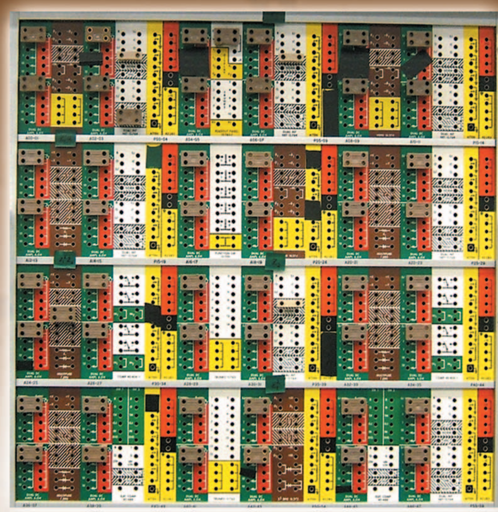
FEATURE

The History of Analog Computing

Introduction to the special section



By Kent H. Lundberg

The history of control is entwined with the history of analog computing. Many of the tools, technologies, and theories of control were enabled by, or are directly descended from, mechanical and electronic analog computers.

As a tool, the MIT differential analyzer [1] was more than a general-purpose, differential-equation solver. It was an educational tool and a research touchstone. Vannevar Bush not only sprouted the seeds of analog simulation and the study of servomechanisms in his laboratory but also nurtured a family of early control researchers, including Harold Hazen who coined the word "servo-mechanism" [2], Gordon Brown [3], and Samuel Caldwell [4]. Bush's computer was a fountainhead of control and computing [5].

The technology of the ubiquitous operational amplifier—now an indispensable component of every control system—was originally invented and perfected for analog computing. Columbia professor John Ragazzini invented the term "operational amplifier" and described the state-of-the-art electronic analog techniques in his landmark paper [6]. Ragazzini based his circuit designs on the work of Clarence Lovell [7] and George Philbrick [8]. Lovell had developed "electrical computing circuits" at Bell Labs for the M9 gun director [9], [10], and Philbrick later founded George A. Philbrick Researches (GAP/R), a successful commercial op-amp supplier. Much of the early technology was documented in books by Granino Korn, Harry Huskey, and Robert Howe (see "Analog Computing Bookshelf").

The simulation of guided missiles in the late 1950s pushed the limits of both analog and digital computing. Digital computers were not yet fast enough to permit hardware-in-the-loop testing of the real-time control systems, but analog computers did not have the accuracy or dynamic range to simulate the long-range trajectories. Electronic analog-to-digital converters, another

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now-indispensable technology, were first commercialized for the purpose of interfacing analog computers with digital machines [11]. These hybrid computers bridged the gap, using analog techniques to simulate the vehicle with its control surfaces and using digital techniques to calculate navigational coordinates [12].

Control theory also owes a great debt to analog simulation. Ten years before Ziegler-Nichols tuning [13], Philbrick built an interactive analog simulator to investigate (and teach!) proportional-integral-differential (PID) control design for process control at the Foxboro Company [14]. Early research in multi-input, multi-output control theory was driven by the needs of flight simulation and autopilot design [15], for which many analog and hybrid computers were built.

Although million-dollar mechanical, hydraulic, and electronic analog computers have faded into the past, the mark left on control engineering, electrical engineering, and all fields of science and engineering in general is indelible (see "Why Analog?"). While the power-hungry, room-filling dinosaurs are now extinct, current research promises to leverage the advantages of analog simulation in modern computing (see "Analog Computers Still Have Much to Offer"). We celebrate the achievements and the legacy of analog computers in this special issue on the history of analog computing.

Analog computers played a key role in enabling the simulation of control systems for several decades, leading to a better understanding of theory and better designs in practice.

Invited Articles

This special issue is one in a series of occasional issues of *IEEE Control Systems Magazine* dedicated to history. The June 1996 issue, "On the History of Control Research," organized by guest editor Linda Bushnell, highlighted the contributions of individual researchers. The April 2002 issue, "History of Control," which was organized by guest editors Dennis Bernstein and Linda Bushnell, took a closer look at the development of technology and its historical context.

The present issue continues those previous contributions by focusing on the development and impact of a pivotal technology. Analog computers played a key role in enabling the simulation of control systems for several decades, leading to a better understanding of theory and better designs in practice. Here we take a closer look at analog-computer technology in its historical context. We have collected eight articles—an analog-simulation tutorial, four personal histories, and three reports of current activities—written by well-known authors in the fields of analog computing and history.

