Kenneth C. (KC) Smith

The Story Behind Microelectronic Circuits

PHOTOS COURTESY OF KENNETH SMITH

The author's 1982 text, coauthored jointly with Adel Sedra, has sold over 1 million copies. This article describes how this book came to be and the genesis of products such as the iPhone.

As the extensive use of *Microelectronic Circuits* (Oxford University Press, 2004, fifth edition) continues and my global travels continue, I am increasingly asked, "How did the book get started?"

In 1955, at the beginning of my master's degree program in control theory and applied psychology at the University of Toronto (UT), my advisor, Prof. James M. Ham, stated farsightedly that I needed to learn as much about computers and computing as I possibly could in addition to other relevant topics. Following his advice, I took the only available course on computing at UT, focusing primarily on numerical analysis but involving a short experience with Canada's first commercial electronic computer, a vacuum-tube machine called FerUT, for Ferranti at University of Toronto (for more on the early history of computing at UT, see http://pages.cpsc.ucalgary.ca/~williams/History_web_site/World%20map%20first%20page/Canada/a2004.pdf). FerUT was built in Britain by Ferranti following a University of Manchester design. This course was presented by an interesting group of individuals. They had been associated with UTEC, a four-bit prototype of a Von Neumann machine

Digital Object Identifier 10.1109/MSSC.2009.934597

whose fabrication at UT began in 1948. As a result of participating in this course, taught jointly but led by Prof. Calvin Gottlieb, I was offered a position as a member of a UT team cooperating with the designers of a next-generation Illiac computer at the Digital Computer Laboratory (DCL), University of Illinois (UI), Urbana-Champaign. Upon my arrival in 1956 at UI, complete with a new master's degree and some vacuum-tube digital-electronics experience but no formal exposure to transistors, I became a member of a team of young designers, embedded in a windowless former coal bunker and intensely focused on the creation of high-speed digital transistor circuits. These young men were at various stages of their academic careers; a small number of them were working on graduate theses in the area, but many were simply employed as research assistants in an interesting job, as I was. The goal of the team was to create a suite of transistor circuits, operating with a delay of a few nanoseconds in speed-independent asynchronous circuits, that would be suitable for a very high-speed multiprocessor computer system. This system was intended by its sponsor, the U.S. Atomic Energy Commission (AEC), as a benchmark against which to compare the contemporaneous development of the IBM 7030 computer (called STRETCH).

Because of the AEC connection, DCL was provided with access to the latest transistors (type WE GF45011) available from the Bell Telephone Laboratories military-products division and intended for an RF application in the Nike Zeus missile defense project. These p-n-p germanium transistors were quite spectacular physically—totally gold-plated except for the glass header through which three long, thick gold-plated leads emerged. The package was roughly the size of a JEDEC T05 but with a top gas-evacuation tip. Beyond that, our only information available was what we could measure externally. In particular, we (in the trenches) were provided no information about the internal structure fabrication technique or expected parameter ranges; all we had was several hundred three-terminal "jewels" on which we could take measurements.

In hindsight, our lack of any certain knowledge of how and why these transistors worked and of their formal parameter values was a blessing in disguise. Certainly, from my point of view, all I felt I could ever know was the result of my own personal measurements. Further—thankfully—at my stage of circuit-design maturity, a major concern was finding dc voltage and current relationships appropriate for the design of asynchronous circuits, which tended to spend much of their time waiting for the next emerging activity. Accordingly, I proceeded to create a number of testers, simple single-function circuits intended to measure some dc parameter of an individual transistor in a rapid, reliable, nondestructive, and minimalist way. Subsequently, many nooks and crannies in our windowless former coal bunker began to fill with small testers, each with a D'Arsonval meter and often battery-operated. With these, one could easily ascertain device-to-device variability and whether some experimental faux pas had damaged anything fundamental. Thus began a view that transistors were building blocks whose terminal behavior alone mediated the design of the circuit in which they were embedded. A further view that this environment supported was that each and every element in the design of a modestly complex circuit such as a flip-flop should embody a critical single element of the circuit specification in such a way that rapid custom design was easily accomplished.

Of course, the previous views were obviously biased by a few simple facts: our gold-plated transistors were relatively rare and apparently expensive (US$40 each, I recall); precision resistors were considerably cheaper and readily available; and fast-recovery (gold-doped) germanium diodes were readily available. One overriding determinant of the design was the fact that our gold-plated transistors were apparently designed for high-frequency amplifier-oscillator applications and behaved abysmally in or near saturation and quite poorly, (due apparently to increased junction capacitance), unless the collector was maintained considerably below the base potential. Accordingly, the circuit style that rapidly evolved was an emitter-coupled current-switching nonsaturating one with resistive diode-clamped level shifters allowing small signal swings (±1.5 V) and follower outputs. To facilitate design and independence from device variability, the design emphasized a current-source architecture employing large power supplies and wire-wound resistors across which the signal-voltage variation was typically very small. Finally, a fast-recovery-diode clamp at the collector ensured that the transistor operated in its highest-speed mode to provide digital circuits of considerable complexity with transition times and delays of only a few nanoseconds.

Generally speaking, the designs that resulted from this early process were quite successful. Eventually, in 1962, a very high-speed computer called Illiac II was completed. Of course, by then many other things had happened. Simple computer simulation had appeared, and even

> ***In hindsight, our lack of any certain knowledge of how and why these transistors worked and of their formal parameter values was a blessing in disguise.***

FIGURE 1: KC lecturing at CPEG (Computer Engineering in Hong Kong) in 1994.

synthesis programs for some of our standard circuit topologies were in use. We even began to understand more about our transistors, acquired second sources, and even graduated to saturating n-p-n circuits for use in the design of peripheral equipment. By that time I had completed my Ph.D. in experimental solid-state physics on switching mechanisms in ferrites at UT (1958–1960) and had been promoted to the position of chief engineer of Illiac II upon my return to UI in 1961.

