

Microprocessor at 50: Looking Back and Looking Forward

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In November 1971, a full two-page ad appeared in the *Electronics News Weekly* announcing the Intel 4004 (see Figure 1). Twenty-three-hundred transistors were integrated into this microprocessor. The year 2021 marks the 50th anniversary of this amazing accomplishment. This milestone coincides with the 50th anniversary of other iconic companies, such as Walt Disney World, Starbucks, and Amtrak. Incidentally, microprocessors have had their impact on all these companies and beyond. Microprocessors are the brains behind almost all equipment from entertainment systems to smart coffee machines. Arthur Clarke, a renowned science-fiction writer, almost got it right in 1979—"Microprocessors are getting into everything. We won't be able to pick up a single piece of equipment in the near future, except maybe a broom that hasn't got a microprocessor in it." It turns out you can now get electronic brooms and mops with microprocessors on most e-commerce sites! Microprocessors have propelled satellites and spacecraft beyond the confines of the Earth. Welcome to the November/December 2021 issue of *IEEE Micro* which celebrates the 50th birthday of the microprocessor with articles from the major participants in this amazing microprocessor story.

Microprocessors have been a passionate topic for designers and users alike. After semesters of studying network analysis, signals and systems, and electromagnetics, when the course on microprocessors came during the seventh semester of my undergraduate engineering curriculum, there was no single person in that undergrad cohort who was not excited. Discussions on microprocessors can get heated like religion and politics. As a 22-year old, while working at organization A, I interviewed for a job that paid half as much at organization B only because company B used my favorite microprocessor (at that

time). I thoroughly enjoyed various microprocessor projects, whether it be an x86 compiler for the FORTH language (my senior design project) or MIPS simulation/pixie-based instruction set analysis during graduate school or MIPS Verilog/VHDL coding for the digital design books I coauthored. And I still cannot forget the excitement from when I first learned about the RST 5.5, RST 6.5, and RST 7.5 maskable interrupts on the 8085.

Microprocessors continue to evolve at a blistering pace. We have come a long way from the 2,300 transistors integrated in the 4004, to billions and trillions of transistors in the processors of 2021. After presenting reflections from industry leaders such as Pat Gelsinger (Intel CEO), Jensen Huang (NVIDIA CEO), Lisa Su (AMD CEO), Simon Segar (ARM CEO), Mark Papermaster (AMD CTO), and Mark Liu (TSMC President), this issue continues with more than 30 articles—describing stories of the major players in the field such as Intel, AMD, ARM, IBM, NVIDIA, Centaur, Cerebras, Motorola, and Texas Instruments. Embedded manufacturers such as Renesas and Microchip participated as well. There are also stories from pioneers at the Standard Performance Evaluation Consortium (SPEC), and perspectives from the U.S. National Science Foundation on funding future research.

The articles were coordinated by Associate Editor-in-Chief Dr. Vijaykrishnan Narayanan and me. I want to thank all the authors who submitted articles and perspectives, and went through iterations of revisions. A separate introduction to the special issue gives a more detailed glimpse of the articles. Be sure to read it to get an overview of the articles in this issue.

To preserve the historic context of events, the articles remain largely unedited and reflect the individual opinions of the contributors in their own language and perception. However, articles were gathered from a broad and diverse set of contributors to ensure diversity of opinions and perspectives. We also ran a public opinion poll on favorite microprocessors and highlight some of those opinions as well. Any additional viewpoints could

