PHYS ORG

Physics Nobel rewards work on complex systems, like climate

October 5 2021

Secretary General of the Royal Swedish Academy of Sciences Goran Hansson, center, flanked at left by member of the Nobel Committee for Physics Thors Hans Hansson, left, and member of the Nobel Committee for Physics John Wettlaufer, right, announces the winners of the 2021 Nobel Prize in Physics at the Royal Swedish Academy of Sciences, in Stockholm, Sweden, Tuesday, Oct. 5, 2021. The Nobel Prize for physics has been awarded to scientists from Japan, Germany and Italy. Syukuro Manabe and Klaus Hasselmann were cited for their

work in "the physical modeling of Earth's climate, quantifying variability and reliably predicting global warming". The second half of the prize was awarded to Giorgio Parisi for "the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales." Credit: Pontus Lundahl/TT via AP

Three scientists won the Nobel Prize in physics Tuesday for work that found order in seeming disorder, helping to explain and predict complex forces of nature, including expanding our understanding of climate change.

Syukuro Manabe, originally from Japan, and Klaus Hasselmann of Germany were cited for their work in developing forecast models of Earth's climate and "reliably predicting global warming." The second half of the prize went to Giorgio Parisi of Italy for explaining disorder in physical systems, ranging from those as small as the insides of atoms to the planet-sized.

Hasselmann told The Associated Press that he "would rather have no global warming and no Nobel Prize."

Manabe said that figuring out the physics behind climate change was "1,000 times" easier than getting the world to do something about it. He said the intricacies of policy and society are far harder to fathom than the complexities of carbon dioxide interacting with the atmosphere, which then changes conditions in the ocean and on the land, which then alters the air again in a constant cycle.

He called climate change "a major crisis."

The prize comes less than four weeks before the start of high-level

climate negotiations in Glasgow, Scotland, where world leaders will be asked to ramp up their commitments to curb global warming.

The Nobel-winning scientists used their moment in the limelight to urge action.

"It's very urgent that we take very strong decisions and move at a very strong pace" in tackling global warming, Parisi said. He made the appeal even though his share of the prize was for work in a different area of physics.

All three scientists work on what are known as "complex systems," of which climate is just one example. But the prize went to two fields of study that are opposite in many ways, though they share the goal of making sense of what seems random and chaotic so that it can be predicted.

Parisi's research largely centers around subatomic particles, predicting how they move in seemingly chaotic ways and why, and is somewhat esoteric, while the work by Manabe and Hasselmann is about large-scale global forces that shape our daily lives.

Syukuro Manabe, right, speaks to reporters at his home in Princeton, N.J., Tuesday, Oct. 5, 2021. Manabe and two other scientists have won the Nobel Prize for physics for work that found order in seeming disorder, helping to explain and predict complex forces of nature, including expanding our understanding of climate change. Credit: AP Photo/Seth Wenig

Italian theoretical physicist Giorgio Parisi , center, poses for a selfie photo with his colleagues at the Accademia dei Lincei , Tuesday, Oct. 5, 2021, in Rome, after being awarded the 2021 Nobel Prize for Physics, together with Syukuro Manabe and Klaus Hasselmann, by The Royal Swedish Academy of Sciences in Stockholm. Credit: AP Photo/Domenico Stinellis

The judges said Manabe, 90, and Hasselmann, 89, "laid the foundation of our knowledge of the Earth's climate and how human actions influence it."

Starting in the 1960s, Manabe, now based at Princeton University, created the first climate models that forecast what would happen as carbon dioxide built up in the atmosphere.

Scientists for decades had shown that carbon dioxide traps heat, but Manabe's work offered specifics. It allowed scientists to eventually show how climate change will worsen and how fast, depending on how much carbon pollution is spewed.

Manabe is such a pioneer that other climate scientists called his 1967 paper with the late Richard Wetherald "the most influential climate paper ever," said NASA chief climate modeler Gavin Schmidt. Manabe's Princeton colleague Tom Delworth called Manabe "the Michael Jordan of climate."

