COMPLEX SYSTEMS

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THE IMPORTANCE OF COMPLEX SYSTEMS

Complex systems, a Nobel prize winning topic that could affect our entire existence. To put it in other words, a thorough understanding of complex systems could allow us to predict phenomena to a certain level and help us make the best possible decision. That might sound a bit unbelievable right know, but let us prove our point. It wasn't until last year that the study of complexity theory gained its popularity. Due to this we know more about a highly discussed theme 'the climate change'.

(Figure 1) Complex wave

Fortunately, this is only the beginning because complex systems can be studied on various disciplines. On scientifical fields like biology we could make an important progress in neurological studies that could save many lives. In the matter of communication we could try to understand patterns we have yet not been able to comprehend. For the study of sociology complex systems would help to explain how humans form social networks or how the population in cities can vary from time to time. The same is possible in the prediction and improvement of the economical business cycle or the issue of wealth and income. Also for subjects like computer science, mathematics, psychology, sociology and anthropology complex systems could explain how different components influence each other. Now this might sound like anyone could do it, so let us give you a deeper explanation.

THE BUTTERFLY EFFECT, BETWEEN CHAOS AND COMPLEXITY

Complex systems are present in our everyday lifetime, even if we are not conscious about them, and this includes our mathematical or economic perspective and contemporary (as in the future) physical conception.

One of the most famous examples of a physical topic nowadays, which is useful in medical science, neurobiology, psychology and especially in meteorology is the " Butterfly Effect " (i.e. small actions that will bring enormous reactions). This phenomenon is based on the chaos theory, a survey that tries to understand the dynamic behaviour of extremely changeable phenomenal models, after a minimal change.

Both chaotic systems (like the solar system, considering its emergent-behaviour in long periods of time) and complex systems are not linear and this is their point in common, but what is it? The non-linearity is characterized by the dependent relation of proportion between the input (data's set) and output (product). In linear systems there is a direct and proportional connection between the previous and the last one and multiple systems' achievements can be added to each other and it can be visually depicted as a straight line. Non-linear systems instead depend on the relationship between elements and different outputs cannot be summed up.

When the product is better than all the amount of the work, we call this a synergic operation or, on the contrary, interference. Non- linearity can be provoked also by feedback loops. This feature is a fundamental component in iterative function and ended up with the management of fractal geometry, a new discipline of mathematics born by the computer science's development, combined by Benoit Mandelbrot, starting from the concept of self-similarities, an object property that has the same appearance, no matter the scale used.

This characteristic demonstrates why practically complex systems (and chaotic systems) are unlikely predictable in a predetermined temporal scale, because several interactions produce consistent approximation error, which will overcome the applicable goal of the prediction.

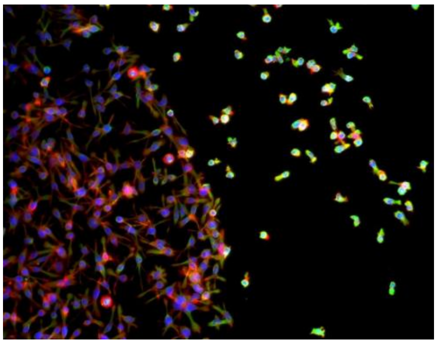
COMPLEX SYSTEMS IN BIOLOGY

In complex systems the so-called agents and the interactions between them lead to results that are not easily predictable, because of that it is therefore necessary to take into account all its parts to understand their mechanisms, and this is also valid in biology.

Indeed, the simplest examples of a complex system are cells. The cell, considered as a single element, is the basis of organic bodies, but what makes it a great example of a complex system is that it is made up of numerous types of components, and there are infinite ways they have of interacting with each other.

To better understand how an organism can be defined as complex, suffice it to say that there are about 37 trillion cells in the human body.

For example, cells make up the immune system, a defence mechanism that protects the body from harmful foreign agents, such as viruses and bacteria, and is made up of specialized cells and organs. As many as six different types of cells operate within this system.



(Figure 2) The "front line troops" in the immune system.

Another example of complex systems are ecosystems, the environments in which millions of animal and plant species develop and are part of the complex cycle of life. They can be considered among all ant colonies: these incredible insects base their survival on complex systems of several individuals, which unite and collaborate. The ants have to cope with the management of an exorbitant number of individuals within the colony, and they manage to make each of them become part of a functioning and unique mechanism, in which every single part becomes essential.

(Figure 3) Ant colony

Complex systems are around us, they are part of us and they regulate almost all parts of our existence, as well as that of all living beings.

