Thoughts on Engineering Creativity

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This short article deals with engineering creativity. In a recent public radio program, creativity was defined as "the ability to generate innovation which works." For engineering creativity, I would make it more specific: it is the ability to change the direction of technological progress drastically and beneficially, or the ability to induce an inflection point in the development of some engineering field. I shall describe here a few examples of creative ideas that I encountered in my area (analog signal processing and data converters) during my long career in the field. I shall start with some sobering thoughts about the limited range of engineering (indeed, of human) creativity.

I. A PERSPECTIVE OF ENGINEERING CREATIVITY

This article is written in celebration of the creativity of engineers, as seen through the narrow window of the experience of the writer. However, I would like to put this celebration in the perspective of the limitations of all human knowledge. The amazing development of the human brain relative to the brains of our fellow animals has probably started around 100 000 years ago [1]. According to the Darwinian theory, it was probably triggered by random mutation and the selective survival of the fittest. The tools available in the struggle for survival were the five senses already developed, the tribal structure, and the instincts for survival. The humans favored by this scenario were strong, brutal, loyal to their tribes, and hostile to outsiders. Somehow, over a long time, the human brain developed further by adding more neurons and richer connections between them. There seems to exist a positive feedback effect in the brain, which, when a threshold number of connected neurons was reached, kicked in and made this effect cumulative. Since we know now that the brain can repair even major damages and faults (even a missing cerebellum!), this is not an unreasonable assumption!

Eventually, the criteria for the fittest surviving humans expanded to include the ones with the most sophisticated brains. This gave rise to the class of scientists and engineers, who prospered by helping their masters (kings, princes, and warlords) develop better weapons, maps, or communication means. Along with these, they also developed instruments that enhanced the human senses, such as telescopes and microscopes. Instruments even enabled humans to discover and utilize phenomena, such as electricity and magnetism, X-rays, cosmic rays, and many others. Useful interaction between experimentalists and theorists enabled physicists to explore the observable universe, even on the very large scale of galaxies and on the extremely small scale of the atom. The infrastructure of the brain, which is the segment developed over most of the existence of the human race, is still that of the primitive tribal one. The more recent developments involving science and engineering are contained in the smaller portion

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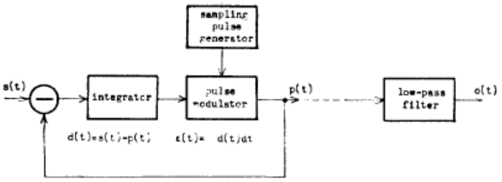

Fig. 1. ***Block diagram of Δ–∑ modulation system.***

of the brain, along with morality and advanced aspects of civilization. Also, there is no reason to assume that all (or even most) physical phenomena of the universe have been detectable (or can ever be detected) by humans with their limited brains. Consider the recent discovery of "dark matter." According to Wikipedia, dark matter is a hypothetical form of matter that is thought to account for approximately 85% of the matter in the universe and about a quarter of its total energy density. With such an "elephant in the living room" unsuspected for such a long time, it is very likely that other huge surprises await the scientists of the 21st century.

It is within such limits that scientists operate. A scientific genius, such as Einstein or Dirac, may be able to jump over some of the lower fences represented by the limits of available experimental knowledge, but the higher ones may not even be visible or knowable to us. We engineers work in an even more restricted area, since we have to use tools and devices available in the practical world. Also, with very few exceptions, we must produce results that have practical (and preferably financially rewarding) applications. Other than universities, there are now few such exalted research organizations as the Bell Laboratories of yore, where researchers were free to pursue interesting but not immediately profitable projects.

The examples of creative achievements and engineering genius, which we shall discuss next, should therefore be viewed in the context of their limited scope. This should not reduce our admiration for the protagonists; they are among the leaders of humanities' progress toward increased knowledge and better life!

II. CREATIVITY AND INFLECTION POINTS IN RESEARCH—CASE HISTORIES

In Sections II-A–II-C, a few examples of engineering creativity in my field will be described. Each triggered a sudden change in the direction of established practice in the analog integrated circuit design.

