# And the 2019 NOBEL PRIZE IN CHEMISTRY *Goes to...*

*by Marca M. Doeff*

It was the week after the announcement of the winners of the 2019 Nobel Prize in Chemistry, and we were gathered together in Atlanta for the 236th meeting of The Electrochemical Society. Given that the prize was awarded to three scientists who performed seminal work leading to the development of the lithium-ion battery—**John Goodenough**, **Stan Whittingham**, and **Akira Yoshino**, the Atlanta Hilton was buzzing with excitement. After all, ECS meetings have been and still are the best settings for hearing about and discussing all things "battery." One of the winners of the award, Stan Whittingham, was attending the meeting, and was stopped in his tracks constantly by people wanting to shake his hand and offer congratulations or to take selfies with him. That got me to thinking (after taking my own selfie with Prof. Whittingham) about the long journey from these initial discoveries, made in the 1970s and 80s, to where we are today.

## The Lithium-Ion Battery Market Today

Lithium-ion batteries enabled the revolution in consumer electronics starting in the late 20th century; there is no doubt that cell phones, tablets, and laptop computers are great conveniences that have made a positive impact on how we conduct our lives and do business in the 21st century. Lithium-ion batteries now are widely used in power tools, cameras, toys, and medical devices as well. The lithium-ion battery market was estimated to be about 37.4 billion USD in 2018, and is projected to grow to 92.2 billion USD in 2024, as demand for electric vehicles (EVs) and hybrid electric vehicles (HEVs) increase.[1] The stellar performance and decreasing cost of lithium-ion batteries have transformed EVs from a niche market only for enthusiasts to products attractive to the average driver. Automobiles like the Tesla Model 3, the Nissan Leaf, and the Chevrolet Bolt are readily available to the public for purchase at affordable prices, and nearly every large automaker has EVs or HEVs for sale or under development. Lithium-ion batteries also are being used for behind-the-meter storage (e.g., Tesla's PowerWall). Another application where lithium-ion batteries will make an impact is grid storage, although they not only have to compete with other types of batteries such as redox flow systems, but other types of energy storage such as pumped hydro. Still, the ever-dropping price of lithium-ion batteries and their excellent reliability make them a natural choice for society's energy storage needs.

## Initial Discoveries that Led to Lithium-Ion Batteries

Whittingham's insight that intercalation chemistry (specifically, lithium insertion into $TiS_2$) could be exploited for use in batteries with lithium metal anodes set the stage. Goodenough discovered $LiCoO_2$, another classical intercalation compound, which undergoes reversible insertion/de-insertion of lithium ions at higher potentials vs. $Li^+/Li$ than $TiS_2$, improving energy density. However, as Goodenough described it, "battery manufacturers at that time could not conceive of assembling a cell with a discharged cathode."[2] The lithium metal anode was, however, unreliable, to say the least. Upon repeated cycling, highly reactive mossy deposits or dendrites of the metal formed, leading to sudden shorts or, worse yet, explosions. When Yoshino revealed that carbons with certain physical characteristics could function as anodes without the drawbacks of lithium metal, the modern version of the lithium-ion battery was born. The system could be cycled much more reliably than lithium metal batteries, and using a pre-lithiated cathode like $LiCoO_2$ was actually an advantage, because cells could be easily assembled in the discharged state and then charged before use.



## The Journey from Initial Discoveries to Lithium-Ion Batteries Today

In 1991, Sony commercialized the first lithium-ion batteries.[3] These cells, made with petroleum coke as the anode and $LiCoO_2$ as the cathode, had practical energy densities of about 200 Wh/L and specific energies of about 80 Wh/Kg, less than half that of state-of-the-art lithium-ion batteries today. Researchers from many different scientific disciplines and countries, in industry, national labs, and academia, worked to advance lithium-ion battery technology, ultimately resulting in a more than doubling of practical energy density as well as a dramatic drop in cost (from more than $1,000/kWh a decade ago to about $175/kWh today).[4] While $LiCoO_2$ is still the cathode of choice for small batteries, low or no-cobalt alternatives such as $LiFePO_4$, variants of $LiMn_2O_4$ spinels, and layered transition metal oxides containing multiple metals such as NMCs ($LiNi_xMn_yCo_zO_2$) and NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) are preferred in devices intended for automotive applications or large-scale energy storage because of cost and sustainability concerns. The original petroleum coke anodes have been replaced with graphite or graphite/silicon composites, which offer higher capacities and better first cycle efficiencies. Optimization of electrolytic solutions resulted in improved performance, as did work on binders and separators, and advances in design of electrodes, cells, and battery packs. While improvement and better understanding of these devices and the materials within them are still high priorities today, research has expanded to include "beyond lithium-ion batteries," many of which are based on the intercalation concept, but with ions like $Mg^{2+}$ or $Na^+$. Most of these next-generation systems are still in their infancy, but the remarkable success story of lithium-ion batteries provides a roadmap for their development as well. In short, the pioneering work of Goodenough, Whittingham, and Yoshino so many years ago, will continue to have positive repercussions for years to come.

