Notes on the Limits to Knowledge Explored with Darwinian Logic

Clarifying and expanding the boundaries of the knowable using learning systems

This essay explores the effects of applying Darwinian logic to the millenarian problem of limits to knowledge. Darwinian logic has solved or clarified many otherwise intractable problems in biology and sociobiology and might give a hand here. Although unable to put electrified barbed wire along the borders of the "knowable," I hope to have set the problem in clearer terms than before. "A well-posed problem is a half-solved problem," according to an old dictum. **Support for this work came from a small grant from the program in "Limits to Knowledge" of the Alfred P. Sloan Foundation.**

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Darwinian logic reduces evolution to intrinsic and basically stochastic exploration of possible configurations tested through selection for their *inclusive fitness.* The immense number of proposals by the combinatorial machine would make selection (i.e., evolution) immensely slow if not for *preselecting* filters to weed out combinations with low probability of success. The filters themselves are obviously subject to evolution and implicitly carry a subtle, general, and efficient "theorization" of the physical world. They are the core of science, in the sense of theoretical physics.

I look at learning systems from the point of view of an *"in"* endowed with sensors and computing machinery, trying to *model* the *"out"* in the sense of *anticipating* the results of its interaction with the *out*. Consciousness is defined as the capacity to include the *in* in a model of *in + out*. Due to the great advantages of such a configuration, in terms of inclusive fitness, consciousness defined in this way can be found very early in evolution (e.g., in single cells). Learning systems include DNA, immune systems, and nerve aggregates such as individual human brains and groups of them when organized in parallel architecture through language. All seem to learn by following the same basic mechanism: *mutate, preselect, select,* and *memorize*.

Computers, even supercomputers, can provide speed but are still rudimentary machines. Conceptually, however, it is possible to endow them with the appropriate software to produce Euclid's *Elements* from the axioms in a single go with no human intervention in between. Knowledge is essentially bounded by the limits of sensors in quality and quantity, and by the limits of the computing system behind them. Thus, I define a

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restricted version of the "knowable," the reachable, and the full one, the attainable.

Quantum rules do not constitute *per se* limits. They represent an *intrinsic* granularity of the physical system. Living things, having evolved bottom-up from the microscopic, are cradled in quantum rules and nest into them. Sensory systems (e.g., vision or hearing) can operate to quantum limits. They preceded *Schrödinger* by a good billion years. Sensors are not necessarily passive. The signal can be stimulated by an action of the *in,* for example, the shrill cry of the bat or the smash of the supercollider. Knowledge, in the human sense, does not necessarily descend from actual *scientific* experiments, as stated by the positivist philosophers of Vienna. The preselection filters carry a subtle knowledge of the physical world that can be deconvoluted into a "quasiphysical" model. For humans, the *prefilters* are *aesthetics* and *logic*. Using only these, one can construct mathematics divinely suited to the description of the universe. Einstein never overcame the shock.

Darwinian logic also allows the positioning of science as a product of the *logos,* the informational system evolved on the physical basis of *language*. In the evolution of DNA, inclusive fitness is the master selector, but mutations in the general sense can occur that are indifferent to fitness. The process is called *genetic drift*. The long-term importance of the drift is that a species becomes quite differentiated and may find ready solutions when its context changes. Science can be seen as the *genetic drift of the logos*. It costs relatively little to society, and it may be used for status, such as art. The *preselectors* and the *experiments* ensure a fitting of its models with the external world. It may become useful in special conditions, such as the mental map of a forest that a cat constructs in its spare time.

The limits of the knowable are related to the presence of decodable signals. Electromagnetic, X-, and gamma rays as well as wave-particles of vast description have greatly expanded the knowable for humans beyond the measurements from our senses. Other signals not yet detected or decoded may expand the sources. Neutrinos were detected only recently, gravitons not yet. The subjacent sea of particles-antiparticles may reserve surprises. Also computing within the *in* is essential, but we do not seem to have problems in this direction in the long run.

ON *INS* AND *OUTS*

At many points in this essay, I will stress the concept of *in* and *out*. Some definitions and considerations may help to clarify the concept. For a single cell (e.g., a microbe) the cell wall clearly defines the concept of *in* and *out*. The *in* is enclosed by the wall and is spatially compact. The *in* is also informationally connected, because informational molecules, in a fraction of a second, can diffuse forth and back, carrying signals and performing calculations. Strict physical connectivity may not be necessary for the purpose. A sponge consists mostly of empty space, inside, but reacts as a coherent body. We may attribute the *in* to the whole *connected* system. The coherent behavior implies an *informational grip*.

At this point, we can make a conceptual jump, defining the *in* as *informational connectivity* that makes the parts move like the fingers of a hand. This brings us far because, as various entomologists have suggested, a beehive behaves like a single animal, its parts nicely coordinated. If I step on the tail of a dog, his teeth will reach my leg. If I step on a bee, another bee will prick my hand. As a system analyst, I see more analogies than differences.

Before making the next, dangerous step, I will come back to the cell. The best, or the only, way to survive for the *in* is to have anticipatory models of the *out* in order to react or *pre-act* in an appropriate way. These single cells do it magnificently with their little ISDN computers, which we find again, probably unchanged, in the neurons of our brain. The next step for the *in* is to model the *in* itself. This is not difficult, because internal sensors, necessary for the modeling, can also be some of the molecules moving around to calculate. I would say a model of the *in* preceded that of the *out,* if life developed in the extremely stable depths of Earth's crust. Having a model of the *in* and one of the *out*, the next step is in connect them. The connected model can then see the *in* immersed in the *out* in an *anticipatory mode*. This is my definition of *self-consciousness*.

In the exhilarated, anthropocentric mood of religions and philosophies, at least the Western ones, only humans have self-consciousness. My definition may appear excessively abrupt. It extends the privilege to very *"low"* creatures. In fact, anyone familiar with animals, typically cats and dogs, is struck by the humanity of their self-conscious, in the sense of guilt and all the rest.

Having chosen information (one should define better the kind of information) as the glue of the *in*, and having named bees (neutral, they are just insects) as spatially disconnected *in,* we can now make the next step, a long one. Subsets of humanity are linked by common language (i.e., common culture) and tend to occupy compact territories. In many ways, the group members feel themselves part of an *in*. They compete or fight carrying a sense of identity and togetherness. This perception has struck all historians and sociologists. The 17th-century English philosopher Thomas Hobbes brought the identification to extreme and implausible limits in his *Leviathan*, the commonwealth as an organism.

More subtle testimonies validate the analogy. The actions of an individual, measured under some quantitative and important aspects, say the paintings of a painter, the murders of a serial killer, or the publications of a researcher fit quite precisely a certain equation in time, a logistic, measured cumulatively for an *in*. But the actions of a band, say, Italy's terrorist Red Brigades, also fit the same equation. So do the actions of organizations such as GM and Mercedes, measured through their outputs. At the level of a country, the equation fits the cumulative growth of GNP and public debt. It also fits the growth of a cauliflower pointing to an extraordinary unity in the working of the *ins*.

ON LIMITS OF KNOWLEDGE IN BIOLOGICAL SYSTEMS

Through evolution, from greedy molecules to the Internet, all learning *ins* basically operate on the same guidelines. But learning became stuck here and there. Looking at what makes the *ins* differ and what defines the limits of their modeling capacity (i.e., their "knowledge,") can illuminate our search on human limits. The first, obviously limiting factor, is *sensory capacity*. Materialist philosophers (e.g., Democritus) used to say: "Nothing is in the mind if not first in the senses." The senses, defined in a broad way as the channels of interaction of the *in* with the *out,* are a prime vehicle of information to the modeling machinery.

The *in* is not necessarily passive. It can stimulate a message from the *out* through its own action, a sort of questioning. Electric eels sense objects in the electric field they create. Bats elicit echo-chirps with their shrieks. The first sense, and probably still the most important in the biosphere, is that of *chemical recognition* or identification. Single-cell organisms have skins with weird resemblance to industrial telecommunication facilities, with lumps of dishes facing everywhere. Molecules can be identified at the surface, and a signal sent to the internal computers. Cells operate with thousands of circuits, as ISDN computers in the "common carrier" of their cytoplasm. The molecules are let in if identified as food or hormones.