Giorgio Parisi poses for photos in Rome, Tuesday, Oct. 5, 2021. The Nobel Prize for physics has been awarded to scientists from Japan, Germany and Italy. Syukuro Manabe and Klaus Hasselmann were cited for their work in "the physical modeling of Earth's climate, quantifying variability and reliably

predicting global warming". The second half of the prize was awarded to Giorgio Parisi for "the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales." Credit: Cecilia Fabiano/LaPresse via AP

"Suki set the stage for today's climate science, not just the tool but also how to use it," said fellow Princeton climate scientist Gabriel Vecchi. "I can't count the times that I thought I came up with something new, and it's in one of his papers."

Manabe's models from 50 years ago "accurately predicted the warming that actually occurred in the following decades," said climate scientist Zeke Hausfather of the Breakthrough Institute. Manabe's work serves "as a warning to us all that we should take their projections of a much warmer future if we keep emitting carbon dioxide quite seriously."

"I never imagined that this thing I would begin to study has such a huge consequence," Manabe said at a Princeton news conference. "I was doing it just because of my curiosity."

About a decade after Manabe's initial work, Hasselmann, of the Max Planck Institute for Meteorology in Hamburg, Germany, helped explain why climate models can be reliable despite the seemingly chaotic nature of the weather. He also developed ways to look for specific signs of human influence on the climate.

Climate researcher Klaus Hasselmann stands on the balcony of his apartment in Hamburg, Germany, Tuesday, Oct.5, 2021. This year's Nobel Prize in Physics goes to the German Klaus Hasselmann, Syukuro Manabe (USA) and the Italian Giorgio Parisi for physical models of the Earth's climate. Credit: Georg Wendt/dpa via AP

Meanwhile, Parisi, of Sapienza University of Rome, "built a deep physical and mathematical model" that made it possible to understand complex systems in fields as different as mathematics, biology, neuroscience and machine learning.

His work originally focused on so-called spin glass, a type of metal alloy whose behavior long baffled scientists. Parisi, 73, discovered hidden patterns that explained the way it acted, creating theories that could be

applied to other fields of research, too.

All three physicists used complex mathematics to explain and predict what seemed like chaotic forces of nature. That is known as modeling.

"Physics-based climate models made it possible to predict the amount and pace of global warming, including some of the consequences like rising seas, increased extreme rainfall events and stronger hurricanes, decades before they could be observed," said German climate scientist and modeler Stefan Rahmstorf. He called Hasselmann and Manabe pioneers in this field.

Italian theoretical physicist Giorgio Parisi speaks to journalists as he arrives at the Accademia dei Lincei , Tuesday, Oct. 5, 2021, in Rome, after being awarded the 2021 Nobel Prize for Physics, together with Syukuro Manabe and Klaus

Hasselmann, by The Royal Swedish Academy of Sciences in Stockholm. Credit: AP Photo/Domenico Stinellis

When climate scientists with the United Nations' Intergovernmental Panel on Climate Change and former U.S. Vice President Al Gore won the 2007 Nobel Peace Prize, some who deny global warming dismissed it as a political move. Perhaps anticipating controversy, members of the Swedish Academy of Sciences, which awards the Nobel, emphasized that Tuesday's was a science prize.

"What we are saying is that the modeling of climate is solidly based on physical theory and well-known physics," Swedish physicist Thors Hans Hansson said at the announcement.

For a scientist who trades in predictions, Hasselmann said the prize caught him off guard.

"I was quite surprised when they called," he said. "I mean, this is something I did many years ago."

But Parisi said: "I knew there was a non-negligible possibility" of winning.

