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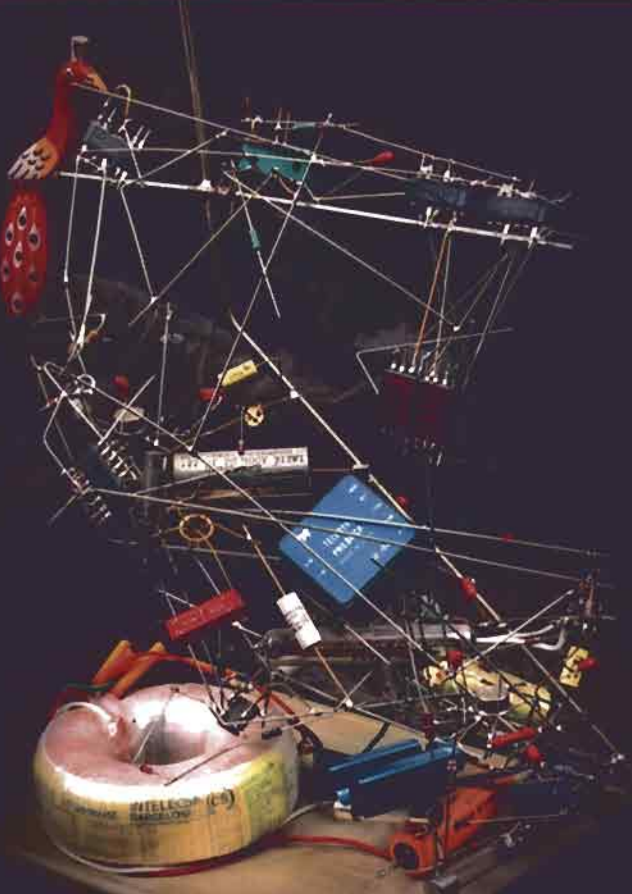
THE ART AND SCIENCE OF Analog Circuit Design



EDITED BY Jim Williams

The Art and Science of Analog Circuit Design

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The Art and Science of Analog Circuit Design

Edited by

Jim Williams

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Preface

This book continues the approach originated in an earlier effort, "Analog Circuit Design—Art, Science, and Personalities." In that book twenty-six authors presented tutorial, historical, and editorial viewpoints on subjects related to analog circuit design. The book encouraged readers to develop their own approach to design. It attempted this by presenting the divergent methods and views of people who had achieved some measure of success in the field. A complete statement of this approach was contained in the first book's preface, which is reprinted here (immediately following) for convenience.

The surprisingly enthusiastic response to the first book has resulted in this second effort. This book is similar in spirit, but some changes have occurred. The most obvious difference is that almost all contributors are new recruits. This seems a reasonable choice: new authors with new things to say, hopefully augmenting the first book's message.

Although accomplished, some of this book's writers are significantly younger and have less experience at analog design than the previous book's authors. This is deliberate, and an attempt to maintain a balanced and divergent forum unencumbered by an aging priesthood.

A final difference is the heavy capitalistic and marketeering influence in many of the chapters. This unplanned emphasis is at center stage in sections by Grant, Williams, Brown, and others, and appears in most chapters. The influence of economics was present in parts of the earlier book, but is much more pronounced here. The pristine pursuit of circuit design is tempered by economic realities, and the role of money as design motivator and modulator is undeniable.

We hope this book is as well received as the earlier effort, even as it broadens the scope of topics and utilizes new authors. As before, it was fun to put together. If we have done our job, it should be rewarding for the reader.

Preface to "Analog Circuit Design—Art, Science, and Personalities"

This is a weird book. When I was asked to write it I refused, because I didn't believe anybody could, or should, try to explain how to do analog design. Later, I decided the book might be possible, but only if it was written by many authors, all with their own styles, topics, and opinions.

There should be an absolute minimum of editing, no subject or style requirements, no planned page count, no outline, no nothing! I wanted the book's construction to reflect its subject. What I asked for was essentially a mandate for chaos. To my utter astonishment the publisher agreed and we lurched hopefully forward.

A meeting at my home in February 1989 was well attended by potential participants. What we concluded went something like this: everyone would go off and write about anything that could remotely be construed as relevant to analog design. Additionally, no author would tell any other author what they were writing about. The hope was that the reader would see many different styles and approaches to analog design, along with some commonalities. Hopefully, this would lend courage to someone seeking to do analog work. There are many very different ways to proceed, and every designer has to find a way that feels right.

This evolution of a style, of getting to know oneself, is critical to doing good design. The single greatest asset a designer has is self-knowledge. Knowing when your thinking feels right, and when you're trying to fool yourself. Recognizing when the design is where you want it to be, and when you're pretending it is because you're only human. Knowing your strengths and weaknesses, prowesses and prejudices. Learning to recognize when to ask questions and when to believe your answers.

Formal training can augment all this, but cannot replace it or obviate its necessity. I think that factor is responsible for some of the mystique associated with analog design. Further, I think that someone approaching the field needs to see that there are lots of ways to do this stuff. They should be made to feel comfortable experimenting and evolving their own methods.

The risk in this book, that it will come across as an exercise in discord, is also its promise. As it went together, I began to feel less nervous. People wrote about all kinds of things in all kinds of ways. They had some very different views of the world. But also detectable were commonalities many found essential. It is our hope that readers will see this somewhat discordant book as a reflection of the analog design process. Take what you like, cook it any way you want to, and leave the rest.

Things wouldn't be complete without a special thanks to Carol Lewis and Harry Helms at High Text Publications, and John Martindale at Butterworth–Heinemann Publishers. They took on a book with an amorphous charter and no rudder and made it work. A midstream change of publishers didn't bother Carol and Harry, and John didn't seem to get nervous over a pretty risky approach to book writing.

I hope this book is as interesting and fun to read as it was to put together. Have a good time.

Contributors

Jim Williams is the editor-in-chief of this second volume on analog circuit design. As with the first volume, Jim developed the basic concept of the book, identified, contacted, and cajoled potential contributors, and edited the contributions. Jim was at the Massachusetts Institute of Technology from 1968 to 1979, concentrating exclusively on analog circuit design. His teaching and research interests involved application of analog circuit techniques to biochemical and biomedical problems. Concurrently, he consulted 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 250 publications relating to analog circuit design. He received the 1992 Innovator of the Year Award from *EDN* Magazine for work in high-speed circuits. His spare time interests include sports cars, collecting antique scientific instruments, art, and restoring and using old Tektronix oscilloscopes. He lives in Palo Alto, California with his son Michael, a dog named Bonillas, and 28 Tektronix oscilloscopes.

Carl Battjes has worked in the analog design of systems with a focus on detailed design at the bipolar transistor device and bipolar IC level. He has been involved in the design of Tektronix, Inc. oscilloscopes and their components, such as delay lines, filters, attenuators, and amplifiers. For the Grass Valley Group, he developed a precision analog multiplier for video effects. Carl has been a consultant for over ten years and has done major detailed designs for the Tektronix 11A72 pre-amp IC, Seiko message watch receiver IC, and IC for King Radio (Allied Signal) receiver. A registered Professional Engineer in Oregon who holds seven patents, he has a BSEE from the University of Michigan and an MSEE from Stanford University.

James Bryant is head of European applications at Analog Devices. He lives in England and is a Eur. Ing. and MIEE and has degrees in philosophy and physics from the University of Leeds. He has over twenty years' experience as an analog and RF applications engineer and is well known as a lecturer and author. His other interests include archery, cooking, ham radio (G4CLF), hypnotism, literature, music, and travel.

Art Delagrange, when he was young, took his electric train apart and reassembled it by himself. Since that day, it has not run. He attended MIT, where he studied digital circuitry, receiving a BS/MS in electrical engineering in 1961/62. During his graduate year he worked on a hybrid digital/analog computer. It did not revolutionize the industry. Beginning as a co-op student, he worked for 33 years for the Naval Surface Warfare Center in Silver Spring, Maryland. Among his other achievements are a PhD in electrical engineering from the University of Maryland, ten patents, and 23 articles in the open literature. Retired from the government, he works for Applied Technology and Research in Burtonsville, Maryland. Art lives in Mt. Airy, Maryland, with his wife, Janice, and his cat, Clumsy. His hobbies are cars, boats, sports, music, and opening packages from the wrong end.

Richard P. Feynman was professor of physics at the California Institute of Technology. He was educated at MIT and Princeton, and worked on the Manhattan Project during World War II. He received the 1965 Nobel Prize in Physics for work in quantum electrodynamics. His life and style have been the subject of numerous biographies. He was an uncommonly good problem solver, with notable ability to reduce seemingly complex issues to relatively simple terms. His *Feynman Lectures on Physics,* published in the 60s, are considered authoritative classics. He died in 1988.

Barrie Gilbert has spent most of his life designing analog circuits, beginning with four-pin vacuum tubes in the late 1940s. Work on speech encoding and synthesis at the Signals Research and Development Establishment in Britain began a love affair with the bipolar transistor that shows no signs of cooling off. Barrie joined Analog Devices in 1972, where he is now a Division Fellow working on a wide variety of IC products and processes while managing the Northwest Labs in Beaverton, Oregon. He has published over 40 technical papers and been awarded 20 patents. Barrie received The IEEE Outstanding Achievement Award in 1970, was named an IEEE Fellow in 1984, and received the IEEE Solid-State Circuits Council Outstanding Development Award in 1986. For recreation, Barrie used to climb mountains, but nowadays stays home and tries to write music in a classical style for performance on a cluster of eight computer-controlled synthesizers and other toys.

Doug Grant received a BSEE degree from the Lowell Technological Institute (now University of Massachusetts–Lowell) in 1975. He joined Analog Devices in 1976 as a design engineer and has held several positions in engineering and marketing prior to his current position as marketing manager for RF products. He has authored numerous papers and articles on mixed-signal and linear circuits, as well as his amateur radio hobby.

Bill Gross is a design manager for Linear Technology Corporation, heading a team of design engineers developing references, precision amplifiers, high-speed amplifiers, comparators, and other high-speed products. Mr. Gross has been designing integrated circuits for the semiconductor industry for 20 years, first at National Semiconductor, including three years living and working in Japan, and later at Elantec. He has a BSEE from California State Polytechnic University at Pomona and an MSEE from the University of Arizona at Tucson. He is married and the father of two teenage sons, whose sports activities keep him quite busy.

Barry Harvey is a designer of bipolar analog integrated circuits at Elantec, Inc. His first electronic projects were dismantling vacuum tube television sets as a child and later in life rebuilding them. These days he tortures silicon under a microscope.

Gregory T.A. Kovacs received a BASc degree in electrical engineering from the University of British Columbia, Vancouver, British Columbia, in 1984; an MS degree in bioengineering from the University of California, Berkeley, in 1985; a PhD degree in electrical engineering from Stanford University in 1990; and an MD degree from Stanford University in 1992. His industry experience includes the design of a wide variety of analog and mixed-signal circuits for industrial and commercial applications, patent law consulting, and the co-founding of three electronics companies. In 1991, he joined Stanford University as Assistant Professor of Electronic Engineering, where he teaches analog circuit design and micromachined transducer technologies. He holds the Robert N. Noyce Family Faculty Scholar Chair, received an NSF Young Investigator Award in 1993, and was appointed a Terman Fellow in 1994. His present research areas include neural/electronic interfaces, solid-state sensors and actuators, micromachining, analog circuits, integrated circuit fabrications, medical instruments, and biotechnology.

Carl Nelson is Linear Technology's Bipolar Design Manager. He has 25 years in the semiconductor IC industry. Carl joined Linear Technology shortly after the company was founded. He came from National Semiconductor and before that worked for Teledyne Semiconductor. He has a BSEE from the Northrup Institute of Technology. He is the designer of the first temperature-sensor IC and is the father of the LT1070/1270 family of easy-to-use switching regulators. He holds more than 30 patents on a wide range of analog integrated circuits.

Robert Reay became an analog designer after discovering as a teenager that the manual for his Radio Shack electronics kit didn't describe how any of the circuits really worked. His scientific curiosity and realization that he wasn't going to make any money as a pianist led him to Stanford University, where he earned his BSEE and MSEE in 1984. He worked for Intersil, designing data conversion products, for four years before Maxim hired away most of the design team. He is currently managing a group of designers at Linear Technology Corporation, doing interface circuits, battery chargers, DACs, references, comparators, regulators, temperature sensors, and anything else that looks interesting. He regularly plays roller blade hockey with the kids in the neighborhood and is helping his children discover the beauty of a Chopin waltz and a well-designed circuit.

Steve Roach received his BS in engineering physics from the University of Colorado in 1984 and his MS in electrical engineering from Ohio State University in 1988. He worked from 1984 to 1986 as a software engineer for Burroughs Corporation and from 1988 to 1992 at Hewlett-Packard Company, designing digital oscilloscopes. From 1992 to 1994, Stephen designed industrial sensors at Kaman Instrumentation Company. He is currently designing digital oscilloscopes for Hewlett-Packard. His hobbies include backpacking, hunting, off-road motorcycling, and tutoring kids at the Boys' and Girls' Club.

Keitaro Sekine received his BE, ME, and Dr. Eng. degrees in electronics from Waseda University in 1960, 1962, and 1968, respectively. Since 1969, he has been with the Faculty of Science and Technology, Science University of Tokyo, where he is now a professor in the Department of Electrical Engineering. His main research interests are in analog integrated circuits and their application systems. His interests in the physical aspects of analog circuits, such as implementation, mutual electro-magnetic couple within the circuits, and EMC, originated from the experiments at his own amateur radio station, which he has had since 1957. He has been chair of the Committee for Investigative Research and Committee on Analog Circuit Design Technologies at the Institute of Electrical Engineers of Japan (IEEJ) and also a member of the Editorial Committee for the Transactions of IEICE Section J-C. He is now president of the Society for Electronics, Information, and System at the IEEJ, as well as a member of the Board of Directors at the Japan Institute of Printed Circuit (JIPC). Dr. Sekine is a member of the Institute of Electrical and Electronics Engineers, the IEEJ, and the JIPC.

Eric Swanson received his BSEE from Michigan State University in 1977 and his MSEE from Cal Tech in 1980. From 1980 to 1985 he worked on a variety of analog LSI circuits at AT&T-Bell Laboratories in Reading, Pennsylvania. In 1985 he joined Crystal Semiconductor in Austin, Texas, where he is currently Vice President of Technology. His development experience includes millions of CMOS transistors, a few dozen bipolar transistors, and nary a vacuum tube. Eric holds 20 patents, evenly divided between the analog and digital domains, and continues to design high-performance data converters. He enjoys swimming and biking with his wife Carol and four children.

John Willison is the founder of Stanford Research Systems and the Director of R&D. Considered a renegade for having left "pure research" after completing a PhD in atomic physics, he continues to enjoy designing electronic instruments in northern California. Married with four children, he's in about as deep as you can get.

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Part One

Learning How

The book's initial chapters present various methods for learning how to do analog design. Jim Williams describes the most efficient educational mechanism he has encountered in "The Importance of Fixing." A pair of chapters from Barry Harvey emphasize the importance of realistic experience and just how to train analog designers. Keitaro Sekine looks at where future Japanese analog designers will come from. He has particularly pungent commentary on the effects of "computer-based" design on today's students. Similar concerns come from Stanford University professor Greg Kovacs, who adds colorful descriptions of the nature of analog design and its practitioners. Finally, Nobel prize-winning physicist Richard P. Feynman's 1974 Cal Tech commencement address is presented. Although Feynman wasn't an analog circuit designer, his observations are exceptionally pertinent to anyone trying to think clearly about anything.

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1. The Importance of Fixing

Fall 1968 found me at MIT preparing courses, negotiating thesis topics with students, and getting my laboratory together. This was fairly unremarkable behavior for this locale, but for a 20 year old college dropout the circumstances were charged; the one chance at any sort of career. For reasons I'll never understand, my education, from kindergarten to college, had been a nightmare, perhaps the greatest impedance mismatch in history. I got hot. The Detroit Board of Education didn't. Leaving Wayne State University after a dismal year and a half seemed to close the casket on my circuit design dreams.

All this history conspired to give me an outlook blended of terror and excitement. But mostly terror. Here I was, back in school, but on the other side of the lectern. Worse yet, my research project, while of my own choosing, seemed open ended and unattainable. I was so scared I couldn't breathe out. The capper was my social situation. I was younger than some of my students, and my colleagues were at least 10 years past me. To call things awkward is the gentlest of verbiage.

The architect of this odd brew of affairs was Jerrold R. Zacharias, eminent physicist, Manhattan Project and Radiation Lab alumnus, and father of atomic time. It was Jerrold who waved a magic wand and got me an MIT appointment, and Jerrold who handed me carte blanche a lab and operating money. It was also Jerrold who made it quite clear that he expected results. Jerrold was not the sort to tolerate looking foolish, and to fail him promised a far worse fate than dropping out of school.

Against this background I received my laboratory budget request back from review. The utter, untrammeled freedom he permitted me was maintained. There were no quibbles. Everything I requested, even very costly items, was approved, without comment or question. The sole deviation from this I found annoying. He threw out my allocation for instrument repair and calibration. His hand written comment: "You fix everything."

It didn't make sense. Here I was, under pressure for results, scared to pieces, and I was supposed to waste time screwing around fixing lab equipment? I went to see Jerrold. I asked. I negotiated. I pleaded, I ranted, and I lost. The last thing I heard chasing me out of his office was, "You fix everything."

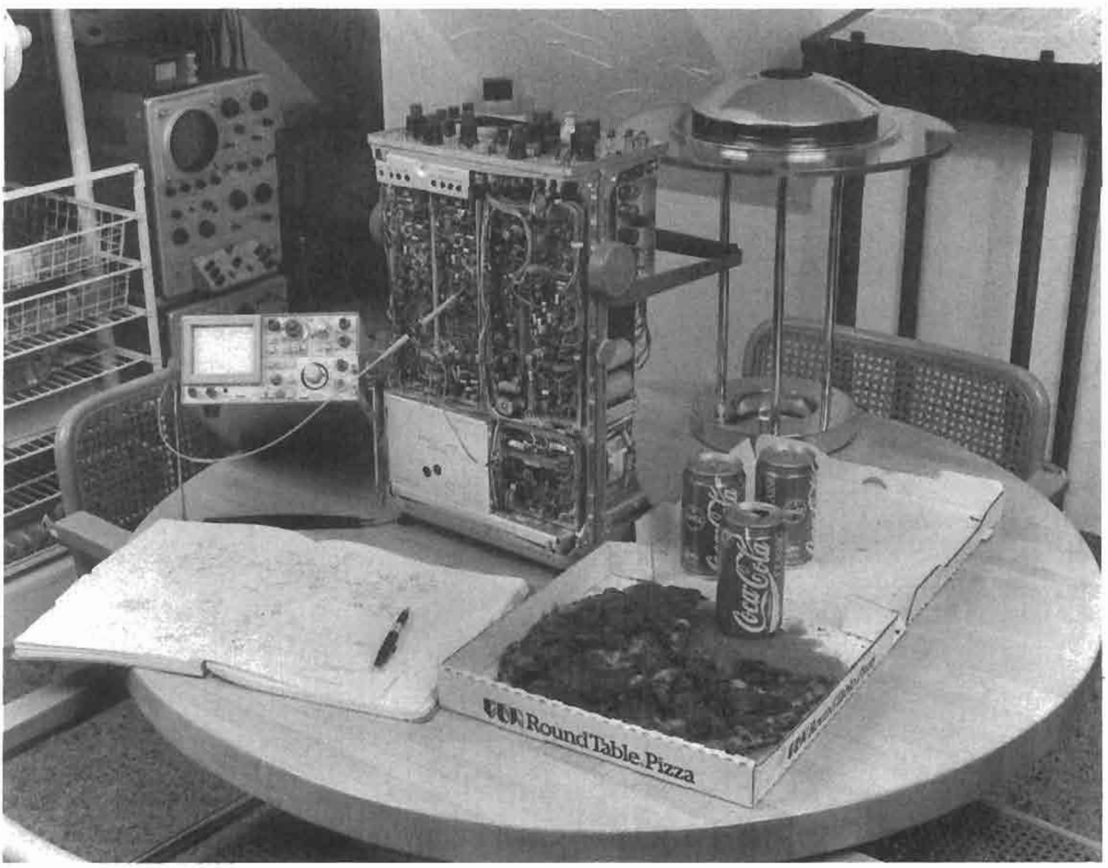
I couldn't know it, but this was my introduction to the next ten years. An unruly mix of airy freedom and tough intellectual discipline that would seemingly be unremittingly pounded into me. No apprenticeship was ever more necessary, better delivered, or, years later, as appreciated.

I cooled off, and the issue seemed irrelevant, because nothing broke for a while. The first thing to finally die was a high sensitivity, differential 'scope plug-in, a Tektronix 1A7. Life would never be the same.

The problem wasn't particularly difficult to find once I took the time to understand how the thing worked. The manual's level of detail and writing tone were notable; communication was *the* priority. This seemed a significant variance from academic publications, and I was impressed. The instrument more than justified the manual's efforts. It was gorgeous. The integration of mechanicals, layout, and electronics was like nothing I had ever seen. Hours after the thing was fixed I continued to probe and puzzle through its subtleties. A common mode bootstrap scheme was particularly interesting; it had direct applicability to my lab work. Similarly, I resolved to wholesale steal the techniques used for reducing input current and noise.

Over the next month I found myself continually drifting away from my research project, taking apart test equipment to see how it worked. This was interesting in itself, but what I really wanted was to test my

Figure 1–1. Oh boy, it's broken! Life doesn't get any better than this.



understanding by having to fix it. Unfortunately, Tektronix, Hewlett-Packard, Fluke, and the rest of that ilk had done their work well; the stuff didn't break. I offered free repair services to other labs who would bring me instruments to fix. Not too many takers. People had repair budgets . . . and were unwilling to risk their equipment to my unproven care. Finally, in desperation, I paid people (in standard MIT currency—Coke and pizza) to deliberately disable my test equipment so I could fix it. Now, their only possible risk was indigestion. This offer worked well.

A few of my students became similarly hooked and we engaged in all forms of contesting. After a while the "breakers" developed an armada of incredibly arcane diseases to visit on the instruments. The "fixers" countered with ever more sophisticated analysis capabilities. Various games took points off for every test connection made to an instrument's innards, the emphasis being on how close you could get utilizing panel controls and connectors. Fixing without a schematic was highly regarded, and a consummately macho test of analytical skill and circuit sense. Still other versions rewarded pure speed of repair, irrespective of method.[1] It really was great fun. It was also highly efficient, serious education.

The inside of a broken, but well-designed piece of test equipment is an extraordinarily effective classroom. The age or purpose of the instrument is a minor concern. Its instructive value derives from several perspectives.

It is always worthwhile to look at how the designer(s) dealt with problems, utilizing available technology, and within the constraints of cost, size, power, and other realities. Whether the instrument is three months or thirty years old has no bearing on the quality of the thinking that went into it. Good design is independent of technology and basically timeless. The clever, elegant, and often interdisciplinary approaches found in many instruments are eye-opening, and frequently directly applicable to your own design work. More importantly, they force self-examination, hopefully preventing rote approaches to problem solving, with their attendant mediocre results. The specific circuit tricks you see are certainly adaptable and useful, but not nearly as valuable as studying the thought process that produced them.

The fact that the instrument is broken provides a unique opportunity. A broken instrument (or anything else) is a capsulized mystery, a puzzle with a definite and very singular "right" answer. The one true reason why that instrument doesn't work as it was intended to is really there. You are forced to measure your performance against an absolute, non-negotiable standard; the thing either works or it doesn't when you're finished.

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1. A more recent development is "phone fixing." This team exercise, derived by Len Sherman (the most adept fixer I know) and the author, places a telephone-equipped person at the bench with the broken instrument. The partner, somewhere else, has the schematic and a telephone. The two work together to make the fix. A surprise is that the time-to-fix seems to be less than if both parties are physically together. This may be due to dilution of ego factors. Both partners simply must speak and listen with exquisite care to get the thing fixed.

The reason all this is so valuable is that it brutally tests your thinking process. Fast judgments, glitzy explanations, and specious, hand-waving arguments cannot be costumed as "creative" activity or true understanding of the problem. After each ego-inspired lunge or jumped conclusion, you confront the uncompromising reality that the damn thing still doesn't work. The utter closedness of the intellectual system prevents you from fooling yourself. When it's finally over, and the box works, and you know why, then the real work begins. You get to try and fix you. The bad conclusions, poor technique, failed explanations, and crummy arguments all demand review. It's an embarrassing process, but quite valuable. You learn to dance with problems, instead of trying to mug them.

It's scary to wonder how much of this sort of sloppy thinking slips into your own design work. In that arena, the system is not closed. There is no arbitrarily right answer, only choices. Things can work, but not as well as they might if your thinking had been better. In the worst case, things work, but for different reasons than you think. That's a disaster, and more common than might be supposed. For me, the most dangerous point in a design comes when it "works." This ostensibly "proves" that my thinking is correct, which is certainly not necessarily true. The luxury the broken instrument's closed intellectual system provides is no longer available. In design work, results are open to interpretation and explanation and that's a very dangerous time. When a design "works" is a very delicate stage; you are psychologically ready for the kill and less inclined to continue testing your results and thinking. That's a precarious place to be, and you have to be so careful not to get into trouble. The very humanness that drives you to solve the problem can betray you near the finish line.

What all this means is that fixing things is excellent exercise for doing design work. A sort of bicycle with training wheels that prevent you from getting into too much trouble. In design work you have to mix a willingness to try anything with what you hope is critical thinking. This seemingly immiscible combination can lead you to a lot of nowheres. The broken instrument's narrow, insistent test of your thinking isn't there, and you can get in a lot deeper before you realize you blew it. The embarrassing lessons you're forced to learn when fixing instruments hopefully prevent this. This is the major reason I've been addicted to fixing since 1968. I'm fairly sure it was also Jerrold's reason for bouncing my instrument repair allocation.

There are, of course, less lofty adjunct benefits to fixing. You can often buy broken equipment at absurdly low cost. I once paid ten bucks for a dead Tektronix 454A 150MHz portable oscilloscope. It had clearly been systematically sabotaged by some weekend-bound calibration technician and tagged "Beyond Repair." This machine required thirty hours to uncover the various nasty tricks played in its bowels to ensure that it was scrapped.

This kind of devotion highlights another, secondary benefit of fixing. There is a certain satisfaction, a kind of service to a moral imperative, that comes from restoring a high-quality instrument. This is unquestionably a gooey, hand-over-the-heart judgment, and I confess a long-term love affair with instrumentation. It just seems sacrilege to let a good piece of equipment die. Finally, fixing is simply a lot of fun. I may be the only person at an electronics flea market who will pay more for the busted stuff!

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2. How to Grow Strong, Healthy Engineers

Graduating engineering students have a rough time of it lately. Used to be, most grads were employable and could be hired for many jobs. Ten years ago and earlier, there were a lot of jobs. Now, there aren't so many and employers demand relevant course work for the myriad of esoteric pursuits in electrical engineering. Of those grads that do get hired, the majority fail in their first professional placement.

We should wonder, is this an unhealthy industry for young engineers? Well, I guess so. Although I am productive and comfortable now, I was not successful in my first three jobs, encompassing nine years of professional waste. Although I designed several analog ICs that worked in this period, none made it to market.

Let me define what I call professional success:

The successful engineer delivers to his or her employer at least 2½ times the yearly salary in directly attributable sales or efficiency. It may take years to assess this.

For many positions, it's easy to take this measure. For others, such as in quality assurance, one assays the damage done to the company for not executing one's duties. This is more nebulous and requires a wider business acumen to make the measure. At this point, let me pose what I think is the central function of the engineer:

Engineers create, support, and sell machines.

That's our purpose. A microprocessor is a machine; so is a hammer or a glove. I'll call anything which extends human ability a machine.

It doesn't stop with the designer: the manufacturing workers and engineers really make the machines, long-term. There's lots of engineering support, and all for making the machines and encouraging our beloved customers to buy them. Some people don't understand or savor this definition, but it's been the role of engineers since the beginning of the industrial revolution. I personally like it. I like the structure of business, the creation of products, the manufacture of them, and the publicizing of them. Our products are like our children, maybe more like our pets. They have lives, some healthy and some sickly. Four of my ICs have healthy, popular lives; ten are doing just OK; and six are just not popular in the market. Others have died.

A young engineering student won't ever hear of this in school. Our colleges' faculties are uneasy with the engineers' charter. The students don't know that they will be held to standards of productivity. They are taught that engineering is like science, sort of. But science need not provide economic virtue; engineering pursuits must.

So what is the state of engineering for the new grad? Mixed. Hopefully, the grad will initially be given procedural tasks that will be successful and lead to more independent projects. At worst, as in my experience, the young engineer will be assigned to projects better left to seasoned engineers. These projects generally veer off on some strange trajectory, and those involved suffer. Oddly enough, the young engineer receives the same raises per year for each possibility. After all, the young engineer is nothing but "potential" in the company's view.

What, then, is the initial value of a young engineer? The ability to support ongoing duties in a company? Not usually; sustaining engineering requires specific training not available in college, and possibly not transferable between similar companies. Design ability due to new topics available in academia? Probably not, for two reasons. First, colleges typically follow rather than lead progress in industry. Second, new grads can't seem to design their way out of a paper bag, in terms of bringing a design through a company to successful customer acceptance. Not just my opinion, it's history.

This is what's wrong with grads, with respect to the electronics industry:

They are not ready to make money for their new employer.

They don't know they're not scientists; that engineers make and sell things. They don't appreciate the economic foundation we all operate with.

They don't know just how under-prepared they are. They are sophomores—from the ancient Greek, suggesting "those who think they know." They try to change that which they don't really understand. They have *hubris*, the unearned egotistical satisfaction of the young and the matriculated.

They see that many of their superiors are jerks, idiots, incompetents, or lazy. Well, sure. Not in all companies, but too often true enough. Our grads often proclaim this truth loudly and invite unnecessary trouble.

They willingly accept tasks they are ill-suited for. They don't know they'll be slaughtered for their failures. Marketing positions come to mind.

Not all grads actually like engineering. They might have taken the career for monetary reward alone. These folks may never be good at the trade.

So, should we never hire young engineers? Should we declare them useless and damn them to eternal disgrace? Should we never party with them? Well, probably not. I can see that at Elantec, a relatively young and growing company, we need them now and will especially need them when we old farts get more lethargic. It's simple economics; as companies grow they need more people to get more work done. Anyway, young people really do add vitality to our aging industry.

It behooves us all, then, to create a professional growth path where the company can get the most out of its investment, and the new grad can also get the most lifelong result from his or her college investment. I have a practical plan. I didn't invent it; the Renaissance tradespeople did. It's called "apprenticeship."

The "crafts" were developed in the 1400s, mostly in Italy. The work was the production of household art. This might be devotional paintings, could be wondrous inlaid marble tables, might be gorgeous hand-woven tapestries to insulate the walls. In most cases, the artistic was combined with the practical. Let me amplify: the art was profitable. There was no cynicism about it; beauty and commerce were both considered good.

We have similar attitudes today, but perhaps we've lost some of the artistic content. Too bad: our industrial management has very little imagination, and seldom recognizes the value of beauty in the marketplace. At Elantec, we've made our reputation on being the analog boutique of high-speed circuits. We couldn't compete on pure price as a younger company, but our willingness to make elegant circuits gave us a lot of customer loyalty. We let the big companies offer cheap but ugly circuits; we try to give customers their ideal integrated solutions. We truly like our customers and want to please them. We are finally competitive in pricing, but we still offer a lot of value in the cheaper circuits.

Do college grads figure into this market approach? Not at all. You can't expect the grad to immediately understand the marketplace, the management of reliable manufacturing, or even effective design right out of college. Just ain't taught. The Renaissance concept of the "shop" will work, however. The shop was a training place, a place where ability was measured rather than assumed, where each employee was assigned tasks aimed for success. Professional growth was managed.

An example: the Renaissance portrait shop. The frame was constructed by the lowliest of apprentices. This frame was carved wood, and the apprentice spent much of his or her time practicing carving on junk wood in anticipation of real product. The frame apprentice also was taught how to suspend the canvas properly. Much of the area of the canvas was painted by other apprentices or journeyman painters. They were allowed to paint only cherubs or buildings or clouds. The young painters were encouraged to form such small specialties, for they support deeper abilities later. So many fine old paintings were done by gangs; it's surprising. Raphael, Tintoretto, and even Michelangelo had such shops. The masters, of course, directed the design and support effort, but made the dominant images we attribute to them alone. Most of the master painters had been apprentices in someone else's shops. We get our phrase "state of the art" from these people.

Today's engineers do practice an art form. Our management would probably prefer that we not recognize the art content, for it derails traditional business management based on power. We engineers have to ensure that artistic and practical training be given to our novices.

So, how does one train the engineering grad? I can only speak for my own field, analog IC design. I'll give some suggestions that will have equivalents in other areas of engineering. The reader can create a program for his or her own work.

1. The grad will initially be given applications engineering duty. Applications is the company's technical link with the buying public. This group answers phone calls of technical inquiries and helps customers with specific problems with the circuits in the lab, when published or designer information is unavailable. Phone duty is only half of applications; they develop applications circuits utilizing products and get the write-ups published, typically through trade magazines such as *EDN*. They produce application notes, which serve as practical and educational reading for customers. A well-developed department will also create data sheets, lifting the burden from the designers but also enforcing a level of quality and similarity in the company's literature. My first two years in the industry were in this job. In one instance, I forced a redesign of a circuit I was preparing the data sheet for because it simply did not function adequately for the end application. Of course, designers always think their circuits are good enough. A truly seasoned applications engineer can be involved in new product selection.

The point of this assignment is to teach future designers what to design, what customers need (as opposed to what they want), how to interact with the factory, and general market information. I wouldn't let new grads speak to customers immediately; first they would make data sheets for new products and be required to play with circuits in the lab to become familiar with the product line. Making application notes would be required, guided by senior applications engineers. I believe that developing good engineering writing skills is important for the designer.

After a couple of months, the engineer would start phone duty. I think the first few calls should be handled with a senior apps engineer listening, to coach the young engineer after the calls. It's important that the engineer be optimally professional and helpful to the customer so as to represent the company best. Most of us have called other companies for help with some product problem, only to reach some useless clone.

This stint in applications would last full-time for six months, then be continued another six months half-time, say mornings for us West Coast folks.

2. Device modeling would be the next part-time assignment. In analog IC circuit design, it's very important to use accurate and extensive model parameters for the circuit simulators. Not having good models has caused extensive redesign exercises in our early days, and most designers in the industry never have adequate models. As circuits get faster and faster, this becomes even more critical. Larger companies have modeling groups, or require the process development engineers to create models. I have found these groups' data inaccurate in the previous companies where I've worked. We recently checked for accuracy between some device samples and the models created by a modeling group at a well-known simulator vendor, and the data was pure garbage. We modeled the devices correctly ourselves.

This being a general design need, I would have the young engineer create model parameters from process samples, guided by a senior engineer with a knack for the subject. This would also be an opportunity to steep the engineer in the simulation procedures of the department, since the models are verified and adjusted by using them in the circuit simulator to play back the initial measurements. It's a pretty tedious task, involving lots of careful measurements and extrapolations, and would probably take three months, part-time, to re-characterize a process. Modeling does give the engineer truly fundamental knowledge about device limitations in circuits and geometries appropriate to different circuit applications, some really arcane and useful laboratory techniques, and the appreciation for accuracy and detail needed in design.

Because of the tedium of modeling, few companies have accurate ongoing process data.

3. A couple of layouts would then be appropriate. Most of our designers at Elantec have done the mask design for some of their circuits, but this is rare in the industry. The usual approach is to give inadequate design packages to professional mask designers and waste much of their time badgering them through the layout. The designer often does an inadequate check of the finished layout, occasionally insisting on changes in areas that should have been edited earlier. When the project runs late, the engineer can blame the mask designer. You see it all the time.

I would have the young engineer take the job of mask designer for one easy layout in the second three months of half-time. He would lay out another designer's circuit and observe all the inefficiencies heaped upon him, hopefully with an eye to preventing them in the future. Actually, we designers have found it very enlightening to draw our own circuits here; you get a feel for what kind of circuitry packs well on a die and what is good packing, and you confront issues of component matching and current/power densities. The designer also gains the ability to predict the die size of circuits before layout. The ultimate gain is in improving engineers' ability to manage a project involving other people.

4. The first real design can be started at the beginning of the second year. This should be a design with success guaranteed, such as splicing the existing circuit A with the existing circuit B; no creativity desired but economy required. This is a trend in modern analog IC design: elaborating functions around proven working circuitry. The engineer will be overseen by a senior engineer, possibly the designer of the existing circuitry to be retrofitted. The senior engineer should be given management power over the young engineer, and should be held responsible for the project results. We should not invest project leadership too early in young engineers; it's not fair to them. The engineer will also lay the circuit out, characterize it, and make the data sheet. Each step should be overseen by an appropriate senior engineer. This phase is a full-time effort for about five months for design, is in abeyance while waiting for silicon, and full-time again for about two months during characterization.

5. The first solo design can now begin. The engineer now has been led through each of the steps in a design, except for product development. Here the designer (we'll call the young engineer a designer only when the first product is delivered to production) takes the project details from the marketing department and reforms them to a more producible definition of silicon. At the end of the initial product planning, the designer can report to the company what the expected specifications, functionality, and die size are. There are always difficulties and trade-offs that modify marketing's initial request. This should be overseen by the design manager. The project will presumably continue through the now-familiar sequence. The designer should be allowed to utilize a mask designer at this point, but should probably characterize the silicon and write the data sheet one last time.

This regimen takes a little over two years, but is valuable to the company right from the start. In the long run, the company gains a seasoned designer in about three years, not the usual seven years minimum. It's also an opportunity to see where a prospective designer will have difficulties without incurring devastating emotional and project damage. The grad can decide for himself or herself if the design path is really correct, and the apprenticeship gives opportunities to jump into other career paths.

