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Complexity and future

Hardly I have the stone
"stone" called,
and behind it,
transparent, ghostly,
like its bright shadow,
a second stone appears,
lighter
and easy to be taken
for the other one.

I pick it up,
I rest on it,
I throw it away.
It belongs to me,
It cannot fight back.
With my stone
I do what I want.

But it weighs nothing.
Heavy is the other,
the first one,
which does not listen to me,
which has no name,
which strikes me.[1]

This beautiful poem by the german poet Hans Magnus Enzensberger is well suited to introduce my paper. In fact, it helps me to stress the difference between any object and our image of it. This image may be made of words, may be a name: “stone”. Or it may be a visual image, together with a number of attributes: its colour, its dimensions, its relation with other stones and with the world… But it can also be a dynamical image: for instance, a forecast of its path when the stone is coming threateningly to strike me.

Let us now consider a less threatening situation, and replace the stone with a tennis ball. A tennis player who serves anticipates the future, creates a “shadow” of the ball, develops a winning anticipation of the serve gestures and of the following motion of the ball. In a sense, she forecasts the future and understands what in her behaviour will build a beautiful ace. Taking into account a lot of variables, as the surface of the court, the force of the wind, the characteristics of his opponent, and so on. There is a true complexity behind a serve!

How this wonderful coordination develops between mind and body, which leads not only to forecast but also to determine the future? How, to paraphrase Enzensberger, is born that "second" ball, that "light shadow" that orients the winning serve, that implicit model to foresee and orient the future? It is born from a mixture of implicit knowledge, even body knowledge, and explicit knowledge (in particular, knowledge of physics:

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[1] - H.M.Enzensberger, *Semantik* (*Semantics*). My translation.

elasticity of the ball and of the strings of the racket, characteristics of the tennis court, etc.).

In the mind of the player, the "shadow" of the tennis ball has already flown over the net, has already touched the ground and has rebounded. Only after being thrown, the other ball, the heavy one, the one that "can fight back", will follow, or will not follow, the same path.

In a different situation, which does not involve mind-body coordination, for example in the launch of a space shuttle, what will be the "shadow" - so to speak - of the spacecraft? Obviously, another type of "shadow" is here required: a completely explicit model of the problem. The quantitative variables of the problem (the weight and the shape of the shuttle, the characteristics of the rocket engine, the altitude to be reached, the air resistance, etc.) must be identified and their relations expressed through differential equations: by means of the mathematics that scientists, especially during the last four centuries, have devised for this purpose. A “virtual world” must then be built:

$dx_i/dt = fi\ (x_1, x_2, ,,, x_n)$ i= 1, 2, ... n.

We can do what we want of this virtual world, Enzensberger told us. This means that we can study the behaviour of the space shuttle under different conditions and determine the values of the control variables in order to obtain the desired result. This explicit mathematical model can thus help us to build the future of the shuttle.

Mathematical models are based on scientific knowledge. But sometimes science, in its effort to simplify situations, to eliminate perturbations, to study the effect of a cause at a time, can give the illusory idea that the world is simple: in particular, that small causes always have small effects, that there is a systematic proportionality between causes and effects. But this is not always the case.

Let us go back to tennis. As the competition goes on, every time the ball is hit there is a thought behind it: an implicit thought, but a thought aware of the complexity of the situation. Now suppose the ball touches the net. Then a new situation takes place. Suddenly, in fact, a more detailed level of aggregation comes into play. Up to this point, the motion of the ball could be approximated as that of a material point. Suddenly, its coating, as well as the tape of the net and the detail of their interaction become important. The ball-net interaction depends on the position and the speed of the ball when it touches the net, but in turn it is able to modify them, in a feedback relation. Moreover, an extremely non-linear future becomes possible: a “bifurcation”. The ball, in fact, can end up on one side or the other of the net due to very small differences in the serve. So, in this case, we have different levels in relation the one with the other (that of the ball as a material point and the one, more detailed, of the interaction of its coating with the tape), we have a non-linearity between causes and effects (a small cause can lead to a big difference), we have bifurcations, we have unpredictability: we have, in short, complexity.

In negative terms, it can be said that a system is complex when it cannot be explained by simple causality. Not only natural systems but also human systems, and systems in which the relationship between man and nature is important, are complex systems. Development of economies, climate changes, evolution of cities, implications of genetic engineering are complex realities that can not be reduced to simple explanations and perspectives.

Simple explanations make sense for simple situations, but do not adapt to complex systems, which require a complex approach. This implies, as I said, the construction of a "virtual world", of a "shadow" world (as defined by Enzensberger): a world populated by mathematical objects, a world in which the variables are connected in a non-linear, even circular way, and are organized in different levels. A virtual world that is built to simulate the other world, that of the "heavy" reality.

