International Journal of Research Publication and Reviews, Vol 3, no 1, pp 847-850 January 2022

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Complex Systems and the 2021 Nobel Prize in Physics

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ABSTRACT

The 2021 Nobel Prize in Physics was awarded to three researchers for their work on different complex systems in global warming. Klaus Hasselmann and Siukuro Manabe took half of the prize for their contributions in the area of climate physics. The other half was awarded to Giorgio Parisi, especially for his contributions to the statistical physics of disordered systems and applications. This year's award recognized the application of the physics of complex systems to climatology and its models. Complex systems are characterized by randomness and disorder and are difficult to understand. In this article we are going to talk a little about the Nobelists and discuss what complex systems is, a relatively new area, with a strong multidisciplinary appeal, and what is its context among the traditional areas of Physics.

INTRODUCTION

According to the Swedish Academy of Sciences, this year's award features new methods for describing complex systems and predicting their long-term behavior. Since these systems are characterized by randomness, disorder, and are difficult to understand. The reason that led the physicists to award this year was the physical modeling of the Earth's climate, quantifying the variability and predicting global warming in a reliable way. This is the first time in history that the Nobel Prize in Physics has been awarded to scientists who have contributed to models of global warming. This proves how relevant this topic is, especially nowadays, where climate change is present and becomes worrying every day. According to the Prize's evaluation committee, Manabe and Hasselmann contributed to the benefit of humanity, in the same way as Alfred Nobel, by providing a solid physical foundation for knowledge of the climate of planet Earth.