I like the concepts of apprentice, journeyman, and master levels of the art. If you hang around in the industry long enough, you'll get the title "senior" or "staff." It's title inflation. I have met very few masters at our craft; most of us fall into the journeyman category. I put no union connotation on the terms; I just like the emphasis on craftsmanship.

There are a few engineers who graduate ready to make a company some money, but very few. Most grads are fresh engineering meat, and need to be developed into real engineers. It's time for companies to train their people and eliminate the undeserved failures. I worked for five years at a well-known IC company that was fond of bragging that it rolled 20% of its income into research and development. The fact is, it was so poorly organized that the majority of development projects failed. The projects were poorly managed, and the company was fond of "throwing a designer and a project against the wall and seeing which ones stick." Most of the designers thrown were recent graduates.

We should guide grads through this kind of apprenticeship to preserve their enthusiasm and energy, ensuring a better profession for us all.

When I read the first Williams compendium (the precursor to this book), I was shocked by the travelogs and editorials and downright personal writings. Myself, I specialize in purely technical writing. But after Jim gave me the opportunity to offer something for the second book, the first book seemed more right and I couldn't resist this chance for blatant editorialization. I'm mad, see, mad about the waste of young engineers. Waste is bad.

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3. We Used to Get Burned a Lot, and We Liked It

I'm a fortunate engineer. My employer sponsors the hobby I've had for thirty of my forty-year life. We don't disagree much; I like most of the aspects of my job, even the tedious ones. However, I'm no lackey. I don't really listen to many people, although I try to appear to. There's no cynicism here; all my associates agree with me that we will produce nifty new ICs and make money. That's the job.

This entry of Jim's compendium is offered to relate what an earlier generation of engineers experienced in preparation for a career in electronics. Many of my associates were quite functional in electronics when they entered college. We were apparently different from most of the students today. We were self-directed and motivated, and liked the subject. I have detected a gradual decrease in proficiency and enthusiasm in college graduates over the last fifteen years; perhaps this writing will explain some of the attitudes of their seniors. I've included some photographs of lovely old tube equipment as background.

My experiences with electronics started with construction projects involving vacuum tubes, then transistors, eventually analog ICs, raw microprocessor boards, and finally the design of high-frequency analog ICs. Through all the years, I've tried to keep the hobby attitude alive. I'm not patient enough to grind through a job for years on end if I don't really enjoy it. I recommend that anyone who finds his or her job boring decide what they do like to do, quit the current job, and do the more enjoyable thing.

My first memory of vacuum tubes is a hot Las Vegas, Nevada morning around 1 A.M. I was young, about ten years old. It was too hot to sleep and the AM radio was gushing out Johnny Cash, Beach Boys, Beatles, and the House of the Rising Sun, as well as cowboy music. It was pretty psychedelic stuff for the time, and with a temperature of 100°F at night, the low humidity and the rarefied air, I spent a lot of late nights awake with the radio.

As I lay listening to the music I noticed that the tubes of the radio projected more blue light on the ceiling than the expected yellow-red filament glow. It's hard to imagine that simple, beautiful, blue projection upon your wall which comes from the miniature inferno within the tubes. It comes from argon gas which leaks into the tube and fluoresces in the electric fields within. Occasionally, you can see the music modulate the light of the output tubes.

My radio, which sat next to my bed so that I could run it quietly without waking the parents, was a humble GE table model. It was built in the mid-50s, so it was made of cheap pine with ash (or maple?) veneer. Typical of the times, it had sweeping rounded corners between the top and front, and inlaid edging. They never did figure out how to make a true accurate corner with cheap wood processes. This radio was B-grade, though; it had a magic-eye tube and included the "MW" band-low MHz AM reception. Allegedly, you could hear ships and commercial service on MW, but in Las Vegas all I heard were ham radio 1.8MHz "rag chewer" conversations. At length.

Radios were magic then. TV wasn't nearly as entrancing as now, being black-and white in most homes and generally inane (the good adult stuff was on too late for me to see). On radio you heard world news, pretty much the only up-to-the-minute news. You heard radio stations that didn't know from anything but variety in music. They didn't go for demographics or intense advertising; they just tried to be amusing. When I was that young, the people who called into the talk shows were trying to be intelligent. Shows what an old fart I am.

The electronic product market of the time was mostly TV and radios. Interestingly, the quality living-room TV of that time cost around $600, just like now. Then you also got a big console, radio, speakers, and

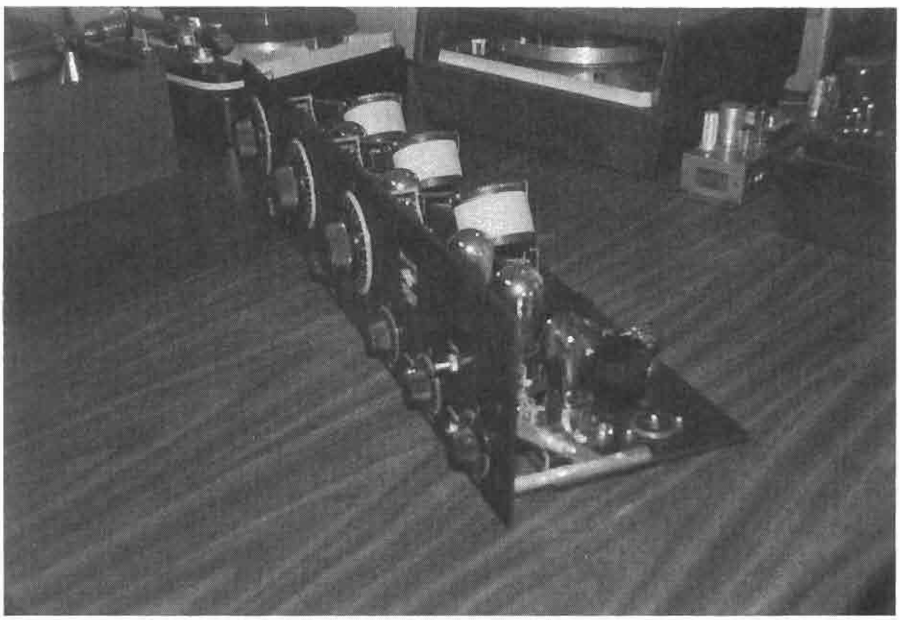


Figure 3–1.
A lovely TRF radio from the 1920s and '30s. This was before superheterodyne reception; you had to tune all three dials to get your station. More or less gain was dialed in with the rheostats in series with the input tubes' filaments. A lot of farm as well as city dwellers used these. The coils were hand-wound, and every component was available for scrutiny. This set will be usable after a nuclear attack. From the John Eckland Collection, Palo Alto, California. Photo by Caleb Brown.

record player for the price (it even played a stack of records in sequence). It worked poorly, but it was a HOME ENTERTAINMENT SYSTEM. We pay only a little more for similar but better today. Lab equipment was really rotten then compared to today. There was no digital anything. Want to measure a voltage? You get a meter, and if you're lucky it has a vacuum-tube amplifier to improve its range, versatility, and resistance to burnout. I couldn't afford one; I had a 20KΩ/V multimeter. I eventually did wreck it, using it on a wrong range.

In the vacuum-tube days, things burned out. The tubes might only last a year, or they might last 20 years. Early 2-watt resistors had wax in them, and always burned out. The later carbon resistors could still burn out. When I say burn out, I mean exactly that: they went up in smoke or even flame. That's where the term came from. Where we have cute switching power supplies today, then the tubes ran from what we call "linear" supplies that included power transformers which in quality gear weighed a dozen pounds or more. The rectifiers might be massive tubes, or they could be selenium rectifiers that also burned up, and they were poisonous when they did. The bypass capacitors were a joke. They would eventually fail and spew out a caustic goop on the rest of the innocent electronics. Let's face it, this stuff was dangerous.

I almost forgot to mention the heat. A typical vacuum tube ran hot; the glass would burn you if you touched it. The wood cabinets needed to be regularly oiled or waxed because the heat inside discolored and cooked them. A power tube ran really hot, hot enough to make the plate glow cherry-red in normal operation. You could get an infrared sunburn from a few inches' proximity to a serious power tube. From a couple of feet away your face would feel the heat from an operating transmitter.

But it wasn't burnout or heat that was the most dangerous thing to an electronics enthusiast; it was the voltage. The very wimpiest tube ran from 45V plate potential, but the usual voltage was more like 200V for a low-power circuit. I made a beautiful supply for my ham transmitter that provided 750V for the output amplifier. Naturally, it knocked me across the room one day when I touched the wrong thing; a kind of coming-of-age ritual. This event relieved me of all fear of electricity, and it gave me an inclination to think before acting. Nowadays, I sneer at bare electrodes connected to semiconductors. I routinely touch nodes to monitor the effect of body capacitance and damping on circuit behavior. I have often amazed gullible peasants by curing oscillations or fixing bypasses with only my touch. Of course, the off-line power supplies command my respect. For them, I submit and use an isolation transformer.

At this point, I think we can explain the lack of females attracted to electronics at the time. In the 50s and 60s, society protected women but offered men up to danger. The same is true for the earlier industrial revolution: women were huddled into protective work environments and men were fodder for the dangerous jobs. I think this attitude was prevalent with respect to vacuum tube electronics. Women (girls, in particular) were not encouraged to enjoy the shock hazards, the burns, the excessive weights of the equipment, or the dirtiness of the surfaces.

Boys, of course, found all this attractive. I suppose this is the historical basis of the male domination of the field. The duress of dealing with this kind of electronics really appealed to young men's macho, just like working on cars appealed to the gearhead set. The difference between the groups was that electronics required a lot more education and intellect than cars, and so appealed to more bookish types. The girls never caught on to how cool electronics was, probably because a radio can't get you out of the house. The electronics hobbyists (creators of today's nerd stereotype) simply found another way to get away from the parents. It worked; the old folks really did keep out of the garage, the rightful dominion of hobby electronics.

A social difference between then and now is how much more prevalent hobbies were. As I mentioned, TV did not occupy as much of people's time. Kids got as bored as now, so they turned to hobbies. When boys got together, they needed something to do, and they could share cars or electronics. This led to a much more capable young workforce, and getting a job after high school seemed easier than now. Furthermore, you probably had strong interests that could guide you through college. Changing majors or not having a major was unusual. Now, kids are generally far less self-directed. They haven't had to resolve boredom; there's too much en-

Figure 3–2.
An original breadboard. The components are on the board, and hopefully Ma has another. This is a phonograph pre-amp and power amplifier, just like 1930-to-1960 home project assemblies. You can really see your solder joints in this construction style. From the John Eckland Collection, Palo Alto, California. Photo by Caleb Brown.

tertainment easily available to them today. Further, drugs destroy hobbies. As a result, the college students I've interviewed over the years have gradually lost pre-college experience with their field. Twenty years ago college grads had typically been working with electronics for two to seven years before college, and the new grad could perform well in industry. Regrettably, it now takes up to three years of professional experience to build a junior engineer, titles notwithstanding.

Perhaps worse is the attitude change over the years. The new grad was considered an amateur; "amateur" from the Latin, meaning "one who loves a field": motivated but inexperienced. Increasingly, the grads are in electronics for the bucks, and seldom play in the art for their own amusement. Present company excepted; I know the readers of this book are not in that category. To be fair, present electronics focuses on computers and massive systems that are hard to comprehend or create in youth. Construction of projects or repairing home electronics is mostly out of the realm of kids not encouraged by a technical adult.

I think this places an obligation on families and schools to support electronics projects for kids, if we are to generate really capable and wise engineers in the future. By the time a present grad has had enough years of experience to become an expert in some area, the technology is liable to change. Breadth of technical experience is the only professional answer

Figure 3–3.
A really beautiful radio from the 1950s. A so-called Tombstone radio; the fins are wood decoration. This is electronics as furniture; the radio is good but the cabinet is exquisite. The dial is artistic and several frequency bands await the curious. Not fully visible is the same radio flanked by different cabinets made by competitive groups within Zenith. From the John Eckland Collection, Palo Alto, California. Photo by Caleb Brown.

to this problem. Employers do not encourage nor support the engineer's development outside his narrow field, so breadth seems something best developed by hobbies before college, and a more varied engineering training during college.

But we digress. Somewhere around 1964 I saw the first transistor radios. They were kind of a novelty; they didn't work too well and were notoriously unreliable. They replaced portable tube radios, which were just smaller than a child's lunch box. They weighed about seven pounds, and used a 45V or 67V battery and a couple of "D" cells for the filaments. The tubes were initially normal-sized but had low-power filaments in the portables, but the latest were socketless and had cases only 1½" long and ½" diameter. These tubes were also used in satellites and were quite good. Even so, the transistor radios were instant winners. They were cheaper than any tube radio, were truly portable, and could be hidden in classrooms. The miniature earphone really made it big.

The transistor radio easily doubled the audience for musicians and advertisers. Perhaps it was the portable transistor radio that accounted for the explosive growth of rock music. . . . While it's true that rock-and-roll was popular as hell in the late 50s and early 60s, the sales of records and the number of radio stations just didn't compare with the activity at the end of the 60s.

As I said, the transistor radios were unreliable. I made spending money repairing radios when I was in grade school. Attempting to repair them; my hit ratio was only 50%. These repairs were on bad hand-soldered joints, on broken circuit boards (they were made of so-called Bakelite—a mixture of sawdust and resin), and unreliable volume controls. Replacement parts were grudgingly sold by TV repair shops; they'd rather do the servicing, thank you. The garbage line of 2SK-prefix transistors was offered. These Japanese part numbers had nothing to do with the American types and surprisingly few cross-references were available. I had no equipment, but most of the failures were due to gross construction or device quality problems.

Only a few years after the transistor radios emerged they became too cheap to repair. They made for a poor hobby anyway, so I turned to ham radio. This was the world-wide society of folks who like to talk to each other. The farther away the better; it's more fun to talk to a fellow in Panama than one in Indiana. People were more sociable then, anyway. The world community seemed comfortably far off and "foreign" had an attraction.

I didn't have enough money to buy real commercial ham gear. Luckily for me, many hams had the same inclinations as I and a dynamic home-construction craze was ongoing. Hams would build any part of a radio station: receivers, transmitters, or antennas. They were quite a game group (of mostly guys), actually; grounded in physics and algebra, they used little calibrated equipment but actually furthered the state of radio art. Congress gave them wide expanses of spectrum to support this renaissance of American engineering. We got a generation of proficient

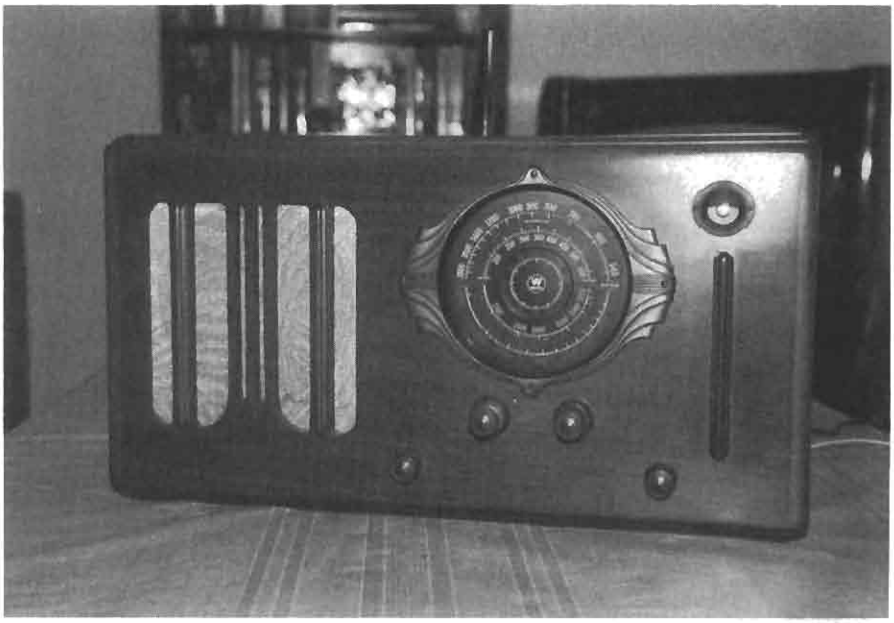
Figure 3–4.
Here's the chassis of a first-rate radio. The base metal is chrome-plated for longevity. All coils are shielded in plated housings, and string tuning indicator mechanisms are replaced with steel wire. These components are as uncorrupted as they were when they were made in 1960. The designers gave extra attention to the quality of everything the customer would see and feel (the knobs play very well). From the John Eckland Collection, Palo Alto, California. Photo by Caleb Brown.

engineers from radio. Hams performed feats of moon bounce communications and even made a series of Oscar repeater satellites. Imagine that, a group of civilians building satellites that NASA launched into space for free. I myself have heard aurora skip signals on the 6-meter band—the bouncing of signals off the northern lights. All this in the days of early space travel and Star Trek. Some fun.

Soon after transistor radios were common, industrial transistors became cheap and available in volume. The hobby books were out with good circuit ideas in them, so I finally started making transistor projects about 1966. I was a bit reluctant at first, because the bipolars were delicate, physically and electrically, and had poor gain and frequency response. Tubes were still superior for the hobbyist because of their availability. You could salvage parts from radios and TVs found at the dump, or discarded sets awaiting the trashman. Because the circuits were relatively simple, we would dismantle old sets right down to separated components and chassis, which would be reassembled into the next hobby project. I began to tap the surplus parts suppliers, and the added supply of tube and related parts delayed my interest in solid-state circuits.

The first commercial transistors were germanium PNP, and they sucked. They just wouldn't work correctly at high temperatures, and their

Figure 3–5.
A medium-quality table radio of the 1950s. Being decorative, the cabinet and dial are of good quality. In the upper-right corner is a magic-eye tube, an oscilloscope-like gizmo that gives an analog indication of tuning accuracy. From the John Eckland Collection, Palo Alto, California. Photo by Caleb Brown.

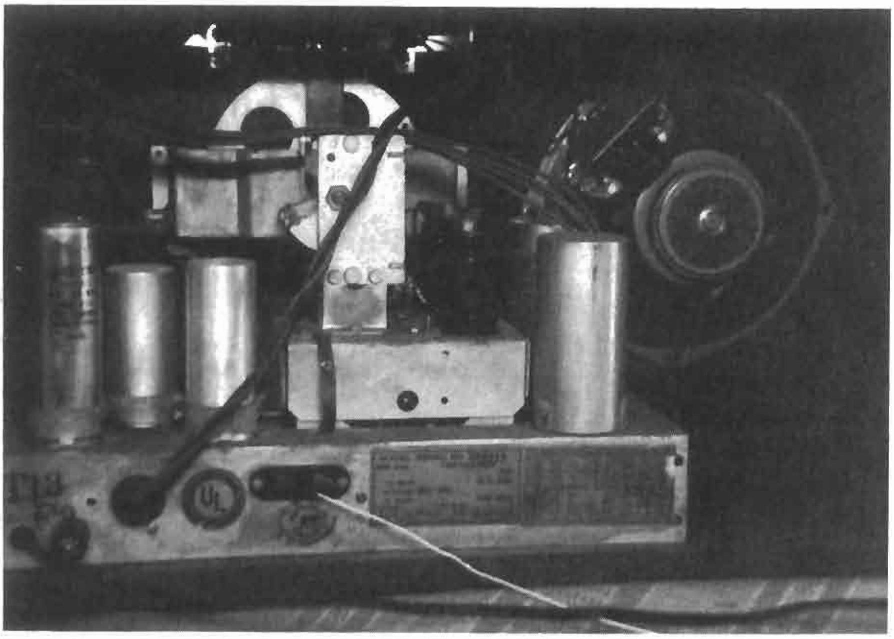


leakage currents skyrocketed past 100°C to the extent of debiasing circuits. Their Vbe went to zero at 200°C; that is, the whole transistor became intrinsic and was a short-circuit. Furthermore, you couldn't find two devices that halfway matched with respect to Vbe and beta and output impedance. You didn't bother making instrumentation circuits with those devices; there just weren't any matched pairs to be found. The Vbe's also suffered from terrible long-term drift, I think because germanium could never be alloyed adequately for a solid contact. It didn't matter; chopper-stabilized tube op amps were common and worked well. I still have one of the best VTVMs ever made, a Hewlett-Packard chopper-stabilized model that has sensitive DC ranges and a 700MHz active AC probe.

What really made my decision to use transistors was the advent of the silicon NPN device. Silicon could tolerate temperature, and was insensitive to excessive soldering. It never went intrinsic, and beta control allowed for matched pairs. The high-quality differential input stage made the industry of hybrid op amps possible, and some of them could handle the same signal voltages as the tube op amps. Silicon transistors even gave decent frequency responses, although the faster devices were still electrically delicate. Silicon made TVs and radios work better too.

Circuit design changed overnight. The threshold voltage of tubes (analogous to the threshold of JFETs) would vary over a 3:1 range. Because of the poor bias point accuracies, most circuits were AC coupled. This precluded them from many industrial applications. Although

Figure 3–6.
The electronics of the previous radio. Because this set was not of the highest caliber, the electronics are humble and have no precious elements. From the John Eckland Collection, Palo Alto, California. Photo by Caleb Brown.



the chopper-stabilized op amp was very accurate, it was expensive and the chopper could wear out, being a mechanical vibrator. The uncertainty of transistor Vbe was really negligible, relative to supply voltages, and biasing transistors was a snap, although not widely understood then. Transistors could seemingly do anything that didn't involve too much power. But until perhaps 1966, if you had to handle power with a transistor, you used a cow of a germanium device.

But between 1961 and 1967, the choice of transistor or tube was often made by the prejudice of the designer. Some applications demanded one device or the other, but in the case of audio amplifiers, there was free choice.

Construction of electronics changed radically in this time. Tubes were mounted in sockets whose lugs served as the supports for components, and a solid steel chassis supported the circuits. Steel was necessary, since the tubes couldn't tolerate mechanical vibration and the massive power supplies needed support. The most elegant construction was found in Tektronics oscilloscopes. They used molded ceramic terminal strips to support components, and only about eight components could be soldered into a pair of terminal strips. Cheaper products used Bakelite strips. These were all rather three-dimensional soldered assemblies: point-to-point wiring literally meant a carpet of components connected to each other and to tubes in space. The assemblies were also very three dimensional; the tubes sprouted vertically above the chassis by three to five inches and the other components sprawled in a two-inch mat below the chassis.

Transistors made construction more two dimensional. The transistors weren't tall, generally the size of our TO-39 package of today, and circuit boards were practical since they didn't have to support heavy or hot components. All passive components became short too. A layer of transistor circuitry thinned to one inch or less. There was a volume reduction of about 20:1 over equivalent tube circuits. For industrial electronics, however, transistors afforded only a 2:1 overall product cost reduction.

In the 1960s, the quality of cabinets really degraded. Transistor equipment was considered cheap, relative to tube gear, and only received cheesy plastic cases. The paint and decals on the plastic rubbed or flaked off, and impact could shatter it altogether. Tube equipment, on the other hand, had enjoyed quality wood casings for decades. Since the tube chassis were so large and heavy, furniture-quality cabinets were needed simply to transport the electronics. The radios and TVs were so obtrusive in tube form that manufacturers really made the cabinets fine furniture to comply with home decor.

Quality in the tube years came to mean both mass and the use of precious materials. Greater mass meant you could transport or physically abuse the equipment with no damage. It also meant that the components would suffer less from thermal changes and microphonics (electrical sensitivity to mechanical vibrations). A really sturdy chassis would not need alignment of the tuned circuits as often as a flimsy frame. Precious materials included quality platings—such as chrome or vanadium—of the chassis, to avoid corrosion and extend useful life. Heavier transformers allowed more power for better bass response and greater volume. A heavier power transformer would burn out less frequently, as would oversize power tubes. Components came in quality levels from cheap organic-based resistors and capacitors that cockroaches could eat to more expensive and long-lived sealed components. The general attitude about electronics construction was akin to furniture: the more mass and the more precious the material, the better.

Since the transistor circuits had no thermal nor microphonic problems, the poorest of cases were given to them. They weighed next to nothing, and a hard fall wouldn't cause too much damage. Since the products had no mass nor special materials in their construction, people thought of transistor products as low-quality. The manufacturers made sure this was true by using the poorest materials available. The circuit boards did indeed tarnish and warp, and the copper could crack and cause opens. The wires soldered to the boards seemed always stressed from assembly and often broke. Even the solder had corrosive rosin.

Because the transistor circuits were small, the traditional soldering guns and irons were far too hot and large to use; we now had to buy new small irons. We even had to get more delicate probes for oscilloscopes and voltmeters. These problems were moot; you couldn't effectively repair transistor stuff then anyway. Even if you could troubleshoot a bad

Figure 3-7.
Electronics for the masses: the 1960 Knight-Kit audio amplifier. For $70, you get a kit of parts and a chassis which can become a stereo 50W audio power amplifier. This was a good deal; since labor was expensive, building the thing at home saved money, and the experience was somewhat educational. More than 100,000 were sold. From the John Eckland Collection, Palo Alto, California. Photo by Caleb Brown.

board, you had only a 50-50 chance of not damaging it when you tried to replace a component. You could not make a profit repairing transistor products.

It got harder to make hobby circuits too. In the mid-60s, printed circuit boards were so bad you might as well try to make your own. So I bought a bottle of ferric chloride and tried it myself. For masking, I tried direct painting (house exterior paint wasn't bad) and resist ink pens. This sort of worked; I had to blob-solder across many splits in the copper of my homemade boards. "Hobby boards" were the solution. These are the pre-etched general-purpose breadboards in printed circuit form. They had DIP package regions and general 0.1" spacing solder holes. Analog hobbyists would obediently solder interconnect wires between pads, but the digital hobbyists had too many connections to make and adopted wire-wrap construction.

Suddenly construction projects lost their artistic appeal. Tubes arrayed on a chassis with custom wiring are very attractive, but the scrambled wire masses of transistor projects are about as pretty as a Brillo pad. You could hardly see the connections of transistor circuits, and this only got worse as ICs displaced groups of transistors. I knew a couple of old codgers who gave up hobby electronics due to failing eyesight. They wouldn't have had trouble with tube projects. Funny thing was, semiconductor projects still cost as much as tube equivalents but were uglier, more difficult to build, and harder to debug and tune.

Professional breadboards were similar to the hobbyboards until perhaps the early '80s. At work you built circuits on higher-quality breadboards. But within only a few years, critical ICs were available in surface-mount packages, or more expensive and clumsy socketed alternatives. The pin count of the packages just skyrocketed. The sockets are expensive and fragile. A transition began which is almost complete today: breadboards are simply not attempted to develop each subsystem of a board; the first tentative schematic will be laid out on a full-fledged circuit board. Any corrections are simply implemented as board revisions. These boards contain mostly surface-mount components. This technique is not practical for the hobbyist.

God, what a nightmare it is to troubleshoot these boards. They are generally multilayer and the individual traces can't be seen, so finding interconnects is impossible. The only connections that can be probed or modified are the IC's leads themselves. You generally can't read the markings on resistors or capacitors, because they are so small. Development work is accomplished with stereo microscopes.

So hobby electronics has taken a major beating in the last twenty years. It's become intellectually difficult to build a really significant project, to say nothing of increased expense and construction difficulty. This portends a generation of relatively green engineers who have only college experience with electronics. God help us. I suppose there still are some handy people, as demonstrated by the continuing component sales of Radio Shack. Too bad that they have diminished the component content of their stores over the years, and traditional hobby suppliers like Lafayette and Heathkit have altogether disappeared. There is no substitute for pre-college electronics experience.

Gone too is the magic people used to see in electronics. As a kid, I saw that other kids and their parents were amazed that radios and TVs worked at all. Our folks used to think of installing a TV antenna as an electronics project. Parents gave their kids science toys. These were great; we had chemistry sets, metal construction kits, build-your-own-radio-from-household-junk sets, model rockets, crystal-growing kits, all sorts of great science projects. The television stations even kept Mr. Wizard alive, the weekly science experiment program.

It seems now that people assume they can't understand science or technology, and accept this ignorance. Kind of like religious belief. People seem to enjoy technology less, and expect more. We even predict future advancements when we have no idea how to accomplish them. We don't give our young children these science toys, even though the kids would find them wondrous. Parents are imposing jaded attitudes on kids.

This would be all right, except that electronics has grown in scope beyond the ability of college to teach it well. Students graduating today have insufficient breadth of knowledge of the field, and not enough depth to really take on a professional project. I don't blame them; it's probably impossible to be the master of anything with a college diploma but no real experience.

I don't know all of the answers, just the problem. As long as our society considers engineering unglamorous and nerdy, kids won't be attracted to it. Industry will wonder why young engineers are not highly productive. Companies never really train people; they just give them opportunities. We'll see a general malaise in design productivity, just as we now see a problem with software production. I could be getting carried away with all this, but we should promote science and technology as suitable hobbies for our kids.

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Keitaro Sekine

4. Analog Design Productivity and the Challenge of Creating Future Generations of Analog Engineers

Introduction

Recently, digital techniques are very commonly used in the fields of electronics. According to the statistics taken by MITI (Figure 4–1), Japanese integrated circuits industry has shown a growth of 5.5 times in the last one decade (from 1980 to 1991). While digital ICs (MOS and bipolar digital) grew 6.24 times in this period, analog ICs did only 3.57 times. This reflects to a analog vs. digital percentage ratio, showing that analog decreases from 25.9% on 1980 to 16.7% on 1991 (Figure 4–2). From these facts, many people in the electronics fields might think that the age of analog has been finished.

	'80	'85	'90	'91
MOS Digital	100	346	650	691
Bipolar Digital	100	352	340	336
Total of Digital	100	348	591	624
Linear	100	261	309	357
Grand Total	100	325	518	555

Figure 4–1. Percentage of Japanese IC production.

Institute of Electronics, Information and Communication Engineers (IEICE), one of the largest academic societies in electronics fields in Japan, held special sessions to discuss many problems with respect to the analog technologies in Japan at the IEICE National Convention in 1989 and again in 1992 chaired by the author. Both sessions attracted much more participants than expected and proved that many serious engineers were still recognizing the importance of analog technology. We discussed the present status of analog technologies, how to create new analog technologies, how to hand them down to the next generation engineers and how to use CAD in design of analog circuits to enhance productivity. This paper is based on several discussions in these sessions and author would like to acknowledge to those who discussed on the problems.

Figure 4–2. Digital–Analog Percentage Ratio (MITI).

	'80	'85	'90	'91
MOS Digital	60.0	63.9	75.3	74.8
Bipolar Digital	14.1	15.3	9.2	8.5
Total of Digital	74.1	79.2	84.5	83.3
Linear	25.9	20.8	15.5	16.7
Grand Total	100.0	100.0	100.0	100.0

To summarize those discussions, we could categorized the problems in to the following three major classes;[1]

First, because of many people cannot understand that analog circuits technologies are not out of date but they really a key to develop digital technologies, the number of students who want to learn analog circuits technologies are has been decreasing year by year. Even student who willingly study analog circuits tends to prefer computer simulation rather than experiments, so they lose a sensitivity to the real world. Accordingly this lead the results that only a very few number of universities in Japan still publish technical papers in the field of analog circuits.

Secondly, in the industries, although the importance of the analog circuits technologies are aware, two things make the number of analog circuits engineer decreased: increasing production of digital hardware system need to increase digital circuits engineers, and analog engineers easily understand digital technologies.

Third, while CAD makes design of digital system very popular, design of analog circuits are still difficult, it requires still expert's skill. It has very insufficient productivity. Besides it takes a long time to educate engineers to be an analog circuits expert. Finally many factories tend to change their main productions from analog to digital systems.

Analog circuits, however, have many advantages over digital technologies: very high functional densities for the same chip size, high speed abilities and high potentials.

So we must make a effort to increase the number of analog engineer and to hand analog circuits technologies down to next generations.

Analog Design Productivity

CAD (Computer Aided Design, but some peoples think it as Computer Automated Design) has been widely adopted in the design of digital integrated circuits. Computers can do everything from logic synthesis to mask pattern generation, taking the place of average design engineers, only if they got functional specification of the system written in some high level descriptive language. Meanwhile analog circuits CAD also become in great request according to the rise of several novel technologies such as personal communication system, multimedia and so on, because we have insufficient number of analog circuits design engineers to cope with this situations. (The reason why they have been decreased shall be mentioned in later section of this paper.) But unfortunately it is believed that there should be no such a powerful analog CAD system like a digital for a while.

Analog circuits design technologies have following features which prevent us from realizing unified approach schemes:

1. While digital systems can be described with a couple of logic equations in principle, specifications of analog circuits are too much complicated to describe in a clear format. For instance, it sometimes is requested to design "excellent sound quality HiFi amplifier." We have no definition for "excellent sound quality" at all. It depends on individual judgment, some feels good the others feels no good, listening to the same amplifier. Besides a feeling judgment, amplifier has many characteristic items such as gain, frequency characteristics, dynamic range, distortion, temperature characteristics, input and output impedance, power consumption and so on. And normally we could not find evident correspondence between these characteristic items and the total performance.

2. Several specifications on a single circuit usually conflict each other, so many trade off should be indispensable during the design procedure, taking restrictions such as performance of devices available, cost, deadline etc. into account. As these compromises could be done with the designer's personal experience and knowledge, there was no straightforward scheme to do them. There were many papers with respect to the optimization of electronic circuits, but difficulties are not in how to do it but in where one should place the goal.

3. To design a good analog circuits, a step by step method is quite insufficient and a breakthrough should be mandatory. Only man of talents can do that. But perhaps he cannot explain how he comes to the breakthrough.

4. There are many circuit topologies and their combinations to realize the same specification. It should be so difficult for CAD to get a unique solution.

Above mentioned features of analog circuits design are based on very essential characteristics of analog. We can not write any program without the knowledge about how it works. We think "computer-automated-design" of analog circuits are still one of challenging problems for us.

We have, however, powerful tools for analog circuit design, a circuit simulator. Among them "SPICE" and its derivatives are widely used by the design engineers. It is very useful as far as he use as literally "computer-aided-design" tools. Circuit simulator requires good understanding of circuits from the design engineer. We discussed about merits/demerits of using circuit simulator in the National Convention of IEICE in 1992 to find the following problems:

1. Simulator could be very useful only for design engineers who really understand how the circuit works.
2. It is very difficult to simulate such a circuit as having more than two widely spread time constants, for instance PLL, AM/FM detector, crystal oscillator.
3. It is also difficult to derive device parameters, and installed model does not reflect many parasitic elements such as substrate current, parasitic transistors, thermal coupling etc. Some of them can be avoided by adding some appropriate circuits, however this is not so easy for the average engineers.
4. It cannot cope with a variation of circuit topology. We need to rewrite net lists and restart program whenever we change a circuit topology.

These show that circuit simulators are indeed user dependent program therefore it is very important to teach beginners how to use it.

Although the author mentioned about the shadow of circuit simulator, it is still very powerful tool. Dr. Minoru Nagata, Director of Central Research Laboratory Hitachi Ltd., showed the following evidence as an example.

In the past 2 years, analog LSI has been developing, number of transistors per chip increases twice while available time for design decreases two thirds. But design engineers have 20% decreased in their fail rate at the first cut. Dr. Nagata also said that layout productivity increased 10 times and design correction decreased one tenth during this period. He stressed that these result could not be got without circuit simulators.

The author pointed out how Japanese engineers thinking about analog circuit design productivity and circuit simulator. However analog circuit design still strongly depends on the designer of talent. Comparing the design of logic system to analog circuit, we would find that an one of apparent difference between them is that analog circuits has usually more than one complex function while one logic circuit element has only one function. Most digital system designers think their design in logic element or logic gate level, while analog designs are carried out in circuit element level such as transistors, resistor etc. A resistor in collector circuit works as a voltage dropper and same time it governs gain and frequency characteristics of that circuit. Analog circuits design engineer should always pay his attention to trade-off between these complex functions. Professional analog circuit designer is a man who knows these trade-off technology and who success to realize compact and high performance circuits.

As demands for analog circuit rising, we should solve this design productivity problem. How could we make beginner or computer designed analog circuits? Professor Nobuo Fujii at Tokyo Institute of Technologies and other members in the Technical Committee for Analog Circuit Design at Institute of Electrical Engineers of Japan (IEEJ), chaired by the author, has been discussed about these problem. We thought at first use of "Expert System" which installed many knowledge of experienced professional designers as a element functional circuit. We tried to categorize analog circuits by their function. However this idea did not work. Because of above mentioned reason, each circuit has complex functions, it was very difficult to find functional element circuit in a database format.

Analog systems can be described with a couple of differential equations and "analog computer" is a tool to solve differential equation. Analog computer consist of some operational element such as integrator, adder, multiplier, limiter etc. Recently we come to the conclusion that by taking this operational circuit as an element we could compose any analog circuit using them in principle, although the circuit compactness should be lost. Several case studies in the committee show that this idea works[6]. There needs further investigation before this idea would be real.

Analog Circuit Engineers in Japanese Industry

It is thought that rising digital technologies has been taking over analog circuits technologies. A number of laboratories in Japanese universities whose activities are in analog circuits fields, has been decreased recently. Dr. Minoru Nagata at Hitachi Ltd. questionnaired managers in several electronics factories to investigate what leading electronics engineers thinking about[2].

The followings are the results of Dr. Nagata's questionnaires.

QUESTIONNAIRE 1

Q. How do you think about an ability of newcome electronics engineers at your company? Please choice from the followings.

a) Newcomers know neither digital circuits nor analog circuit. Nothing about circuits technology.
b) Newcomers know about digital circuit very well but nothing about analog circuits.
c) Newcomers have average knowledge about either analog or digital circuits.
d) Newcomers know about analog circuit very well but nothing about digital circuits.
e) Newcomers know about computer software very well but nothing about hardware technologies.

RESULTS:

a).... 24 b) 16
c).... 11 d) 0
e).... 26

QUESTIONNAIRE 2

Q. We have two professional circuit engineers, one is in digital and the other in analog, available to add to your project troop. Which do you prefer, analog or digital?

RESULTS:

Analog .. 32(62%) Digital .. 20(38%)

QUESTIONNAIRE 3

Q. To support your urgent project, you can add ten more circuit engineers to your troop. What ratio of engineers, analog to digital, do you like?