These molecules usually arrive by diffusion, so that the world of a cell is spatially very limited. Even if the molecules come from a distance, they do not carry a tag about it. The most a cell can do is measure chemical gradients along its length. *Or in time*. Bacteria are sometimes endowed with rotating *flagella* that provide locomotion. They can measure gradients of chemicals (or temperature) along their way and react accordingly. The tiny *electric* motors of the flagella are steered to guide the bacterium into the flesh of a nourishing solution. The chemical knowledge of a single cell in the field of organic compounds is fantastic and far beyond present human knowledge in organic chemistry. However, it may suffer from what I call the thermochemical cycles effect (TCE).

Science *seems* densely to fill all available space. However, this is our brain's trick. About 20 years ago, in an attempt to develop a thermochemical method to decompose water, my laboratory (ISPRA, near Milan) developed a computer program, based on thermodynamic tables, to construct the cycles stochastically and to select among them on the basis of thermodynamic self-consistency. In the first run, we got perhaps 20,000 cycles. When the chemists started browsing through the list, they discovered that at least 99 percent of the chemical reactions making the cycles had never been studied. We think of classical chemistry, the inorganic one, as a squeezed lemon. But only a few veins of knowledge infiltrate a huge block of ignorance.

The follow-up to the "discovery" of thermochemical cycles is interesting, in the light of our search of the limits to knowledge. We asked several chemistry professors in the universities they could assign the study of some of the reactions we thought promising as practicing work or a thesis. The common answer from these uncorrelated persons was that they were not interested in exotic chemistry. It would be interesting to investigate how this mental inhibition operates to set *social* limits to knowledge. And perhaps how unsocialized robots could fill the gap, if they are socially accepted. Because the negative attitude was so well-defined and widespread, we came to conclusion that: the exclusion was cultural. In other words, built-in inhibitions in the learning mechanisms can exclude whole fields of *reachable* knowledge which then becomes *de facto unknowable*.

The fantastic chemistry of our cells developed under the "cultural" rule of selection, if tempered by neutral mutations. Inevitably, some pathways are excluded, perhaps forever. Furthermore, no chemistry will be developed for chemicals that the cell's skin never saw (e.g., transuranic short-lived elements). What was said about the very limited horizon of chemical sensors in single cells is not completely true. Molecules can diffuse only to cell walls, certainly. However, photons can have chemical effects coming from far away and entering directly into the cell's chemical machinery, without even a salute to the doorkeepers. Because the photons were presumably disruptive, cells developed sensors for them, to swim if the interference was too high. These alarm mechanisms opened a fantastic new avenue in the chemistry of cells. Light sensitivity required a new interface, producing standard signaling chemicals out of a broad mix of photons. Photochemistry was invented and, as usual, developed to incredible sophistication.

Photobacteria provided two quintessential breakthroughs in the development of the biosphere: photosensitivity and photosynthesis. Photosensitivity gave range, because light can come from far away in transparent media like air and water. In contrast, millimeters measure the territory of diffusing molecules. Through photosensitivity, humans have expanded their territory to 10^{10} light years. Incidentally, cones and rods in our retina might emerge as photobacteria, enslaved as endosymbionts. Photosynthesis was again revolutionary. The free energy of hydrogen was used to enter the game of carbon synthesis by reducing CO_2, generating almost the total free energy input of today's biosphere. In the form of the chloroplast, photosynthetic bacteria are endosymbionts of all the green plants. Endowed with such a powerful energy input from solar light, photosynthetic bacteria and their hosts exploded in number, releasing into the atmosphere huge quantities of the residual of water splitting, O_2. Oxygen created havoc, but *mitochondria*, presumably the mirror brothers of chloroplasts, found a way to use oxygen backward to burn organic materials to CO_2 and H_2O, recovering the free energy.

This reverse reaction was probably invented by photosynthetic bacteria themselves, to keep going after sunset.

The specialists in the reverse, the mitochondria, again in the form of endosymbionts, can be found in each of the cells of our body and, by the way, of any macrobiont. Because the metabolic intensity reachable with O_2 is 1,000 or 10,000 times higher than with reducing chemistry (as in fermentation), the metabionts, including humans, were clearly made possible only by the convergent action of chloroplasts and mitochondria. The entire process can be dubbed *expanding knowledge scientifically into an applied field* using the normal evolutionary tricks, available to DNA.

Everything started from the interaction with preexisting machinery of a signal coming from the *out*, the photon. Neutrinos can flood the universe and are very energetic, but they do not interact and never started anything inside the biosphere. Knowledge starts from perception, as the materialist philosopher explicitly stated. To recur to our starting point, the craft of identifying molecules as messages at the skins of monocellular organisms was never lost, even when the cells entered the architecture of macrobionts, who host billions or trillions of them. All our physiology, including the functioning of the brain, operates on molecular recognition, and this ability has been used to help the *in* of the animal to get chemical signals from the *out* through olfaction.

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Having such a long evolutionary pedigree, olfaction has reached the utmost in sensitivity: quantum limits. The antennae of certain male moths, sniffing females, can detect a few molecules of scent, just enough to overcome the Brownian noise of the receiver. The sense of smell has been extremely valuable to the mammals, which first evolved as nocturnal beasts. Accordingly, the part of the brain decoding the olfactory signals was very developed. Extreme sensitivity requires extreme specialization. Mammals' nose receptors contain about 1,000 different proteins specialized in identification of molecules or parts of them. The production of these proteins involves about 1 percent of the genome, extraordinarily high for part of a single function. Mammals can differentiate up to 10,000 odors. The sensing terminals contain only one kind of the proteins and refer to 1,000 specific collectors (granules). The brain can identify an odor by the geometric distribution of activated granules. Combinatorial reasoning suggests that odors should be more numerous than 10,000. The perceived number depends on the decoding computers in the brain. As often happens, very young brains have the potential for a very high number of combinations, but the ones that are not activated during a certain time window are suppressed by destruction of the relevant cells (apoptosis).

We see here at work another principle that can systematically reduce the extension of the knowable. If we impose on science to be "useful," a large array of explorations is inhibited. The historical analysis of social attitudes toward scientific research tells us that the inhibition can be forever. Thus, limits to the knowable may not be intrinsic to human brains plus its technological prostheses, but intrinsic to the social game. The result is finally the same, and I would put the two mechanisms into the same ballpark.

Coming back to olfaction, the nose possesses a second, independent molecule identifier, the *vomeronasal system*. A study of the DNA presiding over the production of its sensitive proteins shows they are completely different from those of the sniffing nose, pointing to a different evolutionary process. The *vomeronasal system* in fact tells nothing to our "consciousness" but communicates directly with the limbic system, the brain of the snake so to speak, and detects pheromones and other molecules important for reproduction and social relations. This CIA nose might tell a male, through filtered documents, that a female is okay but the whys are kept secret.

Turning to vision, this sense probably started in bacteria in a form of light-sensitive spots just producing photochemical signals to drive cells out of dangerous illumination levels. The mechanism stuck to all animals who have contact with light, evolving into incredibly perfect (under appropriate conditions) optical and sensory systems. Because light travels on straight lines and the atmosphere is transparent to many electromagnetic bands, the physical prerequisites were set for a fine mapping of the *out,* over large volumes.

Vision's evolution produced wonderful machines. Evolution stops, however, when the advantages in terms of survival are exhausted. Eagle eyes, nature's best in terms of acuity, are much better than that of humans but do not approach Mount Palomar. Perceiving Magnitude 5 stars and galaxies would have zero survival advantage for eagles and an unbearable biological cost.

