But physics also includes another type of material property that does not display this characteristic, properties referred to as “intensive”: temperature, pressure, speed, density, voltage. Subdividing a given volume of water at ninety degrees of temperature, for example, does not yield two half volumes at forty five degrees, but two halves at the original temperature. Divisibility, on the other hand, may not be the most useful way of distinguishing between the extensive and the intensive. Two more significant attributes of the intensive are that differences in intensity store potential energy, energy that may be used to drive processes, and that intensive properties are marked by critical thresholds at which matter spontaneously changes from one to another type of organization.

The first characteristic may be illustrated by comparing extensive and intensive maps of our planet. An extensive map shows the distribution of land masses and oceans, displaying the differently sized areas that they occupy as well as the lengths of coastlines, political frontiers, and other boundaries. Unlike these geographical maps, meteorological ones are intensive: a zone of high pressure here, a zone of low pressure there; a cold front here, a warm front there; a mass of air moving at slow speed here, a fast moving mass there. These intensive differences, in turn, are treated not as static and sterile properties but as mobile and productive ones, since storms, hurricanes, cloud formations and other meteorological entities are produced by them. If these differences managed to cancel themselves out all production of phenomena in the coupled system hydrosphere-atmosphere would stop.

While an extensive map shows the product of a process, an intensive one shows the process itself. But all we have to do is go underneath the map of continental masses, dig deep enough into the lithosphere, to find the intensive processes that produce these extensive masses, driven by temperature differences in the vast lava flows that, like gigantic conveyor belts, transport the tectonic plates on which the continents are embedded. This circulatory system of lava flows underlying plate tectonics illustrates the second characteristic of the intensive. The technical term for these conveyor belts is “convection cells”. Convection is a type of periodic or rhythmic flow very different from uniform or laminar flow, as well as from turbulent flow. The sequence of regimes of flow laminar-convective-turbulent is characterized by sharp transitions from one to the next, transitions that occur at specific critical values of intensity: critical points of temperature, pressure, speed. The sequence is, in this regard, not very different from other well known ones such as the sequence gas-liquid-solid. Both are examples of series of states of matter mediated by phase transitions, abrupt changes in organization happening spontaneously at special intensive values.

The distinction between the intensive and the extensive belongs to thermodynamics, but that does not mean that other branches of physics and engineering do not work with material properties that may be also classified this way. Designers of load-bearing structures, for example, must deal with the property of stress, a material property not usually viewed as intensive. To show in what way stress is intensive two more considerations must be kept in mind. First of all, if stress is related to the weight or load that a structure must carry, in what way is it intensive? After all, weight is an extensive property. The answer is that some intensive properties are the ratio of two extensive properties: the intensive property density, for example, is a measure of mass per unit of volume, both of which are extensive. Similarly, stress is a measure of load per unit of area of the cross section. Secondly, unlike their extensive counterparts most intensive properties are measured at a given point of a material object. Measurements at many points yield a more or less continuous field of values, a distribution of intensities that may be more or less homogenous, or it may vary from one point of the field to another. When the concept of stress was introduced in the nineteenth century to replace that of load, it was also defined at a given point of a structure. This was a great conceptual advance over the concept of an overall load being carried by a building or a bridge, since it allowed consideration of the varying distributions of stress in an load-bearing structure so as to avoid dangerous concentrations that may reach critical values, such as the breaking stress of a column or a beam.

Are there any insights about the intensive that may be transferred to structural engineering from thermodynamics? One possible transfer is the difference between equilibrium thermodynamics and its far from equilibrium counterpart. Until relatively recently, thermodynamics concerned itself only with homogenous distributions of intensity, or to put this differently, with systems that have reached equilibrium after all differences in intensity have been canceled. This implies that these scientists were not very concerned with questions of dynamic process, since once intensive differences disappear there is nothing left to drive a process. But even if we depart a little from homogeneity and study systems near equilibrium, the processes that are available to these systems are only the simplest ones, such as those producing a steady state as their outcome. Far from equilibrium, on the other hand, the number of processes increases in variety, including in addition to steady state ones, periodic or rhythmic processes as well as turbulent ones. In other words, if a system’s intensive differences are large, and if they are maintained through the constant input of new energy or matter, material behavior becomes more complex, having a wider repertoire of possibilities available to it. Most processes in which material systems display self-organization, for instance, take place far from equilibrium. Although structural engineers do not usually use thermodynamic language, it is clear that most of the load-bearing structures they design are near equilibrium, that is, steady state. But this limited approach to their craft may be the result of the long period of time in which all branches of applied science took their inspiration from the dominant paradigm in the more mathematical branches. With the recent triumph of the far from equilibrium paradigm, we may be about to witness a change in engineering practices, a change that may place at their disposal the full self-organizing powers of matter.

Material Expressivity.

