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The First Microprocessor: An Interview with Marcian (Ted) Hoff, Jr.

SPM: *In this issue, creative thinking is the main thread of our discussion with Dr. Ted Marcian Hoff, Jr. Welcome! Informally, how would you define a creative person?*

Dr. Hoff: I believe all humans are inherently creative, but some are discouraged from believing in themselves, while others have more opportunity for their creations to be appreciated. Perhaps the best definition would be "a person who is curious about how things work, and then takes action to make things work better."

SPM: *You were an imaginative kid: chemistry and electronics were your playground from early years. Would you tell us a bit more about that time?*

Dr. Hoff: My first love was chemistry. My parents gave me a chemistry set as a gift when I was about nine. My father's brother, John, who is only 12 years older than me, became a chemical engineer after World War II and gave me many of his chemistry textbooks. I loved the idea of finding out how things worked, and chemistry seemed like magic. When I was about 11, my uncle John gave me a subscription to *Popular Science Magazine* as a Christmas gift. When I saw an ad for a free Allied Radio catalog, I mailed a request for it thinking that it might be fun to learn how a radio worked. The following Christmas, my parents gave me a short-wave radio kit ordered from that catalog. Throughout high school, I studied both electronics and chemistry, and our high school, although small (about 35 in the graduating class of Churchville, New York), had excellent science teachers who offered an after-school science club. While I continued to study chemistry, my interest in electronics grew, and I mail-ordered a cathode-ray tube from a New York City surplus store. I used that tube to build a fairly simple oscilloscope.

SPM: *Soon your interest in technology went beyond a simple hobby. What happened next?*

Dr. Hoff: When it came time to attend college, based on job prospects, my uncle recommended either electrical or chemical engineering. I chose electrical engineering. The summer after I graduated high school, my father got me an interview in an electronics lab at the company where he worked: General Railway Signal Company (GRS), in Rochester, New York. They gave me a summer job as a lab technician, wiring up test circuits. (I was told that having built an oscilloscope really helped me get the job.) One of my first projects at GRS involved the design of an audio frequency track circuit. The basic concepts of the circuit had already been developed by the engineers I was working for. However, in the course of building a prototype, I made some suggestions for improving the reliability and fail-safety of the system. When it came time to patent the system, the engineers insisted that I be included as a named inventor. When I returned to GRS the next summer, it was suggested that I team up with an old-time lightning protection engineer in an effort to improve the audio track circuit. Frank Reese had left school after the eighth grade, was self-taught, and at the

EDITORS' INTRODUCTION

Our guest in this issue is best known as the inventor of the first microprocessor (the Intel 4004) and a coauthor of the LMS adaptive algorithm. Marcian (Ted) Hoff, Jr. was born on 28 October 1937 in Rochester, New York. He received the B.S. degree in 1958 from the Rensselaer Polytechnic Institute, Troy, New York, and the M.S. and Ph.D. degrees from Stanford University in 1959 and 1962, respectively. He was a research associate with Stanford University in 1962–1968, manager of applications research in 1968–1980 and Intel Fellow in 1980–1983 at Intel Corporation, and vice-president of corporate research at Atari in 1983–1984. Dr. Hoff also worked as an independent consultant in 1984–1990. He is currently chief technologist with the consulting company FTI/Teklicon, San Jose. In addition to focusing on the μP and the LMS, Dr. Hoff's work has spanned various aspects of digital signal processing that resulted in the first commercial monolithic telephone CODEC, the first commercially available switched-capacitor filter, an early signal processing chip (the Intel 2920), and speech recognition hardware. He is the 1997 recipient of the prestigious Kyoto Prize and the 1980 IEEE Cledo Brunetti Award. Dr. Hoff was inducted into the National Inventors Hall of Fame in 1996. He remembers that the latter event was "quite a performance, with a song and dance number including dancing chips."

With his collaborators, Dr. Hoff shares a passionate interest in technology. With the DSP History column editors, on behalf of *IEEE Signal Processing Magazine* (SPM), and our readers, he shares the 35th anniversary of the microprocessor, his thoughts on creativity, and his work-as-a-hobby philosophy.

