1. 請任選所附上三篇科普文章其中之一篇（見附件 1, 附件 2, 附件 3), 仔細閱讀理解後, 用一千字左右寫出一篇能在新聞平台或是社群網站上能夠吸引點閱率並且能傳達所選文章中的科學相關重點的中文報導（包含標題）. 所有科學相關的專有名詞可以使用英文表達, 並且在報導外試著說明為何選擇在報導中使用文章內所附的特定圖表.（100 分）

附件 1 請見第 2~5 頁

附件 2 請見第 6~14 頁

附件 3 請見第 15~20 頁

見背面

附件 1

A mobile vaccination team at work during a house call in a remote region of Turkey.

CHRIS MCGRATH/GETTY

HOW COVID VACCINES SHAPED 2021 — IN EIGHT POWERFUL CHARTS

The extraordinary vaccination of more than four billion people, and lack of access for others, were major forces this year – while Omicron's arrival complicated things.

By Smriti Mallapaty, Ewen Callaway, Max Kozlov, Heidi Ledford, John Pickrell & Richard Van Noorden

A year ago, vaccine drives against COVID-19 were just beginning. Now, more than 4.4 billion people have had one or more dose – about 56% of the world population. The vaccination of so many in such a short space of time, so soon after the unparalleled rapid development of the vaccines, has saved huge numbers of lives and is a triumph for science and research.

Sadly, the vaccines have not been shared or taken up equitably across the world, nor even, sometimes, within nations. But the extraordinary roll-out of a plethora of COVID-19 vaccines – or the lack thereof – has been a major force shaping politics, science and everyday life in 2021. In this graphics-led story, *Nature* offers a guide to the successes, failures and impact of COVID-19 vaccines in 2021.

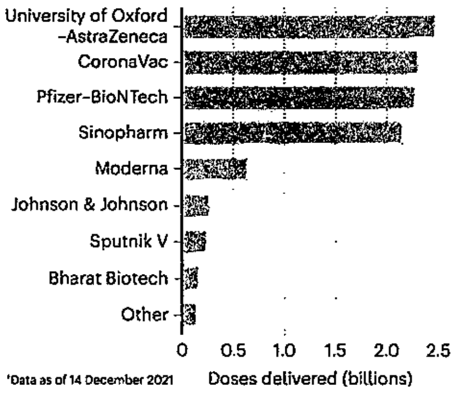
Winning the race

More than eight billion doses, mostly of eight front-runner vaccines, have now been administered around the world, the vast majority in 2021 (see 'The race to vaccinate'). "Just making that much vaccine has been the standout success," says Gagandeep Kang, a virologist at the Christian Medical College in Vellore, India.

"The vaccines have had a huge impact on averting deaths and helping countries' economies return to normal," says Soumya Swaminathan, chief scientist at the World Health Organization (WHO) in Geneva,

THE RACE TO VACCINATE

Nearly 10 billion doses of COVID-19 vaccine have been delivered around the world since mid-2020, 8.5 billion of which had been administered by late 2021. Eight different vaccines make up the vast majority of doses*.



*Data as of 14 December 2021

SOURCE: DATA FROM AIRFINITY

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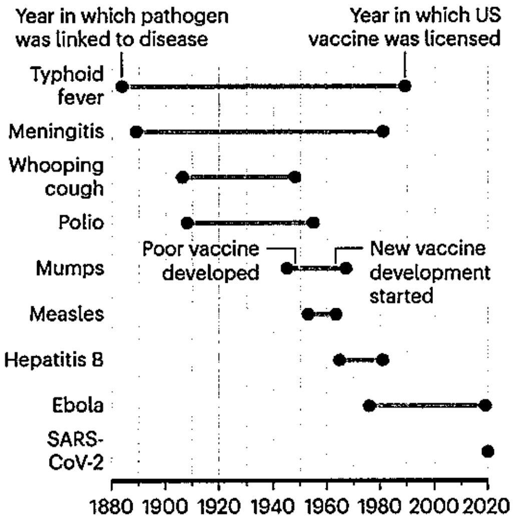
VACCINE INNOVATION

Most vaccines take years to develop, but scientists created multiple vaccines for SARS-CoV-2 within a year.



SOURCE: OUR WORLD IN DATA; *NATURE* ANALYSIS

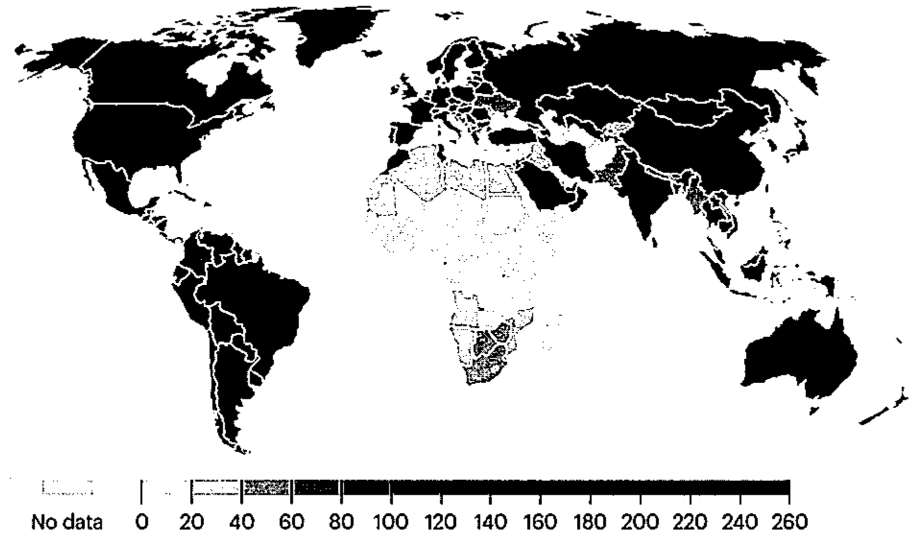
Switzerland. "In countries with high coverage, infections have been uncoupled from deaths, so that even with new surges of infection, deaths have stayed low."

Also noteworthy is the speed of vaccine development (see 'Vaccine innovation'). No vaccines in history have been developed so fast, yet 23 vaccines against SARS-CoV-2 have already been approved for use around the world – and hundreds more are in development.

It is estimated that this astonishingly rapid development and deployment has saved at least 750,000 lives in the United States and Europe alone – and probably many more globally, although researchers are as yet unwilling to commit to a number. A study by the WHO and the European Centre for Disease Prevention and Control in Solna, Sweden, published last month[1], estimated that 470,000 deaths had been averted across 33 European countries in those aged 60 and over alone. Another modelling study, which is yet to be peer reviewed, by epidemiologists at Yale University in New Haven, Connecticut, estimated that 279,000 lives had been saved by late June by the vaccination drive in the United States (see go.nature.com/3gs7kgy).

GLOBAL DOSES

Vaccines have been rolled out unevenly across the world, as shown by the number of COVID-19 vaccine doses administered per 100 people in the total population*.



*Data as of 29 November 2021. Data don't reflect the number of people who have been vaccinated because some people have received two doses of a vaccine. Nature publications remain neutral with regard to contested jurisdictional claims in published maps.

Vaccine haves and have-nots

But despite the astonishing success of the vaccines, it's a story of haves and have-nots, and the roll-out has been anything but equitable. "We were so together and so divided," says Kang. "Very together on the science, very divided on the access."

In the world's most-vaccinated nations, such as the United Arab Emirates, Chile and Cuba, more than 200 doses have been administered per 100 people – but at the opposite end of the scale, in places such as Tanzania, Afghanistan and Papua New Guinea, fewer than 20 people per 100 have received at least one dose (see 'Global doses').