It is a well known fact that a beam of white light is composed of many pure-color components, or wavelengths. In addition, like the pitches of musical sounds, the different color components have their own rate of vibration, or frequency. These two characteristics allow both light and sound to produce distinctive effects on animal and human brains, effects that may be used for expressive purposes by territorial animals and human artists. But possession of a nervous system is not necessary to make expressive use of color or sound. Even humble atoms can interact with light, or other forms of electromagnetic energy, in a way that literally expresses their identity. Atoms in a gas, for example, if energetically excited, will emit light with an arrangement of bright parallel lines, each line corresponding to a single frequency and positioned relative to one another according to their wavelength. Each atomic species, hydrogen, oxygen, carbon, and so on, has its own characteristic pattern of lines, its own distinctive “fingerprint” as it were. And much like fingerprints may be used to determine the identity of humans, these line patterns can be used by spectroscopists to determine the chemical identity of a given material. Born in the nineteenth century, the science of spectroscopy has become quite complex, using a variety of methods and devices to extract fingerprints from materials, but it ultimately relies on the capacities of atoms themselves to produce expressive patterns, through emission, absorption, or other processes.

These expressive patterns are what scientists call “information”. This term does not refer to the semantic information that we may get from, say, newspapers, but to linguistically meaningless physical patterns. That physical information has nothing to do with semantic content is demonstrated by the fact that information theory was developed during World War II to deal with problems of communicating encrypted military messages, that is, messages in which the linguistic form and content were hidden. Physical information pervades the world and it is through its continuous production that matter may be said to express itself. Material expressivity, on the other hand, crossed an important threshold when it ceased to be mere fingerprint and became functional in the form of the genetic code: groups of three nucleotides, the chemical components of genes, came to correspond in a more or less unique way to a single aminoacid, the component parts of proteins. Using this correspondence genes can express themselves through the proteins for which they code. This implies that expression has gone beyond the production of information to include its active storage and processing. And this, in turn, implies that when populations of information-storing molecules replicate themselves, and when this replication is biased in one or another direction by the interactions of proteins with each other and with their environment, the expressive capacities of material entities may evolve and expand in a multiplicity of novel ways. Like atoms, living organisms can express their identity by the emission of patterns, chemical patterns for example. But unlike atoms, this expression has functional consequences since it allows the recognition of an organism’s identity by members of the same species, a recognition that is crucial for genetic replication.

Another important threshold in the history of material expressivity was crossed with the emergence of territorial animals. A simple illustration of the radical transformation this involved may be the conversion of urine and feces, up to then a material byproduct of food chains, into territorial markers expressing not just a species identity but the possession of resources by an individual organism. Sound, color, and behavioral displays involving posture, movement, rhythm and silhouette, are examples of expressive territorial markers, sometimes used in competitions between males, other times in courtship rituals aimed at females. A particularly interesting example is that of bowerbirds. The term “bower” means a pleasant shady place under a tree, but in this case it means a stage or arena built by the bird to perform its displays. Bowerbirds not only clear a small area from leaves and other distractions, but also construct and decorate elaborate structures out of grasses, reeds, and sticks, with an architecture that varies from one species to the next. Of the eighteenth species of bowerbirds some wear bright colors in their bodies, such as the intense blue coloration of the male satin bowerbird, others have lost their color but compensate for it by increasing the number of colored decorations. Indeed, there is a strong inverse correlation, noticed by Darwin, between the expressivity of the bird’s body and the complexity of the bower itself: the less inherited expressive resources a species has the better architects its member organisms must be. It is almost as if material expressivity itself migrated from the surface of the bird’s body to the external construction and its decorations.

Darwin also noticed an inverse correlation between the degree of ornamentation of a bird’s body and the complexity of its song, and believed that birds were the most aesthetic of all animals. Given that the structure of bird songs is only partly inherited (birds must learn to sing) and that the power to attract females depends in part on the richness of a male’s musical repertoire, each individual bird must create new combinations of musical motifs to distinguish himself from other birds of the same species. If fingerprints become markers or signatures with the emergence of territoriality, with bird song signature becomes an individual style. Indeed, a great twentieth century classical composer, Oliver Messiaen, some of whose compositions were directly inspired by bird songs, went as far as calling blackbirds, nightingales, and other bird species that must develop individual styles, “artists”. Thus, the history of material expressivity may be summarized by the sequence fingerprint-signature-style. Finally, we must add the expressive possibilities of bringing many of these non-human artists together. A good illustration of these possibilities is the so-called “dawn chorus” and event taking place usually in the spring and involving many bird species simultaneously. Before sunrise, one or two blackbirds begin the chorus and are then gradually joined by a series of other birds (robin, song trush, wren, great tit, chaffinch) until a symphony of sound is reached by midmorning.

Matter expresses itself in many ways, from the simple emission of physical information to the deliberate use of melody and rhythm. The universe itself may be viewed as a grand symphony of material expressivity. The early human artists who tapped into this expressive reservoir for their cave paintings, body tattoos, and ritual ceremonies, far from introducing artistry into the world were simply adding one more voice to an ongoing material chorus.