While continuing to manage Illiac II developments, primarily emphasizing I/O systems, I continued to enjoy myself as a circuit designer. I helped Gene Leicher start a current-mode power-supply company; I assisted Henry Lippert in his creation of the System for Organizing Content to Review and Teach Educational Subjects (SOCRATES), UI's other renowned teaching-machine project; and I designed and built the pattern-articulation unit of Illiac III, under the direction of Prof. Bruce McCormick.

In 1965, UT offered me a position as associate professor in both electrical engineering and the new Computer Science Department. In electrical engineering, my challenge was to replace the teaching of the late Ed Reid, who was renowned as a practitioner and teacher of vacuum-tube electronics, particularly for radio communications. In computer science, I contributed to the teaching of computer architecture.

In electrical engineering, to attract graduate students, my initial emphasis was on a graduate course called "Digital Circuit Design," the name being intentionally ambiguous, intimating an attention to digital circuits but also to a point of view concerning circuit design in general, emphasizing very-large-signal behavior, which I referred to also as "digital (-circuit) design." I intended to imply a state of mind that I had acquired in my early days with the gold-plated jewels at Illinois. Stripped to its barest essential, the idea was to model terminal behavior of transistors in simple (digital-like) ways, with typical and extreme values of terminal voltage currents and current gains as the basic rules of a game played with three-terminal black boxes called transistors. The course intentionally provided very little in the way of physical electronics, merely a plausibility model of how the device probably worked. Rather, it emphasized circuit topology, accentuating the ways in which the flow of current through the black boxes was particularly convenient and directly fulfilling a goal, which I refer to as "circuit efficiency." In this view, an efficient circuit was one in which the intended current flow naturally took advantage of a transistor's current direction and current gain in order that currents were not wasted in biasing components (dominantly resistors at the early stages and increasingly other transistors as the IC industry matured). This was a particular case of an emphasis on optimum circuit structure, in a process I called "topological design." The goal was to create "design-efficient" topologies where each of the circuit specifications was controlled by a minimum number of components (ideally, one). One of the standard themes in the course was to encourage students to create new circuits whose design fulfilled this goal to the extent that "value design" for a particular application could be done in one's head while driving to work on the freeway. An important part of the course was to analyze large numbers of published circuits of various kinds from this point of view, seeking practice at rapid understanding with little data beyond the schematic. Design practice consisted of being able to evaluate plausible current levels in the circuit rapidly and to identify alternative structures that were available in place of—and often superior to—the original design. The course was supported by a great many handwritten mimeographed

FIGURE 2: KC lecturing at Ewha Womans University, Seoul, Korea, in 2006.

handouts that emphasized circuit schematics. The goal of the presentation was to identify principles to be exposed to the students.

On the undergraduate side, the situation was slightly different. Before my arrival, several other people with doctorates in solid-state physics had joined the department, during the latter years of Prof. Reid's tenure. Their major research emphasis was on processes and devices and, to a very limited extent, on circuits. They presented a sequence of two courses beginning late in the second year of a four-year curriculum in electrical engineering. Thus, my challenge was to design and teach a course in advanced circuits for the fourth-year students, which I proceeded to do in the spring of 1966. Much to my chagrin, I discovered that the students' ability to deal with transistor circuits was extremely limited. It was clear that though they were exposed to what may have been going on inside devices, they were almost totally unaware of what to do with them. It was apparent that what they were likely to know about transistor-circuit design at graduation was going to be perilously limited. I therefore proceeded in parallel on several fronts to correct the situation. First, since their background in circuits was so severely limited, I began to teach them top-down about systems-related issues that involved and motivated circuits. A particularly relevant topic was op amps: we could talk about what to do with them first and wonder how they were made afterwards. Thus began the inverted teaching process I continued to emphasize and that ultimately affected the writing of *Microelectronic Circuits*.

At the same time, I talked to the final-year students about their deficiencies in circuit design. (See Figures 1–4 for KC doing what he enjoys; spending time with students.) I told them that as graduating students they had a large potential impact on curriculum change, and I solicited their help in influencing our department chair. Subsequently, I discussed this issue with the chair, describing how the process of basics first (that is, teaching physical electronics before circuits), while seemingly logical, was clearly not effective. I convinced him that an inverted process was necessary, with electronic circuits taught earlier, in order to motivate the need for a deeper understanding of physical electronics in subsequent courses. When he asked what I would teach in this new second-year course, I told him I would teach exactly what I was now teaching in the fourth year, since in each case the students new nothing about electronic circuits. Interestingly, in those simpler days before the proliferation of committees, the die was rapidly cast, and the second-year electronic circuits course was scheduled for the spring of the following year.

FIGURE 3: KC being introduced by Prof. Eric Lin on "Smith Day" at National Taiwan University, in 2009.

The design of the new course, as represented by copious handwritten course notes full of circuit diagrams, proceeded in much the same way as the initial edition of *Microelectronic Circuits*. General electronic system material came first, then ideal operational amplifiers, followed by hints at amplifier imperfections and an introduction first to diodes and then to transistors as implementing mechanisms.

Meanwhile, Adel Sedra had arrived from Egypt to become one of my early master's students at Toronto. Naturally, he took my graduate course in "Digital Circuit Design." He loved it (he said) and encouraged me to write something more formal about this approach to teaching electronic circuits. While this was very

FIGURE 4: KC with Hoi-Jun Yoo, founder of the System Design Innovation and Application Research Center at KAIST, and visiting students from KAIST at the University of Toronto, 2007.

