

## John Bannister Goodenough

John Bannister Goodenough, who pioneered studies of magnetism, orbital physics, electronic and ionic transport in transition-metal compounds, and materials for energy storage, died on 25 June 2023 in Austin, Texas. He was a corecipient of the 2019 Nobel Prize in Chemistry. At the time of his death, he was a professor at the University of Texas at Austin, where he had been since 1986.

Born on 25 July 1922 in Jena, Germany, to American parents, John and his family moved to Connecticut when he was an infant. He went to Groton School in Massachusetts as a teenager and developed his sense of morality and religious commitment from its headmaster, Endicott Peabody.

John was admitted to Yale University in 1940. With World War II raging, he enlisted in the US Army in 1942. John received a BA in mathematics in spring 1943, and he began serving as an army meteorologist that fall. Egbert Miles, his mathematics professor at Yale, changed the trajectory of John's career by adding John's name on the list of veterans recommended to do graduate studies in physics or mathematics.

John obtained his PhD in physics from the University of Chicago in 1952 under Clarence Zener. Although John did not publish any articles with Zener, Zener's research style can be traced throughout John's papers. And discoveries they each made contributed to the portable-electronics technologies that have changed our everyday life: the Zener diode in miniature chargers and John's cathode materials for lithium-ion batteries in computers and cell phones.

After receiving his PhD, John began a 24-year career at MIT's Lincoln Laboratory. As a team leader, he worked on the magnets used in magnetic RAM. He identified the relationship of magnetic domain-wall dynamics and dynamic Jahn–Teller (JT) distortion in the spinel oxides. That finding led to an ideal square-shaped magnetic-hysteresis loop. When John had the opportunity to reorganize a solid-state research group at the lab, his golden time in science began.

John adopted the JT theorem for

molecules in solids by introducing cooperative JT distortions. He rationalized the rich magnetic orderings of perovskite oxides by connecting the subtle structural change and orbital occupation through cooperative JT distortions. In a milestone in magnetism, John demonstrated spin–spin exchange interactions based on orbital degrees of freedom. His picture of orbital ordering and charge ordering beautifully explained the magnetic ordering and the structural distortions in the perovskite  $\text{La}_{1-x}\text{Ca}_x\text{MnO}_3$ . John's 1955 article on the topic in *Physical Review* was published back-to-back with the neutron experimental paper by Ernest Wollan and Wallace Koehler.

John summarized his groundbreaking approaches in magnetism, as described by the now-famous Goodenough–Kanamori rules, in his 1963 book *Magnetism and the Chemical Bond*. The rules provide the most practical guidance for researching the magnetic materials that are behind numerous technologies, including today's 6G communications.

John established models for a microscopic understanding of physical properties of transition-metal compounds at the time when many scientists were puzzled by why an oxide becomes a metal. He introduced concepts of electron itinerancy through covalent bonds and the first-order localized–itinerant transition, and he constructed the energy diagram based on the electronic configurations and crystal structures. Materials physicist Sang-Wook Cheong tells the story of when he once proposed studying physics in manganites to his boss: He was told, “It has been well done by John Goodenough a long time ago. He left nothing for us to do.”

John's appointment as head of the inorganic chemistry laboratory at Oxford University in 1976 caused some controversy because he was a physicist with no formal chemistry training. His students often had difficulties connecting the dots between their typical chemistry courses and John's lectures, although some later looked back on his teaching with admiration.

Throughout his career, John discussed physics by illustrating some compounds and their connections. As he would often say, he would “do



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chemistry to solve physics problems.” When the 1970s energy crisis hit, John turned his attention to materials for energy storage. He led the inventions of three major cathodes for lithium-ion batteries. Those discoveries were made not because of chance but because of John's fundamental understanding of the physics and chemistry involved. An overdue call from Stockholm in 2019 was a reward for his lifetime contributions to science.

John loved interacting with young researchers. He would tell them, “I would not have sat in this chair if I hadn't learned from my students.” Even into his 90s, John never thought to slow down. He came to his office with fresh ideas every day. He would say, “I have an aged body but a heart like a child.” Determined to solve problems and have a positive impact on society, John never changed how he pursued science: “My feet are on engineering; my heart is on science.”

John wrote in his 2008 book *Witness to Grace*, “Love can create peace out of discord; it can and does create remarkable (miraculous?) changes in human health and character.” John's life was a perfect testament to that statement. A giant in science and a model citizen, John will be greatly missed.

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