Smart Materials.

Ordinary load-bearing structures, such as those built of concrete and steel, would benefit enormously if they could actively damp dangerous vibrations or detect and stop fractures before they propagate. Self-monitoring and self-healing are adaptive capacities characteristic of many biological structures but conspicuously absent from those designed by humans. Research on smart materials is supposed to change this. But what makes a material "smart"? The first ingredient of material intelligence is sensors. Embedding optical fibers into concrete, for example, allows the gathering of information about distributions of stress in structural components because the transmission of light through the fibers changes with stress. A distributed network of fibre optic sensors, complemented by some computing processing power, can use this information to monitor the curing process and to check the structural integrity of concrete structures as they age. A different type of sensor utilizes piezoelectric crystals, that is, crystals that generate an electrical potential difference (a voltage) whenever they are mechanically deformed. Since any structural element that carries a load is so deformed (or strained) embedding such crystals into materials like concrete can generate electrical signals carrying information about its structural health.

Sensors, however, are only one component of smart materials. As cybernetics teaches us, implementing a negative feedback control loop involves both the ability to monitor conditions as well as the ability to causally intervene in reality to modify those conditions. The thermostats that regulate air conditioners or toaster ovens, for example, must be able not only to detect changes in temperature relative to the desired one, but also to change that temperature if it falls outside the desired range by turning the appliance on or off. In other words, a thermostat (or any other servomechanism using negative feedback) must possess not only sensors but also actuators. In principle, piezoelectric crystals could act as actuators because they not only generate a voltage in response to deformation, they can also perform the opposite function, mechanically deform in response to an applied voltage. The problem is that this deformation is literally microscopic, too small to be able to drive the necessary changes in shape that a structural component would need to actively counteract spreading cracks. Deformations on the scale of centimeters would be needed for this. Fortunately there is a new class of materials that may be able to perform this task: shape memory alloys.

Certain metallic alloys, such as alloys of Nickel and Titanium, display the ability to return to their original shape after being deformed. While this peculiar capacity was discovered in the 1930's it was not seriously studied until three decades later. Today we know that the shape memory effect is a kind of phase transition. This term is usually associated with the changes of state (from gas to liquid or from liquid to solid) that a material undergoes as a result of spontaneous molecular rearrangements taking place at critical points of intensity. Shape memory alloys also undergo molecular rearrangements but without loosing their solidity. The phase change is between two states of crystalline structure, a relatively soft and deformable state (called "martensite") and a more rigid state (referred to as "austenite"). The difference between the two states is that successive planes of atoms in the martensite state are realigned so that one portion of the crystal becomes a mirror-image of the other. In a sense, the two regions of the crystal are like "twins", a reflection of each other, so this type of deformation is called "twinning". It is these highly ordered internal deformations that give the martensite state its ductility by allowing entire planes of atoms to slide over one another.

The shape memory effect may be described by the following sequence. Materials are given a rigid shape at the relatively high temperatures favoring the austenite state. This overall shape is maintained when the material cools down and spontaneously transitions to the heavily twined martensite state. When a load is applied the material deforms (by a process of detwinning) and changes shape. If at this point the material is heated and its temperature increased it will spontaneously return to the austenite state, the original orientation of the crystals will be restored and with it the original shape. Although Nickel-Titanium alloys can be given a variety of shapes they are still limited to those with a small cross-section, such as wire, tubing, and foils. In other words, load-bearing components like columns and beams cannot be made out of these materials. Nevertheless, their peculiar thermomechanical behavior can be highly useful in the creation of actuators, as is their behavior during a related phase transition (called "pseudo-elasticity") that is stress-induced rather than temperature-induced.

In one proposed scheme, for example, load-bearing components are made of "intelligent reinforced concrete", that is, ordinary concrete augmented with piezo ceramics and shape memory alloys to make it self-monitoring and self-healing. Patches of piezoelectric material are embedded in the concrete structure to detect incipient cracks. Cables made of a shape memory alloy are used to reinforce the concrete, much as steel cables are, using the method of post-tensioning, that is, stretching the cables after the concrete has been poured and has had time to cure. A spreading fracture will deform both the piezoelectric sensors and the cables acting as actuators. The sensors respond by producing electrical signals that are analyzed by special damage-monitoring software, software that, in turn, activates a mechanism to electrically heat the cables, causing them to contract to their original shape and close up the cracks.

As our civil infrastructure ages a variety of challenges will have to be faced. One of these challenges will be to achieve a better understanding of the aging process itself, such as better mathematical models of fatigue and corrosion processes, or accelerated testing methods to simulate deterioration in the laboratory. But a different kind of challenge will be to inject new life into this infrastructure by embedding into its constitutive materials some of the negative feedback that already animates servomechanisms in other spheres of engineering design.

Crucial Eccentricities.