In this way, the scientific approach helps to imagine the future, to identify possible interventions, to face future uncertainties with greater awareness and involvement. The scientific approach can become a methodological kit of every citizen of the world facing the complexity of the systems and problems of the planet. At the same time, the contents of the various scientific disciplines also acquire a new interest, because they provide, so to speak, the bricks for projects aimed at conceiving the future of climate, nanosciences, artificial intelligence and so on. The disciplines (mathematics, physics, chemistry, sciences) take on a new sense, which for students is perhaps easier to understand and more motivating than the one, which they usually meet, of an ordered and abstract set of knowledge.

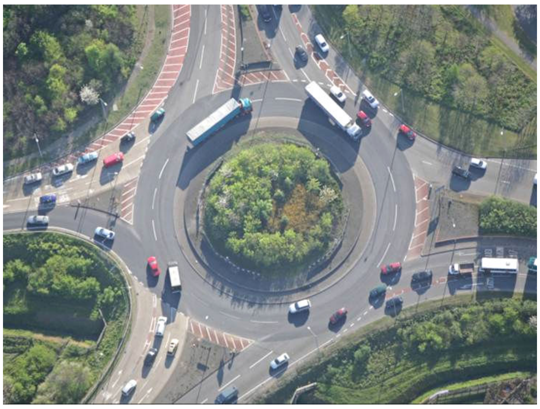
So, the future no longer is simply to be forecast or suffered, but rather to be desired and prepared.

Let me make a quick reference to the problem of climate change. Significant variables are many, and often they are interconnected in a non-intuitive way. Think for example of the non-linear relationship that links the temperature rise and the melting of glaciers. Here the temperature increase not only melts the glaciers, but makes them darker, and therefore more absorbent, so the melting is faster and faster.

Building a model of a complex system requires identifying the variables, defining their relationships, studying the future effects (possible, probable, desirable, achievable) - on different time scales - of the actions on one or more variables available to the different planetary actors. This leads to complex models of complex situations, which only the use of computers allows to use at best for simulation.

Many complex systems are composed of a large number of similar elements in a dynamic relationship between them. This leads to the rise of unpredictable collective behaviours at the level of the elements: "emergencies", "self-organizations" created from the dynamics of interaction and that feed back on it.

These self-organizations have a paradoxical characteristic: the system as a whole, in fact, is "more" than the sum of its constituent parts, precisely because at its level a self-organization emerges, but it is also "less" than this sum, because it only shows a particular organization among the many possible, repressing and channeling the potentialities of its elements.



Let me give a daily example, to indicate how complexity is pervasive. Cars at a traffic light are a simple system. Instead, cars at a roundabout give rise to a complex system. In fact, its dynamics cannot be forecast, because it arises from the behaviour of individual drivers, while feeding back on them.

Let us also think of a flock of birds, of its extraordinary and changing forms. This surprising reality also enchanted Mr. Palomar, the character created by the great italian writer Italo Calvino.

> In the purple air of sunset, Mr. Palomar watches a tiny dust, a cloud of flying wings, which emerge from one side of the sky. He realizes that there are thousands and thousands of them: the dome of the sky is invaded. What so far seemed to him a quiet and empty immensity has revealed itself to be covered by very rapid and light presences. [...] The thickening and thinning of the birds is a sort of long zigzag waving ribbon. Where this ribbon curves, the flock appears thicker, like a swarm of bees; where instead it stretches without twisting there is only a punctuation of dispersed flights.[2]

This self-organization is not prescribed from the outside, but rises at a higher level than that of the individual birds. It is not foreseeable by them, but conditions them: as I said before, it conditions. almost paradoxically, the individuals who contribute to form it.

How can we study a complex system like this one? In principle, perhaps, writing a system of differential equations. But the elements are too many, the interconnections are too many. This approach cannot therefore be followed.

To simulate a complex system of this kind, we can start from the observation that the emerging order originates from activities, even simple ones, of information processing by single individuals.

Scholars at the highest level (I mention only one of them: Giorgio Parisi, one of the most authoritative theoretical physicists in the world) have studied for a long time the behaviour of flocks and that of individual birds, and have come to the unexpected conclusion that the complexity of the flock is born from rather simple behaviours of individuals. Each of them keeps an eye on a limited number of other birds (7, 8, no more), controls the distance between them (approaching if it is too far or going away if it is too close) and adapts its speed to that of the others. The change of course is decided by just a few birds, and the information spreads within the flock at a high speed, of several tens of meters per second. Even the so-called “terror wave” following the attack by a predator spreads at a great speed.

