Reconfigurable Computer Origins: The UCLA Fixed-Plus-Variable (F+V) Structure Computer

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Gerald Estrin and his group at the University of California at Los Angeles did the earliest work on reconfigurable computer architectures. The early research, described here, provides pointers to work on models and tools for reconfigurable systems design and analysis.

The earliest work on reconfigurable computer architecture was done at the University of California at Los Angeles (UCLA), as a 1999 report in *The Economist* noted (see "*The Economist*: Reconfigurable Systems Undergo Revival" sidebar, p. 4). Clearly, in retrospect, digital technology was not ready for such a revolutionary change. Now that digital technology is enabling commercial realization, however, the time seems right to tell this story. Of equal interest might be the saga of how a professor and his graduate students, in an academic setting, can work on one complex problem over a prolonged period and bring to the computer science world original ideas that can themselves be commercially realized. This is a process unique to academia where the research of students and faculty is not judged by its immediate applicability but instead by its creativity and the cumulative impact of discovered side effects.

My first attempts at telling this tale were overwhelmed by the duration of the research program multiplied by the productivity of the researchers. Telling everything made it too deep and narrow. I have instead highlighted the research goals and the issues they exposed. I begin with the challenge that triggered my proposal for a reconfigurable computer structure in the first place, then reveal the issues and support that kept our research productive for almost three decades. In an attempt to avoid encumbering the reader with an outlandishly long bibliography, I have been arbitrarily selective and possibly unscholarly. I count on modern Internet search tools to help the reader's search for more source materials.

Pasta's challenge

What triggered the UCLA work on reconfigurable computer systems? In the spring of 1959, John Pasta, a highly respected applied mathematician and physicist and chairman of the Mathematics and Computer Science Research Advisory Committee to the Atomic Energy Commission, expressed concern about many vital computational problems whose solutions were beyond the capabilities of existing electronic computers. In his opinion, commercial computer manufacturers had lost interest in exploring risky, innovative computer architectures. Instead, the manufacturers wanted to serve the growing market for conventional computer systems. Consequently, when Pasta visited me at UCLA, he challenged me to propose new ways to organize computer systems in the hope that research advances in the public domain would lead to a surge of computer development in the private domain.

Pasta's challenge to me was timely. I had come to UCLA from von Neumann's Electronic Computer Project at the Institute for Advanced Study in Princeton[1] after directing construction of a von-Neumann-type computer at Israel's Weizmann Institute of Science.[2] Both projects sought to solve problems in applied mathematics and applied physics. The projects motivated me to explore computational concurrency, which had been made more feasible by new semiconductor technology. They also opened the door to departures from the conventional von Neumann machine architecture.[3]

When I joined the UCLA engineering faculty in the fall of 1956, I was partially supported by the Department of Mathematics' Numerical

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Analysis Research Laboratory. NARL was responsible for applied mathematics research and for the Standards Western Automatic Computer (SWAC), whose development had been completed by Harry Huskey in 1952. C.B. Tompkins, head of NARL, had joined Engineering Dean L.M.K. Boelter to aggressively recruit me. During 1957, I was visited by Marshall Yovits, a program manager from the Office of Naval Research (ONR). He suggested that I submit a proposal seeking support for my research at UCLA. In May 1958, I was awarded a contract for research in digital technology. That ONR contract enabled me, in turn, to support research by graduate students and, in the summer of 1959, to totally immerse myself in considering John Pasta's challenge to extend the capabilities of electronic digital computers.

Reconfigurable architecture response

I presented the first results of my brainstorming at the May 1960 Western Joint Computer Conference in a paper titled "Organization of Computer Systems—The Fixed Plus Variable Structure Computer."[4] Figure 1, from that paper, illustrates the relations between a fixed general-purpose computer (labeled F) and a variable structure inventory of reconfigurable building blocks (labeled V). The "Reconfigurable Architecture Defined" sidebar quotes from that paper to highlight the primary goal of the proposed new architecture.