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## About the Author

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https://orcid.org/0000-0002-2148-8047

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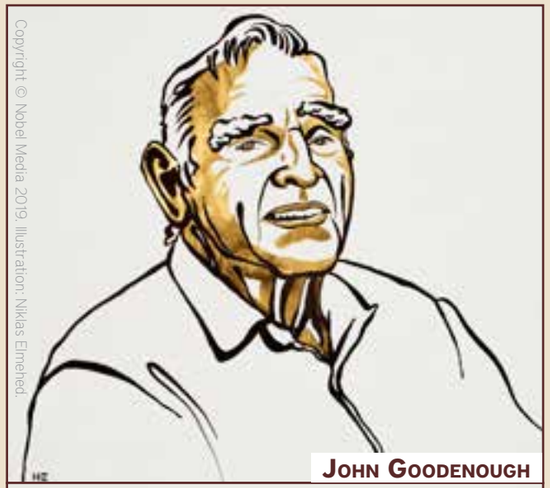




**John Goodenough**



**Stan Whittingham**



**Akira Yoshino**

Photo: The University of Texas at Austin

# JOHN BANNISTER GOODENOUGH

*"I like to think that part of my heritage is that I contributed to the wedding of physics and chemistry. I didn't do it alone, of course. We are moving inevitably, inexorably, to interdisciplinarity between material physic and material chemistry.*

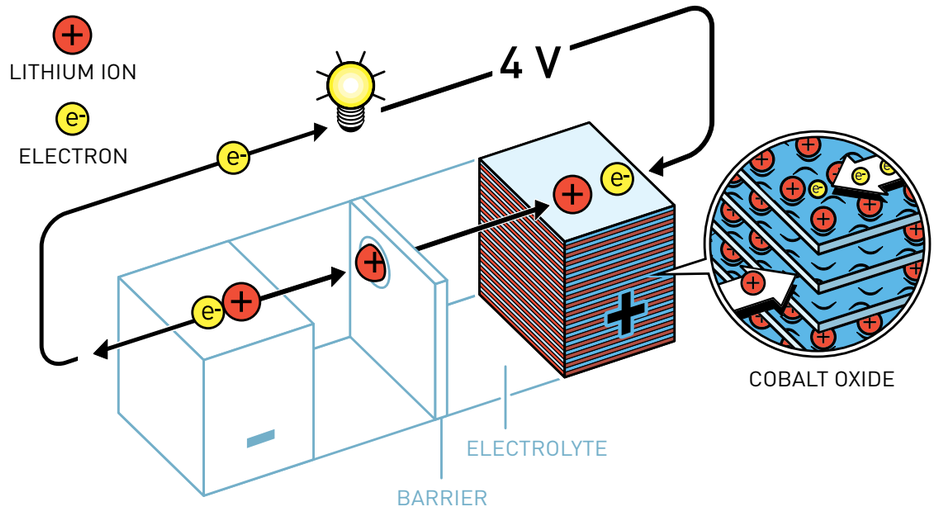
(*ECS Masters—John B. Goodenough*; The Electrochemical Society: Pennington, 2016.)

**John Bannister Goodenough** is internationally recognized as one of the key minds behind the development of the first commercial lithium-ion battery. The ECS Fellow and honorary member was born on July 25, 1922, in Jena, Germany, to American parents who soon thereafter returned to the United States.[1] He completed his BS in math and graduated summa cum laude from Yale University in 1943.[2] After serving in World War II as a meteorologist, he completed his PhD in physics at the University of Chicago (1952).[3] As a research scientist at the Lincoln Laboratory at the Massachusetts Institute of Technology (1952-1976), he developed the SAGE air defense computer's memory cores—the first random access memory (RAM).[4] In 1976, Goodenough moved to the University of Oxford as professor and head of the Inorganic Chemistry Lab.[5]

In 1979-1980, Goodenough improved on the first lithium-ion battery invented by M. Stanley Whittingham in 1976.[6] Whittingham's battery used an anode of metallic lithium, and a cathode of lithium ions between layers of titanium disulfide. It had a potential of 2.5 volts. To produce a higher voltage battery, Goodenough and collaborators used a cathode of lithium ions between layers of cobalt oxide. The new battery had a potential of 4 volts.