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age of 60 had some 65 patents. He was a truly remarkable character and had a wonderful sense of humor. (Among other stories, he told the story of having an idea at a lunch, writing up a patent disclosure on a paper napkin, having it signed and witnessed, and using the bonus from the resulting patent to buy a car for cash, which car his son crashed; he then realized that, having paid cash for the car, he had neglected to get insurance!) Since systems used on the railroads are subject to some pretty violent abuse, such as being hit by lightning bolts, Frank had a test setup that was used to simulate lightning bolts. That summer I came up with a technique that allowed the audio track circuit to absorb large amounts of energy without damage, which resulted in my second patent.

SPM: *Starting with your Stanford years as a Ph.D. candidate and then as a postdoc, your work produced results that became well known. If you were to look back, which were the "aha" moments (aka the "Eureka!" moments) in your professional life to date?*

Dr. Hoff: I believe most of my "aha" moments have come from wondering about how something worked and then seeing if it could be made to work better. For instance, one such moment was related to the audio track circuit. One of its goals was the following: should the circuit fail, it should not indicate the presence of a train. This goal was the opposite of most track circuits. It occurred to me that if the receiver had an amplifier included, then that amplifier might break into oscillation and give a false train-presence indication. The solution seemed to be having a passive receiver. That required a sensitive relay in the detector and sufficient audio power into the rails to be able to operate that relay when detected. GRS had relays that could be operated with one-tenth of a watt, and we were able to fairly easily generate about a watt of audio power to apply to the rails. The numbers looked good, so a passive receiver proved feasible. Another goal of the audio track circuit was that it should only detect trains that were very close to the place where it was connected to the rails. Trains at a further distance would not be detected because of the inductance of the rails. It occurred to me that we might get a better response characteristic by making a series tuned resonant circuit using that inductance. The numbers indicated that a reasonable capacitance value in series would work, and sure enough, when tested on real rails, the response characteristic was closer to the ideal.

Another such moment was later on at Intel, when I wondered about how well components would match in our silicon-gate metal-oxide-semiconductor (MOS) process. I knew that bipolar transistors printed next to each other matched pretty well, but I didn't know about our MOS components. I had figured I could make a digital-to-analog (D/A) converter by using a string of resistors to divide a reference voltage and use MOS transistors as analog switches to connect to taps on the resistor string. However, I needed to know how good a string of resistors I could make, so I asked my boss, who was an expert on MOS, how well resistors would match. When he told me "not very well," I complained, saying that I needed a quantitative measure, a number. Then he admitted that he didn't know the number. I decided to try to find out for myself. I located some wafers that consisted of nothing but test devices. Unfortunately each test device had only one of each type of resistor, so I could not test adjacent devices. However, I figured it would be interesting to see how values varied over the wafer. I plotted the data, and there was quite a variation over the wafer. However, I noticed that the variation wasn't random but rather a nice smooth gradient over the wafer. A little mathematical analysis indicated that had two identical resistors been printed side by side, they would match to a fraction of 1%. Using this information about matching and gradients, I was able to design a D/A converter that was small and accurate.

SPM: *In 1960, you created and implemented the least mean square (LMS) algorithm (presented in the January 2005 issue of the* IEEE Signal Processing Magazine*) together with Prof. Bernard Widrow. What can you tell us about the creative process that led to the algorithm?*

Dr. Hoff: Prof. Widrow described to me some previous work he had done in pattern recognition: a process for reducing the overall error in recognizing a set of patterns by presenting the patterns in rapid succession and making parameter adjustments to reduce an aggregate measure of error. Again, in an effort to understand what was happening in such a system, I tried to analyze the behavior mathematically. The resulting equations seemed to indicate that similar error reduction could be obtained by making parameter adjustments one pattern at a time, rather than require the patterns to be applied as a group. We then built a model that allowed us to test the algorithm, and it worked. Despite being quite simple, the algorithm seems to work very well in many applications. In addition, the concept of reducing mean-squared error is relatively easy to understand and seems to be quite effective for improving system performance.