Density is a measure of the amount of matter existing in a given amount of space. Or to put it differently, a measure of how tightly packed together a material's component molecules are. Matter may exist in several states or phases, such as the gas, liquid, and solid phases. For most materials, the molecules in gases have more room to move around than they do in liquids, and much more so than in solids where they are confined to relatively immobile positions in crystals. In other words, in most materials the solid phase is much denser than the liquid phase which, in turn, is denser than the gaseous one. Since the weight of a given material is the sum of the weights of its components, the denser a material the heavier it will tend to be, and this implies that solid pieces should always sink if placed in a pool of liquid of the same material. So why does ice float? Moreover, in most materials the colder a liquid gets the denser it becomes, since high temperature implies a more energetic motion of the component molecules, and hence more free space around them to carry on this motion. So in a pool of normal liquid the colder portions should always exist at the bottom. So why do lakes and oceans freeze from the top down instead of from the bottom up?

The explanation for the eccentric behavior of liquid water is that it reaches its maximum of density not when it is coldest, that is, right before it turns into ice, but a few degrees lower. Liquid water crosses the phase transition to solid at 0˚C but it is at its densest at 4˚C. In other words, the eccentricity is highly localized, liquid water warmer than 4˚C behaving quite normally. Nevertheless, however small the temperature range over which the eccentricity exists it has very large consequences. It is well known that the climate of Europe should be colder than it is given the latitudes at which the continent is located. It is also well known that the anomalously warmer temperatures are the effect of the circulation of ocean currents that bring heat from the tropics. If water did not display its anomalous behavior, if ice (or very cold water) sank as it should, this would interfere with the motion of these currents perhaps even bringing them to a halt. One eccentricity sustains another eccentricity. And more importantly, the water anomaly itself is explained by yet another one: the eccentric chemical bonds called "hydrogen bonds".

Normal chemical bonds, such as the ones that glue atoms together into a molecule, emerge from the sharing of one or more pairs of electrons. An electron belonging to one atom is simultaneously owned by another atom, and vice versa, and it is this simultaneous ownership that holds the molecule together. The oxygen and hydrogen atoms in a molecule of water are glued together this way. But the ability to use this type of bonding (called "covalent bonding") is limited by the number of electrons an atom has. Hydrogen possesses a single electron, an electron that it gives up as it shares it with oxygen, so its capacity for further covalent bonding is exhausted. Nevertheless, hydrogen alone has the anomalous ability of retaining a partial positive electric charge when coupled with certain other chemical elements (such as oxygen, nitrogen, or fluorine). This residue allows a molecule containing hydrogen to create weaker, more flexible bonds with free, unbounded, negatively charged electrons in another molecule. These bonds are eccentric not only because of the singular role played by hydrogen but also because their dynamics are nonlinear: the probability that a bond will break depends on whether other nearby bonds break or not. In other words, unlike covalent bonds, hydrogen bonds do not form or break independently but cooperatively, an eccentricity that highly complicates their study.

It is these eccentric bonds that determine the eccentric properties of water. The two hydrogen atoms in a water molecule share electrons with its single oxygen atom, forming a "V" shape. But oxygen, with six available electrons, uses only two to bond with hydrogen. The other four form two "lone pairs". When these lone pairs are taken into account, the shape of the molecule is not a two dimensional "V" but a three dimensional tetrahedron, in which the four corners are the two hydrogen atoms and the two lone pairs of electrons. This happens to be the ideal architecture to make maximal use of hydrogen bonding: each hydrogen atom in one water molecule can bond with each of the two lone pairs in another water molecule. In other words, each water molecule can bond with four others forming an extensive tetrahedral network. While many other substances (such as ammonia or hydrogen fluoride) can form hydrogen bonds, only water can do so in three dimensions.

At the air pressures prevalent at sea level, the range of pressures that matters as far as the effect of water on climate is concerned, ice displays this tetrahedral structure. This is in contrast with most other solids which are held together by strong covalent bonds, although metallic crystals also have access to somewhat weaker ionic bonds, a fact that explains their ductility. The tetrahedral network of molecules joined by four hydrogen bonds, however, can only form if enough distance is kept between the water molecules. In other words, the crystal structure of ice has lots of empty space, and this explains its low density. Though water molecules in the liquid state also tend to arrange themselves tetrahedrally, theirs is a much more flexible network: some bonds are not straight but bent, and not all possible bonds form. Above 4˚C too many bonds are broken, so water behaves like a normal liquid. But at 4˚C the right balance of numerousness, flexibility, and distortion is reached allowing liquid water to occupy the empty spaces between ice crystals, and hence to become more tightly packed than the solid. Thus, one eccentricity sustains another eccentricity.

The task of philosophy may be defined as sorting out the unimportant from the important, separating the ordinary from the singular, telling apart the trivial from the remarkable. This is a task that may be carried out in many spheres of reality. A materialist philosophy must take this labor right to the heart of matter, discovering how one piece of remarkable behavior becomes the basis for another extraordinary one which, in turn, may lead to further departures from normality. A materialist philosophy, in short, must acknowledge that, sometimes, eccentricities can make all the difference in the world.

