WESLEY L. NYBORG

1917–2011

Elected in 1996

"For the applications of acoustic physical theory to the safety of medical ultrasound."

BY HAROLD M. FROST III
SUBMITTED BY THE NAE HOME SECRETARY

WESLEY L. NYBORG, professor emeritus in the Department of Physics at the University of Vermont (UVM), in Burlington, died on September 24, 2011, at the age of 94. Born May 15, 1917, in Ruthven, Iowa, he was the last of six children born to Isaac Nyborg and Leva Larson. In his childhood he lived on a farm before rural electrification was widely available and was taught in a one-room schoolhouse. Early social life included family sing-alongs at the piano. With humble beginnings, he had a rare chance to attend Luther College in Decorah, Iowa, which was founded by Norwegian immigrants. There he earned a B.A. in physics and mathematics in 1941. In 1945 he married Beth, his wife of 44 years until her death in 1989.

As a graduate student during and shortly after World War II, Wes earned an M.S. in 1944 and a Ph.D. in 1947 in physics from the Pennsylvania State University. His physics dissertation was titled "High Frequency Whistles: Edge Tones and Resonance," with adviser Harold K. Schilling, consummate teacher and researcher and a future dean of the Graduate College at Penn State. He helped Wes form his own style of teaching and research, including striking a balance between the aims of science and religion. Wes's early research there had an application of ultrasonic signaling for the U.S. Army Signal Corps. Soon, though, he turned to liquids. What resulted

was a lifelong career of research on the physical acoustics of ultrasound in condensed matter, mostly liquids and liquid-like media such as emulsions and soft solids, with special interests in ultrasound bioeffects and analytical assessments of the risk versus safety of medical ultrasound.

From 1947 to 1950, Wes was an instructor and assistant professor of physics at Penn State. Then he was assistant and associate professor of physics at Brown University (1950–1960), brought there by R. Bruce Lindsey, then chair of the Department of Physics. After a stint as a visiting scientist at Oxford University in 1960 to work with A. Rogers and D. E. Hughes, Wes arrived that year as a professor of physics at UVM. On sabbatical in 1969 he returned to the United Kingdom as a visiting scientist in the Department of Microbiology, University College, Cardiff, Wales, to collaborate with W. T. Coakley, D. E. Hughes, and A. R. Williams. In 1984, Wes was UVM University Scholar in the physical sciences. The next year he received the American Institute of Ultrasound in Medicine's Joseph H. Homes Pioneer Award, named after a developer of early B-mode ultrasound imaging and contact scanning. In 1986, Wes retired from UVM as professor emeritus.

To Wes, people were very important, not only functionally as students or colleagues in science, technology, engineering, and mathematics (STEM) education and research but also as individuals with needs and aspirations. The lists provided here only sample those he worked with. Postdocs, scientists, and faculty members visiting UVM included E. E. Fill (Austria), Robert K. Gould (Middlebury College, deceased), S. Hawkins (U.K.), E. A. Neppiras (U.K., deceased), T. K. Saksena, A. R. Williams (U.K.), and Marvin C. Ziskin (Temple University School of Medicine). Fellow UVM faculty members Wes interacted with included N. R. Alpert, J. A. Crowell (deceased), Alex Gershoy (deceased), Wm. Halpern, J. E. Krizan, B. K. Kusserow, F. J. Wiercinski, W. L. Wilson, and Junru Wu.

His students were many. Those coauthoring papers with Wes in his favorite *Journal of the Acoustical Society of America* included Douglas L. Miller (now at the University of Michigan), Richard E. Packard (now at the University of

California, Berkeley), James A. Rooney (University of Maine, Orono; then Jet Propulsion Laboratory; now deceased), William E. Rowe (IBM), R. M. Schnitzler, and R. Bruce Steele (deceased). Other thesis students at UVM who shared Wes's interest in research on the action of ultrasound on liquids or liquid-like media were Brian B. Brennan, Colin C. Connolly (of England), and Donald Storm. In retirement Wes continued to do scientific research, with J. S. Abramowicz, A. J. Bramer, A. A. Brayman, E. L. Carstensen, S. Z. Child, W. C. Dewey, Floyd Dunn, M. J. Edwards, M. W. Miller, S. Norton, O. Rudenko, A. P. Sarvazyan, G. R. ter Haar, G. Whitworth, and Junru Wu, among others.

