Nobel Prize in Physics awarded for pioneering research in climate change and chaos theory

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The Royal Swedish Academy of Sciences has awarded this year's Nobel Prize in Physics for work on Earth's climate and the theory of chaos and disordered systems. The first half of the prize was given jointly to Syukuro Manabe and Klaus Hasselmann for their foundational work on our atmosphere and how humanity changes it. The second half of the prize was granted to Giorgio Parisi for his contributions toward understanding chaos theory, the underlying laws governing seemingly random phenomena.

The connection between the two halves of the award is the "complexity of physical systems," as explained in the prize's scientific background. "[F]rom the largest scales experienced by humans" down to "microscopic structure and dynamics," there are many processes that have numerous interacting parts that have proven difficult to describe mathematically. This year's Nobel celebrates key milestones in understanding such systems, including modeling the links between weather and climate and understanding the underlying patterns in disordered molecular structures.

The basic feature of complex systems is that even tiny changes in the initial conditions over time produce very different results. Small differences in the temperature, pressure or humidity, for example, can cause very different weather patterns to emerge. Early computer simulations that looked at this question were done in the 1960s by mathematician Edward Lorenz, who observed that weather models changed drastically when the initial conditions were rounded from 0.506127 to just 0.506. The results produced in each scenario were completely different.

Lorenz summarized this as, "Chaos: When the present determines the future, but the approximate present does not approximately determine the future."

In popular culture, this is often referred to as the butterfly effect. The term was highlighted in a question asked by meteorologist Philip Merrilees in 1972, "Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" Continuing the metaphor, is the tiny gust of wind from the flap of a butterfly's wings one of the many interconnected events that ultimately leads to a tornado? Is the event part of a cascade that leads to large-scale alterations of a weather system? And if a tornado still formed without the wing flap, how would its trajectory change?

These experiments provided the backdrop for Manabe's work. Manabe was born in 1931 and came of age during and in the aftermath of the devastation wreaked on Japan by the United States during World War II. After earning his doctorate at the University of Tokyo in 1958, he was hired by the General Circulation Research Section of the US Weather Bureau (now the Geophysical Fluid Dynamics Laboratory at NOAA). There, he began developing climate models studying how differences in amount of carbon dioxide in the atmosphere impacted global temperatures.

The very earliest climate model was developed by French physicist Joseph Fourier in the early 1800s, who studied the balance between the amount of solar radiation hitting the ground, the amount of energy reemitted by Earth's surface, and how this balance determined the temperature of the atmosphere.

Further work was done by Svante Arrhenius in 1896, who showed that the amount of heat captured by the atmosphere is dependent on the gases present. He found that doubling the amount of carbon dioxide in the atmosphere caused temperature changes of up to 6 degrees Celsius, an overestimate due to the accuracy of atmospheric measurements of the time. This process is now called the greenhouse effect.

Manabe built on this work by adding to Arrhenius' model the vertical flow of air due to convection and the evaporation and condensation of water vapor. This involved solving the full equations for atmospheric heat, motion and radiation using a then state of the art computer that had a mere half a megabyte of RAM. This more complex but still relatively simple climate model confirmed that 1896 result, that an increase of carbon dioxide in the atmosphere increases the global average surface temperature. The more sophisticated calculations predicted a temperature change of between 2 and 3 degrees Celsius from doubling carbon dioxide.

The simulations further revealed that changing the levels of oxygen and nitrogen in the atmosphere, which comprise 99 percent of what we breathe, produced negligible effects on the surface temperature. In addition, when the amount of carbon dioxide in the atmosphere increases, while temperatures at the surface get warmer, temperatures in the upper atmosphere get colder, ruling out the hypothesis that increasing solar radiation causes increasing temperatures. Both these results decisively proved in 1967 that increased amounts of carbon dioxide cause increased temperatures at the Earth's surface, what we today call global warming.

There still was not, however, a connection between rapidly changing weather conditions experienced every day to the more protracted changes to climate as a whole. In the mechanical formulation of the world's physical laws set forth by Isaac Newton, one should be able to accurately predict both the climate and the weather. If one knows the position and momentum of every particle in the universe, according to Newton and later Pierre-Simon de Laplace, the world is *linear* and it should be possible to calculate exactly both what has happened and what will happen.

Yet one can at best predict the weather about ten days in advance, while changes in Earth's climate can and have been accurately predicted for decades. There is of course the practical consideration that there is no way to know the air temperature, humidity, wind and pressure at every point. There is also a more fundamental issue, the butterfly effect described earlier: small and local changes in the atmosphere can domino into much larger changes. In mathematical parlance, the evolution of a weather system (and a great many other natural phenomena) is chaotic and *nonlinear*.