Syukuro Manabe speaks to reporters at his home in Princeton, N.J., Tuesday, Oct. 5, 2021. Manabe and two other scientists have won the Nobel Prize for physics for work that found order in seeming disorder, helping to explain and predict complex forces of nature, including expanding our understanding of climate change. Credit: AP Photo/Seth Wenig

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Climate researcher Klaus Hasselmann sits in his apartment in Hamburg, Germany, Tuesday, Oct.5, 2021. This year's Nobel Prize in Physics goes to the German Klaus Hasselmann, Syukuro Manabe (USA) and the Italian Giorgio Parisi for physical models of the Earth's climate. Credit: Georg Wendt/dpa via AP

Italian Scientist Giorgio Parisi uses his phone on the balcony of his home in Rome, Tuesday, Oct. 5, 2021. The Nobel Prize for physics has been awarded to scientists from Japan, Germany and Italy. Syukuro Manabe and Klaus Hasselmann were cited for their work in "the physical modeling of Earth's climate, quantifying variability and reliably predicting global warming". The second half of the prize was awarded to Giorgio Parisi for "the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales." Credit: AP Photo/Alessandra Tarantino

Giorgio Parisi, center, opens a bottle of sparkling wine at the Accademia dei Lincei scientific institution in Rome, Tuesday, Oct. 5, 2021. The Nobel Prize for physics has been awarded to scientists from Japan, Germany and Italy. Syukuro Manabe and Klaus Hasselmann were cited for their work in "the physical modeling of Earth's climate, quantifying variability and reliably predicting global warming". The second half of the prize was awarded to Giorgio Parisi for "the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales." Credit: Cecilia Fabiano/LaPresse via AP

Italian theoretical physicist Giorgio Parisi, right, is passed phone calls by colleague Massimo Inguscio, president of the Italian National Research Council, as he arrives at the Accademia dei Lincei, Tuesday, Oct. 5, 2021, in Rome, after being awarded the 2021 Nobel Prize for Physics, together with Syukuro Manabe and Klaus Hasselmann, by The Royal Swedish Academy of Sciences in Stockholm. Credit: AP Photo/Domenico Stinellis

Pedestrians take copies of an extra edition of the Yomiuri newspaper reporting scientist Syukuro Manabe was awarded the 2021 Nobel Prize in physics in Tokyo, Tuesday, Oct. 5, 2021. Credit: AP Photo/Koji Sasahara

The award comes with a gold medal and 10 million Swedish kronor (over $1.14 million). The money comes from a bequest left by the prize's creator, Swedish inventor Alfred Nobel, who died in 1895.

On Monday, the Nobel in medicine was awarded to Americans David Julius and Ardem Patapoutian for their discoveries into how the human body perceives temperature and touch.

Over the coming days prizes will be awarded in the fields of chemistry, literature, peace and economics.

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Nobel Committee Press release: The Nobel Prize in Physics 2021

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2021

"for groundbreaking contributions to our understanding of complex physical systems"

with one half jointly to

Syukuro Manabe

Princeton University, USA

Klaus Hasselmann

Max Planck Institute for Meteorology, Hamburg, Germany

"for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

and the other half to

Giorgio Parisi

Sapienza University of Rome, Italy

"for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales"

Physics for climate and other complex phenomena

Three Laureates share this year's Nobel Prize in Physics for their studies of chaotic and apparently random phenomena. Syukuro Manabe and Klaus Hasselmann laid the foundation of our knowledge of the Earth's climate and how humanity influences it. Giorgio Parisi is rewarded for his revolutionary contributions to the theory of disordered materials and random processes.

Complex systems are characterised by randomness and disorder and are difficult to understand. This year's Prize recognises new methods for describing them and predicting their long-term behaviour.

One complex system of vital importance to humankind is Earth's climate. Syukuro Manabe demonstrated how increased levels of carbon dioxide in the atmosphere lead to increased temperatures at the surface of the Earth. In the 1960s, he led the development of physical models of the Earth's climate and was the first person to explore the interaction between radiation balance and the vertical transport of air masses. His work laid the foundation for the development of current climate models.

About ten years later, Klaus Hasselmann created a model that links together weather and climate, thus answering the question of why climate models can be reliable despite weather being changeable and chaotic. He also developed methods for identifying specific signals, fingerprints, that both natural phenomena and human activities imprint in he climate. His methods have been used to prove that the increased temperature in the atmosphere is due to human emissions of carbon dioxide.