After retirement, Wes's star in the engineering world rose even higher, with a Silver Medal in 1990 from the Acoustical Society of America (ASA) in the "Interdisciplinary" category for contributing to "Physical Acoustics and Bioresponse to Vibration." That year he also received the W. J. Fry Memorial Lecturer Award from the American Institute of Ultrasound in Medicine (AIUM). In 1996, besides receiving the Distinguished Service Award from Luther College, his alma mater, he was elected to the National Academy of Engineering (NAE) for contributions to physical acoustics and ultrasound bioeffects. The following year he became a member of the Vermont Academy of Science and Engineering, and in 2001 he received the Lauriston S. Taylor Lecture Award from the National Council on Radiation Protection and Measurements (NCRP), with a lecture titled "Assuring the Safety of Medical Diagnostic Ultrasound."

Wes was a fellow of the ASA, AIUM, and American Association for the Advancement of Science and a life member of the Institute of Electrical and Electronics Engineers. A special symposium of talks by colleagues and former students was held at UVM in October 2009 to celebrate Wes's 50 years on its faculty and to honor his path-breaking research.

How can one sum up the major accomplishments of Wesley L. Nyborg in the context of so many scientific and engineering collaborators with each of whom he valued a relationship? This can be done in three major categories: education, research, and leadership.

In *education*, Wes learned from role models H. K. Schilling and R. Bruce Lindsay that science has an underlying unity and serves society and its needs. That unity was bimodal, important, and interdisciplinary in which laboratory research and education in the classroom complemented each other. Not just students but even members of Congress require scientific knowledge for intelligent decision making. Wes passed this sense on to his own undergraduate and graduate students. As a UVM example, in 1968 Wes taught the course Biological Physics (Physics 122) from his own notes as used and then tested by students so that extensive revision occurred before his book based on these notes came out, *Intermediate Biophysical Mechanics* (Cummings Publishing Co., 1975). Lab experiments were integral to the required coursework, plus precise definitions of terms and rigorous logic in solving assigned problem sets. This method worked well with Wes's thesis students, too, whom he expected to achieve great clarity and precision in their writing.

In the *research* category, Wes was not afraid to explore the jungle of mathematics of nonlinear partial differential equations for motion in continuous fluid media. Vital was the Navier-Stokes equation, a version of Newton's second law of motion for continuous media and one of the grand mathematical challenges of the 20th century. Solutions to this master equation required the use of supporting equations for conservation of mass, momenta, and energy; Hooke's law; and laws for mass and heat diffusion and for thermodynamics. Wes applied perturbation expansions of field variables (i.e., for acoustic pressure, $p = p_0 + p_1 + p_2 +$ higher order) that generated many terms. So, Wes was a careful bookkeeper who developed accurate solutions to zero, first, second, and even higher orders, in a time before symbolic math programs ran on a personal computer. (Perhaps he was looking over his shoulder at his former colleagues at Brown—nonlinear acousticians Robert T. Beyer and Peter J. Westervelt!)

Thus, Wes was sure-footed in understanding troublesome concepts of radiation pressure, radiation force, and radiation torque arising in equations in his papers in peer-reviewed

scientific and engineering journals that withstood the scrutiny of peers over the span of decades. To this writer's knowledge, Wes never published an inconsistent definition or an unsound theory in the process of interpreting the results of ultrasound experiments via models such as for cause-and-effect laws. His high standard of scholarship was matched by confidence as an applied mathematician, as evidenced by publishing early in his career at UVM (1965) a book chapter titled "Acoustic Streaming" in the renown series Physical Acoustics (Academic Press, 1964), edited then by Warren P. Mason of Bell Labs of whose own experimental methods Wes made skillful use.