Goodenough became a professor at the University of Texas at Austin in 1986 in the departments of mechanical engineering and electrical and computer engineering.[7] He now holds the Virginia H. Cockrell Centennial Chair of Engineering at the University of Texas at Austin. Goodenough continues to work on lithium-ion breakthrough technology, determined to make the batteries stronger, cheaper, and safer, and the world less dependent on fossil fuels.[8]






©Johan Jarnestad/The Royal Swedish Academy of Sciences

**John B. Goodenough's** *lithium-based battery using $Li_xCoO_2$ as the cathode.*
Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences



**Goodenough** *was among 12 researchers to receive the National Medal of Science from* **President Obama**. *"I am proud to honor these inspiring American innovators," President Obama said. "They represent the ingenuity and imagination that has long made this nation great, and they remind us of the enormous impact a few good ideas can have when these creative qualities are unleashed in an entrepreneurial environment."*
Photo: Ryan K. Morris, National Science & Technology Medals Foundation

**Goodenough** *posing with his research equipment in his laboratory at The University of Texas at Austin.*
Photo: The University of Texas at Austin

**Prof. Goodenough** *takes time to consult with inspired students in his office.*
Photo: The University of Texas at Austin

## AWARDS

- 2019 Nobel Prize in Chemistry
- ECS Fellow (2016)
- Fellow, National Academy of Inventors (2016)
- Member, U.S. National Academy of Science (2012)
- Foreign member, Royal Society, England (2010)
- Member, National Societies of France, Spain, and India
- Member, National Academy of Engineering (1976)
- Royal Society's Copley Medal (2019)
- The Benjamin Franklin Award in Chemistry (2018)
- The Welch Award in Chemistry (2017)
- C. K. Prahalad award, Corporate EcoForum (2017)
- The Eric and Sheila Samsun Prime Minister's Prize for Innovation in Alternative Fuels for Transportation (2015)
- Thomson Reuters Citation Laureate (2015)
- Stark Draper Prize of the National Academy of Engineering (2014)
- Institute of Electrical and Electronics Engineers (IEEE) Medal for Environmental and Safety Technologies (2012)
- National Medal of Science (2011)
- Presidential Enrico Fermi Award (2009)
- Japan Prize (2001)
- ECS Olin Palladium Award (1999)

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Photo: Robb Cohen Photo & Video

# M. STANLEY WHITTINGHAM

*"We have to look after the planet for our children and our grandchildren. So we have to move the technology forward, but not by using more energy, but by using less energy, and not by messing up the environment. As electrochemists we can do that. And we've got to do that."*

(*ECS Masters—M. Stanley Whittingham*; The Electrochemical Society: Pennington, 2015.)

**Michael Stanley Whittingham** was born in Nottingham, England on December 22, 1941.[1] He received his BA (1964), MA (1967), and PhD (1968) in chemistry from the University of Oxford.[2] He was at Stanford University as a research associate (1968-1972) before joining the Exxon Research and Development Company in Linden, New Jersey.[3] At Exxon, Whittingham studied titanium disulfide and its superconductive properties. Using intercalation, he created the first rechargeable lithium-ion battery in 1976.[4] He used metallic lithium as the anode and titanium disulfide intercalated with lithium ions as the cathode. The battery had an electromotive force of 2.5 volts.