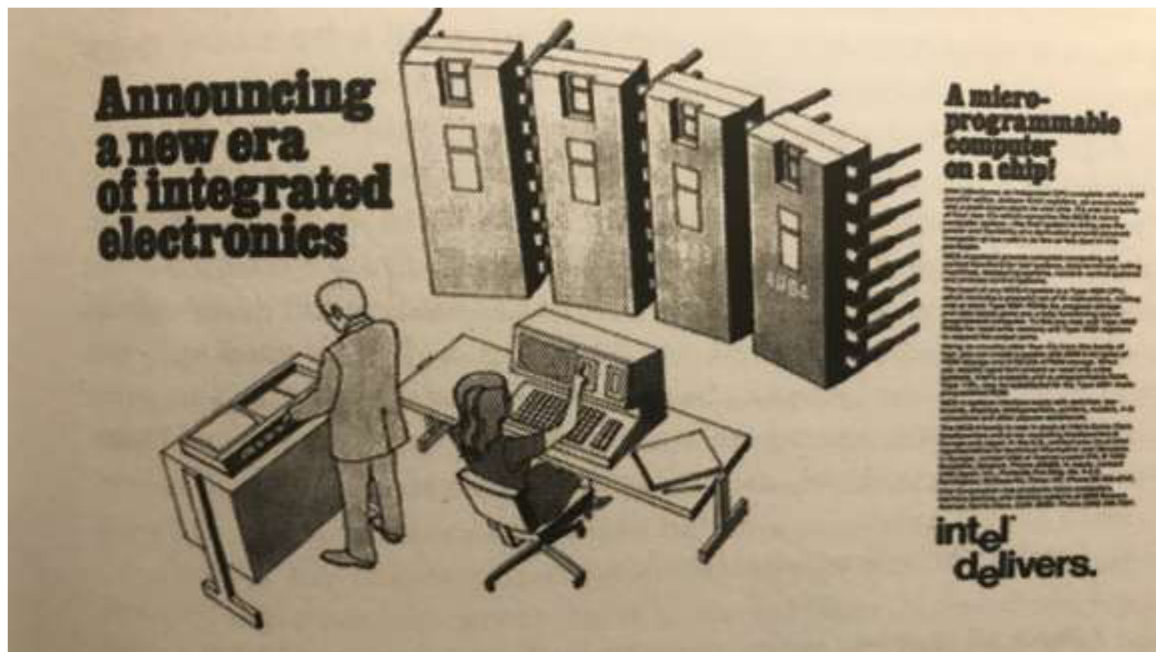


FIGURE 1. Advertisement in the *Electronics News Weekly* in November 1971 announcing the Intel 4004.

still be provided to the editor for consideration for future issues.

In addition to the articles mentioned previously, there are three department articles, accompanying the historic theme on the 50th birthday. I express my gratitude to all three department editors for composing articles, so appropriate, for this special issue.

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Michael Mattioli of Goldman Sachs writes about the Apollo Guidance Computer that successfully guided, navigated, and controlled the spacecraft, which carried Neil Armstrong and Buzz Aldrin to the surface of the moon and back in 1969, as part of the Apollo 11 mission. It is a fantastic article to accompany this historic issue on the 50th anniversary of the microprocessor. If the microprocessor existed, the Apollo mission would have been lighter!

Joshua Yi presents an article on several early computer architecture patents. Among patents described, there is one from Hoff, Mazor, and Faggin, filed in 1973, and one from James Smith on the first 2-bit branch predictor from when Smith was working for Control Data Corporation, filed in 1980. Read the article to learn more about early intellectual property in this field and also some trends.

This issue also features a Micro Economics column by Shane Greenstein, "Virtuous Cycles." He says that better and cheaper microprocessors raised the value of innovating in better software applications and peripherals. Improvements generate additional gains in revenue and productivity, and fuel renewal of a virtuous cycle. He concludes saying that he is hoping for a similar virtuous cycle in the domain of machine learning and artificial intelligence.

I express my gratitude to all authors and contributors, especially Federico Faggin, John Hennessy, John Henning, Glenn Henry, Scott Gardner, Richard Grisenthwaite, Gary Lauterbach, Linley Gwennap, John Mashey, Kathryn McKinley, Raghu Raghunathan, Mark McDermott, Steven Vansingel, Bob Martin, Steve Keckler, Bill Dally, David Christie, Margaret Martonosi, Bob Colwell, Ravishankar Iyer, Ray Simar, John Goodacre, Randy Steck, Robert R. Chodorek, Wanda Gass, Pete Harrod, Ann Marie Maynard, Jim Bondi, Preethi Preethichandra, Cliff Young, Murray