"Vaccine inequity has been one of the most painful experiences of the pandemic," says Swaminathan, who notes that there now exist two parallel worlds. In some regions, infections have been uncoupled from deaths and life is normalizing. But in others, there is "fear in opening up, schools remain shut, long-term plans cannot be made, and surges in infections translate soon into higher deaths," she says.

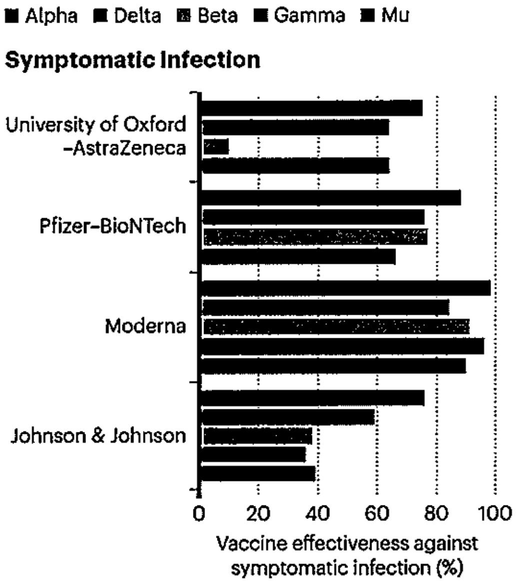
On average, in high-income countries, 83% of the eligible populations have had at least one shot, but in low-income countries that number falls to 21%. These figures "never cease to amaze", says Andrew Azman, an infectious-disease epidemiologist at Johns Hopkins University in Baltimore, Maryland, who co-authored an analysis on the inequities in doses, posted as a preprint[2] in October.

It was expected that poorer nations would get increased supplies once demand fell in wealthy nations, but most rich countries are now administering boosters. This, combined with the fact that many countries are stockpiling doses, could be contributing to a lack of access for those who really need them, says Kang.

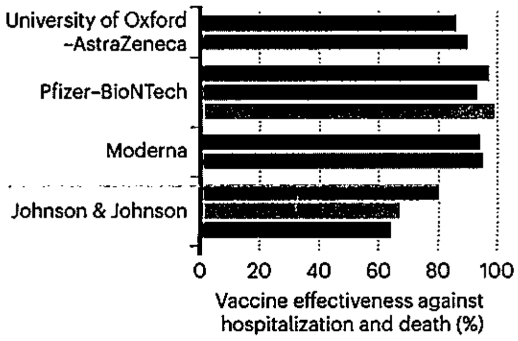
VARIANTS AND VACCINES

Over the course of the past year, the emergence of SARS-CoV-2 variants Alpha, Beta, Gamma, Delta and Mu has challenged the effectiveness of vaccines, although most have held their ground. How vaccines will fare in the face of highly mutated Omicron is yet to be determined*.

Symptomatic infection



Hospitalization/death



*Data as of 25 November. Estimates of vaccine effectiveness modelled by Airfinity, based on available data. Figures on effectiveness against hospitalization and death not available for all variants.

SOURCE: DATA FROM AIRFINITY

Disparities exist not just between countries, but also within them. One study in the United States found lower vaccination coverage in areas that had larger numbers of people on low incomes, or who were single parents, or who had disabilities[3]. Other studies show disparities in vaccination coverage along racial or ethnic lines[4].

Waning immunity and variants

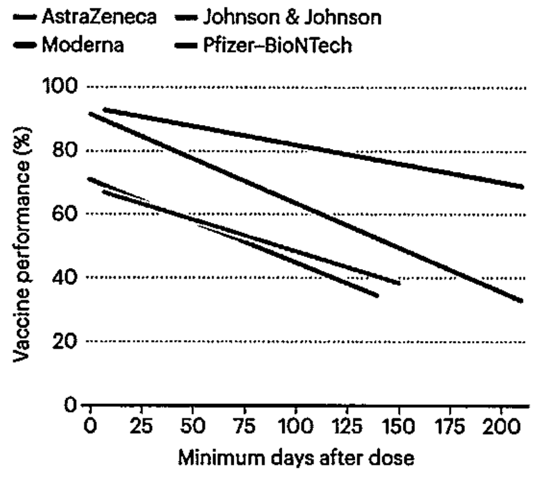
2021 was the year of COVID-19 vaccines, but it was also the year of variants. Researchers identified a trio of SARS-CoV-2 'variants of concern' in late 2020 and early 2021, now called Alpha, Beta and Gamma (see 'Variants and vaccines'). These seemed to spread faster than viral lineages in circulation earlier, and scientists worried that these variants might also blunt the effectiveness of vaccines.

Laboratory studies and real-world epidemiology confirmed that vaccines remained highly effective against the most widespread of the three, Alpha, which was identified in the United Kingdom. But Beta and Gamma – first

365 days the year in science

WANING IMMUNITY

The immunity conferred by COVID-19 vaccines, particularly to prevent infections, falls over time — as shown in these estimates of vaccine efficacy against Delta in the months following a second dose*



*Data as of 25 November 2021. Estimates of vaccine effectiveness modelled by Airfinity, based on available data.

SOURCE: DATA FROM AIRFINITY

spotted in South Africa and Brazil, respectively – were linked to reduced effectiveness of some vaccines, particularly those based on viral vectors, such as the Oxford–AstraZeneca vaccine, or on inactivated viruses, such as those developed in China and India.

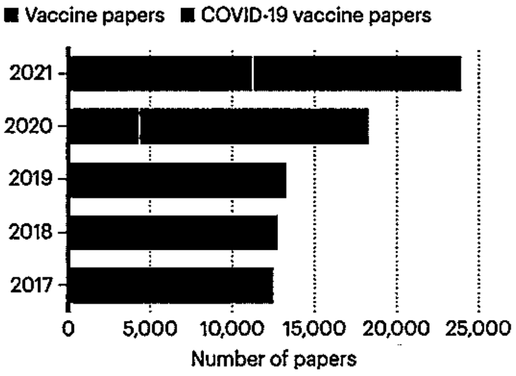
Delta, designated by the WHO as a variant of concern in May, is currently responsible for most new infections globally and has further challenged vaccines. Countries such as Israel, the United States and the United Kingdom that began their vaccination campaigns early are now seeing signs that vaccines lose their potency over time (see 'Waning immunity').

Despite these challenges, the vaccines are still doing a good job at protecting against the most severe forms of COVID-19, says Laith Jamal Abu-Raddad, an infectious-disease epidemiologist at Weill Cornell Medicine–Qatar in Doha. "We now have lots of data and we see a very clear pattern that the vaccines are working very well against severity."

However, researchers are racing to determine how different vaccines will hold up against the fast-spreading Omicron, designated a variant of concern in late November. A preliminary study from the United Kingdom found that two vaccine doses offer little protection against becoming infected with Omicron (a third booster dose restored vaccine effectiveness to above 70%). Researchers expect that vaccines will continue to prevent severe disease caused by the variant – but to what extent is not yet clear.

EXPLOSION OF KNOWLEDGE

More than 15,000 vaccine-related papers that mention COVID-19 or SARS-CoV-2 have been published since early last year; 11,000 were published in 2021 alone, making up an astonishing 47% of all vaccine-related publications this year*.



*Journal articles, preprints, and clinical trial reports indexed on the PubMed database. Data as of 24 November 2021.

SOURCE: DATA FROM PUBMED; *NATURE* ANALYSIS

New vaccines on the horizon

While a little less than half the world's population still awaits a first dose of a COVID-19 vaccine, researchers are developing more than 300 fresh options. (see 'Under development').

Some of these next-generation vaccines could have key advantages over those currently available. For example, protein vaccines use SARS-CoV-2 proteins to rouse the immune system, and promise to be easier to produce and transport than some existing vaccines.