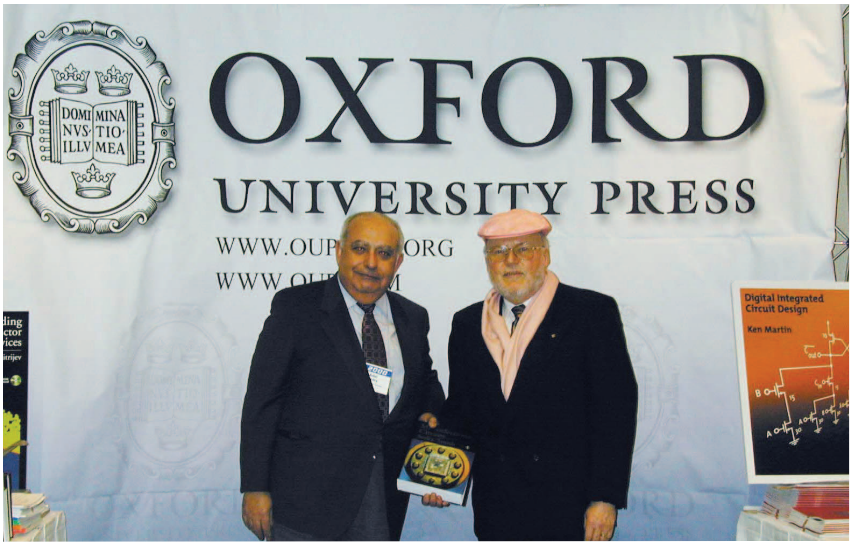

FIGURE 5: KC and coauthor Adel Sedra at ISSCC 2000.

encouraging, particularly when suggested by a very creative person, and motivated me to be more organized with my course notes, other distractions intervened.

As time wore on, Sedra completed a master's degree and Ph.D., the latter with the invention of the current conveyor (of which more will be said elsewhere). To my delight, in 1969 he accepted the position of assistant professor in the department. In his new role, he was busy of course but continued to encourage the writing idea, offering to help me with the work. This was even more encouraging, but my threshold of distraction had grown higher. Finally, he offered to start the writing, with me helping. This mode of helping brilliant people do things I want done has always pleased me, and my career has been blessed with many such occurrences. Near the end of my five-year sojourn as department chair, the first edition of the book was completed and vetted. It appeared in early 1982. (See Figure 5.)

The book was unusual in its day. With respect to operational amplifiers, for instance, it began with the inverted theme, emphasizing op amp applications. It then motivated curiosity about the internal structure, dealt with basic circuits and then with more complex ones, and proceeded later to a discussion of the internals of operational amplifiers. The text included an extremely large number of examples, exercises, and problems, following the direction of my "Digital Circuit Design" course. In general, the book was completely different than its competitors, which emphasized almost exclusively a circuit-theoretic linearized view of transistor devices rather than the large-signal (or "digital") approach of our text.

What is more remarkable has been its continued and growing success, particularly around the world. Now in its fifth edition, with the sixth planned for the end of 2009, the book has enjoyed many translations. As of June 2008, the total sales in all editions and translations had reached 1 million copies. Interestingly, the use of the international English edition prevails in many universities around the world.

Now that you have been exposed to a brief version of the origins of *Microelectronic Circuits*, it is important to know the context in which the work on the book and its ancillaries has proceeded. In the following sections, a sampling of my cognate academic activities is outlined. While they may seem at first sight to be unconnected, they share the integrity of my enduring interest in the broad implications of the electronic revolution on the world around us.

Current Conveyors

On my return to Toronto in 1965, my research focus intentionally moved away from the big-contract mode, which in my view often has a negative impact on the ultimate Ph.D. graduate product, to a smaller-scale, more locally defined and flexible one. This move was supported by the fact that there was no large-scale funding available in Canada from our predominantly branch-plant-driven economy at the time. Thus, while I created research themes for the ultimate cohesion of my own research career, I allowed students a great deal of latitude in choices about their work. I wanted to encourage their spontaneity and creativity; my goal for them, particularly at the Ph.D. level, was to encourage these traits as important to their later careers. To further facilitate this process, one arranged for a large number of research-focused master's degree students, only some of whom were selected for the doctoral program, where the focus was on the independence and creativity required of a Ph.D. academic.

One of the early themes alluded to above was the creation of an analog-computer-like simulator for electronic circuits, in which the simulator's core active elements were ideal transistors created physically (in the style of an op amp) from the usual transistor components. The scheme envisaged was a physical parallel-operating simulation environment, as an alternative to the serial slow computer-based simulations of the day. While active components were simulated by "ideal transistors" and secondary parasitic components, the rest of the circuit used the resistors and capacitors of the original design. Accordingly, a task for several students was looking for possible candidates for "ideal transistor" topologies to provide this key element in the system. Therein lay the origin of the circuit building block called the *current conveyor* (CC).

The CC—of which there were two versions, CCI and CCII—was created in conjunction with the Ph.D. work of Adel Sedra. From its origins as an ideal transistor, the CC quickly took on a life of its own as a novel building block for filters and similar devices and as a potential alternative to operational amplifiers and other, more theoretical circuit building blocks. Current conveyors (particularly the CCII variety) have been the subject of a great deal of academic research extending to the present time. Interestingly, related developments include what is usually called the *current-feedback amplifier*, which consists of a complete CCII driving a second CCII, acting as a follower. While the utility of this configuration was known earlier, its separate functional integrity was patented by Analog Devices some 20 years after the original CCI and CCII patents were granted.

CCII is the more flexible of the two three-terminal designs. One of its terminals, which can be considered as both input and output like the emitter or source of a transistor, was (regrettably) called *X*. A second in put terminal called *Y*, like the base or gate of a transistor, controls the voltage on terminal *X*. A third terminal, called *Z*, acts as a current-source output (like the collector or drain of a transistor), providing a current equal to that flowing in terminal *X*. Note from this description the transistor-like but idealized behavior—with two important additional features, namely, that the potential of *X* and *Y* are the same (as defined by the voltage at *Y*) and the current in *Z* is the same as that in *X* but is bipolar and can flow in the same or the opposite direction of that in *X*, depending on the variant of the CCII used. In the most popular CCII, the current flowing out of (or into) *X* causes current to flow into (or out of) *Z*. In this notation, a differential-input current-mode feedback amplifier consists of a CCII with inputs Y_1 and X_1, with its output Z_1 feeding the input Y_2 of the second conveyor, whose output X_2 is the overall amplifier output; feedback is connected from X_2 to X_1 (see [1]–[3]). An interesting example of the flexibility of the idea embodied in CCII is its use as a remote-located sensor input system in which terminal *Y* is a high-impedance sensor input terminal, *X* is connected through a gain-controlling resistor to local (sensor ground), and the mirrors whose outputs are joined to create output *Z* are located at some distance, with power and signal being communicated on the positive and negative mirror input leads. A very simple implementation of this scheme uses two matched complimentary depletion-mode FETs whose gates are joined to create *Y* and sources joined (possibly through resistors) to create X, with drains going to the positive and negative mirrors through a twisted-pair cable.