Our reconfigurable computer systems research at UCLA sought a new way to evolve higher performance computing from any general-purpose computer. Starting in 1959, we tried to design special-purpose subsystems that could run concurrently with programs in a coupled general-purpose computer. We developed "miniaturized" circuit modules and a removable, replaceable etched signal harness (see Figure 2). We were aware of the gap between available technology and our needs for more automatic electronic control, but the inexorable advances in semiconductor technology were already evident. We had many other computer science and computer engineering issues to deal with if reconfigurable systems were to be realizable. The "Early Researchers" sidebar (on p. 6) highlights the earliest investigations in our group and offers some personal insight about them.

The Economist: Reconfigurable Systems Undergo Revival

On 22 May 1999, *The Economist* (vol. 351, no. 8120, p. 89) reported the following.

> In 1960 Gerald Estrin, a computer scientist at the University of California, Los Angeles, proposed the idea of a "fixed plus variable structure computer". It would consist of a standard processor, augmented by an array of "reconfigurable" hardware, the behavior of which could be controlled by the main processor. The reconfigurable hardware could be set up to perform a specific task, such as image processing or pattern-matching, as quickly as a dedicated piece of hardware. Once the task was done, the hardware could be rejigged to do something else. The result ought to be a hybrid computer combining the flexibility of software with the speed of hardware.
>
> Although Dr. Estrin built a demonstration machine, his idea failed to catch on. Instead, microprocessors proved to be cheap and powerful enough to do things on their own, without any need for reconfigurable hardware. But recently Dr. Estrin's idea has seen something of a renaissance. The first-ever hybrid microprocessor, combining a conventional processor with reconfigurable circuitry in a single chip, was launched last month. Several firms are now competing to build reconfigurable chips for use in devices as varied as telephone exchanges, televisions and mobile telephones. And the market for them is expected to grow rapidly. Jordan Selburn, an analyst at Gartner Group (an American information-technology consultancy), believes that annual sales of reconfigurable chips will increase to a value of around $50 billion in 10 years time.

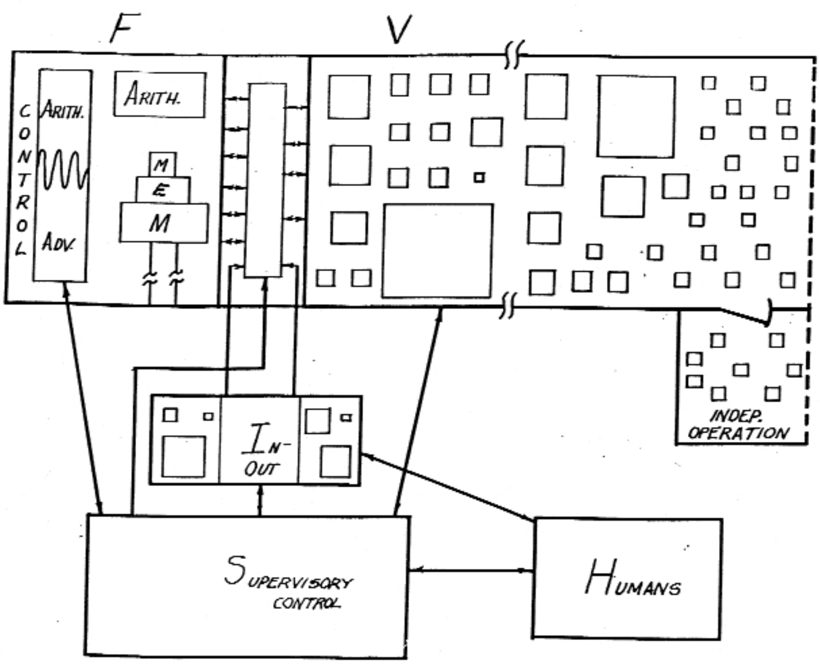

Figure 1. This diagram shows the relations between the fixed machine, the variable structure part, the input-output, the supervisory control, and the humans. (Courtesy of the 1960 Western Joint Computer Conference.)