Around 1980, Giorgio Parisi discovered hidden patterns in disordered complex materials. His discoveries are among the most important contributions to the theory of complex systems. 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, neuroscience and machine learning.

"The discoveries being recognised this year demonstrate that our knowledge about the climate rests on a solid scientific foundation, based on a rigorous analysis of observations. This year's Laureates have all contributed to us gaining deeper insight into the properties and evolution of complex physical systems," says Thors Hans Hansson, chair of the Nobel Committee for Physics.

Popular information

They found hidden patterns in the climate and in other complex phenomena

Three Laureates share this year's Nobel Prize in Physics for their studies of complex phenomena. Syukuro Manabe and Klaus Hasselmann laid the foundation of our knowledge of the Earth's climate and how humanity influences it. Giorgio Parisi is rewarded for his revolutionary contributions to the theory of disordered and random phenomena.

All complex systems consist of many different inter-acting parts. They have been studied by physicists for a couple of centuries, and can be difficult to describe mathematically – they may have an enormous number of components or be governed by chance. They could also be chaotic, like the weather, where small deviations in initial values result in huge differences at a later stage. This year's Laureates have all contributed to us gaining greater knowledge of such systems and their long-term development.

The Earth's climate is one of many examples of complex systems. Manabe and Hasselmann are awarded the Nobel Prize for their pioneering work on developing climate models. Parisi is rewarded for his theoretical solutions to a vast array of problems in the theory of complex systems.

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The greenhouse effect is vital to life

Two hundred years ago, French physicist Joseph Fourier studied the

energy balance between the sun's radiation towards the ground and the radiation from the ground. He understood the atmosphere's role in this balance; at the Earth's surface, the incoming solar radiation is transformed into outgoing radiation – "dark heat" – which is absorbed by the atmosphere, thus heating it. The atmosphere's protective role is now called the greenhouse effect. This name comes from its similarity to the glass panes of a greenhouse, which allow through the heating rays of the sun, but trap the heat inside. However, the radiative processes in the atmosphere are far more complicated.

The task remains the same as that undertaken by Fourier – to investigate the balance between the shortwave solar radiation coming towards our planet and Earth's outgoing longwave, infrared radiation. The details were added by many climate scientists over the following two centuries. Contemporary climate models are incredibly powerful tools, not only for understanding the climate, but also for understanding the global heating for which humans are responsible.

These models are based on the laws of physics and have been developed from models that were used to predict the weather. Weather is described by meteorological quantities such as temperature, precipitation, wind or clouds, and is affected by what happens in the oceans and on land. Climate models are based upon the weather's calculated statistical properties, such as average values, standard deviations, highest and lowest measured values, etcetera. They cannot tell us what the weather will be in Stockholm on 10 December next year, but we can get some idea of what temperature or how much rainfall we can expect on average in Stockholm in December.

Establishing the role of carbon dioxide

The greenhouse effect is essential for life on Earth. It governs temperature because the greenhouse gases in the atmosphere – carbon

dioxide, methane, water vapour and other gases – first absorb the Earth's infrared radiation and then release this absorbed energy, heating up the surrounding air and the ground below it.

Greenhouse gases actually comprise a very small proportion of the Earth's dry atmosphere, which is largely nitrogen and oxygen – these are 99 per cent by volume. Carbon dioxide is just 0.04 per cent by volume. The most powerful greenhouse gas is water vapour, but we cannot control the concentration of water vapour in the atmosphere, while we can control that of carbon dioxide.

The amount of water vapour in the atmosphere is highly dependent on temperature, leading to a feed-back mechanism. More carbon dioxide in the atmosphere makes it warmer, allowing more water vapour to be held in the air, which increases the greenhouse effect and makes temperatures rise even further. If the carbon dioxide level drops, some of the water vapour will condense and the temperature will fall.