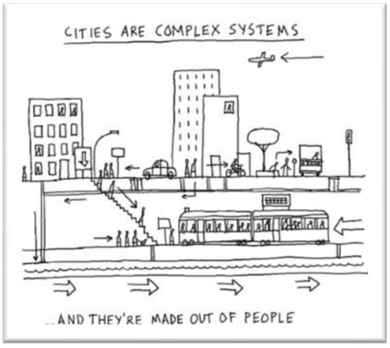
COMPLEX SYSTEMS IN SOCIAL PHENOMENA

By this point, it may not surprise how this model has been successfully applied to the study of the social sciences, such as sociology and anthropology, as well as psychology. Differently from the previous unitary and deterministic approaches, it claims that society is not evolving towards a renewed perfection (the Clockwork Universe), but to an increasing complexity.

In fact, our society itself possesses all the necessary requirements in order to be regarded as a complex system: a high number of elements, a natural tendency to self-organize while maintaining various *interactions* with other elements based on a non-linear behaviour (lack of proportion in cause-effect) and the fundamental influence of its initial state on the "final" one, unsteady and variable, therefore unpredictable.

For instance, the understanding of a major historical event like the outbreak of the First World War cannot reach an acceptable point; by looking into the general political, social, economic and cultural condition it is still not possible to predict the dynamics and the causes of it. Considering the uncertainty of the past, future events are essentially unknown to us.

Each individual (the so-called agent) is able to make choices and acts, but this process is affected by many different factors, including complexity theory’s concepts like emergence and surprise. Institutions are formed by relatively large groups of these individuals. They have diverse collective functions in order to produce some good or service (e.g., governance) that support the survival of the entire organism. However, their own behaviour is essentially chaotic.



(Figure 4) City as a complex system

It is truly amazing to comprehend the actual impact of this physical concept, to discover how widely it can be implemented. The human brain itself is proved to be a complex aggregate of billiards of interrelated nerve cells, able to elaborate impulses of various kinds. The cities we live in are not the natural-organic complex systems we would find in nature as ecosystems, but they show the same dynamical features, even our urban transportation. Thus, all around us.

NOBEL PRIZE IN PHYSICS 2021

Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi were awarded the Nobel Prize in Physics in 2021 for their contribution in understanding complex systems. Their research was utilized to improve computer models of global warming’s impact on the Earth’s climate. They made sure that we can predict what is happening with the climate in the future.

The Nobel Prize for Physics was this time separated in two different categories: “the physical modelling of Earth’s climate, quantifying variability and reliably predicting global warming” and “the discovery of the physical systems from atomic to planetary scales”.

Klaus Hasselmann & Syukuro Manabe

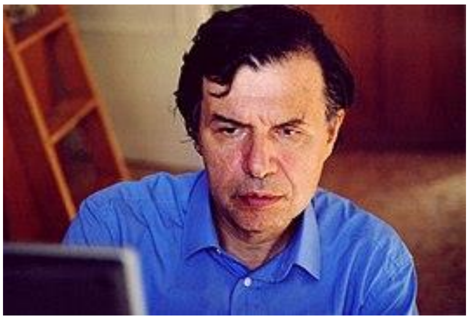
The Nobel Prize in Physics 2021 was awarded one half jointly to Syukuro Manabe and Klaus Hasselmann for the physical modelling of Earth’s climate, quantifying variability and reliably predicting global warming. They both studied the same topic and eventually got awarded for this part of the Nobel Prize, Manabe demonstrated how and why rising carbon dioxide caused global warming and Hasselmann showed that this is happening.


(Figure 5) Alfred Nobel

Manabe demonstrated in the 1960s how growing amounts of carbon dioxide in the atmosphere lead to higher temperatures at the surface and built early climate mathematical models. He was the first to analyse the link between radiation balance and vertical air mass movement. He also led the development of physical models of the Earth's climate. His work set the groundwork for the current generation of climate models.

Hasselmann expanded this work a decade later to develop a model that linked weather and climate. With that, he answered the question why climate models can be reliable despite the weather is changeable and chaotic. He also discovered ways for identifying specific signals imprinted on the climate by both natural events and human activities. His methods have been used to demonstrate that the rising temperature in the atmosphere is caused by human emissions of carbon dioxide.

Giorgio Parisi



(Figure 6) Griogi Parisi

Giorgi Parisi was born on the 4th of August 1948. He is an Italian theoretical physicist, whose research has focused on quantum field theory, statistical mechanics and complex systems. He won the 2021 Nobel Prize because of the ground-breaking contributions to the theory of complex systems, in particular “for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."

In his career, Parisi has studied very different topics, that we can call “complex systems”. These topics variated from the interactions between neurons in the brain to the Higgs boson. This all led him to deal with neural networks and artificial intelligence, up to the behaviour of individual birds. Nowadays, he works on the research of the structure of heterogeneous materials, for example glass.