Sound, in the band that propagates, has properties similar to light, although long wavelengths limit acuity. As in the nose, the signal in the ear is analyzed with extreme sophistication, witnessing long evolution and high survival value. The where is not given with much precision, but the who is almost tridimensional. Hidden in the forest, bushmen can identify members of a different tribe by listening to a couple of words. The ear can still defy the physicist's abilities. To give a curious example, sophisticated mathematics had problems sorting seismograms of far away atomic bombs from those of small quakes here and there. By speeding up the signals so that the ear can grab them as sound, it can tell them as a ping from a peng. The problem of poor definition can be vastly improved if the receiver animal is also an emitter. Bats excel in this respect because their acoustic radars are able to identify the distance and somehow the quality of an insect at a distance of tens of meters. Bats can also map with great definition and avoid wires and flying objects.

Why electromagnetic radar never appeared in biological systems is puzzling. The basics were developed in the electric eel, which uses the geometry of flowing electrical currents to detect obstacles and prey as well as show oscillations. With the voltages an electric eel can produce, spark radars are conceivable. They are now proposed for short-distance imaging, although the source is not a spark but produces a similar electric noise. One argument why animals never developed electric radar could be that it requires hyperfast processing, "hyper" referring to the speed of the nervous system, which is still a chemical system masquerading as an electrical one.

This example illustrates that the finesse of the sensory system must by matched by the capacity in hardware, software (firmware), and speed of the data-processing system. The two usually develop in a ratchet fashion, so that in actual cases they are almost perfectly matched. Once some basics are fitted and the sensory system has moved to limits, the processing system can keep developing new tricks. Birds can use stars to guide their migrations, or their nose, as for homing pigeons. This is an extremely important mechanism for including *new territories* in the modeling system, which finally comes out as the system in which one can live.

We see here other processes limiting the knowable for a learning system. An electromagnetic radar is by no means outside the evolutionary capacities of DNA in conceptual terms. Bats have acoustic radars with all the functions of an electromagnetic one. But the limits come from the speed of the computing system in the *in*. I wonder at this point why truly electric computers were never developed by DNA. Producing semiconductors is not a problem; many biological membranes are semiconductors. Producing electricity is not a problem, as electric eels show. Producing complex circuitry is not a problem; no computer can parallel our brain in circuits' complexity. What lacked was a starting point, a bud produced for some reason which finally develops into a CRAY for completely different reasons. Chance is extremely important in determining the knowable.

Examples abound, and the case of the light alarm chlorophyll, that became the largest industry in the world, has been touched on already. But I give another example, nearer to humanity in time and scope. The hand, evolved for deftly grabbing branches with superb timing and precision in order to do it *in flight*, can now play Bach on a violin, without extra steps in neuromuscular evolution. A similar story can be said for the brain, a late addition to the panoply of biological skills. ATP-AMP are the molecules ferrying energy inside the cells, probably since time zero and are common to all living things. Here and there they have been used as messenger molecules. Most of the information processing in the brain is, in fact, done using molecules originally devoted to other purposes, millions or billions of years ago. Opportunism is in fact almost synonymous with evolution.

ON IMMUNE SYSTEMS

In the spirit of Parkinson's Law, living things strive to fill all potential niches, meaning that the *out* is full of greedy and rapacious *ins*. Defenses must be efficient and alert. The most common menaces are molecules entering the *in* and interfering with its delicate chemical machinery. The order is tall, because the defense mechanisms must be able to distinguish between the hundreds of thousands of different molecules constituting the *in* and provide appropriate blocking reactions for the hundreds of thousands of different kinds of molecules that can penetrate from the *out*.

The complexity of the machinery mirrors the complexity of the task. Our bodies have about 10^{11} B-lymphocytes and a more or less equivalent variety of antibodies. Each is capable of producing a different one. The system operates as a unitary one, but the lymphocytes move around freely, like a swarm of bees, and are connected by an ISDN-type informational network of molecules. The immune system is very interesting as a learning system, because it solves problems by *producing solutions and plastering them on the problems,* hoping that one will fit. DNA has a similar approach, but its tests are serial. For the immune system there is no time for tinkering, so the approach is massively (10^{11}) parallel. The idea has fascinated some computer theorists who have proposed using it for actual human computing.

The immune system is also interesting for the systems analyst, because it represents an *in-bis,* a kind of double located in the *in* and watching it. In fact, it takes care of deviations inside the *in* itself. It strongly resembles the working of conscience at a chemical (but informational) level. The message has to be kept clear from any form of noise.

Once a problem meets a solution, the corresponding solution carrier is speedily multiplied, so that it takes macroscopic dimensions and is saved for further use. We call the result "acquired immunity." We have here a very complex and bounded learning system, with all the paraphernalia: hypothesis generator, testing mechanism, replication, and memorization. The limits are fairly clear. They depend on the inputs, which are chemical and, in a sense, stochastic. The inputs from the *in* have a similar character. Its final learning depends on its potential (the 10^{11} solutions) and on the problems it has to face.

Incidentally, sexual reproduction mixes the *a priori* libraries of the partners. Females are attentive to the health of the male, a good index of the quality of its immune system. I cannot resist the analogy with cultures, which become very creative in the places where they can mix and interact. Viruses seem to be great artists at fooling immune systems but do not seem to have one. Their *in* is tiny, just RNA with a little fur of proteins—no fluids to burden it. The existence of organisms, even people, whose immune system can fool the viruses shows the battle can be won. Thus, the viruses must have a reason to survive, and a plausible one is their capacity to ferry chunks of DNA (if in the form of RNA) across species, making the viruses the precious messengers of the biosphere.

ON THE EVOLUTION OF EYES

Vision is an extremely swift tool for the model-maker inside to get in touch with the external world. For this reason we can take for granted that all evolutionary resources and pressures tend to improve vision to the best profit of the individual.

This evolutionary showcase may help in learning about mechanisms that have impeded the production of natural optical instruments competitive with what humans have been able to construct. The limit can be contextual. No animal could gain inclusive fitness with eyes competing in resolution with the Hubble telescope. A microscopic eye resolving or magnifying 2,000 times might help microbes see prey and avoid predators. However, the advantage of this mighty machine (physically not compressible into the scale of a microbe) is much reduced by the fact that at very small scales, the diffusion of chemicals takes short times, and consequently a sharp nose may be more handy than a keen eye. Noses, because they are based on chemical reactions, can be scaled down to almost molecular size. Bacteria have excellent "noses."

When the driving force exists, evolutionary forces lead to technological miracles. Certain eagles that thrive on very small objects dashing in a visually noisy background have eyes with visual acuity approaching 100/10, but only on the eye's upper part, where images of the ground are projected when the eagle soars. The lower part, imaging the sky, has an acuity of 10/10 to 20/10. Astronomy does not seem to improve the inclusive fitness of eagles, which are sedentary birds. Nor do they fear menaces from above.

The capacity to *construct extremely sophisticated machines* adjusted to preset purposes is fully equivalent to the concept of *knowledge*. The learning through indefatigable experimentation is done by DNA.

A review of the eyes across all animal species, from the light-sensitive spots of bacteria to the eagles and the octopuses, which seem to have the best machinery on the market, shows that all technical possibilities have been explored and the machines brought to perfection *in terms of our scientific judgment*, inside the constraints of the context. In fact, many solutions appear technically brilliant. For example, fishes benefit from the construction of lenses with finely adjusted gradients in the refraction index, which human engineers are not yet able to reproduce. The final sensors, like rods and cones, put to use *waveguide properties*. From the point of view of sensitivity, the receptors are very near to *quantum limits* inside the constraints of visible light and room temperature.

In my context, the capacity to *construct extremely sophisticated machines* adjusted to preset purposes is fully equivalent to the concept of *knowledge*. The learning through indefatigable experimentation is done by DNA. Just to show how sophisticated this knowledge as coded in the equipment can be, I will list some of the optical sophisticates used by various phyla to provide various levels of vision and visual acuity. Generally speaking, eyes can be divided into two classes: those with split optics as forming composite eyes of various descriptions and those with single optics. These optics can operate in transmission, with lenses, optical fibers, and pinholes, or in reflection with mirrors or totally reflective surfaces. Single optics are superior because they can reduce diffraction problems, although well-engineered composites may have an acuity of 10/10, comparable to that of the human eye.

