In Memory of Barrie Gilbert (1937–2020)

In 1972, I [Ray Stata] tracked down Barrie Gilbert in a small town southwest of London. He had taken a sabbatical from Tektronix to care for his failing mother. Barrie had already established a reputation as one of the industry's most creative analog designers with the invention of the famous Gilbert cell mixer and a trove of other patents. I convinced him to set up Analog Devices' first remote design center in one of the rooms of his mother's home. He later returned to America, where he established a design center in Oregon and recruited and mentored a remarkable team of analog designers.

Barrie's impact at Analog Devices was felt immediately, as analog IC products began to replace discrete transistor designs in a wide range of applications. However, he turned out the industry's first analog ICs in several product categories. Over nearly 50 years with Analog Devices, Barrie designed an impressive array of innovative IC products whose cumulative lifetime revenues are estimated to be US$2 billion. Some of the seminal IC products designed in the 1970s remain best in class and continue to be shipped today.

His career aligns with the evolution of electronic circuits based on transistors. He joined Mullard in the United Kingdom in 1959, where he developed almost all key circuits for a transistorized sampling oscilloscope that could capture waveforms with gigahertz bandwidths. In 1964, he moved to Tektronix in the United States to work on the legendary 7000 series of oscilloscopes. As an early user of Tektronix's in-house bipolar IC process, Barrie was among the first to recognize that a new style of circuit design, which must depart greatly from discrete bipolar circuits, was needed to actualize the unique potential of monolithic circuits. In the early 1970s, he was a pioneer in exploring super-integration to shrink the chip area, and thus cost, to realize novel functions, such as an analog character generator that displayed the knob settings on the CRT, that would set Tek oscilloscopes apart.

Digital Object Identifier 10.1109/MSSC.2020.2987235
Date of current version: 24 June 2020

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In December 1968, two landmark papers, solely authored by Gilbert, appeared in *IEEE Journal of Solid-State Circuits*. The first described a new circuit topology for amplification across very wide bandwidths, with the unique property that it is linear to large signals with a gain that is set precisely by the ratio of two biasing currents. Obviously, this was motivated by the needs of the vertical amplifier in an oscilloscope, which receives input waveforms of very different levels and whose gain is therefore selected across a large range. The second paper showed how an accurate algebraic multiplier of two independent analog waveforms emerges from this circuit. Years later, Barrie would describe how both circuits descended from the current mirror, which was an iconic monolithic analog circuit concept itself.

At the time, analog computation was used extensively in real-time control systems for mission-critical applications such as aircraft and space vehicles. While the op-amp had enabled most algebraic and calculus-based operations, multiplication remained elusive, and many of the op-amp-based solutions were inaccurate, irreproducible, and temperature dependent. The Gilbert multiplier changed all that. In the debut paper, Barrie brought forth and analyzed all obvious forms of residual inaccuracy arising from device and circuit imperfections in the computed product. To this day, the Gilbert four-quadrant multiplier circuit is definitive.

An indefatigable enquirer, Barrie noticed that a certain principle was at work in these two circuits. In the clearest possible terms, he pinpointed it in the debut publication as arising from the exponential relation of each PN junction of an even number configured in a loop and called it the *translinear principle*. Briefly, the principle states that the products of the current densities that are clockwise in the loop balance those that are counterclockwise. Importantly, it enables interesting, often unexpected uses. For example, a handful of properly configured bipolar transistors calculate the exact instantaneous vector sum of two input waveforms. It is a sign of Barrie's brilliance that in short order he would discover a nearly exhaustive catalog of useful circuit topologies based on the translinear principle.

An exact multiplication of a waveform with itself using as few as three transistors suggested to him other integrated nonlinear functions, most usefully the real-time computation of the true root-mean-square (rms) value of arbitrary waveforms, even ones with a high crest factor. The circuit displayed Barrie's virtuoso mastery of implicit computation through feedback. These *rms–dc converters*, as he called them, displaced cumbersome earlier methods to realize the same functions and are just one example of his contributions to the instrument-on-a-chip concept. These precise and accurate nonlinear computational cores radiated into families of products at Analog Devices.

Other notable contributions include a very linear and stable voltage-frequency converter (1976), which provided cheap (for the time) analog-to-digital conversion at sensor interfaces, transmitting a square wave into a counter. Variable-gain amplifiers are used for automatic gain control in every communication system but are seldom recognized as a circuit form worthy of investigation in their own right. Barrie maintained an enduring interest in these circuits, expressed most recently in the design of industry-leading logarithmic amplifiers based on new circuit principles. These ICs are ubiquitous in wireless communication infrastructure and devices for their precise measurement of signal strength.

For almost every analog circuit engineer, Barrie Gilbert's name first evokes a mixer circuit. Interestingly, someone else had patented that circuit topology in 1963. The doubly balanced mixer is a special use of Gilbert's analog multiplier. A periodic waveform overdriven at one input port will multiply the waveform at the other input port with a biphase square wave to realize the theoretical switching mixer. The Gilbert multiplier circuit is universally used as a mixer in this way. Although Barrie had first disclaimed this mixer circuit, over time he let the eponym take hold. In important ways, he contributed to expanding the input dynamic range of the mixer, which must handle large unwanted signals in today's radio systems. For example, in 1997 he presented a new circuit topology for the mixer input circuit with an unprecedented instantaneous dynamic range.

Barrie was acutely aware that a gulf exists between the exploration of a circuit idea and its development into a product. He often wrote that he would spend more time on the design of the support and auxiliary circuits than on the functional core. He liked to design IC products end-to-end, worrying about matters such as the IC layout and the most user-friendly pin allocation on the package. He wrote data sheets for his products, their test plans when put into mass production, and extensive application notes that make for masterly tutorials.

He advocated that in many instances the marketing department or even the customer may not have envisaged uses for a product conceived by the circuit designer that, when introduced into the market, would open unforeseen applications. He was right about this many times, but not always. For example, in 1977 he discovered that a set of differential pairs with graduated input offsets, whose output currents summed in alternating polarity, could approximate a sinewave input–output characteristic quite accurately. However, efforts to promote an analog circuit that computed sine, cosine, and even tangent could not discover a viable market. Later, in the hands of others, the circuit topology would find new life as a folding amplifier in analog-to-digital converters and as a frequency multiplier.

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Barrie was unconventional in every possible way. He never lived the same day twice but continuously built on his experience to reveal new insights and discoveries. There were no rule books, only fundamental principles and learning from experience. As one of Analog Devices' first two corporate fellows, he attracted talented engineers to the company and was an inspiring teacher and mentor in developing many world-class designers.

His accomplishments were acknowledged in many ways. He won the International Solid-State Circuits Conference best paper award five times and the IEEE Solid-State Circuits award (now known as the Pederson award) three times over its long history. The Fall 2007 issue of *IEEE Solid-State Circuits Magazine* featured Barrie. He was elected to the National Academy of Engineering, and his office walls were lined with more than 100 patents. He retired from active product development at the age of 82.

Barrie's vision and dedication to excellence in everything he undertook was an inspiration for all who had the privilege to know him.

—Ray Stata and Asad Abidi