RESULTS:

10 digital engineers	1
1 analog, 9 digital	1
2 analog, 8 digital	14
3 analog, 7 digital	16
4 analog, 6 digital	9
5 analog, 5 digital	2
6 analog, 4 digital	3
7 analog, 3 digital	3
8 analog, 2 digital	2
9 analog, 1 digital	0
10 analog engineers	1

Results of Questionnaire 1 confirm that a few universities are interested in analog circuit technology and most student are fond of computer software rather than hardware technology. This shows at the same time that most general people's interests are in digital field. It is, however, very interesting that industries need a lot of analog circuit engineers. Dr. Nagata said "Analog technology is a Key technology, while digital is a Main technology." It means that what governs the final performance of digital system such as speed and reliability is an analog circuit technology. Digital circuits are analog circuits in topological sense, they use only two states of the circuits. Therefore faster the digital LSI, more troubles arise which analog technologies are mandatory to solve.

As mentioned at the beginnings main productions of Japanese IC industries are digital LSI, they need much digital circuit engineer to hold their production. It is difficult for a digital circuit engineer to understand rather complicated analog circuit, but to the contrary analog circuit engineer can easily design digital circuits. By this reason analog engineers are tend to be thrown into digital project, it forms one way flow (diode) of engineers from analog to digital, making the number of analog circuit engineers in the industry decreased year by year. Nevertheless many leading project managers become aware of importance of analog technologies. Results of questionnaire 2 and 3 seem to show this situation.

Recent high speed digital LSI such as memory and CPU requests much more analog circuit technology and digital signal processing system (DSP) need AD/DA converter at their interface most of which are analog circuits. Furthermore raising new system such as VHF/UHF communication, HDTV, multimedia etc. should request much analog circuit engineers.

From historical view, in the field of high speed and high frequency, systems are implemented with analog technology at first, then according process technologies developing, they are took over by digital. For example in communication digital system are implemented in 9.6 kbit/s, while coaxial 400 Mbit/s and light 1.6 Gbit/s use analog technology. Another very interesting difference between two technologies are the number of transistors to realize the same function. Digital systems use a lot of transistors while analog use only one hundreds or less transistors. (Unfortunately this does not mean that design of analog system needs less human resources including designer's skill.)

To summarize, our industries become aware of importance of analog technologies and look for newcome analog engineer from university, but insufficient number of analog circuit engineers are supplied by universities.

Creation and Education of Next-Generation Engineers at the University

It is said recently that the number of Japanese high school students who want to take entrance examination for science or technology course of university has been decreasing year by year. Meanwhile the number of graduating students in technology course of university who want to get job at non-industrial company such as securities company and bank. For 30 years ago most student in department of electronics selected their course because they wanted to be an electronics engineer. But at present time, more than two thirds of them came with other reasons. In other words, many students in electronics course do not have their interest in electronics and study their curriculum only with a sense of duty. Instead, many students are fond of hitting a keyboard. They tend to play not in real world but in computer created virtual world. As a result, they think what circuit simulator outputs as a real circuit itself. Even young researcher in the doctor course sometimes write a paper using simulator only without simple experiment.

This seems an origin of why young analog circuits engineers disappear. Our discussion at the National Convention came to the conclusion that it is because of disappearance of "Radio boy." Radio boy means such a boy who likes assembling parts to make a radio receiver, HiFi reproducer or transmitter as his hobby. We think many of them grew up to be analog engineers and play an important role in the development of Japanese electronics industries. Professor Yanagisawa at Tokyo Institute

Technology (now moves to Shibaura Institute Technology) pointed out that the criminal of disappearance of radio boy is spread of LSI into electronics. LSI is quite a "black box" and to look into a package of LSI can never stimulate his curiosity! Therefore, in most university, professors are gradually increasing a percentage of basic experiments in their curriculum such as assembling a simple transistor circuits using a solder iron after designing it himself with a SPICE simulator. The author's experience shows that most student are attracted by these type of experiments.

The author believes that to increase "radio boy" is one of the most efficient means to increase good analog circuit engineers and it is an urgent matter for creating next generation analog engineer. Therefore it is very important to create system which inspire young people to be interesting in real electronics world. We must pay our effort to looking for such a system.

Conclusion

The author describes several problems with respect to the analog circuits technologies in Japan, design productivities, challenge to creation and how hand them down to the next generations. Potential analog circuits engineer are decreasing here. But it should be stressed that analog circuit technologies are always necessary in the wave front region of electronics technologies, therefore the key technologies to develop much higher performance digital system and much high frequency circuits. So we must make as many younger peoples as possible to be interesting in learning analog technologies.

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Gregory T. A. Kovacs

5. Thoughts on Becoming and Being an Analog Circuit Designer

Special commentary by Laurel Beth Joyce, Greg's wife

"My favorite programming language is solder."
—Todd K. Whitehurst
Stanford University, 1988

Well, here I am, finally writing this book chapter! Instead of trying to tell the reader how to design analog circuits (I'll leave it to the folks with circuits named after them to do that, unless you take my courses), I will discuss several aspects of becoming and being an analog circuit designer. I will try to cover a few areas that I think are important, particularly to someone considering a career in this field. My wife's comments near the end of this chapter will also be of considerable interest to the significant other (S.O.) of anyone considering this career choice.

Analog Circuit Designers

What type of person becomes an analog circuit designer? Perhaps the best way to address that question is to start by describing the types of people who do *not* become analog circuit designers! Examples are folks whose second career choice would have been accounting, people who say "dude" a lot, people who have time to sit around wondering why their belly-button lint is gray,[1] people who wear Birkenstock sandals and eat alfalfa, people who are frustrated by devices more complex than a paper clip, and people who are repeatedly abducted by space aliens.

In other words, analog circuit designers tend to be a creative, practical, and curious bunch of folks who are rarely abducted by space aliens. The typical analog designer doesn't worry too much about shaving on weekends (especially the female ones), drinks beer and eats pizza, owns an oscilloscope (see "Things You Need to Survive as a 'Real' Analog Designer" below), thinks modern art consisting of blank white canvases is a bunch of crap, occasionally uses "swear words," and may be considered a bit "eccentric" by his or her friends and colleagues. Over the years, knowing a fair number of analog designers, I have only encountered one notable exception: Jim Williams.[2]

1. Actually, my friends at the Office of Navel Research in Washington, DC, have studied this issue extensively. They have found that belly-button lint color is a complex function of clothing color, belly-button humidity, and the amount of cheese consumed.
2. He doesn't drink beer.

Why should anyone want to become an analog designer? Aside from the large amounts of money you earn, the hordes of attractive members of the opposite sex that are drawn to you by the heady smell of solder, the ability to simulate circuits in your head, and the undying respect of all other engineers, there is one really important advantage to this line of work: it's fun!

In fact, designing circuits can be absolutely wonderful. You create, from scratch, a complete working[3] circuit that accomplishes a function you (or your boss) desire. Once you get some experience, you can visualize how the circuit building blocks you know can be combined to get what you want. Sometimes you realize that you need to invent something really new to do a particular function. Creativity and a bit of insanity really helps with that.

You don't need big power tools, a yard full of old cars up on blocks, or a trip to the Himalayas to build analog circuits. Actually, what you do need are small power tools, a garage full of old oscilloscopes up on blocks, and a trip to some surplus stores in Mountain View. In any case, once you reach some level of "analog enlightenment," it is really addictive. This is good, because the majority of engineers have gotten so seduced by digital circuits and software that some very big electronics companies exist that do not have a single decent analog circuit designer in house. In other words, if you learn analog circuit design, you can get a job!

"I've heard enough! Sign me up!" If that's what you are thinking,[4] you may want to know how you can become an analog designer. One way is to learn "on the street" ("Hey buddy, wanna pick up some transistors cheap? . . . They've got high betas and they're clean!"). That works eventually (the word "eventually" is key), but most people go to a university and learn there. If you are remotely interested in the latter option, please read on . . .

Analog Boot Camp: One Way to Become an Analog Designer

I teach analog circuit design at Stanford,[5] along with my colleagues in the Department of Electrical Engineering. In recent years, we have taken great pains to upgrade the electronics courses to include more practical, design-oriented material. My own courses are considered "analog boot camp" for undergraduates who think of transistors only in

3. (eventually)
4. (if not, please put this book down and read that biography of Bill Gates over there to the left)
5. The opinions and/or other crap in this chapter are completely the fault of the author and do not reflect the opinions and/or other crap of Stanford University in any way.

terms of band diagrams. I'll share with you some of our "indoctrination" techniques . . . [6]

First, we administer an exam to weed out the people who should really be learning about French history or something like that. Here are a few sample questions:

Choose the single best answer.

1) The best all-around programming language is:

a) C
b) C++
c) BASIC
d) Fortran
e) solder

2) A "GUI" is:

a) a productivity-enhancing graphical user interface for modern computers
b) useful for opening beer bottles
c) a voltage regulation circuit invented by famous Dutch EE Cornelius von Fritzenfratz
d) who gives a crap, this test is about analog circuits!

3) Analog circuits are:

a) circuits involving only resistors and capacitors, like in first-year electronics, dude
b) circuits built with digital logic and no more than two discrete transistors that you debug by reprogramming EPROMS until they work
c) not needed now that we have the "Newton"
d) really cool

4) SPICE is:

a) stuff like salt and pepper you put on your food
b) the reason nobody needs to build real circuits at all
c) a program designed to see how quickly your computer bogs down when doing floating-point operations
d) the only reason we need computers, other than Tetris.™

5) "Solder suckers" are:

a) PG-rated, but can occasionally be seen on National Geographic specials
b) the black holes of circuits, often seen running around with current sources invented by Mr. Wilson (from "Dennis the Menace")
c) people who are lured into analog circuit design by evil professors
d) plastic pumps used to remove solder from component leads where those uneducated about analog design have made mistakes

6. These techniques have been developed over several decades by carefully selected teams of scientists from all over the world.

That sort of thing helps weed out the sick, the feeble-minded, and the history majors. Then we begin analog "basic training," which involves learning the following song for drill practice and considerable healthful marching and shouting.

Analog Boot Camp Drill Routine

by G. Kovacs

(The words are first barked out by the professor, then shouted back by students marching in formation.)

Analog circuits sure are fine,
Just can't get 'em off my mind.

Digital circuits ain't my kind,
Zeros and ones for simple minds.

I guess NAND gates aren't all that bad,
'Cause I need them for circuit CAD.

One, two, three, four,
Gain and bandwidth, we want more.

Five, six, seven, eight,
We don't want to oscillate.

Widlar, Wilson, Brokaw too,
They've got circuits, how 'bout you?

(*repeat*)

I also ask a few random questions and have been known to order a few push-ups here and there if, for example, a student cannot correctly distinguish between the Miller and Budweiser Effects. Now the students are ready for their plunge into the world of analog . . .

At this point, they are taught theory in one class and hands-on aspects in another. Essentially, the idea is to progress from the basic idea of an operational amplifier (op amp) through the necessary circuit building blocks that are required to design one. Finally, we reach the point where the students know enough to do that, and then we get into feedback and stability. Meanwhile, in the laboratory part of the class, the students are learning how to destroy most of the circuits covered in lecture. It is in the lab that we teach them the all-important "smoke principle" of solid-state devices. This is the formerly very closely guarded industrial secret that each discrete or integrated circuit is manufactured with a certain amount of smoke pre-packaged inside. If, through an inadvertent wiring error, conditions arise through which the smoke is permitted to escape, the device ceases to function. We also train the students to recognize and distinguish the smells of different burning components ("Ah yes, a carbon resistor seems to have burned up in this circuit . . . smells like 220KΩ.").

I am not kidding about this, but not more than ⅓ of the EE students at this level have ever used a soldering iron before! In contrast, nearly all of them have driven a BMW and can explain leveraged buyouts in great detail (I presume this is a phenomenon more common at schools where yuppy pupae are present in large numbers). After a little trial and error, most of them learn which end of the soldering iron is hot (I am told that those who never really figure this out generally transfer to a local state-run university where they can just write software, but I have no concrete evidence of this). Pretty soon, they not only know how to solder, but also how to use a wide range of up-to-date test equipment. (I worry about the ones who keep looking for an "auto setup" button on a voltmeter, though! . . . more on this below.)

At this point, we get the students into the guts of Boot Camp: design it, SPICE it, make it work, and examine the differences between the SPICE model and the real thing. The idea is to teach simulation as "virtual instruments" and then introduce the real ones (the type with knobs). We provide SPICE decks[7] for each circuit that are already on the student computers. We leave out critical component values for the students to choose. They have to come to lab with a running simulation and then build the circuit. This can be fun to watch the first time, as the students look around the lab for 10,000 amp current sources, diodes with forward voltages of exactly 0.700V, and 13.4567E3 ohm resistors. Eventually, they figure things out and get things working.[8]

We ask them to simulate and build a lot of discrete circuits, including power supplies, basic op amp circuits, single-transistor amplifiers, a simple op amp built from discretes, and power amplifiers. After that they build a project of their own choosing, demonstrating their analog design skills. This exercise gives them a chance to construct a complete circuit from scratch and write an instruction manual, specification sheet, and marketing sheet for whatever it is. Some students have built really amazing things, such as a waveform synthesizer, a heterodyne spectrum analyzer, an infrared remote control system, an acoustic rangefinder, etc. Some have built devices that are also humorous, including a fake leopard

7. "Gee, Dad, why do they call them SPICE decks?"
"Well, son, way back before they found a practical use for the 'Newton' in 2027, computers used punched paper cards as a way to enter data and programs. We called a stack of those cards a 'deck'."

8. Our current sources only go to 9,000 amps, we keep the 0.700-V diodes in another room, and they need to specify resistor values to a few more decimals or our component supplier doesn't know which value to provide.

fur-covered[9] laser/galvanometer system for a light show, a guitar amplifier that "goes to eleven," and a contraption that the student proudly described as a "large vibrator" (he meant "multivibrator," but it was terribly funny at the time).

Does it work? Are we able to turn out decent analog designers? Well, it seems to be working, and feedback from companies who have hired our students is positive.[10] For me, success can be measured by the number of students who actually learn to love analog circuit design despite the fact that they are growing up in a world devoid of Heathkits and basements full of surplus electronics to hack circuits with.

To illustrate the transformations that occur, I have reproduced a letter home from one of the students on his first and last days in Boot Camp (the names have been changed to protect the student's identity):

Day 1 of Boot Camp:

Dear Mom,

Things are going fine here at Stanford! Today we learned about "operational amplifiers." They are triangle-shaped things that can do basically anything. The textbook says they have an "ideal voltage source" inside. Tell Pop that this means I can hook one up to power the whole farm when I get home this summer! I can't wait!

Love,
Billy

Last day of Boot Camp:

Dear Mom,

I just finished my analog circuit training at Stanford! I now know I was wrong about operational amplifiers being able to power the whole farm! That was totally silly, because they are simply integrated circuits, and thus require external power. Also, their non-zero output resistance and short-circuit protection circuitry means that they can only supply a few milliamps of current.

Do you know why smoke comes out of transistors when they get too hot? I will explain it all to you, Pop, and the farmhands when I get back there in a few weeks.

I think we should consider turning the barn into a circuit design laboratory. Bossie could stay in my room, since I will probably spend most of my time out there. Please let me know if this is OK, because I would rather do this than take a job doing software-

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9. Of course, we use only fake leopard fur because it is an endangered species, and we are very politically correct. The only type of skin that is still OK to use for decorative purposes is that of Caucasian heterosexual males, but we were out of it at the time.
10. We all know that positive feedback can lead to oscillations, so we will have to keep an eye on this situation. Raising tuition seems to provide the necessary negative feedback to keep the system stable.

simulated power consumption validation of a subset of indirect-jump instructions of the new Valium computer chip at Interola's new lab in Lumbago, Oregon.

Love,
Billy

What Should Aspiring Analog Designers Read?

There is good stuff on analog circuits to read out there, and generally it is reasonably easy to locate. I am not going to go into the large number of books available other than to point out that you really need to have Horowitz and Hill, *The Art of Electronics* (Cambridge Press) and Gray and Meyer, *Analysis and Design of Analog Integrated Circuits* (John Wiley and Sons). Those two books are simply the essentials;[11] it's easy to supplement them from the droves of texts out there.

As far as journals go, there are several good ones out there. Of course, the IEEE has a few. Then there's *Wireless World*, put out by a bunch of hackers in the United Kingdom, with real depth mixed right in there with fun projects. Another good foreign offering is *Elektor*, which is put out by a bunch of hackers in Holland (the closed-loop cheese fondue controller project last year was awesome). The *Computer Applications Journal* (alias *Circuit Sewer*) is worth reading, but is aimed at those who think debugging a piece of hardware involves mainly fixing software (it is 90% digital subject matter, with occasional forays into scary things like op amps). What about those old standards like *Popular Electronics*? Well, they are OK for the occasional project idea, but as for technical content, I generally say, "Later!" (especially to ones with names like *Electronics Now!*).

One of the richest sources of information, and probably the least obvious to beginners, is the application notes written by the manufacturers of integrated circuits. Just think about it . . . they are trying to sell their wares by getting you excited about their uses.[12] They are absolutely packed with interesting circuits! Usually, you can get them for free, as well as sets of data books, just by calling the manufacturers. Saying you are a student usually helps, and will often get you free samples too. In case you don't know, the best ones are from National Semiconductor, Linear Technology, Maxim, Analog Devices, and Burr Brown.

11. Did I mention that this book is also one of the essentials? In any case, you are already clever enough to be reading it, so why bother!
12. They have to accomplish this by showing you cool circuits you can build, as opposed to traditional marketing approaches, such as those used to sell beer. I am still waiting for the Swedish Bipolar Bikini Team, though!

Things You Need to Survive as a "Real" Analog Designer

I am occasionally asked what you need to survive as a "real" analog designer. Well, this is a highly personal matter, but I can at least give my standard answer, which is the things I need (in order of importance):

1. An understanding significant other (S.O.)
2. A laboratory dog to keep my feet warm
3. A basic supply of discrete and integrated components
4. A decent oscilloscope
5. A power supply
6. A soldering iron
7. Basic hand tools
8. Cheap beer
9. A pad and pencil

An understanding S.O. is critical, because when you start coming home with large chunks of blue-colored equipment and go misty-eyed when you see an old Tektronix catalog, it takes a special kind of person to understand! Analog designers tend to build up huge collections of old oscilloscopes, circuit boards, random metal boxes, and all sorts of "precious" items that will come in handy some day. I think meeting an analog designer who isn't a packrat is about as likely as meeting the Swedish Bipolar Bikini Team.

A typical workbench for analog circuit design is shown in Figure 5–1. In addition, the "analog workstation," where most of the really good circuit ideas are developed, is shown in Figure 5–2. The very useful labora-

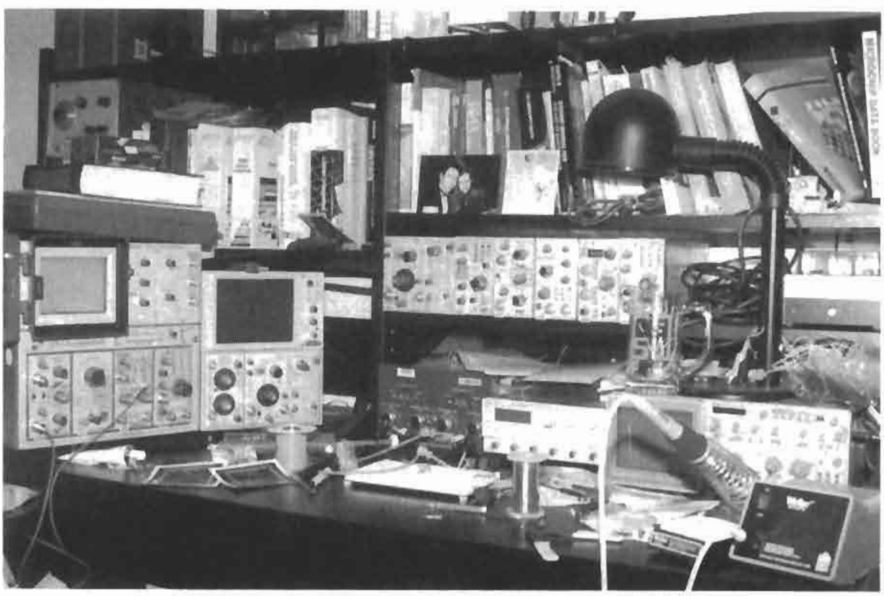

Figure 5–1. A typical workbench used for analog circuit design.

Figure 5–2.
An analog work station. This is the place many great circuit designs are developed.

tory dog (black Labrador called Rosie) is shown in Figure 5–3. She is better with a soldering iron than most engineers I know!

Comments on Test Instruments

Good test instruments are critical to a person's success as an analog circuit designer! They are the equivalents of musical instruments to a musician . . . you never share your Stradivarius (i.e., Tektronix 7904A oscilloscope) and need to be intimately familiar with its nuances to get the best performance out of it. Bottom lines here: 1) don't buy cheesy foreign test gear unless you absolutely have to, and 2) when you find

Figure 5–3.
Rosie, the laboratory dog in our house. She will debug any circuit for a piece of beef jerky.

your beautiful oscilloscope, spot-weld it to some part of your body so that it is not borrowed without your knowledge.

I am an absolute hard-core fan of Tektronix test equipment. Tektronix oscilloscopes (the most important item) are available with a wonderful user interface and provide extremely high performance plus real versatility. The only problem is that they don't make that kind any more.

In recent years, there has been a trend toward computer-controlled, menu-driven test instruments, rather than instruments that use a dedicated switch or knob for each function (so-called "knob-driven" instruments). In most cases, the push for menu-driven test instruments has an economic basis—they are simply cheaper to build or provide more features for the same price. However, there are practical drawbacks to that approach in many cases. A common example, familiar to anyone who has ever used an oscilloscope, is the frequent need to ground the input of a vertical channel to establish a "zero" reference. With a knob-driven instrument, a simple movement of the index finger and thumb will suffice. With a menu-driven instrument, one often has to fumble through several nested menus. This really sucks, and I think it is because they are starting to let MBAs design oscilloscopes. (I suppose one possible benefit of this is that soon 'scopes will have a built-in mode that tells you when to refinance your mortgage!)

Grounding a vertical channel's input is something you need to do often, and it is quite analogous to something familiar even to digital engineers, like going to the bathroom. You simply wouldn't want to scroll through a bunch of menus during your mad dash to the bathroom after the consumption of a bad burrito! There are several similar annoyances that can crop up when using menu-driven instruments (how about ten keystrokes to get a simple sine wave out of a signal generator?!).

To be fair, menu-driven instruments do have advantages. However, since I am not a big fan of them, I'll conveniently omit them here.[13] It always pisses me off to watch students hitting the "auto setup" button on the digital 'scopes in our teaching lab and assuming it is doing the right thing for them every time (not!). If we didn't force them to, most of them would not even explore the other functions![14] Advertisements for these new instruments often brag that they have a more "analog-like feel" (as opposed to what, a "primordial slime ooze feel"?). Let's get real here . . . at least in part, this is just another incarnation of the old engineering saying, "If you can't fix it, make it a feature." Since when was a "more chocolate-like taste" a real key reason to buy brown sludge instead of chocolate?

13. One of the key advantages is that they can help us lure would-be engineers into the lab. The type of EE student who doesn't like hands-on hardware engineering (you know, the ones who end up working for Microsloth) can be attracted by the nice menus long enough to actually see how much fun electronics can be.

14. At this point, I will admit that our VCR does blink "12:00," but I hear there will be an "auto-setup" mode on new ones! I had to fiddle with it for hours to get it to blink "12:00."

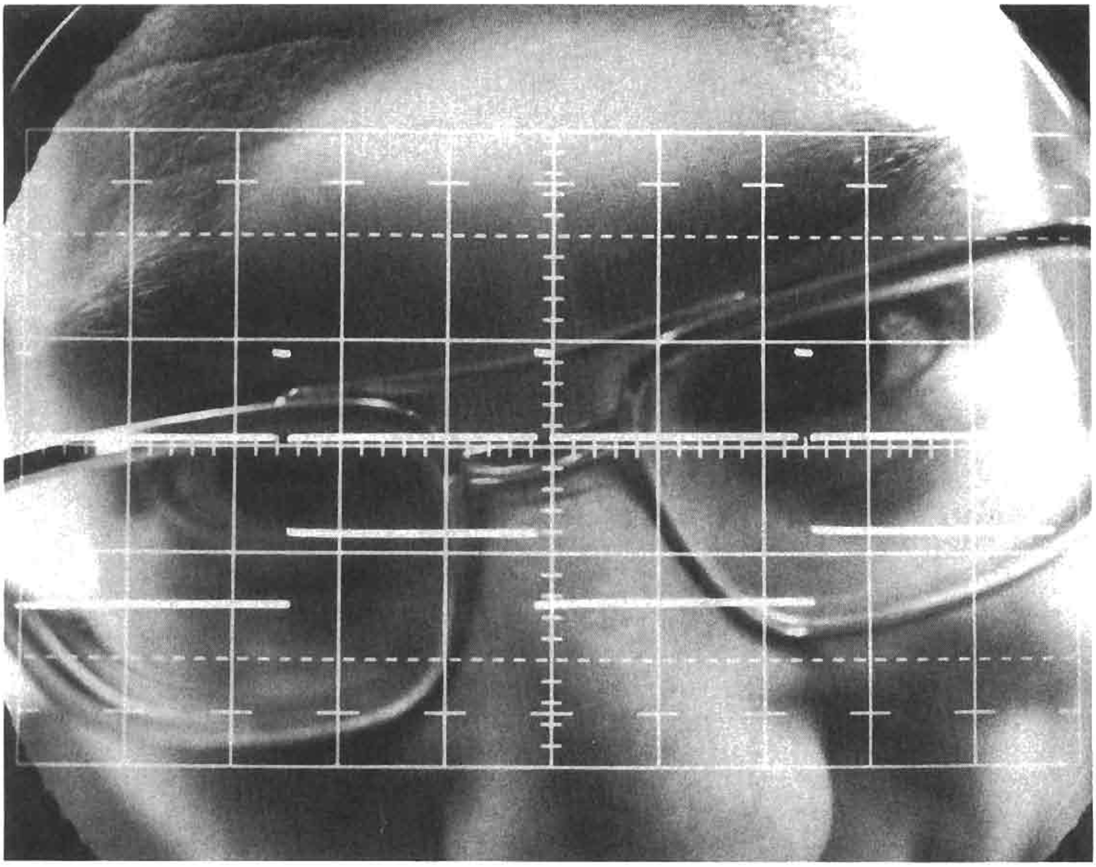

Figure 5–4.
What you look like to your oscilloscope (yuk!). Actually, this is what Jim Williams looks like to his oscilloscope. You probably won't look that silly.

I am sad to report that knob-driven analog test instruments are becoming more difficult to get. I also have to admit that performance is improving while relative prices are dropping, so "user-friendly" instruments aren't all that bad. Students take note: at least try to check out instruments with knobs, in between pressing "auto-setup" and "help" keys! A great place to find this stuff is at your friendly neighborhood university (we'll never surrender!), local "ham radio" swap meets, and companies that specialize in used test equipment. Also, remember to be nice to your oscilloscope! What you look like to that faithful piece of test gear is shown in Figure 5–4.

What Does My Wife Think about All of This?

This section was written by my wife, Laurel Beth Joyce, the pride of Mars, PA.[15] It is added to provide an extra sense of realism and to prepare

15. I am not making this up. This is because I don't need to. Western PA has tons of great names of towns, like Beaver, Moon, etc., as well as great names for public utilities, like "Peoples' Natural Gas." Naturally, nobody from there thinks any of this is funny.

a would-be analog circuit designer for the impact this career choice has on one's home life.[16]

If your S.O. is an analog designer, your relationship will be much happier once you come to understand and accept some of the basic differences between analog circuit designers and normal people.

1. Analog circuit designers consider beer one of the major food groups and an essential hacking tool. (See "Things You Need to Survive as a 'Real' Analog Designer.") To avoid major altercations, be sure there's always beer in the house.

Fortunately, my husband's students signed him up for a Beer-of-the Month club. Each month the UPS lady drops a big box of beer on our doorstep, putting him in hacker heaven and saving me many trips to the beer store.

2. Circuit designers don't tell time in the same way that the rest of us do. Unfortunately, I still haven't figured out the exact formula for converting circuit design time into regular time.

For example, let's say my husband is in the middle of a hacking project at work and he calls to tell me that he's going to head home in about half an hour. If he's alone and I know he's working on a project that doesn't require an oscilloscope, I simply multiply the time by two. If there is an oscilloscope involved, I multiply by three. If he's got any circuit design friends with him, I generally add at least 40 minutes per friend if they're not drinking beer and an extra 2 hours per friend if they are. I believe the beer effect is nonlinear. My current empirical formula for computing circuit design time in minutes is thus:

$$t_{cd} = (2 + N_{scopes})\, t + (40 + 120\, k_{brewski})\, N_{friends}$$

where N_{scopes} is the number of oscilloscopes present, $k_{brewski}$ is the linear approximation for the nonlinear beer effect (taken to be one, but can be replaced by a suitable time-dependent nonlinearity) and $N_{friends}$ is the number of circuit design friends present.

My calculations are rarely perfect, so I'm pretty sure there are some other variables involved. It may have something to do with the number of op amps in the project, but since I'm still trying to figure out what an op amp is, I haven't quite determined how that should factor into the formula.

My suspicion is that this formula varies slightly among hackers, but you're probably safe to use this as a starting point for deriving your own formula.

3. Circuit designers have an interesting concept of economics. Last weekend we wandered down the breakfast cereal aisle of our local

16. The opinions and/or other crap written by my wife are completely her fault and do not reflect the opinions and/or other crap of Stanford University or myself in any way.

grocery and my husband was astounded that the big box of Cap'n Crunch cost $4.58. He considered it so expensive, he wanted to put it back on the shelf.

In contrast, he tells me that $2,000 is a bargain for a 20-year-old, used oscilloscope that only smokes a little bit and will only require one or two weekends to fix up. And $1,000 is a great deal on a 'scope that doesn't work at all, because it can be cannibalized for parts to repair the 'scopes that smoke comes out of (assuming that it has enough parts left that never smoked).

4. When an analog circuit designer brings home a new piece of equipment, the S.O. becomes invisible for several hours.

I used to get jealous every time a new 'scope or signal generator came into the house. He'd burst in the door all breathless and say, "Hi, Laurel, look what I found today. Isn't she beautiful? I'm just going to take her upstairs for a few minutes." The two would disappear into the lab and I'd hear lots of cooing and giddy chatter that went on until daybreak. It was as if my S.O. was bringing home his mistress and dashing up to our bedroom right under my nose.

If the dog or I went into the room, he wouldn't even notice us. I could tell him that beer had just been outlawed in the United States or the dog could vomit on his shoes. He'd just say, "I'll be with you in a minute," and go back to grinning and twiddling the knobs of his new toy.

When you realize it's no use being jealous and that you'll never be able to compete with these machines (unless you want to turn to the folks at Tektronix for fashion advice and get some clothes in that particular shade of blue, some 'scope knob earrings and some WD-40 cologne), you can actually have some fun when your S.O. is in this condition. If you like to watch TV, you've got the remote control to yourself for a few hours. If you have friends that your S.O. can't stand, invite them over for a party. If you're angry with your S.O. you can stand there and say nasty things ("You solder-sucking slimeball!"), get all the anger out of your system, and he'll remain totally oblivious. Be creative!

I was miserable before I learned that these basic differences and quirks are characteristic of *most* analog circuit designers, not just my husband. When I finally understood that they're simply a different species, my bills for psychoanalysis decreased significantly.

There are a couple of other things that help, too. First, ask all of your relatives to move to towns where there are used test equipment shops or frequent swap meets. If you don't, you may never see them again. It took six years for my husband to meet my Aunt Gertrude, but as soon as he found out that Crazy Egbert's World of 'Scopes was only 12 miles from her house, we were on an airplane—"Because I feel terrible that it has taken me so long to meet your aunt"—within 24 hours.

And, when all else fails, you may have to resort to the spouse alignment unit (SAU). Mine is a wooden rolling pin (shown in Figure 5–5),

Figure 5–5. The pride of Mars, PA, with her spouse alignment unit (SAU).

but I hear a baseball bat or cast-iron skillet works just as well. The SAU comes in handy, for example, when you're hosting a large dinner party, all the guests have arrived and are waiting for their meal, and your analog circuit designer has said he'll join the party "in just a minute" for the past two hours. In this situation you should quietly hide the SAU up your sleeve, excuse yourself while flashing a charming smile at your guests, waltz into the lab, yank the plug on the soldering iron and strike a threatening pose with the SAU.

It's kind of like training a dog with a rolled-up newspaper—you only have to use it once. After that, the sight of the unit or the threat that you're in the mood to do some baking will yield the desired response.

Conclusion

I hope this chapter has given you some sense of what you need to learn and obtain to become an analog circuit designer, as well as some of the emotional challenges in store for you. It would be great if you considered it as an alternative to the digital- or software-based engineering drudgery that you are statistically likely to end up doing. There may yet be some burnt resistors and oscillations in your future!

6. Cargo Cult Science*

During the Middle Ages there were all kinds of crazy ideas, such as that a piece of rhinoceros horn would increase potency. Then a method was discovered for separating the ideas—which was to try one to see if it worked, and if it didn't work, to eliminate it. This method became organized, of course, into science. And it developed very well, so that we are now in the scientific age. It is such a scientific age, in fact, that we have difficulty in understanding how witch doctors could ever have existed, when nothing that they proposed ever really worked—or very little of it did.

But even today I meet lots of people who sooner or later get me into a conversation about UFOs, or astrology, or some form of mysticism, expanded consciousness, new type of awareness, ESP, and so forth. And I've concluded that it's not a scientific world.

Most people believe so many wonderful things that I decided to investigate why they did. And what has been referred to as my curiosity for investigation has landed me in a difficulty where I found so much junk that I'm overwhelmed. First I started out by investigating various ideas of mysticism, and mystic experiences. I went into isolation tanks and got many hours of hallucinations, so I know something about that. Then I went to Esalen, which is a hotbed of this kind of thought (it's a wonderful place; you should go visit there). Then I became overwhelmed. I didn't realize how much there was.

At Esalen there are some large baths fed by hot springs situated on a ledge about thirty feet above the ocean. One of my most pleasurable experiences has been to sit in one of those baths and watch the waves crashing onto the rocky shore below, to gaze into the clear blue sky above, and to study a beautiful nude as she quietly appears and settles into the bath with me.

One time I sat down in a bath where there was a beautiful girl sitting with a guy who didn't seem to know her. Right away I began thinking, "Gee! How am I gonna get started talking to this beautiful nude babe?"

I'm trying to figure out what to say, when the guy says to her, "I'm, uh, studying massage. Could I practice on you?"

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*Adapted from the Cal Tech commencement address given in 1974.

"Sure," she says. They get out of the bath and she lies down on a massage table nearby.

I think to myself, "What a nifty line! I can never think of anything like that!" He starts to rub her big toe. "I think I feel it," he says. "I feel a kind of dent—is that the pituitary?"

I blurt out, "You're a helluva long way from the pituitary, man!"

They looked at me, horrified—I had blown my cover—and said, "It's reflexology!"

I quickly closed my eyes and appeared to be meditating.

That's just an example of the kind of things that overwhelm me. I also looked into extrasensory perception and PSI phenomena, and the latest craze there was Uri Geller, a man who is supposed to be able to bend keys by rubbing them with his finger. So I went to his hotel room, on his invitation, to see a demonstration of both mindreading and bending keys. He didn't do any mindreading that succeeded; nobody can read my mind, I guess. And my boy held a key and Geller rubbed it, and nothing happened. Then he told us it works better under water, and so you can picture all of us standing in the bathroom with the water turned on and the key under it, and him rubbing the key with his finger. Nothing happened. So I was unable to investigate that phenomenon.

But then I began to think, what else is there that we believe? (And I thought then about the witch doctors, and how easy it would have been to check on them by noticing that nothing really worked.) So I found things that even more people believe, such as that we have some knowledge of how to educate. There are big schools of reading methods and mathematics methods, and so forth, but if you notice, you'll see the reading scores keep going down—or hardly going up—in spite of the fact that we continually use these same people to improve the methods. There's a witch doctor remedy that doesn't work. It ought to be looked into; how do they know that their method should work? Another example is how to treat criminals. We obviously have made no progress—lots of theory, but no progress—in decreasing the amount of crime by the method that we use to handle criminals.

Yet these things are said to be scientific. We study them. And I think ordinary people with commonsense ideas are intimidated by this pseudoscience. A teacher who has some good idea of how to teach her children to read is forced by the school system to do it some other way—or is even fooled by the school system into thinking that her method is not necessarily a good one. Or a parent of bad boys, after disciplining them in one way or another, feels guilty for the rest of her life because she didn't do "the right thing," according to the experts.

So we really ought to look into theories that don't work, and science that isn't science.

I think the educational and psychological studies I mentioned are examples of what I would like to call cargo cult science. In the South Seas there is a cargo cult of people. During the war they saw airplanes land with lots of good materials, and they want the same thing to happen now. So they've arranged to make things like runways, to put fires along the sides of the runways, to make a wooden hut for a man to sit in, with two wooden pieces on his head like headphones and bars of bamboo sticking out like antennas—he's the controller—and they wait for the airplanes to land. They're doing everything right. The form is perfect. It looks exactly the way it looked before. But it doesn't work. No airplanes land. So I call these things cargo cult science, because they follow all the apparent precepts and forms of scientific investigation, but they're missing something essential, because the planes don't land.