BRIEF BIOGRAPHY OF THE NOBELISTS

According to the Britannica Encyclopedia (1) MANABE SYUKURO was born on September 21, 1931, in the village of Shingu, Japan. Manabe received a bachelor's degree in meteorology in 1953 from the University of Tokyo, having completed his doctorate in 1957 in meteorology at the same institution. In 1958, he became a research meteorologist at the U.S. Weather Bureau, where he explored the use of physics in developing weather models. In 1968 he joined the faculty at Princeton, where he served as a professor until 1997. He later became the senior meteorologist at this university in 2005. MANABE developed, in 1967, the world's first reliable three-dimensional climate model of the atmosphere. Two years later, he and American oceanographer KIRK BRYAN produced the first general circulation model that united the ocean and atmosphere. The model was not complex by modern standards, as it simplified the atmosphere into a single vertical column and made general assumptions about topography and cloud cover. Still, it has become a useful tool for examining seasonal climate variability and global warming scenarios, including the relationships between insolation and the vertical movement of air masses. Manabe's general circulation model was used to measure the sensitivity of climate to carbon dioxide concentrations in 1975 in a paper he co-authored with American meteorologist Richard Wetherald. Manabe and his collaborator demonstrated how increasing levels of carbon dioxide [CO2] in the atmosphere lead to increasing temperatures on the Earth's surface. For his contributions to the environment, Manabe also received the Blue Planet Prize (1992), the Roger Revelle Medal of the American Geophysical Union (1993) and the Crafoord Prize (2018), awarded by the Royal Swedish Academy of Sciences. As mentioned in the Britannica Encyclopedia(2), KLAUSS FERDINAND HASSELMANN, born October 25, 1931, Hamburg, Germany, is a German oceanographer who received the Nobel Prize in Physics in 2021 for the fundamental progress made in the scientific development of models of the Earth's climate, quantifying variability and predicting global warming. Hasselmann studied physics and mathematics at the University of Hamburg and graduated in 1955 after completing a thesis on isotropic turbulence. He continued his work in physics and fluid dynamics at the University of Göttingen and the Max Planck Institute for Fluid Dynamics, obtaining a Ph.D. from the University of Göttingen in 1957. He worked as a research assistant at the Institute of Naval Architecture at the University of Hamburg from 1957 to 1961. He held the chair at the Institute of Geophysics and Planetary Physics and at the Scripps Institution of Oceanography, University of California, San Diego, from 1961 to 1964. In 1970, Hasselmann then returned to the University of Hamburg, obtained the title of full professor of theoretical geophysics and served as administrative director of the university's Institute of Geophysics until 1975. He later became founding director of the Max Planck Institute for Meteorology in Hamburg, where he served as director until 1999. He also served as scientific director of the German Climate Computing Center, also in Hamburg, from 1988 to 1999. Hasselmann's seminal work in 1976 involved the creation of a stochastic climate model that shows how climate disturbances can be integrated into larger and more stable atmospheric and oceanic circulation patterns to produce climate change. In other words, he showed how weather that appears as noise and that can change quickly and chaotically can be incorporated into a model to frame long-term climate change. This model led him to consider how warming signals generated by human activities, such as those produced by greenhouse gas emissions and their effects on temperature, could be separated from the background noise of natural climate variability. In 1979, he published statistical techniques that allowed climate scientists to identify the presence and relative strength of these warming signals. This work became the basis for attribution studies – which seek to explain the links between human activities that contribute to climate change and specific weather and climate events such as tropical cyclones (hurricanes), droughts, extreme rainfall events, and the pattern of rising global average temperatures, which often appear in national and global climate risk assessments that help guide climate policy. Among Hasselmann's many accolades, he is the recipient of the American Meteorological Society's Sverdrup Gold Medal (1971), the Royal Meteorological Society's Symons Memorial Medal (1997), and the European Geophysical Society's Vilhelm Bjerknes Medal (2002). Hasselmann is the author or co-author of more than 175 scientific publications and has contributed to six books on Meteorology and Climatology. According to the Britannica Encyclopedia(3) , GIORGIO PARISI, born on August 4, 1948, in Rome, Italy, received the 2021 Nobel Prize in Physics for his work on spin glasses, which has proven to be widely applicable in the study of complex systems. . Parisi graduated in physics from the University of Rome in 1970 and, from 1971 to 1981, was a researcher at the Frascati National Laboratory. He became a professor at the University of Rome in 1981. In the late 1970s, Parisi became interested in spin glasses as a result of his work in particle physics theory. Giorgio Parisi, around 1980 discovered hidden patterns in disordered complex materials, highlights the Royal Swedish Academy of Sciences. His discoveries are among the most important contributions to the theory of complex systems, as they make it possible to understand and describe many different and apparently entirely random materials and phenomena, not only in physics but also in other very different areas, such as mathematics, biology, neurosciences. and machine learning. Modern studies of complex systems have their roots in statistical mechanics, an area of physics developed in the late 19th century from the realization that a new formalism was needed to describe systems such as gases or liquids, composed of a large number of particles. This method took into account the random motions of particles and the average effect of their displacements, rather than the displacement of each individual particle, and generated a microscopic explanation for macroscopic properties of gases and liquids, such as temperature and pressure. Parisi found a way to mathematically express how simple individual behavior results in complex collective behavior by studying an exotic material called spin glass. A spin glass is a metallic alloy in which atoms of a magnetic chemical element, such as iron, are randomly dispersed between atoms of a non-magnetic metal, which can be copper or gold, and functions as a model of complex systems.

WHAT ARE COMPLEX SYSTEMS?