Reconfigurable Architecture Defined

The following excerpt is from a 1960 conference paper[1] describing my initial thinking on reconfigurable architectures. The goal was

> … to permit computations which are beyond the capabilities of present systems by providing an inventory of high speed substructures and rules for interconnecting them such that the entire system may be temporarily distorted into a problem oriented special purpose computer.
>
> The fixed plus variable structure computer will consist of a set of independent digital complexes ranging in size from individual switching elements or flip-flops to, say shift registers and counters to a high speed general purpose computer. The latter element is "fixed" in the sense that the machine user is presented with some minimum vocabulary and some minimum set of machine characteristics which do not change rapidly with time and which do not require the specification of some variable set of interconnections for each problem.
>
> The existence of the "fixed" general purpose computer as an element in the system is considered essential to the evolution of higher level languages for man-machine communication. If either the instruction code were always changing or the meaning of the instructions were always changing, any tendency for humans to invest effort in the definition of more complex instructions would be quickly damped despite the ability to make use of the variable structure inventory to effect higher language operations.
>
> If it is found that a number of the inventory items is used very frequently, then it may be desirable to introduce that assembly as a separate inventory item with speed-optimized fixed wiring. In fact over longer periods, it may be observed that some substructures are used so frequently that they should be part of the "fixed" structure general purpose computer so that there is no need to explicitly specify the substructure each time it is used.

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1. G. Estrin, "Organization of Computer Systems—The Fixed Plus Variable Structure Computer," *Proc. Western Joint Computer Conf.*, Western Joint Computer Conference, New York, 1960, pp. 33-40.