Multiple-Valued Logic

As part of an extended departmental plan, upon my return to Toronto in 1965, I helped cofound the Computer Group in Electrical Engineering. The group idea had been created to provide focus for the interests of the enlarging academic staff, making department-wide decisions easier for the department chair. Somewhat characteristically, besides starting the Computer Group, I joined several other groups, including the Biomedical, Communications, and Electronics groups. Early on, Zvonko Vranesic, a master's degree student of Prof. Stewart Lee, cofounder (for software) of the Computer Group, had been assigned the task of understanding multiple-valued logic as an alternative to binary in various contexts. Vranesic, having a diverse background and varied interests, chose to explore the radix-3 circuits he had discovered in the literature and to improve on them if possible. I was asked to assume the role of informal circuit adviser. Upon completion of this work, and intrigued about the possible generality of higher radices, Vranesic began his Ph.D. on a much more elegant mathematical and algebra-based study of historic multiple-valued logic systems, with a view to uncovering schemes of potential use in then-current computing systems. Realizing he had to make choices among various competing mathematical systems, he wisely decided the potential for circuit implementation might clear the air. Consequently, when I was asked about the possibility of implementing a wide variety of mathematical constructs, I would suggest possible competing implementation topologies. This process proved very effective in allowing him to pick a subset of possible constructs on which he based his theoretical analysis. His work was very successful, resulting in a seminal paper published in the *Proceedings of the IEEE*, in which I participated as the third author, providing an appendix on possible circuit realizations [4], [5]. Thus the die was cast: the electrical engineering department at UT was suddenly renowned as a hotbed of multiple-valued circuit design. Correspondingly, I and my colleagues began decades of supervision of students in multiple-valued logic and circuit design. Shortly thereafter, in 1971, Vranesic, having become an assistant professor at UT and a colleague from SUNY Buffalo, initiated the first International Symposium on Multiple-Valued Logic, which will celebrate its 40th anniversary in Barcelona, Spain, in May 2010.

Human Factors

My first foray into human-factors aspects of electronics and systems design began with my master's degree (1955–1956), for which my thesis topic was the "Human Operator of Control Systems." Unusually, three students worked on this one large master's thesis under the direction of Prof. James M. Ham, a renaissance man who later served as president of UT (1978–1983). The issue he posed to us had come up during his stint as a controls consultant at Avro Aircraft; it concerned limitations on the role of pilots for the high-speed Avro Arrow (for more information, see http://en.wikipedia.org/wiki/Avro_Canada_CF-105_Arrow), a delta-winged interceptor

FAVORITE APHORISMS (SELECTED)

- On being disappointed: Early is best; one has longer to recover.
- On impediments to technical progress: If you can't fix it, feature it.
- On students requiring handholding: Remember, this is a master's degree, not a slave's degree.
- On professorial roles: Young academics should work for themselves; older academics should work for society.
- On evaluating academic institutions: The better the school, the thinner the rule book.
- On timeliness: "There is a tide in the affairs of men, which, taken at the flood, leads on to fortune" (Shakespeare).
- On praise for accomplishment: "A thing of beauty is a joy for ever" (Keats).
- On being "lucky": "Luck is the encounter of preparation with opportunity" (paraphrased from Seneca).
- On premature action: A creatively lazy engineer thinks first and acts second.
- On life and its vagaries:
  —Life is a laboratory.
  —Life is an iterative process.
  —Take advantage of adversity.
  —If it is worth doing, it is worth doing well.
  —Life is a sequence of opportunities to be continuously detected but (only) selectively taken.
- On coping with life: If you can't handle the answer no, never ask.
- On engineering: Engineering is a state of mind, taught and nurtured in an example world, whether electrical, mechanical, or civil.
- On perfection: Perfection can be a delusion, merely a measure of ignorance.
- On success: Success is an iterative process.
- On expertise: Experts are of two kinds: actor experts are limited to the script of their own education; real experts can say something useful about their specialty in any specified time.
- On the role of academic laboratories: Exploration should dominate verification.

being built in Toronto in the early 1950s. Our challenge was to create a large-screen tracking system providing a digitally controlled target and operator-tracking-error data acquisition for analysis using Canada's first electronic computer, FerUT. So began a lifelong concern for why and how data should be exchanged between humans and machines, dominated by an aversion to keyboards.

My career in this domain involved a diverse collection of activities:

- concern for the simplicity of device-data measurement (see above)
- provision of computer services and facilities for music creation and performance, as a means to evaluate computer system design at UI
- design of a computer-controlled, film-transport-based teaching-machine system at UI (SOCRATES)
- concern for the layout and functionality of medical instrument controls, particularly on commercial RF lesion generators, intended to avoid ambiguity and accidents (these instruments are still in use around the world today) [6]
- concern for music composition, performance, and conducting as a metaphorical computer-controllable process (SSSP, a graphics-based music composition and performance system at UT [7], [8])
- several projects on multitouch tablets, including what is said to be the first such implementation [9], leading to current common uses such as the Apple iPhone [10]
- several projects on machine vision for flexible manufacturing [11]–[13]
- several projects on touch sensor systems for robotic manufacturing
- investigations concerning reactive environments in which repeated behavior is appropriately predicted without user intervention [14].