In particular, two protein vaccines made by Novavax, in Gaithersburg, Maryland, and Clover Biopharmaceuticals in Chengdu, China, will be pivotal to hitting the COVID-19 Vaccines Global Access (COVAX) initiative's goal of distributing two billion doses to low-income nations next year, says Nicholas Jackson, head of programmes and innovative technology at the Coalition for Epidemic Preparedness Innovations (CEPI) in Oslo.

Other upcoming COVID-19 vaccines are being formulated so that they can be administered by mouth or inhaled through the nose, such as nasally administered vaccines being developed by CanSino in Tianjin, China, and AstraZeneca. Because these vaccines would be administered into tissues that SARS-CoV-2 first infiltrates when it enters the body, it is hoped that oral or nasal vaccines could work well to prevent infection. They would also require fewer trained personnel to administer.

Some COVID-19 vaccines are being developed to tackle specific SARS-CoV-2 variants or even a variety of coronaviruses. Three diseases caused by novel coronaviruses have already emerged in less than 20 years, says Jackson – severe acute respiratory syndrome (SARS) in 2002, Middle East respiratory syndrome (MERS) in 2012 and COVID-19 in late 2019. "A broadly protective coronavirus vaccine could revolutionize our response to future infectious-disease outbreaks," he says.

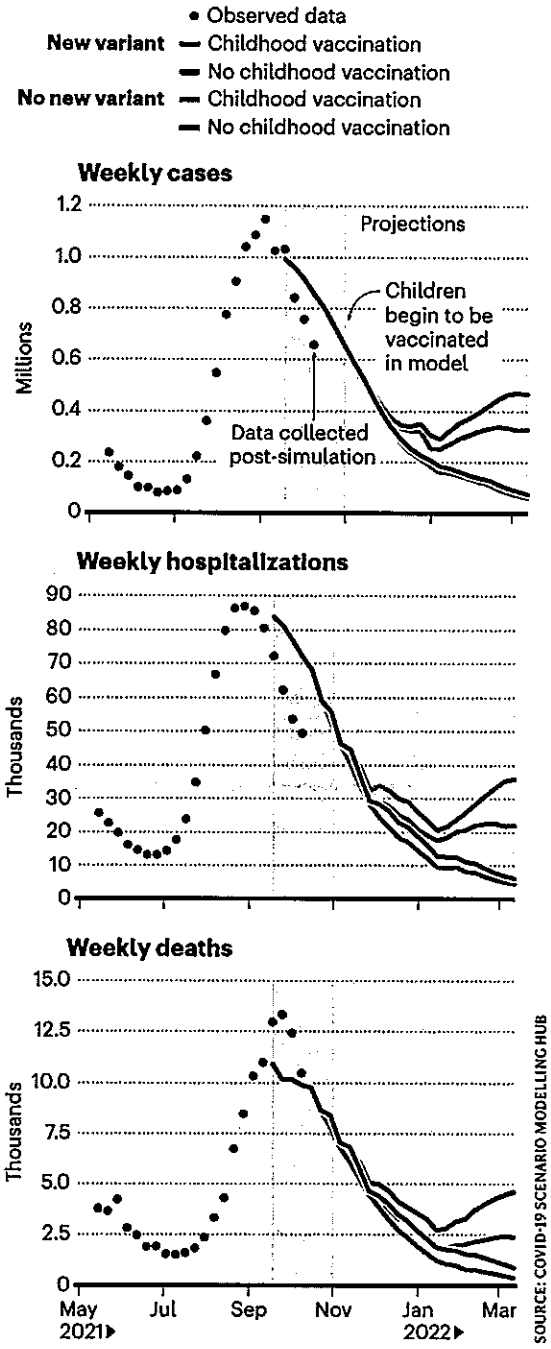
Vaccinating children

How the pandemic unfolds from now on might be driven not only by novel variants, but also by how quickly vaccines reach another large part of the global population that is yet to be vaccinated – children.

During 2021, the highly transmissible Delta variant caused a sharp rise in paediatric COVID-19 cases worldwide. Although only a relatively small proportion of kids develop severe disease, that still translates to huge numbers of severe cases globally, says Andrew Pavia, a paediatric infectious-disease researcher at the University of Utah Health in Salt Lake City. Widespread vaccination of children will limit the number of severe cases in that age group and help to control the spread of the virus, he says.

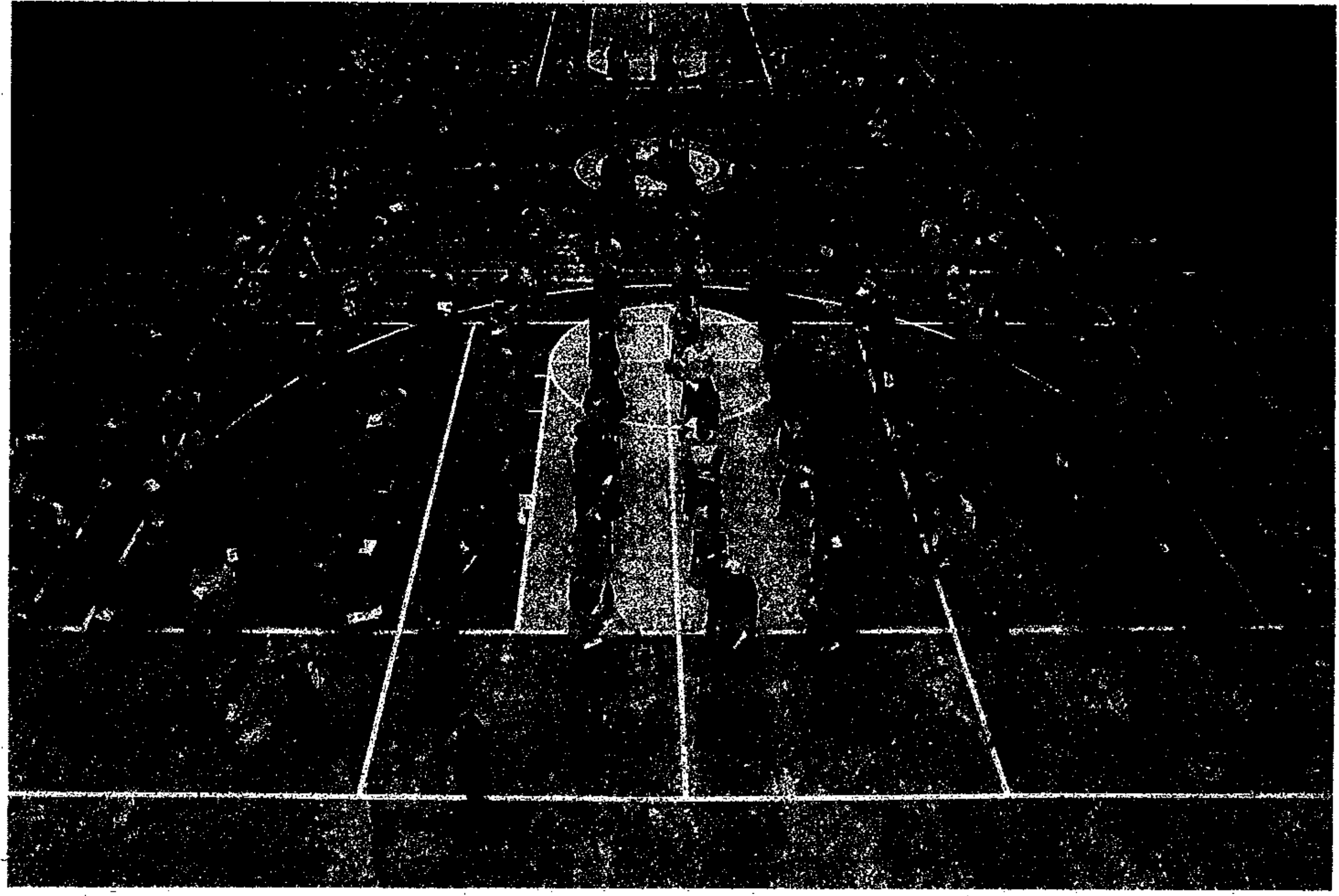
THE KID EFFECT

A simulation of the US pandemic, run in September and averaging multiple models, found that starting to vaccinate children aged 5 to 11 would not only lower COVID-19's toll, but would also have a large impact if a new, more transmissible coronavirus variant emerged.