The bibliography of Complex Systems is very extensive, but the basic concepts can be found in the MORIN (4) and BAR-YAM (5) basic books, listed in the references of this article. As is well known, the methodology normally adopted in the study of a natural phenomenon consists of analyzing it in stages, dividing it into smaller parts and investigating each one separately. In the specific case of linear systems, in which the performance of the whole is the superposition of the effects of each of its forming parts, the separate study is sufficient for a global evaluation of the system. However, the previous strategy becomes inoperative in cases where the global behavior of the system is markedly different from that obtained by considering only the sum of its parts, or ignoring the reciprocal influence of its constituent elements. Thus, due to their markedly systemic behavior, the properties of these systems can only be identified during their collective behavior, being irreducible at the level of their elementary cells. Such systems are therefore called complex. It can be clearly seen from what has just been observed that, in this context, the adjective complex does not have the meaning of complicated. In fact, these systems are constituted by innumerable units of very simple behavior, influencing each other in an intricate network of connections and thus generating the global complex behavior. The impossibility of separating complex systems into their constituent parts, in addition to the notorious difficulty in their analytical treatment, of which the phenomenon of turbulence is the best known example, has until recently prevented further development of its study. However, thanks to the development of computers and the improvement of increasingly sophisticated numerical models, its investigation has become one of the most promising research areas. A common note in the complex field of research is the scope and interdisciplinarity of the phenomena it proposes to explain, being, therefore, an area averse to specialists and reductionist formal thinking. Thus, natural phenomena related to different fields of knowledge, such as mathematics, physics, chemistry, biology, economics, among others, have been the object of study and research in this totalizing way of seeing. Therefore, there is no clear and comprehensive definition of complex systems. However, several phenomena share certain common characteristics, which makes it possible to encompass and analyze them together. MORIN (4) e BAR-YAM (5) present, in a very didactic way, some of these characteristics: a) They are non-linear dynamic systems in permanent evolution, open to the outside, constituted by a large number of units that interact with a certain much smaller number of neighbors. b) Each constituent unit can present the phenomenon of frustration, since the character of the messages received from each neighbor can be extremely contradictory, preventing the fulfillment of each one of them simultaneously. c) The system can develop, throughout its evolutionary process, spatio-temporal coupling, presenting long-range temporal (memory) and spatial (fractal structures) correlations. Thus, the system spontaneously self-organizes, creating order from an initially disordered or completely structureless state, the formation of hierarchical structures is a typical and fascinating example of this emergent order effect. d) In view of its systemic behavior, it is possible for the emergence of emerging collective properties, which are qualitatively new, and which cannot be identified in any of their forming units. Such properties arise through the process of local competition and cooperation, in a repetitive and imitative way (the herd effect on stock exchanges, precursors of economic crashes, is a famous example of this process. e) The system normally presents (hyper) surfaces of energy with several local minima (multiple attractors), which leads to a temporal development that is extremely dependent on all previous history, with a large number of quasi-equilibrium configurations.

PHYSICAL MODELING OF THE EARTH CLIMATE

As mentioned ALBERT & BARABÁSI(6), physical modeling of Earth's climate is a technology to simulate Earth's physical phenomena on a computer. The objective is to create a digital model of the real world, which will be used as an indispensable tool for discussing plans for the future of humanity, such as predictions about global warming, and the effects of measures to combat this climate change. Weather and climate are complicated because they involve so many different physical processes, from the movement of air to the flow of electromagnetic radiation such as sunlight to the condensation of water vapor, over a wide range of spatial scales and temporal. The system is incredibly complex and interconnected. For example, a cluster of small storms can influence a weather system that spans a continent. Before about 1955, meteorologists extrapolated future weather from changes in previous days. They used simple but labor-intensive methods, partly quantitative and partly based on experience. In the late 1950s, it became possible to make forecasts by running weather models on newly emerging but rapidly improving digital computers. A meteorological model is a system of equations that expresses the physical laws that govern the climate. Running a weather model means solving the equations on a computer, using data from today's weather to predict tomorrow's weather. Partly because of computer limitations, early weather models could only cover parts of the Earth, such as North America. But in the early 1960s, faster computers made it possible to create models that represented the entire global atmosphere. Manabe(1) led the development of one of these models, building an interconnected web of thousands of equations that could simulate climate and climate change. With this model, Manabe and his colleagues were able to produce very realistic simulations of things like jet streams and monsoons. While global weather forecasting and modern climate models are much more powerful, they can be seen as descendants of Manabe's early model. Manabe demonstrated how increasing concentrations of carbon dioxide in the atmosphere results in an increase in temperature at the Earth's surface. His discovery indicates that if the level of CO2 in the atmosphere doubles, the global temperature will increase by more than 2ºC.

STOCHASTIC CLIMATE MODEL

HASSELMANN(7) was contemplated by its stochastic climate model that interpreted the changes in reliable proposals. Broadly speaking, a stochastic process is a phenomenon that varies to some degree, unpredictably, as time passes. The unpredictability in this case implies that an entire time sequence of the process was observed on several different occasions, under presumably "identical" conditions, the sequences in resulting observations would, in general, be different. So probability appears, but not in the sense that each outcome of a random experiment determines only a single number. Rather, random experience determines the behavior of some system for an entire time sequence or interval. That is, the result of random experience is a sequence or series of values, a function, not just a single number. So, for example, if you observe climate change in a certain place in a certain country, for a period of 24 hours, you will be observing a random process, a single sampling point of a certain random experience. Hasselmann's work shows that time remains related to climate, despite all the changes that are constantly occurring. Hasselmann's great merit was the creation of a climate model capable of identifying specific signs, as if they were the fingerprints that natural phenomena and human activities imprint on the climate. In addition, Hasselmann discovered how to incorporate into climate prediction models the random changes that occur at all times in atmospheric variables. Inspired by the theory of Brownian motion, developed by Albert Einstein in 1905, Hasselmann created a climate model that took these variations into account. He also developed methods to identify human impact on the climate system. These methods have been used to prove that the rise in temperature in the atmosphere is caused by human emissions of carbon dioxide. If you want to delve deeper into the subject, you can consult BOCCARA (8), that presents a good summary of modeling in complex stochastic systems

