and connect to new communities that share our excitement about IC innovation and its democratization toward a new wave of global impact. The program will provide education, mentoring, and collaboration opportunities as well as sponsored fabrication runs. It will also increase volunteering opportunities and is expected to help create new outreach programs to undergraduate and precollege students as well as enhance existing ones (such as the SSCS design contest). You can read more about the PICO program and how to get involved on page 151.

Murmann is also heavily involved with SSCS conferences. He was a program committee member for the IEEE International Solid-State Circuits Conference (ISSCC) for data converters and machine learning from 2007 to 2012 and 2007 to 2018, respectively; the ISSCC subcommittee chair on data converters from 2013 to 2015; the ISSCC Technical Programming Committee cochair and chair in 2016 and 2017, respectively; and a European Solid-State Circuits Conference Technical Program Committee member from 2012 to 2014. He organized the first double-blind review process at ISSCC 2017 and ran the conference's future directions committee in 2018 and 2019. He also organized the "Meet a Mentor" event at ISSCC 2020.

Murmann and his wife Yukiko at a reception in 2018.

Murmann's accolades include being the corecipient of the Best Student Paper Award at the Very Large-Scale Integration Circuits Symposium and a recipient of the Best Invited Paper Award at the IEEE Custom Integrated Circuits Conference. He received the Agilent Early Career Professor Award in 2009, the Friedrich Wilhelm Bessel Research Award in 2012, and the Semiconductor Industry Association–Semiconductor Research Corporation University Researcher Award in 2021 for lifetime research contributions to the U.S. semiconductor industry.

When he's not in the lab, you can find Murmann hiking and playing soccer. He has a basketball coaching and referee license and lives on the Stanford campus with his wife, Yukiko, and cat, Dwayne.

*—Abira Altvater*

# In Memory of Paul Penfield Jr. (1933–2021)

***Hae-Seung Lee, Duane Boning, Anantha Chandrakasan, Asu Ozdaglar, Jacob White, Mark Horowitz, Thomas Crowe, and Jeffrey Hesler***

Paul Penfield Jr., Dugald C. Jackson Professor of Electrical Engineering, Emeritus, at the Massachusetts Institute of Technology (MIT), passed away on 22 June 2021. He was an extraordinarily dedicated educator, researcher, and mentor for all of his life.

*Digital Object Identifier 10.1109/MSSC.2021.3110148*
*Date of current version: 17 November 2021*

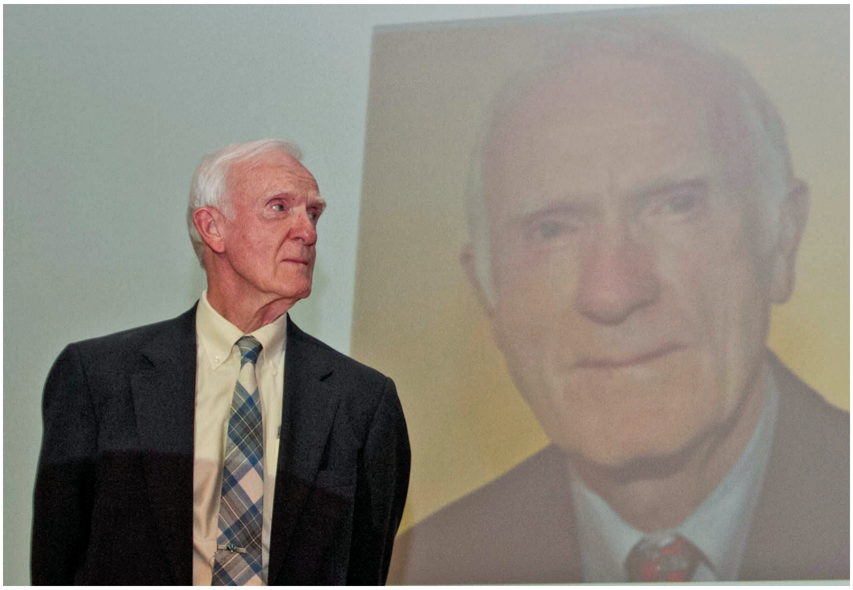
A long-time member of Microsystems Technology Laboratories (MTL), Penfield was with the MIT Electrical Engineering and Computer Science (EECS) faculty for 45 years, beginning in 1960. He served as associate head of the department from 1974 to 1978, as director of the Microsystems