A. Delta–Sigma Data Converters

The signals that our sensors provide to us about the physical worlds (voltages, currents, and charges) are analog, but in most cases, they are processed and/or stored as sequences of numbers, i.e., in the digital form. *Vice versa*, for actuators, read-out devices, or loudspeakers, the digital output of a computer needs to be converted into the analog form. Therefore, analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) play important roles in electronics. For many years, these devices were designed for sample-to-sample operation. In an ADC, the analog input signal was sampled, and each sample converted separately into a corresponding digital word. The converter had no memory of earlier operations. The accuracy of each conversion was limited by the matching accuracy of the components of the analog circuit elements (resistors, capacitors, and current sources). This in turn was limited to about 0.1% by technological constraints. In 1962, Inose, Yasuda, and Murakami proposed an alternative approach to A/D conversion [2], [3]. It uses a negative feedback loop with high loop gain, which forces the digital output to track the analog output (see Fig.1). The loop filter is an integrator, which provides high gain in the signal band well below its unity-gain frequency. The output of the integrator is fed to a Schmitt trigger, acting as a comparator. Since there is a subtraction (differencing) at the input, followed by a summation, they named the circuit a delta–sigma ($\Delta\Sigma$) converter. The measured performance was not impressive (SNR $<$ 40 dB and 4-kHz bandwidth), and hence, initially, there was not much attention paid in industry to the new structure. However, the novel aspects of the new structure attracted the attention of many circuit and system theorists both in industry and academia. Its unique feature is that instead of trying to reduce the error of each individual output sample, it filters the whole sequence of errors so that the in-band error power is suppressed. A group at Bell Labs headed by James Candy explored the generalization of the structure and analyzed its operation. Researchers at the University of California Berkeley and Robert Adams at dbx (now defunct) implemented in the mid-1980s integrated versions of the $\Delta\Sigma$ data converter. Soon books appeared on the subject, and eventually, industry recognized that in many important consumer and communication applications, $\Delta\Sigma$ ADCs and DACs are the best choice for interfacing the analog world with the digital signal processors. Thus, they were produced and sold by the billions. The long-term impact of this idea was enormous.

B. Low-Sensitivity Filters

Filters have been key components of communication networks and consumer electronics for at least 100 years. The usual implementation for many years used inductors and capacitors to achieve a selective transfer function. However, inductors have many unlovable properties: they tend to be lossy, bulky, nonlinear, and pick up as well as transmit noise. Hence, when integrated operational amplifiers became available, the *LC* filters were replaced by the active-*RC* ones, with integrated amplifier chips, but with the *R*s and *C*s still being discrete components. As the technology of analog integrated circuits progressed, attempts were made to integrate all components on chip. However, the absolute accuracy of both Rs and Cs realized on-chip was poor: the error was 15%–25% of the nominal value. Since the time constants of the filter were determined by the *RC* products of filter elements, and the frequency response was determined by the time constants, this caused a large uncertainty of the response of the fabricated filter. Trimming the resistors could remove this error, but trimming was time-consuming and costly.

In 1966, Orchard was working on the development of active filters at Lenkurt Electric Co. He had decades of experience with *LC*-based filters and found the high sensitivity of the active-*RC* filters frustrating. The sensitivity of these was 100–1000 times higher than that of the *LC* ones. He looked for reasons for this and, in the process, found a method to overcome the problem. He published his thoughts in a brief letter [4], which contained no figures and only two simple equations. It had a large impact; it was cited 176 times subsequently.

The secret of the low sensitivity of a doubly terminated *LC* filter, as revealed by Orchard, laid in the optimum matching between the resistive source feeding it and the rest of the circuit in the filter passband when all the element values were exact. Any change in any L or C value, up or down, would cause the output voltage V_{out} to drop. This meant that the sensitivity $S = dV_{\text{out}}/dt$ was zero at the optimum matching frequencies. At other passband frequencies, $|S|$ remained low as long as the reflection coefficient between the source and the filter was small [5].

Having found the reason for this low sensitivity, Orchard recommended a method of designing active-*RC* filters that took advantage of it. He suggested the use of gyrators, rather than operational amplifiers, as active elements. One gyrator, terminated in a capacitor, could simulate the behavior of a grounded inductor; two gyrators and a capacitor could act as a floating inductor. Thus, starting with an *LC* filter designed for maximum power transmission and replacing all inductors with gyrator–capacitor combinations, a low-impedance active filter was possible to be designed. The gyrator itself could be realized by two transconductances connected in the opposite directions or other active circuit [6].