Graduate-Student Supervision

Graduate-student supervision is a tricky business: whether, when, or how to direct, guide, lead, pull, push, or drive the student toward his/her (or your) goal is a vexing question! With some few exceptions, I have been blessed with unusual students, many (but not all) of whom were capable of good grades; most of them were also capable of achievements in many other areas. They were inherently broad individuals who went onto diverse and illustrious careers.

Though there are those who equate the supervision of Ph.D. students with the apprenticeship process, the comparison is fundamentally flawed. While apprenticeship is concerned with creating an exact copy of a particular expertise, the ideal Ph.D. education process has a much grander goal. Although the ideal Ph.D. graduate might embody some of the expertise of the adviser, next-generation creativity demands more. And while there is nearly universal agreement that the Ph.D. graduate must demonstrate knowledge beyond that of the adviser, that is not enough to ensure the process of intellectual regeneration of which Ph.D. education is an important part.

For the sake of the future, the graduate should also be *different*. Ideally, the graduate should be broader or should at least have additional elements of breadth (as compared with the adviser) in order to fulfill this destiny. But how can this be accomplished effectively? Clearly, a breadth requirement in the Ph.D.-qualification process helps. But it is not enough, since it is course work–like, assimilated and studied, examined, and forgotten. What is needed is a long-term tension on the candidate in the breadth dimension. Such stretching can be provided by multiple supervisors, each of whose expertise must be accommodated and assimilated over time. If personalities allow, having two advisers is quite desirable and possible. To enable conflict resolution among the advisers, I have found that three may be necessary.

KENNETH SMITH, MASTER TEACHER AND RESEARCHER

On 4 May 2009, Kenneth Smith was presented with the IEEE Canada Computer Medal (see Figure S1). He was cited "for lasting technical and educational contributions to electronics for computing." The presentation was made by Dr. Ferial el-Hawary, IEEE Canada president, at the IEEE Canada Awards Banquet (see Figure S2), held in conjunction with the Canadian Conference on Electrical and Computer Engineering, which was held this year in St. John's, Newfoundland, Canada.


FIGURE S1: **Kenneth Smith was presented with the IEEE Canada Computer Medal "for lasting technical and educational contributions to electronics for computing" on 4 May 2009 by Dr. Ferial el-Hawary, IEEE Canada president.**

The recipients of the IEEE Canada Computer Medal are "outstanding Canadian engineers recognized for their important contributions to the field of computer engineering and science."

Smith was born 8 May 1932 in Toronto, Ontario, Canada. He obtained a bachelor's in engineering physics in 1954, a master's in electrical engineering in 1956, and a Ph.D. in physics in 1960, all from the University of Toronto (UT).

Smith's electronics career began as a transmission engineer in carrier telephony in 1954 with the Canadian National Telegraphs. His computer career began as a research engineer in high-speed digital-circuit design in 1956 at the Digital Computer Laboratory (DCL) at the University of Illinois (UI), where he was employed by UT to assist in a project of mutual interest. His academic career began as an assistant professor of electrical engineering at UT in 1960, and later in 1961 at the University of Illinois, where he attained the rank of associate professor. He then returned to Toronto in 1965 as associate professor of electrical engineering and computer science. He became a full professor in 1970 and served as the chairman of the Department of Electrical Engineering from 1976 to 1981. At his retirement from UT in 1997, when he was appointed a professor emeritus, he was a professor of electrical and computer engineering, computer science, mechanical and industrial engineering, and information science.

In 1989, he was appointed advisory professor in communications at Shanghai TieDao University. For the period 1993 to 1998, he was a visiting professor in the Department of Electrical and Electronic Engineering at the University of Science and Technology, Hong Kong (HKUST), where he was the founding director of a new program in computer engineering. He formally retired from HKUST in 1997 but continued as an adviser on accreditation matters until 1998.

Prof. Smith was elected Fellow of the IEEE in 1978 for "contributions to digital circuit design" and made a Life Fellow in 1996. In 2003, he was recognized for his many contributions to the field of multiple-valued logic in a special issue of *Journal of Multi-Valued Logic and Soft Computing*, marking his 70th birthday, and in 2004 he received an IEEE MVL Long-Service Recognition Award.

Among his numerous affiliations with professional associations is his former directorship and presidency of the Canadian Society for Professional Engineers, an engineering service organization. He has held a variety of posts in IEEE societies; currently he is the press and publicity chair and awards and recognition chair for the Executive Committee of the International Solid-State Circuits Conference (ISSCC).

From 1971 to the present, Smith has also been active in the formation and operation of the International Symposium on Multiple-Valued Logic (ISMVL), in connection with which he has had several roles, including chair of the Technical Committee on Multiple-Valued Logic of the IEEE Computer Society from 1994 to 1996.

His extensive research career has been founded on a long-held interest in developments in electronics and their evolving applications. He has done extensive work in the electronics of computing, computer architecture, medical instrumentation, flexible manufacturing, human factors, and music. In the latter area he was, in the late 1970s, one of the few engineering recipients of a Social Sciences and Humanities Research Council of Canada grant for developments in computer music.

Smith is the coauthor (with Adel Sedra, the former provost of UT and currently dean of engineering at the University of Waterloo) of *Microelectronic Circuits*, now in its fifth edition, Oxford University Press. The sixth edition is scheduled to appear in late 2009. He is also the author of several ancillary laboratory and problems books. Smith is the coauthor of a specialty text on the integrated-circuit implementation of analog neural networks. Overall, he is the author or coauthor of well over 200 technical publications, six U.S. patents, and well over a dozen books and book chapters.


FIGURE S2: **IEEE Canada Awards Banquet recipients and presenters (back row from left): Bob Alden—Awards Chair, David Dodds - CHECE, John Cartledge, David Whyte, Rajni Patel, Dave Michelson, Lorry Wilson, Wolfgang Hoefer, Dave Kemp, Husseon Mouftah-Awards Vice Chair. Front Row from Left: Wally Read—ICF, KC Smith, Ferial El-Hawary-President, Bill McDermid, David Falconer.**

FIGURE 6: Striving upward: KC in a powered hang glider over Oahu.