Research Program from 1985 to 1989, and as Department Head from 1989 to 1999. He was the Dugald C. Jackson Professor of Electrical Engineering from January 2000 until his retirement in June 2005. Even after his retirement, he remained active, teaching a course every term until fall 2018, participating in faculty meetings, and collaborating on research and educational issues with other faculty. From 1996 to 1997, he served as president of the National Electrical Engineering Department Heads Association and, in March 2000, received its Outstanding Service Award.

One of Penfield's most significant educational contributions at MIT was the development of a course on information, entropy, and computation, offered jointly by the EECS and Mechanical Engineering Departments for almost 20 years. This course helped make the second law of thermodynamics more accessible to first-year students by treating entropy as a form of information. Penfield cared deeply about education in EECS, articulating the importance of both "the electron and the bit" in the past and future evolution of the field. His devotion to his students was fittingly commemorated with the Paul L. Penfield Student Service Award, which is granted to undergraduate and graduate students alike to honor his devotion to the department.

Another lasting contribution is Penfield's establishment of the master of engineering (M.Eng.) degree as an accessible and primary path for MIT EECS undergraduates, following (or integrated with) their bachelor's degree. To address the chronic congested curricula in the field, he established a flagship five-year program in MIT's EECS in which students receive both bachelor's and master's degrees. In the 1992 Frontiers in Education Conference paper that he coauthored [1], the authors wrote,

> By reducing significantly the time to the master's degree, we expect to be able to raise significantly the number of students allowed into the program without overloading either facilities or faculty. . . . [W]ith reduced curricular congestion, we hope to be able to redesign most of our academic subjects so that our master's graduate students will be better prepared to contribute immediately to the organizational effectiveness of technology-based industry in a highly competitive world. . . .



**Penfield in 2013 at MIT's EECS Celebrates, where the inaugural Paul L. Penfield Student Service Award at MIT was announced.**

The EECS M.Eng. program has been in place for more than two decades and is currently the choice of more than two thirds of EECS undergraduates (and nearly a fifth of all MIT undergraduates), so Penfield accomplished these goals with flying colors.

*Penfield was an extraordinarily dedicated educator, researcher, and mentor for all of his life.*

Penfield was instrumental in building up MIT's activity in silicon ICs. He played a key role in bringing Lynn Conway, as a visiting professor, to the MIT EECS Department in 1978 to teach the first very large-scale integration (VLSI) system design course, which culminated with student-designed ICs that were fabricated by Hewlett-Packard. This launched not only a universally accepted syllabus but also the concept of the multioutcrop sharing and interpretation system foundry. As associate head of the EECS Department and, subsequently, founding director of the Microsystems Research Program, he also spearheaded the establishment of MTL, which allowed MIT to establish a prominent position in silicon technology. As associate head, he built MIT's strength not just in ICs, but also in the computer architecture that this field of study enabled.

Penfield's wide-ranging research interests included inquiry into solid-state microwave devices and circuits, noise and thermodynamics, the electrodynamics of moving media, circuit theory, computer-aided design, A Programming Language extensions, IC design automation, the computer-aided fabrication (CAF) of ICs, and the equivalence of information and thermodynamic entropy. His work with J. Rubinstein [2] and, later, in collaboration with Mark Horowitz (Horowitz's account of the interaction is quoted later in the article) [3] on the signal delay in resistance–capacitance (*RC*) tree networks set the upper and lower bounds of signal delay in tree networks, such as complex metal–oxide semiconductor digital circuits. This work is considered seminal by many and has been extensively cited. The article was awarded the IEEE Circuits and Systems Society Darlington Prize Paper Award in 1985.