SPM: *After receiving your Ph.D. degree at Stanford in 1962, you continued to work there. How did your transition to Intel happen?*

Dr. Hoff: I stayed on as a research associate at Stanford working with Prof. Widrow. Much of our work was supported by government contracts. Another faculty member working with us was Prof. Jim Angell, who also consulted for Fairchild. He apparently gave my name to Bob Noyce about the time when Intel was being formed. I had met Bob once before when we demonstrated some speech recognition results. One day, in the summer of 1968, I got a phone call from Dr. Noyce, who asked if I might be interested in a new company he was starting. I think I was ready to try something different than government sponsored research, so I replied affirmatively. I was interviewed at Bob Noyce's home. Talk about luck; but I had been interested in developments in integrated circuits while at Stanford and had conversations with several people from the industry. I had also worked with magnetic core memory and knew how touchy those little cores could be. So when Bob asked me what I thought the next big semiconductor development should be, I answered "memory." Then he told me that the goal of his new company was to develop semiconductor memory. I accepted Intel's offer and became employee number 12, officially starting in September of 1968. I was given the title manager of applications research and was expected to help define Intel products and to generate applications information for these products.

SPM: *How did these initial plans lead to the birth of the 4004 microprocessor?*

Dr. Hoff: Intel planned to develop both bipolar and MOS memory circuits. It began by developing two new processes: the self-aligned silicon gate process for MOS and the Schottky diode bipolar process. It was believed there could be a relatively long time before any new memory devices would have a substantial market because the computer industry was too committed to magnetic cores to make a quick change. For that reason, Intel decided to do some custom development, i.e., build circuits to one customer's specifications. Our first such customer was a Japanese calculator manufacturer. While the calculators would be sold under the name Busicom, we knew the customer as Nippon Calculating Machines Corporation and Electro-Technical Industries (ETI). In April of 1969, Intel agreed to make calculator chips based on ETI specifications. In June of 1969, three engineers came from Japan to spend the summer transferring their design. I was assigned to act as liaison but had no design responsibility. Again my curiosity took over, and I studied the design that was to be transferred. I quickly became concerned, because the circuits seemed quite complex and would severely tax Intel's limited chip-design resources. I expressed my concerns to Bob Noyce (then Intel's president), who urged me to pursue any ideas for simplifying the design.

SPM: *What allowed you to simplify the design?*

Dr. Hoff: I had been working with a Digital Computer Corporation PDP-8 computer, in the hopes of automating some of the chip layout processes. One of our technicians used a program called FOCAL, which made the PDP-8 behave like a very powerful scientific calculator. However, the instruction set of the PDP-8 was remarkably simple. The complexity represented by FOCAL was in the programming, not the hardware. The proposed calculator set from ETI was to be programmable, but it seemed to me that the proposed instruction set was unnecessarily complex. One thing that made the calculator set so complex was that many instructions were performing serial multidigit binary coded decimal (BCD) arithmetic, which involved some extensive control logic. It seemed to me that a more primitive instruction set, preferably using 4-b binary arithmetic, could do the more involved operations by suitable programming. Such programming would be aided by having good subroutine capability. I also figured that a very simple instruction could be added to a primitive binary arithmetic set to allow it to do both binary and BCD arithmetic. When you use a binary adder to add two BCD digits and a possible carry, you get a result between zero and 19. Held as a binary value in a 4-b accumulator and associated carry, that binary result could easily be converted back to a BCD result with carry. I called the proposed instruction "decimal adjust accumulator." It then looked like I could make a very simple 4-b binary and BCD computer and program it to do the calculator arithmetic.

Once the instructions were made rather primitive, they could be executed much more rapidly. This fact suggested that the original memory technology for the calculator set, serial dynamic shift registers, might not be optimum. Each bit in such a memory takes six transistors, while our dynamic random access memory (DRAM) cell, at that time, took only three. The fast access of a DRAM would be more compatible with the shorter execution times of the primitive instructions. It also appeared that the faster but primitive instructions could perform many of the control functions that were to be performed in the original design by special custom logic chips.