SOURCE: COVID-19 SCENARIO MODELLING HUB

In the United States – where children have accounted for the largest numbers of COVID-19 cases of any age group since late October – the Food and Drug Administration (FDA) approved Pfizer–BioNTech's vaccine for the nation's roughly 28 million kids aged 5 to 11 in early November. Since then, more than five million children there have received a dose – and modelling studies run in September that looked at the impact in scenarios where there were no new variants and where there were, show that the benefits could be significant



ELOISA LOPEZ/REUTERS

People wait to get inoculated at a mass-vaccination hub in Manila.

– particularly now, as we face the impacts of Omicron (see 'The kid effect'). The same researchers are now starting to model the possible impacts of Omicron on case numbers in the United States.

Elsewhere, vaccinations for younger children have slowly been taking off too. Regulators in Canada and Israel, and the European Medicines Agency, for example, all provisionally approved the Pfizer vaccine for children in late November, followed by Australia in early December. Colombia, Chile, Argentina and Venezuela are all now offering China's Sinopharm vaccine to children.

Vaccine papers soar

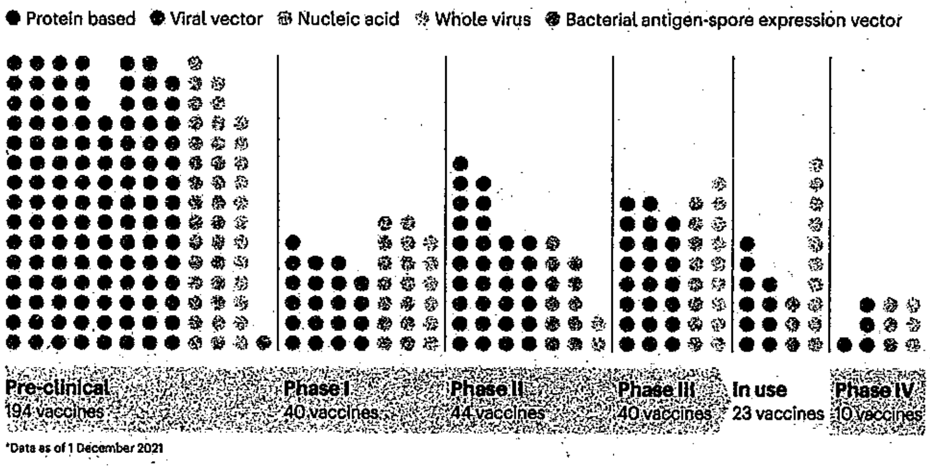
The development and deployment of COVID-19 vaccines has seen an extraordinary research effort over the past year. According to *Nature*'s calculations, at least 15,000 papers on vaccines mentioning COVID-19 or SARS-CoV-2 have been published since early last year, with more than 11,000 of those during 2021 (see 'Explosion of knowledge'). These made up more than 47% of all papers on vaccines published in 2021 – and made it a record-breaking year for vaccine-related publications.

The benefits of that research extend beyond just COVID-19 to vaccines more generally, say researchers. "Humanity coming together to develop and deploy vaccines has opened up a lot of doors for vaccines and understanding what they are, how they work and why we might want to use them in the future," says Azman.

Vaccines will continue to save lives and help some semblance of normal life to return, and energize researchers. But the extent to which the world curtails the pandemic in 2022 will depend on how quickly it provides access in low-income nations, administers boosters in populations with waning immunity, and provides doses to children – as well as the nature and extent of new variants, such as Omicron.

UNDER DEVELOPMENT

Researchers are developing more than 300 COVID-19 vaccines in addition to the 23 already in use around the world; 84 are in early-stage clinical trials and 40 are at much later stages of development*.



SOURCE: GAVI

*Data as of 1 December 2021

1. Meslé, M. M. I. *et al. Euro Surveill.* **26**, pii=2101021 (2021).
2. Chen, Z. *et al.* Preprint at medRxiv https://doi.org/10.1101/2021.10.25.21265504 (2021).
3. Barry, V. *et al. Morb. Mortal. Wkly Rep.* **70**, 818–824 (2021).
4. Wrigley-Field, E. *et al.* Preprint at medRxiv https://doi.org/10.1101/2021.11.19.21266612 (2021).

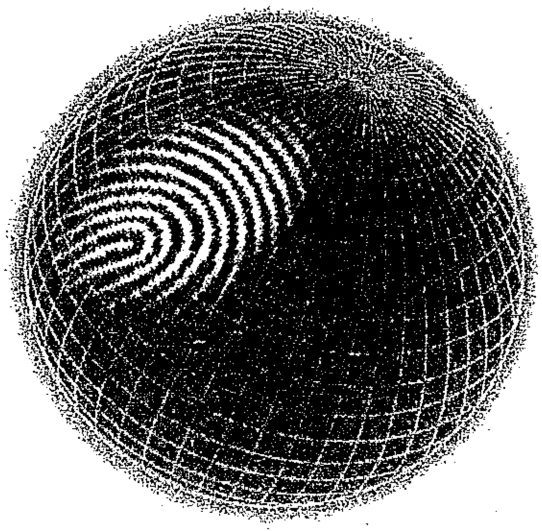
附件 2

THE NOBEL PRIZE IN PHYSICS 2021

POPULAR SCIENCE BACKGROUND

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 interacting 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.

Syukuro Manabe demonstrated how increased concentrations 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 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 the 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 complex materials and phenomena, not only in physics but also in other, very different areas, such as mathematics, biology, neuroscience and machine learning.

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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 feedback 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.

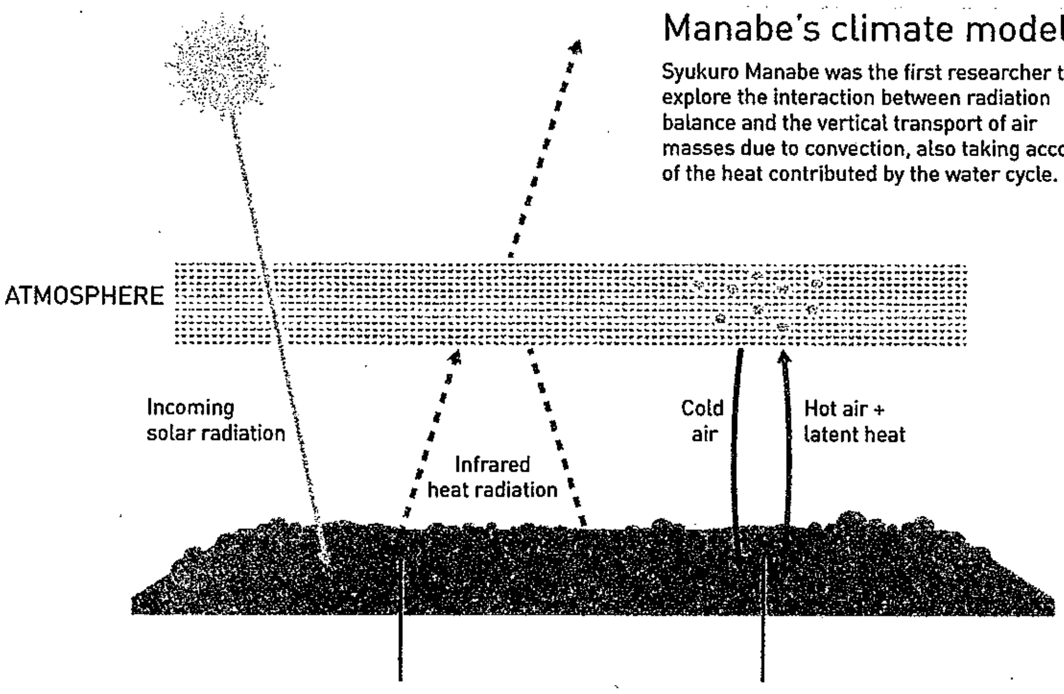
Arrhenius understood the physics responsible for the greenhouse effect by the end of the 19th century – that outgoing radiation is proportional to the radiant body's absolute temperature (T) to the power of four (T^4). The hotter the source of the radiation, the shorter the rays' wavelength. The Sun 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.