Pit eyes get some directionality just by reducing the angle of view of the sensors. They are the night weapon of sidewinder snakes and also adopted in antiaircraft rockets. Eighty-five percent of the phyla have them.

Single-lens eyes always improve on pit eyes, even when endowed with a pinhole pupil. However, matching the dimensions and available refractive index to produce a focused image on the sensors (retina-like) is hard, especially for aquatic animals where the cornea curvature is useless because of the high refractive index of water. The problem has been neatly solved a dozen times in convergent evolution, by making onion lenses with graded refractive index (Matthessen lenses). In that way, for given dimensions the focal length can be reduced by half. Fishes, cephalopod and gastropod mollusks, annelids, and copepod crustaceans have them.

Multiple lenses can be found in copepod crustaceans, where two of the lenses are not in the eye, but in the rostrum (rather like eyeglasses). The parabolic surface of the first corrects the spherical aberrations of the others.

Scanning eyes give great luminosity but small field, as in a telescope. For example, the copepod *Copilia* has a "telescope" with an objective lens and an "eyepiece" in front of five receptors. The eyepiece and sensors then move in unison to scan the total image produced by the telescope. Scanning eyes with small fields are not uncommon. Heteropod sea snails such as *Oxygyrus* oscillate the eye through 90 degrees in about a second. The eye has a linear retina a few receptors wide and several hundreds long. It reads lines. These scanning eyes are strongly reminiscent of television procedures to construct images from a linear time signal.

Although the vision machines, the eyes of macrobionts, display the most dazzling variety, *the basic machinery is extraordinarily similar*. All the photosensors in all the eyes descend from photobacteria, induced into endosymbiosis in one way or another. This points to a general fact that keeps popping up when we pierce into the origins. *DNA culture is ecumenical* inside the biosphere. The chemical sweatlab is run by bacteria, which fill every niche where free energy can be extracted, chewing dangerous molecules or grinding rock—and making quintillions of experiments to find a good solution.

Living creatures select to keep the information channels open. I have known a few people who were never sick during their lives, meaning their immune systems could face any attack, bacterial or viral. This resistance looks like an obvious survival value. But viruses can peddle chunks of DNA (RNA) across species, creating an *information bazaar* that seems to enrich everybody. *They provide an incalculable number of experiments* extending *DNA "knowledge" of the external world to the* *limits of the “knowable,” inside the DNA-world context.* Although relatively slow and cumbersome, channels to spread this knowledge over the entire DNA realm—the biosphere—exist. The biosphere, in many aspects, can be considered a single creature. James Lovelock’s concept of Gaia may well be overextended, but it certainly contains a core of truth. Earth would be very different without (microbial) life, and feedback loops are unavoidable when the interaction is so intense and extended in space and time.

TOWARD THE NERVOUS SYSTEM

Although single cells are the building stones of large organisms, they themselves are already very complex organisms, well-endowed with a capacity to interact constructively with the external world, to remember, and to learn. Single cells often have motility. They can creep around with the equivalent of muscles and a rigid frame of fibers or lamellae equivalent to a skeleton. Many monocellular organisms can also swim, propelled by cilia and flagella. Bacterial flagella are operated by tiny, reversible, electrostatic motors that nanotechnologists would happily be able to build.

My interest centers on knowledge acquisition and information processing. These are accomplished using feedback reaction cycles that are perturbed by external signals and induce appropriate reactions in the organisms. To give a simple example, a single cell often feeds on molecules dissolved in the medium in which it floats. When it swims, its sensors measure the molecules and the computer checks that the gradient of concentration is positive in the direction of movement. So, the cell tends to move toward the source of the nutrient. If the gradient is not satisfactory, the cell turns the motors of the cilia in reverse for a while, takes another direction *at random*, and then pushes forward again. In fact this behavior strongly resembles that of a large grazing animal. We see again and again a stochastic process as the basis search for an optimization procedure. *Exploring, testing, and choosing:* mutation, selection, and diffusion.

Communication inside a cell is done through coded molecules recognizing their counterparts in an ISDN mode. With current temperatures and cell sizes, however, diffusion times are on the order of a second, so that the computing is relatively slow, but sufficient for a monocellular organism. If the system becomes large, like the macrobionta to which we belong, then two strategies have finally been adopted in terms of signal transmission. One still relies on diffusion, aided by transportation in circulating fluids or air outside. This is the system adopted in plants, which search for a good niche (via the seeds) and settle for a sedentary life. Defense against predators and competitors is done by both mechanical weapons (stings and barks) and, especially, an extraordinary panoply of chemicals.

Animals, which are all predators, bet on movement, the faster the better. Significant times becoming short ones, fractions of a second, animals had to develop a fast system to connect their various parts. *This is the driving force for the development of the nervous system.* Brooding cells connect with a fast wire, receiving a chemical signal and *repeating it* at a distance in a short time. Instead of diffusion from cell to cell, a fast *propagating instability* is at work, like using a nitroglycerin pipe to transmit a bit. The nerve, however, recharges rapidly for another pulse.

The mechanism, if rudimentary in principle and primarily designed to run the muscles, had immense potential, because computer cells could operate in large parallel computing blocks speeding and amplifying their capacity. At the end of this evolutionary chain, the human brain has about 10^{13} neurons, each endowed with a number of connecting lines; meaning 10^{16} axons build all the necessary parallels and series and bring very complex operations into acceptable operational times, even for a fast, nervous-muscled animal. A mark of its importance in terms of inclusive fitness is that in humans the nervous system takes about 20% of the metabolism, more than the muscles, although it weighs only 2% of the total organism.

The fast system did not eliminate the slow one, which was preserved for actions linked to long time-constant processes. The messengers can just diffuse or be transported in the blood current or the lymph. Due to the fine spatial architecture of nervous terminals, it pays that the nerve fibers can also carry chemicals in small tubules laid inside them. In the brain itself, chemicals modulating moods and attitudes are often simply diffused in the fluids. This is the realm of the endorphins and the hallucinogenic drugs that simulate them. Their study has produced more than one kick in the knee of human pride. To quote one case, high serotonin levels induce dominant attitudes and “big-chief” behavior. Kings should invoke God for serotonin much more than for ascendancy. Because serotonin production is stimulated by submissive attitudes from the subjects, a socio-visual feedback, they too contribute to the making of the king, democratically.

The brain has the drawback of poor speed at the nodes, where chemical diffusion is dominant. As hinted earlier, we can wonder why it was never “electrified” in the strict sense. Biologically speaking, the problem appears soluble. Eels can make electricity, the axons are electrically insulated, semiconductors are not a problem for biological systems, and miniaturization is there. A house fly compacts one million neurons in one cubic millimeter of brain. The fact that neurons are already small computers per se is a boon for small brains. *C. elegans*, a tiny worm of about 1,000 cells, thrives by the billions. Its little brain of 250 neurons can perform the sophisticated tasks to survive in the complexities of the *“out,”* live a vigorous life, and reproduce.

ON LANGUAGE

Language is considered the main characteristic distinguishing humans from other animals. We speak of *syntactic* language, because most animals have languages to communicate, if only *grammatical*. The distinction is between hierarchical organization of signals assuming new meanings (syntax) and a listing of signals that should be decodified separately (grammar). In my opinion, the importance of human language does not in fact stem so much from its capacity for

The importance of human language does not in fact stem so much from its capacity for syntactic constructions, because animals also think syntactically. Rather, its importance stems from its capacity to permit *syntactic parallel operation of brains* on a vast scale, and to create *external memories*. Such memories can also be external to the species.

syntactic constructions, because animals also think syntactically. Rather, its importance stems from its capacity to permit *syntactic parallel operation of brains* on a vast scale, and to create *external memories*. Such memories can also be external to the species. The messages can be coded in some way into a physical object, tendentially ROMs, including manuscripts, books, and carved stones.