These latter methods included applying so-called resonant Mason horns of solid metal machined into various profiles for achieving high acoustic pressure levels in media such as gassy liquids, single plant cells, and soft solids. Invented by Mason, these horns mechanically amplified ultrasonic motion at 20 to 100 kHz well enough to permit use of conventional transducers bonded to them as driven by off-the-shelf RF power supplies. Wes's research group integrated a novel capacitance bridge developed by E. E. Fill into the Mason horn system to enhance sensitivity of measured transducer currents to localized motion in sonicated media. These motions included resonant oscillations of ultrasonically cavitating microbubbles, plus the acoustic microstreaming they caused. The vibrating tip could also indent a single plant cell or a soft solid. Experiments with other localized ultrasound sources used vibrating wires and bubbles trapped at ends of capillary tubes or in pores of polymer films to yield high hydrodynamic shear rates in contiguous viscous media. Methods at megahertz frequencies included calibrated plane-wave, hollow-waveguide, and resonant-cavity sources to cause ultrasonic motion.

Wes was also a pioneer in the use of high-speed cinematography in biological physics studies, as during his year at Oxford, to view directly the complex localized motions arising from the effects of high-power ultrasonics on complex media, especially when cavitation was present. Wave interference methods with both laser and incoherent light sources, plus displacement transducer techniques,

enabled measurement of motion directly. Sonoluminescence was recruited to further peer into the mysteries of ultrasonic cavitation.

However, Wes's level of *leadership* as a researcher and an educator eclipses the standards of his achievements in the educational and research categories per se. One begins to see this through the many book chapters he wrote, especially in retirement as professor emeritus at UVM. In these he made accessible to a large readership (1) the physical principles of ultrasound; (2) how it acts on biological media in laboratory settings and medical diagnosis, therapy, and surgery; and (3) what the implications of that action are for the public's benefit and safety versus harm and risk. In this regard, Wes's true identity as a soft-spoken but firmly moral exemplar to the medical ultrasound bioeffects research community begins to emerge, in the best traditions of "engineers and scientists behaving well" under difficult circumstances. As argued below, his name can thus be added to that short list of such exemplars maintained at NAE's Online Ethics Center/Center for Engineering, Ethics, and Society (OEC/CEES).

Wes behaved very well to chair over a two-decade period the three definitive reports that his Scientific Committee 66 prepared for the NCRP as chartered by the U.S. Congress in 1964: (1) No. 74 (1983), *Biological Effects of Ultrasound: Mechanisms and Clinical Implications*; (2) No. 113 (1992), *Exposure Criteria for Medical Diagnostic Ultrasound: I. Criteria Based on Thermal Mechanisms*; and (3) No. 140 (2002), *Exposure Criteria for Medical Diagnostic Ultrasound: II. Criteria Based on All Known Mechanisms* (including nonthermal and cavitation).

The scale of Wes's achievements can be inferred from the list of members who served on this committee: P. L. Carson, E. L. Carstensen, F. Dunn, D. L. Miller, M.W. Miller, H. E. Thompson, and M. C. Ziskin. Advisers and consultants included R. E. Apfel (deceased), C. C. Church, L. A. Crum, and M. Edwards. An array of specialties, perspectives, and interests gathered year after year at a conference table in midtown Bethesda, Maryland, at which conflicts were resolved and consensus was reached on technically daunting topics. To hold such an

effort together for over two decades required good working relationships and mutual respect for opposing viewpoints.

Moral as well as intellectual leadership was crucial to achieving this, as provided by Wes's well-known laser-like focus when solving a problem, his tenacity while surmounting difficulties, and his inner drive to transform rigorous thinking into the right action to serve societal needs. Wes's gentle leadership style engendered loyalty from fellow committee members, advisers, and consultants. Among Wes's 11 associates just listed, 6 stayed with him as chair over this period. From this can be inferred the operation of effective infrastructure and protocols to keep these group efforts for radiation protection and measurement going for so long. This required a leader to hold everything together and on goal. That leader was Wes.