Recapitulations

What can be said after five decades of an academic career? [Editor's note: See "Favorite Aphorisms" for Ken Smith's viewpoints on other subjects.) In my view, one thing is for sure: the success I have enjoyed is largely the result of an early recognition of the fact that an academic life in a good institution is best viewed as a self-employment opportunity. It is with this view that one is easily motivated to do one's best with the resources available while striving for more resources and better results!

In this enterprise, one teaches and one learns. [Editor's note: See Figure 6 for KC's forays into hang gliding, learning once again something new.] In the best of all worlds, each of these actions reinforces the other. Thus, the ultimate success in teaching is to be taught by one's student. [Editor's note: In addition to his success as a teacher, Ken Smith has also been honored in his profession; see "Kenneth Smith, Master Teacher and Researcher" for his most recent honor, being awarded the IEEE Canada Computer Medal.]

I am grateful to have had so many excellent students from whom I have learned so much.

References

[1] Maxim New CCII Current Conveyor Application Note 4198, Mar. 27, 2008.

[2] Analog Devices, "60 MHz 2000 /V/µs monolithic op amp," AD844, 2009.

[3] Analog Devices, "8-bit octal, 4-quadrant multiplying, CMOS TrimDAC," AD8842, 2009.

[4] Z. G. Vranesic, E. S. Lee, and K. C. Smith, "A many-valued algebra for switching systems," *IEEE Trans. Comput.*, vol. C-19, no. 10, pp. 964–971, Oct. 1970.

[5] K. C. Smith, "A multiple valued logic: A tutorial and appreciation," *IEEE Comput.*, vol. 21, no. 4, pp. 17–27, Apr. 1988.

[6] R. R. Tasker, L. W. Organ, and K. C. Smith, "Physiological guidelines for the localization of lesions by percutaneous cordotomy," *Acta Neurochir. (Wien)*, suppl. 21: 111-7, 1974.

[7] W. Buxton, G. Fedorkow, R. Baecker, W. Reeves, K. C. Smith, G. Ciamaga, and L. Mezei, "An overview of the structured sound synthesis project," in *Proc. 3rd Int. Conf. Computer Music*, Northwestern Univ., Evanston, Illinois, 1978, vol. 2, pp. 471–485.

[8] W. Buxton, A. Fogels, G. Fedorkow, L. Sasaki, and K. C. Smith, "An Introduction to the SSSP digital synthesizer," *Comput. Music J.* vol. 11, no. 4, pp. 28–38, 1978.

[9] N. Mehta, K. C. Smith, and F. Holmes, "Feature extraction as a tool for computer input," in *Proc. IEEE Int. Conf. Acoustics, Speech, and Signal Processing*, May 1982, vol. 7, pp. 818–820.

[10] W. Buxton. (Sept. 2009) *Multi-touch systems that I have known and loved* [Online]. Available: http://www.billbuxton.com/multitouchOverview.html

[11] R. Safaee-Rad, I. Tchoukanov, B. Benhabib, and K. C. Smith, "Three-dimensional location estimation of circular features for machine vision," *IEEE Trans. Robot. Automat.*, vol. 8, no. 5, pp. 624–640, Oct. 1992.

[12] A. Bonen, R. E. Saad, K. C. Smith, and B. Benhabib, "A novel electrooptical proximity sensor for robotics: Calibration and active sensing," *IEEE Trans. Robot. Automat.*, vol. 13, no. 3, pp. 377–386, June 1997.

[13] R. E. Saad, A. Bonen, K. C. Smith, and B. Benhabib, "Tactile sensing," in *Mechanical Variables Measurement–Solid, Fluid, and Thermal*, J. G. Webster, Ed. Boca Raton, FL: CRC, ch. 6, 2000, pp. 6.1–6.7.

[14] J. Cooperstock, S. Fels, W. Buxton, and K. C. Smith, "Reactive environments: Throwing away your keyboard and mouse," *Commun. Assoc. Comput. Machine.*, vol. 40, no. 9, pp. 65–73, 1997.

For Further Reading (Selected)

Books

—A. Sedra and K. C. Smith, *Microelectronic Circuits*, 6th ed. London, U.K.: Oxford Univ. Press, to be published.

—A. Sedra and K. C. Smith, *Microelectronic Circuits*, 5th ed. London, U.K.: Oxford Univ. Press, 2004.

—K. C. Smith, *KCs Problems and Solutions to Microelectronic Circuits*, 4th ed. London, U.K.: Oxford Univ. Press, 1998.

—K. C. Smith, *Laboratory Explorations to Microelectronic Circuits*, 4th ed. London, U.K.: Oxford Univ. Press, 1998.

—S. M. Fakhraie and K. C. Smith, *VLSI-Compatible Implementations for Artificial Neural Networks*. Norwell, MA: Kluwer, 1997.

Computer Architecture

—J. Corinthios, K. C. Smith, and J. L. Yen, "A parallel Radix-4 fast Fourier transform computer," *IEEE Trans. Comput.*, vol. 24, no. 1, pp. 80–92, Jan. 1975.

—E. A. Ozkarahan, S. A. Schuster, and K. C. Smith, "RAP: An associative processor for data base management," in *Proc. AFIPS Joint Computer Conf.*, Anaheim, CA, May 1975, pp. 379–387.

—S. A. Schuster, E. A. Ozkarahan, and K. C. Smith, "A virtual memory system for a relational associative processor," in *Proc. AFIPS Joint Computer Conf.*, New York, NY, June 1976, pp. 855–862.

—S. A. Schuster, H. B. Nguyen, E. Z. Ozkarahan, and K. C. Smith, "RAP – As associative processor for data bases," in *Proc. Int. Symp. Computer Architecture*, 1978, pp. 52–59.

—M. A. Scott and K. C. Smith, "VLSI microprocessors," in *Hardware and Software Concepts in VLSI*, G. Rabbat, Ed. New York: Van Nostrand, 1983.