An important first piece of the puzzle about the impact of carbon dioxide came from Swedish researcher and Nobel Laureate Svante Arrhenius. Incidentally, it was his colleague, meteorologist Nils Ekholm who, in 1901, was the first to use the word greenhouse in describing the atmosphere's storage and re-radiation of heat.

Arrhenius understood the physics responsible for the greenhouse effect by the end of the 19th century – that outgoing radiation is proportional to the radiant body's absolute temperature (T) to the power of four (T^4). The hotter the source of the radiation, the shorter the rays' wavelength. The Sun has a surface temperature of 6,000°C and primarily emits rays in the visible spectrum. Earth, with a surface temperature of just 15°C, re-radiates infrared radiation that is invisible to us. If the atmosphere did not absorb this radiation, the surface temperature would barely exceed –18°C.

Arrhenius was actually attempting to work out what caused the recently discovered phenomenon of ice ages. He arrived at the conclusion that if the level of carbon dioxide in the atmosphere halved, this would be enough for the Earth to enter a new ice age. And vice versa – a doubling of the amount of carbon dioxide would increase the temperature by 5–6°C, a result which, somewhat fortuitously, is astoundingly close to current estimates.

Pioneering model for the effect of carbon dioxide

In the 1950s, Japanese atmospheric physicist Syukuro Manabe was one of the young and talented researchers in Tokyo who left Japan, which had been devastated by war, and continued their careers in the US. The aim of Manabes's research, like that of Arrhenius around seventy years earlier, was to understand how increased levels of carbon dioxide can cause increased temperatures. However, while Arrhenius had focused on radiation balance, in the 1960s Manabe led work on the development of physical models to incorporate the vertical transport of air masses due to convection, as well as the latent heat of water vapour.

To make these calculations manageable, he chose to reduce the model to one dimension – a vertical column, 40 kilometres up into the atmosphere. Even so, it took hundreds of valuable computing hours to test the model by varying the levels of gases in the atmosphere. Oxygen and nitrogen had negligible effects on surface temperature, while carbon dioxide had a clear impact: when the level of carbon dioxide doubled, global temperature increased by over 2°C.

The model confirmed that this heating really was due to the increase in carbon dioxide, because it predicted rising temperatures closer to the ground while the upper atmosphere got colder. If variations in solar radiation were responsible for the increase in temperature instead, the entire atmosphere should have been heating at the same time.

Sixty years ago, computers were hundreds of thousands of times slower than they are now, so this model was relatively simple, but Manabe got the key features right. You must always simplify, he says. You cannot compete with the complexity of nature – there is so much physics involved in every raindrop that it would never be possible to compute absolutely everything. The insights from the onedimensional model led to a climate model in three dimensions, which Manabe published in 1975; this was yet another milestone on the road to understanding the climate's secrets.

Weather is chaotic

About ten years after Manabe, Klaus Hasselmann succeeded in linking together weather and climate by finding a way to outsmart the rapid and chaotic weather changes that were so troublesome for calculations. Our planet has vast shifts in its weather because solar radiation is so unevenly distributed, both geographically and over time. Earth is round, so fewer of the sun's rays reach the higher latitudes than the lower ones around the Equator. Not only this, but the Earth's axis is tilted, producing seasonal differences in incoming radiation. The differences in density between warmer and colder air cause the colossal transports of heat between different latitudes, between ocean and land, between higher and lower air masses, which drive the weather on our planet.

As we all know, making reliable predictions about the weather for more than the next ten days is a challenge. Two hundred years ago, the renowned French scientist, Pierre-Simon de Laplace, stated that if we just knew the position and speed of all the particles in the universe, it should be possible to both calculate what has happened and what will happen in our world. In principle, this should be true; Newton's three-century old laws of motion, which also describe air transport in the atmosphere, are entirely deterministic – they are not governed by chance.