Together with John Goodenough, Whittingham published *Solid State Chemistry of Energy Conversion and Storage* in 1977. Whittingham founded the journal *Solid State Ionics* in 1981. He served as its editor for 20 years.[5]

Whittingham joined Schlumberger-Doll Research in Ridgefield, Connecticut, as director of physical sciences in 1984.[6] He was then named distinguished professor of chemistry and materials sciences and engineering at Binghamton University, New York, in 1988.[7] He is also director of the Northeastern Center for Chemical Energy Storage (NECCES), a Department of Energy (DOE) Energy Frontier Research Center (EFRC) at Binghamton. There Whittingham continues his research on finding new materials for advancing energy storage. ☆

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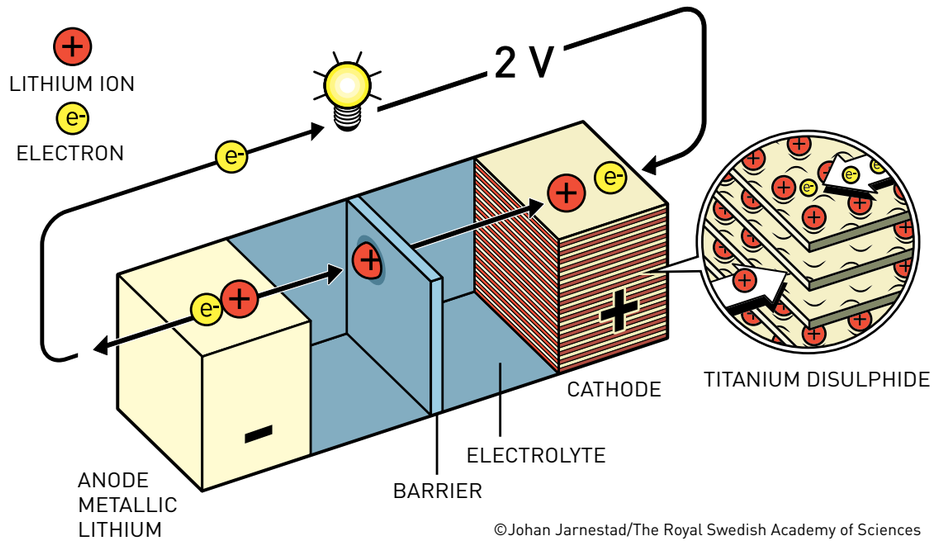


**M. Stanley Whittingham's** *lithium-based battery using $Li_xTiS_2$ as the cathode.*
Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences



**Whittingham** *during one of his in-depth student lectures.*
Photo: Jonathan Cohen, Binghamton University

**M. Stanley Whittingham** *pictured here in one of his Science II laboratories.*
Photo: Jonathan Cohen, Binghamton University

**Whittingham** *in another Binghamton University lab setting. He has been a professor of chemistry and materials sciences and engineering there since 1988.*
Photo: Jonathan Cohen, Binghamton University

## AWARDS

- 2019 Nobel Prize in Chemistry
- ECS Fellow (2004)
- JSPS Fellow, Tokyo University Physics Department (1993)
- Member, National Academy of Engineering (2018)
- Fellow, Materials Research Society (2013)
- Turnbull Award (Materials Research Society, 2018)
- International Society for Solid State Ionics Senior Scientist Award (2017)
- Thomson Reuters Citation Laureate (2015)
- IBA Yeager Award for Lifetime Contribution to Lithium Battery Materials Research (2012)
- ACS NERM Award for Contributions to Chemistry (2010)
- GreentechMedia Top 40 Innovators for Contributions to Advancing Green Technology (2010)
- SUNY Research Foundation Outstanding Research Award (2007)
- Chancellor's Award for Excellence in Scholarship and Creative Activities (2006-2007)
- ECS Battery Division Research Award (2002)
- ECS Young Author Award (1971)
- Gas Council Scholar, Oxford University (1964-1967)

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# AKIRA YOSHINO

Photo: Asahi Kasei

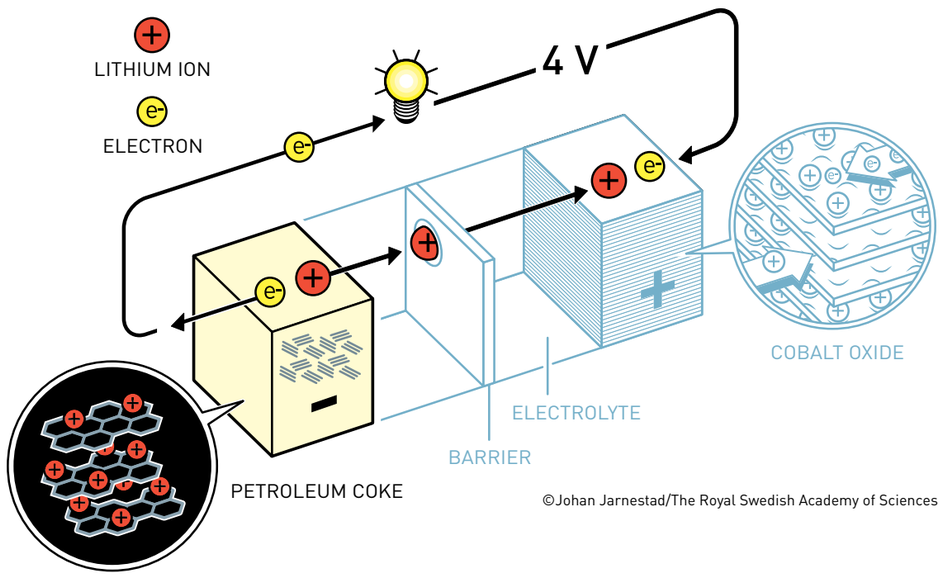
> *"If you hit the wall, you should thank God for placing it in front of you—that's when something new is born."*[11]
>
> *(Yoshino to his students)*