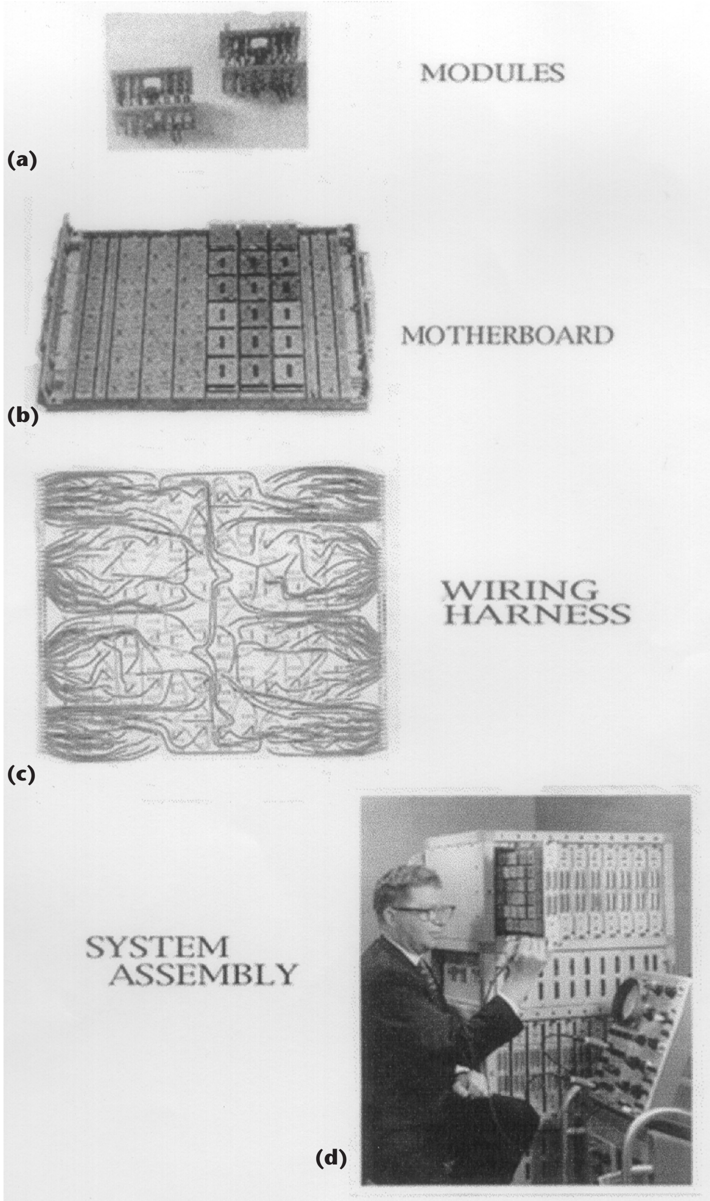

Figure 2. Basic reconfigurable modules (a), motherboard (b), wiring harness for the motherboard (c), and system assembly constructed for the supervisory control and transfer path between the fixed and variable structure computers. The author is shown using an oscilloscope probe to observe electrical activity of the system assembly (d). (Courtesy of IEEE.)

Our early experiments made it clear that we needed a way to predict the performance of different concurrently operational systems, and we realized that we needed computational tools to accelerate the rate at which we could explore new special-purpose designs. Therefore, in the mid-1960s and early 1970s:

- we formalized the UCLA Graph Model of Computation,[5-9]
- we proposed a dedicated computer as well as

Early Researchers

Consistent with traditional articles in this journal, I offer some personal insight into the work of the earliest contributors to this work instead of depending on a voluminous bibliography. In the early 1960s, I directed a small cadre of ONR-supported researchers. They added to the ongoing work and critiqued the reconfigurable architecture concept. In every case, I tried to interest them in seeking a solution to a problem of particular interest to each of them. Below, I highlight some of the key people involved in that early research.

David Cantor was a bright young mathematics faculty member who became interested in the challenge of special-purpose design involving both hardware and software. He served on many master's and doctoral advisory committees. Cantor collaborated with us on two elegant works on computation that set a standard for others.[1,2]

Aviezri Fraenkel was an Israeli engineer who had worked with me on the Weizmann Institute of Science computer development in Israel in 1954 and 1955. His dedicated and successful work there was rewarded by an opportunity to work with me at UCLA for a year. While at UCLA, Fraenkel became enamored with number theory research. He applied his creativity to, among other things, designing and evaluating a numerical sieve to search a prescribed space of numbers.[2] Fraenkel went on to complete his PhD in mathematics at UCLA and returned to the Weizmann Institute to join the mathematics faculty where his outstanding research contributions continue.

Rein Turn, an Estonian immigrant, was challenged by the need to develop a model that would enable a computer to automatically assign tasks to an inventory of software and hardware building blocks in the reconfigurable system. Turn's systematic thinking and perseverant management of complexity produced groundbreaking results.[3,4] Turn later joined RAND, lending his expertise to study the future impact of new technologies on computer performance. After a decade of such work, he joined the faculty of California State University–Northridge to teach and lead less mission-oriented research.

Bertram Bussell, an engineering instructor teaching circuit analysis, was introduced to me by a meteorology professor who had been at Princeton's Institute for Advanced Study when we were building the von Neumann computer in the early 1950s. When I came to UCLA, Bussell was searching for a PhD dissertation topic and was interested in working with me. He focused on the solution of partial differential equations[5] because of his general background in mathematics and his particular interest in heat transfer problems. In addition to his research, Bussell knew the UCLA engineering environment very well, having worked as a graduate student and researcher in the Department of Engineering for many years. He also turned out to be indispensable in managing daily problems. Having completed his dissertation in 1962, Bussell joined the faculty and remained at UCLA until his retirement in the 1990s. He played an important role in developing the prototype reconfigurable system, in attracting excellent graduate students from South America, and in building a nurturing environment for the students who joined our research effort.

