The concept of emergence

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Complex systems are omnipresent. Everywhere in the real world we can see them. First of all in biology, a living cell, the genetic system, the brain are complex systems. But there are lots of complex systems of different kind. A galaxy, a financial market, an ants colony, Internet, a supply chain are also complex systems. They are in general not easy to understand because they are made up of many components interacting not linearly. Their global behaviour is difficult to predict because it results from the many local interactions of their components. Frequently this behaviour is surprising and counter intuitive even though it is the simple consequence of these interactions: It seems that from the mere consideration of these interactions it is not possible to deduce the behaviour actually observed. This is the so called "emerging behaviour". One can also speak of the "emerging properties" of a complex system. Beyond this simple intuition, the concept of emergence is not so easy to define because, though not very recent, it can be understood in different acceptation more or less objective.

The apparition of the concept of emergence

In the last century, John Stuart Mill, Alexander Bain et George Henry Lewes were the first philosophers to study the difference between the resulting effects and the emerging effects when several causes are mixed. Mill distinguishes between the homeopathic effects which are reducible to the sum of the effects of each of their causes and the heteropatic effects for which such a reduction is not possible. Lewes seems to be the first one to have introduced the word "emergence". According to Lewes, though every effect is the consequence of all its factors, it is not always possible to follow the process through which each factor contributes to the resulting effect. In this case, he calls the effect "emerging". This corresponds to Mill's heteropatic effects. He also says that the emerging effect is not similar to its constituents because it is reducible neither to their sum nor to their difference. In the twenties, Samuel Alexander et Lloyd Morgan proposed a theory according to which the universe has a growing complexity and that when the complexity reaches some particular thresholds, really new properties appear. At the first level matter appears then life, then consciousness, then the divine. Of course, such a theory seems funny today. At the same time, C.D. Broad used the concept of emergence as a way out of the debate between the vitalists and the mecanists. The mecanists think that life and biological phenomena can be explained by the mean of physical laws acting on material things. The vitalists think that there are some not material entities such as the entelechy which are present in living organisms and not elsewhere. Broad proposed an intermediate theory in which life comes only from material things but with the hypothesis that for some systems (eg living organisms) their behaviour can't be deduced from the mere knowledge of the behaviour of their constituents. This allows to accept simultaneously that nothing else than material things exists inside living organisms and that it is impossible from the inspection of its constituents to infer a priori that a system is a living organism.
The important point in this conception is the fact that a property at a given level is emerging if first, it is totally due to the interaction of the constituents of the lower level, second it is

impossible to predict the apparition of this property from the knowledge of the behaviour of the constituents even with an infinite capacity of computation. An emerging property is both totally due to the lower level and totally new. This is the so called non reductive materialism. This position can be better understood when we replace the debate inside the scientific context of the time. Quantum mechanics was not invented and the problem of chemical bond was very embarrassing for the scientists. How is it possible to explain that a molecule made up of two chemical elements has properties totally different from the properties of each of its constituents? It was tempting to postulate that some configurations give birth to new strength or news laws not reducible to the known ones. This is the strong thesis of emergence that nobody supports nowadays. Quantum mechanics gave a good explanation to all these mysteries and we don't need to postulate that new laws are emerging at the upper level (even if the problem of explaining the consciousness from the brain has replaced the old problem of chemical bonds). We are left with a weak version of the thesis according to which an emerging property is a property happening at a given level, entirely due to the behaviour of the constituents of the lower level, that it should be possible in principle to compute from the lower level but that is in practice very difficult if not impossible to compute. This definition is not so clear and asks for being précised. This is what we are going to do in the following.

The new debate

There has been a renewal of interest in the debate recently because of many conceptual breakthroughs. Thanks also to the use of computers. First of all, the study of the non linear dynamic systems (well known under the name of deterministic chaos) showed the importance of the phenomena of auto organisation such as appearing for example in the Belousov-Zhabotinsky reaction. It has also been realised that simple rules don't always produce simple behaviour. A good example is given by the cellular automata. Very simple underlying rules can give birth to extremely complex behaviour seeming impossible to predict and even looking at random. Thanks to the power of the modern computers it is possible to explore the behaviour of these cellular automata and of many complex systems whose behaviour would otherwise have been inaccessible. Often the only way to predict the behaviour of a complex system is to simulate it on a computer. Through such a simulation it is clear that the global behaviour of a set of many constituents while resulting directly from the individual behaviour of each constituent, can be different from what we could have intuitively anticipated from a mere inspection of the properties of these constituents. The concept of emerging behaviour has lost the magic flavour it had in Broad's conception to become a word designating a phenomenon appearing at a global level and not easily reducible to the properties of the constituents giving birth to it.

Objective or subjective Emergence?

So defined, the concept of emergence seems to rest on the difficulty that we have to link intuitively what we see at the global level and the laws that govern the constituents. Thus emergence would be a property depending on our human intellectual capacities. To avoid this conclusion, some objective definitions of emergence have been proposed. It is nowadays usual to distinguish between synchronic emergence and diachronic emergence. The first one refers to what happens when we identify a pattern or a property at some level and which is not relevant at the lower levels. The recognition of a face inside a pointillist picture, invisible when we are too close but that appears at the right distance is a good example of synchronic emergence. Synchronic emergence has been sometimes associated with a sudden decrease of

the algorithmic complexity of the description of the system. The reason is that the global identification of a structure allows giving a much shorter description of the system. Diachronic emergence is related to the dynamic behaviour of the system. The series of the states of a cellular automaton, the oscillation of some chemical reactions, the apparition of the rings of Saturn are some examples. Diachronic emergence is often defined as: a system will be said to have an emerging behaviour if the only way to predict the series of its states is to simulate the working of the system. The main idée behind this definition is that here is no faster way to know how the system is going to behave than to observe the system itself through a simulation). This is what Wolfram said when he assumed that for some cellular automata there is no other way to know what their state is, say at the 1000^{th} iterations, than to go through the 999 previous ones. Wolfram doesn't prove that this is true and this idea needs to be made rigorous, what is not easy. But the interesting point is that it can be formulated in an objective way and doesn't depend on our human limitations.

Comprehension

What about the possibility to understand emerging properties? The concept of comprehension is not simple and would need to be analysed carefully but it is possible to notice that the following two elements are important: A phenomenon is said to have been understood if i) the rules giving birth to it are identified, ii) it is possible to follow mentally the different steps from the initial state to the final state. If the repeated use of the rules of a cellular automaton clearly shows that such or such pattern is going to appear (for example alternated black and white cells) then it will be possible to say that the behaviour of this automaton is understood and that it is emerging. If on the contrary, such a repeated use is not mentally possible, then the behaviour will be obscure and qualified as emerging because it will not be fully understood. However a more careful thinking shows that the two situations are not really different and that this is just a matter of degree. Understanding a phenomenon is being able to follow mentally the different steps of the process leading to the final state from the initial one. When these steps are too many or too complex then we need to use a computer to perform a simulation and the feeling of understanding disappears. Thus it seems possible to argue that understanding is partly being able to mentally simulate. It is then natural to distinguish between two kinds of emergence: a subjective one when a process is too complex for being mentally simulated and an objective one when there is no faster way to predict the behaviour than to observe or to simulate the system (there is no shortcut and to know a given state it is necessary to go through all the previous ones). Then, the fact that for us, an objectively emerging behaviour seems to be subjectively emerging could well be due to the limitation of our capacities. For beings with superior capacities, some phenomena emerging in the objective sense could well not be emerging in the subjective sense.