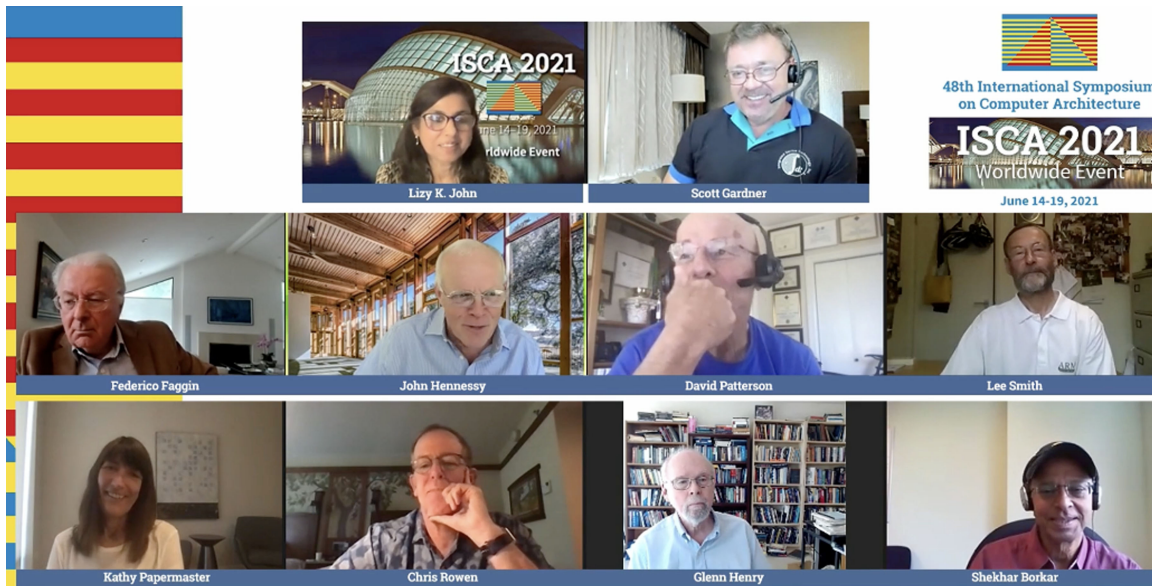


FIGURE 2. Participants of the ISCA 2021 panel, Microprocessors at 50: Looking Back and Looking Forward.¹

Goldman, Jensen Huang, Lisa Su, Pat Gelsinger, Simon Segar, Mark Liu, Mark Papermaster, Timothy Pinkston, Kathy Papermaster, Kunle Olukuton, Pradip Bose, Karthik Swaminathan, and Charles Webb for responding to my various emails and making this happen. Special thanks go to Pat Gelsinger (Intel CEO), Jensen Huang (NVIDIA CEO), Lisa Su (AMD CEO), Simon Segar (ARM CEO), Mark Papermaster (AMD CTO), and Mark Liu (TSMC President) for sending their thoughts and memories to *IEEE Micro* at this important milestone event.

Let me also thank Associate Editor-in-Chief Vijaykrishnan Narayanan, who enthusiastically helped in the creation of this special issue. The IEEE staff also deserves special mention. Joanna Gajlik patiently dealt with the numerous issues that surfaced during the compilation of this issue, and the assistance and advice from Kimberly Sperka, Robin Baldwin, Carrie Clark, Heather McAlinn, Christine Anthony, and Diane Burton at IEEE are sincerely appreciated. Bagus Hanindhito, my Ph.D. student, also spent numerous hours assisting me with various tasks that went under the hood to bring this issue to light. A special appreciation to Raghu Raghunathan, Motorola Fellow, who reminded me around April 2021 that it is the 50th anniversary of the microprocessor.

Let me personally appreciate ScholarOne, the publication portal used by IEEE. While dealing with the not-so-friendly interface of ScholarOne, many authors and I have at times expressed frustration with the interface. However, manually handling more than 30

articles, their submissions, reviews, all correspondence with authors, I have come to appreciate the automation provided by ScholarOne.

The “In-Memory Computing” special issue, guest edited by Prof. Reetu Das of the University of Michigan and the “Smart Agriculture” special issue, guest edited by Neeraj Kumar of Thapar University and Sudip Misra of IIT Kharagpur will appear in 2021. Apologies to the authors and guest editors for the rescheduling of those two themes.

I conclude with some excerpts from a panel at the 2021 International Symposium on Computer Architecture (ISCA) that took place on June 14, 2021, celebrating the 50th anniversary of the microprocessor,^{1,2} and thinking about the future. As shown in Figure 2, the following panelists attended the discussion:

- Federico Faggin: Designer of the first commercial microprocessor (Intel 4004), winner of the National Medal of Technology and Innovation (2009), founder of Zilog and Synaptics;
- John Hennessy: Co-founder of MIPS Technologies, pioneer of RISC, winner of the Turing Award, Chairman of Alphabet, 10th President of Stanford, author of a popular computer architecture book;
- David Patterson: He led the Berkeley RISC project (which became the basis for Sun SPARC), pioneer of RISC, winner of the Turing Award, currently at Google, author of a popular computer architecture book;

- ▶ **Glenn Henry:** He designed computers spanning from IBM mainframes to personal computers and custom x86 CPUs, IBM Fellow, Senior Vice President at Dell, President of Centaur Technology;
- ▶ **Kathy Papermaster:** She has 26 years of experience at IBM, led multiple IBM projects, Director of Sony-Toshiba-IBM Center that designed the Cell Processor;
- ▶ **Lee Smith:** He co-founded Arm, led development of software tools at Acorn and Arm, Arm Fellow;
- ▶ **Shekhar Borkar:** He directed Intel microprocessor research for 34 years, former Intel Fellow, currently at Qualcomm;
- ▶ **Chris Rowen:** Co-founder of MIPS Technologies, Tensilica, and Babblelabs.