—M. Hancu and K. C. Smith, "Implementing probabilistic algorithms on VLSI architectures," *VLSI J. Integrat.*, vol. 6, no. 1, pp. 59–82, May 1988.

—R. Rafati, S. M. Fakhraie, and K. C. Smith, "A 16-bit barrel-shifter implemented in data-driven dynamic logic," *IEEE Trans. Circuits Syst. I*, vol. 53, no. 10, pp. 2194–2202, Oct. 2006.

Current Conveyors

—K. C. Smith and A. Sedra, "The current conveyor—A new circuit building block," *Proc. IEEE*, vol. 56, no. 8, pp. 1368–1369, Aug. 1968.

—A. Sedra and K. Smith, "A second-generation—current conveyor and its applications," *IEEE Trans. Circuit Theory*, vol. 17, no. 1, pp. 132–134, Feb. 1970.

Computer Music

—W. Buxton, G. Fedorkow, R. Baecker, W. Reeves, K. C. Smith, G. Ciamaga, and L. Mezei, "An overview of the structured sound synthesis project," in *Proc. 3rd Int. Conf. Computer Music*, Northwestern Univ., Evanston, Illinois, 1978, vol. 2, pp. 471–485.

—W. Buxton, A. Fogels, G. Fedorkow, L. Sasaki, and K. C. Smith, "An introduction to the

SSSP digital synthesizer," *Comput. Music J.*, vol. 11, no. 4, pp. 28–38, 1978.[videos] [Online]. Available: http://billbuxton.com/buxton/ssspvideos.html

—W. Buxton, W. Reeves, G. Fedorkow, K. C. Smith, and R. Baecker, "A microcomputer-based conducting system," *Comput. Music J.*, vol. 4, no. 1, pp. 8–21, 1980.[video] [Online]. Available: http://billbuxton.com/SSSPconduct.swf

—J. Kitamura, W. Buxton, M. Snelgrove, and K. C. Smith, "Music synthesis by simulation using a general-purpose signal processing system," in *Proc. 1985 Int. Computer Music Conf.*, Vancouver, 1985, pp. 155–158.[video] [Online]. Available: http://billbuxton.com/katosizer.swf

—W. Buxton, A. Fogels, G. Fedorkow, L. Sasaki, and K. C. Smith, "An introduction to the SSSP digital synthesizer," in *Foundations of Computer Music*, C. Roads and J. Strawn. Cambridge, MA: MIT Press, 1985, pp. 206–224.

Descendants

—G. G. A. Black, R. T. Friedmann, and A. S. Sedra, "Gyrator implementation with integrable current conveyors," *IEEE J. Solid-State Circuits*, vol. 6, no. 6, pp. 396–399, Dec. 1971.

—A. S. Sedra, G. W. Roberts, and F. Gohh, "The current conveyor: History, progress and new results," *Proc. Inst.. Elect. Eng., G: Circuits Devices Syst.*, vol. 137, no. 2, pp. 78–87, Apr. 1990.

—G. Ferri and N. C. Guerrini, *Low-Voltage Low-Power CMOS Current Conveyors.* New York: Springer-Verlag, 2003.

—T. Hanyu and M. Kameyama, "A 200 MHz pipelined multiplier using 1.5 V-supply multiple-valued MOS current-mode circuits with dual-rail source-coupled logic," *IEEE J. Solid-State Circuits*, vol. 30, no. 11, pp. 1239–1245, Nov. 1995.

—W. Buxton, "Surface and tangible computing, and the "small" matter of people and design," in *IEEE Int. Solid-State Circuits Conf. Dig. Technical Papers*, Feb. 2008, vol. 51, pp. 24–29.

—W. Buxton. *Multi-touch systems that I have known and loved,* Sept. 2009 [Online]. Available: http://www.billbuxton.com/multitouchOverview.html

—Maxim New CCII Current Conveyor Application Note 4198, Mar. 27, 2008.

—Analog Devices, "60 MHz 2000/V/µs monolithic op amp," AD844, 2009.

—Analog Devices, "8-bit octal, 4-quadrant multiplying, CMOS TrimDAC," AD8842, 2009.

Human Factors

—N. Mehta, K. C. Smith, and F. Holmes, "Feature extraction as a tool for computer input," *IEEE Int. Conf. Acoustics, Speech, Signal Process.*, vol. 7, pp. 818–820, May 1982.

—W. Buxton, M. R. Lamb, D. Sherman, and K. C. Smith, "Towards a comprehensive user interface management system," *Comput. Graph.*, vol. 17, no. 3, pp 35–42, 1983.[video] [Online]. Available: http://billbuxton.com/menulay.swf

—Lee, W. Buxton, and K. C. Smith, "A multi-touch three dimensional touch-sensitive tablet," in *Proc. Conf. Human Factors in Computer Systems (CHI'85)*, San Francisco, Apr. 1985, pp. 21–26.[video]

—J. Cooperstock, S. Fels, W. Buxton, and K. C. Smith, "Reactive environments: Throwing away your keyboard and mouse," *Commun. Assoc. Comput. Machine.*, vol. 40, no. 9, pp. 65–73, 1997.

Instrumentation

—K. C. Smith and A. S. Sedra, "A new simple wide-band current-measuring device," *IEEE Trans. Instrum. Meas.*, vol. 18, no. 2, pp. 125–128, June 1969.

—E. Vannerson and K. C. Smith, "Fast amplitude stabilization of an RC oscillator," *IEEE J. Solid-State Circuits*, vol. 9, no. 4, pp. 176–179, Aug. 1974.

—C. P. Chong and K. C. Smith, "sinusoidal oscillators employing current conveyors," *Int. J. Electron.*, vol. 62, no. 4, pp. 515–520, 1987.

—R. E. Saad, A. Bonen, K. C. Smith, and B. Benhabib, "Distributed-force recovery for a planar photoelastic tactile sensor," *IEEE Trans. Instrum. Meas.*, vol. 45, no. 2, pp. 541–546, Apr. 1996.