Now it behooves me, of course, to tell you what they're missing. But it would be just about as difficult to explain to the South Sea Islanders how they have to arrange things so that they get some wealth in their system. It is not something simple like telling them how to improve the shapes of the earphones. But there is one feature I notice that is generally missing in cargo cult science. That is the idea that we all hope you have learned in studying science in school—we never explicitly say what this is, but just hope that you catch on by all the examples of scientific investigation. It is interesting, therefore, to bring it out now and speak of it explicitly. It's a kind of scientific integrity, a principle of scientific thought that corresponds to a kind of utter honesty—a kind of leaning over backwards. For example, if you're doing an experiment, you should report everything that you think might make it invalid—not only what you think is right about it: other causes that could possibly explain your results; and things you thought of that you've eliminated by some other experiment, and how they worked—to make sure the other fellow can tell they have been eliminated.

Details that could throw doubt on your interpretation must be given, if you know them. You must do the best you can—if you know anything at all wrong, or possibly wrong—to explain it. If you make a theory, for example, and advertise it, or put it out, then you must also put down all the facts that disagree with it, as well as those that agree with it. There is also a more subtle problem. When you have put a lot of ideas together to make an elaborate theory, you want to make sure, when explaining what it fits, that those things it fits are not just the things that gave you the idea for the theory; but that the finished theory makes something else come out right, in addition.

In summary, the idea is to try to give all of the information to help others to judge the value of your contribution; not just the information that leads to judgment in one particular direction or another.

The easiest way to explain this idea is to contrast it, for example, with advertising. Last night I heard that Wesson oil doesn't soak through food. Well, that's true. It's not dishonest; but the thing I'm talking about is not just a matter of not being dishonest, it's a matter of scientific integrity, which is another level. The fact that should be added to that advertising statement is that no oils soak through food, if operated at a certain temperature. If operated at another temperature, they all will—including Wesson oil. So it's the implication which has been conveyed, not the fact, which is true, and the difference is what we have to deal with.

We've learned from experience that the truth will come out. Other experimenters will repeat your experiment and find out whether you were wrong or right. Nature's phenomena will agree or they'll disagree with your theory. And, although you may gain some temporary fame and excitement, you will not gain a good reputation as a scientist if you haven't tried to be very careful in this kind of work. And it's this type of integrity, this kind of care not to fool yourself, that is missing to a large extent in much of the research in cargo cult science.

A great deal of their difficulty is, of course, the difficulty of the subject and the inapplicability of the scientific method to the subject. Nevertheless, it should be remarked that this is not the only difficulty. That's why the planes don't land—but they don't land.

We have learned a lot from experience about how to handle some of the ways we fool ourselves. One example: Millikan measured the charge on an electron by an experiment with falling oil drops, and got an answer which we now know not to be quite right. It's a little bit off, because he had the incorrect value for the viscosity of air. It's interesting to look at the history of measurements of the charge of the electron, after Millikan. If you plot them as a function of time, you find that one is a little bigger than Millikan's, and the next one's a little bit bigger than that, and the next one's a little bit bigger than that, until finally they settle down to a number which is higher.

Why didn't they discover that the new number was higher right away? It's a thing that scientists are ashamed of—this history—because it's apparent that people did things like this: When they got a number that was too high above Millikan's, they thought something must be wrong—and they would look for and find a reason why something might be wrong. When they got a number closer to Millikan's value they didn't look so hard. And so they eliminated the numbers that were too far off, and did other things like that. We've learned those tricks nowadays, and now we don't have that kind of a disease.

But this long history of learning how to not fool ourselves—of having utter scientific integrity—is, I'm sorry to say, something that we haven't specifically included in any particular course that I know of. We just hope you've caught on by osmosis.

The first principle is that you must not fool yourself—and you are the easiest person to fool. So you have to be very careful about that. After you've not fooled yourself, it's easy not to fool other scientists. You just have to be honest in a conventional way after that.

I would like to add something that's not essential to the science, but something I kind of believe, which is that you should not fool the layman when you're talking as a scientist. I am not trying to tell you what to do about cheating on your wife, or fooling your girlfriend, or something like that, when you're not trying to be a scientist, but just trying to be an ordinary human being. We'll leave those problems up to you and your rabbi. I'm talking about a specific, extra type of integrity that is not lying, but bending over backwards to show how you're maybe wrong, that you ought to have when acting as a scientist. And this is our responsibility as scientists, certainly to other scientists, and I think to laymen.

For example, I was a little surprised when I was talking to a friend who was going to go on the radio. He does work on cosmology and astronomy, and he wondered how he would explain what the applications of this work were. "Well," I said, "there aren't any." He said, "Yes, but then we won't get support for more research of this kind." I think that's kind of dishonest. If you're representing yourself as a scientist, then you should explain to the layman what you're doing—and if they don't want to support you under those circumstances, then that's their decision.

One example of the principle is this: If you've made up your mind to test a theory, or you want to explain some idea, you should always decide to publish it whichever way it comes out. If we only publish results of a certain kind, we can make the argument look good. We must publish both kinds of results.

I say that's also important in giving certain types of government advice. Supposing a senator asked you for advice about whether drilling a hole should be done in his state; and you decide it would be better in some other state. If you don't publish such a result, it seems to me you're not giving scientific advice. You're being used. If your answer happens to come out in the direction the government or the politicians like, they can use it as an argument in their favor; if it comes out the other way, they don't publish it at all. That's not giving scientific advice.

Other kinds of errors are more characteristic of poor science. When I was at Cornell, I often talked to the people in the psychology department. One of the students told me she wanted to do an experiment that went something like this—it had been found by others that under certain circumstances, X, rats did something, A. She was curious as to whether, if she changed the circumstances to Y, they would still do A. So her proposal was to do the experiment under circumstances Y and see if they still did A.

I explained to her that it was necessary first to repeat in her laboratory the experiment of the other person—to do it under condition X to see if she could also get result A, and then change to Y and see if A changed. Then she would know that the real difference was the thing she thought she had under control.

She was very delighted with this new idea, and went to her professor. And his reply was, no, you cannot do that, because the experiment has already been done and you would be wasting time. This was in about 1947 or so, and it seems to have been the general policy then to not try to repeat psychological experiments, but only to change the conditions and see what happens.

Nowadays there's a certain danger of the same thing happening, even in the famous field of physics. I was shocked to hear of an experiment done at the big accelerator at the National Accelerator Laboratory, where a person used deuterium. In order to compare his heavy hydrogen results to what might happen with light hydrogen, he had to use data from someone else's experiment on light hydrogen, which was done on different apparatus. When asked why, he said it was because he couldn't get time on the program (because there's so little time and it's such expensive apparatus) to do the experiment with light hydrogen on this apparatus because there wouldn't be any new result. And so the men in charge of programs at NAL are so anxious for new results, in order to get more money to keep the thing going for public relations purposes, they are destroying—possibly—the value of the experiments themselves, which is the whole purpose of the thing. It is often hard for the experimenters there to complete their work as their scientific integrity demands.

All experiments in psychology are not of this type, however. For example, there have been many experiments running rats through all kinds of mazes, and so on—with little clear result. But in 1937 a man named Young did a very interesting one. He had a long corridor with doors all along one side where the rats came in, and doors along the other side where the food was. He wanted to see if he could train the rats to go in at the third door down from where he started them off. No. The rats went immediately to the door where the food had been the time before.

The question was, how did the rats know because the corridor was so beautifully built and so uniform that this was the same door as before? Obviously there was something about the door that was different from the other doors. So he painted the doors very carefully, arranging the textures on the faces of the doors exactly the same. Still the rats could tell. Then he thought maybe the rats were smelling the food, so he used chemicals to change the smell after each run. Still the rats could tell. Then he realized the rats might be able to tell by seeing the lights and the arrangement in the laboratory like any commonsense person. So he covered the corridor, and still the rats could tell.

He finally found that they could tell by the way the floor sounded when they ran over it. And he could only fix that by putting his corridor in sand. So he covered one after another of all possible clues and finally was able to fool the rats so that they had to learn to go in the third door. If he relaxed any of his conditions, the rats could tell.

Now, from a scientific standpoint, that is an A-number-one experiment. That is the experiment that makes rat-running experiments sensible, because it uncovers the clues that the rat is really using—not what you think it's using. And that is the experiment that tells exactly what conditions you have to use in order to be careful and control everything in an experiment with rat-running.

I looked into the subsequent history of this research. The next experiment, and the one after that, never referred to Mr. Young. They never used any of his criteria of putting the corridor on sand, or being very careful. They just went right on running rats in the same old way, and paid no attention to the great discoveries of Mr. Young, and his papers are not referred to, because he didn't discover anything about the rats. In fact, he discovered all the things you have to do to discover something about rats. But not paying attention to experiments like that is a characteristic of cargo cult science.

Another example is the ESP experiments of Mr. Rhine, and other people. As various people have made criticisms—and they themselves have made criticisms of their own experiments—they improve the techniques so that the effects are smaller, and smaller, and smaller until they gradually disappear. All the parapsychologists are looking for some experiment that can be repeated—that you can do again and get the same effect—statistically, even. They run a million rats—no, it's people this time—they do a lot of things and get a certain statistical effect. Next time they try it they don't get it any more. And now you find a man saying that it is an irrelevant demand to expect a repeatable experiment. This is science?

This man also speaks about a new institution, in a talk in which he was resigning as Director of the Institute of Parapsychology. And, in telling people what to do next, he says that one of the things they have to do is be sure they only train students who have shown their ability to get PSI results to an acceptable extent—not to waste their time on those ambitious and interested students who get only chance results. It is very dangerous to have such a policy in teaching—to teach students only how to get certain results, rather than how to do an experiment with scientific integrity.

So I have just one wish for you—the good luck to be somewhere where you are free to maintain the kind of integrity I have described, and where you do not feel forced by a need to maintain your position in the organization, or financial support, or so on, to lose your integrity. May you have that freedom.

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Part Two

Making It Work

Five authors in this section give guided tours into what it takes to go from concept to a completed, functional circuit. Steve Roach shows how monstrously complex a "simple" voltage divider can become when it's an oscilloscope input attenuator. Bill Gross gives an eye-opening trip through the development process of an analog integrated circuit, with special emphasis on how tradeoffs must be dealt with. James Bryant explores a fast, flexible way to breadboard analog circuits which is usable from DC to high frequency. A true pioneer in wideband oscilloscope design, Carl Battjes, details the intricacies of T-coil design, an enabling technology for wideband oscilloscopes. In the section's finale, Jim Williams writes about how hard it can be to get your arms around just what the problem is. Imagine taking almost a year to find the right way to turn on a light bulb!

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7. Signal Conditioning in Oscilloscopes and the Spirit of Invention

The Spirit of Invention

When I was a child my grandfather routinely asked me if I was going to be an engineer when I grew up. Since some of my great-uncles worked on the railroads, I sincerely thought he wanted me to follow in their footsteps. My grandfather died before I clarified exactly what kind of engineer he hoped I would become, but I think he would approve of my interpretation.

I still wasn't sure what an engineer was when I discovered I wanted to be an inventor. I truly pictured myself alone in my basement toiling on the important but neglected problems of humanity. Seeking help, I joined the Rocky Mountain Inventors' Congress. They held a conference on invention where I met men carrying whole suitcases filled with clever little mechanical devices. Many of these guys were disgruntled and cranky because the world didn't appreciate their contributions. One of the speakers, a very successful independent inventor, told of a bankrupt widow whose husband had worked twenty years in isolation and secrecy inventing a mechanical tomato peeler. The tomato peeler had consumed the family savings, and the widow had asked the speaker to salvage the device. With sadness the speaker related the necessity of informing her that tomatoes were peeled in industrial quantities with sulfuric acid. Apparently the inventor had been too narrowly focused to realize that in some cases molecules are more powerful than machines.

I didn't want to become disgruntled, cranky, or isolated and I didn't even own a basement. So I went to engineering school and adopted a much easier approach to inventing. I now design products for companies with such basic comforts as R&D budgets, support staff, and manufacturing operations. Along the way I have discovered many ways of nurturing inventiveness. Here are some techniques that seem to work:

Give yourself time to invent. If necessary, steal this time from the unending rote tasks that your employer so readily recognizes and rewards. I try to work on things that have nothing to do with a particular product, have no schedule, and have no one expecting results. I spend time on highly tangential ideas that have little hope for success. I can fail again and again in this daydream domain with no sense of loss.

Get excited. Enjoy the thrilling early hours of a new idea. Stay up all night, lose sleep, and neglect your responsibilities. Freely explore tangents to your new idea. Digress fearlessly and entertain the absurd. Invent in the morning or whenever you are most energetic. Save your "real" work for when you are tired.

Master the fundamentals of your field. The most original and creative engineers I have known have an astonishing command of undergraduate-level engineering. Invention in technology almost always stems from the novel application of elementary principles. Mastery of fundamentals allows you to consider, discard, and develop numerous ideas quickly, accurately, and fairly. I believe so much in this concept that I have begun taking undergraduate classes over again and paying very careful attention.

Honestly evaluate the utility of your new idea at the right time: late enough not to cut off explorations of alternatives and wild notions, but early enough that your creativity doesn't go stale. In this stage you must ask the hardest questions: "Is this new thing useful to anyone else? Exactly where and how is it useful? Is it really a better solution or just a clever configuration of parts?" Even if you discover that your creation has no apparent utility, savor the fun you had exploring it and be thankful that you don't have the very hard work of developing it.

Creativity is not a competitive process. It is sad that we engineers are so inculcated with the competitive approach that we use it even privately. You must suspend this internal competition because almost all of your new ideas will fail. This is a fact, but it doesn't detract a bit from the fun of inventing.

Now it's time to get on to a very old and interesting analog design problem where there is still a great deal of room for invention.

Requirements for Signal Conditioning in Oscilloscopes

Most of my tenure as an electrical engineer has been spent designing analog subsystems of digital oscilloscopes. A digital oscilloscope is a rather pure and wholesome microcosm of signal processing and measurement, but at the signal inputs the instrument meets the inhospitable real world. The input signal-conditioning electronics, sometimes referred to as the "front-end" of the instrument, includes the attenuators, high-impedance buffer, and pre-amplifier. Figure 7–1 depicts a typical front-end and is annotated with some of the performance requirements.

The combination of requirements makes the design of an oscilloscope front-end very difficult. The front-end of a 500MHz oscilloscope develops nearly 1GHz of bandwidth and must have a very clean step response. It operates at this bandwidth with a 1MΩ input resistance! No significant resonances are allowed out to 5GHz or so (where everything wants to resonate). Because we must maintain high input resistance and low capacitance, transmission lines (the usual method of handling microwave

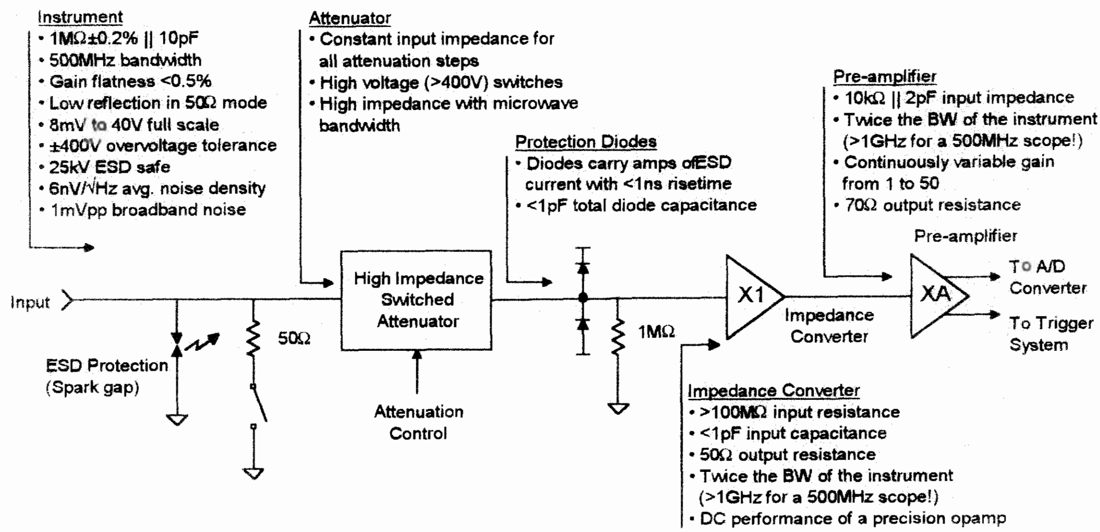


Figure 7–1. Annotated diagram of an oscilloscope front-end, showing specifications and requirements at each stage.

signals) are not allowed! The designer's only defense is to keep the physical dimensions of the circuit very small. To obtain the 1GHz bandwidth we must use microwave components. Microwave transistors and diodes are typically very delicate, yet the front-end has to withstand ±400V excursions and high-voltage electrostatic discharges. Perhaps the most difficult requirement is high gain flatness from DC to a significant fraction of full bandwidth.

A solid grasp of the relationships between the frequency and time domains is essential for the mastery of these design challenges. In the following I will present several examples illustrating the intuitive connections between the frequency magnitude and step responses.

The Frequency and Time Domains

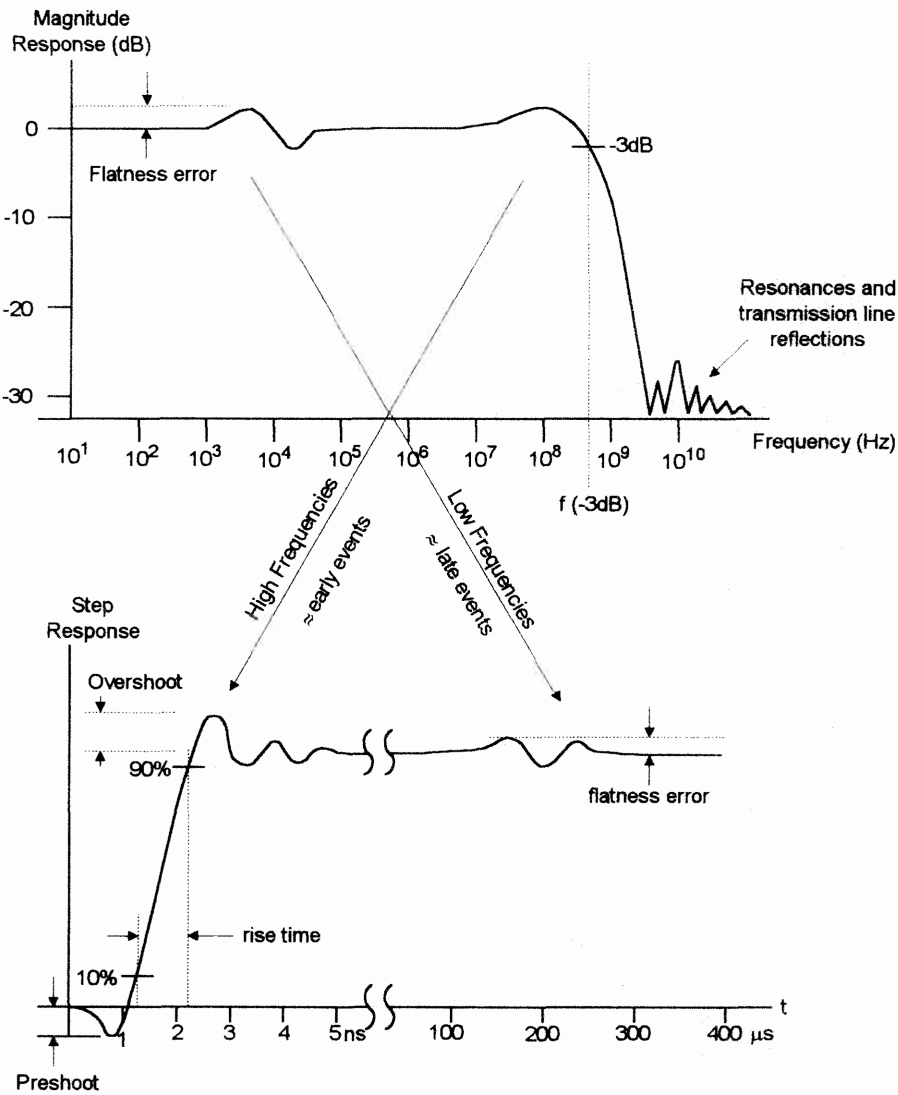
Oscilloscopes are specified at only two frequencies: DC and the -3dB point. Worse, the manufacturers usually state the vertical accuracy at DC only, as if an oscilloscope were a voltmeter! Why is a time domain measuring device specified in the frequency domain? The reason is that bandwidth measurements are traceable to international standards, whereas it is extremely difficult to generate an impulse or step waveform with known properties (Andrews 1983, Rush 1990).

Regardless of how oscilloscopes are specified, in actual practice oscilloscope designers concern themselves almost exclusively with the step response. There are several reasons for focusing on the step response: (1) a good step response is what the users really need in a time domain instrument, (2) the step response conveys at a glance information about a very wide band of frequencies, (3) with practice you can learn to intuitively relate the step response to the frequency response, and (4) the step response will be used by your competitors to find your weaknesses and attack your product.

Figure 7–2 defines the terms of the frequency and step responses and shows the meaning of flatness error. Response flatness is a qualitative notion that refers roughly to gain errors not associated with the poles that determine the cutoff frequency, or equivalently to step response errors following the initial transition. To assess flatness we generally ignore peaking of the magnitude near the 3dB frequency. We also ignore short-term ringing caused by the initial transition in the step response.

Figure 7–2 illustrates the rough correspondence between the high-frequency portions of the magnitude response and the early events in the step response. Similarly, disturbances in the magnitude response at low frequencies generate long-term flatness problems in the step response

Figure 7–2. Definition of terms and relationships between the frequency magnitude and step responses.



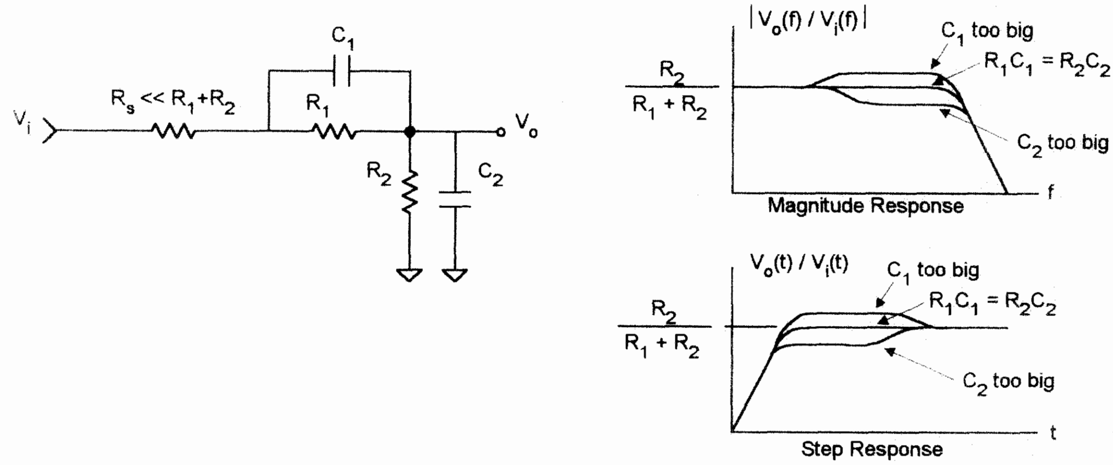
(Kamath 1974). Thus the step response contains information about a very wide band of frequencies, when observed over a long enough time period. For example, looking at the first ten nanoseconds (ns) of the step conveys frequency domain information from the upper bandwidth of the instrument down to approximately 1/(10ns) or 100MHz.

Figure 7–3 shows an RC circuit that effectively models most sources of flatness errors. Even unusual sources of flatness errors, such as dielectric absorption and thermal transients in transistors, can be understood with similar RC circuit models. The attenuator and impedance converter generally behave like series and parallel combinations of simple RC circuits. Circuits of this form often create flatness problems at low frequencies because of the high resistances in an oscilloscope front-end. In contrast, the high-frequency problems are frequently the result of the innumerable tiny inductors and inadvertent transmission lines introduced in the physical construction of the circuit. Notice how in Figure 7–3 the reciprocal nature of the frequency and step responses is well represented.

High Impedance at High Frequency: The Impedance Converter

Oscilloscopes by convention and tradition have 1MΩ inputs with just a few picofarads of input capacitance. The 1MΩ input resistance largely determines the attenuation factor of passive probes, and therefore must be accurate and stable. To maintain the accuracy of the input resistance, the oscilloscope incorporates a very high input impedance unity gain buffer (Figure 7–1). This buffer, sometimes called an "impedance converter," presents more than 100MΩ at its input while providing a low-impedance, approximately 50Ω output to drive the pre-amp. In a 500MHz oscilloscope the impedance converter may have 1GHz of bandwidth and very carefully controlled time domain response. This section

Figure 7–3.
A simple circuit that models most sources of flatness errors.



shows one way in which these and the many additional requirements of Figure 7–1 can be met (Rush 1986).

A silicon field effect transistor (FET) acting as a source follower is the only type of commercially available device suitable for implementing the impedance converter. For 500MHz instruments, we need a source follower with the highest possible transconductance combined with the lowest gate-drain capacitance. These parameters are so important in a 500MHz instrument that oscilloscope designers resort to the use of short-channel MOSFETs in spite of their many shortcomings. MOSFETs with short channel lengths and thin gate oxide layers develop very high transconductance relative to their terminal capacitances. However, they suffer from channel length modulation effects which give them undesirably high source-to-drain or output conductance. MOSFETs are surface conduction devices, and the interface states at the gate-to-channel interface trap charge, generating large amounts of 1/f noise. The 1/f noise can contribute as much noise between DC and 1MHz as thermal noise between DC and 500MHz. Finally, the thin oxide layer of the gate gives up very easily in the face of electrostatic discharge. As source followers, JFETs outperform MOSFETs in every area but raw speed. In summary, short-channel MOSFETs make poor but very fast source followers, and we must use a battery of auxiliary circuits to make them function acceptably in the impedance converter.

Figure 7–4 shows a very basic source follower with the required 1MΩ input resistance. The resistor in the gate stabilizes the FET. Figure 7–5 shows a linear model of a typical high-frequency, short-channel MOSFET. I prefer this model over the familiar hybrid-π model because it shows at a glance that the output resistance of the source is $1/g_m$. Figure 7–6 shows the FET with a surface-mount package model. The tiny capacitors and inductors model the geometric effects of the package and the surrounding environment. These tiny components are called "parasitics" in honor of their very undesirable presence. Figure 7–7 depicts the parasitics of the very common "0805" surface-mount resistor. This type of resistor is often used in front-end circuits built on printed circuit boards. Package and circuit board parasitics at the 0.1pF and 1nH level seem negligibly small, but they dominate circuit performance above 500MHz.

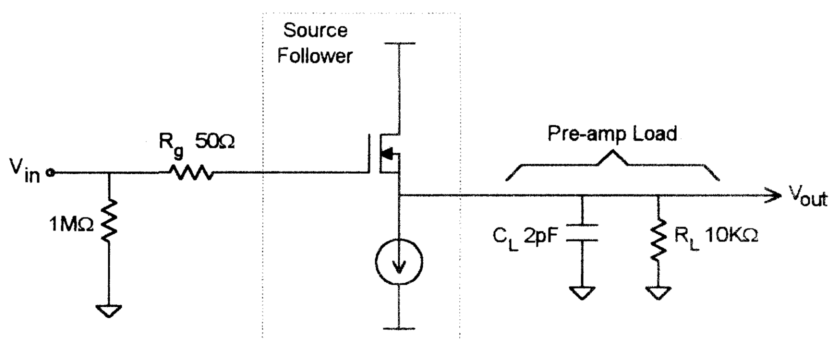


Figure 7–4. A simple source follower using a MOSFET.

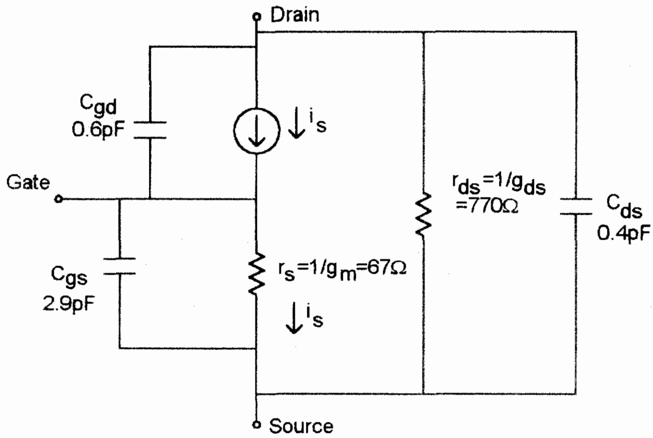


Figure 7–5.
A linear model of a BSD22, a typical high-frequency, short-channel MOSFET. The gate current is zero at DC because the controlled current source keeps the drain current equal to the source current.

In oscilloscope circuits I often remove the ground plane in small patches beneath the components to reduce the capacitances. One must be extremely careful when removing the ground plane beneath a high-speed circuit, because it always increases parasitic inductance. I once turned a beautiful 2GHz amplifier into a 400MHz bookend by deleting the ground plane and thereby effectively placing large inductors in the circuit.

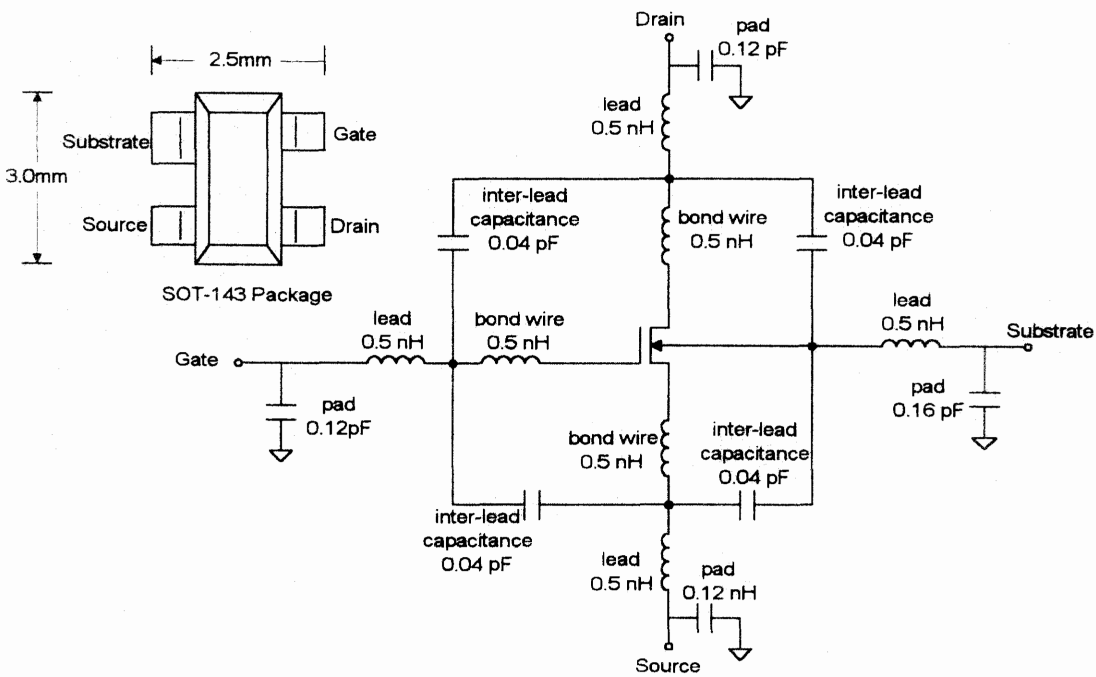


Figure 7–6.
A MOSFET with SOT-143 surface-mount package parasitics. The model includes the effects of mounting on a 1.6mm (0.063") thick, six-layer epoxy glass circuit board with a ground plane on the fourth layer from the component side of the board.

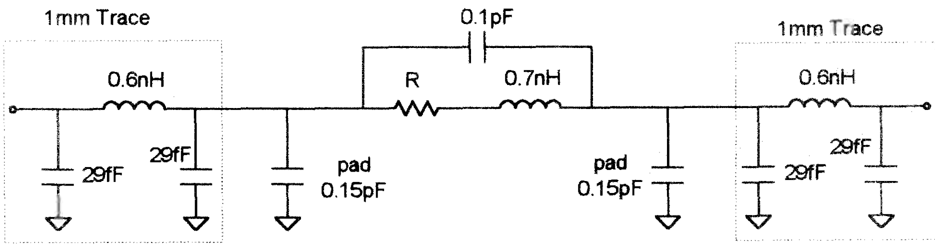


Figure 7–7.
A model of an 0805 surface-mount resistor, including a 1mm trace on each end. The model includes the effects of mounting on a 1.6mm (0.063") thick, six-layer epoxy glass circuit board with a ground plane on the fourth layer from the component side of the board.

Parasitics have such a dominant effect on high-frequency performance that 500MHz oscilloscope front-ends are usually built as chip-and-wire hybrids, which have considerably lower parasitics than standard printed circuit construction. Whether on circuit boards or hybrids, the bond wires, each with about 0.5 to 1.0nH inductance, present one of the greatest difficulties for high-frequency performance. In the course of designing high-frequency circuits, one eventually comes to view the circuits and layouts as a collection of transmission lines or the lumped approximations of transmission lines. I have found this view to be very useful and with practice a highly intuitive mental model.

Figure 7–8 shows the magnitude and step responses of the simple source follower, using the models of Figures 7–5 through 7–7. The bandwidth is good at 1.1GHz. The rise time is also good at 360ps, and the 1% settling time is under 1ns!

Our simple source follower still has a serious problem. The high drain-to-source conductance of the FET forms a voltage divider with the source resistance, limiting the gain of the source follower to 0.91. The pre-amp could easily make up this gain, but the real issue is temperature stability. Both transconductance and output conductance vary with temperature, albeit in a self-compensating way. We cannot comfortably rely on this self-compensation effect to keep the gain stable. The solution is to bootstrap the drain, as shown in Figure 7–9. This circuit forces the drain and source voltages to track the gate voltage. With bootstrapping, the source follower operates at nearly constant current and nearly constant terminal voltages. Thus bootstrapping keeps the gain high and stable, the power dissipation constant, and the distortion low.

There are many clever ways to implement the bootstrap circuit (Kimura 1991). One particularly simple method is shown in Figure 7–10. The BF996S dual-gate, depletion-mode MOSFET is intended for use in television tuners as an automatic gain controlled amplifier. This device acts like two MOSFETs stacked source-to-drain in series. The current source shown in Figure 7–10 is typically a straightforward bipolar transistor current source implemented with a microwave transistor. An ap-

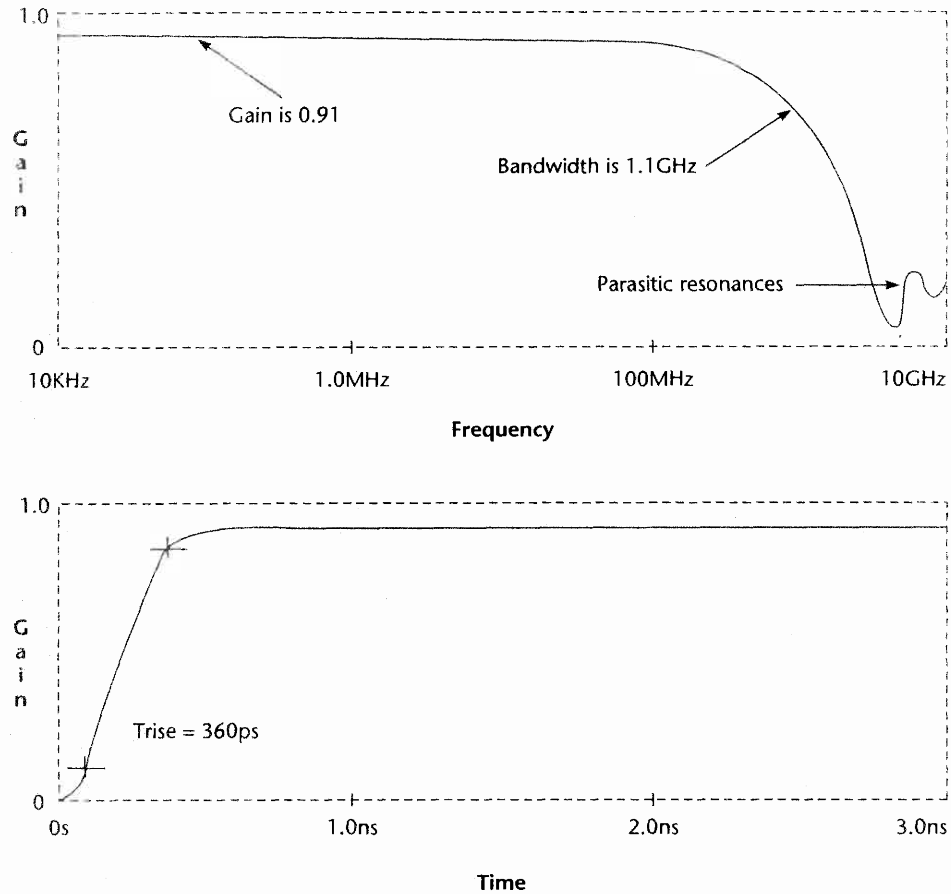


Figure 7–8. The magnitude and step responses of the simple source follower.

proximate linear model of the BF996S is shown in Figure 7–11. The BF996S comes in a SOT-143 surface-mount package, with parasitics, as shown in Figure 7–6.

Figure 7–12 shows the frequency and step responses of the bootstrapped source follower. The bootstrapping network is AC coupled, so

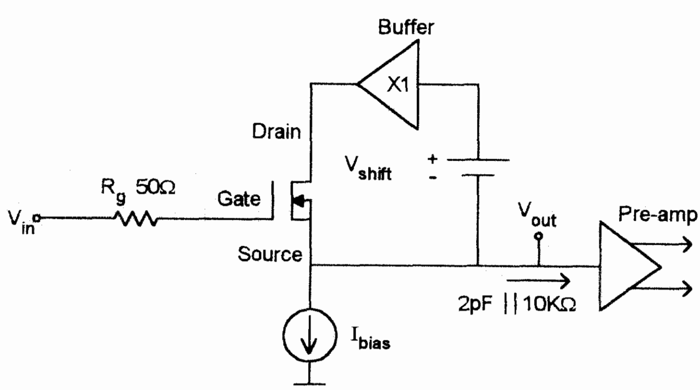


Figure 7–9. The bootstrapped source follower. Driving the drain with the source voltage increases and stabilizes the gain.