The panel was moderated by J. Scott Gardner, an independent microprocessor-technology analyst with 10 years of experience from IDT, and who served as the VP of Intrinsity, CEO of Nanowatt Design, and as a former senior analyst at *Microprocessor Report*.

During the panel, the panelists described their personal microprocessor stories, discussed inflection points in the technology, and made future predictions. This article presents only a few excerpts from the panel. A video of the panel¹ and a transcript of the panel² can give interested readers the complete picture.

Scott Gardner: I want to make sure everybody understands that everybody watching and everybody on this panel, owes their career to the microprocessor.

Shekhar Borkar: So, what will the microprocessor in 2040 look like? A microprocessor will be a building block. It will look the same, and it's the whole system that matters even now and more so in the future. So, don't get fixated on what the microprocessor will look like, but really more think about what the system will look like.

David Patterson: Microprocessor at 75: RISC-V Open ISA architecture will have become as significant for microprocessors as Linux is for operating systems today...

If quantum computing works, it will be for the cloud, not for the edge.

2045: The stored program concept is too elegant to be easily replaced. I believe future computers will be very much like machines of the past, even if they are made of very different stuff.

Chris Rowen: A modern application developer does not think very much about instruction-set architecture. They don't even think about the OS interface or the compiler very much. They're very often working

at the level of ... Python or JavaScript ... They're invoking libraries, they're invoking cloud services, and how they stitch those together is centrally important to what is the distribution of work that needs to be done.

Federico Faggin: Where can we get a technology that can work at room temperature and that can do better than silicon? I think, ... that biology is the answer. But that biology, the answer, will come probably 30–40 years from now. The beginning of the answer will come 30–40 years from now.

John Hennessy: I think we are going to find that machine learning is even more useful than we thought. Just lots of applications are going to get moved to that space. We are going to use massive amounts of computing resources to do training and massive amounts of data to train those machines.

Lee Smith: The way we prolong Moore's Law is by exploiting more special-purpose hardware ... The proof point is in your pocket. You know, the baseband processor in your mobile phone contains a shedload of special purpose hardware for every radio modem your phone can do, and for the camera, and for video encoding, and probably video decode too ... all of those functions that go on in the base station. They are all done by software on more general-purpose machines.

Kathy Papermaster: It is exciting to see more and more ... heterogeneous compute ... leveraging vector computation, ... as pioneered by Cell. Cell was difficult to program at the time. The burden on software to utilize these accelerators, hopefully, they are lowered.

Glenn Henry: Pouring more transistors into the general-purpose processor is bad in my opinion. That is where the security leaks of today, which, by security leaks I'm including, of course, bugs.

The security leaks today come from ... evilness of out-of-order execution.

Benchmark performance is not the critical issue; security is.

I AM HUMBLD TO BE THE EDITOR-IN-CHIEF OF IEEE MICRO IN THIS HISTORIC YEAR WHEN THE MICROPROCESSOR TURNS 50.

As we celebrate the 50th, there are also many concerns on the sustainability of computing and the

environmental effects of computer systems. A panel at the International Symposium on Computer Architecture, *Microprocessor at 50: Societal Challenges* provided some opportunity to examine the powerful technologies we are developing, and responsibilities and societal impacts we must keep in mind when developing the technologies. This panel discussed some of the societal challenges brought by digital technologies—the ever-increasing carbon emissions from computing, bias and fairness issues facing AI technologies, and the disparate social justice. If interested, watch the video of the panel available on YouTube.³

I spent the last several months communicating with many pioneers in the microprocessor story. In light of the pandemic, Zoom calls made it possible, and I certainly cherish the opportunity to at least e-meet the various contributors.

In this process, I also learned that Federico Faggin was the Editor-in-Chief of *IEEE Micro* during the 25th anniversary of the microprocessor. I enjoyed reading the various articles in the 25th anniversary issue^{4–6} and “SILICON,” his recently published autobiography.⁷ I am humbled to be the Editor-in-Chief of *IEEE Micro* during this historic year when the microprocessor turns 50.

This was a real treat to me. I hope you enjoy the articles—this amazing collection that we present to you in this issue. Hope the saga of the microprocessor stays alive forever, serving humanity in ways unimaginable.

Happy reading!

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