**Akira Yoshino** was born on January 30, 1948, in Suita, Japan.[1] He was nine years old when he discovered Faraday's "The Chemical History of a Candle."[2] The book describes the energy stored in a candle and the chemistry behind it. Reading that book sparked Yoshino's interest in science and shaped his entire life. He received his BA (1970) and MA (1972) in petro chemistry from Kyoto University.[3] In graduate school, he focused on chemistry, submitting research papers to the international journals of chemistry societies. After receiving his MA, Akira joined the Asahi Chemical Industry Company (now Asahi Kasei Corporation) in 1972.[4]

By combining Goodenough's cathode with a carbon anode, Yoshino created the first working lithium-ion battery. Yoshino filed a patent on his safer, commercially viable lithium-ion battery in 1985.[5] The new lithium-ion battery was commercialized by Sony in 1991, and in 1992 by A&T Battery, a joint venture company of Asahi Kasei and Toshiba.[6]

In 2005, Yoshino received a doctorate in engineering from Osaka University.[7] He became president of the Lithium-ion Battery Technology and Evaluation Center in 2010.[8] In 2015, he became a visiting professor at the Research and Education Center for Advanced Energy Materials, Devices, and Systems, Kyushu University, a post he holds today[9]. Since 2017, he has also served as a professor in the Graduate School of Science and Technology, Meijo University.[10] Today, Yoshino is an honorary fellow at the Asahi Kasei Corporation. He continues his research, looking at ways that the lithium-ion battery can address global environmental problems. ☆






**Akira Yoshino's** *ion transfer cell lithium-ion battery configuration.*
Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences



**Dr. Yoshino** *proudly talks about the lithium-ion battery. Today you can find the battery in laptop computers, cell phones, electric cars, and energy storage systems.*
Photo: Asahi Kasei

**Akira Yoshino** *at the corporate headquarters of Asahi Kasei. His specialty is electrochemistry and quantum organic chemistry. He enjoys encouraging new researchers.*
Photo: Asahi Kasei

## AWARDS

- 2019 Nobel Prize in Chemistry
- Fellow, Chemical Society of Japan (2012)
- European Inventor Award (2019)
- Japan Prize (2018)
- National Institute for Materials Science Award (2016)
- Charles Stark Draper Prize for Engineering, The National Academy of Engineering (2014)
- Global Energy Prize (2013)
- Kato Memorial Prize, Kato Foundation for Promotion of Science (2013)
- Institute of Electrical and Electronics Engineers (IEEE) Medal for Environmental and Safety Technologies (2012)
- C&C Prize, NEC C&C Foundation (2011)
- Yamazaki-Teiichi Prize, Foundation for Promotion of Material Science and Technology of Japan (2011)
- Medal with Purple Ribbon, Government of Japan (2004)
- Prize for Science and Technology, Development Category, Ministry of Education, Culture, Sports, Science, and Technology (2003)
- National Commendation for Invention—Invention Prize of the Minister of Education, Culture, Sports, Science, and Technology, Japan Institute of Invention and Innovation (2002)
- Kanto-block Commendation for Invention—Encouragement Prize of Invention of the Minister of Education, Culture, Sports, Science, and Technology, Japan Institute of Invention and Innovation (2001)
- Ichimura Prizes in Industry—Meritorious Achievement Prize, New Technology Development Foundation (2001)
- ECS Battery Division Technology Award (1999)
- Chemical Society of Japan Fiscal 1998 Chemical Technology Prize (1999)

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# ECS NOBEL GREATS

With **John Goodenough**, **M. Stanley Whittingham**, and **Akira Yoshino** recently winning the 2019 Nobel Prize in Chemistry we were inspired to research our membership for past Nobel laureates. We were able to compile awardees in chemistry, as well as physics. Please enjoy this walk through ECS history. (Note that due to our limitations in digitized content this may not be a complete listing of ECS Nobel winners.)