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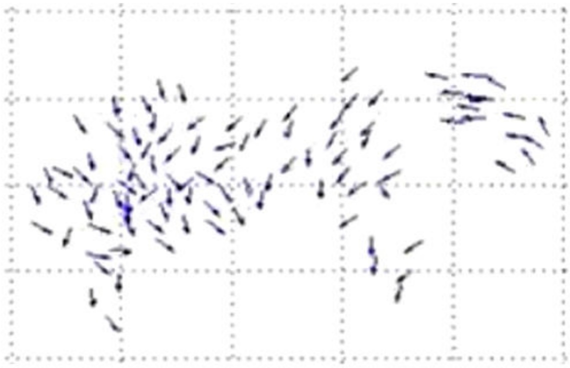
[2] I.Calvino, *L’invasione degli storni*, in *Romanzi e racconti*, Mondadori, Milano, 1991, vol. 2, p. 929. My translation.

Starting from these observations, it is possible to build computer simulation models. And the behaviour of these virtual worlds is very similar to that observed in the sky of Rome.



Morphogenesis, i.e. the development of living organisms starting from a fertilized cell, is an extraordinary manifestation of self-organization, which develops through a never ending information processing by molecules.

Also animal societies, and not just their temporary aggregations in flocks or herds, can be seen as self-organizations. Consider for example the apparently random and disorganized behaviour of a multitude of ants carrying twigs or seeds. Without any project, from these random activities self-organizations "emerge": huge pyramids are built or new paths toward the nest that bypass obstacles are found.

The computer simulation allows us to show that, even in this case, some simple rules are sufficient for the rise of a self-organization of the system.

These complex systems are then composed of agents that process and send information. According to the type of agent, information processing activities are inscribed in the nervous system of a living being (this is the case of flocks of birds), or explicitly decided by human beings. Of course, agents also perform actions, as well as process information. But actions also spring from information and produce information.

The decisions may depend on information about the present and the past, or even about future. The agents within a complex system can be few or many, can rely on very simple decision-making structures or on more complex ones.

Complex systems often show a very important feature, although not so intuitive. In many cases the self-organizations that emerge are robust: even multiple and drastic attempts to disrupt them can have no effect. Think of a stone that interrupts a procession of ants. Massive actions can therefore have little effect. But often the opposite is also true. A procession of ants can originate from a single ant, and then grow bigger and become stable. Small actions can then have great effects.

The criteria used by agents for processing information - such as those mentioned for birds in a flock - can be simulated by means of computer programs, creating "shadow systems" composed of "virtual agents" which show behaviours similar to those observed in real world. This type of simulation has now reached a very high degree of realism, so there is a growing use of these complex virtual systems: in video games, but also in movies. Here you can see a frame from *Agorà* (Alejandro Amenábar, 2009), showing a computer simulated mass scene.

The keywords in the study of complex systems based on agents are therefore *complexity, information, simulation*. The word *simulation* has the same root as "similar": there is a similarity between the computation of the machine and the behaviour of real systems.

This approach is not limited to the study of natural systems. Today it is also used to study human systems: production, storage, distribution, commerce, transport, service systems. But also to study social phenomena such as fashion, financial markets, macroeconomic fluctuations. That's why even great scientists are now devoting themselves to the study of these systems. They study complex systems to understand them, to change them, to modify their organization, to simulate the effect of new rules and procedures on their behaviour.

Complex systems can be seen as "thinking systems" at multiple levels. So much more, therefore, it is interesting to look at the brain, the seat of human thought, under a new light. The activity of the brain is not only that, at a high level, of performing logical deductions or demonstrations. It also performs much less stringent operations, such as recognition of images, interpretation of data, learning, prediction, control of body movements, etc. ... just as in a serve of a tennis match!

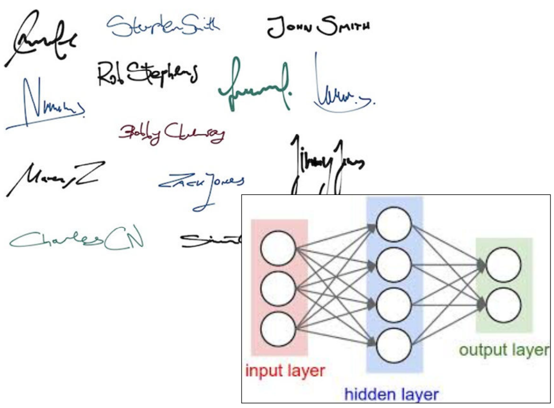
In the information processing perspective, the brain can be thought of as a complex system made up of a huge number of elements that compute at each instant their next state based on information stored and received, and send information to other neurons. So, "virtual brains" have been developed in which “virtual neurons” are organized in interconnected layers. These virtual brains are called “neural networks”.