Manabe's climate model

Syukuro Manabe was the first researcher to explore the interaction between radiation balance and the vertical transport of air masses due to convection, also taking account of the heat contributed by the water cycle.

Infrared heat radiation from the ground is partially absorbed in the atmosphere, warming the air and the ground, while some radiates out into space.

Hot air is lighter than cold air, so it rises through convection. It also carries water vapour, which is a powerful greenhouse gas. The warmer the air, the higher the concentration of water vapour. Further up, where the atmosphere is colder, cloud drops form, releasing the latent heat stored in the water vapour.

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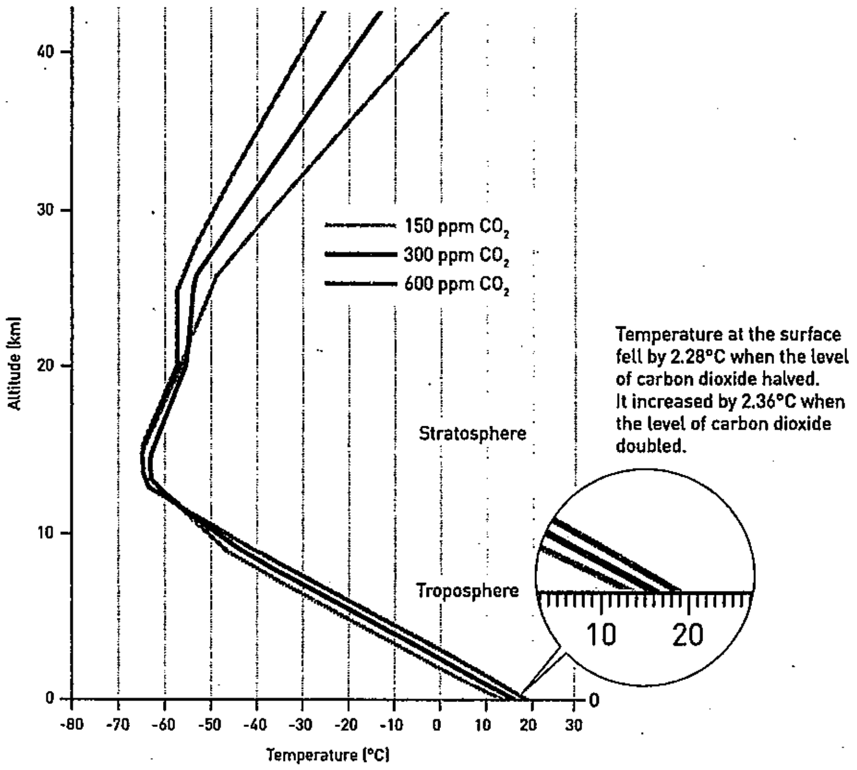
Carbon dioxide heats the atmosphere

Increased levels of carbon dioxide lead to higher temperatures in the lower atmosphere, while the upper atmosphere gets colder. Manabe thus confirmed that the variation in temperature is due to increased levels of carbon dioxide; if it was caused by increased solar radiation, the entire atmosphere should have warmed up.



Temperature at the surface fell by 2.28°C when the level of carbon dioxide halved. It increased by 2.36°C when the level of carbon dioxide doubled.

Source: Manabe and Wetherald (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity, *Journal of the atmospheric sciences*, Vol. 24, Nr 3, May.

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 one-dimensional 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.

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Discerning traces of human impact

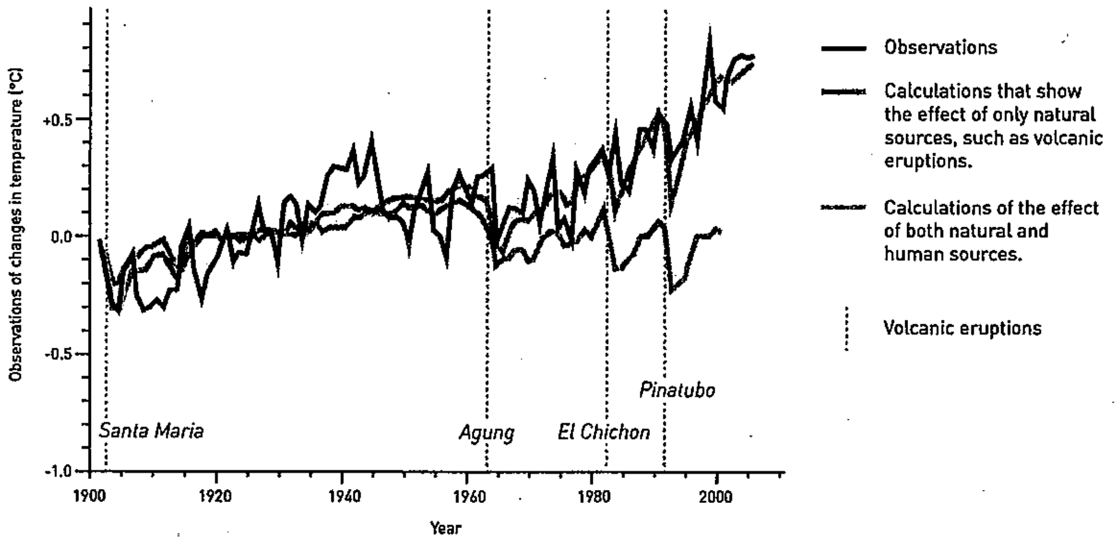
Once the model for climate variations was finished, Hasselmann developed methods for identifying human impact on the climate system. He found that the models, along with observations and theoretical considerations, contain adequate information about the properties of noise and signals. For example, changes 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.

Identifying fingerprints in the climate

Klaus Hasselmann developed methods for distinguishing between natural and human causes (fingerprints) of atmospheric heating. Comparison between changes in the mean temperature in relation to the average for 1901–1950 (°C).



Source: Hegerl and Zweirs (2011) Use of models in detection & attribution of climate change, *WIREs Climate Change*.