SPM: *Was your initial goal to make a one-chip computer?*

Dr. Hoff: While my original goal had nothing to do with trying to make a one-chip computer, the architecture I was developing seemed to indicate that most of the control and arithmetic could be done with a single chip. My original approach included a master timing chip, which would be a part of the central processor. Most of the original design exercises were performed in July and August of 1969. Stanley Mazor joined my group at the beginning of September. He had been at Fairchild working on a high-end computer. Stan recognized that we might be able to eliminate the timing chip, which resulted in a single-chip central processor.

SPM: *What happened next?*

Dr. Hoff: By mid month, we had a proposal written that our marketing department passed on to the management of the Japanese calculator company. While the Japanese engineers at Intel were not supportive of our design, the Japanese managers were interested. They came to the United States in October 1969 for a meeting, where both the original solution and the Intel approach were presented. The Intel approach was approved. Once approved, we needed to staff the project. I had no experience in chip layout, and all of Intel's chip designers were committed to the memory projects. It took a while, but finally, Dr. Federico Faggin joined us in April of 1970. He worked very rapidly and had four chips working by early 1971.

SPM: *So the first 4004 chip was on the market in 1971. What applications did it have?*

Dr. Hoff: As of early 1971, we had contractual conditions that limited our sales only to Busicom. Several of the engineers, including Dr. Faggin and myself, realized the potential use of the device for a wide variety of applications and urged our marketing staff to renegotiate the contract. When Busicom asked for some price concessions, our marketing staff succeeded in getting the rights to sell to others. However, even then, there were major concerns within Intel. Selling computers might be seen as competing with potential memory customers, and support requirements for computers were perceived as formidable. Finally, a decision to offer the devices was made, and they were officially announced for sale in November of 1971. We suggested many applications such as process control, elevator control, highway signal control, computer peripheral device control, cash registers, point of sale terminals, and medical electronics. Our customers soon found many more.

SPM: *Has the 4004 microprocessor been your most challenging technical assignment so far in terms of problem analysis (or what is sometimes called "making the strange familiar" in creative thinking)?*

Dr. Hoff: Once the microprocessor was introduced, I was asked by Dr. Noyce to see if there were any opportunities for Intel in the telephone industry. That seemed almost impossible for two reasons. First, a lot of signal levels in the telephone industry were incompatible with Intel's processes. Second, the telephone industry at the time was pretty much a regulated monopoly. Let me explain each. Many of the signals were analog, and it seemed almost a given that anything involving analog signal processing required a bipolar process. However, Intel's bipolar process was not really well suited to analog designs. I hoped to find a way to use one of Intel's MOS processes for our analog work. Then my group at Intel got very fortunate in that we persuaded Prof. Paul Gray of the University of California at Berkeley to come and consult for us. He was also very interested in analog applications of MOS processes, and he had done some outstanding pioneering work toward that end at Berkeley. We had a number of his students join our group at Intel and solved many of the problems of applying MOS technology to analog signal processing and analog-to-digital (A/D) and D/A conversion.

The best process for analog work at Intel seemed to be the one we used for EPROM memory, because it could take relatively large voltages for programming yet operate with normal logic levels. When we started performing reliability tests on some of our circuits, we found some unexplained failures, even when operating at well below the programming voltages. I finally got some help from Intel's process experts, who used scanning electron microscopy to find out what was going wrong. A simple process tweak eliminated the problem. So I consider the overall challenge to find a way to use Intel's capabilities for analog applications to have been the most difficult. (Overall, the higher density of the MOS processes over bipolar processes gave us many advantages, once problems on noise and amplifier design had been solved. MOS processes were considered noisier, but the nature of the noise was such that there were ways to compensate.)

The other difficult aspect of the project was that the telephone industry at the time was rather closed. We had several contacts at telephone equipment manufacturing companies, and they made it quite clear to us that they resented our invading their territory. We were told by one of these companies that they would be the ones to design products, and once those designs were specified, we might try to qualify as a foundry.