Four other graduate students went beyond their graduate work to contribute to the early study of reconfigurable systems. **Masanao Aoki** had come from Japan on a one-year grant to complete his master's degree under my supervision. Aoki, whose master's thesis concerned switching circuit analysis, became interested in dynamic programming techniques proposed by the RAND mathematician Richard Bellman. I arranged a meeting between Aoki and Bellman, and when Aoki became excited about continuing his graduate research, I suggested that Bellman join Aoki's dissertation committee as an external member. Aoki requested permission from his Japanese sponsor and was shocked by their refusal and insistence that he return home at the end of his allotted year. There ensued heavy pressure on Aoki's parents to get their son to return to Japan, but he stood his ground. Aoki completed his PhD in early 1960. As part of our computer project, Aoki collaborated with **Tom Tang**, a graduate student working on his master's degree. They worked on methods to generate pseudorandom numbers.[6] Aoki joined the UCLA School of Engineering faculty and made significant contributions to system science. He was recognized for contributions to economic theory and was recruited as a professor in UCLA's Department of Economics. After graduating with his master's degree, Tang went on to become vice president of research at National Cash Register in Dayton, Ohio. Until his recent retirement, Tang was a staunch supporter of our research program.

Richard H. Fuller had done pioneering work on developing early small computers at Librascope. He was interested in exploring the potential of content-addressable memory systems in which information would be addressed by its content rather than its location in the memory system. His doctoral dissertation was remarkably complete and included novel use of reconfigurable system design to implement the search algorithms. Fuller filed his PhD dissertation in 1963[7] and went on to become vice president of technology at General Instrument until his retirement.

C.R. Viswanathan was a graduate student in physics at UCLA when he joined our research group. At the time, we were studying temperature effects on magnetic materials used to store digital information. Viswanathan's PhD study was concerned with very low temperature research, and his lab experience was critical to our studies. To become better informed about our reconfigurable system research, I encouraged Viswanathan to work on improving the performance of computational algorithms important to his studies. He chose to work on matrix computations—that is, computation of eigenvalues and eigenvectors of real, symmetric matrices.[8] Viswanathan was a superb teacher as well as a distinguished researcher. He was recruited into

UCLA's electrical engineering faculty, became department chair, was elected head of the Academic Senate, and was recently appointed to university-wide leadership. Throughout his career, he has been recognized for outstanding teaching.

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dedicated software as instruments to measure in vivo computational performance,[10] and
- we showed how to discover and correct pathologies in control flow during concurrent computation.[11]

We experimented with microprogrammable computers, and we also developed the Digital Control Design System to facilitate the design process.[12,13] From 1976 to 1986, we built and rebuilt a software system, called System Architects Apprentice (SARA).[11,14-18] Using SARA, we could model, analyze, and simulate concurrent systems involving hardware and software building blocks to discover and cure problems before physically assembling new systems. Because UCLA had been intimately involved in building the Arpanet,[19] the software system, SARA, was developed remotely on the Honeywell Multics computer system at the Massachusetts Institute of Technology from our UCLA terminals. Anyone with an account at MIT's Multics system site and access to the Arpanet could use it from their terminals.

The UCLA research program on reconfigurable computing was successfully carried out by small groups of graduate students and faculty. For more than 20 years, it was supported by funding from the US government (around $7 million), the University of California (around $420,000 overhead-free), and industry (around $540,000 in cash or in kind from 10 companies). About 50 graduate students were involved over the years. Then and now, it stands out clearly as an example of US higher education engineering research with dual goals: training future leaders and breaking new research ground.