Digging even deeper, it can be seen that Wes has left a legacy not only of these three NCRP reports and all his publications and presentations preceding and supporting them, plus a fire-tested way of developing consensus under difficult conditions, but also an institutional infrastructure at the NCRP for accommodating what now-unknown future research discoveries will reveal in medical ultrasound bioeffects. For research results on the action of ultrasound on biological media is a potential two-edged sword cutting out new image contrast and other interaction mechanisms beneficial for practical and efficient use of ultrasound in medicine but also mechanisms yet to be discovered for ultrasonically producing permanent or delayed damage in biological tissue. Such discoveries will for the large part be made by the upcoming generation of scientists, engineers, and physicians, many of whom have not yet even entered the science, technology, engineering, and mathematics (STEM) educational standard pipeline.

It is mostly for the sake of these neophytes to come that Wes served so tirelessly as chair of NCRP Scientific Committee 66, a service to which he brought all his decades in academia and that consumed most of his intellectual energies over the entire periods of his retirement and NAE membership. This is because forthcoming research-driven discoveries of new knowledge will lead to new conundrums of whether it is safe

to use ultrasound in medicine in given situations where there is a rational basis for concern. The horizon for these forthcoming concerns can be envisaged, for example, in the increasing use of contrast agents and higher ultrasound power and intensity levels in biomedical imaging.

Sadly, another NAE member working along the same lines as Wes—Harry E. Bovay, Jr.—died at age 96 in May 2011. A civil engineer who started his own company of consulting engineers in 1946, he came to support the best-possible uses of the engineering profession to benefit the general public through philanthropic activities over the last 20 years of his life. This philanthropy supported NAE's new Center for Engineering Ethics and Society (CEES), founded by former NAE President Bill Wulf. This giving brought the center to life, and and also provided support to keep the NAE's Online Ethics Center (OEC) in operation today.

Thus, with this moral vision and mission embedded within the core of the NAE, it is easy to see the parallel between Wes Nyborg and Harry Bovay. As a businessman, Harry did for the NAE what Wes as an academician did for the NCRP—building bridges for the neophyte engineer or scientist. This is illustrated by the poem "The Bridge Builder," written by Will Allen Dromgoole about a century ago, a poem that Harry and his Dad valued. The last eight lines are quoted:

> The builder lifted his old gray head:
> "Good friend, in the path I have come," he said,
> "There followeth after me today,
> A youth, whose feet must pass this way.
> This chasm, that has been naught to me,
> To that fair-haired youth may a pitfall be.
> He, too, must cross in the twilight dim;
> Good friend, I am building this bridge for him."

Professionally speaking, then, in the area of the action and effects of one type of societally useful radiation on materials and people—ultrasound—Wes built a bridge between the wisdom of an older generation and the energy of a newer

generation so that the latter, when its own day comes, can span its own gaps between ignorance and knowledge, conflict and consensus. In this sense, Wes will be sorely missed by all who knew him.

This conclusion also refers to the family he loved, of not only his cherished wife Beth and their daughter Elsa Mondou, and son-in-law Philip M. Mondou of Raleigh, North Carolina, but also their four children—Christine, Julie, Michael, and Martin. That is, it was very evident at the funeral service for Wes on October 1, 2011, at his longstanding place of worship—Community Lutheran Church in South Burlington, Vermont—that his family loved him immensely and was very aware of the high ethical standards of conduct that he put into practice in all his actions, whether public or private. Indeed, in his personal life Wes was a devoted husband, father, and grandfather who provided unconditional love and patient kindness. Underlying this was a gentle spirit of one who enjoyed gardening, singing, and playing the piano. For example, as a member of the church choir for years, he welcomed neighbors to his house for evenings of song and friendship.

A little-known aspect of Wes's giving that extended beyond his immediate family and social circle was his compassion for those engineers or scientists who suffered from short- or long-term disability. He lifted their spirits by helping them socially, intellectually, and even materially as they struggled to recover function and enter or return to mainstream life, at work or in their studies. Consistency in how Wes treated those he came to meet and know, whether they could give him something back or not, marked the single-minded strength of character of one at peace with himself. Though Wes was too modest to so recommend himself, he was indeed a role model for other engineers and scientists to emulate. In this sense of an exemplary vision of a higher moral order for practicing the engineering profession today, the legacy Wes Nyborg passed on to us will have its greatest impact.