Methods for disordered systems

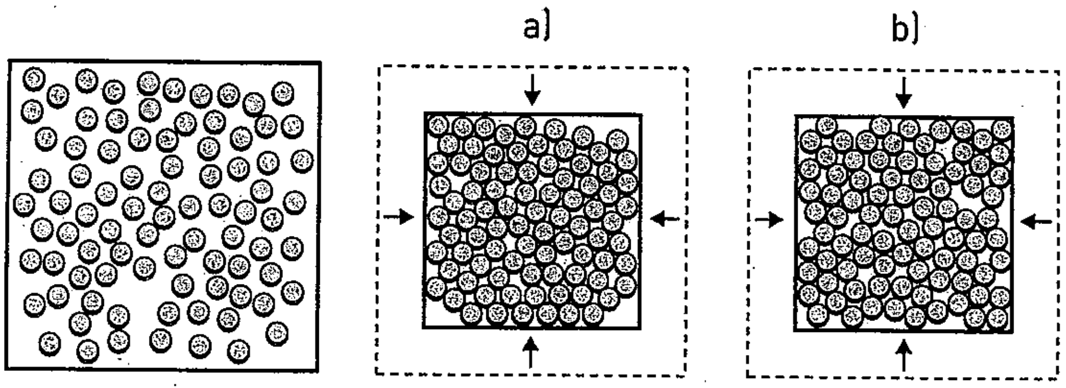
Around 1980, **Giorgio Parisi** presented his discoveries about how apparently random phenomena are governed by hidden rules. His work is now considered to be among the most important contributions to the theory of complex systems.

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?

Mathematics for complex disordered systems

Every time many identical discs are squeezed together, a new irregular pattern is formed despite them being squeezed in exactly the same way. What governs the result? Giorgio Parisi discovered a hidden structure in such complex disordered systems, which these discs represent, and found a way of describing them mathematically.



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?

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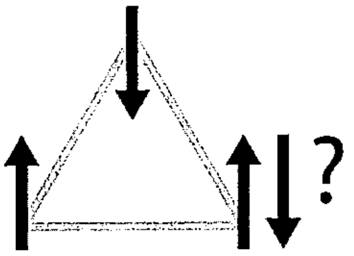
In the introduction to his book about spin glass, Parisi writes that studying spin glass is like watching the human tragedies of Shakespeare's plays. If you want to make friends with two people at the same time, but they hate each other, it can be frustrating. This is even more the case in a classical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

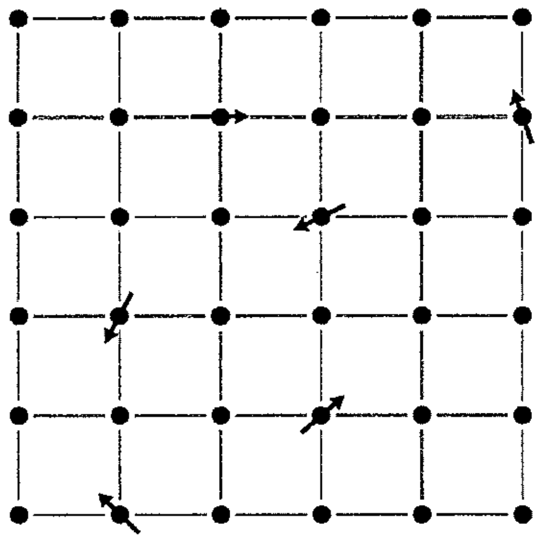


Frustration

When one spin points upward and the other downward, the third one cannot satisfy them both at the same time, because neighbouring spins want to point in different directions. How do the spins find an optimal orientation? Giorgio Parisi is a master at answering these questions for many different materials and phenomena.

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.



Spin glass

A spin glass is a metal alloy where iron atoms, for example, are randomly mixed into a grid of copper atoms. Each iron atom behaves like a small magnet, or spin, which is affected by the other magnets around it. However, in a spin glass they are frustrated and have difficulty choosing which direction to point. Using his studies of spin glass, Parisi developed a theory of disordered and random phenomena that covers many other complex systems.

● Iron

● Copper

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.

FURTHER READING

Additional information on this year's prizes, including a scientific background in English, is available on the website of the Royal Swedish Academy of Sciences, *www.kva.se*, and at *www.nobelprize.org*, where you can watch video from the press conferences, the Nobel Lectures and more. Information on exhibitions and activities related to the Nobel Prizes and the Prize in Economic Sciences is available at *www.nobelprizemuseum.se*

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
Born 1931 in Shingu, Japan. Ph.D. 1958 from University of Tokyo, Japan. Senior Meteorologist at Princeton University, USA.

KLAUS HASSELMANN
Born 1931 in Hamburg, Germany. Ph.D. 1957 from University of Göttingen, Germany. Professor, 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
Born 1948 in Rome, Italy. Ph.D. 1970 from Sapienza University of Rome, Italy. Professor at Sapienza University of Rome, Italy.

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

Science Editors: Ulf Danielsson, Thors Hans Hansson, Gunnar Ingelman, Anders Irbäck, John Wettlaufer, the Nobel Committee for Physics
Text: Joanna Rose
Translator: Clare Barnes
Illustrations: ©Johan Jarnestad/The Royal Swedish Academy of Sciences
Editor: Sara Gustavsson

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附件 3

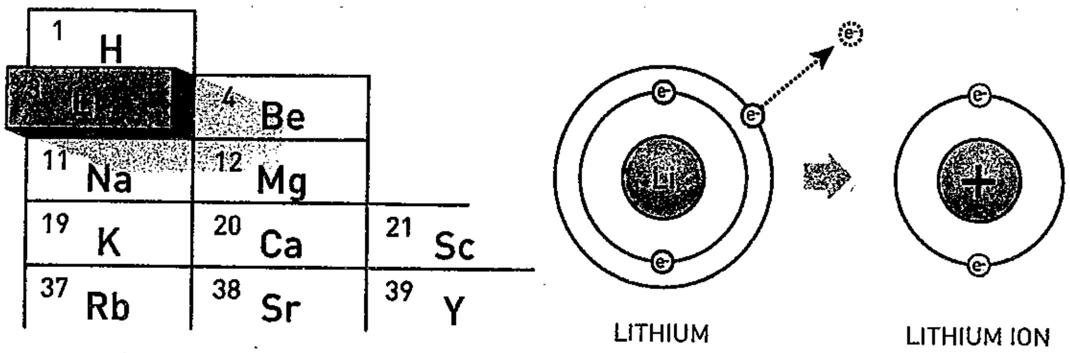
KUNGL VETENSKAPS AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES
THE NOBEL PRIZE IN CHEMISTRY 2019
POPULAR SCIENCE BACKGROUND

They developed the world's most powerful battery

The Nobel Prize in Chemistry 2019 is awarded to John B. Goodenough, M. Stanley Whittingham and Akira Yoshino for their contributions to the development of the lithium-ion battery. This rechargeable battery laid the foundation of wireless electronics such as mobile phones and laptops. It also makes a fossil fuel-free world possible, as it is used for everything from powering electric cars to storing energy from renewable sources.

An element rarely gets to play a central role in a drama, but the story of 2019's Nobel Prize in Chemistry has a clear protagonist: lithium, an ancient element that was created during the first minutes of the Big Bang. Humankind became aware of it in 1817, when Swedish chemists Johan August Arfwedson and Jöns Jacob Berzelius purified it out of a mineral sample from Utö Mine, in the Stockholm archipelago.

Berzelius named the new element after the Greek word for stone, lithos. Despite its heavy name, it is the lightest solid element, which is why we hardly notice the mobile phones we now carry around.



Lithium is a metal. It has just one electron in its outer electron shell, and this has a strong drive to leave lithium for another atom. When this happens, a positively charged – and more stable – lithium ion is formed.

To be completely correct – the Swedish chemists did not actually find pure metallic lithium, but lithium ions in the form of a salt. Pure lithium has set off many fire alarms, not least in the story we will tell here; it is an unstable element that must be stored in oil so it does not react with air.

Lithium's weakness – its reactivity – is also its strength. In the early 1970s, **Stanley Whittingham** used lithium's enormous drive to release its outer electron when he developed the first functional lithium battery. In 1980, **John Goodenough** doubled the battery's potential, creating the right conditions for a vastly more powerful and useful battery. In 1985, **Akira Yoshino** succeeded in eliminating pure lithium from the battery, instead basing it wholly on lithium ions, which are safer than pure lithium. This made the battery workable in practice. Lithium-ion batteries have brought the greatest benefit to humankind, as they have enabled the development of laptop computers, mobile phones, electric vehicles and the storage of energy generated by solar and wind power.