Local Area Network (Analog/Digital)

—J. N. Potvin, P. Chenevert, K. C. Smith, and P. Boulton, "Star-ring: A computer intercommunication and I/O system," *IFIP Congress*, Ljubljana, Yugoslavia, vol. 1, pp. 721–728, 1971.

—G. Fedorkow, W. Buxton, and K. C. Smith, "A computer controlled sound distribution system for the performance of electroacoustic music," *Comput. Music J.*, vol. 2, no. 3, pp 33–42, 1978.

Medical Instrumentation

—L. W. Organ, A. Bernstein, I. H. Rowe, and K. C. Smith, "The pre-ejection period of the fetal heart: Detection during labor with Doppler ultrasound," *Amer. J. Obstet. Gynecol.*, vol. 115, no. 3, pp. 369–376, Feb. 1973.

—R. R. Tasker, L. W. Organ, and K. C. Smith, "Physiological guidelines for the localization of lesions by percutaneous cordotomy," *Acta Neurochir (Wien)*, suppl. 21, 111-7, 1974.

—J. Cousin, K. C. Smith, I. H. Rowe, and L. W. Organ, "A cardiac pre-ejection period monitor for foetal assessment during labour," *J. Med. Biol. Eng. Comput.*, vol. 12, no. 4, pp. 140–118, July 1974.

—L. W. Organ, A. Bernstein, K. C. Smith, and I. H. Rowe, "The pre-ejection period of the fetal heart: Patterns of change during labour," *Amer. J. Obstet. Gynecol.*, vol. 120, no. 1, pp. 49–55, Sept. 1974.

—A. Bernstein, L. W. Organ, L. E. Eisner, K. C. Smith, and I. H. Rowe, "Measurement of the pre-ejection period during labour with the use of arterial pulse time," *Amer. J. Obstet. Gynecol.*, vol. 126, no. 2, pp. 238–242, Sept. 1976.

—J. Ironstone, M. Graovac, P. Eng, J. Martens, M. Rozee, and K. C. Smith, "Novel lead configurations for robust bio-impedance acquisition," in *Proc. IEEE 29th Int. Conf. Engineering in Medicine and Biology Society*, Lyon, France, Aug. 2007, pp. 2764–2767.

Multiple-Valued Logic

—Z. G. Vranesic, E. S. Lee, and K. C. Smith, "A many-valued algebra for switching systems," *IEEE Trans. Comput.*, vol. C-19, no. 10, pp. 964–971, Oct. 1970.

—K. C. Smith, "The prospects for multivalued logic: A technology and applications view," *IEEE Trans. Comput.*, vol. C30, no. 9, pp. 619–634, Sept. 1981.

—K. C. Smith, "A multiple valued logic: A tutorial and appreciation," *IEEE Comput.*, vol. 21, no. 4, pp. 17–27, Apr. 1988.

—K. C. Smith and P. G. Gulak, "Prospects for multiple-valued integrated circuits", *IEICE Trans. Electron.*, vol. E76-C, no. 3, pp. 372–382, Mar. 1993.

Machine Vision

—F. Bumbaca and K. C. Smith, "A practical approach to image restoration for computer vision," *J. Comput. Vis. Graph. Image Process.*, vol. 42, no. 2, pp. 220–233, May 1988.

—C. P. Loui, A. N. Venetsanopoulos, and K. C. Smith, "Flexible architectures for morphological image processing and analysis," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 2, no. 1, pp. 72–83, Mar. 1992.

—R. Safaee-Rad, I. Tchoukanov, B. Benhabib, and K. C. Smith, "Three-dimensional location estimation of circular features for machine vision," *IEEE Trans. Robot. Automat.*, vol. 8, no. 5, pp. 624–640, Oct. 1992.

—C. P. Chong, C. A. T. Salama, and K. C. Smith, "Image-motion detection using analog VLSI," *IEEE J. Solid-State Circuit*, vol. 27, no. 1, pp. 93–96, Jan. 1992.

Neural Networks (Hardware)

—S. M. Fakhraie, H. Farshbaf, and K. C. Smith, "Scalable closed-boundary analog neural networks," *IEEE Trans. Neural Netw.*, vol. 15, no. 2, pp. 492–504, Mar. 2004.

—S. M. Fakhraie, A. Konrad, and K. C. Smith, "Neuro-computation techniques in sampled-data electromagnetic-field problems," *IEEE Trans. Magnet.*, vol. 30, no. 5, pp. 3637–3640, Sept. 1994.

—P. C. Y. Chen, J. K. Mills, and K. C. Smith, "Performance improvement of robot continuous-path operation through iterative learning using neural networks," *J. Mach. Learn.*, vol. 23, no. 2–3, pp. 191–220, May 1996.

—S. M. Fakhraie and K. C. Smith, *VLSI-Compatible Implementations for Artificial Neural Networks*. Norwell, MA: Kluwer, 1997.

Sensors

—A. Bonen, R. E. Saad, K. C. Smith, and B. Benhabib, "A novel electrooptical proximity sensor for robotics: calibration and active sensing," *IEEE Trans. Robot. Automat.*, vol. 13, no. 3, pp. 377–386, June 1997.

—R. E. Saad, A. Bonen, K. C. Smith, and B. Benhabib, "Tactile sensing," in *Mechanical Variables Measurement–Solid, Fluid, and Thermal*, J. G. Webster, Ed. Boca Raton, FL: CRC, 2000, ch. 6.

About the Author

Kenneth C. (KC) Smith lives with his wife Laura Fujino in Toronto. He has been working part-time since the age of 14 when he was a retail store delivery and stocking assistant and, through concentrated summer work, ultimately becoming an electrical technician for the Ontario power company by the time of his first degree graduation. His work experience has extended from the Toronto area to Southern Ontario, across Canada to Newfoundland, then to Central Illinois, and ultimately Hong Kong. Now, in his 78th year, legally blind with a genetic retinal disorder, he continues to work as a volunteer, consultant, author, and lecturer. With the assistance of Laura, he continues to travel, primarily in North America, East Asia, and Europe.