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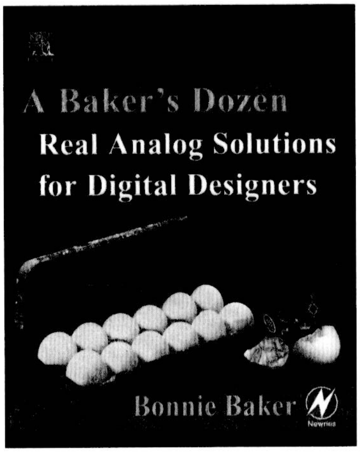

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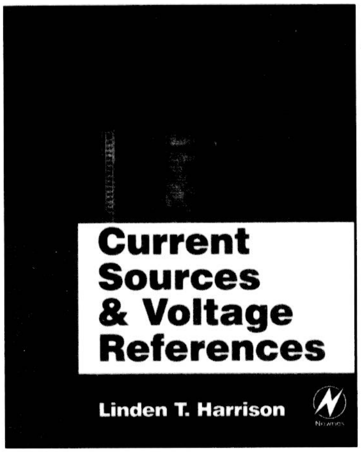

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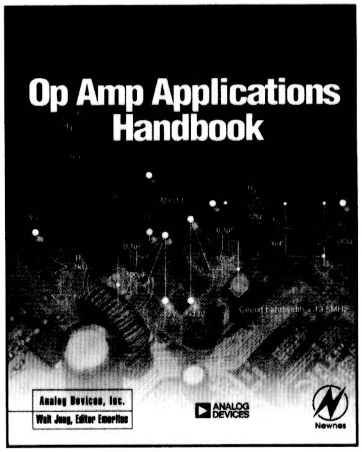

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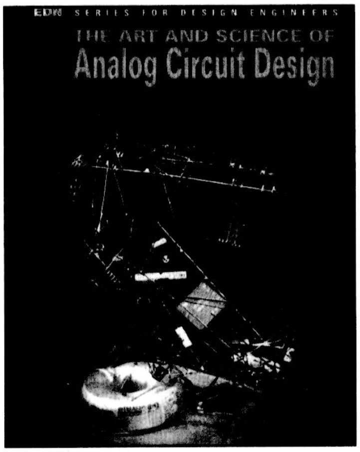

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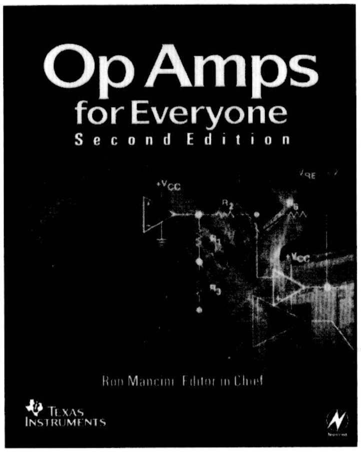

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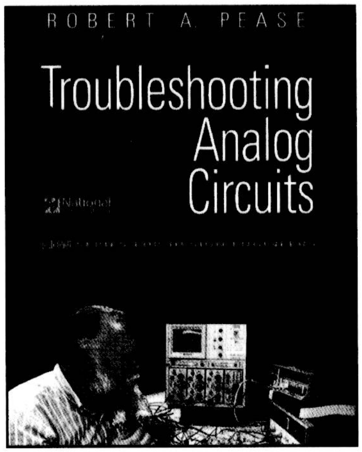

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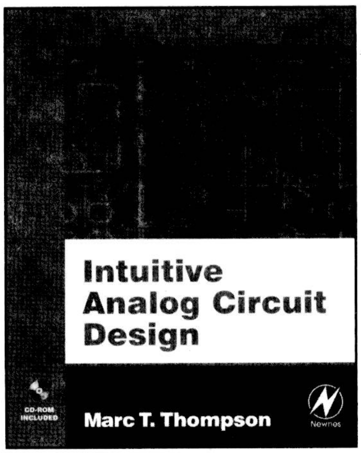

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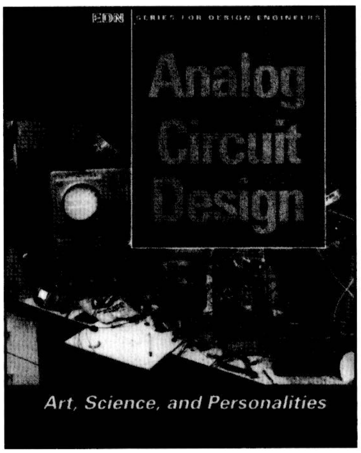