Later on, a different design approach was developed for using Orchard's theorem. This involved modeling the state equations of the doubly terminated reactance two-port using an active-*RC* integrator for every L and C. The modeling approach turned out to be usable also for other filter circuits [G_m–C, switched capacitor (SC), even for digital filters], and it was widely applied to the design of low-sensitivity and low-noise filters.

C. Switched-Capacitor Filters

Then, in 1970, Fried, an expert on optical design, found another solution to the matching problem in active filters. He was asked to help with the realization of the focal plane of an optical sensor. This involved the implementation of a large number of integrated filters, each with a cutoff frequency of a few hertz. Conventional implementation with active-*RC* circuitry was impractical, so he considered first the use of switched resistors whose effective values could be tuned by the duty cycle of the switches. However, he also conceived and analyzed the first SC filters [7], [8]. The basic idea can be described as follows: a capacitor stores energy, so it has a memory. It does not dissipate power. By contrast, a resistor has no memory and dissipates power. A capacitor may simulate a resistor, if it is periodically discharged and recharged by switches. Thus, a circuit containing both switched and unswitched capacitors may simulate an *RC* circuit, if the signal frequency is much lower than the switching rate. (Much later, it was discovered that the same idea was described in Maxwell's iconic work: *A Treatise on Electricity and Magnetism*, Dover, 1873, pp. 374–375.) The great advantage of SC filters was that they only required the accurate matching of capacitors to each other to achieve good control of the time constants of the filter and, thus, of the frequency response. With careful design and layout technique, matching accuracy of the order of 0.1% could be achieved for switched and unswitched capacitors. The time constants of the earlier active filters were determined by *RC* products or C/Gm ratios, which (as discussed earlier) were poorly controlled for integrated circuits. Thus, SC filters could be implemented with an accuracy at least 100 times better than the continuous-time ones!

The publication of Fried's invention remained largely unnoticed for the following interesting reasons.

1) The author was unknown in the circuits' community.
2) His paper did not describe any experimental (or even simulated) results.
3) He did not discuss the practical advantages of his circuits.
4) All circuits were passive—no amplifiers or even buffers were included. This limited their applicability to simple tasks.

Thus, this idea remained dormant for a number of years when two research groups rediscovered it simultaneously [9], [10]. Since then, it has been used in most analog and mixed-mode integrated circuits. Applications included communication systems, sensor interfaces, data converters, instrumentation, biomedical electronics, watches, and many other aspects of everyday living. Its effect on technology and everyday life has been enormous.

III. PROMOTING CREATIVITY WITHIN IEEE

I am deeply grateful to the IEEE for maintaining a forum for creative thoughts through many high-level journals and conferences. When I joined the Institute of Radio Engineers (one of the two parent organizations of the IEEE) about 58 years ago, circuit researchers in the United States had one journal, the IRE TRANSACTIONS ON CIRCUIT THEORY, and one conference, the IRE Annual Convention, for disclosing novel circuits and design techniques. Today, there are a large number of specialized journals and conferences, which makes the publication of new ideas much easier (although it makes keeping up with the state of the art significantly more difficult). Also, IEEE Xplore is a tremendous help for researchers who want to make sure that they are not reinventing an old concept.

However, I have a suggestion for easing the publication of more creative ideas. In my own research area (mixed-mode CMOS ICs), reviewers of papers generally require experimental evidence confirming any novel idea for architectures or algorithms. This is a justified demand, because integrated circuits are so complex that hidden flaws may not be revealed until the implemented device is tested. However, fabricating a chip is very expensive (thousands of dollars) and time-consuming (several months). This causes many excellent ideas to be discarded undisclosed for lack of time or funds. (Note that the pioneering papers of Orchard and Fried would be rejected today, since they did not contain either experimental or even simulation results.) To help more ideas see the daylight, I would suggest that IEEE journals reserve space for very short (say, one page) idea disclosures. These should be reviewed rapidly, and acceptance should be based on originality and potential usefulness, without the need for experimental evidence.

IV. CONCLUSION

This article was written in celebration of some creative researchers, who changed the discipline of analog integrated circuit design. It also contained an attempt to put all engineering and scientific research in a broader and less celebratory context. Finally, a suggestion was made to make the disclosure of new ideas easier. ■

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