SPM: *Between 1975–1980 you headed a group that produced the first commercial monolithic telephone (CODEC), the first commercially available switched capacitor filter, and an early signal processing chip known as the Intel 2920. What can you tell us about these products?*

Dr. Hoff: After studying the telephone industry, it seemed to me that our best hope was to offer products to promote more use of digital technology in the industry. Our first basic design was for a telephone CODEC, a device to convert telephone quality analog signals to the standard telephone digital formats in use at the time, and vice versa. I believe our group was the first to offer a commercially available single-chip CODEC. For every CODEC, two filters are needed: one to band-limit the analog signal before it is digitized, and another one to eliminate digital noise from the analog signal derived from a digital input. I believe our group was also the first to produce a commercially available switched capacitor filter to perform those switching functions.

We also recognized that there were other functions performed in telephone systems, such as decoding the touch-tone signals used in dialing and generating a dial tone. We designed an EPROM-programmed DSP chip that included A/D and D/A conversion on the same chip in the hopes of performing many of those functions with one chip design. Our hope was to offer the analog designer the type of flexibility that the microprocessor offered to the digital designer. However, our design was not very successful. I believe there were a number of reasons. We probably made too many compromises in combining the conversions with the digital processor, resulting in a digital processor that was less than spectacular in its performance. We also found that there seemed to be relatively few analog engineers at that time (around 1979) that were really comfortable with DSP. Lastly, switched capacitor techniques allowed relatively inexpensive custom designs for many of the functions we had expected our digital chip to perform.

SPM: *Later, from 1980 to 1983, you headed a group that developed speech recognition hardware at Intel. What was the main idea of this work and where was it applied?*

Dr. Hoff: We built a speech recognition system that used our digital signal processor for the analog input and conventional microprocessors for the subsequent recognition. It included a type of state machine to reduce the amount of vocabulary search needed at each point in the recognition process. Some units had speech synthesizers, so they could carry on a type of conversation with the user. My understanding is that one of the applications of our hardware was in equipment inspection systems: a user could carry the recognizer with him while crawling into small spaces, where a keyboard would have been very awkward to use. If the recognizer failed to understand an input, it would ask for clarification, so that the inspector didn't have to repeat the uncomfortable crawling into small spaces.

SPM: *How much of Osborne's brainstorming was involved in your solving of these technical problems?*

Dr. Hoff: I do not remember ever having any type of formal session to try to solve problems or to come up with new ideas. Perhaps the closest thing to brainstorming was when Stan Mazor and I were working on a target specification for what would become the 8008 microprocessor. We drew on our plan for the 4004 (which was only on the drawing board) and were a bit concerned because the 8008 would have 8-b logic rather than 4-b, which would make the chip bigger. Nevertheless, we wanted the chip to have other features that went beyond the 4004. One feature that the 4004 lacked was an interrupt. We therefore posed a question. What was the least amount of logic that would have to be added to the 8008 to allow an interrupt to be added at a later date? We came up with a design that needed only one extra flip-flop circuit. There have been many similar situations over the years, typically with one or two engineers and myself discussing what our options are in trying to solve some design problem.

SPM: *After 1984, you were with Atari for a while and then worked as a consultant. An important part of your work is to recreate in your home lab (or home shop, as you call it) experiments to verify the claims of various patents. What does your home shop consist of?*

Dr. Hoff: Since my high school days, I have had some form of home lab/shop. I generally try to pursue home projects that are unrelated to my official work projects (otherwise it would feel like work and not a hobby). However, I almost invariably have found that whatever I pursued at home eventually became useful for my work. My home shop includes an electronics lab equipped with power supplies, various signal sources (audio, radio frequency, pulse), a 500 MHz analog Tektronix oscilloscope, logic analyzers, and computers for both writing microprocessor code and programming EPROMs and programmable logic devices. I also have some high-vacuum and high-voltage equipment and some limited chemistry capability (e.g., solvents for various electronic coatings and photoresist development). I have a small metal lathe, a metal cutting band saw, and a Bridgeport milling machine. I have a small oxy-acetylene welding torch. I also have a fairly extensive library that includes many semiconductor data books as well as books on various aspects of computers, electronics, optics, physics, and chemistry. I also have copies of several IEEE journals, typically representing issues from around 1970 to the present. It currently takes about 360 linear feet of shelf space to house it.