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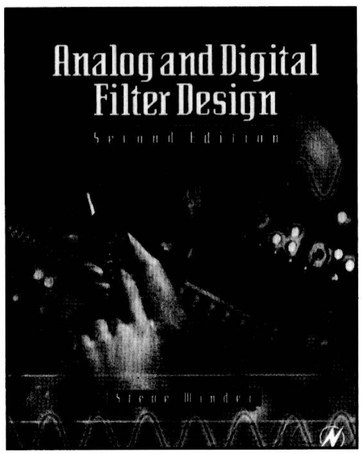

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Preface

Comments on "World-Class" Analog Design

Achieving excellence in analog circuit design has always been challenging. These days it is still not always easy, so we want to help with some general advice. All the authors of these chapters have presented their best ideas as the kinds of things a good analog circuit designer must know to consistently accomplish very good circuits.

These days so much of analog circuit design can be done using operational amplifiers (op-amps) with a small number of discrete resistors and capacitors. It is often very easy to slap in resistors and the circuit works well. However, this is still not trivial. You might have to pick sets of matched resistors or add a trimpot. Even these days some young engineers have to ask, "So, should I make a 1-ohm/1-ohm unity-gain inverter?" Some kids really don't know how to pick appropriate resistor values; they have never done any practical work or lab work. So we have to teach them about practical circuits. We have to teach them about error budgets. Sometimes 1% resistors are quite appropriate; other times 5%, 10%, 0.1%, or 0.01% might be right. Richard Burwen has good comments on resistors. More on error budgets later.

Recently a guy showed me his design with eight precision op-amps and sixteen precision resistors. After I did some whittling out, we got it down to two precision resistors and one precision op-amp and a greatly improved error budget. More on error budgets later.

Once upon a time, in the 1950s, there were no operational amplifiers that you could buy. The engineers at Philbrick Researches wrote a twenty-eight-page *Applications Manual for Octal Plug-In Computing Amplifiers* (such as the K2-W, see **Figure P-1**). With a little advice from this pamphlet, you could design analog computing circuits and some simple instrumentation, too. I came to work at Philbrick about that time (1960). I studied operational amplifiers based on vacuum tubes and then high-performance solid-state amplifiers.

Applications Notes

Then about 1965, the new arts and applications using transistorized op-amps showed the need for a comprehensive *Applications Manual for Computing Amplifiers for Modeling,*

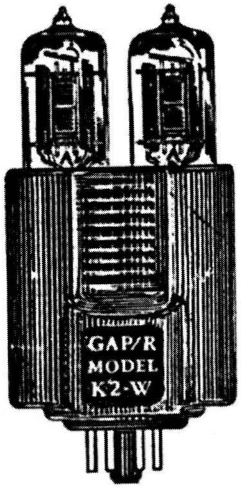

Figure P-1: Philbrick K2-W, 1952 to 1992.

Measuring, Manipulating, and Much Else. Dan Sheingold, George Philbrick, Bruce Seddon, and several others wrote a lot. I contributed a small bit. This book was *very* useful. My theory is that when Bob Widlar brought out the μA709, he couldn't have *given* it away, but Philbrick had sold and given away many thousands of these books, which made it reasonably easy to apply those IC op-amps. This book was sold for several years for $3. Recently, a good copy sold on e-bay for $300+. It's darn near worth it. Can you get the basic info off the Web? I'll have to look it up on Analog Devices' Website.

Other companies such as Burr Brown, Analog Devices, and TI wrote lots of App Notes and books on op-amp applications. I was never very impressed with them; they were not good explainers. NSC published lots of App Notes. Not all were well documented, but they were pretty good circuits.

Which Op-Amp?

Even for experienced engineers, this can be a bewildering question. There are many low-voltage and high-voltage op-amps; low-voltage noise and high-voltage noise; low-power and high-speed amplifiers; and cheap and expensive ones. Let's see what insights Bonnie Baker can offer.

Precision Capacitors?

How many kid engineers know the price of 1% capacitors? Precision capacitors are rarely justifiable. Yet not all 1% capacitors are really high priced. Sometimes a dime will get you that; other times, it could take a dollar or two. And sometimes a circuit really does *need* 1% capacitors. I just got a *thick* Digikey Catalog the other day, and it has 2% and 1% tolerance polypropylene capacitors at surprisingly reasonable prices, even in small quantities!

Inductors?