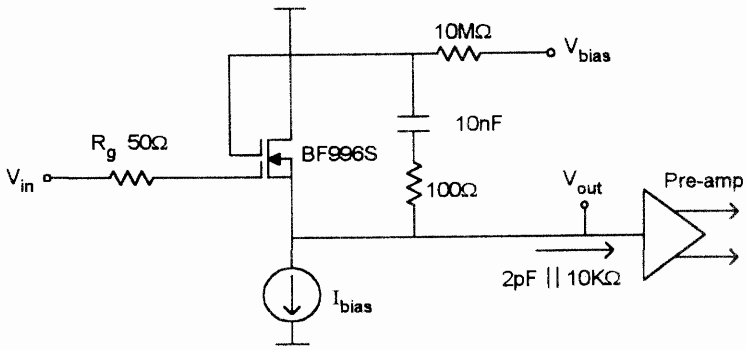


Figure 7–10. Bootstrapping the drain with a dual-gate MOSFET.

it does not boost the gain at DC and low frequencies. The response therefore is not very flat, but we can fix it later. From 1kHz to 100MHz the gain is greater than 0.985 and therefore highly independent of temperature. The 1% settling time is very good at 1.0ns.

Several problems remain in the bootstrapped source follower of Figure 7–10. First, the gate has no protection whatever from overvoltages and electrostatic discharges. Second, the gate-source voltage will vary drastically with temperature, causing poor DC stability. Third, the 1/f noise of the MOSFET is uncontrolled. The flatness (Figure 7–12) is very poor indeed. Finally, the bootstrapped source follower has no ability to handle large DC offsets in its input.

Figure 7–13 introduces one of many ways to build a "two-path" impedance converter that solves the above problems (Evel 1971, Tektronix 1972). DC and low frequencies flow through the op amp, whereas high frequencies bypass the op amp via C1. At DC and low frequencies, feed-

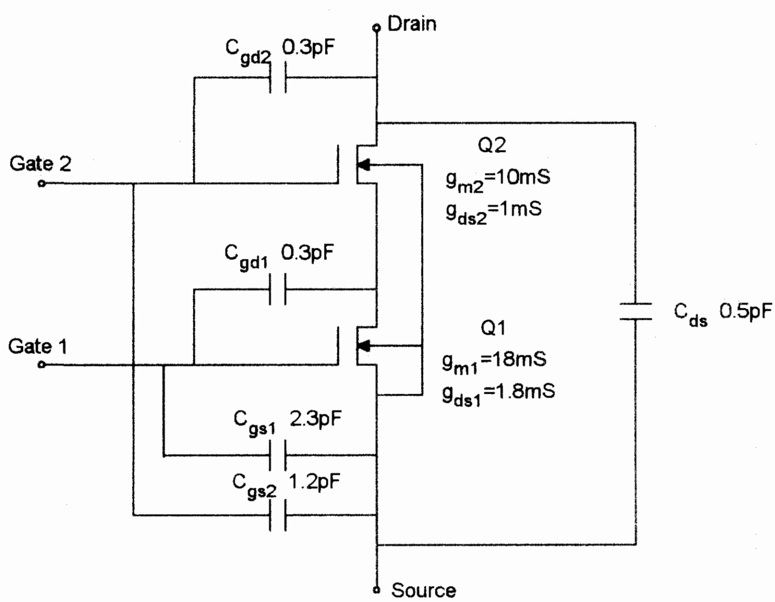


Figure 7–11. Linear model of the BF996S dual-gate, depletion MOSFET.

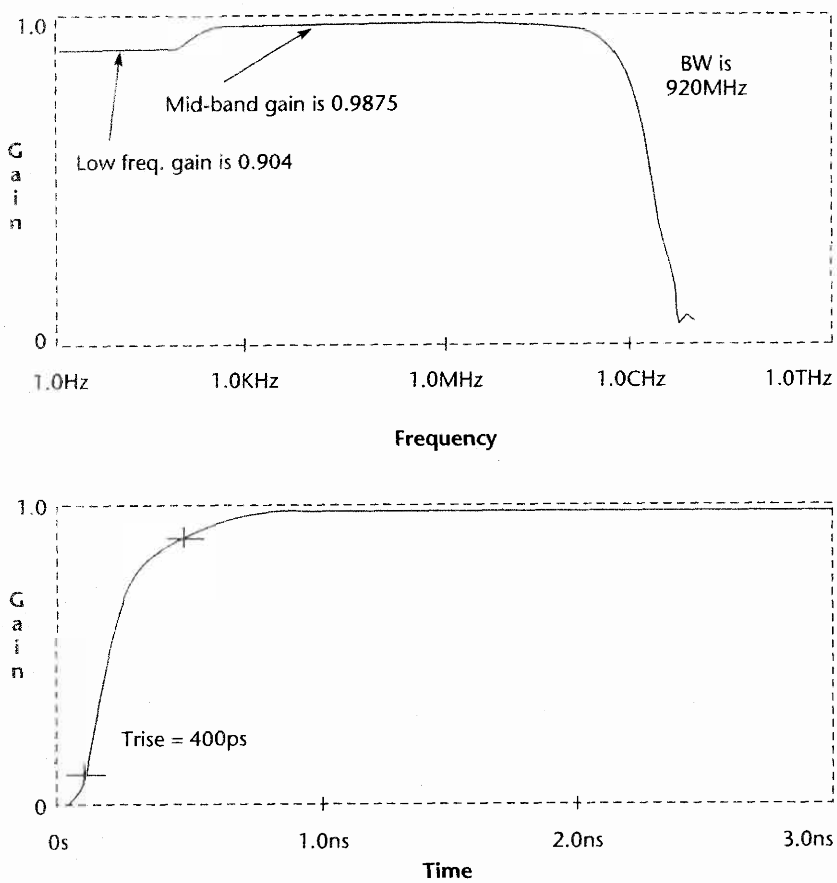


Figure 7–12.
The magnitude and step responses of the bootstrapped source follower.

back gives the two-path source follower the accuracy of a precision op amp. At high frequencies, the signal feeding through C1 dominates control of gate 1, and the source follower operates open loop. The FET is protected by the diodes and the current limiting effects of C1. The 1/f noise of the FET is partially controlled by the op amp, and the circuit can offset large DC levels at the input with the offset control point shown in Figure 7–13.

Figure 7–14 shows the flatness details of the two-path impedance converter. Feedback around the op amp has taken care of the low-frequency gain error exhibited by the bootstrapped source follower (Figure 7–12). The gain is flat from DC to 80MHz to less than 0.1%. The "wiggle" in the magnitude response occurs where the low- and high-frequency paths cross over.

There are additional benefits to the two-path approach. It allows us to design the high-frequency path through C1 and the MOSFET without regard to DC accuracy. The DC level of the impedance converter output is independent of the input and can be tailored to the needs of the preamplifier. Although it is not shown in the figures, AC coupling is easily implemented by blocking DC to the non-inverting input of the op amp.

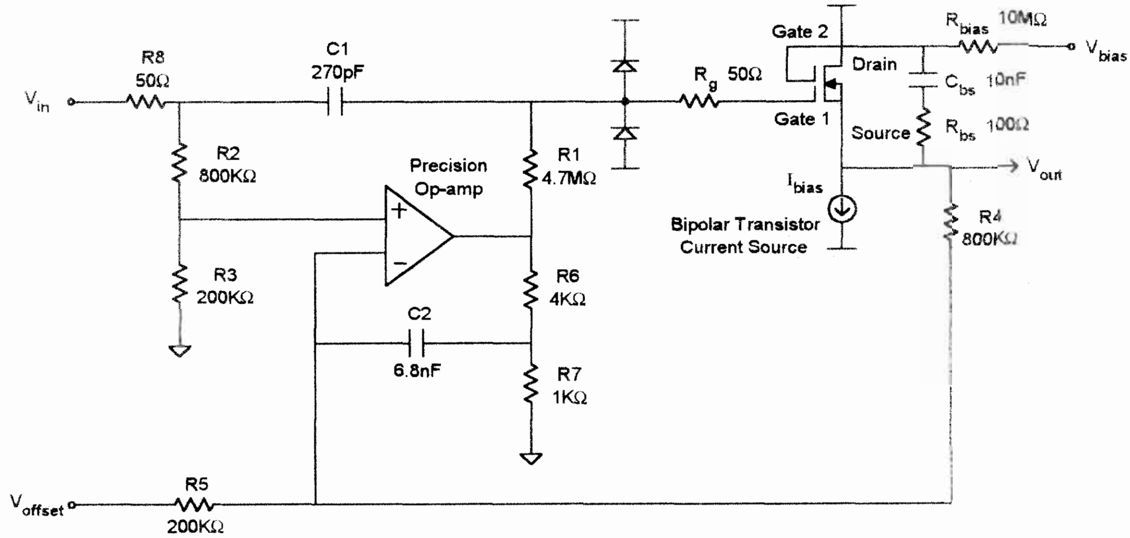


Figure 7–13. A two-path impedance converter.

Thus we avoid putting an AC coupling relay, with all its parasitic effects, in the high-frequency path.

There are drawbacks to the two-path impedance converter. The small flatness errors shown in Figure 7–14 never seem to go away, regardless of the many alternative two-path architectures we try. Also, C1 forms a capacitive voltage divider with the input capacitance of the source follower. Along with the fact that the source follower gain is less than unity, this means that the gain of the low-frequency path may not match that of the high-frequency path. Component variations cause the flatness to vary further. Since the impedance converter is driven by a precision high-impedance attenuator, it must have a very well-behaved input impedance that closely resembles a simple RC parallel circuit. In this regard the most common problem occurs when the op amp has insufficient speed and fails to bootstrap R1 in Figure 7–13 to high enough frequencies.

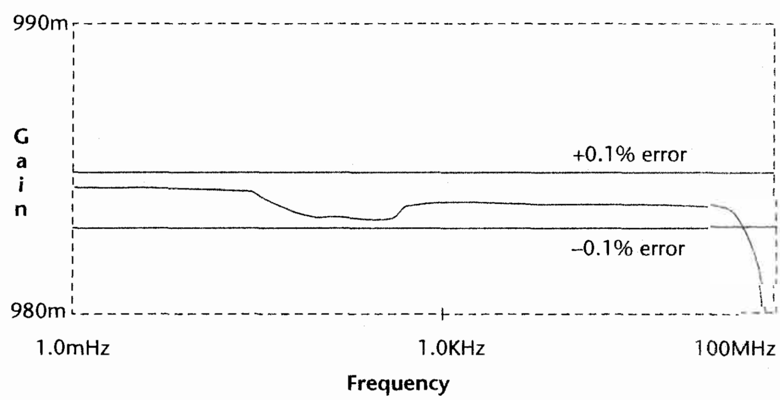


Figure 7–14. Flatness details of the two-path impedance converter.

The overdrive recovery performance of a two-path amplifier can be abysmal. There are two ways in which overdrive problems occur. If a signal is large enough to turn on one of the protection diodes, C1 charges very quickly through the low impedance of the diode (Figure 7–13). As if it were not bad enough that the input impedance in overdrive looks like 270pF, recovery occurs with a time constant of 270pF • 4.7MΩ, or 1.3ms! Feedback around the op amp actually accelerates recovery somewhat but recovery still takes eons compared to the 400ps rise time! Another overdrive mechanism is saturation of the source follower. When saturation occurs, the op amp integrates the error it sees between the input and source follower output, charging its 6.8nF feedback capacitor. Recovery occurs over milliseconds. The seriousness of these overdrive recovery problems is mitigated by the fact that with careful design it can take approximately ±2V to saturate the MOSFET and ±5V to activate the protection diodes. Thus, to overdrive the system, it takes a signal about ten times the full-scale input range of the pre-amp.

I apologize for turning a simple, elegant, single transistor source follower into the "bootstrapped, two-path impedance converter." But as I stated at the beginning, it is the combination of requirements that drives us to such extremes. It is very hard to meet all the requirements at once with a simple circuit. In the next section, I will extend the two-path technique to the attenuator to great advantage. Perhaps there the two-path method will fully justify its complexity.

The Attenuator

I have expended a large number of words and pictures on the impedance converter, so I will more briefly describe the attenuator. I will confine myself to an introduction to the design and performance issues and then illustrate some interesting alternatives for constructing attenuators. The purpose of the attenuator is to reduce the dynamic range requirements placed on the impedance converter and pre-amp. The attenuator must handle stresses as high as ±400V, as well as electrostatic discharge. The attenuator maintains a 1MΩ input resistance on all ranges and attains microwave bandwidths with excellent flatness. No small-signal microwave semiconductors can survive the high input voltages, so high-frequency oscilloscope attenuators are built with all passive components and electromechanical relays for switches.

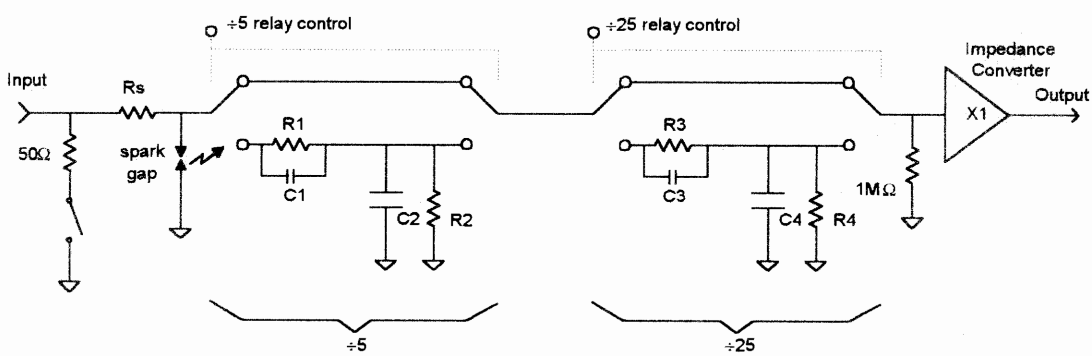
Figure 7–15 is a simplified schematic of a 1MΩ attenuator. It uses two stages of the well-known "compensated voltage divider" circuit. One stage divides by five and the other by 25, so that division ratios of 1, 5, 25, and 125 are possible. There are two key requirements for the attenuator. First, as shown in Figure 7–3, we must maintain $R_1C_1 = R_2C_2$ in the ÷5 stage to achieve a flat frequency response. A similar requirement holds for the ÷25 stage. Second, the input resistance and capacitance at each stage must match those of the impedance converter and remain very nearly constant, independent of the switch positions. This requirement assures that we maintain attenuation accuracy and flatness for all four combinations of attenuator relay settings.

Dividing by a high ratio such as 125 is similar to trying to build a high-isolation switch; the signal attempts to bypass the divider, causing feed-through problems. If we set a standard for feedthrough of less than one least-significant bit in an 8-bit digital oscilloscope, the attenuator must isolate the input from the output by $20\log_{10}(125 \cdot 2^8) = 90\text{dB}$! I once spent two months tracking down such an isolation problem and traced it to wave guide propagation and cavity resonance at 2GHz inside the metallic attenuator cover.

Relays are used for the switches because they have low contact impedance, high isolation, and high withstanding voltages. However, in a realm where 1mm of wire looks like a transmission line, the relays have dreadful parasitics. To make matters worse, the relays are large enough to spread the attenuator out over an area of about 2 × 3cm. Assuming a propagation velocity of half the speed of light, three centimeters takes 200ps, which is dangerously close to the 700ps rise time of a 500MHz oscilloscope. In spite of the fact that I have said we can have no transmission lines in a high-impedance attenuator, we have to deal with them anyway! To deal with transmission line and parasitic reactance effects, a real attenuator includes many termination and damping resistors not shown in Figure 7–15.

Rather than going into extreme detail about the conventional attenuator of Figure 7–15, it would be more interesting to ask if we could somehow eliminate the large and unreliable electromechanical relays. Consider the slightly different implementation of the two-path impedance converter depicted in Figure 7–16. The gate of the depletion MOSFET is self-biased by the 22MΩ resistor so that it operates at zero gate source voltage. If the input and output voltages differ, feedback via the op amp and bipolar current source reduces the error to zero. To understand this circuit, it helps to note that the impedance looking into the source of a self-biased FET is very high. Thus the collector of the bipolar current source sees a

Figure 7–15. A simplified two-stage high-impedance attenuator.



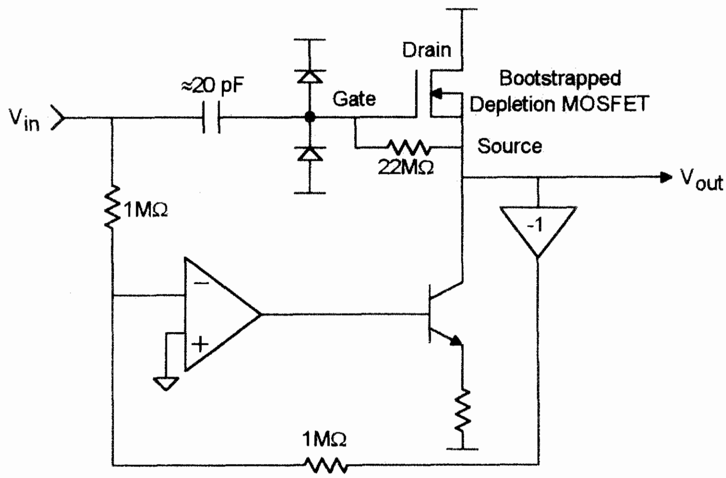


Figure 7–16. A variation on the two-path impedance converter.

high-impedance load. Slight changes in the op amp output can therefore produce significant changes in the circuit output.

The impedance converter of Figure 7–16 can easily be turned into a fixed attenuator, as shown in Figure 7–17. As before, there is a high-frequency and a low-frequency path, but now each divides by ten. There is an analog multiplier in the feedback path to make fine adjustments to the low-frequency gain. The multiplier matches the low- and high-frequency paths to achieve a high degree of flatness. A calibration procedure determines the appropriate gain for the multiplier.

Now we can build a complete two-path attenuator with switched attenuation, as shown in Figure 7–18 (Roach 1992). Instead of cascading attenuator stages, we have arranged them in parallel. In place of the two double-pole double-throw (DPDT) relays of Figure 7–15, we now need only two single-pole single-throw (SPST) relays. Note that there is no need for a switch in the ÷100 path because any signal within range for

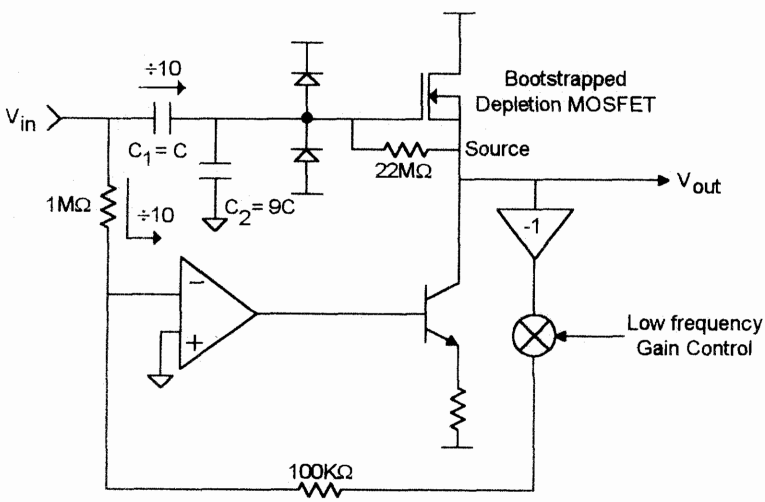


Figure 7–17. An attenuating impedance converter, or "two-path attenuator."

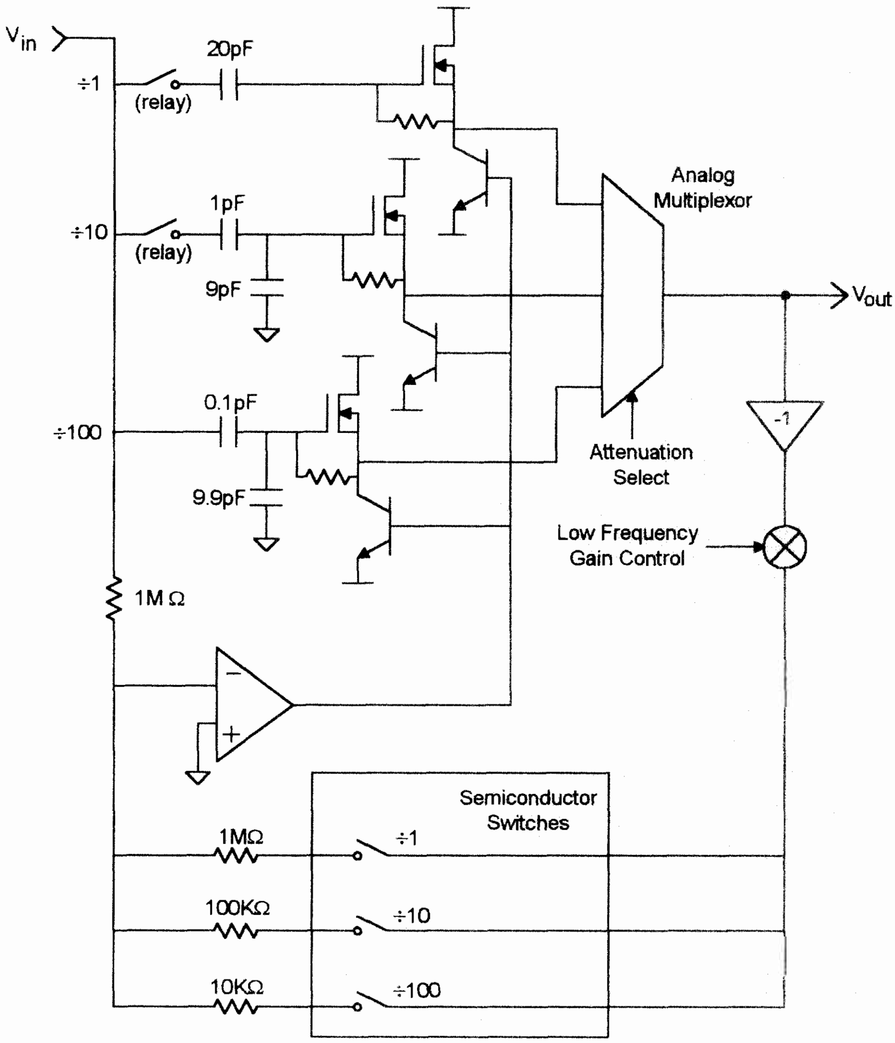


Figure 7–18. A two-path attenuator and impedance converter using only two SPST electromechanical relays. The protection diodes and some resistors are omitted for clarity.

the ÷1 or ÷10 path is automatically in range for the ÷100 path. The switches in the low-frequency feedback path are not exposed to high voltages and therefore can be semiconductor devices.

A number of advantages accrue from the two-path attenuator of Figure 7–18. The SPST relays are simpler than the original relays, and the high-frequency path is entirely AC coupled! The relays could be replaced with capacitive switches, eliminating the reliability problems of DC contacts. One of the most important contributions is that we no longer have to precisely trim passive components as we did in Figure 7–15 to make $R_1C_1 = R_2C_2$. This feature eliminates adjustable capacitors in printed circuit (PC) board attenuators and difficult laser trimming procedures on hybrids. With the need for laser trimming eliminated, we can build on inexpensive PC board attenuators that formerly required expensive hybrids.

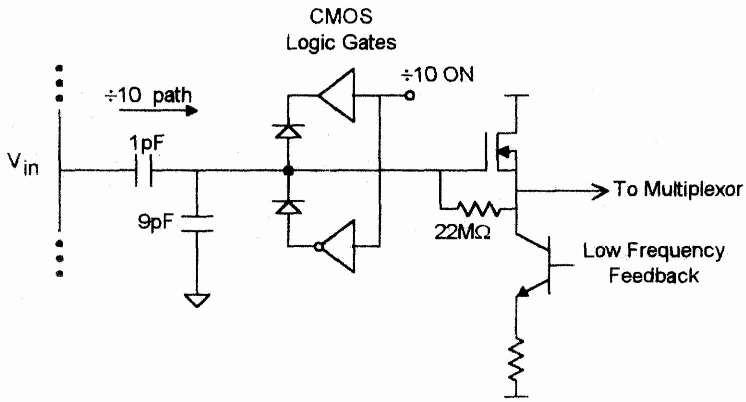


Figure 7–19. Using the protection diodes as switches in the ÷10 path.

We can take the new attenuator configuration of Figure 7–18 further. First observe that we can eliminate the ÷10 relay in Figure 7–18, as shown in Figure 7–19. The diodes are reverse biased to turn the ÷10 path on and forward biased to turn it off. Forward biasing the diodes shorts the 1pF capacitor to ground, thereby shunting the signal and cutting off the ÷10 path. The input capacitance changes by only 0.1pF when we switch the ÷10 path.

Now we are down to one electromechanical relay in the ÷1 path. We can eliminate it by moving the switch from the gate side of the source follower FET to the drain and source, as shown in Figure 7–20. In doing so we have made two switches from one, but that will turn out to be a good trade. With the ÷1 switches closed, the drain and source of the FET are connected to the circuit and the ÷1 path functions in the usual manner. The protection diodes are biased to ±5V to protect the FET.

To cut off the ÷1 path, the drain and source switches are opened, leaving those terminals floating. With the switches open, a voltage change at

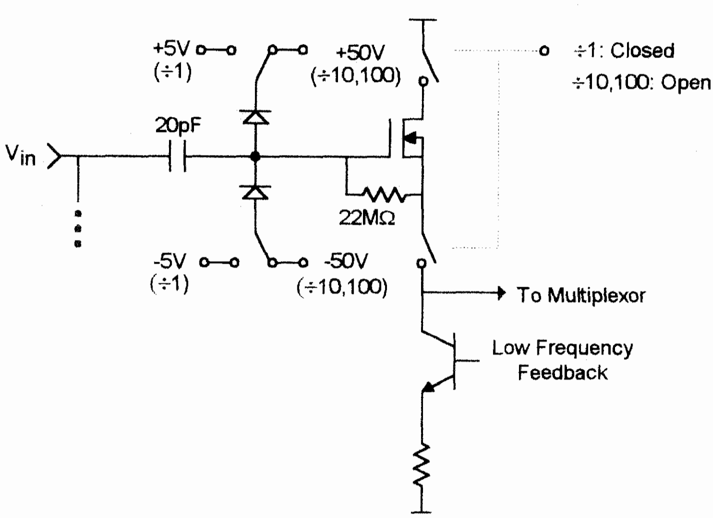
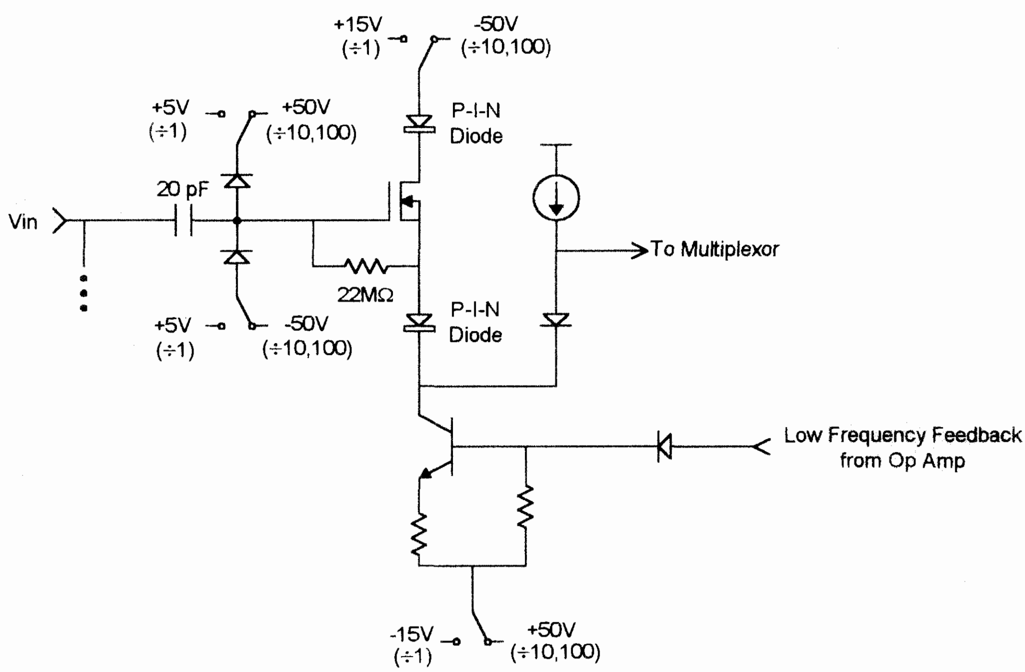


Figure 7–20. Moving the ÷1 switch from the high-impedance input side to the low-impedance output side of the FET.

the input drives the gate, source, and drain of the FET through an equal change via the 20pF input capacitor and the gate-drain and gate-source capacitances. Since all three terminals of the FET remain at the same voltage, the FET is safe from overvoltage stress. Of course, the switches must have very low capacitance in the open state, or capacitive voltage division would allow the terminals of the FET to see differing voltages. In ÷100 mode, the floating FET will see 40V excursions (eight divisions on the oscilloscope screen at 5V per division) as a matter of course. For this reason the ÷1 protection diodes must be switched to a higher bias voltage (±50V) when in the ÷10 and ÷100 modes. The switches that control the voltage on the protection diodes are not involved in the high-frequency performance of the front-end and therefore can be implemented with slow, high-voltage semiconductors.

Can we replace the switches in the drain and source with semiconductor devices? The answer is yes, as Figure 7–21 shows. The relays in the drain and source have been replaced by PIN diodes. PIN diodes are made with a p-type silicon layer (P), an intrinsic or undoped layer (I), and an n-type layer (N). The intrinsic layer is relatively thick, giving the diode high breakdown voltage and extremely low reverse-biased capacitance. A representative packaged PIN diode has 100V reverse breakdown and only 0.08pF junction capacitance. To turn the ÷1 path of Figure 7–21 on, the switches are all set to their "÷1" positions. The PIN diodes are then forward biased, the bipolar transistor is connected to the op amp, and the FET is conducting. To turn the path off, the switches are set to their "÷10,100" positions, reverse-biasing the PIN diodes. Since these switches

Figure 7–21. Using PIN diodes to eliminate the relays in the ÷1 path.



are not involved in the high-frequency signal path, they too can be built with slow, high-voltage semiconductors.

The complete circuit is now too involved to show in one piece on the page of a book, so please use your imagination. We have eliminated all electromechanical switches and have a solid-state oscilloscope front-end. Although I had a great deal of fun inventing this circuit, I do not think it points the direction to future oscilloscope front-ends. Already research is under way on microscopic relays built with semiconductor micro-machining techniques (Hackett 1991). These relays are built on the surface of silicon or gallium arsenide wafers, using photolithography techniques, and measure only 0.5mm in their largest dimension. The contacts open only a few microns, but they maintain high breakdown voltages (100s of volts) because the breakdown voltages of neutral gases are highly nonlinear and not even monotonic for extremely small spacing. The contacts are so small that the inter-contact capacitance in the open state is only a few femtofarads (a femtofarad is 0.001 picofarads). Thus the isolation of the relays is extraordinary! Perhaps best of all, they are electrostatically actuated and consume near zero power. I believe micro-machined relays are a revolution in the wings for oscilloscope front-ends. I eagerly anticipate that they will dramatically improve the performance of analog switches in many applications. Apparently, even a device as old as the electromechanical relay is still fertile ground for a few ambitious inventors!

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William H. Gross

8. One Trip Down the IC Development Road

This is the story of the last IC that I developed. I use the word develop rather than design because there is so much more involved in the making of a standard part than just the circuit design and layout. My goal is to give the reader an idea of what is involved in this total development. The majority of this description will be on the evolution of the product definition and the circuit design since that is my major responsibility. I will also describe many of the other important steps that are part of the IC development. To give the reader an idea of what is required, I made an approximate list of the steps involved in the development of an IC.

The steps in the development of a new IC:

1. Definition
2. Circuit design
3. Re-definition
4. More circuit design
5. The first finalizing of the specifications
6. Test system definition
7. Mask design
8. Test system design
9. Waiting for wafers to be made
10. Evaluation
11. Test system debug
12. Redesign (circuit & masks)
13. More waiting
14. Finalizing the test system
15. IC characterization
16. Setting the real specifications
17. Pricing
18. Writing the data sheet
19. Promotion
20. Yield enhancements

Circuit design (steps 2, 4, and 12) is what we usually think of when we talk about IC design. As you can see, it is only a small part of the IC development. At some companies, particularly those that do custom ICs, circuit design is all the design engineers do. In the ideal world of some MBAs, the customer does the definition, the designer makes the IC, the test engineer tests, the market sets the price, and life is a breeze. This simple approach rarely develops an IC that is really new; and the companies that work this way rarely make any money selling ICs.

Most successful IC designers I know are very good circuit designers and enjoy circuit design more than anything else at work. But it is not just their circuit design skills that make these designers successful; it is also their realization that all the steps in the development of an IC must be done properly. These designers do not work to a rigid set of specifications. They learn and understand what the IC specs mean to the customer and how the IC specs affect the system performance. Successful IC designers take the time to do whatever it takes to make the best IC they can.

This is quite different from the custom IC designer who sells design. If you are selling design, it is a disadvantage to beat the customer's spec by too much. If you do the job too well, the customer will not need a new custom IC very soon. But if you just meet the requirement, then in only a year or so the customer will be back for more. This kind of design reminds me of the famous Russian weight lifter who set many world records. For many years he was able to break his own world record by lifting only a fraction of a kilogram more than the last time. He received a bonus every time he set a new world record; his job was setting records. He would be out of a job if he did the best he could every time; so he only did as much as was required.

Product Definition

Where do we get the ideas for new products? From our customers, of course. It is not easy, however. Most customers will tell you what they want, because they are not sure what they need. Also, they do not know what the different IC technologies are capable of and what trade-offs must be made to improve various areas of performance. The way questions are asked often determines the answers. Never say, "Would you like feature XYZ?" Instead say, "What would feature XYZ be worth to you?"

When an IC manufacturer asks a customer, it is often like a grandparent asking a grandchild. The child wants all the things that it cannot get from its parents and knows none of the restrictions that bind the others. The only thing worse would be to have a total stranger do the questioning. That may sound unlikely, but there are companies that have hired non-technical people to ask customers what new products they want. At best, this only results in a very humorous presentation that wastes a lot of people's time.

Talking to customers, applications engineers, and salespeople gives the clues and ideas to a designer for what products will be successful. It is important to pick a product based on the market it will serve. Do not make a new IC because the circuit design is fun or easy. Remember that circuit design is only a small part of the development process. The days of designing a new function that has no specific market should be long gone. Although I have seen some products recently that appear to be solutions looking for problems!

This is not to say that you need marketing surveys with lots of paperwork and calculations on a spreadsheet. These things are often management methods to define responsibility and place blame. It is my experience that the errors in these forms are always in the estimate of the selling price and the size of the market. These inputs usually come from marketing and maybe that is why there is such a high turnover of personnel in semiconductor marketing departments. After all, if the marketers who made the estimates change jobs every three years, no one will ever catch up with them. This is because it typically takes two years for development and two more years to see if the product meets its sales goals.

So with almost no official marketing input, but based on conversations with many people over several years, I began the definition of a new product. I felt there was a market for an IC video fader and that the market was going to grow significantly over the next five years. The driving force behind this growth would be PC based multi-media systems. At the same time I recognized that a fader with only one input driven is a very good adjustable gain amplifier and that is a very versatile analog building block. The main source of this market information was conversations with customers trying to use a transconductance amplifier that I had designed several years earlier in fader and gain control applications.

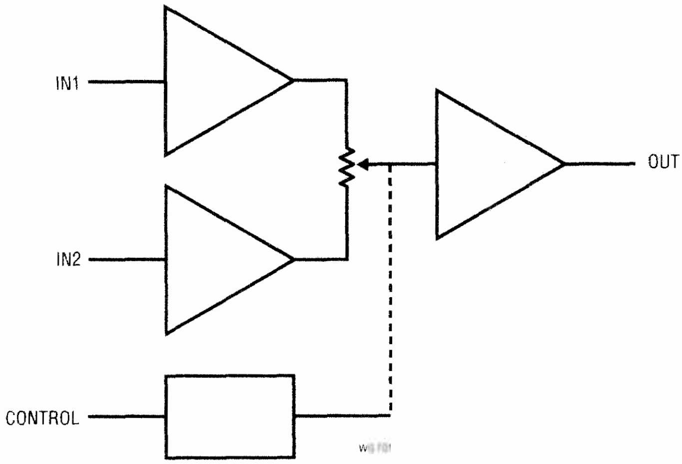
The Video Fader

The first step is figuring out what a video fader is. The basic fader circuit has two signal inputs, a control input and one output. A block diagram of a fader is shown in Figure 8–1. The control signal varies the gain of the two inputs such that at one extreme the output is all one input and at the other extreme it is the other input. The control is linear; i.e., for the control signal at 50%, the output is the sum of one half of input 1 and one half of input 2. If both inputs are the same, the output is independent of the control signal. Of course implementing the controlled potentiometer is the challenging part of the circuit design.

The circuit must have flat response (0.1dB) from DC to 5MHz and low differential gain and phase (0.1% & 0.1 degree) for composite video applications. For computer RGB applications the -3dB bandwidth must be at least 30MHz and the gain accuracy between parts should be better than 3%. The IC should operate on supply voltages from ±5V to ±15V, since there are still a lot of systems today on ±12V even though the trend is to ±5V. Of course if the circuit could operate on a single +5V supply, that would be ideal for the PC based multi-media market.

The control input can be in many forms. Zero to one or ten volts is common as are bipolar signals around zero. Some systems use current inputs or resistors into the summing node of an op amp. In variable gain amplifier applications often several control inputs are summed together.