Computer pioneer Robert Howe provides two articles. His first article is a tutorial on the circuits and technology of analog computers and the methods of simulation. He describes how to employ summers and integrators to simulate linear dynamics problems and how to use other simple circuits to investigate a wide variety of nonlinear systems. The operation of stepping-relay systems, servomultipliers, and quarter-square multipliers is explained.

Howe's second article recounts his personal history as a graduate student and faculty member at the University of Michigan and as a founder of Applied Dynamics International (ADI). He traces the use of analog computers in various research projects for the U.S. Air Force, Rand Corporation, and the Office of Naval Research, including the development of a simulator for aircraft flight equations with six degrees of freedom. He also discusses the founding of ADI in 1957 and the development of their product line of analog computers.

In the third article, classic-textbook author Granino Korn provides a general overview of early developments and applications, from operational-amplifier design to large aerospace simulation projects. Korn explains the methodology of simulation, the challenges of programming, and the drive toward hybrid analog/digital machines. He concludes with a description of some of his own research at the University of Arizona on high-speed, envelope-pushing, hybrid computers.

The fourth article is an interview with Soviet pioneer Boris Kogan by Danny Abramovitch, chair of the IEEE Control Systems Society History Committee [16]. Kogan was instrumental in the development of the Soviet Union's first analog and hybrid computers. He immigrated to the United States in 1987 and joined Walter Karplus at UCLA. In the interview, Kogan discusses computer technology, life under Stalin, his colleagues, his emigration, and his current work. Abramovitch also reports on a celebration of Boris Kogan's life and work held at UCLA for his 90th birthday.

Derek Atherton from the Univerity of Sussex provides the fifth contribution, drawing on his earlier articles [17], [18]. He surveys the early days of British analog computers and relates several stories of war-time pioneer F.C. Williams from his time at the University of Manchester. Atherton also compares the early commercial developments in the United

Analog Computing Bookshelf

As the field of analog computing expanded, many popular books were published to document the technology and disseminate simulation methods. No analog-computing library is complete without them.

Classic Texts

Granino Korn worked for Sperry Gyroscope, Lockheed, and the University of Arizona. He and his wife Theresa wrote one of the first books on analog computing [1], which became the classic text and evolved through several editions and revisions. Thomas Truitt and Alan Rogers, both of Electronic Associates, Inc. (EAI), wrote a popular introductory book [2], covering basic material for the new user (and potential customer). Their book is packed with pictures, diagrams, and cartoons. Other early books include those by Clarence Johnson at the U.S. Air Force Institute of Technology [3], Albert Jackson at Control Technology, Inc. [4], and Robert Howe at the University of Michigan [5]. The *Computer Handbook*, edited by Korn and Harry Huskey [6], contains a wealth of technical details contributed by researchers in the field.

The analog computing bookshelf. These books are some of the classics of analog computing. From left: Korn and Korn [1], Truitt and Rogers [2], Johnson [3], Jackson [4], Howe [5], Huskey and Korn [6], Karplus [7], Tomovic and Karplus [8], Karplus and Soroka [9], Bekey and Karplus [10], Korn and Korn [12], Rogers and Connolly [13], Levine [14], Scott [15], Small [21], and Mindell [22].

UCLA professor Walter Karplus wrote the definitive textbook on the application of analog computers to field problems [7]. Karplus also coauthored books on high-speed (repetitive) computers [8], general analog methods [9], and hybrid analog-digital computers [10]. After Karplus passed away in 2001, George Bekey and Boris Kogan organized a conference in his memory. The proceedings [11] includes several tributes.

As the field of hybrid computation developed, Korn and Korn updated their popular text to include hybrid computers [12]. In addition, the well-known book by Bekey and Karplus [10] provides a discussion of hybrid techniques and components, as well as eight chapters on applications, including a chapter on flight simulation by Robert Howe.

The McGraw-Hill Series

In the late 1950s and 1960s, McGraw-Hill published the *McGraw-Hill Series in Information Processing and Computers*. Although most of the books in the series cover digital-computing topics, the early volumes include several analog books, such as the aforementioned text by Karplus [7]. Rogers (of EAI) and T.W. Connolly (of Sperry Gyroscope) wrote a book on industrial applications [13]. The text by Leon Levine [14] emphasizes problem solving. Oddly, the half-analog, half-digital book by Norman Scott [15] makes no mention of hybrid computers.