Inductors are specialized animals that may be required for filters and for switch-mode regulators. Usually the designer of the switcher provides detailed advice on what to buy. If not, then designing with inductors, or redesigning to adjust the inductor type or values, is a special advanced area of expertise. Most schools don't teach much of this. The design of switchers can be either a high-tech specialty or a monkey-see, monkey-do exercise. The latter might not be as cheap, but it usually does work well.

Diodes

Diodes can be a truly bewildering field. Some can carry small milliamperes; some can leak less than a picoampere; some rectifiers can carry amperes without overheating. But the big ones (such as 1N4005) often cannot be used at high frequencies. The 2N5819 Schottky rectifier can carry a couple amperes, but it is somewhat leaky. Still, it can rectify up to 1 MHz without misbehaving. Who's going to teach everybody about diodes?

Especially tricky is the fact that some good, fast small-signal diodes (1N4148/1N914) do turn on and off quickly—faster than 1 nanosecond sometimes—but at low rep rates, some of them sort of forget how to turn on and have a bad overshoot. That's annoying.

Transistors and Designing With Them

Now, when you get to transistors, this becomes complicated. Designing with transistors is a whole 'nother game. Even experienced analog designers try to minimize that when they can. But sometimes you have to use transistors. Sometimes the transistor's inherent log characteristics are very important. Can you buy a logger? Yes, several companies make and sell loggers. But loggers can be designed for special cases, which a store-bought logger cannot handle, such as low voltage. I've done a couple of these in the last year. I still design low-noise and high-speed amplifiers occasionally using selected transistors, such as 2N3904 and LM394. I often use the curves from "What's All This V_{BE} Stuff, Anyhow?" Or you might merely need to use a transistor as a switch—a crude one or a precision switch.

Filters

When you need a filter, it might not be hard to figure out what is needed; other times more research is needed. Can you avoid inductors? Can you avoid expensive op-amps?

Can you avoid high impedances *or* large capacitors? As with all of analog design, this covers a *huge* dynamic range, and there is usually nothing simple about it. Yet it gets done.

SPICE

I usually try to avoid using SPICE. I use pen and paper; I call it "back-of-envelope SPICE." I do mostly hand computations, and good approximations, using my slide rule or by doing the math in my head. You might say I am in agreement with Dick Burwen's chapter, "How to Design Analog Circuits Without a Computer." Other people think that SPICE is acceptable over a wide range of applications. That makes me nervous. I find that you can use SPICE to save an hour of computation every day for a month and then discover that SPICE has made a costly mistake that wastes all the time you thought you saved. Some people agree with me on that.

Also, when people use monolithic transistor models (such as the ones in the monolithic array, LM3046), that is different from designing with discrete transistors. I mean, who will give you a free model of a 2N3904 that is worth what you paid for it? And in what regimes do you trust it? I would trust it for *only* the crudest noncritical applications.

Some people say they like to trust SPICE. If they get good models and they know what they are doing, good luck to them.

I will mention a few particular places where SPICE models do not usually work well:

- At low values of *Vce* (or *Vds*), where the transistors are starting to saturate.
- At high frequencies at low values of *Vce* (or *Vds*), where the frequency response of the transistor does not ring true.
- Monolithic transistors are *often* badly modeled where they saturate (or start to saturate) since the substrate currents get large.
- Sometimes when an op-amp's inputs get reversed, it will still appear to work like an op-amp without saturating. *Some* kinds of SPICE do work right in this situation, but not all.
- If somebody gives you a bad model, you might have problems. Even when you make your own model, it could have problems.
- Sometimes SPICE fails to converge and wastes a lot of your time.
- Sometimes SPICE gives an absurd answer, such as saying that a 10 exp-25 ampere current step has a real risetime. How can a "current" that consists of 1 electron per day show a "risetime"?

- Usually in a band-gap reference, the fine details of a temperature characteristic do not go in the right direction. SPICE cannot lead you to a better answer. My old LM131 from 1977 had (and still has) a good tempco because it was based on good breadboards. When I tried to run it in SPICE many years later, SPICE said it did not work and could not be made to work. It's a good thing I didn't try it in SPICE in 1977. SPICE was wrong.
- In any circuit where transistors are heated or self-heated, the temp rise of the transistors is *very* hard to model, especially in a distributed layout.
- And sometimes SPICE just *lies*. Sometimes it just gives incorrect answers.

I've had debates with many "SPICE experts" and they try to tell me I am wrong. But I have seen too many cases where I was right and SPICE was wrong. I say this because people bring me their problems when their circuit does not work. I can see through the errors of SPICE; I use special test techniques (mostly in the time domain or in thought experiments) to show why a circuit is misbehaving. SPICE is not only *no help*, it leads to "computer-hindered design."