Matter Singing in Unison.

We live surrounded by material rhythms. Some of these are technological, the rhythms of radio transmitters, electrical generators, watches, and clocks. Others are not: fireflies emitting pulses of light or crickets and cicadas singing. Rhythms not only surround us they constitute us: the beating of our hearts, the daily cycle of sleeping and awakening, the firing of our neurons. Thus, our bodies are large collections of oscillating entities existing in an environment made largely of diverse populations of other oscillating entities.

Oscillators, natural and artificial, may be divided into two classes. On one hand, there are those that acquire their rhythmic behavior from an external source, pulsing periodically as long as this outside influence forces them to pulse. The ebb and flow of the tide is a good example of this kind of oscillation. On the other hand, there are self-sustained oscillators, systems with their own internal source of energy capable of maintaining a stable rhythm even in the presence of small shocks and noise. All of the examples mentioned above belong to this class. Perhaps the most important characteristic of self-sustained oscillators is their ability to spontaneously synchronize with each other by adjusting their internally generated rhythms. The adjustment may be mutual or it may be caused by the action of a master clock, but in either case the result is a material system with components beating in unison. An example of mutual adjustment is the spectacular displays of thousands of fireflies emitting light simultaneously, as observed along the tidal rivers of Malaysia or Thailand. An instance of oscillators synchronized by a single source is the human body's sleep-awake cycle (our "circadian rhythm") locked in step to the rotation of the earth acting as master clock. Oscillators that are not self-sustained may display resonance (the forced oscillation having the same beat as the forcing one) but not synchronization.

Another crucial ingredient for synchronization is a weak coupling between the oscillators. A coupling must exist since it is by interacting with one another that rhythmic entities can adjust their frequency, or their phase, or both. The means to achieve this coupling, on the other hand, can vary widely: periodic light signals provide the coupling for both fireflies and circadian rhythms; electrical signals can synchronize generators in a power grid; chemical signals may be responsible for the spontaneous synchronization of the menstrual periods of women that interact daily and routinely. Thus, the nature of the signal does not matter, only its intensity. The reason the latter must be relatively low is that too strong a coupling basically transforms two oscillators into a single one, but one of the conditions for synchronization is the separability of the components, that is, that each separate component can continue to oscillate if separated from the other. A weak coupling guarantees that this relative autonomy is preserved.

While in the last few decades the scientific study of synchronization has focused on biological rhythms, historically it has been technological objects that have attracted most attention. Indeed, the first observation of the phenomenon was done by the Dutch physicist and clockmaker Christiaan Huygens in 1665. Two of the pendulum clocks he had built, and which were placed in a common support that transmitted weak mechanical vibrations from one to the other, began quite unexpectedly to swing in exact contrary form, that is, synchronized each other in anti-phase. While at first Huygens was impressed by this almost magical event, soon his awe turned into despair. Accurate pendulum clocks had been created to solve the problem of determining longitude during long sea voyages, but the sensitivity of the time-keeping devices to other oscillating entities (and the oceans have plenty of these) compromised their accuracy. This shows that the effects of spontaneous synchrony may not always be desirable.

The case of London's Millennium Bridge is a good example of undesirable consequences. Every bridge designer is familiar with the danger posed to the integrity of these structures by a large group of soldiers marching in step. If the rhythm of their periodic motion happens to coincide with that of the vibrations they induce in the bridge these may be amplified out of control. The system formed by the soldiers and the bridge is not, of course, one of self-sustained oscillators: once the soldiers leave the bridge the latter does not continue pulsating on its own. In other words, the effect is one of resonance. But the bridge can act like the common support on which Huygens' clocks were hung, that is, it can act as the coupling device. And this is exactly what happened on opening day in June of 2000. Hundreds of people, with entirely unsynchronized walking cycles, began to cross the bridge. Their out of rhythm steps should have cancelled each other out but instead the walkers began to adjust their pace to the small lateral vibrations they were inducing in the bridge. At some point their independent steps became locked in the same rhythm, causing the Millennium Bridge to start swaying dangerously and, eventually, to be closed down.

The best example of desirable consequences of synchronized oscillations is laser light. Actually, like the wobbling Millennium Bridge, lasers are a consequence of both resonance and synchronization. All atoms can be excited by an injection of energy and, as they eventually return to their unexcited state, they emit a quantum of light (a photon). In ordinary light these emissions happen out of synch, so light of all colors (frequencies) and phases is produced. But if the light emitted by one atom happens to strike another that is already excited, the photon emitted by the latter will be synchronized (same color, same phase) with the former. So the first step in generating a coherent laser beam is to create a population of atoms in the excited state to increase the chances of creating this effect and generate clusters of synchronized photons. These are then amplified using a resonance chamber in which the photons are forced to bounce back and forth between two mirrors. Only those photons that do not hit the walls of the chamber eventually survive (all the other frequencies and phases are filtered out) and begin to produce more and more copies of themselves as they strike other excited atoms. One of the two mirrors is in fact not fully reflective, allowing some light to escape and this is what we observe as an intense laser beam.