SPM: *To verify the claims of patents, do you try to evaluate all possible combinations of technical factors (as astrophysicist Fritz Zwicky's morphological method for creativity suggests) or do you approach the problem differently?*

Dr. Hoff: For patent claims, what really counts is how the terms are defined using three basic sources: generally accepted meaning, any special definition within the patent, and the impact of arguments made to the examiner to get the patent granted. However, in solving a design problem, I do like to try several approaches and compare the results of each to find which is simpler, which works better, and which has the most potential for further development.

SPM: *In 1997, you were awarded the Kyoto Prize (the Japanese version of the Nobel prize) for the invention of the microprocessor. Would you tell us a bit about this event?*

Dr. Hoff: There have been many happy professional moments but certainly receiving the Kyoto Prize stands near the top of the list. The award ceremony in Kyoto was incredible and included a full symphony orchestra. Then we were taken to Tokyo, where we were driven into the Imperial Palace and met the emperor and empress. The empress was very friendly and spoke perfect English. She expressed some frustration in understanding what our technology was about. I tried to explain to her how our microprocessors had many uses, one of which was to control automobile engines in an effort to reduce air pollution. She agreed with my observation that the air in Tokyo seemed much cleaner than it had been several decades earlier, hopefully aided by better automobile engine control.

SPM: *In addition to electronics and computer applications, one of your hobbies is metalworking. What have you been creating in metal?*

Dr. Hoff: Most of my metalworking is directed toward building electronic devices. I have made metal bending jigs for use when making enclosures for electronic gear, knobs, and parts to repair other equipment. I have made molds for casting plastic parts. I also made a mounting for a 10-in reflecting telescope. I have also made other optical odds and ends, such as lens mountings and diffraction grating assemblies.

SPM: *Among your favorite books are Dr. Folkman's* War: Angiogenesis and the Struggle to Defeat Cancer *by Robert Cooke,* The Merck Index *(a one-volume encyclopedia of chemicals, drugs, and biologicals) and the* Handbook of Chemistry and Physics. *Among the fiction and other nonscientific works, what areas are of most interest to you?*

Dr. Hoff: Most of my reading is directed toward finding a solution to some problem, but on occasion I read just for pleasure. When I do, I like detective and spy stories and biographies, i.e., mostly tales that describe the solving of puzzles of various types.

(continued on page 96)

dispersion and PMD [9]. A feedback scheme (that we do not display in Figure 4) could be used to track system changes to optimize the equalizer performance.

Although a straightforward and elegant approach, the electronic equalizer has an inherent shortcoming. Some information about the optical signal such as polarization and phase is lost during the O/E conversion. As a result, the electronic equalizer illustrated in Figure 4 has a limitation on its performance. A special modulation scheme could be used to solve this problem to some extent. It has been demonstrated that when a single side band modulation scheme is applied in optical systems, the performance of an electronic equalizer can be improved significantly [10].

CONCLUSION

Optical communication plays a significant and increasing role in our society. The public demand for higher network speed requires an optical backbone network with larger capacity. Accompanying high transmission-rate optical communications system are severe technical specifications for optical devices and systems. Many popular optical devices could be represented with a digital filter model as described in this article. Use of well-developed signal processing techniques and algorithms to design these optical devices is a wise use of existing technology. As demonstrated in this article, signal processing could play an important role in the development of advanced optical communication systems. However, as demonstrated in the case of an electronic equalizer, some optical system characteristics may require special attention if signal processing techniques are to be applied successfully. Therefore, interdisciplinary cooperation between researchers in optics and signal processing will be crucial for optical communications to fully benefit from signal processing.

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DSP HISTORY *(continued from page 81)*

SPM: *Let us wrap up by looking in the past with a thought for the future: your invention of the microprocessor was a major breakthrough. Where do you consider that breakthroughs are needed now in DSP?*

Dr. Hoff: The more speed we can offer in both the DSP and the associated A/D and D/A conversions, the more applications we will find. When we combine traditional DSP with other logical processing such as data encryption and addition or elimination of redundancy, we can expect to improve reliability and security of all of our communication channels. I would also like to see more natural language processing, including recognition, understanding, and translation. In particular, fast and accurate language translation would seem to offer a huge potential for improving human communication and cooperation, and better machine understanding of language should help make computers even more useful.

SPM: *Thank you.*

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