How Many?

How many are you going to build? If you are going to build large numbers or small, it makes a difference how you engineer it, for minimum overall cost and maximum output.

Low Noise?

Many general-purpose op-amps are pretty quiet, but some that are quiet at low impedance are noisy at high impedances. Others that are quiet at high impedance are noisy at low impedance. Let's see what comments Bonnie Baker has on this topic.

Troubleshooting?

Once you get your circuit built, you apply power and then it does (or does not) work correctly. How do you do the troubleshooting? Better yet, how do you plan in advance a way that you can easily do the needed troubleshooting?

Check out the Bob Pease book *Troubleshooting Analog Circuits*. With 39,000 copies in print in six languages, it has *legs*—and that's because analog circuit troubles do not go away by wishing and sometimes not even by engineering. Sometimes they are solved only by real troubleshooting. But planning ahead can help. See www.national.com/rap/Book/0,1565,0,00.html.

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The Future?

People often ask, "Would you encourage your son or daughter to go into engineering?" I reply, "Yes, if it is analog circuit design." They say, "Explain!"

I respond, "My friends and I know many analog design techniques, tricks, and secrets. They cannot be learned from SPICE. Every year there are 200,000 Chinese engineering graduates, and they don't know what we know. We can solve problems they cannot."

I rest my case. /rap

—Robert A. Pease
Staff Scientist, NSC
Santa Clara, CA
August 2007
rap@galaxy.nsc.com

P.S. One of the authors of a chapter in this book said that he took a "well-designed" system and put a good model of it into SPICE. When he ran it, he was surprised to find a sneaky sampling error. So we should not say that SPICE cannot be helpful. We just have to be cautious about trusting SPICE—in any positive or negative way.

About the Editor

Robert A. Pease (Chapters 16, 17, and Appendix B)

Robert A. Pease attended Mt. Hermon School, and graduated from MIT in 1961 with a BSEE. He worked at Philbrick Researches up to 1975 and designed many OpAmps and Analog Computing Modules.

He joined National Semiconductor in 1976. He has designed about 24 analog ICs including power regulators, voltage references, and temp sensors. He has written 65+ magazine articles and holds about 21 US patents. Pease is the self-declared Czar of Bandgaps since 1986. He enjoys hiking and trekking in Nepal, and ferroequinology. His position at NSC is Staff Scientist. He is a Senior Member of the IEEE.

Pease wrote the definitive book, "Troubleshooting Analog Circuits", now in its 18th printing. It has been translated into French, German, Dutch, Russian, and Polish. Pease is a columnist in *Electronic Design* magazine, with over 240 columns published. The column, "Pease Porridge", covers a wide range of technical topics.

He also has posted many technical and semi-technical items on his main web-site: http://www.national.com/rap. Many of Pease's recent columns are accessible there.

Pease was inducted into the E.E. Hall Of Fame in 2002. Refer to: http://www.elecdesign.com/Articles/Index.cfm?ArticleID=17269&Extension=pdf. See Pease's other web site at http://www.transtronix.com. He can be contacted at rap@galaxy.nsc.com.

P.S. Pease is also the self-declared Czar of Proofreading, for ~20 years. He has proofread several books and many technical articles. Without his sharp eye, this book would have been hard to bring out with fully accurate information, as there are so many opportunities for errors in a technical document of this magnitude.

About the Authors

Bonnie Baker (Chapters 4, 8, 13, 14, 15, and Appendix A) writes the monthly "Baker's Best" for *EDN* magazine. She has been involved with analog and digital designs and systems for over 20 years. Bonnie started as a Manufacturing Product Engineer supporting analog products at Burr-Brown. From there, Bonnie moved up to IC Design, Analog Division Strategic Marketer, and then Corporate Applications Engineering Manager. In 1998, she joined Microchip Technology and served as their analog division Analog/mixed signal Applications Engineering manager and Staff Architect Engineer for one of their PICmicro divisions. This expanded her background to not only include analog applications, but also the microcontroller. She is now, back in the Burr-Brown fold, working for Texas Instruments in their Precision Analog Division.

Along with her expertise in analog design, Bonnie has a drive to share her knowledge and experience and has written over 250 articles, design notes, and application notes. In addition to being an *EDN* columnist, she is also a frequent presenter at technical conferences and shows.