We will now step fifty years back in time, to the beginning of the lithium-ion battery's highly charged story.

Petrol haze revitalises battery research

In the mid-20th century, the number of petrol-driven cars in the world increased significantly, and their exhaust fumes worsened the harmful smog found in big cities. This, combined with the growing realisation that oil is a finite resource, sounded an alarm for both vehicle manufacturers and oil companies. They needed to invest in electric vehicles and alternative sources of energy if their businesses were to survive.

Electric vehicles and alternative sources of energy both require powerful batteries that can store large amounts of energy. There were really only two types of rechargeable batteries on the market at this time: the heavy lead battery that had been in invented back in 1859 (and which is still used as a starter battery in petrol-driven cars) and the nickel-cadmium battery that was developed in the first half of the 20th century.

Oil companies invest in new technology

The threat of oil running out resulted in an oil giant, Exxon, deciding to diversify its activities. In a major investment in basic research they recruited some of that time's foremost researchers in the field of energy, giving them the freedom to do pretty much what they wanted as long as it did not involve petroleum.

Stanley Whittingham was among those who moved to Exxon in 1972. He came from Stanford University, where his research had included solid materials with atom-sized spaces in which charged ions can attach. This phenomenon is called intercalation. The materials' properties change when ions are caught inside them. At Exxon, Stanley Whittingham and his colleagues started to investigate superconducting materials, including tantalum disulphide, which can intercalate ions. They added ions to tantalum disulphide and studied how its conductivity was affected.

Whittingham discovers an extremely energy-dense material

As is so often the case in science, this experiment led to an unexpected and valuable discovery. It turned out that potassium ions affected the conductivity of tantalum disulphide, and when Stanley Whittingham started to study the material in detail he observed that it had a very high energy density. The interactions that arose between the potassium ions and the tantalum disulphide were surprisingly energy rich and, when he measured the material's voltage, it was a couple of volts. This was better than many of that time's batteries. Stanley Whittingham quickly realised that it was time to change track, moving to the development of new technology that could store energy for the electric vehicles of the future. However, tantalum is one of the heavier elements and the market did not need to be laden with more heavy batteries – so he replaced tantalum with titanium, an element which has similar properties but is much lighter.

Lithium in the negative electrode

Isn't lithium supposed to have pride of place in this story? Well, this is where lithium enters the narrative – as the negative electrode on Stanley Whittingham's innovative battery. Lithium was not a random choice; in a battery, electrons should flow from the negative electrode – the anode – to the positive one – the cathode. The anode should therefore contain a material that easily gives up its electrons, and lithium is one of the elements that most willingly releases an electron.

The result was a rechargeable lithium battery that worked at room temperature and – literally – had great potential. Stanley Whittingham travelled to Exxon's headquarters in New York to talk about the project. The meeting lasted about fifteen minutes, with the management group subsequently making a rapid decision: they would develop a commercially viable battery using Whittingham's discovery.

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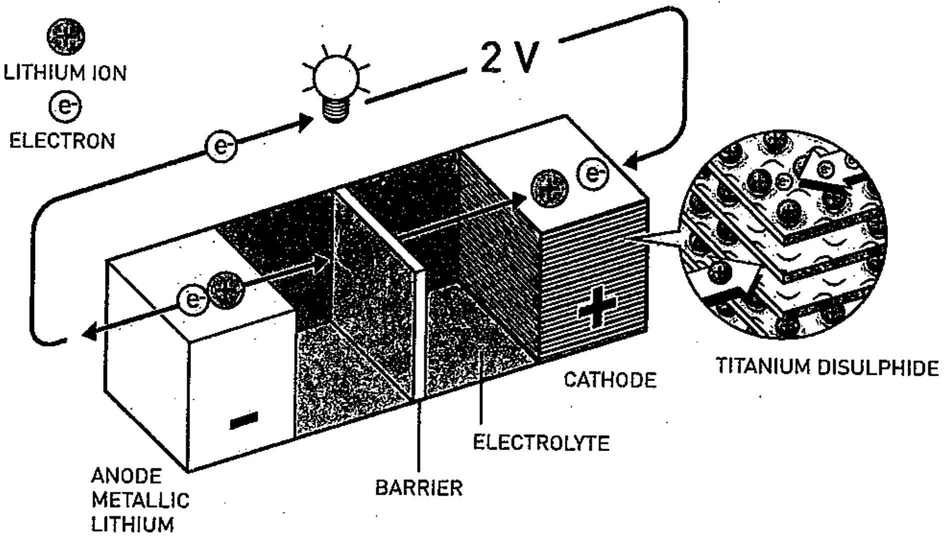
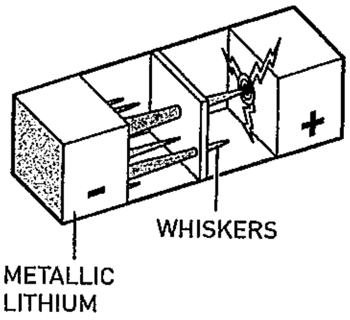


The first rechargeable batteries had solid materials in the electrodes, which broke down when they reacted chemically with the electrolyte. This destroyed the batteries. The advantage of Whittingham's lithium battery was that lithium ions were stored in spaces in the titanium disulphide in the cathode. When the battery was used, lithium ions flowed from the lithium in the anode to the titanium disulphide in the cathode. When the battery was charged, the lithium ions flowed back again.

The battery explodes and the oil price falls

Unfortunately, the group that was to start producing the battery suffered some setbacks. As the new lithium battery was repeatedly charged, thin whiskers of lithium grew from the lithium electrode. When they reached the other electrode, the battery short-circuited which could lead to an explosion. The fire brigade had to put out a number of fires and finally threatened to make the laboratory pay for the special chemicals used to extinguish lithium fires.

To make the battery safer, aluminium was added to the metallic lithium electrode and the electrolyte between the electrodes was changed. Stanley Whittingham announced his discovery in 1976 and the battery began to be produced on a small scale for a Swiss clockmaker that wanted to use it in solar-powered timepieces.



Whiskers of lithium form when a battery with pure lithium in the anode is charged. These can short-circuit the battery and cause fires and even explosions.

The next objective was to scale up the rechargeable lithium battery so it could power a car. However, the price of oil fell dramatically in the early 1980s and Exxon needed to make cutbacks. The development work was discontinued and Whittingham's battery technology was licenced to three different companies in three different parts of the world.

However, this did not mean that development stopped. When Exxon gave up, John Goodenough took over.

The oil crisis makes Goodenough interested in batteries

As a child, John Goodenough had significant problems learning to read, which was one reason why he was drawn to mathematics and eventually – after World War Two – also physics. He worked for many years at the Lincoln Laboratory at the Massachusetts Institute of Technology, MIT. While there, he contributed to the development of random access memory (RAM) which is still a fundamental component of computing.