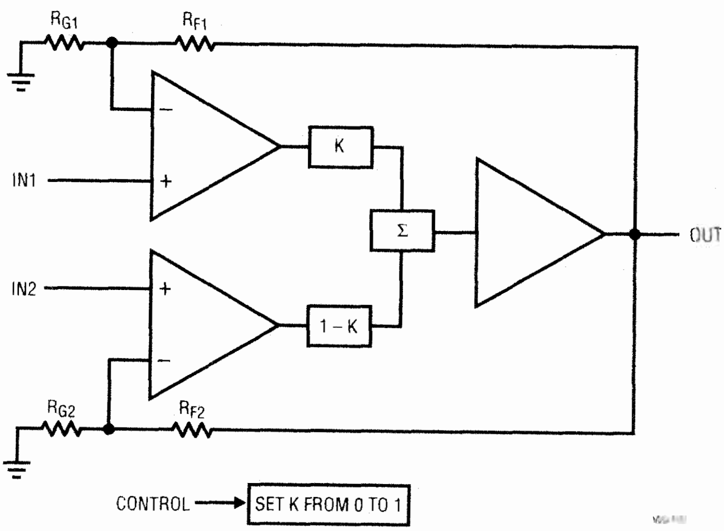
Figure 8–1.
Basic fader circuit.



In order to make a standard IC that is compatible with as many systems as possible, it is desirable to make the control input user defined. At the same time it is important that the IC not require a lot of external parts.

To make the circuit more immune to errors in the potentiometer circuit, we can take feedback from the output back to both inputs. Figure 8–2 shows this feedback and replaces the potentiometer with the mathematical equivalent blocks: K, 1-K, and summation. Now the output is better controlled, since the value of K does not determine the total gain, only the ratio of the two input signals at the output. The gain is set by the feedback resistors and, to a smaller degree, the openloop gain of the amplifiers.

Figure 8–2.
Feedback fader circuit.



Circuits

At this point it is time to look at some actual circuits. Do we use voltage feedback or current feedback? Since the current feedback topology has inherently better linearity and transient response, it seemed a natural for the input stages. One customer showed me a class A, current feedback circuit being implemented with discrete transistors. Figure 8–3 shows the basic circuit. For the moment we will not concern ourselves with how the control signal, V_C, is generated to drive the current steering pairs. Notice that the fader is operating inverting; for AC signals this is not usually a problem, but video signals are uni-polar and another inversion would eventually be needed. I assumed that the inverting topology was chosen to reduce the amount of distortion generated by the bias resistors, R_{B1} and R_{B2}, in the input stages.

Since transistors are smaller than resistors in an IC, I intended to replace the bias resistors with current sources. Therefore my circuit could operate non-inverting as well as inverting, and as a bonus the circuit would have good supply rejection. The complementary bipolar process that I planned to use would make class AB implementations fairly straightforward. I began my circuit simulations with the circuit of Figure 8–4; notice that there are twice as many components compared to the discrete circuit and it is operating non-inverting.

After a bit of tweaking the feedback resistor values and the compensation capacitor, the circuit worked quite well. The transistor sizes and

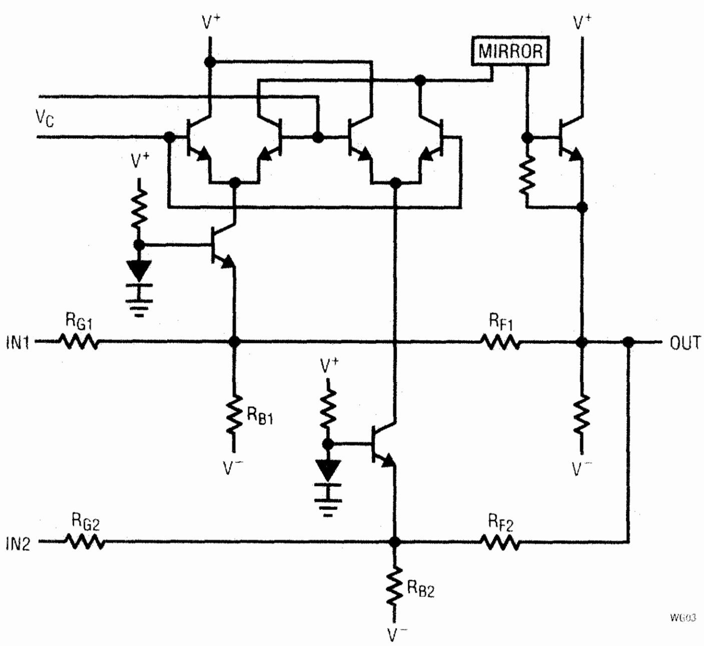


Figure 8–3. Discrete design, class A current feedback fader.

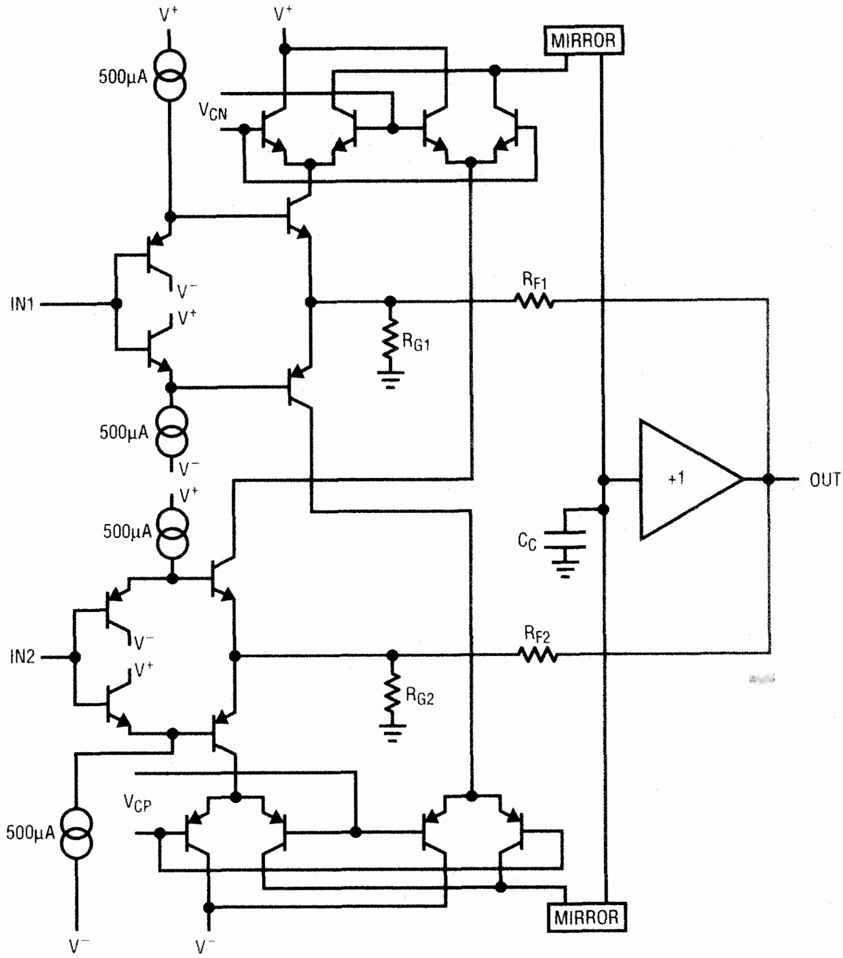


Figure 8–4. Class AB current feedback fader.

current levels were set based on previous current feedback amplifiers already designed. It was time to proceed to the control section.

For linear control of the currents being steered by a differential pair, the voltage at the bases of the steering transistors must have a nonlinear characteristic. This TANH characteristic is easily generated with "pre-distortion" diodes. The only requirement is that the currents feeding the diodes must be in the same ratio as the currents to be steered. The circuit of Figure 8–5 takes two input control currents, K and (1-K), and uses Q1 and Q2 as the pre-distortion diodes to generate the control signal V_{CN} for the NPN steering transistors. The collector currents of Q1 and Q2 then feed the pre-distortion diodes Q3 and Q4 that generate V_{CP} to control the PNP steering transistors.

I noticed that the linearity of the signal gain versus diode current is strongly influenced by the bulk R_b and R_e of the current steering transistors. After consulting some papers on multipliers (thank you Barry Gilbert) I found that there are some topologies where the bulk R_b and R_e of the pre-distortion diodes compensate the equivalent in the steering

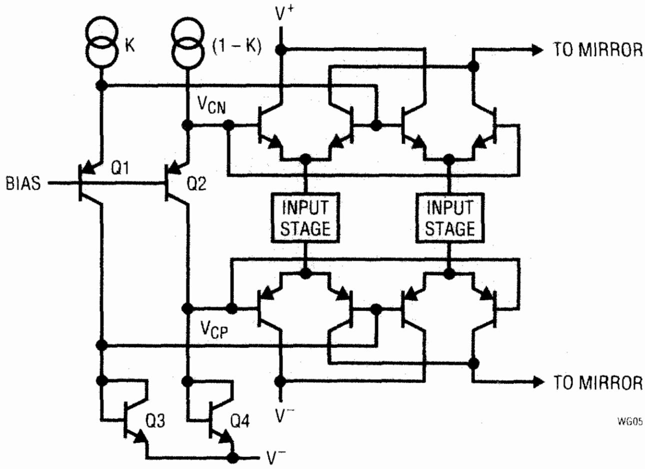


Figure 8–5. Basic circuit to drive the steering transistors.

transistors. Unfortunately, in my circuit I am using PNPs to drive NPNs and vice versa. In order to match the pre-distortion diodes to the steering transistors, a more complicated circuit was required. I spent a little time and added a lot more transistors to come up with a circuit where the pre-distortion diodes for the NPN steering transistors were NPNs, and the same for the PNPs. Imagine my surprise when it didn't solve the linearity problem. I have not included this circuit because I don't remember it; after all, it didn't work.

So I had to learn a little more about how my circuit really worked. In the fader circuit, the DC current ratio in the steering transistors is not important; the small signal current steering sets the ratio of the two inputs. Figure 8–6 shows a simplified circuit of the pre-distortion diodes and the steering transistors. The diodes and transistors are assumed perfect with 18Ω resistors in series with the emitters to represent the bulk R_b and R_e of the devices. The control currents are at a 10:1 ratio; the DC currents in the

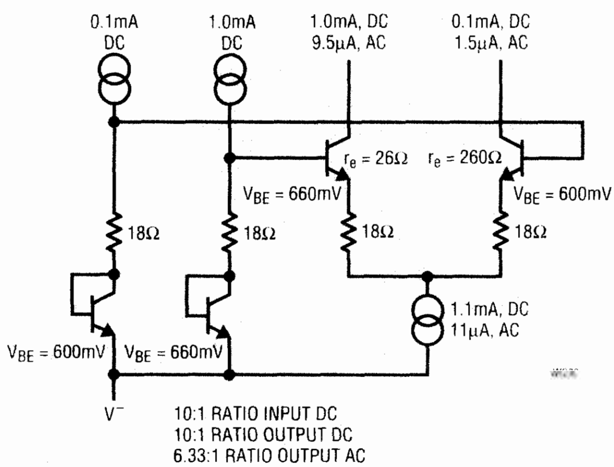


Figure 8–6. Bulk resistance problems in steering.

steering transistors are also at a 10:1 ratio. But the small signal steering is set by the ratio of the sum of the r_e and the bulk resistance in each transistor, and in this case the result is a 6.33:1 ratio!

In the fader circuit, the only way to improve the gain accuracy is with low R_b and R_e steering transistors. Unfortunately this requires larger transistors running at low current densities and that significantly reduces the speed (F-tau) of the current steering devices. I went back to the simpler circuit of Figure 8–5, increased the size of the current steering transistors, and tweaked the compensation capacitor and feedback resistors to optimize the response.

Now it was time to find a way to interface the external control signal(s) to the pre-distortion diodes of Figure 8–5. The incoming signal would have to be converted to a current to drive the pre-distortion diodes, Q1 and Q3. A replica of that current would have to be subtracted from a fixed DC current and the result would drive the other pre-distortion diodes, Q2 and Q4.

I did not want to include an absolute reference in this product for several reasons. An internal reference would have to be available for the external control circuitry to use, in order not to increase the errors caused by multiple references. Therefore it would have to be capable of significant output drive and tolerant of unusual loading. In short, the internal reference would have to be as good as a standard reference. The inaccuracy of an internal reference would add to the part-to-part variations unless it was trimmed to a very accurate value. Both of these requirements would increase the die size and/or the pin count of the IC. Lastly, there is no standard for the incoming signals, so what value should the reference be?

I decided to require that an external reference, or "full scale" voltage, would be applied to the part. With an external full scale and control voltage, I could use identical circuits to convert the two voltages into two currents. The value of the full scale voltage is not critical because only the ratio between it and the control voltage matters. With the same circuit being used for both converters, the ratio matching should be excellent.

Figure 8–7 shows the basic block diagram that I generated to determine what currents would be needed in the control section. The gain control accuracy requirements dictated that an open loop voltage-to-current converter would be unacceptable. Therefore a simple op amp with feedback would be necessary. It became clear that two control currents (I_C) were needed but only one full scale current (I_{FS}) was. Mirror #1 must have an accurate gain of unity in order to generate the proper difference signal for mirror #3. Mirrors 2 and 3 must match well, but their absolute accuracy is not important. All three mirrors must operate from zero to full scale current and therefore cannot have resistive degeneration that could change their gain with current level.

In order to use identical circuits for both voltage-to-current converters, I decided to generate two full scale currents and use the extra one to bias the rest of the amplifiers. You can never have too many bias currents available.

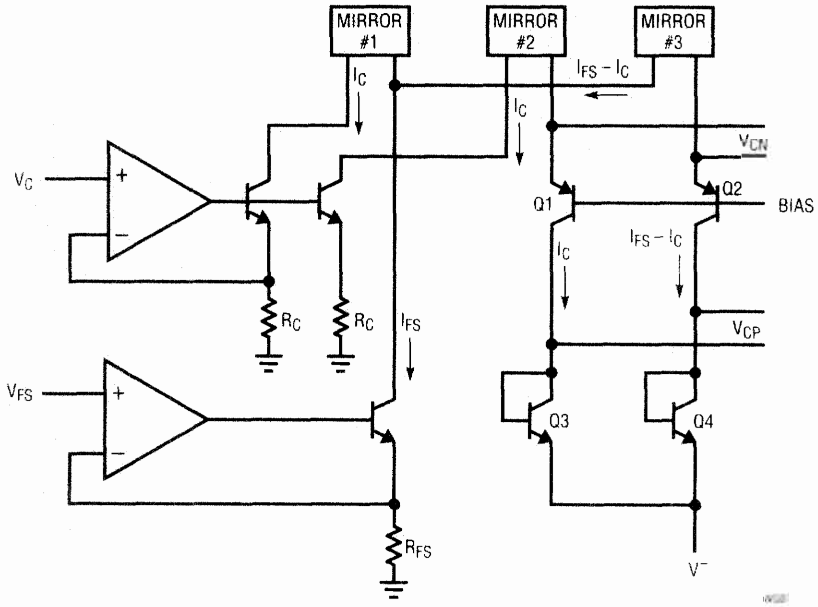


Figure 8–7. Block diagram of the control circuit.

The block diagram of Figure 8–7 became the circuit of Figure 8–8 after several iterations. The common mode range of the simple op amp includes the negative supply and the circuit has sufficient gain for the job. Small current sharing resistors, R1, R2, R3, and R4, were added to improve the high current matching of the two output currents and eliminate the need for the two R_C resistors. The small resistors were scaled so they could be used for short circuit protection with Q5 and Q6 as well.

Mirror #l is a "super diode" connection that reduces base current errors by beta; the diode matches the collector emitter voltages of the matched transistors. Identical mirrors were used for #2 and #3 so that any errors would ratio out. Since these mirrors feed the emitters of the pre-distortion cascodes Q1 and Q2, their output impedance is not critical and they are not cascoded. This allows the bias voltage at the base of Q1 and Q2 to be only two diode drops below the supply, maximizing the common mode range of the input stages.

While evaluating the full circuit, I noticed that when one input was supposed to be off, its input signal would leak through to the output. The level increased with frequency, as though it was due to capacitive feedthrough. The beauty of SPICE came in handy now. I replaced the current steering transistors with ideal devices and still had the problem. Slowly I came to the realization that the feedthrough at the output was coming from the feedback resistor. In a current feedback amplifier, the inverting input is driven from the non-inverting input by a buffer amp and therefore the input signal is always present at the inverting input. Therefore the amount of signal at the output is just the ratio of the feedback resistor to the amplifier output impedance. Of course the output impedance rises with frequency because of the single pole compensation necessary to keep

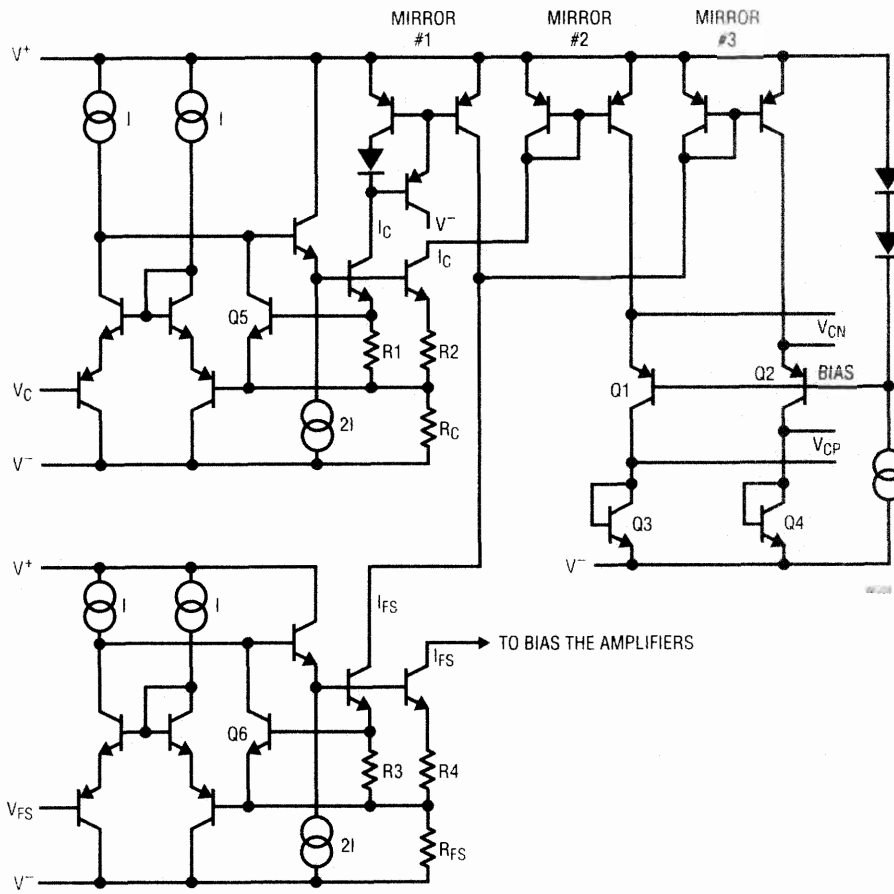


Figure 8–8.
The control circuit.

the amplifier stable. The basic current feedback topology I had chosen was the feedthrough problem. Now it was obvious why the discrete circuit was operating inverting. The problem goes away when the non-inverting input is grounded because then the inverting input has very little signal on it.

Redefinition

At this point I realized I must go back to the beginning and look at voltage feedback. I started with the basic folded cascode topology and sketched out the circuit of Figure 8–9. It seemed to work and there were no feedthrough problems. It also appeared to simplify the control requirements, since there were no PNPs to steer. While working with this circuit I realized that the folded cascode transistors, Q7 and Q8, could be used as the steering devices, and sketched out Figure 8–10. This looked great since it had fewer devices in the signal path and therefore better bandwidth. The only downside I could see was the critical matching of the current sources; all eight current sources are involved in setting the gain. While I was pondering how to get eight current sources coming

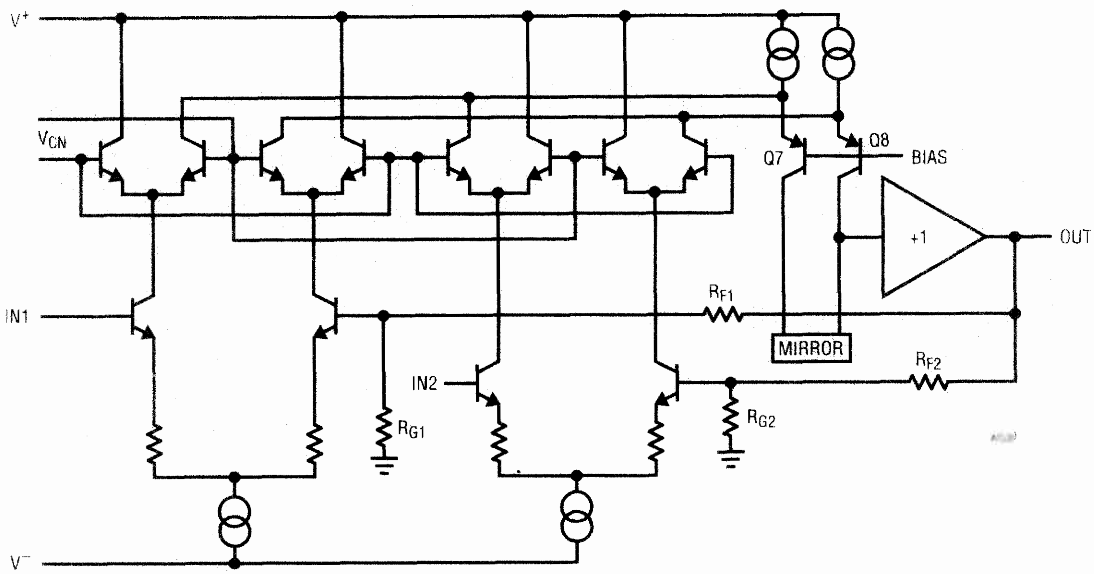


Figure 8–9. Voltage feedback fader.

from opposite supplies to match, I decided to run a transient response to determine how much input degeneration was required.

The bottom fell out! When the fader is set for 10% output, the differential input voltage is 90% of the input signal! This means that the *open loop* linearity of the input stage must be very good for signals up to one volt or more. To get signal linearity of 0.1% would require over a volt of degeneration. With that much degeneration in each input stage, the mismatch in offset voltage between the two would be tens of millivolts and that would show up as control feedthrough. Big degeneration resistors

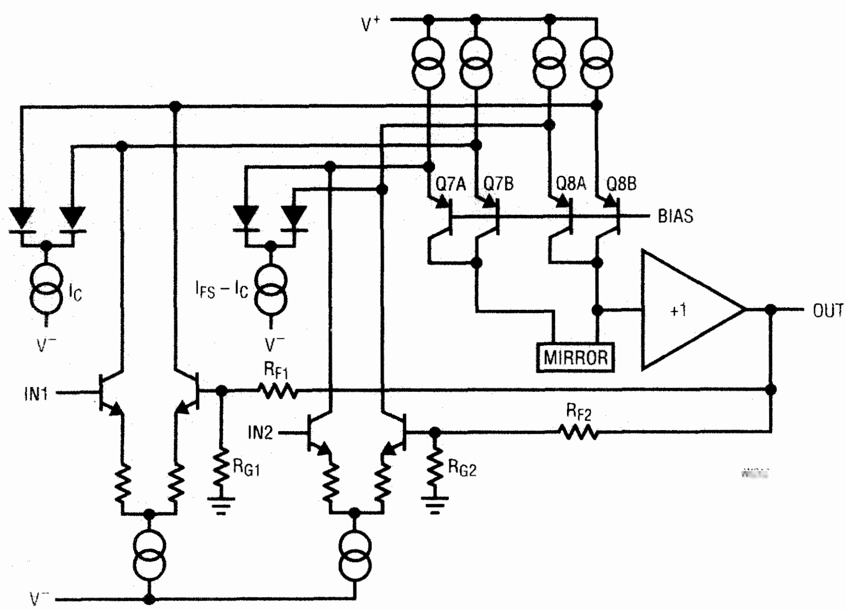


Figure 8–10. Voltage feedback with cascode steering.

also generate serious noise problems and cause the tail pole to move in, reducing the speed of the amplifier. It was time to retreat to the current feedback approach and see how good I could make it.

The current feedback topology has very low feedthrough when operated inverting, so I started with that approach. Unfortunately the feedthrough was not as good as I expected and I started looking for the cause. The source of feedthrough was found to be the emitter-base capacitance of the current steering transistor coupling signal into the pre-distortion diode that was holding the transistor off. Unfortunately the off diode was high impedance (no current in it) so the signal then coupled through the collector base capacitance of the steering transistor into the collector, where it was not supposed to be. Since the steering transistors had to be large for low R_b and R_e, the only way to eliminate this problem was to lower the impedance at the bases of the steering transistors.

What I needed was four buffer amplifiers between each of the four pre-distortion diodes and the current steering transistors. To preserve the pre-distortion diodes' accuracy, the input bias current of the buffers needed to be less than one microamp. The offset of the buffers had to be less than a diode drop in order to preserve the input stage common mode range so that the circuit would work on a single 5V supply. Lastly, the output impedance should be as low as possible to minimize the feedthrough.

The first buffer I tried was a cascode of two emitter followers, as shown on the left in Figure 8–11. By varying the currents in the followers and looking at the overall circuit feedthrough, I determined that the output impedance of the buffers needed to be less than 75Ω for an acceptable feedthrough performance of 60dB at 5MHz. I then tried several closed loop buffers to see if I could lower the supply current. The circuit shown in Figure 8–11 did the job and saved about 200 microamps of supply current per buffer. The closed loop buffer has an output impedance of about 7Ω that rises to 65Ω at 5MHz. Since four buffers were required, the supply current reduction of 800 microamps was significant.

At this point it became obvious to me that for the feedthrough to be down 60dB or more, the control circuitry had to be very accurate. If the full scale voltage was 2.5V and the control voltage was 0V, the offset errors had to be less than 2.5mV for 60dB of off isolation. Even if I trimmed the IC to zero offset, the system accuracy requirement was still very tough. I therefore wanted to come up with a circuit that would insure that the correct input was on and the other input was fully off when the control was close to zero or full scale. I thought about adding intentional offset voltage and/or gain errors to the V-to-I converters to get this result, but it didn't feel good. What was needed was an internal circuit that would sense when the control was below 5% or above 95% and force the pre-distortion diodes to 0% and 100%. Since the diodes were fed with currents, it seemed that sensing current was the way to go.

Since the currents that feed the pre-distortion diodes come from identical mirrors, I wanted to see if I could modify the mirrors so that they

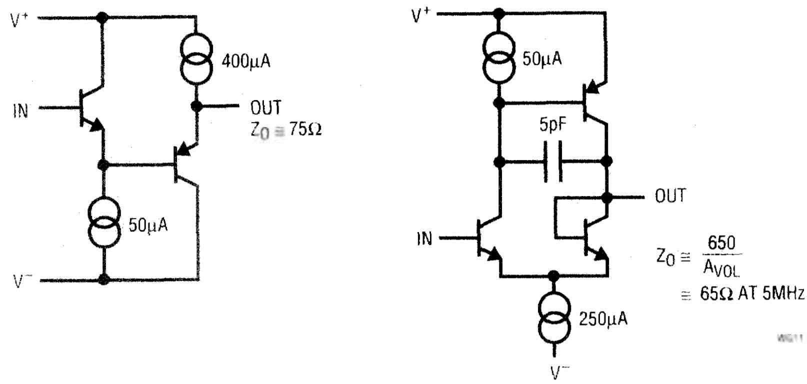


Figure 8–11. Open- and closed-loop buffers.

would turn off at low currents. This would work at both ends of the control signal because one mirror is always headed towards zero current. The first thought was to put in a small fixed current that subtracted from the input current. This would add an offset near zero (good) and a gain error everywhere else (bad). Now if I could turn off the offset current when the output current was on, it would be perfect. Current mirrors #2 and #3 in Figure 8–8 were each modified to be as shown in Figure 8–12. The offset current is generated by Q9. A small ratio of the output current is used to turn off Q9 by raising its emitter. The ratios are set such that the output goes to zero with the input at about 5% of full scale. The nice thing about this mirror is that the turn-off circuit has no effect on mirror accuracy for inputs of 10% or more. The diode was added to equalize the collector-base voltage of all the matching transistors.

At this point the circuit was working very well in the inverting mode and I went back to non-inverting to see how the feedthrough looked. Since the output impedance of the amplifier determines the feedthrough performance, I eliminated all the output stage degeneration resistors. I set the output quiescent current at 2.5 milliamps so the output devices would be well up on their F-tau curve and the open loop output impedance would be well under 10 Ohms. The feedthrough was still 60dB down at 5MHz. I added a current limit circuit that sensed the output transistors' collector current, and the circuit topology was finalized.

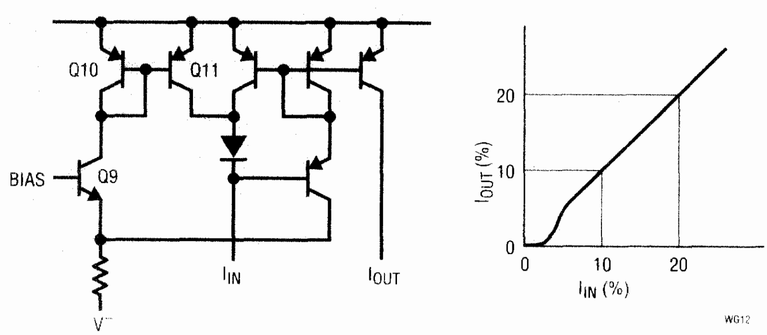


Figure 8–12. Mirror with a turn-off.

The last step in the circuit design is rechecking and/or optimizing the area of every transistor. This is usually done by checking the circuit's performance over temperature. I always add a little extra area to the transistors that are running close to saturation when the additional parasitic capacitance won't hurt anything.

Mask Design

Experienced analog IC designers know how important IC layout is. Transistors that are supposed to match must have the same emitter size and orientation as well as the same temperature. The fader output amplifier is capable of driving a cable and generating significant thermal gradients in the IC. For this reason I put both input stages on one end of the die next to the current steering devices and put the output stage at the other end. The bias circuits and the control op amps went in the middle. The best way to minimize thermal feedback is distance. The 14-pin SO package set the maximum die size and the pad locations.

The IC process used had only one layer of metalization and therefore I provided the mask designer with an estimate of where "cross-unders" would be needed. For those of you not familiar with the term "cross-under," I will explain. A cross-under is a small resistor, usually made of N+, inserted in a lead so that it can "cross-under" another metal trace. Normally these cross-unders are inserted in the collectors of transistors, since a little extra resistance in the collector has minimal effect.

The fader circuit, with over 140 transistors and very few resistors, was clearly going to have a lot of cross-unders. I was resigned that both supplies would have many cross-unders; in order for the circuit to work properly, the voltage drops introduced by the cross-unders must not disturb the circuit. For example, the current mirrors will common mode out any variation in supply voltage as long as all the emitters are at the same voltage. This is easy to do if the emitters all connect together on one trace and then that trace connects to the supply. As mask design progresses, it is important that each cross-under added to the layout be added to the schematic and that circuit simulation is re-checked. Time spent before the silicon comes out to insure that the circuit works is well spent.

I would like to make a comment or two on mask design and the time that it takes. For as long as I can remember, speeding up mask design has been the Holy Grail. Many, including myself, have thought that some new tool or technique will cut the time required to layout an IC significantly. When computer layout tools became available, they were sold as a productivity enhancement that would cut the time it takes to layout ICs. The reality was that the ICs became more complex and the time stayed about the same.

The analog ASIC concept of a huge library of functions available as standard cells that are just plopped down and hooked up sounds great; except that very few innovative products can be done with standard functions. What typically happens is that each new product requires modifications to the "standard" cells or needs some new standard cells. You're right back at transistor level optimizing the IC. Of course no one ever plans for the extra time that this transistor level optimization takes, so the project gets behind schedule.

The "mono-chip" or "master-chip" idea is often used to speed up development. This technique uses just the metal layer(s) to make the new product; a large standard IC with many transistors and resistors is the common base. The trade-off for time saved in mask design is a larger die size. The argument is often made that if the product is successful, a full re-layout can be done to reduce die size and costs. Of course, this would then require all the effort that should have been done in the first place. I would not argue to save time and money up front because I did not expect my part to be successful!

In summary, mask design is a critical part of analog IC development and must be considered as important as any other step. Doing a poor job of mask design will hurt performance and that will impact the success of a product much more than the extra time in development.

Testing

IC automatic test system development is an art that combines analog hardware and software programming. We cannot sell performance that we cannot test. It is much easier to measure IC performance on the bench than in an automatic handler. In successful companies, the good test development engineers are well respected.

The fader IC requires that the closed loop AC gain be measured very accurately. The gain is trimmed at wafer sort by adjusting the value of resistor R_C. This trim is done with the control input fixed and the linearity of the circuit determines the gain accuracy elsewhere. The errors due to the bulk resistance of the steering transistors have no effect at 50% gain; therefore it seemed like the best place to trim the gain.

While characterizing the parts from the first wafer, I noticed that there were a few parts that had more error than I expected at 90% gain. I also determined that these parts would be fine if I had trimmed them at 90%. It was also true that the parts that were fine at 90% would not suffer from being trimmed at 90%. So, I changed my mind as to where the circuit was to be trimmed and the test engineer modified the sort program. More wafers were sorted and full characterization began.

Setting the data sheet limits is a laborious process that seems like it should be simpler. The designer and product engineer go over the distribution plots from each test to determine the maximum and minimum limits. In a perfect world we would have the full process spread represented in these distributions. Even with a "design of experiments" run that should give us the full spread of process variations, we will come up short of information. It's Murphy's law. This is where the designer's knowledge of which specs are important, and which are not, comes into play. It makes no sense to "over spec" a parameter that the customer is not concerned about because later it could cause a yield problem. On the other hand, it is important to spec all parameters so that any "sports" (oddball parts) are eliminated, since they are usually caused by defects and will often act strangely. The idea is to have all functional parts meet spec if they are normal.

Data Sheets

The data sheet is the most important sales tool the sales people have. Therefore it is important that the data sheet is clear and accurate. A good data sheet is always late. I say this based on empirical data, but there seems to be a logical explanation. The data sheet is useless unless it has all the minimums and maximums that guarantee IC performance; as soon as those numbers are known, the part is ready to sell and we need the data sheet. Of course it takes time to generate the artwork and print the data sheet and so it is late. One solution to this problem is to put out an early, but incomplete, data sheet and then follow it a few months later with a final, complete one.

Analog ICs usually operate over a wide range of conditions and the typical curves in the data sheet are often used to estimate the IC performance under conditions different from those described in the electrical table. The generation of these curves is time consuming and, when done well, requires a fair amount of thought. Human nature being what it is, most people would rather read a table than a graph, even though a table is just an abbreviated version of the data. As a result, the same information is often found in several places within the data sheet. I am often amazed at how inconsistent some data sheets are; just for fun, compare the data on the front page with the electrical tables and the graphs.

Beware of typical specs that are much better than the minimums and maximums. I once worked with a design engineer who argued that the typical value should be the average of the distribution; he insisted that the typical offset voltage of his part was zero even though the limits were ±4mV. Most companies have informal definitions of "typical", and it often varies from department to department. George Erdi added a note to several dual op amp data sheets defining the typical value as the value that would yield 60% based on the distributions of the individual amplifiers. I like and use this definition but obviously not everyone does, since I often see typicals that are 20 times better than the limits! Occasionally the limits are based on automatic testing restrictions and the typicals are real; for example, CMOS logic input leakage current is less than a few nanoamps, but the resolution of the test system sets the limit at 1 microamp.

Summary

Since you are still reading, I hope this long-winded trip was worth it. The development of an IC is fun and challenging. I spent most of this article describing the circuit design because I like circuit design. I hope, however, that I have made it clear how important the other parts of the development process are. There are still more phases of development that I have not mentioned; pricing, press releases, advertising, and applications support are all part of a successful new product development. At the time of this writing, the video fader had not yet reached these phases. Since I am not always accurate at describing the future, I will not even try. Those of you who want to know more about the fader should see the LT1251 data sheet.

At this time I would like to thank all of the people who made the video fader a reality and especially Julie Brown for mask design, Jim Sousae for characterization, Dung (Zoom) Nguyen for test development, and Judd Murkland in product engineering. It takes a team to make things happen and this is an excellent one.

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James M. Bryant

9. Analog Breadboarding

Introduction

While there is no doubt that computer analysis is one of the most valuable tools that the analog designer has acquired in the last decade or so, there is equally no doubt that analog circuit models are not perfect and must be verified with hardware. If the initial test circuit or "breadboard" is not correctly constructed it may suffer from malfunctions which are not the fault of the design but of the physical structure of the breadboard itself. This chapter considers the art of successful breadboarding of high-performance analog circuits.

The successful breadboarding of an analog circuit which has been analyzed to death in its design phase has the reputation of being a black art which can only be acquired by the highly talented at the price of infinite study and the sacrifice of a virgin or two. Analog circuitry actually obeys the very simple laws we learned in the nursery: Ohm's Law, Kirchoff's Law, Lenz's Law and Faraday's Laws. The problem, however, lies in Murphy's Law.

Murphy's Law is the subject of many engineering jokes, but in its simplest form, "If Anything Can Go Wrong—It Will!", it states the simple truth that physical laws do not cease to operate just because we have overlooked or ignored them. If we adopt a systematic approach to breadboard

MURPHY'S LAW

Whatever can go wrong, will go wrong.

Buttered toast, dropped on a sandy floor, falls butter side down.

The basic principle behind Murphy's Law is that all physical laws always apply - when ignored or overlooked they do not stop working.

Figure 9–1.

construction it is possible to consider likely causes of circuit malfunction without wasting very much time.

In this chapter we shall consider some simple issues which are likely to affect the success of analog breadboards, namely resistance (including skin effect), capacitance, inductance (both self inductance and mutual inductance), noise, and the effects of careless current routing. We shall then discuss a breadboarding technique which allows us to minimize the problems we have discussed.