The link between his work and that of Manabe and Hasselmann is that fluctuations are the key for predictability. He said: “We’re recognizing that emerging phenomena sometimes require you to look at all the individual complicated physical mechanisms and knit them together to make a prediction.”

BIBLIOGRAPHY

- De Domenico M., Sayama H., *What is Complexity Science?*, #ComplexityExplained. (https://complexityexplained.github.io/)
- Earl E., *Understanding Complex Systems*, University of Minnesota. (https://www.csh.umn.edu/education/whole-systems-healing/understanding-complex-systems)
- University of Waterloo, What are complex systems?, Waterloo Institute for complexity & innovation. (https://uwaterloo.ca/complexity-innovation/about/what-are-complex-systems#:~:text=These%20rules%20evolve%20under%20selection,science%20have%20made%20important%20contributions)
- Wikipedia, Complex adaptive system, (2022, 16 January). (https://en.wikipedia.org/wiki/Complex_adaptive_system)
- Gibson B., (Nov 11, 2016), "Sytems Theory", Britannica. (https://www.britannica.com/topic/systems-theory)
- Rubino U., "Il tutto è maggiore della somma delle parti", Fisici Senza Palestra. (https://fisicisenzapalestra.com/il-tutto-e-maggiore-della-somma-delle-parti.html)
- Washington G., "Applications of graph theory in complex systems research", SlidePlayer. (https://slideplayer.com/slide/13517112/)
- Condorelli R., (July 2016), "Complex Systems Theory: Some Considerations for Sociology", Scientific Research Publishing. (https://www.scirp.org/journal/paperinformation.aspx?paperid=69101) (1st and 8th paragraphs)
- Gray D., "Cities are complex systems", Flickr. (https://www.flickr.com/photos/davegray/5640776419)
- Castelvecchi, D. & Gaind, N. (2021, 5 October). *Climate Modellers and theorist of complex systems share physics Nobel*, Climate models. (https://www.nature.com/articles/d41586-021-02703-3)
- Dusi, DE,(October 5, 2021), *Giorgio Parisi wins the Nobel Prize in physics with Manabe and Hasselmann*,Breakinglatest.news. (https://www.breakinglatest.news/health/giorgio-parisi-wins-the-nobel-prize-in-physics-with-manabe-and-hasselmann/)
- Nobel Prize. (z.d.). *Press release: The Nobel Prize in Physics 2021.* (https://www.nobelprize.org/prizes/physics/2021/press-release/)
- The Royal Society, Journal of the Royal Society "Complex Systems biology" (September 20, 2017) (https://royalsocietypublishing.org/doi/10.1098/rsif.2017.0391)
- Biologist Minicone S., Sanità Senza Problemi "Il sistema immunitario complesso e delicato" (https://sanitasenzaproblemi.it/il-sistema-immunitario-complesso-e-delicato/)
- Wikipedia "Complex System" (https://en.m.wikipedia.org/wiki/Complex_system)

- Deborah M. Gordon "Inside the ant colony", YouTube (July 8, 2014) (https://m.youtube.com/watch?v=vG-QZOTc5_Q)
- Cancer Research Institute "How does the immune system work?" (April 30, 2019) (https://www.cancerresearch.org/en-us/blog/april-2019/how-does-the-immune-system-work-cancer)
- Figure 1 (https://theconversation.com/super-microscope-shines-light-on-the-immune-systems-front-line-defenders-1693)
- Figure 2 (https://www.ripleys.com/weird-news/ant-mega-colony)
- FS, *The Butterfly Effect: Everything You Need to Know About This Powerful Mental Model.* *(*https://fs.blog/the-butterfly-effect/ *)*
- Wikipedia, *The Butterfly Effect, 2021.* *(https://it.m.wikipedia.org/wiki/The_Butterfly_Effect)*
- Systems Innovation, (2015, 19 July), *Nonlinear Dynamics & Chaos*, YouTube. (https://www.youtube.com/watch?v=qz6gXyfzV9A)
- Systems Innovation, (2017, 6 May), *What is a Complex System?*, YouTube. (https://www.youtube.com/watch?v=vp8v2Udd_PM)
- Systems Innovation, (2014, 1 June), *Nonlinear Systems Overview?*, YouTube. (https://www.youtube.com/watch?v=VSsXxM1Wm2M)
- De Brabandère L., (2020, 11 June), What is fractal geometry?, The History of Mathematics with Luc de Brabandère, What makes it tick?, Youtube. (https://www.youtube.com/watch?v=jMqgJOr0veo)