He was also fascinated by Tellegen's theorem, which he and his colleagues generalized [4] so that it can be applied to operated variables, such as differentiated, Fourier- or Laplace-transformed, and wave variables. They also wrote a book on the same subject [5].

In his 1966 paper titled "Circuit Theory of Periodically Driven Nonlinear Systems," Penfield developed a framework for periodically driven nonlinear networks with small perturbations [6]. In the 2016 paper "Oscillator Phase Noise: A 50-Year Review" [7], author D.B. Leeson noted, "The Penfield paper showed that subject only to conditions that were typically met in oscillators, small AM [amplitude modulation] and PM [phase modulation] noise in a nonlinear circuit driven by a periodic input could be treated as strictly linear and stochastic, and thus could be described in terms of spectral densities." This work was found to enable the noise analysis and simulation of many circuits, including sampled-data analog circuits, oscillators, and frequency multipliers, that would otherwise have been intractable.

Well before varactors found a common application, Penfield foresaw their usefulness and analyzed their maximum cutoff frequency [8] and noise [9]. He eventually wrote a book on varactor applications with R. Rafuse [10], which is still followed by many field engineers. Thomas Crowe, president and CEO of Virginia Diodes, Inc., and Jeffrey Hesler, CTO, write,

> *Varactor Applications* (Penfield and Rafuse) was initially published nearly 60 years ago. It was considered essential for circuit designers and is still known today for its clarity and completeness in covering the range of varactor circuit applications. Even today, in a world dominated by powerful computer-aided simulation and design tools, the experts in the field continue to use the design equations from *Varactor Applications* in developing state-of-the-art terahertz sources.
>
> The insights from the design equations in Penfield's work give accurate predictions of the efficiency and required embedding impedances to achieve the best performance for varactor multipliers. If a computer-aided simulation of a varactor multiplier disagrees with *Varactor Applications*, then the engineer should likely double check the simulation for errors! *Varactor Applications* continues to help accelerate the pace of terahertz circuit development, and it is quite rare for an engineering text to maintain such a relevance after 50 years.

Penfield also made substantial contributions to the area of computer-integrated manufacturing for semiconductors, an area he called *CAF*. Based on analogies with the thriving university software developments and sharing of implementations in electronic CAD, he spearheaded the fostering of a multiuniversity community of researchers and university fab facilities to systematize and advance the ability to represent, model, control, automate, and support flexible fabrication both in university fabs and more broadly.

With collaborators at MIT; the University of California, Berkeley; and Stanford, he led the joint definition of requirements for CAF [11] that became the basis for a substantial program funded by DARPA to prototype and implement such an architecture. At MIT, the resulting development of the CAF environment [12] was both a research prototype and the system that all staff, students, and researchers using the microfabrication facilities at MIT depended on for their work.

Research contributions from this effort included work on process flow languages to represent the fabrication process [13], with interpreters for connecting to process simulators to help with the design of the process, downloading recipes, and running equipment as well as tracking and scheduling jobs in the fab. Additional contributions included advancements in run-by-run control, scheduling, and processing modeling for semiconductor and microelectromechanical systems fabrication [14], [15].

Penfield's leadership in cultivating an active university community in the 1980s continues to have impact, with the evolution of software systems in use to this day across university fabs as well as an ethos of mutual support among university, government, and other research fabrication facilities. His meaningful contributions to the field were recognized with the Centennial Medal from IEEE in 1984, the IEEE Circuits and Systems Society Darlington Prize Paper Award in 1985, and the IEEE Circuits and Systems Society Golden Jubilee Award in 1999 as well as election to Fellow of IEEE and membership in the National Academy of Engineering, Sigma Xi, IEEE Antennas and Propagation Society, Association for Computing Machinery, and Audio Engineering Society.