Resistance

As an applications engineer I shall be relieved when room-temperature superconductors are finally invented, as too many engineers suppose that they are already available, and that copper is one of them. The assumption that any two points connected by copper are at the same potential completely overlooks the fact that copper is resistive and its resistance is often large enough to affect analog and RF circuitry (although it is rarely important in digital circuits).

CONDUCTORS ARE NOT *SUPER*CONDUCTORS

Consider 10 cm of 1 mm PC track

Standard track thickness is 0.038 mm
ρ for copper is 1.724 X 10^{-6} Ω cm @ 25°C
∴ PCB sheet resistance is 0.45 mΩ/sq
Resistance of the track is 45 mΩ
THIS IS ENOUGH TO MATTER!

Figure 9–2.

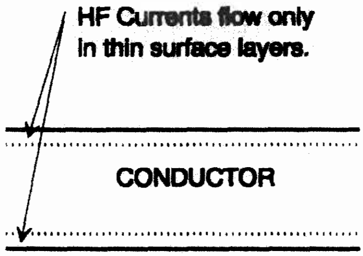
The diagram in Figure 9–2 shows the effect of copper resistance at DC and LF. At HF, matters are complicated by "skin effect." Inductive effects cause HF currents to flow only in the surface of conductors. The skin depth (defined as the depth at which the current density has dropped to 1/e of its value at the surface) at a frequency f is

$$\frac{1}{\sqrt{\mu\sigma\pi f}}$$

where μ is the permittivity of the conductor, and σ is its conductivity in Ohm-meters. $\mu = 4\pi\times10^{-7}$ henry/meter except for magnetic materials, where $\mu=4\mu_r\pi\times10^{-7}$ henry/meter (μ_r is the relative permittivity). For the purposes of resistance calculation in cases where the skin depth is less than one-fifth the conductor thickness, we can assume that all the HF current flows in a layer the thickness of the skin depth, and is uniformly distributed.

SKIN EFFECT

At high frequencies inductive effects cause currents to flow only in the surface of conductors.



Skin depth at frequency f in a conductor of resistivity ρ ohm-metre and permittivity μ henry/metre is

$$\sqrt{\frac{\rho}{\mu\pi f}}$$

In copper the skin depth is $6.61/\sqrt{f}$ cm and

the skin resistance is $2.6\mathrm{X}10^{-7}\sqrt{f}$ Ω/sq

(Remember that current *may* flow in both sides of a PCB [this is discussed later] and that the skin resistance formula is only valid if the skin depth is less than the conductor thickness.)

Figure 9–3.

Skin effect has the effect of increasing the resistance of conductors at quite modest frequencies and must be considered when deciding if the resistance of wires or PC tracks will affect a circuit's performance. (It also affects the behavior of resistors at HF.)

Capacitance

Good HF analog design must incorporate stray capacitance. Wherever two conductors are separated by a dielectric there is capacitance. The formulae for parallel wires, concentric spheres and cylinders, and other more exotic structures may be found in any textbook but the commonest structure, found on all PCBs, is the parallel plate capacitor.

CAPACITANCE

Wherever two conductors are separated by a dielectric (including air or a vacuum) there is capacitance.

For a parallel plate capacitor $C = {.0885 E_r A}/{d}$ pF

where A is the plate area in sq.cm
d is the plate separation in cm
& E_r is the dielectric constant

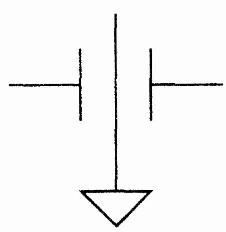
Epoxy PCB material is often 1.5 mm thick and E_r =4.7
Capacity is therefore approximately 2.8 pf/sq.cm

Figure 9–4.

When stray capacitance appears as parasitic capacity to ground it can be minimized by careful layout and routing, and incorporated into the design. Where stray capacity couples a signal where it is not wanted the effect may be minimized by design but often must be cured by the use of a Faraday shield.

Figure 9–5.

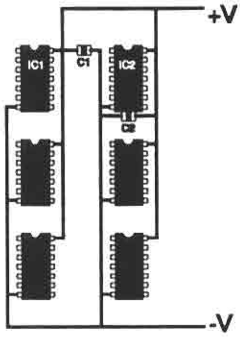
FARADAY SHIELDS



Capacitively coupled noise can be very effectively shielded by a grounded conductive shield, known as a Faraday Shield. But it must be grounded or it increases the problem.
For this reason coil and quartz crystal cans should always be grounded.

If inductance is to be minimized the lead and PC track length of capacitors must be kept as small as possible. This does not mean just generally "short," but that the inductance in the actual circuit function must be minimal. Figure 9–6 shows both a common mistake (the leads of the capacitor C1 are short, but the decoupling path for IC1 is very long) and the

CAPACITOR LEADS MUST BE SHORT



Although the leads of C1 are short the HF decoupling path of IC1 is far too long.
The decoupling path of IC2 is ideal.

Figure 9–6.

correct way to decouple an IC (IC2 is decoupled by C2 with a very short decoupling path).

Inductors

Any length of conductor has inductance and it can matter. In free space a 1cm length of conductor has inductance of 7–10nH (depending on diameter), which represents an impedance of 4–6Ω at 100MHz. This may be large enough to be troublesome, but badly routed conductors can cause worse problems as they form, in effect, single turn coils with quite substantial inductance.

INDUCTANCE

Any conductor has some inductance
A straight wire of length L and radius R (both mm & L>>R)

has inductance $$0.2L\left[\ln\left(\frac{2L}{R}\right)-.75\right]\text{ nH}$$

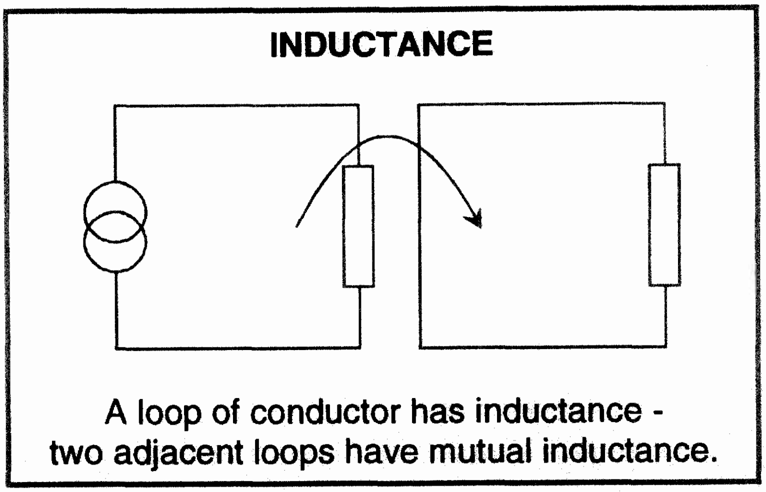
A strip of conductor of length L, width W and thickness H (mm) has inductance

$$0.2L\left[\ln\left(\frac{2L}{W+H}\right)+0.2235\left(\frac{W+H}{L}\right)+0.5\right]\text{ nH}$$

1 cm of thin wire or PC track is somewhere between 7 and 10 nH

Figure 9–7.

Figure 9–8.



If two such coils are close to each other we must consider their mutual inductance as well as their self-inductance. A change of current in one will induce an EMF in the other. Defining the problem, of course, at once suggests cures: reducing the area of the coils by more careful layout, and increasing their separation. Both will reduce mutual inductance, and reducing area reduces self inductance too.

It is possible to reduce inductive coupling by means of shields. At LF shields of mu-metal are necessary (and expensive, heavy and vulnerable to shock, which causes loss of permittivity) but at HF a continuous Faraday shield (mesh will not work so well here) blocks magnetic fields too, provided that the skin depth at the frequency of interest is much less

Figure 9–9.

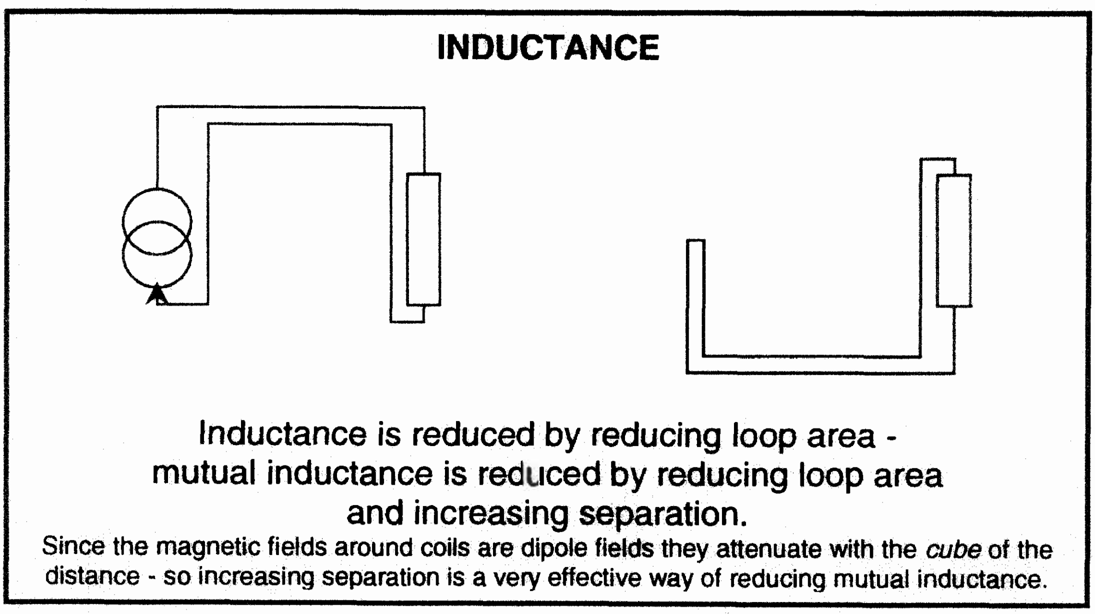


Figure 9–10.

MAGNETIC SHIELDS
At LF magnetic shielding requires Mu-Metal which is heavy, expensive and vulnerable to shock.
At HF a conductor provides effective magnetic shielding provided the skin depth is less than the conductor thickness.
PC foil is an effective magnetic shield above 10-20 MHz.

than the thickness of the shield. In breadboards a piece of copper-clad board, soldered at right angles to the ground plane, can make an excellent HF magnetic shield, as well as being a Faraday shield.

Magnetic fields are dipole fields, and therefore the field strength diminishes with the *cube* of the distance. This means that quite modest separation increases attenuation a lot. In many cases physical distance is all that is necessary to reduce magnetic coupling to acceptable levels.

Grounds

Kirchoff's Law tells us that return currents in ground are as important as signal currents in signal leads. We find here another example of the "superconductor assumption"—too many engineers believe that all points marked with a ground symbol on the circuit diagram are at the same potential. In practice ground conductors have resistance and inductance—and potential differences. It is for this reason that such breadboarding techniques as matrix board, prototype boards (the ones where you poke component leads into holes where they are gripped by phosphor-bronze contacts) and wire-wrap have such poor performance as analog prototyping systems.

The best analog breadboard arrangement uses a "ground plane"—a layer of continuous conductor (usually copper-clad board). A ground

Figure 9–11.

KIRCHOFF'S LAW
The net current at any point in a circuit is zero.
OR
What flows in flows out again.
OR
Current flows in circles.
THEREFORE
All signals are differential.
AND
Ground impedance matters.

plane has minimal resistance and inductance, but its impedance may still be too great at high currents or high frequencies. Sometimes a break in a ground plane can configure currents so that they do not interfere with each other; sometimes physical separation of different subsystems is sufficient.

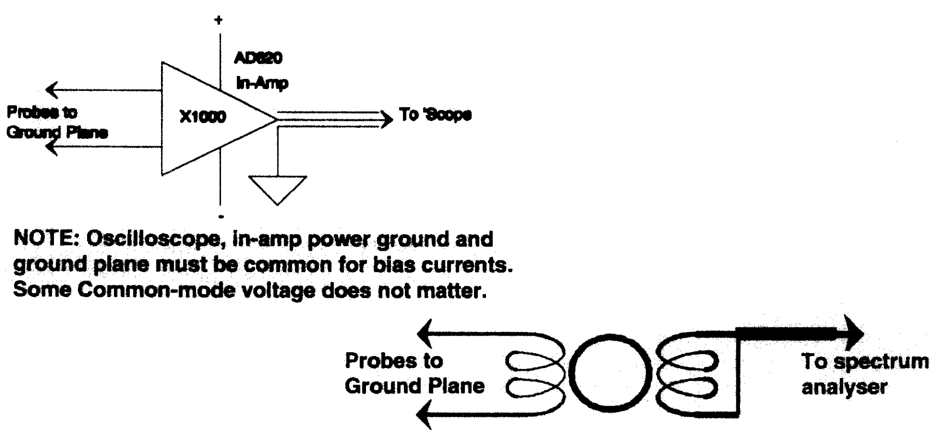
Figure 9–12.

GROUND PLANE BREADBOARD

The breadboard ground consists of a single layer of continuous metal, usually (unetched) copper-clad PCB material. In theory all points on the plane are at the same potential, but in practice it may be necessary to configure ground currents by means of breaks in the plane, or careful placement of sub-systems. Nevertheless ground plane is undoubtedly the most effective ground technique for analog breadboards.

Figure 9–13.

GROUND PLANE



To measure voltage drop in ground plane it is necessary to use a device with high common-mode rejection and low noise. At DC and LF an instrumentation amplifier driving an oscilloscope will give sensitivity of up to 5 µV/cm - at HF and VHF a transmission line transformer and a spectrum analyser can provide even greater sensitivity.

It is often easy to deduce where currents flow in a ground plane, but in complex systems it may be difficult. Breadboards are rarely that complex, but if necessary it is possible to measure differential voltages of as little as 5µV on a ground plane. At DC and LF this is done by using an instrumentation amplifier with a gain of 1,000 to drive an oscilloscope working at 5 mV/cm. The sensitivity at the input terminals of the inamp is 5µV/cm; there will be some noise present on the oscilloscope trace, but it is quite possible to measure ground voltages of the order of 1µV with such simple equipment. It is important to allow a path for the bias current of the inamp, but its common-mode rejection is so good that this bias path is not critical.

The upper frequency of most inamps is 25–50kHz (the AD830 is an exception—it works up to 50 MHz at low gains, but not at ×1,000). Above LF a better technique is to use a broadband transmission line transformer to remove common-mode signals. Such a transformer has little or no voltage gain, so the signal is best displayed on a spectrum analyzer, with µV sensitivity, rather than on an oscilloscope, which only has sensitivity of 5mV or so.

Decoupling

The final issue we must consider before discussing the actual techniques of breadboarding is decoupling. The power supplies of HF circuits must be short-circuited together and to ground at all frequencies above DC. (DC short-circuits are undesirable for reasons which I shall not bother to discuss.) At low frequencies the impedance of supply lines is (or should be) low and so decoupling can be accomplished by relatively few electrolytic capacitors, which will not generally need to be very close to the parts of the circuit they are decoupling, and so may be shared among several parts of a system. (The exception to this is where a component draws a large LF current, when a local, dedicated, electrolytic capacitor should be used.)

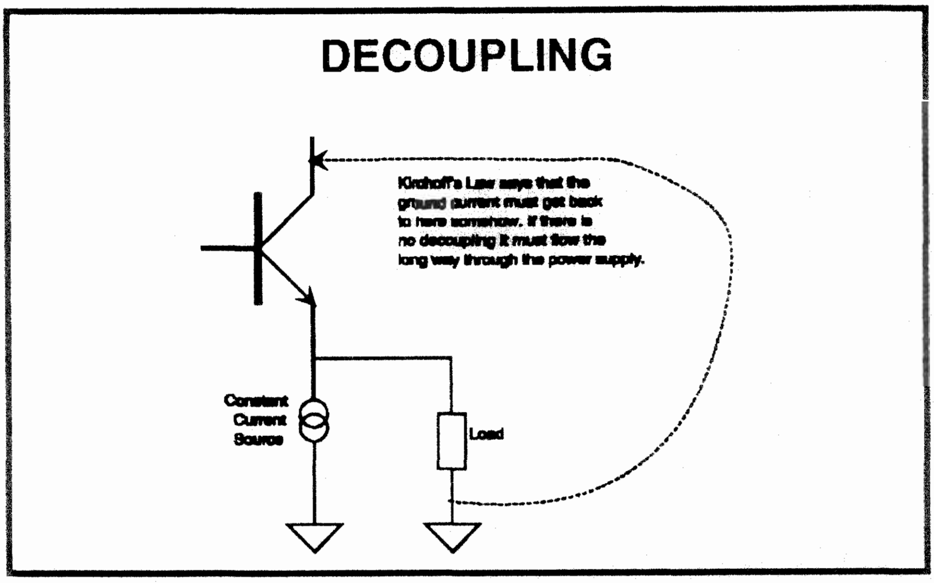
At HF we cannot ignore the impedance of supply leads (as we have already seen in Figure 9–6) and ICs must be individually decoupled with low inductance capacitors having short leads and PC tracks. Even 2–3mm of extra lead/track length may make the difference between the success and failure of a circuit layout.

DECOUPLING

Supplies must be short-circuited to each other and to ground at *all* frequencies. (But not at DC.)

Figure 9–14.

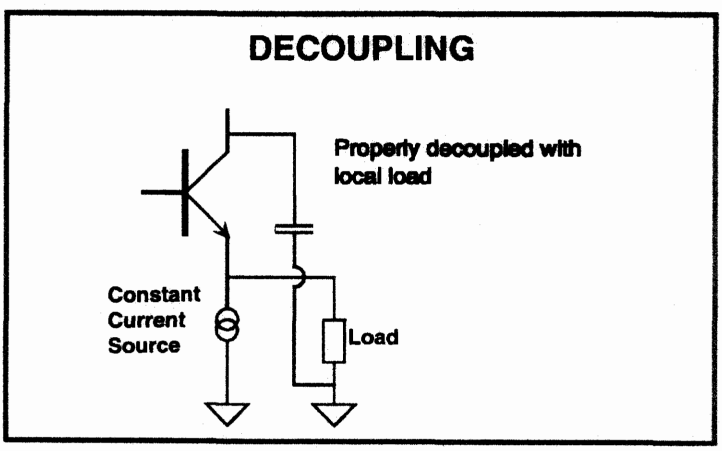
Figure 9–15.



Where the HF currents of a circuit are mostly internal (as is the case with many ADCs) it is sufficient that we short-circuit its supplies at HF so that it sees its supplies as stiff voltage sources at all frequencies. When it is driving a load, the decoupling must be arranged to ensure that the total loop in which the load current flows is as small as possible. Figure 9–15 shows an emitter follower without supply decoupling—the HF current in the load must flow through the power supply to return to the output stage (remember that Kirchoff's Law says, in effect, that currents must flow in circles). Figure 9–16 shows the same circuit with proper supply decoupling.

This principle is easy enough to apply if the load is adjacent to the circuit driving it. Where the load must be remote it is much more difficult, but there are solutions. These include transformer isolation and the use of a transmission line. If the signal contains no DC or LF compo-

Figure 9–16.



nents, it may be isolated with a transformer close to the driver. Such an arrangement is shown in Figure 9–17. (The nature of the connection from the transformer to the load may present its own problems—but supply decoupling is not one of them.)

A correctly terminated transmission line constrains HF signal currents so that, to the supply decoupling capacitors, the load appears to be adjacent to the driver. Even if the line is not precisely terminated, it will constrain the majority of the return current and is frequently sufficient to prevent ground current problems.

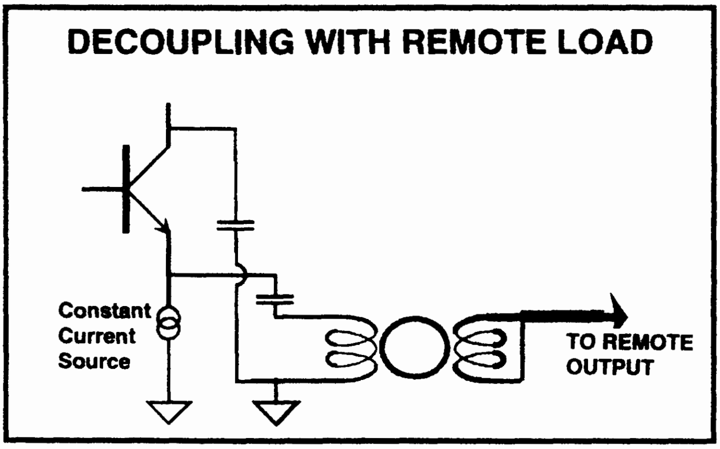


Figure 9–17.

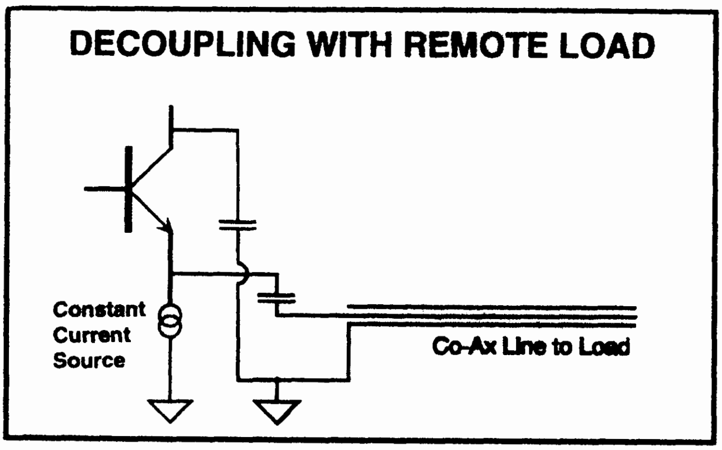


Figure 9–18.

Breadboarding Principles

Having considered issues of resistance, capacitance, and inductance, it is clear that breadboards must be designed to minimize the adverse effects of these phenomena. The basic principle of a breadboard is that it is a temporary structure, designed to test the performance of a circuit or system, and must therefore be easy to modify.

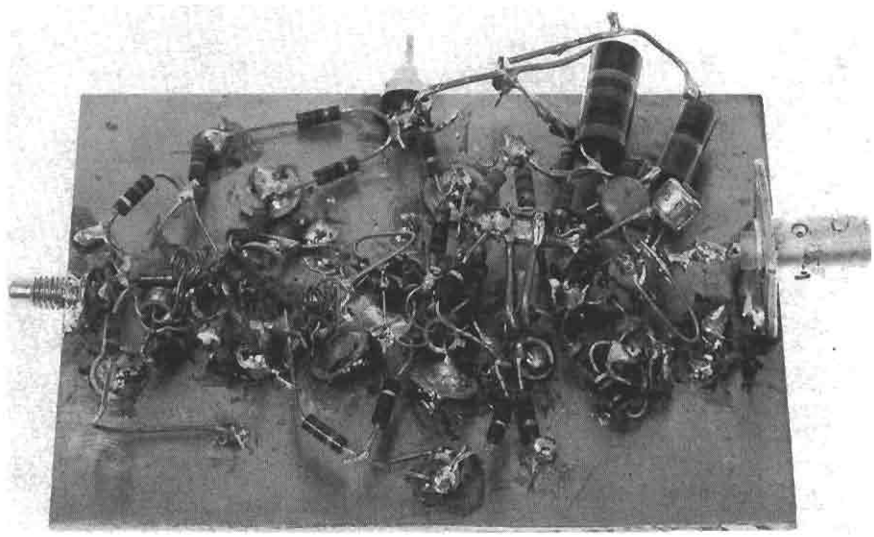
There are many commercial breadboarding systems, but almost all of them are designed to facilitate the breadboarding of digital systems, where noise immunities are hundreds of millivolts or more. (We shall discuss the exception to this generality later.) Matrix board (Veroboard, etc.), wire-wrap, and plug-in breadboard systems (Bimboard, etc.) are, without exception, unsuitable for high performance or high frequency analog breadboarding. They have too high resistance, inductance and capacitance. Even the use of IC sockets is inadvisable. (All analog engineers should practice the art of unsoldering until they can remove an IC from a breadboard [or a plated-through PCB] without any damage to the board or the device—solder wicks and solder suckers are helpful in accomplishing this.)

Practical Breadboarding

The most practical technique for analog breadboarding uses a copper-clad board as a ground plane. The ground pins of the components are soldered directly to the plane, and the other components are wired together above it. This allows HF decoupling paths to be very short indeed. All lead lengths should be as short as possible, and signal routing should separate high-level and low-level signals. Ideally the layout should be similar to the layout to be used on the final PCB.

Pieces of copper-clad may be soldered at right angles to the main ground plane to provide screening, or circuitry may be constructed on both sides of the board (with connections through holes) with the board itself providing screening. In this case the board will need legs to protect the components on the underside from being crushed.

Figure 9–19.



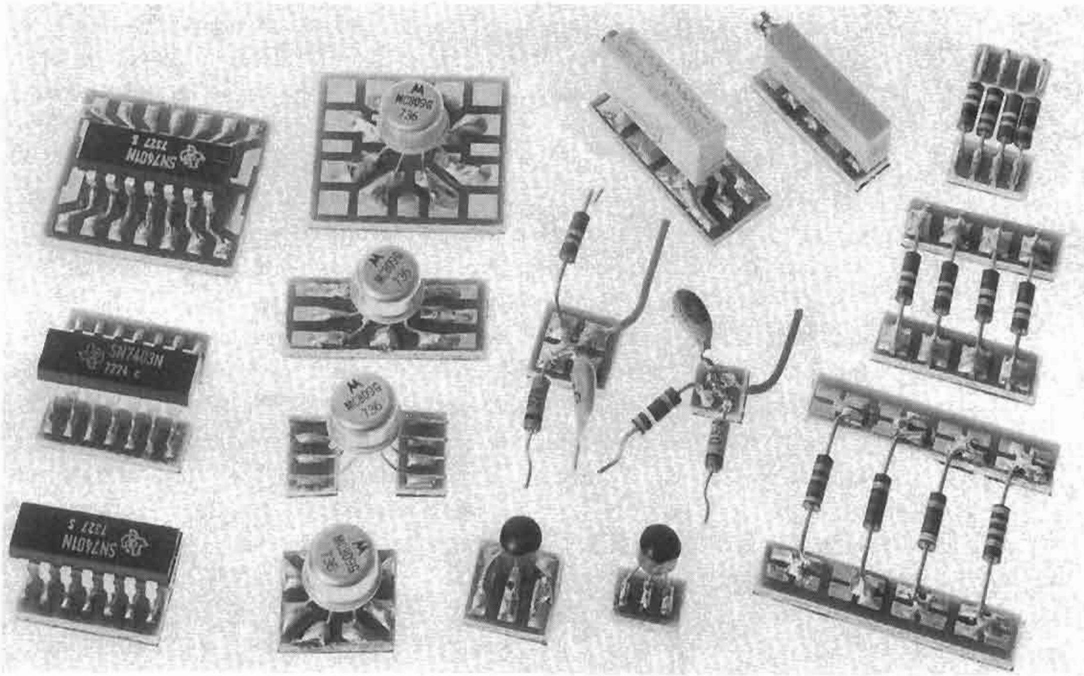


Figure 9–20.

When the components of a breadboard of this type are wired point-to-point in the air (a type of construction strongly advocated by Robert A. Pease of National Semiconductor[1] and sometimes known as "bird's nest" construction) there is always the risk of the circuitry being crushed and resulting short-circuits; also, if the circuitry rises high above the ground plane, the screening effect of the ground plane is diminished and interaction between different parts of the circuit is more likely. Nevertheless the technique is very practical and widely used because the circuit may so easily be modified.

However, there is a commercial breadboarding system which has most of the advantages of "bird's nest over a ground plane" (robust ground, screening, ease of circuit alteration, low capacitance, and low inductance) and several additional advantages: it is rigid, components are close to the ground plane, and where necessary node capacitances and line impedances can be calculated easily. This system was invented by Claire R. Wainwright and is made by WMM GmbH in the town of Andechs in Bavaria and is available throughout Europe and most of the world as "Mini-Mount" but in the USA (where the trademark "Mini-Mount" is the property of another company) as the "Wainwright Solder-Mount System."[2] (There is also a monastery at Andechs where they brew what is arguably the best beer in Germany.)

Solder-Mounts consist of small pieces of PCB with etched patterns on one side and contact adhesive on the other. They are stuck to the ground plane and components are soldered to them. They are available in a wide variety of patterns, including ready-made pads for IC packages of all sizes from 8-pin SOICs to 64-pin DILs, strips with solder pads at intervals (which intervals range from .040" to .25"; the range includes strips with 0.1" pad spacing which may be used to mount DIL devices), strips with conductors of the correct width to form microstrip transmission lines (50Ω, 60Ω, 75Ω or 100Ω) when mounted on the ground plane, and a variety of pads for mounting various other components. A few of the many types of Solder-Mounts are shown in Figure 9–20.

The main advantage of Solder-Mount construction over "bird's nest" is that the resulting circuit is far more rigid, and, if desired, may be made far smaller (the latest Solder-Mounts are for surface-mount devices and allow the construction of breadboards scarcely larger than the final PCB, although it is generally more convenient if the prototype is somewhat larger). Solder-Mounts are sufficiently durable that they may be used for small quantity production as well as prototyping—two pieces of equipment I have built with Solder-Mounts have been in service now for over twenty years.

Figure 9–21 shows several examples of breadboards built with the Solder-Mount System. They are all HF circuits, but the technique is equally suitable for the construction of high resolution LF analog circuitry. A particularly convenient feature of Solder-Mounts at VHF is the ease with which it is possible to make a transmission line.

If a conductor runs over a ground plane it forms a microstrip transmission line. The Solder-Mount System has strips which form microstrip lines when mounted on a ground plane (they are available with impedances of 50Ω, 60Ω, 75Ω and 100Ω). These strips may be used as transmission lines, for impedance matching, or simply as power buses. (Glass fiber/epoxy PCB is somewhat lossy at VHF and UHF, but the losses will probably be tolerable if microstrip runs are short.)

It is important to realize that current flow in a microstrip transmission line is constrained by inductive effects. The signal current flows only on the side of the conductor next to the ground plane (its skin depth is calculated in the normal way) and the return current flows only directly beneath the signal conductor, not in the entire ground plane (skin effect naturally limits this current, too, to one side of the ground plane). This is helpful in separating ground currents, but increases the resistance of the circuit.

It is clear that breaks in the ground plane under a microstrip line will force the return current to flow around the break, increasing impedance. Even worse, if the break is made to allow two HF circuits to cross, the two signals will interact. Such breaks should be avoided if at all possible. The best way to enable two HF conductors on a ground plane to cross without interaction is to keep the ground plane continuous and use a microstrip on the other side of the ground plane to carry one of the signals past the other (drill a hole through the ground plane to go to the other side of the board). If the skin depth is much less than the ground plane thickness the interaction of ground currents will be negligible.

Figure 9–21

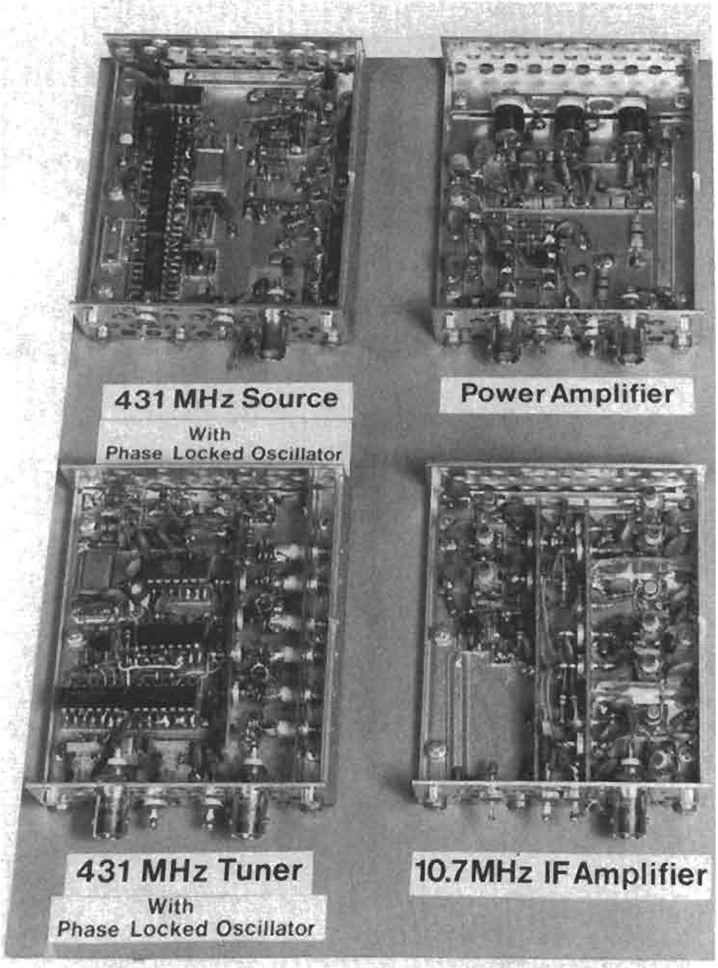
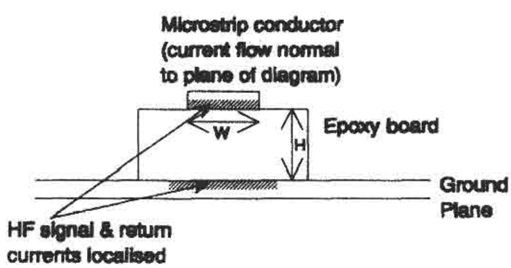


Figure 9–22.

MICROSTRIP TRANSMISSION LINE



When a conductor runs over a ground plane it forms a microstrip transmission line.

The characteristic impedance is $\frac{377H}{W\sqrt{E_r}}\ \Omega$ (note that the units of H and W are unimportant).

The transmission line determines where both the signal *and return* currents flow.

Conclusion

It is not possible in a short chapter to discuss all the intricacies of successful analog breadboard construction, but we have seen that the basic principle is to remember all the laws of nature which apply and consider their effects on the design.

Figure 9–23.

SUCCESSFUL ANALOG BREADBOARDS

Pay attention to:
Resistance
Capacitance
Inductance
Decoupling
Ground
&
Separating sensitive circuits from noisy ones

In addition to the considerations of resistance, skin effect, capacitance, inductance and ground current, it is important to configure systems so that sensitive circuitry is separated from noise sources and so that the noise coupling mechanisms we have described (common resistance/inductance, stray capacitance, and mutual inductance) have minimal opportunity to degrade system performance. ("Noise" in this context means a signal we want [or which somebody wants] in a place where we don't want it; not natural noise like thermal, shot or popcorn noise.) The general rule is to have a signal path which is roughly linear, so that outputs are physically separated from inputs and logic and high level external signals only appear where they are needed. Thoughtful layout is important, but in many cases screening may be necessary as well.

A final consideration is the power supply. Switching power supplies are ubiquitous because of their low cost, high efficiency and reliability, and small size. But they can be a major source of HF noise, both broadband and at frequencies harmonically related to their switching frequency. This noise can couple into sensitive circuitry by all the means we have discussed, and extreme care is necessary to prevent switching supplies from ruining system performance.

Prototypes and breadboards frequently use linear supplies or even batteries, but if a breadboard is to be representative of its final version it should be powered from the same type of supply. At some time during

Figure 9–24.

SWITCHING POWER SUPPLIES

Generate noise at every frequency under the Sun (and some interstellar ones as well).

Every mode of noise transmission is present.

If you must use them you should filter, screen, keep them far away from sensitive circuits, and still worry!

development, however, it is interesting (and frightening, and helpful) to replace the switching supply with a battery and observe the difference in system performance.

Figure 9–25.

OBEY THE LAW

Unexpected behaviour of analog circuitry is almost always due to the designer overlooking one of the basic laws of electronics. Remember and obey Ohm, Faraday, Lenz, Maxwell, Kirchoff **and MURPHY.**

"Murphy always was an optimist" - Mrs. Murphy.

References

1. Robert A. Pease, *Troubleshooting Analog Circuits* (Butterworth-Heinemann, 1991).
2. Wainwright Instruments Inc., 7770 Regents Rd., #113 Suite 371, San Diego, CA 92122 (619) 558 1057 Fax: (619) 558 1019.

   WMM GmbH, Wainwright Mini-Mount-System, Hartstraße, 28C, D-82346 Andechs-Frieding, Germany, (+49)8152-3162 Fax: (+49)8152-4025.

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10. Who Wakes the Bugler?

Introduction: T-Coils in Oscilloscope Vertical Systems

Few engineers realize the level of design skill and the care that is needed to produce an oscilloscope, the tool that the industry uses and trusts. To be really effective, the analog portion of a vertical channel of the oscilloscope should have a bandwidth greater than the bandwidth of the circuit being probed, and the transient response should be near perfect. A vertical amplifier designer is totally engrossed in the quest for this unnatural fast-and-perfect step-response. The question becomes, "How do 'scope designers make vertical amplifier circuits both faster and cleaner than the circuits being probed?" After all, the designers of both circuits basically have the same technology available.

One of many skillful tricks has been the application of precise, special forms of the T-coil section. I'll discuss these T-coil applications in Tektronix oscilloscopes from a personal and a historical perspective, and also from the viewpoint of an oscilloscope vertical amplifier designer. Two separate stand-alone pages contain "cookbook" design formulas, response functions, and related observations.