The fact that spontaneous synchronization does not depend on the nature of the oscillators, or on the type of energy they use to fuel their stable vibrations, or on the medium that serves to couple them, shows that this is a universal phenomenon. And given that all matter oscillates one way or another, singing in unison may come quite naturally to it.

High Intensity Environments.

Military and heavy industry applications of materials tend to push the limits of their endurance, forcing them to perform under extremes of temperature and pressure, or exposing them to conditions leading to corrosion and chemical attack by strong acids or abrasive substances. In such demanding environments sophisticated metallic alloys have traditionally been the material of choice. But the raw materials that go into these superalloys, metals like chromium, cobalt, manganese, or titanium, are classified as both "strategic" and "critical". The first term refers to any material that is extensively used in the production of munition and weapons; the second one refers to the degree of actual or potential political instability of the country from which these metals are imported. In the 1980's, for example, South Africa was the main source of several strategic metals while at the same time its racial politics were coming under increasing attack and embargoes from other countries, making it an unreliable supplier. While the stockpiling of strategic and critical metals was one solution to the problem, substitution by novel materials proved to be a more sustainable long-term response.

Technical ceramics, such as silicon carbide or silicon nitride, are proving to be the best substitutes for metallic alloys in high intensity environments. For example, while silicon carbide has a tensile strength (resistance to pulling) markedly inferior to that of superalloys at room temperature, beyond 1640 C_ the tensile strength of most alloys drops down to zero while that of technical ceramics is retained to a large extent. In terms of their bending strength (resistance to flexing) metals and ceramics are competitive at room temperature, but again only ceramics retain this property at high temperatures. Finally, the compressive strength (resistance to crushing) of technical ceramics is typically higher than that of most alloys at any temperature. On the other hand, while ceramics can be harder than metals they are for that same reason more brittle: the bonds holding the molecular components of technical ceramics are the strongest, most rigid bonds (covalent bonds) while those holding metals together are more flexible (ionic bonds), allowing them to yield without breaking. But having covalent bonds has an advantage: these bonds involve the sharing of electrons, electrons that are therefore unavailable for chemical reactions, and this gives ceramics the inertness necessary to resist corrosion and chemical attack.

While there are many applications for new ceramics that do not involve their load-bearing abilities, it is in this capacity that they can act as substitutes for strategic and critical metals. Hence, their inherent brittleness is a major problem. Brittleness is only partly explained by lack of ductility. In addition there is the role played by internal voids and defects. This aspect of the problem must be tackled at the manufacturing level. The industrial production of technical ceramics involves at least three stages: the blending of mineral powders in different proportions; the consolidation of these powders into a solid by sintering, that is, partial melting and fusing by the application of fire; and finally, the shaping of the final product either by molding or by machining the part to a desired size and form. The three stages need not be sequential. Sintering and forming may be done simultaneously (as in hot pressing) or the powders may be mixed with a solvent and poured in liquid form into a mold (as in sol-gel processing).

The secret to combat brittleness is controlling the size of the powders' crystals as well as their distribution. Either large crystal size or a random distribution of sizes allow large, irregular grains to form, leaving relatively big spaces in between. While these defects may be a source of toughness in metals, allowing them to yield under stress thanks to their easily broken and reformed bonds, the stronger bonds of ceramics do not permit this flexible response. Thus, the component crystals must be made as small, and their distribution as uniform, as possible. Another strategy to avoid brittleness is to use novel methods for monitoring the consolidation process of the mineral powders (using X-rays and ultrasonics) permitting the early detection of dangerous voids. Finally, manufactures may blend ceramics with metals into hybrid or composite materials: ceramic fibers can be mixed with a metallic matrix (silicon carbide in aluminum, for example) to combine the wear-resistance of the former with the ductility of the latter.

Unlike older ceramics, like the clays used in ancient pottery, or ceramic-like materials, like glass or concrete, products using the new ceramics are mostly hidden from view. Sintered silicon carbide, for example, is used to manufacture the internal components of heavy industry equipment: pumps, valves, nozzles, bearings, seals, and rings. In the hostile environment of a chemical factory, for example, where exposure to dangerous chemicals is routine, the inertness of ceramics can prove highly valuable. On the other hand, as engine components (turbine blades, heat exchangers) the much greater heat resistance of technical ceramics gives them an advantage over metals, since the higher the temperature at which an engine can operate the more efficient it can be. This means that higher fuel prices, in addition to the strategic and critical status of a material, can serve as an incentive for substitution.