On a more personal note, Penfield was devoted to his family, whose growth and successes he chronicled with pride, as well as his hometown of Weston, Massachusetts, where he championed the development of an ecologically sound rail trail through town. He was a beloved mentor to many of us. Horowitz, Yahoo! Founders Professor in the School of Engineering at Stanford University, remembers,

> I was one of the many fortunate MIT students who greatly benefited from my interaction with Penfield during time at MIT. I also was lucky and able to work with him again while I was a Ph.D. degree student at Stanford. I first interacted closely with Penfield during his efforts to bring work on silicon ICs to campus. As hard as it might be to believe, back in the early 1970s, while I was an undergraduate, there was no work in silicon ICs done on campus. To do research in that area, I ended up working at Lincoln Laboratory.

Penfield realized this was a mistake, and, back in 1977, he helped organize a class on IC design for MIT professors and a few students in this area. This course was taught by Botchek, an IC design consultant. I was a lucky student who took the class and got to see my MIT professors in a new light. Penfield, in particular, seems to delight in learning new concepts.

It was an amazing experience for me, and I have tried to replicate Penfield's interest in lifelong learning in my career. It also convinced Penfield and others to bring VLSI design to campus, which started when Lynn Conway taught a VLSI design course in 1978. This push changed the course of EECS research at MIT. Silicon ICs have driven the information revolution, and, as a result of this change, MIT has been one of the key research centers driving this effort.

Mostly because I got to know Penfield during the VLSI class, I reached out to him while I was doing my Ph.D. degree research. He had just published a paper on bounding the delay in RC trees, which could be used to estimate delays in CMOS circuits. For my Ph.D. degree, I was trying to extend their work to handle a nonlinear model of an MOS device. I was close to a solution, but I couldn't understand how they did one step in their algorithm. Penfield explained that they didn't have a forward path for that step, but they guessed the answer, and could prove that it worked, which was great for them, but didn't help me.

After working on it for a (long) while, I did come up with a forward path, which solved my problem and allowed me to improve their delay bounds. I excitedly wrote Penfield to tell him about my results. He was genuinely excited and wrote back about how he was able to improve on them!

I learned a great lesson from this exchange. First, the importance of sharing work freely and being open to improvements on your work—we both benefited from the exchange. The second lesson was probably more important for me: don't worry about who invented what when working in a team. Many people can invent the same thing, and, in collaboration, it never really matters who invented it first.

While I am sure that Penfield knew this instinctively, I initially was less gracious than Penfield when he improved my results. Fortunately for me, since I knew Penfield was such a nice guy, I had that argument only internally, learned my lesson, and responded in a gracious way. As a result of this exchange, Penfield added me as a coauthor to the journal paper about this method (which won the Darlington Paper Award), which was a better result than I could have ever hoped for. Penfield was an amazing teacher and mentor. I will miss him.

Penfield's passion for getting to what is right, rather than being right, also made him a good shepherd for junior faculty. As department head, Penfield was responsible for assembling promotion cases, a process that begins by convening senior faculty to collect input. As Prof. Jacob White, Cecil H. Green Professor of EECS recalls, "These meetings were often nodding consensuses followed by silence, leaving Penfield without the specifics he needed to make compelling cases. To spark discussion, Penfield was always willing to serve as devil's advocate, and I always picture him as frantically taking notes as his colleagues rapidly fired their detailed rebuttals."

For Penfield, changing his mind in response to a compelling argument was about more than just getting to the right answer. He clearly enjoyed, even took pride in, being correctly contradicted, a trait that was an important early influence on White. "Junior faculty are told that doctoral students should stand on your shoulders and see further, but it is very different when your student shows that you got it wrong. Having one's ideas overturned, it is so easy to respond defensively, but I had Penfield as a role model and could recognize this as a milestone worth celebrating." We will all miss you, Paul.

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