Secondary Sources for History

Interest in the history of a field is a sign of the field's maturity [16], [17]. While the field of analog computing was overtaken by digital computing, and thus never reached maturity in its own time, the appreciation of its importance to the development of computing and control has matured over the past two dozen years. Several resources are recommended for further research.

Articles in *IEEE Annals of the History of Computing* have covered many related topics, including Philbrick's first process simulator [18], gun-director development at Bell Labs [19], and Helmut Hoelzer's analog machines in Germany [20]. In addition, two special issues of the *Annals*, in 1993 (vol. 15, no. 2) and 1996 (vol. 18, no. 4), are dedicated to analog computing. The 1993 issue includes three articles covering general-purpose electronic analog computers, mechanical computers for the U.S. Navy, and an electrical analog model built by Westinghouse. The 1996 issue contains six articles with extensive coverage of mechanical differential analyzers around the world.

More recently, James Small's book [21] covers the development and commercialization of electronic analog computers in the United States and Britain. He covers the heyday of analog computing in the postwar period and fully refutes the notion that analog computers were a "failed technology." David Mindell's book [22] focuses on the development of control systems for gun directors in WWII, which he traces back to the analog-computing efforts of Vannevar Bush, Bell Labs, and Sperry Gyroscope. Reviews of Small's book and Mindell's book appeared in the August 2003 issue of *IEEE Control Systems Magazine* [23], [24].

Primary references on analog computing can be found in the original journals, of course, and also in two noteworthy collections. MIT professor Henry Paynter collected papers, including several of historical interest, for a palimpsest [25] published by George A. Philbrick Researches. (Paynter gave a keynote address on the history of analog computing at the 1989 American Control Conference, the text of which was printed in the December 1989 issue of *IEEE Control Systems Magazine* [26].) John McLeod edited a collection of articles [27] from the journal *Simulation*, which includes a forward by Korn and papers by Ragazzini, Howe, Rogers, Karplus, Bekey, and many others.

The original, classic op-amp manual from Philbrick [28] was recently republished online by Analog Devices, Inc. [29]. It contains a wealth of applications information from the early days of op-amp use. Finally, Doug Coward's Web site, the "Analog Computer Museum and History Center" [30], includes numerous pictures of vintage machines and an extensive bibliography of books, manuals, and technical reports.

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Why Analog?

A dozen years ago, I was flipping through a magazine, and I came across an interesting advertisement. It had a picture of a beautiful rose, and it said

"The world, as everyone knows, is analog."

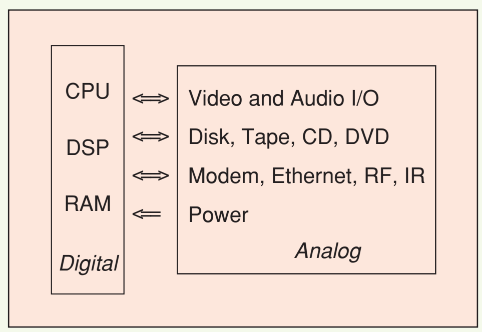
On the second page, there was another picture, with the line,

"Unless, of course, it's digital."

This ad is good, and bad, and horrible. It's good because I still remember it more than a decade later. It's bad because I don't remember what they were selling. Even worse, it's horrible because they got it completely wrong.

There is a perceived competition between "analog" and "digital," but this "competition" is a complete fallacy. Digital circuits rule the world. No one can deny the computational power of desktop computers, laptops, cell phones, embedded digital signal processors, and all the digital building blocks that make them possible. The ever-increasing capability implied by Moore's Law is a fantastic and intoxicating thing. However, a completely digital computer would be completely useless.

A completely digital computer is an academic curiosity; it's a boat anchor. To make a computer useful, we need video and audio inputs and outputs, which are analog. We need magnetic and optical storage systems, which require analog interfaces. We need wire-line and wireless networking, which require analog transmitters and receivers. Even the power supply is an analog system. The analog pieces of the computer make it useful:



Analog circuits allow you to listen to music and make your iPod more than a pretty white paperweight. Analog circuits make your cell phone ring. Analog circuits store your photos and charge your battery. You can build an entirely analog computer (as discussed in this issue), but you can't build an entirely digital computer. Here's what the ad should have said:

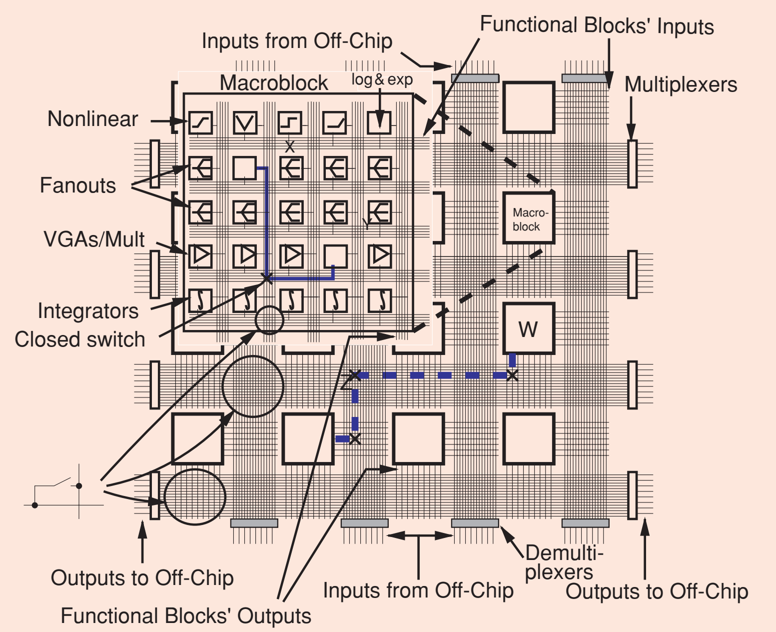
The world, as everyone knows, is analog.
Unless, of course, it's a hybrid analog/digital system,
which requires an enormous variety
of essential analog pieces.

But that's not as catchy.

Analog Computers Still Have Much to Offer

The field of analog computing remains an active research area. Researchers at Columbia University recently fabricated a general-purpose analog computer on a modern VLSI chip [1]. The complete integrated circuit includes 80 integrators, 80 variable-gain amplifiers (VGAs) that serve as multipliers, as well as 96 nonlinear function blocks. With these components, the chip can solve nonlinear differential equations up to the 80th order. The architecture of the analog computer is shown in the figure to the right. Testing of the chip demonstrates solution accuracies of 2%, with simulation speeds up to 400 times faster than a high-end workstation running MATLAB.

The analog computer provides fast approximate solutions to many types of simulation problems, with guaranteed convergence to physical solutions. One potential application of the chip is to act as a math coprocessor in a digital computer, improving the speed and convergence of numerical algorithms. An approximate solution from the analog computer can be used as the starting point for a high-accuracy numerical simulation, reducing the time needed for the algorithm to converge to the final result.



Block diagram of the analog-computer integrated circuit developed by Cowan, Melville, and Tsividis. The function blocks are divided into a 4 × 4 array of macroblocks, as shown in the detail. Crosspoint switches route signals from the function blocks around the chip to other blocks, allowing the analog computer to be quickly programmed to solve differential equations. The figure shows the output of block X patched to the input of block Y and the output of macroblock W patched to the input of macroblock Z.

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States and the United Kingdom. He concludes with some personal recollections of the use—and the cost—of analog computers at Manchester in research and education.

The final three articles highlight some current activities with analog computers in education and reconstruction. The article by Ray Spiess, president and founder of Comdyna, Inc., discusses the development and educational impact of the Comdyna GP-6, an analog computer that is still in production and is widely used in control education. The GP-6 recently appeared in the pages of this magazine [19]. Spiess relates several testimonials describing this analog computer's current use in education and research.

Tim Robinson [20] traces the history of mechanical differential analyzers, and in particular, those analyzers built from Meccano kits. He follows the trail from Vannevar Bush in the United States, to Hartree, Porter, and others in England, and around the world to New Zealand. We conclude with a second article by Robinson, describing his award-winning differential-analyzer reconstruction efforts.

We hope you find these articles interesting, enlightening, and entertaining.

Acknowledgments

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Playing Catch Up

At project Cyclone digital computers were, from time to time, used to verify the accuracy of results from the analog computer. In a typical application, such as the simulation of a guided missile in three dimensions, the average runtime for a single solution on the analog computer facility was approximately one minute. The check solution by numerical methods on an IBM CPC took 75 hours to run, on an Elecom 100 it took from 60 to 130 hours to solve the same problem.

—James S. Small, "General-purpose electronic analog computing: 1945–1965," *IEEE Annals of the History of Computing*, vol. 15, no. 2, p. 11, 1993.