When and why humans acquired the new skill still remains in dispute. Research takes it progressively backward in time. The Pithecanthropus Erectus of six million years ago probably did not have it. Articulate language requires a very sophisticated and fast coordination of muscle movements in the tongue and mouth. The coordination center (Broca region) has a precise position in the brain, and examination of skulls gives an idea of when it was sufficiently developed to get the corresponding little bump, although probably already requiring a great level of development for the center and the related skills.

Speaking skills require extreme dexterity in the operation of the muscles implicated. Attentive ears recognize minimal hues in dialect variances that develop in small, strongly connected groups, such as bands of hunters, or today's villages, or the different "contrade" (neighborhoods) of Siena. Valuable for the discriminating ear, the tiny variances must be *consistently produced* at the source. To provide a progenitor for this center of extremely subtle control, some researchers hypothesized that it was implanted near the region generating the dexterous movements of the right hand. Left-handed people have, in fact, the Broca center on the opposite side of the brain.

Once acquired, language evolves in terms of aiding survivability. However, the current hypothesis among anthropologists that language helped organize the bands of hunters and coordinate them during the attack seems weak. Packs of hunting dogs beautifully coordinate their behavior when searching and attacking. Sophisticated language appears unnecessary. Incidentally, it is too slow, so much that in armies talk is shortened almost to monosyllables. As the Romans said; *"Imperatoria brevitas."* Orders must be short. Moreover, animals have syntactic thought; they can switch their behavior according to what others do.

An alternate proposal about the development of language is that Australopithecus females chose elaborated sound to boost the effect of grooming the dominant males. Certainly 95 percent of modern talk is centered on the affairs of neighbors. It is not improper to project back in terms of functions. Naming the members of the group greatly helped the gesticulations which mimicked their behavior. It also helped the visualization of the group. With language, groups can become three to four times larger. Hunter-gatherer bands are not larger than about 100 individuals, like the invisible colleges of scientific researchers, or family enterprises. Everybody knows everybody personally and information flows mainly through nonverbal channels. *The Stone Age haunts us all the time*.

The development of language to Shakespearean finesse must have been an evolutionary branching on an already well-developed stump, as in the case of the hand. In evolutionary terms, the success of language holds much of the capacity to make a set of brains work in parallel. Next to the gossip still dominant today, the most important subject could have been knowledge and planning. The two operations can become very complex and consequently require more sophisticated instruments, like a certain precision in the definition of objects and the explication of the rules of logic. Science restates these principles when solid foundations are in demand.

I would take away *logic* from the mythical position of the judge of truths. Gödel showed the black holes of logic systems. In the Darwinian context, logic can be classified as *a preselection filter statistically efficient* to identify causal hierarchies having *high probability of matching experimental results*. Gödel's theorem means that the set of tautologies created using axioms and logic does not exhaust the total set of tautologies. This means that I can find tautologies that logic cannot prove.

Gödel castrates authoritatively the immanent idea that logic can divinely penetrate all latebrae of "truth," and firms my hypothesis that *logic* is a "hint tool" or, more precisely, a *"preselector."* In nature, preselecting filters are used with a statistical eye to their hypothetical nature, meaning that a certain amount of short-circuiting is allowed to keep the experiments in feasible limits but to allow in some oddballs. For reasons the preselector does not know, these oddballs, at acceptable cost if with small probability, can lead to new successful avenues. For biological systems working with large numbers over very long periods of time, low probabilities can be very important.

Language is the store of our knowledge about the external world, and the modeling thereof, and is thus central to science. Mathematical equations can be deconvoluted into a linguistic description, though often long. I see the equations as shorthand. They belong to language, even if formulated with constraints much stricter than usual. Incidentally, if we suppress the spacings, written language is strongly reminiscent of the aperiodic crystal describing DNA in Schrödinger's image. Spoken language keeps society organized in much the way DNA keeps order in the biological realm. A hint of the equivalence comes from the fact that the mathematics describing the behavior of biological systems, mostly contained in the Volterra-Lotka equations, mirrors perfectly the behavior of social systems at all hierarchical levels, as extensive analyses have shown.

In science, which in our Western ideology is the main source of knowledge, the basic social workings of bands of hunter-gatherers emerge again. This matters in delineating the limits of knowledge, because some of the limits may come simply from the operations of this social mechanism. Basically a line of research starts from a certain observation, like a bee discovering a flowering tree and reporting back to the beehive. The rush, measured by the cumulative articles on the very special subject, is perfectly described by a logistic equation, which also describes perfectly the growth of a new branch in a tree. The time required for the development of a branch of scientific research is typically about ten years. Science penetrates into the big block of ignorance as the roots of a tree in the soil, branching and branching again, *but* leaving large parts of the soil unexplored. This somewhat arbitrary penetration is what I called earlier the "thermochemical cycle effect."

The social system may also operate at broader levels. As the brain manipulates inputs to produce effects that may finally be beneficial but certainly break our definitions of objectivity, so does society. Medievalist Lynn White dealt skillfully with the quintessential importance of social attitudes in defining the limits to knowledge. In the year 1025, a nova star appeared in the Northern skies so brilliant that it could be seen during the day, but no record is left in Europe. Patient search unveiled a script from a monk in Switzerland who had the task of writing of the ephemeris and noted the strange appearance. Because the heavens *had to be* immutable, the prior of the monastery erased the note. Respectable scientists refused to look into Galileo's famous telescope to see personally that the moon had mountains, arguing that if Aristotle had not mentioned the fact, it was not worth looking. The social system, *by social consensus*, can decide to break to pieces the devilish telescope that started it all and burn the rest. Long before the stopping of the supercollider, *it has been done explicitly* by the Moslem on the verge of the first millennium, stopping abruptly the brilliant career of Islamic science and technology.

The drive to know and the ability to observe and discover are grounded on cultural premises, defining basically the position of the social *in* toward the *out*. It is extraordinary (I am flashing figures to give the orders of magnitude) that Jewish scientists pick 50 times more Nobel Prizes than their non-Jewish counterparts in proportion, and that Japanese scientists 50 times fewer. The formal preparation and personal wit of scientists from different cultures do not seem very different, but, making the big jump unaided into the virgin forest of the unknown, one has to make an act of faith, and the subjacent religion defines the level of daring. Modern science and technology have Judeo-Christian roots.

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ON AESTHETICS AS A PRESELECTOR

Aesthetics, *prima facie*, evolved as a mechanism to select a reproductively efficient partner. It is natural to speculate if, like the hand holding the branch or picking the fruit, particular skill developed later on this original stump. Extensive observations and experimentation have shown a consistent pattern in the behavior of mating of vertebrates (and insects). The female chooses the male with whom she will mate. Males try anything conceivable to sway the decision in their favor. They show strength with interminable and sometimes ferocious fights with competitors. Stags and walruses show precise muscular control and sensory fitness with dances and gymnastic exploits. Male birds, such as the black grouse, will expose themselves in the limelight of the *lek* to an audience of chuckling female connoisseurs. Male fruitflies tiptoe around the female, "sing" with one wing like a gypsy violinist, and tap her foot gently like a meek Don Giovanni, praying she does not fly away.

Selection being pitiless and survival the only real intrinsic objective of living creatures (or selfish genes), the whole circus obviously aims at producing efficient offspring. This capacity to carry the Olympic flame of life (i.e., that particular message) into the next generation is the quintessence of *inclusive fitness*. The game is extremely subtle. The females did not read Darwin, nor did they study physics, but their offspring *must* be able to fit competitively into an extremely complex *physical context*. The only sensible conclusion to me is that *Darwin and physics are incorporated in the criteria of choice of the females, the aesthetic "preselector."* This is a tall order, because the criteria cannot be too complicated, nor can they be written in the false simplicity of general relativity equations.

