RETROSPECTIVE

Calvin F. Quate (1923–2019)

Nanoscience pioneer who invented advanced microscopes

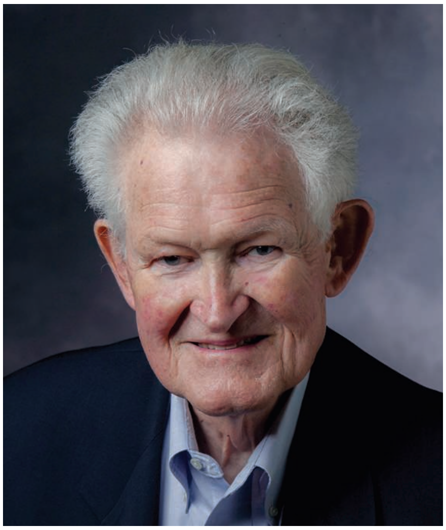
By **Daniel Rugar**[1] *and* **Franz Giessibl**[2]

Calvin ("Cal") Forrest Quate, a pioneer in nanoscience and inventor of new forms of microscopy, passed away on 6 July 2019. He was 95. Cal was always on the lookout for science's practical applications. His inquisitive and inventive mind led to important advances in disparate fields ranging from electron beam interactions in microwave devices to high-resolution acoustical imaging. He is best known today for his role in developing the atomic force microscope (AFM), now an indispensable nanoscience tool.

Cal was born in Baker, Nevada, on 7 December 1923 and spent his early years riding horses, herding sheep, and exploring the nearby mountains. He earned a bachelor's degree in electrical engineering from the University of Utah in 1944 and a Ph.D. in electrical engineering from Stanford University in 1950. After graduation, Cal joined Bell Labs and soon became a department head, working on microwave amplification using electron beams. He moved to the Sandia Corporation (now Sandia National Laboratories) in 1959 and was appointed vice president and director of research. Cal joined the faculty of Stanford University in 1961, where he stayed for the rest of his career.

At Stanford, Cal switched research directions and began working in the emerging field of microwave acoustics, where sound waves at megahertz and gigahertz frequencies were used for new types of signal processing devices. While doing this work, he made a key realization that the wavelength of sound in water at gigahertz frequencies can be shorter than the wavelength of light. The only problem was that sound waves at such high frequencies are extremely attenuated. To minimize the path through the water, Cal and his graduate students developed tiny acoustic lenses that could focus sound waves to a diffraction-limited submicrometer spot size. Thus, the scanning acoustic microscope was born, along with Cal's enduring passion for microscopic imaging.

Using sound waves to image materials at the microscopic level was a completely new concept. Nobody knew what to expect. D.R. joined Cal's group in 1976 and remembers the great enthusiasm Cal had for every sample that was imaged. The acoustic waves could penetrate the surface of the sample and reveal, for example, subsurface defects in semiconductors that could not be seen by optical or electron microscopes. When applied to living biological samples, the scanning acoustic microscope could reveal changes in internal viscosity, stiffness, and adhesion. In a related invention, Cal found that focused, high-frequency sound waves can eject tiny droplets of liquid. Although his first application—inkjet printing—was not a commercial success, the method is now used to precisely dispense nanoliter volumes of liquids for biological applications.



At the age of 59, Cal changed the course of his research dramatically when he learned of the scanning tunneling microscope (STM). As Cal told it, he was on a flight to London in 1982 to receive the prestigious Rank Prize in Optoelectronics when he read in *Physics Today* about work being done at the IBM Zurich lab using electron tunneling to form topographical images of atomic steps on gold. After accepting his prize, Cal changed his travel itinerary to visit the IBM lab, where he met future Nobel Prize–winning physicists Gerd Binnig and Heinrich Rohrer. Although the STM results were quite rudimentary at that time, Cal saw the technique's potential and returned to Stanford greatly excited. He held one of the few group meetings that any of his students can recall and announced that STM would be the new direction of the group's research. Cal's students built the first working STMs in the United States and were soon producing beautiful atomic-resolution images.

The next great leap in nanoscale imaging came in 1985, while Binnig and physicist Christoph Gerber were on sabbatical in Cal's lab. Binnig proposed that the limitation of the STM to conducting samples could be overcome by measuring tiny displacements of a sharp tip on a cantilever spring. Gerber and Binnig built the first working prototype in Cal's lab using a diamond tip glued to a piece of gold foil, which served as the cantilever. Although the first measurements were rather crude, their paper, audaciously titled "Atomic force microscope," became one of the most highly cited papers ever published in *Physical Review Letters*.

Cal realized that the key to the AFM's progress was improving the cantilever. Over the next several years, his students devised myriad cantilever designs, eventually allowing atomic resolution to be achieved. The AFM has become one of the most important and versatile tools for nanoscience and now even exceeds the spatial resolution of the STM. Extensions of the force detection concept have led to important applications in molecular imaging, chemical sensing, tribology, lithography, and the sensitive measurement of magnetic, electric, and optical fields.

F.G. met Cal in 1988 and later worked at Park Scientific Instruments, a company founded by Cal's former student Sang-il Park. Cal, who was on the board of directors, would visit frequently. He would look deep into the eyes of his students and co-workers and express his confidence in them by gently saying "You can do it." He also continued to contribute to papers late in life, once thanking F.G. for including him, adding, "I have gotten a lot of mileage from the article by showing it to people who assumed that I was over the hill."

Outside of the laboratory, Cal had a love of outdoor adventure. His daughters remember the smell of epoxy wafting from their garage as Cal built his own whitewater kayak. In his 60s, he took up windsurfing. He especially enjoyed hiking and backpacking in the mountains and canyons of the western United States.

Cal was an inspiring figure to us and to the many students and postdocs who came through his laboratory. His love for science and engineering radiated to those he worked with. He was humble in spirit and generous in the credit he gave to students and colleagues. Cal left a rich legacy and will be deeply missed. ■

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