However, nothing could be more wrong when it comes to the weather. This is partly because, in practice, it is impossible to be precise enough – to state the air temperature, pressure, humidity or wind conditions for every point in the atmosphere. Also, the equations are nonlinear; small deviations in initial values can make a weather system evolve in entirely different ways. Based on the question of whether a butterfly flapping its wings in Brazil could cause a tornado in Texas, the phenomenon was named the butterfly effect. In practice, this means that it is impossible to produce long-term weather forecasts – the weather is chaotic; this discovery was made in the 1960s by the American meteorologist Edward Lorenz, who laid the foundation of today's chaos theory.

Making sense of noisy data

How can we produce reliable climate models for several decades or hundreds of years into the future, despite weather being a classic example of a chaotic system? Around 1980, Klaus Hasselmann demonstrated how chaotically changing weather phenomena can be described as rapidly changing noise, thus placing long-term climate forecasts on a firm scientific foundation. Furthermore, he developed methods for identifying human impact on the observed global temperature.

As a young doctoral student in physics in Hamburg, Germany, in the 1950s, Hasselmann worked on fluid dynamics, then began to develop observations and theoretical models for ocean waves and currents. He moved to California and continued with oceanography, meeting colleagues such as Charles David Keeling, with whom the Hasselmanns started a madrigal choir. Keeling is legendary for beginning, back in 1958, what is now the longest series of atmospheric carbon dioxide measurements at the Mauna Loa Observatory in Hawaii. Little did Hasselmann know that in his later work he would regularly use the Keeling Curve, which shows changes in the carbon dioxide levels.

Obtaining a climate model from noisy weather data can be illustrated by walking a dog: the dog runs off the lead, backwards and forwards, side to side and around your legs. How can you use the dog's tracks to see whether you are walking or standing still? Or whether you are walking quickly or slowly? The dog's tracks are the changes in the weather, and your walk is the calculated climate. Is it even possible to draw conclusions about long-term trends in the climate using chaotic and noisy weather data?

One additional difficulty is that the fluctuations that influence the climate are extremely variable over time – they may be rapid, such as in wind strength or air temperature, or very slow, such as melting ice sheets and warming oceans. For example, uniform heating by just one degree can take a thousand years for the ocean, but just a few weeks for the atmosphere. The decisive trick was incorporating the rapid changes in the weather into the calculations as noise, and showing how this noise affects the climate.

Hasselmann created a stochastic climate model, which means that chance is built into the model. His inspiration came from Albert Einstein's theory of Brownian motion, also called a random walk. Using this theory, Hasselmann demonstrated that the rapidly changing atmosphere can actually cause slow variations in the ocean.

Discerning traces of human impact

Once the model for climate variations was finished, Hasselmann developed methods for identifying human impact on the climate system. He found that the models, along with observations and theoretical considerations, contain adequate information about the properties of noise and signals. For example, changes in solar radiation, volcanic particles or levels of greenhouse gases leave unique signals, fingerprints, which can be separated out. This method for identifying fingerprints can

also be applied to the effect that humans have on the climate system. Hasselman thus cleared the way to further studies of climate change, which have demonstrated traces of human impact on the climate using a large number of independent observations.

Climate models have become increasingly refined as the processes included in the climate's complicated interactions are mapped more thoroughly, not least through satellite measurements and weather observations. The models clearly show an accelerating greenhouse effect; since the mid-19th century, the levels of carbon dioxide in the atmosphere have increased by 40 per cent. Earth's atmosphere has not contained this much carbon dioxide for hundreds of thousands of years. Accordingly, temperature measurements show that the world has heated by 1°C over the past 150 years.

Syukuro Manabe and Klaus Hasselmann have contributed to the greatest benefit for humankind, in the spirit of Alfred Nobel, by providing a solid physical foundation for our knowledge of Earth's climate. We can no longer say that we did not know – the climate models are unequivocal. Is Earth heating up? Yes. Is the cause the increased amounts of greenhouse gases in the atmosphere? Yes. Can this be explained solely by natural factors? No. Are humanity's emissions the reason for the increasing temperature? Yes.