SPIN GLASSES

In 1980 GIORGIO PARISI(9) found the exact solution of the infinite-range spin glass model using a new order parameter, which parameterizes the spontaneous breaking of replica symmetry in these models. In later work, the deeper meaning of the solution was found and this led to the introduction of ultrametricity in physics. A probability interpretation of the approach was obtained. A sequence of large-scale simulations of three-dimensional spin glasses was performed to numerically verify the validity of the replica theory. The theoretical results are in fact in very good agreement with the numerical simulations. A great deal of effort has been made to better understand the physical implications of replica symmetry breaking. In fact, it was finally proved that replica symmetry breaking has a direct experimental counterpart in the validity of the dissipation relations of generalized fluctuations in out-of-equilibrium dynamics.

Numerical simulations are in agreement with theoretical predictions for both spin and brittle glasses. Experiments that aim to find these relationships in spin glasses and in structural glasses are currently being carried out. Some positive results were obtained. Spins are intrinsic magnetic moments of atoms, which in a usual magnetic material, such as a magnet; tend to align in the same direction, producing an ordered structure that gives the magnet its macroscopic magnetic property. This property is lost at high temperatures, where individual spins churn in any direction. A spin glass is an unusual magnetic material where interactions between spins are random - one spin tends to align with a neighboring spin but anti-align with another. The presence of these conflicting interactions leads to the phenomenon of frustration, in which a spin cannot adopt a direction that simultaneously satisfies all interactions between its neighboring spins. The theory that Parisi developed in the 1980s showed that, unlike the disordered phase at high temperatures, regions far from the spin glass have disordered structures or states that are not statistically equivalent to each other. This is because there are many stable disordered states and it is difficult for a transition to occur between them, which also gives this material a slow dynamic. Later this theory, called replica symmetry breaking, was extended to the study of glass, granular materials such as sand, and other disordered materials. More information about Parisi's scientific work can be provided by NESTORE (9).

HIDDEN ORDER EMERGES IN DISORDERED SYSTEMS

The fundamental contribution of PARISI (10) for which he was awarded the Nobel Prize was to understand and mathematically describe how a hidden order emerges in disordered systems such as glass. Liquids are characterized by their disordered structure, composed of a very large number of atoms or molecules moving around, colliding with each other and diffusing through the liquid. Once cooled, this state of matter (phase) undergoes a transition to a crystalline solid, characterized by its ordered structure - the atoms or molecules organize themselves in a periodic structure in space. These states of matter have very different emergent (macroscopic) properties, such as their ability to deform and their rigidity. Some liquids, when cooled too quickly, fail to form a crystal and form a glass - a state characterized microscopically by the same disordered structure as a liquid, but rigid, with its atoms or molecules diffusing slowly over astronomical timescales.

ADDITIONAL CONSIDERATIONS

How can we predict complex and random things? Our world is full of complex and disordered phenomena and processes. For example, the climate can be described as a system of many components that interact in many ways. How can we describe and predict how these systems change? That's what the 2021 Nobel Prize laureates in Physics explained. The laureates' models have been used to demonstrate how high levels of greenhouse gases in the atmosphere lead to higher temperatures at the Earth's surface and to show that global warming is a result of humanity's greenhouse gas emissions. Complex systems are characterized by randomness and disorder and are difficult to understand. This year's Award recognizes new methods for describing them and predicting their long-term behavior. A complex system of vital importance to humanity is the Earth's climate. For decades, people have legitimately wondered how well climate models will perform in predicting future weather conditions. Based on solid physics and the best understanding of the Earth system available, they deftly reproduce the observed data. However, they have a broad response to rising carbon dioxide levels, and many uncertainties remain in the details. The hallmark of good science, however, is the ability to make testable predictions, and climate models have been making predictions since the 1970s. How reliable have they been? Most models were quite accurate.

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