Interestingly, in the history of substitution of materials, ceramics played a pioneering role. They represent the first modern attempt at replacing an expensive foreign material, Chinese porcelain in the 1600's, by a locally produced one, an attempt backed by systematic science as well as by government financial support. The seventeenth century featured both the centralization of political authority across Europe and the propagation of the methods of physics and chemistry throughout the continent. The two came together in Saxony, where the ruler possessed the largest collection of imported porcelain, and where one of the earliest laboratories for the study of materials, with furnaces capable of extreme intensities of temperature, had been established. In a few years, porcelain of a quality comparable to that of China, in color, translucency, and even sonorous quality, was produced there. Today's combination of the resources of military and heavy industry organizations with the knowledge of material scientists is achieving the same degree of success, even if the products are not as visible, or as displayable, as the items in the Saxon monarch's collection.

The Foam and the Sponge.

We are all familiar with the three basic states that materials can have: gas, liquid, and solid. What state a material is in at any one point in time depends on the critical value of intensity at which it spontaneously makes the transition from one state to another. Because different materials have different critical values they can combine with each other in different states. Thus, an aerosol is a mixture of a material in its gas state with extremely small particles of another material in its solid state. Similarly, gels combine materials in their liquid and solid states. These mixtures are referred to a “colloids”. But a more interesting coexistence of states, one with a more complex internal architecture and thus with more scope for material design, is that of foams and sponges. A foam can be created in a liquid by a variety of operations that inject gas in it. Some of these operations are physical, such as the beating or stirring that creates whipped cream, others are chemical, like the fermentation used to create such edible foams as beer or bread.

The geometrical properties of the resulting foam will depend on the proportion of liquid to gas: if the former predominates, resulting in a wet foam, the spatial forms are simple spheres, gas-filled bubbles floating in a pool of liquid; if the latter dominates the mix we have a dry foam in which the bubbles are now packed so tightly together that they loose their spherical form and become irregular polyhedrons, varying in size, shape, and orientation. The architecture of dry foams is much more complex than that of wet foams but it nevertheless exhibits clear geometrical regularities: whenever there is a common edge we will always find three bubble walls meeting to form it, and a common point will always involve four walls coming together. Moreover, the regularities in the network of polyhedrons result from the same process that produces the spherical shape of the simple bubbles: the elastic skin that forms their walls needs energy to be created and maintained and, as in the case of crystals, the amount of energy used tends to be minimized. Mathematically it is easy to show that a sphere is indeed a minimal surface; what constitutes the minimal polyhedron, on the other hand, is still a matter of debate: nineteenth century physicists proposed a candidate with fourteen faces, eight of them hexagonal and six square, but contemporary computer simulations have found some that are even more economical in energy terms.

Foams formed by the coexistence of liquids and gases tend to be relatively ephemeral, but special substances called “surfactants” can be used to increase their longevity. Some surfactants, like ordinary soap, allow the elastic skin of a bubble to adjust its distribution of energy (more precisely, of surface tension) in response to fluctuations in the forces that impinge on it. This gives bubbles the means to adapt and respond to changes that would otherwise destroy them. Other surfactants become a structural part of a bubble’s wall, giving it a degree of solidity. We may use the term “sponge” for these solid foams, even though strictly speaking it is the name used to refer to a primitive animal whose skeleton has been used to absorb, hold, and deliver liquids since ancient times. Like living sponges, solid foams are filled with cavities that enormously increase their surface area, but unlike living sponges they can be formed by the same foaming operations mentioned before. The surfactants tend to be chain-like molecules, or polymers, like the proteins that are used as structural materials in our bodies or the synthetic polymers that compose most plastics.

From the point of view of the design of new materials, foamed plastics display great versatility due to the number of parameters that can be manipulated to generate novel properties. All plastics, foamed or not, share two design parameters. The first one is the component molecules of the polymer chain. These can be very simple, as in polyethylene, or more complex, as in polyurethane. The second one is the linking geometry of the polymer, ranging from simple linear chains to branching ones and even loops. Cross-linkages between different chains augment the repertoire of molecular architectures that can be created. Since the process of polymerization that produces all plastics is typically performed in the liquid state, creating foamed versions of them is relatively easy involving only the introduction of a gas through mechanical, thermal, or chemical operations. As the liquid solution hardens the foam becomes a sponge, and this adds two additional design parameters. The first one is the ratio of gas to solid, allowing the manipulation of the weight of the material over a wide range of values. The second one is the connectivity of the internal cavities created as the bubble walls harden. These cavities may be connected to one another forming an open network or, on the contrary, each cavity may be isolated from the rest in a closed network. In an open network the gas trapped in the cavities can circulate around so that pushing down on a foamed plastic object simply redistributes the gas elsewhere. This yields a plastic that is soft to the touch. In a closed network, each cavity holds on to its own gas resisting compression. The plastic material that results is relatively hard.