Methods for disordered systems

Around 1980, Giorgio Parisi presented his discoveries about how apparently random phenomena are governed by hidden rules. His work is now considered to be among the most important contributions to the theory of complex systems.

Modern studies of complex systems are rooted in the statistical mechanics developed in the second half of the 19th century by James C.

Maxwell, Ludwig Boltzmann and J. Willard Gibbs, who named this field in 1884. Statistical mechanics evolved from the insight that a new type of method was necessary for describing systems, such as gases or liquids, that consist of large numbers of particles. This method had to take the particles' random movements into account, so the basic idea was to calculate the particles' average effect instead of studying each particle individually. For example, the temperature in a gas is a measure of the average value of the energy of the gas particles. Statistical mechanics is a great success, because it provides a microscopic explanation for macroscopic properties in gases and liquids, such as temperature and pressure.

The particles in a gas can be regarded as tiny balls, flying around at speeds that increase with higher temperatures. When the temperature drops, or pressure increases, the balls first condense into a liquid and then into a solid. This solid is often a crystal, where the balls are organised in a regular pattern. However, if this change happens rapidly, the balls may form an irregular pattern that does not change even if the liquid is further cooled or squeezed together. If the experiment is repeated, the balls will assume a new pattern, despite the change happening in exactly the same way. Why are the results different?

Understanding complexity

These compressed balls are a simple model for ordinary glass and for granular materials, such as sand or gravel. However, the subject of Parisi's original work was a different kind of system – spin glass. This is a special type of metal alloy in which iron atoms, for example, are randomly mixed into a grid of copper atoms. Even though there are only a few iron atoms, they change the material's magnetic properties in a radical and very puzzling manner. Each iron atom behaves like a small magnet, or spin, which is affected by the other iron atoms close to it. In an ordinary magnet, all the spins point in the same direction, but in a

spin glass they are frustrated; some spin pairs want to point in the same direction and others in the opposite direction – so how do they find an optimal orientation?

In the introduction to his book about spin glass, Parisi writes that studying spin glass is like watching the human tragedies of Shakespeare's plays. If you want to make friends with two people at the same time, but they hate each other, it can be frustrating. This is even more the case in a classical tragedy, where strongly emotional friends and enemies meet on stage. How can the tension in the room be minimised?

Spin glasses and their exotic properties provide a model for complex systems. In the 1970s, many physicists, including several Nobel Laureates, searched for a way to describe the mysterious and frustrating spin glasses. One method they used was the replica trick, a mathematical technique in which many copies, replicas, of the system are processed at the same time. However, in terms of physics, the results of the original calculations were unfeasible.

In 1979, Parisi made a decisive breakthrough when he demonstrated how the replica trick could be ingeniously used to solve a spin glass problem. He discovered a hidden structure in the replicas, and found a way to describe it mathematically. It took many years for Parisi's solution to be proven mathematically correct. Since then, his method has been used in many disordered systems and become a cornerstone of the theory of complex systems.

The fruits of frustration are many and varied Both spin glass and granular materials are examples of frustrated systems, in which various constituents must arrange themselves in a manner that is a compromise between counteracting forces. The question is how they behave and what the results are. Parisi is a master at answering these questions for many different materials and phenomena. His fundamental discoveries about

the structure of spin glasses were so deep that they not only influenced physics, but also mathematics, biology, neuroscience and machine learning, because all these fields include problems that are directly related to frustration.

Parisi has also studied many other phenomena in which random processes play a decisive role in how structures are created and how they develop, and dealt with questions such as: Why do we have periodically recurring ice ages? Is there a more general mathematical description of chaos and turbulent systems? Or – how do patterns arise in a murmuration of thousands of starlings? This question may seem far removed from spin glass. However, Parisi has said that most of his research has dealt with how simple behaviours give rise to complex collective behaviours, and this applies to both spin glasses and starlings.

Advanced information: www.nobelprize.org/prizes/phys … dvanced-information/

More information:
www.nobelprize.org/prizes/physics/2021/summary/

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