Our rash anthropocentrism relegates the *aesthetic* sense to humans. But male birds-of-paradise are the final product of aesthetic choices of their females. Their elegance, the silky finesse of their feathers, the way they fall, and the subtle intermingling of soft nuances of color are flabbergasting to us. No artist could conceive such a bird, nor could any stylist dress it. Female birds-of-paradise have a magic eye. This statement says something important: *I understand, appreciate, and enjoy what the she-paradise birds have in a sense created*. This means a coincidence of the aesthetic sense of a bird with that of a human, if in a limited context.

Some years ago, I pondered why all attempts at putting mathematics into the box of logic have floundered. There was always a poltergeist saluting from a window in the box. I arrived at the solution by observing that the problem is insoluble set in the classical form (e.g., of Italian mathematician and logician Giuseppe Peano). How things really work can best be appreciated by observing mathematicians in their creative act. They do not search for propositions that only meet the rules of the game, that *fit the axioms and respect the logic*. This normally produces tautologies that mathematicians dub *trivial*. Computers can easily be programmed to produce such sludge.

What the mathematician really searches for are *important* theorems. In terms of logic and axioms, a theorem can be only *right or wrong,* and the grid of tautologies one can logically create is absolutely dull. When we ask mathematicians how they made their choices, inevitably they describe the process as an *aesthetic orgy,* just like a she-paradise chuckling at a new set of moiré patterns in the feathers of the exhibiting male. The bird fights for life and death of its genes, and the mathematician, if successful, draws presumably from a fat tenure. How can their behavior be so parallel?

My guess is that mathematicians use their modeling powers to simulate the battle of life. This is done all the time in the animal realm. The young, especially, *play* interminable simulated battles with wooden swords, so to speak. And *dream* of them, as every owner of hunting dogs knows well. The game mathematicians play is to apply *real-life selection rules* to a set of characters they have artificially created. Animals, or at least the mammals and birds with whom I am familiar, currently use this *Abbildungskraft* to create various pathways of action, choose one, and implement it.

When the mathematician turns natural philosopher and tries to use pet theorems to organize observations of the external world, (s)he discovers in rapture that they work. They "contain" the results of many more observations than those used to select the match. Einstein's exclamation, that the most incomprehensible thing in the world is that we can comprehend it, can find here its *trivial* interpretation. The wing produced by transcoding genetic information can fly, just because that genetic information has been selected and encoded through sequences of wings that could fly, better and better.

Finding new tricks for old dogs is a common feature in the evolutionary lines. Hands are appendixes that evolved and specialized in our arboreal cousins, the right one providing a sure power clutch, and the left moving in space, nimbly and precisely, to reach and retrieve the fruit. It looks like a Pindaric jump to see precisely these skills, acquired in millions of years of arboreal competition and selection, operating in terms of a Menuhin power-clutching the bow and nimbly pressing the strings of a violin. The jump is only in time. The mechanisms are exactly the same.

In the context of the present exploration, one may ask not only what is the contribution of aesthetics to acquisition of knowledge in terms of appropriate models (i.e., the mathematical ones), but also what are the limits that it inevitably brings? A male bird-of-paradise dressed in black like an undertaker could well be the superwinner in the struggle for *his* life, but he will be a loser in reproduction and his "message" would be lost. In favor of females, animal and human, one should say that some of them have an eye for the oddball and can spare a *Seitensprung*. Consequently, oddball genes are not necessarily thrown away in the first go as dimly implied in the previous sentence. To provide diverse solutions to engineering problems, the Lockheed Corporation had its skunk works.

Aesthetics provide a holistic filter strongly remembering the minimum principles of variational calculus. The fact that a ray of light going from A to B, *whatever the complexity of the interposed optical system*, always "chooses" the fastest (not the shortest) path, has always been a source of (aesthetic) fascination to me as a physicist. General relativity equations have been filtered twice, by the mathematician who invented them and by Einstein, who keyed them in the appropriate lock. Their consequences are anti-intuitive, and their inputs from data were slim, so they cannot be constructed assembling grains of sand into sandcastles. They must come from a dark memory built in a billion years of experimenting life. Similarly for de Broglie's electron equations, which came up as a sort of mental quirk, if we believe the French physicist's story.

Without the *aesthetic trap,* such outlandish and improbable configurations would never have landed in the web of our modeling of the external world. The discoverers themselves were flabbergasted in finding in them a cornucopia they never put there. Thermodynamics, originally concocted to try to improve little puffing steam engines, starts looking now like an eternal beauty, miraculously unscratched for more than a century, and smoothly dealing with giant black holes, neutron stars, *novae*, Cheshire cats, and gluons, always telling right from wrong, possible from impossible. Its hypersharp edge has never become blunt.

Also remarkable is the vertical homogeneity of aesthetic criteria along lines evolutionarily very far apart. Flowers usually appear beautiful to humans. None of them has evolved to please us. They interact with their pollinators, evolutionarily adding and taking away to adjust to their taste. The result means that insects, *in their tiny heads*, harbor aesthetic criteria very similar to ours. This is not difficult to understand, as the world in which flies and humans operate is the same, but it leads to two conclusions: (1) the coding of these criteria must be relatively simple and (2) the criteria must be unique, because evolution tends to converge toward similar configurations. These conclusions will be of enormous use, as we try to teach our computers to make mathematics.

Holistic checks, including the aesthetic one, obviously offer great selective advantages. They provide evolutionary shortcuts by discarding unpromising "messages" before expensively testing them in the field. About 80 percent of fertilized ova in human females are naturally aborted. It appears that most of these carry some genetic defect. The quality control appears efficient, but its working is obscure. Many traits of behavior imply holistic perceptions. Tadpoles band according to their genetics and recognize if they are brothers. A single mutation in the very long DNA string can be perceived by smelling, so to speak, the counterpart.

Aesthetic quality checks can be located in the nervous system the way a sperm operates. Selection by the eggs is inevitably chemical. We may then expect to have a hierarchical set of "aesthetic" centers all helping to shorten the path to the "truth," by checking for constraints that truth should possess. *Logic may appear as one of them.* Like almost everything in biology, the value of such black boxes can only be statistical. Their objective is to reduce the probability of entering a cul de sac. But a certain leakage can be inevitable or perhaps finally useful. She-birds mating with occasional male oddballs make a risky investment that might be very good (e.g., branching a species into a new one). A genetically defective embryo (e.g., in terms of myosin production) may also produce an individual with a spectacular brain capacity. The services of logic in weeding out improbable cause-effect relationships overcompensate for Gödel's black holes. DNA produces powerful enzymes to correct damage to its structure. Yet, this capacity is never exploited to its end, to allow some oddball filtering into the test bed.

CONCLUSIONS

Every living thing has or is a machinery for learning, remembering, and forecasting. The objective is to provide anticipatory reactions to the interactions with the external world. For very simple organisms, the machinery concentrating all the functions centers on DNA or RNA. The procedures are usually encoded in proteins produced inboard or sometimes outboard (e.g., for viruses). DNA is an active memory that learns through hypothesis (mutation in a broad sense) and experiment (survival value of the mutated offspring).

Mutation in a broad sense refers to changes that may come not only through the point mutations at the center of the biologists' interest until a few years ago, but also through reorganization of the DNA strings by spatial or regulatory rearrangements. Furthermore, the great homogeneity of the basic mechanism in living things makes it possible, in principle *and* in fact, to swap strings of DNA or RNA between individuals and species, *making the biosphere an immensely complex information bazaar.*

At the most basic level, DNA or RNA do not necessarily have any sort of perception of the *out*. The only link to the external world can be the *survival feedback*. This is a brutal, low-yield matching process requiring quintillions of experiments to obtain any progress. The extreme free-energy parsimony of DNA operations makes that possible. The parsimony comes both from the miniaturization (DNA or RNA are single molecules, if longish) and from intrinsic efficiency. DNA multiplication operates near thermodynamic reversibility. On the other hand, chemical-free energy sources in the Earth's crust, measured with the yardstick of DNA mechanisms, are immense. In the ~200°C interval where biochemistry can work, they all appear to have been exploited. *Life is everywhere.* And because the trial-and-error procedure has gone on for billions of years, the organisms are splendidly adapted to their context, and *very complex* even in the most elementary forms.