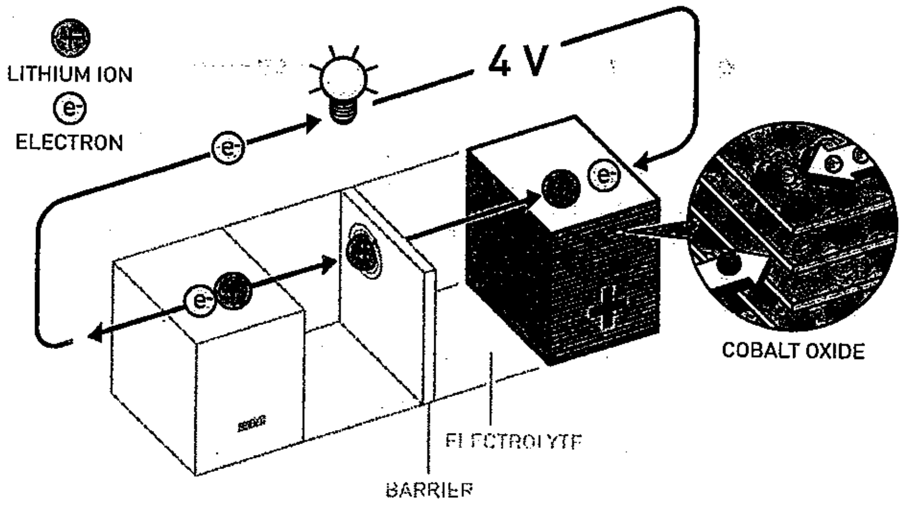
John Goodenough, like so many other people in the 1970s, was affected by the oil crisis and wanted to contribute to the development of alternative sources of energy. However, the Lincoln Laboratory was funded by the US Air Force and did not permit all kinds of research, so when he was offered a position as professor of inorganic chemistry at Oxford University in Great Britain, he took the chance and entered the important world of energy research.

High voltages when lithium ions hide in cobalt oxide

John Goodenough knew about Whittingham's revolutionary battery, but his specialised knowledge of matter's interior told him that its cathode could have a higher potential if it was built using a metal oxide instead of a metal sulphide. A few people in his research group were then tasked with finding a metal oxide that produced a high voltage when it intercalated lithium ions, but which did not collapse when the ions were removed.

This systematic search was more successful than John Goodenough had dared to hope. Whittingham's battery generated more than two volts, but Goodenough discovered that the battery with lithium-cobalt oxide in the cathode was almost twice as powerful, at four volts.

One key to this success was John Goodenough's realisation that batteries did not have to be manufactured in their charged state, as had been done previously. Instead, they could be charged afterwards. In 1980, he published the discovery of this new, energy-dense cathode material which, despite its low weight, resulted in powerful, high-capacity batteries. This was a decisive step towards the wireless revolution.



Goodenough started to use cobalt oxide in the lithium battery's cathode. This almost doubled the battery's potential and made it much more powerful.

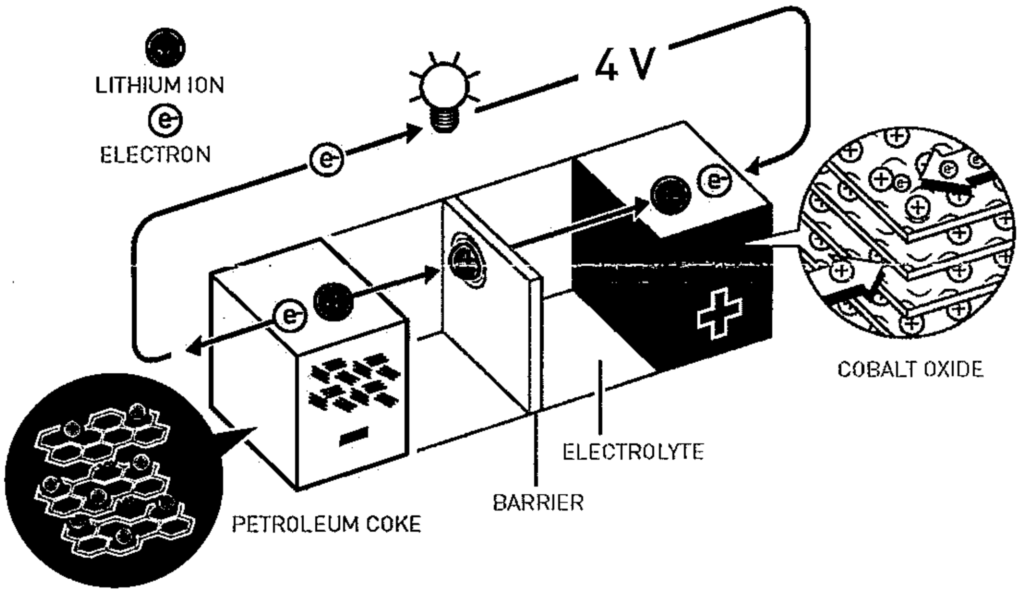
Japanese companies want lightweight batteries for new electronics

However, in the West, as oil became cheaper, interest paled in investments in alternative energy technology and the development of electric vehicles. Things were different in Japan; electronics companies were desperate for lightweight, rechargeable batteries that could power innovative electronics, such as video cameras, cordless telephones and computers. One person who saw this need was Akira Yoshino from the Asahi Kasei Corporation. Or as he put it: "I just sort of sniffed out the direction that trends were moving. You could say I had a good sense of smell."

Yoshino builds the first commercially viable lithium-ion battery

When Akira Yoshino decided to develop a functional rechargeable battery, he had Goodenough's lithium-cobalt oxide as the cathode and tried using various carbon-based materials as the anode. Researchers had previously shown that lithium ions could be intercalated in the molecular layers in graphite, but the graphite was broken down by the battery's electrolyte. Akira Yoshino's eureka moment came when he instead tried using petroleum coke, a by-product of the oil industry. When he charged the petroleum coke with electrons, the lithium ions were drawn into the material. Then, when he turned on the battery, the electrons and lithium ions flowed towards the cobalt oxide in the cathode, which has a much higher potential.

The battery developed by Akira Yoshino is stable, lightweight, has a high capacity and produces a remarkable four volts. The greatest advantage of the lithium-ion battery is that the ions are intercalated in the electrodes. Most other batteries are based on chemical reactions in which the electrodes are slowly but surely changed. When a lithium-ion battery is charged or used, the ions flow between the electrodes without reacting with their surroundings. This means the battery has a long life and can be charged hundreds of times before its performance deteriorates.



Akira Yoshino developed the first commercially viable lithium-ion battery. He used Goodenough's lithium-cobalt oxide in the cathode and in the anode he used a carbon material, petroleum coke, which can also intercalate lithium ions. The battery's functionality is not based upon any damaging chemical reactions. Instead, the lithium ions flow back and forth between the electrodes, which gives the battery a long life.

Another big advantage is that the battery has no pure lithium. In 1986, when Akira Yoshino was testing the battery's safety, he exercised caution and used a facility designed for testing explosive devices. He dropped a large piece of iron on the battery, but nothing happened. However, on repeating the experiment with a battery that contained pure lithium, there was a violent explosion.

Passing safety testing was fundamental to the future of the battery. Akira Yoshino says that this was "the moment when the lithium-ion battery was born".

見背面

The lithium-ion battery – necessary for a fossil fuel-free society

In 1991, a major Japanese electronics company started selling the first lithium-ion batteries, leading to a revolution in electronics. Mobile phones shrank, computers became portable and MP3 players and tablets were developed.

Subsequently, researchers around the world have searched through the periodic table on the hunt for even better batteries, but no one has yet succeeded in inventing something that beats the lithium-ion battery's high capacity and voltage. However, the lithium-ion battery has been changed and improved; among other things, John Goodenough has replaced the cobalt oxide with iron phosphate, which makes the battery more environmentally friendly.

Like almost everything else, the production of lithium-ion batteries has an impact on the environment, but there are also huge environmental benefits. The battery has enabled the development of cleaner energy technologies and electric vehicles, thus contributing to reduced emissions of greenhouse gases and particulates.

Through their work, John Goodenough, Stanley Whittingham and Akira Yoshino have created the right conditions for a wireless and fossil fuel-free society, and so brought the greatest benefit to humankind.