Klaus Hasselmann linked climate and weather by making an analogy to a signal and its noise. Hasselmann was born in 1931 in Hamburg, Germany, to a family which was politically active with the Social Democratic Party of Germany (SPD). They fled to England in 1934 to escape the Nazi persecution of communists and social democrats, eventually settling in Welwyn Garden City, England. Hasselmann only returned to Hamburg in 1949, well after the defeat of the Nazis by the Soviet Union and other Allied powers. He completed his education at the University of Hamburg and has worked there and at the Max Planck Institute for Meteorology, which he founded, for most of his career.

Hasselmann's early research was on the connection between small fluctuations on the ocean's surface and larger waves and currents. Rather than trying to keep track of each ripple in the water, he observed that the deviations caused by these ripples, the "noise," ultimately produced an average result for many large-scale oceanic properties, the "signal." This stochastic (probabilistic) method was able to show that rapidly changing local conditions produce slow variations in the ocean as a whole.

He then generalized his results for climate as a whole. Instead of identifying small changes in the ocean, Hasselmann isolated changes in solar radiation, levels of greenhouse gases and other factors and treated them as noise that over time averaged out to changes in the climate as a whole. In doing so, he also provided a way to identify changes caused specifically by humans on the climate system. All subsequent climate research has used Hasselmann's work to find many impacts of human agricultural and industrial activity on the climate through numerous independent observations.

The mathematics that connects weather to climate is not limited, however, to merely meteorological studies. They are a subset of a much broader field of physics known as statistical mechanics and the mathematical studies of the disordered systems known as chaos theory.

Statistical mechanics was developed by James C. Maxwell, Ludwig Boltzmann and J. Willard Gibbs in the second half of the 19th century. They were driven by the inability of Newtonian mechanics to describe the motion of gases, liquids and any system that contained large numbers of particles. Rather than try to find the initial position and momentum of each particle, they treated the motion of each particle as random, and proceeded to calculate the average physical properties of the ensemble as a whole.

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Temperature, for example, is a macroscopic property of a gas that can be calculated as the average energy of each microscopic gas particle. Pressure is the macroscopic property produced by the average force of numerous microscopic particles as they impact and bounce off a surface.

Chaos theory again confirms that underneath the apparent random motion of a complex system are underlying patterns and organization. It was initially largely developed by the great polymath Henri Poincaré, who showed the orbits of restricted classes of three or more planetary bodies can simultaneously constantly change in unstable ways, but within knowable bounds.

These two fields were used by Giorgio Parisi to solve the puzzle of materials known as spin glasses. Parisi was born in Rome in 1948 and received his doctorate in physics at the University of Rome La Sapienza in 1970. He has since worked as a researcher at the Laboratori Nazionali di Frascati, Columbia University and many others. He is currently a professor at the Sapienza University of Rome and is the president of one of the oldest European scientific organizations, the Accademia dei Lincei.

Parisi's theoretical work with spin glasses made him internationally known. Consider a metal alloy of copper atoms with a few iron atoms randomly mixed in. Each iron atom acts like a small magnet, which prior physical theory suggested should align their orientation in the same direction. Iron atoms scattered throughout copper instead are frustrated—some point in one direction while others point in the opposite. Through the 1970s, while the material could be made and observed, there was no physical model that described how the orientation of the iron atoms could stay in a random stable state and not locally self-organize, as in ordinary magnets.

Parisi's solution was simple and ingenious; rather than allow for only two states, up and down, he allowed for an infinite number of orientations of the iron atoms. And he found an ingenious mathematical simplification, known as the "replica trick," that allowed the otherwise intractable problem to be easily solved. This technique has since been applied to many other fields of science, from quantum field theory to the development of machine-learning algorithms.

Another point arises from both statistical mechanics and chaos theory: by clearly defining the randomness and disorder of a system, one can predict certain broad outcomes of nonlinear systems. One can also measure with high precision when those predictions break down and need to be reexamined. In other words, the seemingly random evolution of and chaotic nature of matter still admits *knowable properties*.

This is a subtle point. These theories, and science in general, do not state that everything everywhere is known. Rather, every aspect of nature, no matter how complex, is governed by laws that can be used to understand and predict phenomena. Most importantly, these laws can be understood by human beings developing ever more correct approximations of reality, all of which have steadily increased our mastery over nature.

That nature is knowable also has social implications. The need to avert an ecological catastrophe induced by climate change is one example. The immense dangers presented by the ongoing coronavirus pandemic are another.

On the microscopic scale, the spread of the disease is governed broadly by its reproductive number, how many other people will be infected by a single person. The Delta variant of SARS-CoV-2 is estimated to have an initial reproductive number of six. On the macroscopic scale, however, the fact that the deadly contagion persists nearly two years after it was first identified is bound up with the much more complex system of social ties governed by the division of the world into rival nation-states and the drive for the accumulation of private profit, capitalism.