Because learning is based on death and survival—but especially death —efficient reproduction of the message is at the center of the game. In the most elementary forms of life, most of the free-energy flux is devoted to the multiplication of DNA and ancillary structures. To survive, even DNA length can be reduced by selection. Some viruses actually resorted to the extraordinary trick of multiple significant messages written on the same strip of RNA and readable by a shift of the *start* position. Also the size of the ancillary machinery can be drastically condensed. Nanobacteria recently discovered in the depth of the Earth's crust are a thousand times smaller than the bacteria that Pasteur first saw.

At the ground level, the biosphere thus has quintillions of stochastic experimenters that bet their life for new knowledge. *New knowledge may be defined as new schemes that work.* Most of biochemistry has presumably been invented this way by bacteria. They remodeled the chemical structure of the Earth's crust. Through a number of mechanisms, this knowledge diffuses upward to more sophisticated living objects. The fact that oxygen respiration is mediated by *mitochondria*, symbiotic organisms present in all cells of metabionta, including humans, is well-known (if recently) and amply debated. In parallel we have the *chloroplasts*, operating the synthetic machinery of plants and generating perhaps the most important flux of *chemical-free energy into the biosphere.*

The bacterial influence, however, must be much more articulated. Cones and rods in our visual system, and in that of all animals endowed with vision, are most probably endosymbiontic photobacteria. Nanobacteria in the Earth's crust extract oxygen from ferric oxides and reduce them to ferrous compounds of magnetites. Many animals, from birds to humans, have grains of magnetite connected to their nervous system to improve orientation inside the Earth's magnetic field. Presumably the chemistry has been genetically imported from nanobacteria. Perhaps they are in the flesh, sitting invisible and manufacturing for the host. (How are the magnetite-teeth seashells that are used to graze stones fabricated?)

From time to time, mathematicians have gone into biological thinking, showing—usually in a very crude way—that living things are statistically so improbable as to be impossible. Our quintillions of blind experiments are certainly an impressive workforce, but actually their blindness is not so complete. Any system of checks that *puts a weight on the probability* of success in terms of survival, of a certain DNA message, would be of extreme value, because it saves the expense of improbable experiments. Consequently, if it appears somewhere, even in a rudimentary form, it is bound to be fixed and start evolving into more sophisticated expressions.

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These *preselectors*, which break the naïve estimates of the mathematicians, seem to be present everywhere and at every level that has been explored in this sense. To give an example, I identified *aesthetics* in the reproduction of sexuated animals as a *preselector*. This view casts the suspicion that sexuated plants must have preselectors of some kind, and it has recently been discovered that the stamen can receive many grains of pollen, and that the egg checks in some way their DNA quality and selects one. The natural abortion of fertilized eggs, most showing DNA defects, also shows that preselection probably operates every time an *in* has to make choices about the *out*. Sexual reproduction provides preselectors in series, and this could be the reason of its fixation in many disparate contexts.

Preselection, being quintessential in reducing needed experiments (i.e., in saving lives), must have appeared very early in evolution. It should be present in the living things nearest to this stage—archaeobacteria, nanobacteria, and viruses. Preselection is also present in the most advanced learning system—our verbal culture, operated by a network of human brains. The most important *preselectors* I have identified are *aesthetics*, promoted from sexual selection to plausibility selection for mental models (after all, both must face the same external world) and logic, which is concerned with the plausibility of causal connections. Curiously, these are the prime motors of mathematics, the most human product of primate brains, and the most powerful instrument to articulate models for the external world.

Making another step in the same direction, computers up to now have been used basically to speed up complicated computing operations. Having memory and data elaboration capacity, they can be dressed as learning machines. Their *out* could be concocted, meaning they have to learn to produce anticipatory models in relation to a preset environment. For example, they could be set to find efficient criteria (models) to detect primes. Their *out* can also be the real world, *mediated through sensors*, and they could *explore it through experiments*. In this case they would begin to make science. They would need a *combinatorial software* producing new configurations matching the observation at hand, plus the *preselectors* to weed out the implausible ones. The question is whether these computers could only expand the knowable, operating faster and cheaper than human minds (plus the expensive attached human bodies nursing them) or also enter into the unknowable.

The answer is in part linked to definitions. If, with Rolf Landauer, we accept as knowledge only what can be *reached* with a procedure finite in time, then computers can sound the unknowable (something human minds could reach but only with 10^{10} years of calculations. I would, however, make a certain distinction between such knowledge, which I would define as *beyond reach,* and knowledge quintessentially more isolated, which I would define as *beyond grasp*. Because our models require an input and provide an output to be matched to another input, worlds that are isolated in the sense that no signal can go in or come out are unknowable *beyond grasp*.

Preselectors are a typical gadget that reduces the time to grasp, not by doing things faster, like the computer, but by playing on *probability* criteria. Due to their probabilistic nature, however, preselectors may leave out a good combination (e.g., one lying in areas of inaccessibility to the logic preselector). Occasional wild experiments may pay. The Athenians, in the same spirit perhaps, had a temple outside the city to the unknown god. The logic of their highly articulated theogony could well have missed something important. Conceptually, it could be seen as a temple to Gödel.

In a nutshell, *modeling cannot go beyond observation*. Most breakthroughs in science follow breakthroughs in the precision of the measurements or in the discovery of new information carriers. But at a point we start observing that the world is granular and quantum theory defines how precise measurements can be. This does not change the definition of *reach* or *grasp*, because the limits appear intrinsic to the *out*. Incidentally, the sensory systems of animals stopped evolving at the quantum limits. DNA knew long before Erwin Schrödinger.

Cells contain thousands of different kinds of molecules that can react selectively with one another and produce "cycles," powered as usual by ATP. Many of these cycles are used for information processing, and most of the *functions* of our brains are already present in single cells. Their behavior, in fact, in reaction to external change, is complex and articulated. Cells have internal channels and membranes that limit the informational chatter between them. But connections are mostly limited by chemical, electrical, and stereotactic hindrances.

The mechanisms can then be well-described by ISDN concepts where *addressed* information packages (the molecules) navigate into a *common carrier* (the cell fluids) trying to reach their "address." Moving across a cell by *diffusion,* a small molecule may need 0.1 seconds, which sets an order of magnitude for the period of the computer's clock. Incidentally, the frequency of our brain clock, as exemplified by alpha waves, is about 12 cycles/second, just in this time range. Consequently, to get to complex matters fast, if slow computing neurons sit at the nodes, the *brain's architecture has to resort to massive parallel computing*. This has recently been visually expressed by looking through magnetic resonance and positron emission at the activation of brain "subroutine" centers when processing, for example, words or images.

Coming back to our cells, neurons taken one-by-one can compute internally, like any cell. The gist of the brain is that these small computers can input-output to other computer cells to which they are linked with *fast transmission lines*, the *axons*, which operate on the fast propagation of an unstable flip-flop, chemo-electric state. The *axons*, which permit speedy vertical and parallel organization of the neurons, presumably developed in order to coordinate muscle action in relatively large macrobionts. Plants do not move and do not have axons. For moving macrobionts, speed in mechanical reactions is of obvious survival advantage, both in attack and in escape.

Coming back to the cell (and to the neurons), the "circuits" operating inside can be numbered in the thousands and take care of the information that reaches the surface membrane to produce internal and external reactions. To give an example, flagellates, which turn their flagellae with tiny electric motors (reversible), regulate the speeds of rotation in order to penetrate into gradients of nourishing materials, measured by the sensors. They also have a stochastic "clock" that induces a brief reversal of the motors that make them wobble. Then, they start the exploration in a new direction.