A network of this type will be more and more able to establish correct associations between input and output the more it will be trained by examples (reinforcing or weakening appropriate connections between elements). Many of the artificial intelligence applications with which we interact and more and more often we will interact every day, also through our phones, are based on multi-level neural networks.

In order to understand how neural networks can show cognitive processes, let's start with some very simple questions. What makes an "A" an "A"? How can we easily recognize this letter even if it is handwritten in very different ways? What allows to recognize a signature or a fingerprint? And finally: how is it possible to instruct a neural network to simulate these astonishing performances of our mind?

The recognition of handwritten letters is a special case of a class of problems that are very easy to solve intuitively, but which are terribly difficult to program in computer language. Here is a paradox: it is very easy to program a computer to perform calculations which exceed the possibilities of any human mind; but, at the same time, it is very difficult to teach a computer to perform activities that appear to us to be very simple. For this reason, it is particularly interesting to set the problem in terms of self-organization of a complex system.

Neural networks are made up of a large number of independent elements (virtual neurons) organized in layers. Each of these neurons receives input signals from the others, processes them and, if it is turned “on”, sends signals to the neurons to which it is connected. As we see, structure and behaviour are similar to those of biological neurons, albeit drastically simplified. The collective behaviour of a network like this is determined, as well as by the structure of the connections, by the "weights" of the connections themselves.

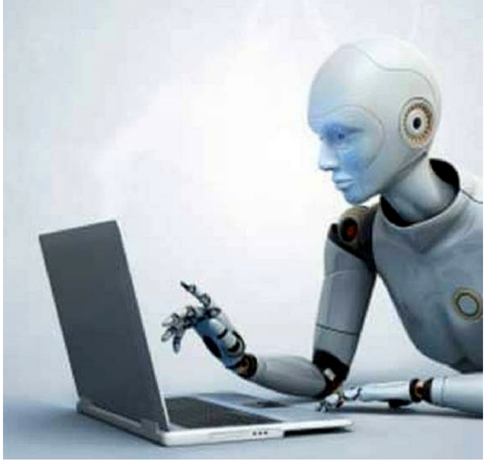


For a better understanding of neural networks, let us consider a simple network model: the three-layer model. The signal (for example, the shape to be recognized) arrives at the input layer; the output layer shows the result of the recognition; the intermediate layer stores a self-organized image of the recognition problem. Each virtual neuron can send signals to all those of the next layer, but not to those of the previous layer. In order to train networks of this kind, the images to be recognized are sent to the input layer, for thousands of times or more; each output is then compared to the desired result and, depending on the outcome of this comparison, the weights of the connections are modified on the basis of predefined algorithms. After an appropriate sequence of training episodes, the network will be able not only to recognize known shapes, but even to generalize the knowledge acquired, classifying forms never seen before.

The representation of knowledge within the network (in the intermediate layer) is totally self-organized, not foreseen by a designer. Knowledge, therefore, is not formalized in logical propositions, as happens in classical computer systems, but is, so to speak, a non-verbal, “pre-symbolic” knowledge. Even if, at the most basic level, the individual neurons perform elementary logic operations.

The applications of neural networks are widespread, from voice recognition to medical diagnosis, up to the classification of events in high energy physics. But also the recognition of fingerprints and the facial recognition in pocket devices are done by neural networks. These neural networks may be more complicated than the three-layer network I mentioned before, but the basic idea is that of interconnected virtual neurons organized in layers, each of which follows simple rules of information processing.

For the first time in a massive way, virtual worlds find their place even within the real world. In fact, inside a latest-generation phone, inside a robot, inside an automated production system there is a virtual brain that simulates a real brain. It is also possible, with the use of neural networks, to build a virtual brain connected to an artificial body, and to let a robot simulate, e. g., the complex brain of a tennis player by means of a complex system made of virtual neurons. And the robot could help itself to understand the world by means of computer simulation…



We are part of a complex system, both real and virtual, that “thinks” at a level higher than that of each one of us. But our intelligence - the extraordinary human intelligence - allows us, with the help of science, to look at the world from above, from the outside and not only from within. It allows us to build "virtual worlds": it allows us to model, to foresee, to design probable, possible and desirable futures: it allows us to conceive the future as a world we can actively take part in.