Richard S. Burwen (Chapter 9) received a S.B. (cum laude) in physics in 1949 and an A.M. in engineering sciences and applied physics in 1950 from Harvard. He was one of three founders of Analog Devices and worked as a consultant to the company, designing several of the circuits for its initial product lines. Other companies with which he was associated in their beginning phases included Mark Levinson Audio Systems, Cello Ltd., Novametrix Medical Systems, and KLH Burwen Research. He became a founder of Copley Controls in 1984 and designed many of the company's products. In the case of all the companies he helped start, Richard maintained his independence by working as a consultant in his own laboratory. He designed his home and laboratory in 1965, in Lexington, Massachusetts, around his 20,000 watt, 169-speaker, 5-channel recording and reproducing studio. Since retiring from circuit design consulting in 2002, he has been even more active consolidating his 63 years of audio development into audio digital signal processing software described at www.burwenaudio.com and www.burwenbobcat.com.

Sergio Franco (Chapter 12) is a professor of electrical engineering at San Francisco State University, where he teaches microelectronics courses and acts as an industry consultant. Prior to assuming his current professorship, Sergio was employed at Zeltron, Zanussi's Electronics Institute (Udine, Italy). He received a B.S. in physics from the University of Rome, a M.S. in physics from Clark University, and a Ph.D. in computer science from the University of Illinois. Sergio is a member of the IEEE, and in his spare time enjoys classical music, gardening, and mountain hiking.

Phil Perkins (Chapter 2) is a Fellow of LTX Corporation, Norwood, Massachusetts. He was a cofounder of LTX in 1976. Before LTX he was an engineer at Teradyne, Inc., Boston, Massachusetts. His work includes designing analog instrumentation for the LTX semiconductor test systems. His designs include V/I Sources, Test Heads, and DSP measuring instruments. He holds a patent for "Mixed signal device under test board interface". He received Bachelor's, Master, and Engineer degrees in Electrical Engineering from Massachusetts Institute of Technology.

Phil's interests include walking in the woods looking for wildflowers, church activities, home computer hobbying plus consulting for friends. He lives in Needham, Massachusetts with his lovely wife, Laurie. Phil can be contacted at phil_perkins@ltx.com.

Dr. Marc Thompson (Chapters 1, 3, and 5) was born on Vinalhaven Island, Maine. He specializes in custom R/D, analysis, and failure investigations into multi-disciplinary electrical, magnetic, and electronic systems at his engineering consulting company Thompson Consulting, Inc. in Harvard, Massachusetts. He is also an Adjunct Professor in the Electrical and Computer Engineering Department of Worcester Polytechnic Institute where he teaches graduate-level courses in advanced analog circuit design, power electronics, electric motors, and power distribution.

Dr. Thompson is author of a textbook entitled "Intuitive Analog Circuit Design", published in 2006 by Elsevier Science/Newnes. Another text entitled "Power Quality in Electronic Systems", was co-authored with Dr. Alexander Kusko, and was published by McGraw-Hill in 2007.

Dr. Thompson has seven U.S. patents and is a Firefighter with the Harvard, Massachusetts Fire Department, and has the B.S., M.S., and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology. In his spare time he enjoys biking, travel, and repairing his c. 1899 vintage house in Maine.

Jim Williams (Chapter 18) was at the Massachusetts Institute of Technology from 1968 to 1979, concentrating exclusively on analog circuit design. His teaching and research interests involved applications of analog circuit techniques to biochemical and biomedical problems.

Concurrently, he consulted for U.S. and foreign concerns and governments, specializing in analog circuits. In 1979, he moved to National Semiconductor Corporation, continuing his work in the analog area with the Linear Integrated Circuits Group. In 1982, he joined Linear Technology Corporation as staff scientist, where he is presently employed. Interests include product definition, development, and support. Jim has authored over 350 publications relating to analog circuit design. Awards include the 1992 Innovator of the Year Award from *EDN* magazine and election to the Electronic Design Hall of Fame in 2002.

His spare-time interests include sports cars, collecting antique scientific instruments, art, and restoring and using old Tektronix oscilloscopes. He lives in Palo Alto, CA with his wife, son, and 84 Tektronix oscilloscopes.

Steve Winder (Chapters 6, 7, 10, and 11) is now a European Field Applications Engineer for Supertex Inc. Steve works alongside design engineers throughout Europe to design circuits using components made by Supertex, a US-based manufacturer of high voltage MOSFETs and CMOS ICs.

Prior to joining Supertex in 2002, Steve was, for many years, a team leader at British Telecom research laboratories. There he designed analog circuits for wideband transmission systems, mostly high frequency, and designed many active and passive filters.

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