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## CHEMISTRY

**Richard E. Smalley**
Nobel Prize in Chemistry 1996 (jointly)
Prize motivation:
*"for the discovery of fullerenes."*

**Jean-Marie Lehn**
Nobel Prize in Chemistry 1987 (jointly)
Prize motivation:
*"for the development and use of molecules with structure-specific interactions of high selectivity."*

**Fritz Haber**
Nobel Prize in Chemistry 1918
Prize motivation:
*"for the synthesis of ammonia from its elements."*

**Rudolph Marcus**
Nobel Prize in Chemistry 1992
Prize motivation:
*"for his contributions to the theory of electron transfer reactions in chemical systems."*

**Irving Langmuir**
Nobel Prize in Chemistry 1932
Prize motivation:
*"for his discoveries and investigations in surface chemistry."*
Photo: Nobel Foundation Archive

**Theodore Williams Richards**
Nobel Prize in Chemistry (1914)
Prize motivation:
*"in recognition of his accurate determinations of the atomic weight of a large number of chemical elements."*
Photo: Nobel Foundation Archive

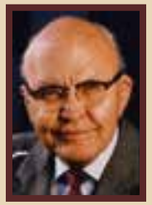
## PHYSICS

**Isamu Akasaki**
Nobel Prize in Physics 2014 (jointly)
Prize motivation:
*"the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources."*

**William D. Phillips**
Nobel Prize in Physics 1997 (jointly)
Prize motivation:
*"for development of methods to cool and trap atoms with laser light."*

**Hiroshi Amano**
Nobel Prize in Physics 2014 (jointly)
Prize motivation:
*"the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources."*
©Nobel Media AB. Photo: A. Mahmoud

**Steven Chu**
Nobel Prize in Physics 1997 (jointly)
Prize motivation:
*"for development of methods to cool and trap atoms with laser light."*
Photo: Nobel Foundation Archive



**Jack S. Kilby**
Nobel Prize in Physics 2000 (jointly)
Prize motivation:
*"for basic work on information and communication technology…for his part in the invention of the integrated circuit."*

**Gerd Binnig**
Nobel Prize in Physics 1986 (jointly)
Prize motivation:
*"for their design of the scanning tunneling microscope."*

## THE NOBEL PRIZE



The Nobel Prize is named for Swedish inventor, entrepreneur, scientist, and businessman Alfred Nobel (1833-1896). In addition to inventing dynamite, Nobel held 355 different patents. Nobel stipulated in his will that his sizable estate fund prizes for those who "shall have conferred the greatest benefit to mankind" in the areas of physics, chemistry, physiology or medicine, literature, and peace. Since they were first awarded in 1901, the Nobel Prizes have been considered the most important prize in the world for intellectual achievement. In 1969, Sweden's central bank funded a sixth prize in economics, the Bank of Sweden Prize in Economic Sciences in Memory of Alfred Nobel.

The winners of the 2019 Nobel Prize for Chemistry join a pantheon of celebrated scientists. Marie Curie was the sole winner of the 1911 Nobel Prize in Chemistry. Linus Pauling was the only person to win two unshared Nobel Prizes, the first in 1954 and the second in 1962. Other celebrated chemistry Nobel laureates include Ernest Rutherford, Aziz Sancar, Fritz Haber, Otto Hahn, and Glenn T. Eabord. The only women to win the Nobel Prize in Chemistry are Marie Curie, Irène Joliot-Curie, Dorothy Crowfoot Hodgkin, Ada E. Yonath, and Frances H. Arnold.

Probably the most famous winner of the Nobel Prize in Physics is Albert Einstein. The first physics prize was awarded to Wilhelm Conrad Röntgen in 1901. Other Nobel laureates of renown in physics include Richard Feynman, William B. Schockley, Werner Heisenberg, Niels Bohr, Max Planck, Guglielmo Marconi, and Enrico Fermi. Three women have won the physics prize: Marie Curie, Maria Goeppert Mayer, and Donna Strickland.

(https://www.nobelprize.org/alfred-nobel/)