The variation in the properties of materials that foams and sponges afford results from their hybrid nature. Like gels and aerosols, they are hybrids of different states of matter. But unlike colloids, they are also hybrids of material architectures of different dimensionality: three dimensional voluminous materials containing a large proportion of two dimensional surfaces. In this sense, foams and sponges belong to the same class as metallic alloys, fiberglass composites, and other heterogeneous materials, that is, materials in which the coexistence of differences opens the doors to endless variability.

Opportunities and Risks.

How do animals perceive their material environments? This question is intimately related to another one: what opportunities for action are supplied to an animal by its environment? The complementarity of the two questions points to the fact that when it comes to animal perception it is the interaction of organic bodies and the materiality of their surroundings that matters. A cluttered space, for example, supplies a walking animal with the possibility of locomotion in only some directions, those exhibiting openings or passages, but not in others, while an open, uncluttered space offers it the possibility of locomotion in all directions. To use a different example, the edge of a cliff presents a walking animal with a risk, the risk of falling, and the sharp edges of the rocks below, the risk of piercing its flesh. In both of these examples it was important to specify that the animal in question is a walking one, because a space full of obstacles or the edge of a cliff do not constrain flying animals in the same way. Only to an animal lacking the capacity to fly would those opportunities and risks seem significant, and the fact that they are indeed perceptually relevant to the animal will be displayed in the way it accommodates its behavior: moving to avoid collisions or keeping a safe distance from the dangerous edge.

We could say that an animal perceives not the properties of its material environment, but the potential for action that those properties supply it with: a piece of ground is perceived not as horizontal, flat, and rigid, but as affording the opportunity to walk. Conceptually, the distinction that we need here is that between the properties of an object and its capacities: a knife may possess the property of being sharp and this may give it the capacity to cut, but the latter can only be exercised with respect to another object that has the capacity of being cut. In other words, unlike properties that an object either has or does not have, capacities are relational: a capacity to affect always goes with a capacity to be affected. This is why a given distribution of opportunities and risks depends both on an environment's materiality as well as on the behavioral capacities of an animal. And whether an animal will pay attention to a given environmental feature, that is, find that feature worthy of perception, will depend as much on its own abilities as on the objective properties of the feature.

A given environment contains a variety of material components in different states: gas, liquid, solid. The first two tend to offer animals a medium to move through, to fly, or to swim. Air and water are also media that transmit signals: light moves through them, chemical substances are carried by them, and waves form in them. This supplies an animal with information about its surroundings but only if it has evolved the capacity to be affected by those signals, that is, the ability to see, smell, or hear. Solid objects, on the other hand, present an animal with opaque surfaces, but it is at these surfaces that light rays are bounced, chemical substances emitted, and vibrations passed on to the surrounding medium. In other words, it is mostly surfaces that an animal perceives. In addition, it is mainly the layout of these surfaces that supplies it with opportunities and risks. A good example of this is the capacity of cavities to serve as shelter: a layout of rigid surfaces facing inward, like a hole on the side of a mountain, supplies an animal with a place to hide, either to escape from a predator or, on the contrary, to conceal its presence from its unsuspecting prey. But again, the cavity becomes a shelter, and it is perceived as such, not only because of its physical form and capacity to resist penetration, but also because it is a participant in a predator-prey drama. In other words, it is because animals supply one another with opportunities and risks – a predator affords danger to its prey while the prey affords nutrition to the predator – that surface layouts become significant to them as perceptual entities.

Many animals are also capable of manipulating surface layouts changing the distributions of opportunities and risks in their favor. Examples of this abound: spider webs, ant and termite mounds, rodent burrows, bird nests, beaver dams. Producing these new layouts involve a variety of activities, from excavating and carving, to piling up, gluing together, molding, rolling and folding, and even weaving and sewing. The materials used may be secreted by the animals themselves, like spider silk or honeybees wax, or collected from the surroundings, like the wood pulp used in wasp nests, or the grass and twigs used in bird nests. Through an evolutionary process that has meshed the activities of animal bodies to the properties of materials, the resulting surface layouts display the right capacities: a spider web is able to absorb the kinetic energy of flying prey, then glue it and retain it; the branches and cut down trees of a beaver dam are not only capable of blocking a water current to create a deep pond, but their arrangement also possesses air openings to afford ventilation and climate control; the subterranean architecture of ant nests provides the right connectivity between vertical or inclined shafts and horizontal chambers to permit movement, storage, and protection.

As part of predator-prey dynamics these artifactual surface layouts can act as traps or shelters, but they can also participate in processes of animal cooperation and communication. When insects build a nest, for example, they communicate with one another through the changes they make to their environment – physical deformation as well as impregnation with hormones capable of affecting the animals themselves – their behavior becoming coordinated as they modify the way solid surfaces around them affect them and are affected by them. This indirect communication (called "stigmergy") allows the insects to construct a nest without any one of them having an internalized representation of it. Builders of robots, particularly in the field of behavioral robotics, are learning from the way animals use the changes they make in their surroundings to store information. As they say, why build robots capable of creating internal models of the world when the world is its own best model?