Transitions

The dedicated work of our project's graduate students, both those acknowledged in the "Early Researchers" sidebar as well as others, made it possible for us to successfully propose that the Atomic Energy Commission fund our "Research Program for the UCLA Variable Structure Computer System," which began in March 1962. The period leading up to the program's kickoff had been intense. From 1958 through 1963, I had supervised completion of more than 30 master's theses and five doctoral dissertations. I had coauthored more than 10 papers with my students, which culminated with two papers in a special issue of the December 1963 *Transactions on Electronic Computers*.[20-21] Ultimately, our initial response to John Pasta's challenge had demonstrated promise, and we were now ready to support a new group of researchers.

That same year, my personal work was recognized by a Guggenheim Fellowship award to do research on restructurable computer systems with an emphasis on computations in x-ray crystallography. I was fortunate in being able to spend a sabbatical year to think about the future. My wife's engineering career (with the UCLA Brain Research Institute) had taken off, and we went overseas with support of her Fulbright Fellowship, and with our three young daughters.

Conclusion

The computing community recognized early on that the success of our work at UCLA on

Editor's Note

The SWAC computer has been the subject of earlier articles in the *Annals*. For additional information, please see:

- H.D. Huskey, "The National Bureau of Standards Western Automatic Computer (SWAC)," *IEEE Annals of the History of Computing*, vol. 2, no. 2, Apr.–June 1980, pp. 111-121.
- H.D. Huskey et al., "The SWAC Design Features and Operating Experience," *IEEE Annals of the History of Computing*, vol. 19, no. 2, Apr.–June 1997, pp. 46-50.
- H.D. Huskey, "SWAC—Standards Western Automatic Computer: The Pioneer Day Session at NCC July 1978," *IEEE Annals of the History of Computing*, vol. 19, no. 2, Apr.–June 1997, pp. 51-61.

See also: D. Rutland, *Why Computers Are Computers: The SWAC and the PC*, Wren, Philomath, Ore., 1995.

reconfigurable computers depended heavily on modeling methods and computer-aided tools, which would build confidence that system requirements and observed behavior were mutually consistent. Our 1986 paper reviewed the SARA effort up to that date, detailing the unusual demonstrations of the modeling power, the analysis power, and the effectiveness of the integral help tools that had enhanced the SARA system since its inception.[16] Research continued after 1986 as graduate students sought to enhance tools for collaborative design and design of interactive systems.[22] Although the predicted rate of growth of reconfigurable systems has been slowed by changes in the world economy, the related technology keeps increasing its market penetration. The body of knowledge created in the studies reported here remain openly available for future access.

Acknowledgments

I'd like to acknowledge the research support effort by Dorab Patel over many years during which he participated in the SARA work while independently pursuing separate research in functional programming. Several other doctoral students played strong leadership roles during this extended research program, notably Hanan Potash, Robert Gardner, Vinton Cerf, Steve Crocker, Kim Gostelow, Robert Fenchel, Rami Razouk, Mary Vernon, Maria Penedo, and Duane Worley. Our research life was enriched by a string of students from Brazil and Chile. Professors B. Bussell and D. Berry played special roles in providing student guidance over several years with Berry having particular impact in the domain of software design.

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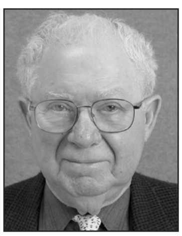

Gerald Estrin was a member of John von Neumann's Electronic Computer Group at the Institute for Advanced Study in Princeton, New Jersey, from 1950 to 1956. He took leave from 1953 to 1955 to direct the WEIZAC computer's development at Israel's Weizmann Institute of Science. In 1956, Estrin joined the University of California, Los Angeles, where he built the digital computer engineering academic program and led research on reconfigurable computer architecture and methods and tools to support computer system design. Estrin, involved in ARPA networking projects since 1965, sparked interest of the energy research community in resource sharing through networks. He chaired UCLA's Computer Science Department from 1979 to 1982 and from 1985 to 1988.

Estrin received a PhD in electrical engineering at the University of Wisconsin, Madison. His honors include AAAS Fellow, Guggenheim Fellow, IEEE Fellow, and IEEE Computer Society Pioneer.

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