The *number of neurons in a human brain* is estimated to be in the *range of* 10^{13}. Each of them is a small computer, operating a few thousand circuits, with external "gates" controlling their functioning. The gates are chemical. The inducer spreads relatively slowly in the brain and, in a sense, produces moods. The best-known are endorphins. Plants produce simulators, like morphine and cocaine, to disrupt brain functioning of their parasites. Usually neurons receive impulses from a number of other neurons and elaborate them into an outgoing impulse moving to another set of neurons.

At this point we can comment on the possibility that computer systems can extend the barriers of human knowledge. From the point of view of the architecture, the brain seems to have exploited all possibilities known today. Neurons are organized in blocks representing subroutines. The blocks operate in series and parallel. For example, the signals coming from the retina of a bird in flight go to a number of blocks, one analyzing shape, another color, another movement, etc., until the results, well mixed, tell the block operating the models (consciousness?) that it is a seagull, male, holding a fish, and moving against the wind.

On top of that, via language, the whole brain can go into parallel operation, divided into blocks operating as different subroutines, making science A, B, and C, organizing a cafeteria, or running a football match. External memories are provided, using paper, electronics, and occasionally stone. These memories can be decoded long after the encoding system has passed away.

The only new thing *computer* can provide is *speed*. In this sense I do not see computers capable of extending into the *unreachable*, but certainly into the *ungraspable*. Even without going to the extreme purity of the Landauer position, where a reasoning to the limit is not legal because it has to be calculated (calculable) in real terms down to the last operation and not given to repetitious algorithms, many operations become suddenly possible and practical (e.g., numerical solutions for differential equations).

Due to their speed (their clocks may have frequencies 10^{12} times higher than those of the brain) and almost unfailing operation, computers are progressively taking up human brain functions. They run the books of the banks and operate machine tools. They have started translating languages, if stumbling here and there. Will they keep climbing to more sophisticated brain operations?

In think yes, and give a precise example. Many years ago, trying to unlock the deep meaning of beauty, or more precisely its function in a Darwinian context, I came to the conclusion, referred to earlier, that mathematics cannot be reduced to logic because mathematicians currently discard as *trivial* theorems that are logically perfect. So on top of axioms and logic, mathematicians introduce a selection machine (*the preselector*) that, when asked, they define as aesthetic. According to my analysis, aesthetics in Darwinian terms is an algorithm for organisms endowed with sexual reproduction for choosing an appropriate mate in view of an efficient progeny.

This choice, whose results project into the future and into a physical world, must be soaked with physics and, in my opinion, it is. Einstein marveled why mathematics is so supremely efficient in encoding physical laws. The Darwinian answer is simply that the *preselectors* had to be matched to them. That said, aesthetic choices being born out of subroutines in our brains, it may be possible to identify and explicitate them in computer format. Once done, computers can start competing with human mathematicians. Given *logic* and *axioms*, the machine might produce, in ten minutes, Euclid's *Elements* and print them with a frontispiece *laudatio* to IBM. In a similar way, computers may start to make physics or any other sort of science, because finally everything reduces to finding rules into a set of "sensory" measurements about the external world.

Computers can obviously have a "conscience," like HAL in *2001: A Space Odyssey*, if they have sensors supervising their operation and can model the external world including themselves as separate, if meshed, entities. The 10^{13} tiny PCs in our brains do not compete head-on, because most of them are bound to firmware that has specialized roles (e.g., in running the physiology of the human machine). I have no idea of the complexity and speed necessary to simulate *aesthetic* choices.

The two basic mechanisms to provide models are, as said, the *sensors* and the *elaborators of sensory signals*. In biological evolution, sensors developed down to quantum limits in olfaction and probably in touch. The new machines can only try to compete for olfaction. Touch made a quantum jump with the tunneling electron microscope, where single atoms can be contacted. Here it is unclear whether living things can compete; nobody seems to have looked. Tiny cells wobbling in Brownian movements have perhaps some measure for molecular hits.

In the acoustic area, quantum limits have again been reached. The problem of receiving high-frequency signals with low-frequency electronics has been solved using mechanical resonators whose state of activity reveals the presence of the signal. A similar solution was struck in the eyes, where rods are sort of optical waveguides with an on-off signaling to the nervous system. The high frequencies on the electromagnetic spectrum are not in the sensory system, presumably because these tricks did not work for geometric reasons, X-rays requiring resonators extremely small and microwaves excessively large. And neither was present in sufficient amount to start. In the case of acoustics, sperm whales developed sensors for long waves, useful for long-range communication in the ocean, by using their whole heads, filled with appropriate fluids, as antennae. Electric fishes, in spite of their incredible sophistication in extracting information from electric signals, never went beyond the low frequencies that their nerve cells could manipulate.

These basic frequencies can be raised by reducing the size of the neuron cell, because they are defined by chemical diffusion times. So, there is striving for miniaturization. A fly has 10^{6} neurons compacted in one cubic millimeter and can easily defy, through speed and specialization, our 10^{13} neurons brain.

Apart from speed, sensors and elaborators are bound to the mechanisms to build them and to the somehow fragile materials that biology can concoct. With organic materials, it is not possible to produce very intense and extensive magnetic fields. Consequently magnetic resonance perception could never develop, even if the sensory system could have done something. Animals, humans, and even mud bacteria are endowed with tiny magnetite crystals that permit a sensing of magnetic fields, mostly unconscious, down to small fractions of the Earth's field, to use for orientation. The compass is not a new invention, but a *prise de conscience*. Whales can memorize magnetic maps, as humans do with optical maps, and navigate into the real thing. In the case of magnetic resonance, our machines broke the electric current limit, and the computers came in for the fast and complex elaboration of the signals, to simulate an image, *as if* we were looking *optically* into, for example, a brain.

Knowledge coming from radar, magnetic resonance, and X-rays could be classified as *unattainable*, because all biological constructs we could imagine could not *reach* the conditions necessary to construct the appropriate machinery which is *outside any conceivable biological evolutionary map*. Extrapolations using all conceivable maps do not provide the quantum jump that came with the *external tool and machine*, a basically new invention by DNA, entering into a new dimension of evolutionary maps.

The main breakthroughs can be reduced to materials that made new architectures and new functions possible and to fitness criteria, vastly removed from those of living things. A large telescope invents nothing in basic principles, as certain crabs are endowed even with reflecting telescopes, but plays on size, linked to materials and to an objective: looking into the sky to a distance of 10^{10} light years, which bears little significance to the inclusive fitness of any living individual or species. Evolutionary forces seem to run amok, out of Darwinian guidelines, even if the process might be rewritten using Darwinian logic.

In a nutshell, the sensory system and the computing system can still expand, as new things to be sensed may appear, and the appropriate mechanical interfaces may be invented. This repeats the logo of the materialist philosophy: Nothing is in the mind if not first in the senses. Appropriate modeling may give the contrary feeling, the logo of idealist philosophy: Nothing is in the senses if not first in the mind. Biology permits a nice compromise between the two points of view, through a feedback system that makes internal "models" equivalent, to a point, to external "facts" *adaequatio intellectus ad rem*. Mathematics then can be "true" when applied firsthand to the external world, although it has been secreted by our brains, and theology or philosophy can provide efficient guidelines to make our lives self-consistent and fit the external world. Positivist points of view did not take that into account.

Thus, the expansion of the knowable is basically linked to the improvement in sensitivity of the present carriers of information from the *out* to the *in*, and also to the discovery of new ones. Neutrinos are almost invented. Particle physics have unearthed a bunch of them. Perhaps the plus-minus particle continuum that seems to fill every niche of space can still hold surprises. Biological systems do not always develop in terms of better inclusive fitness. Most of the time, they coast on *corniches* of constant fitness, *genetic drift*. The extra configurations they gain at almost zero cost may become very useful if the geography of fitness is changed abruptly. Perhaps science is a form of *genetic drift* in our cultures and can enter again into a Darwinian logic. Society, however, still holds the keys and can stop the shifting.

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