The T-coil section is one of the most fun, amazing, demanding, capable, and versatile circuits I have encountered in 'scopes. Special forms

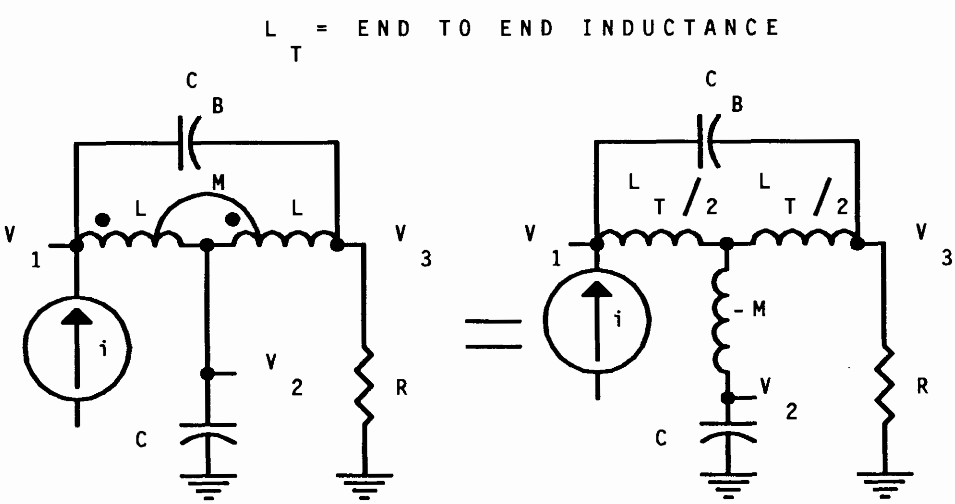


Figure 10–1.
The T-coil Section.

of this basic circuit block are used with precision and finesse to do the following:

Peak capacitive loads
Peak amplifier interstages
Form "loop-thru" circuits
Equalize nonlinear phase
Transform capacitive terminations to resistive terminations
Form distributed deflectors in cathode ray tubes
Form artificial delay line sections
Form distributed amplifier sections

I have successfully used T-coils in all of these applications except the last two. Recently, however, some successful designers from the '40s and '50s shared their experiences with those two applications.

Over My Head

While on a camping trip in Oregon in 1961, I stopped at Tektronix and received an interview and a job offer the same day. Tektronix wanted me. They were at a stage where they needed to exploit transistors to build fast, high-performance 'scopes. I had designed a 300MHz transistor amplifier while working at Sylvania. In 1961, that type of experience was a rare commodity. Actually, I had designed a wide-band 300MHz IF amplifier that only achieved 200MHz. What we (Sylvania) used was a design that my technician came up with that made 300MHz. So I arrived at this premier oscilloscope company feeling somewhat of a fraud. I was more than just a bit intimidated by the Tektronix reputation and the distributed amplifiers and artificial delay lines and all that "stuff" that really worked. The voltage dynamic range, the transient response cleanliness, and DC response requirements for a vertical output amplifier made my low-power, 50 Ohm, 300MHz IF amplifier seem like child's play. Naturally, I was thrown immediately into the job of designing high-bandwidth oscilloscope transistor vertical-output amplifiers. I felt like a private, fresh out of basic training, on the front lines in a war.

The Two Principles of Inductive Peaking

The primary and most obvious use of a T-coil section is to peak the frequency response (improve the bandwidth, decrease the risetime) of a capacitance load. Inductances, in general, accomplish this through the action of two principles.

Principle Number One: Separate, in Time, the Charging of Capacitances

The coaxial cable depicts a limiting case of Principle Number One. A coaxial cable driven from a matched-source impedance has a very fast risetime. The source has finite resistance and the cable has some total capacitance. If the cable capacitance and inductance are uniformly distrib-

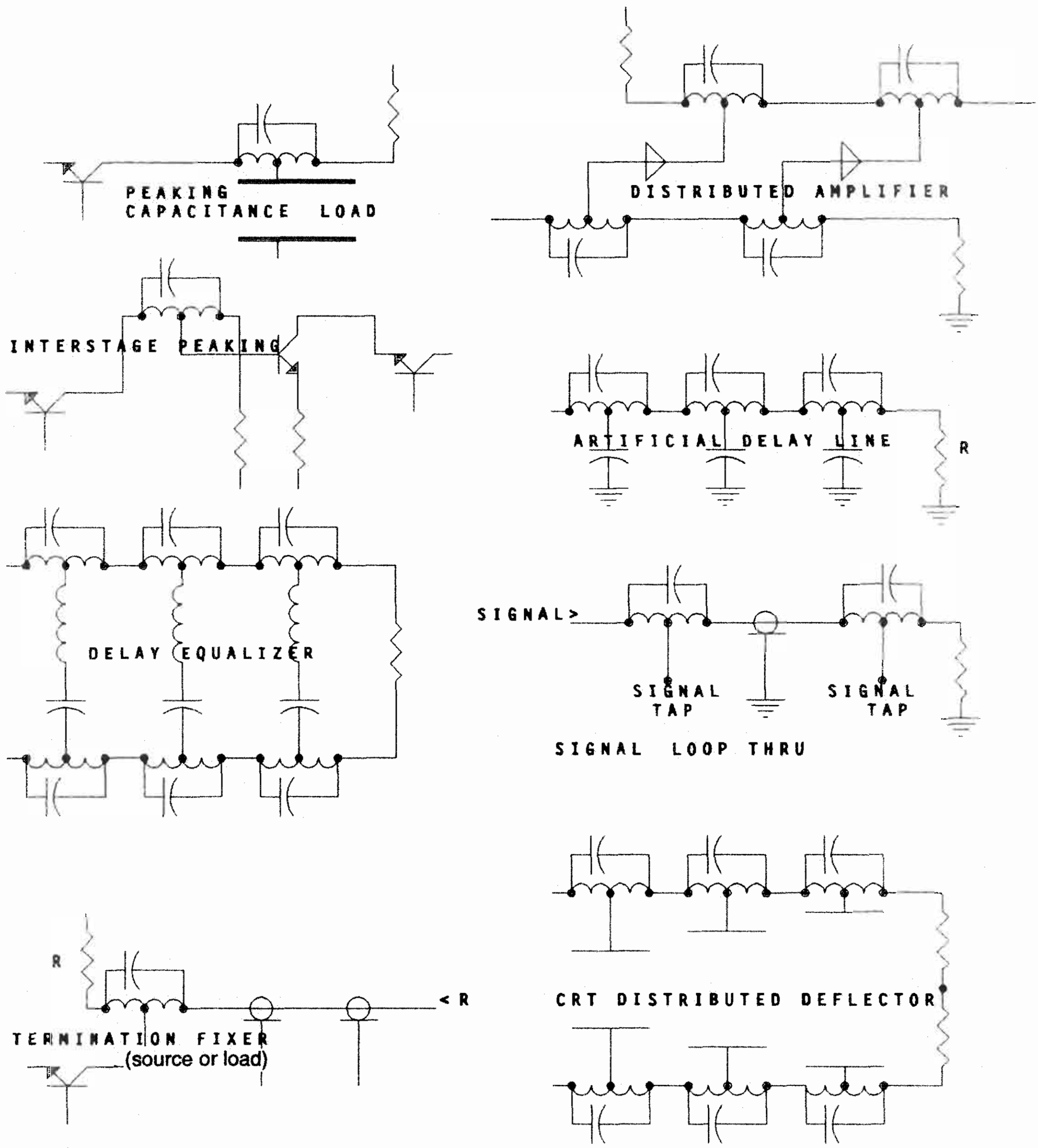


Figure 10–2.
The Versatile T-coil.

uted and the cable is situated in the proper impedance environment, the bandwidth is >> $1/2\pi RC_{cable}$ and the risetime << 2.2 RC_{cable}. The distributed inductance in the line has worked with the distributed capacitance to spread out, in time, the charging of this capacitance. A pi-section LC filter could also demonstrate Principle Number One, as could a distributed amplifier.

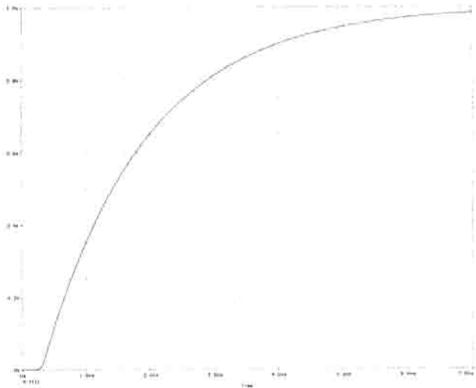
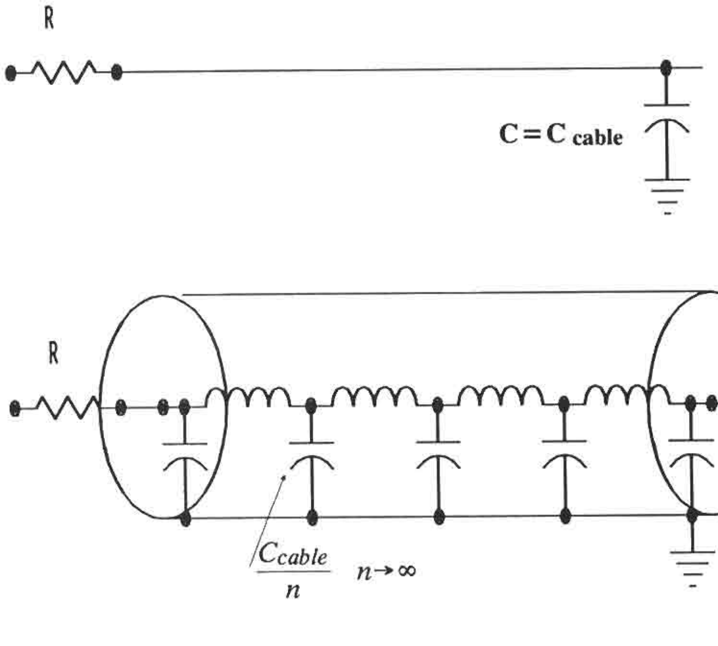
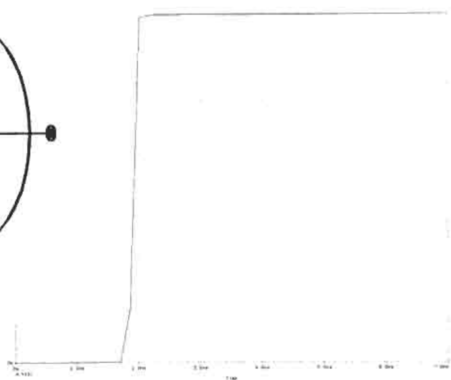


Figure 10–3. Separate, In Time, the Charging of Capacitances.
Peaking Principle 1





Principle Number Two: Don't Waste Current Feeding a Resistor When a Capacitor Needs to Be Charged In Figure 10–4 a helpful elf mans the normally closed switch in series with the resistor. When a current step occurs, the elf opens the switch for RC seconds, allowing the capacitor to take the full current. After RC seconds, the capacitor has charged to a voltage equal to IR. The elf then closes the switch, allowing the current

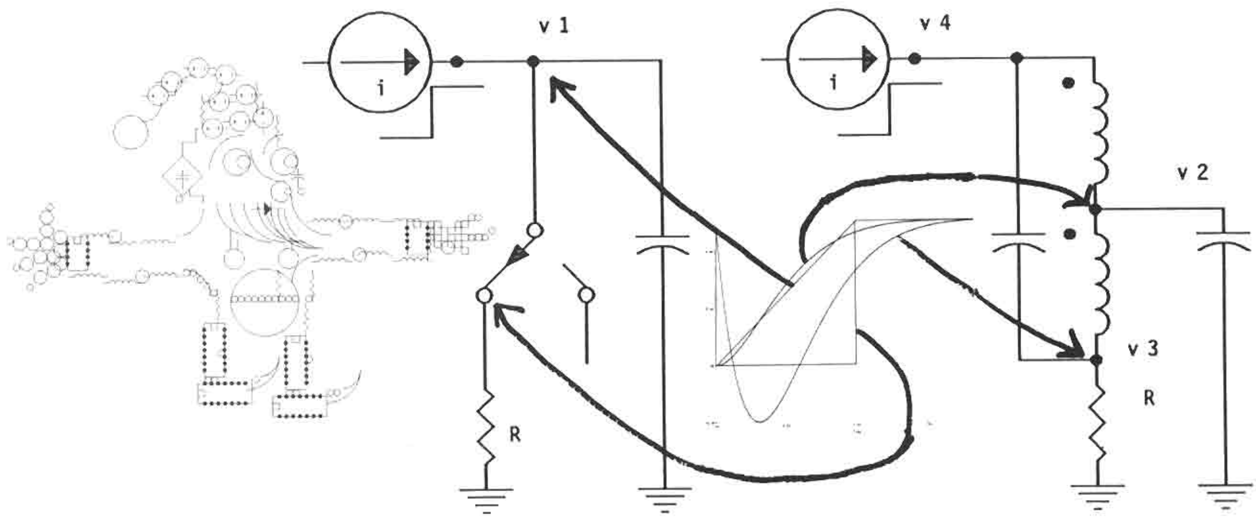


Figure 10–4.
Don't Waste Time Feeding a Resistor When a Capacitor Needs to be Charged.
Peaking Principle 2

to feed the resistor, also producing a voltage equal to IR. No current is wasted in the resistor while the capacitor is charging.

A current step applied to the constant-resistance bridged T-coil yields the same capacitor voltage risetime, 0.8 RC, as the elf circuit. In both cases, during the rise of voltage on the capacitor, the voltage waveform on the termination resistor is negative, zero, or at least low. Without the helpful elf, or without the T-coil, the risetime would have been 2.2 RC. With these risetime enhancers, the risetime is lowered to 0.8 RC. This is a risetime improvement factor of 2.75. If there are two or more capacitor lumps, Principle Number One can combine with Principle Number Two to obtain even higher risetime improvement factors.

When both principles are working optimally, reflections, overshoot, and ringing are avoided or controlled. This is a matter of control of energy flow in and out of the T-coil section reactances. A T-coil needs to be tuned or tolerated. In the constant-resistance T-coil section, given a load capacitance, there is only one set of values for the inductance, mutual inductance, and bridging capacitance which will satisfy one set of specifications of the driving point resistance (may imply reflection coefficient) and desired damping factor (relates to step response overshoot).

T-Coils Peaking Capacitance Loads

A cathode ray tube (CRT) electrostatic deflection plate pair is considered a pure capacitance load. In the '50s and '60s, T-coils were often used in deflection plate drive circuits. Usually a pentode-type tube was used as the driver, rather than a transistor, because of the large voltage swing required. The pentode output looked like a capacitive high-impedance source. A common technique was to employ series peaking of the driver capacitance, cascaded with T-coiled CRT deflection plate capacitance.

The 10–MHz Tektronix 3A6

The 3A6 vertical deflection amplifier works really hard. The 3A6 plug-in was designed to operate in the 560 series mainframes, where the plug-ins drove the CRT deflection plates directly. The deflection sensitivity was poor (20 volts per division) and the capacitance was high. To cover the display screen linearly and allow sufficient overscan, the output beam power tube on each side had to traverse at least 80 volts. The T-coils on the 3A6 made the bandwidth and dynamic range possible without burning up the large output vacuum tubes.

A Real T-Coil Response

A vertical-output deflection-amplifier designer has a unique situation—the amplifier output is on the screen—no other monitor is needed. This is the case with the 3A6 circuit shown here. The input test signal is clean and fast. The frequency and step response of the entire vertical system is dominated by the "tuning" of the T-coil L384 and its opposite-side

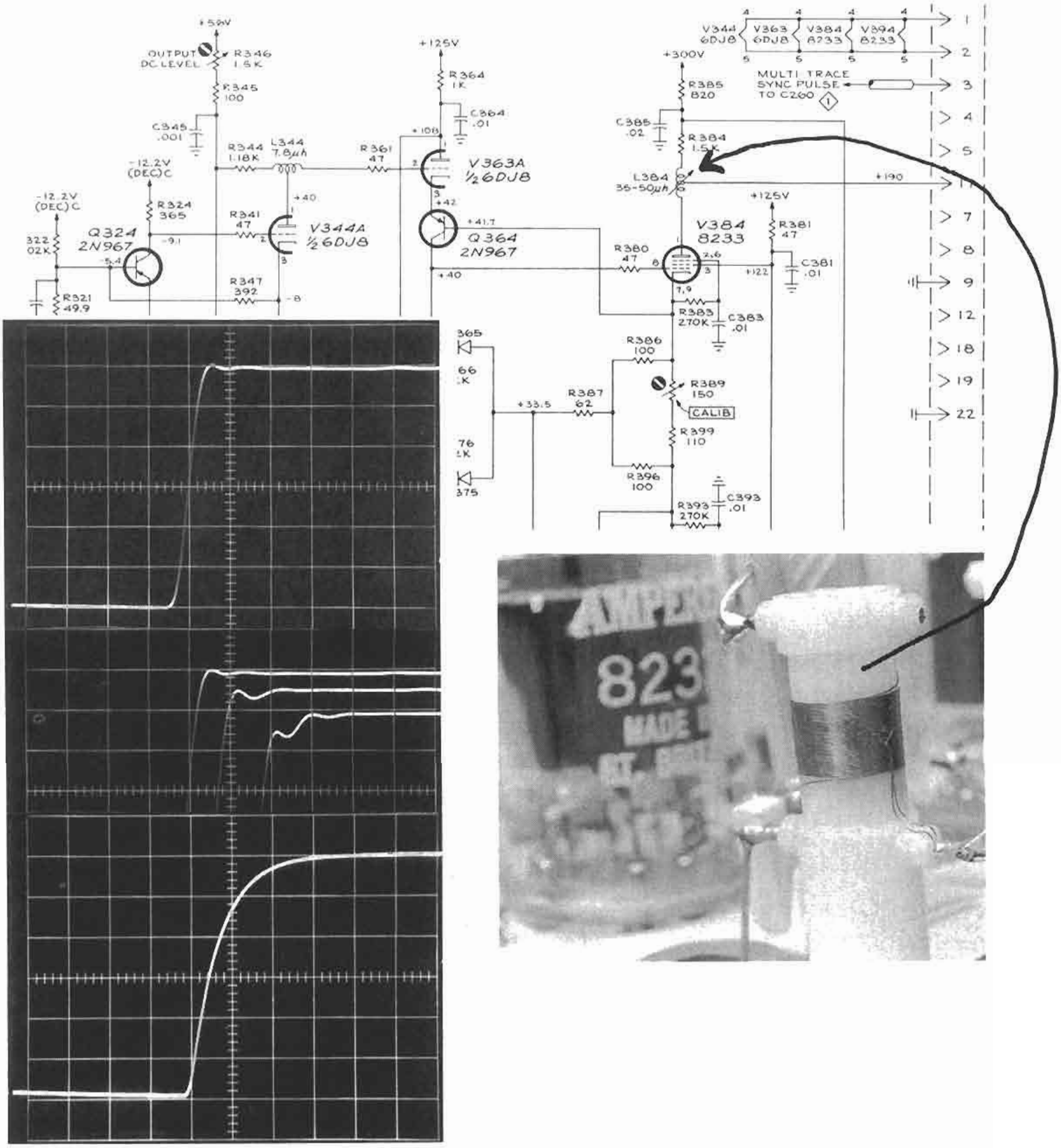
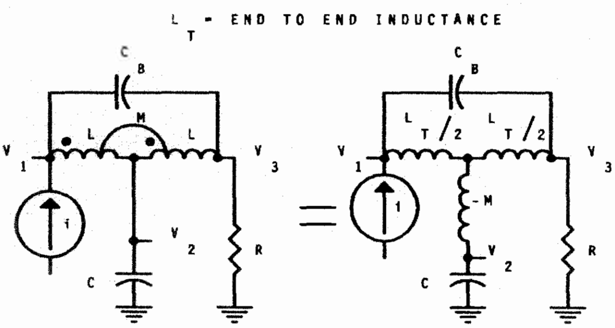


Figure 10–5.
Step Response Waveforms 3A6 T-coil Peaking.

FACT SHEET FOR CONSTANT-RESISTANCE T-COILS



damping factor

$$\delta = \frac{1}{2}\sqrt{\frac{(1+k)}{(1-k)}}$$

L_T = 2L + 2M $\quad$ *k=coupling coefficient* $\quad k=\frac{M}{L}$ **and** $\quad \frac{M}{L_T}=\frac{k}{2(1+k)}$

If $\quad L_T=R^2C$ and $C_B=\frac{(1-k)C}{4(1+k)}$

Then $\quad \frac{v1}{i}=R$ $\quad$ **the Constant Resistance Property**

and $\quad \frac{v2}{i}=\frac{R}{1+\frac{RCs}{2}+\frac{(1-k)R^2C^2s^2}{4(1+k)}}$ $\quad$ **a Quadratic (2 pole) Response at v2**

and $\quad \frac{v3}{i}=R\,\frac{1-\frac{RCs}{2}+\frac{(1-k)R^2C^2s^2}{4(1+k)}}{1+\frac{RCs}{2}+\frac{(1-k)R^2C^2s^2}{4(1+k)}}$ $\quad$ **an ALL PASS response at v3**

	v2 step response overshoot
k= .6 (CRITICAL DAMPING)	**0.0%**
k=.5 (FLAT DELAY)	**0.4 %**
k=.333 (FLAT AMPLITUDE)	**4.3%**
k= 0.0 (high frequency DELAY BOOST)	**16.0%**

SPECIAL NOTE ON m-DERIVED T-COILS.

The m-derived t-coils arise from m-derived filter theory. They do not have the constant-resistance property. The total inductance = R^2C. They have no bridging capacitance. They do not have a simple quadratic (2 pole) response. The value of "m" implies a coupling coefficient $k=\frac{m^2-1}{m^2+1}$

Figure 10–6.
Fact Sheet on Constant Resistance T-coils.

counterpart. The bottom picture shows the response when the coils (L384 and its mate) were disabled. (All three terminals of each coil were shorted together.) This reveals that, without the coils, the response looks very much like a single-time-constant response. The middle picture illustrates the progression of tuning after the shorts are removed. The powdered iron slugs in the coil forms are adjusted to optimize the response. The top picture shows the best response. The 10–to-90% risetime of the beginning waveform is 75 nanoseconds, and in the final waveform it drops to 28 nanoseconds. This is a ratio of risetimes of 2.6—near the theoretical bandwidth improvement factor of 2.74. The final waveform has peak-to-peak aberrations of 2%.

The total capacitance at the deflector node includes the deflection plates, the wires to the plates, the beam power tube plate capacitance, the wiring and coil body capacitance, the plug-in connector capacitance, the mounting point capacitances, the chassis feedthrough capacitance, the resistor capacitance, and possibly virtual capacitance looking back into the tube. We can solve for the equivalent net capacitance per side by working back from the 75nsec risetime and the 1.5k load resistance. This yields about 23pF per side. Although each coil is one solenoidal winding, it actually performs as two coils. The coil end connected to the tube plate works as a series peaking coil, and the remainder as the actual T-coil.

L344, which is also a T-coil, appears upstream in the 3A6 schematic fragment. Notice that the plate feeds the center tap of this coil. This is an application of reciprocity (Look in your old circuit textbook!). If the driving device output capacitance is significantly greater than the load capacitance, it may be appropriate to use this connection.

Distributed Amplifiers in Oscilloscopes

The idea of a distributed amplifier goes back to a British "Patent Specification" by W.S. Percival in 1936. In August 1948, Ginzton, Hewlett, Jasberg, and Noe published a classic paper on distributed amplifiers in the "Proceedings of IRE." At about the same time, Bill Hewlett (yes, of HP) and Logan Belleville (of Tektronix) met at Yaws Restaurant in Portland. Bill Hewlett described the new distributed amplifier concepts (yes, he "penciled out" the idea on a napkin!). In 1948, from August through October, Howard Vollum and Richard Rhiger built a distributed amplifier under a government contract. This amplifier was intended for use in a high-resolution ground radar. It had about a 6nsec risetime and a hefty output swing. In order to measure the new amplifier's performance, Vollum and Rhiger had outboarded it on the side of an early 511 'scope, directly feeding the deflectors.

It soon became clear that what the government and industry really needed was a very fast oscilloscope. I am not sure of the details or sequence of events, but Tektronix—Howard Vollum's two-year-old company—was making history. Vollum, Belleville, and Rhiger developed the 50MHz 517 oscilloscope, an oscilloscope with a distributed amplifier in the vertical deflection path. Vollum and Belleville had successfully refined the distributed amplifier enough to satisfy this oscilloscope vertical amplifier application. The product was successful and order

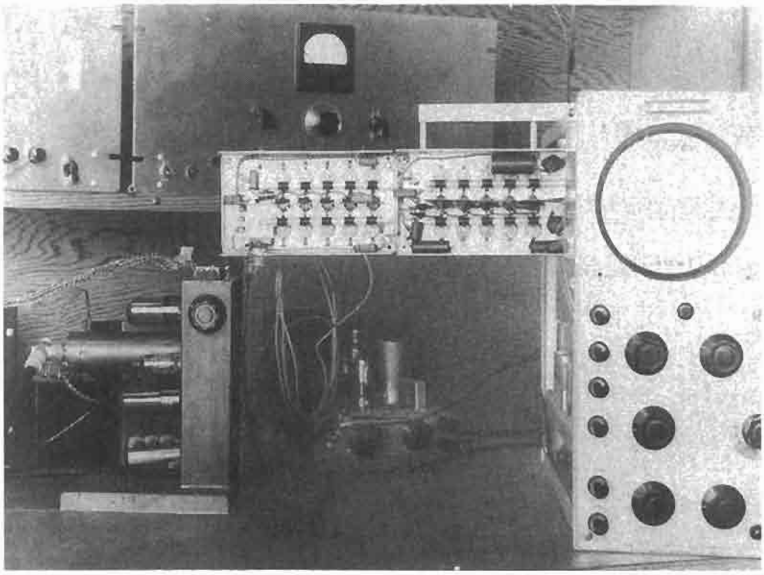


Figure 10-7.
1948 Experiment—Outboarded Distributed Amplifier.

rates exceeded Tek's ability to manufacture. Logan left Tektronix in the early '50s and Vollum and Rhiger were left managing this new big company. John Kobbe, Cliff Moulton, and Bill Polits, as well as other key electrical circuit designers, took up where Vollum, Belleville, and Rhiger had left off. Other distributed amplifiers were designed for other 'scopes during the '50s, including the 540 series at 30MHz and the 580 series at 100MHz.

Manufacturing Distributed Amplifier Oscilloscopes

The whole idea of using a distributed amplifier as an oscilloscope vertical amplifier is rather incredible to me. Obtaining a very fast, clean step response is a hard job. When T-coils are employed, the job is even harder. When they are employed wholesale, as in a distributed amplifier, they are "fussy squared or tripled." The tuning of an oscilloscope distributed amplifier and/or an artificial delay line is tricky. Tuning is done in the time domain, with clues about where and in which direction to adjust, coming from observations of the "glitches" in the step response. If the use of a distributed amplifier in the vertical channel of an oscilloscope was proposed in today's business climate, it would be declared "unmanufacturable." It would never see the light of day. However, the Tektronix boom expansion in the '50s occurred largely through the development, manufacture, and sale of distributed amplifier 'scopes.

The 100MHz 580 series was the last use of distributed amplifiers in Tektronix 'scope vertical systems. Dual triodes, low cathode connection inductance, cross-coupled capacitance neutralization, and distributed deflectors in the CRT helped to achieve this higher bandwidth.

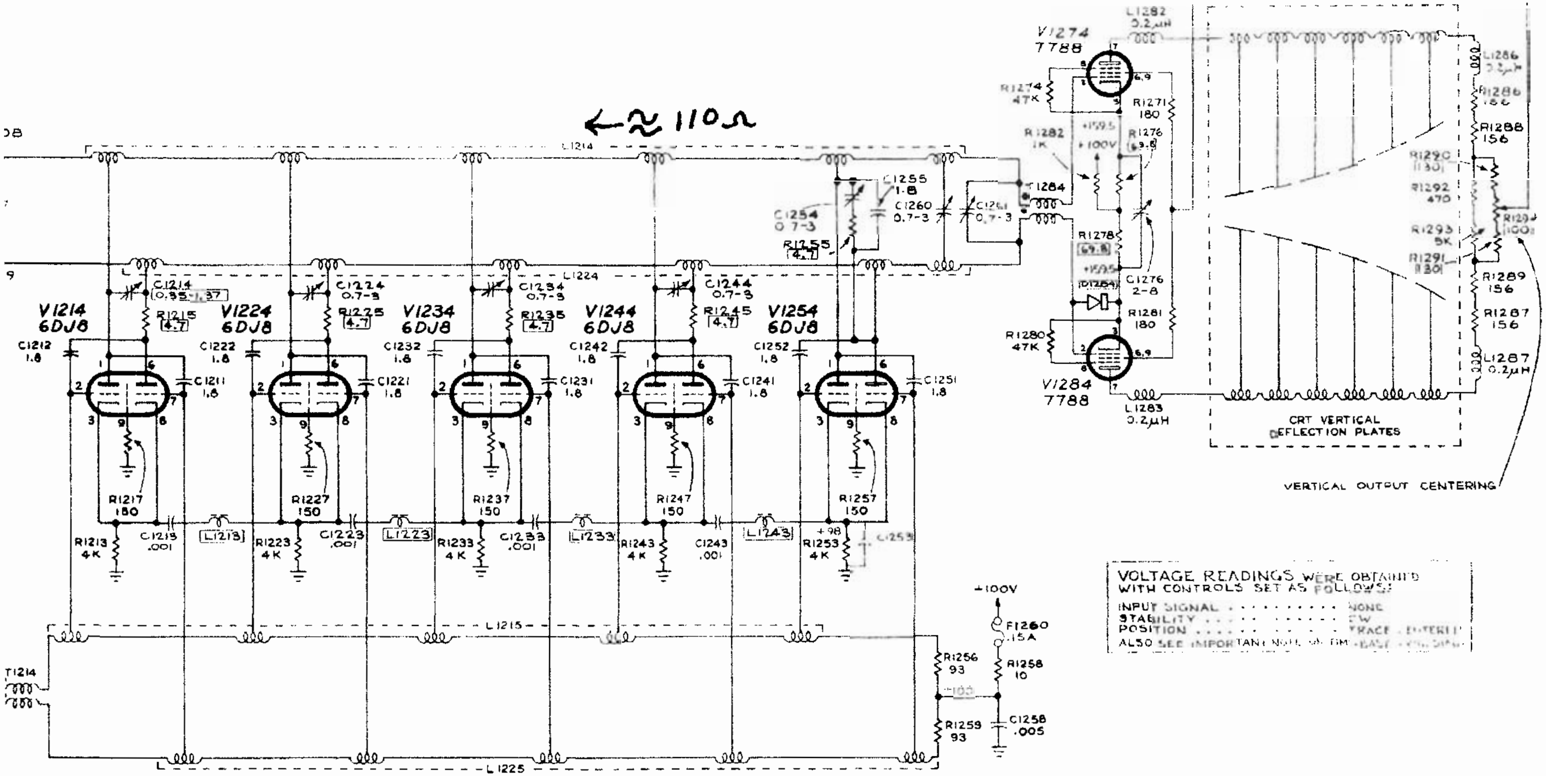


Figure 10–8.
Tektronix 585 Distributed Amplifier Vertical Output.

Distributed Deflector for a Cathode Ray Tube

In 1961, Cliff Moulton's 1GHz 519 'scope led the bandwidth race. This instrument had no vertical amplifier. The input was connected to a 125-ohm transmission line which directly fed a single-ended distributed deflection system. Schematics in Figures 10–8 and 10–9 show somewhat pictorially what a distributed deflector looks like. The 519 deflector is not shown. Within the CRT envelope was a meander line distributed deflection plate. Tuning capacitors were located at the sharp bends of the meander line. The line was first tuned as a mechanical assembly and later incorporated into the CRT envelope.

Terminated distributed deflector structures create a resistive driving-point impedance in place of one lumped capacitance. They also synchronize the signal travel along the deflection plate to the velocity of the electron beam speeding through the deflection plate length. If a distributed deflector is not used, deflection sensitivity is lost at high frequency due to transit time. Relative sensitivity is

$$\frac{\sin\frac{f}{f_{tx}}}{\frac{f}{f_{tx}}}$$

where f is frequency and f_{tx} is an inverse transit time function.

This is usually significant at 100MHz and above, and therefore distributed deflectors show up in 'scopes with bandwidths of 100MHz or higher. Various ingenious structures have been used to implement distributed deflectors. All could be modeled as assemblies of T-coils. The effective electron beam deflection response is a function of all of the T-coil tap voltages properly delayed and weighted.

Theoretical and Pragmatic Coil Proportions

The basis for the earliest T-coil designs was m-derived[1] filter theory. The delay lines and the distributed amplifier seemed to work best when the coils were proportioned—as per the classic Jasberg-Hewlett paper[2]—at m = 1.27 (coupling coefficient = 0.234). This corresponds to a coil length slightly longer than the diameter. In the design phase, there was an intelligent juggling of coil proportions based on the preshoot-overshoot behavior of the amplifier or delay line. The trial addition of bridging capacitance invariably led to increased step response aberrations.

1. m-derived filters were outcomes of image-parameter filter theory of the past. The parameter "m" determined the shape of the amplitude and phase response. "m"=1.27 approximated flat delay response. Filters could not be exactly designed, using this theory, because the required termination was not realizable.
2. This classic paper described both the m-derived T-coil section and, very briefly, the constant-resistance T-coil section. The use of these sections in distributed amplifiers was the main issue and nothing was mentioned of other uses.

In contrast with the artificial delay lines and the distributed amplifiers, the individual peaking applications usually needed a coil with more coupling ($k = 0.4$ to 0.5), which was realized by a coil shorter than its diameter. When the coil value is near or below 100 nanohenries, the goal is then to get as much coupling as possible so that the lead inductance of the center tap connection can be overcome. Flat pancake or sandwich coils of thin PC board material, thin films, or thick films are used to achieve high coupling.

The Importance of Stray Capacitance in T-Coils

The stray interwinding capacitance of a T-coil can be crudely modeled by one bridging capacitance C_{bs} across the whole coil. It is defined by the coil self-resonance frequency "f_{res}."

$$C_{bs} = \frac{1}{(2\pi f_{res})^2 L_T}$$

where L_T is the coil total inductance. If C_B is the required bridging capacitance for constant-resistance proportions, then $C_x = C_b - C_{bs}$ needs to be added. This is an effective working approximation. The recent coils built for high-frequency 50 Ohm circuits usually need additional bridging capacitance. On the other hand, the old nominally m-derived circuits never needed any added bridging capacitance. They were high-impedance circuits with very large coils and probably had enough effective bridging from the stray interwinding capacitance. They were probably constant-resistance coils in disguise. Capacitance to ground of the coil body is always a significant factor also.

Interstage Peaking

The Tektronix L and K units of the '50s were good examples of interstage T-coil peaking. The T-coils were used to peak, not the preamp input or the output, but in the middle of the amplifier. The interstage bandwidth was boosted well above the

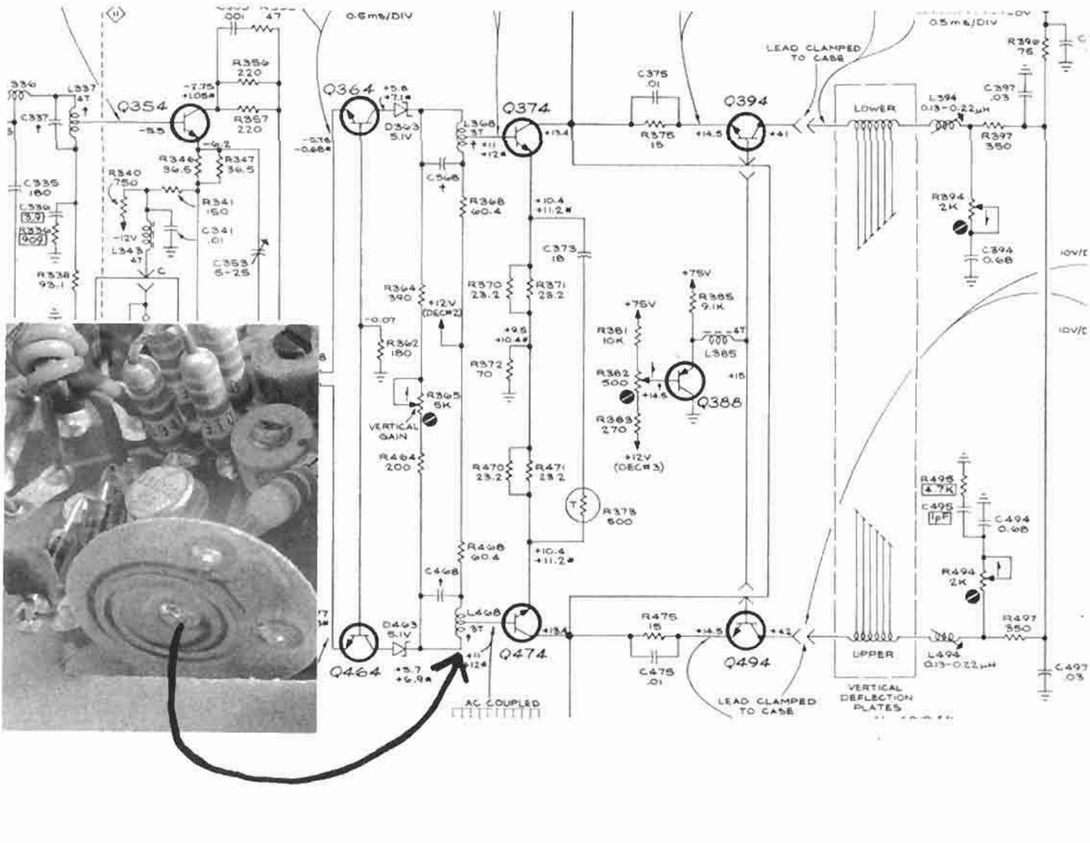
$$f_{interstage} = \frac{1}{2\pi R_L C_{total}} = \frac{g_m}{gain\ 2\pi C_{total}} < \frac{g_m}{gain\ 2\pi C_{subtotal}} = \frac{f_T}{gain}$$

The individual pre-amp bandwidths are 60MHz. This is amazing because the effective f_t of the tubes was only 200MHz or so. Both inductive peaking and f_t doubling techniques were needed to "hot rod" these plug-ins to this bandwidth.

T-Coils in Transistor Interstages

The 150MHz 454 evolved from the 50MHz 453 oscilloscope by adding distributed deflection plates to the cathode ray tube and, among other things, using a new output amplifier. This amplifier employed T-coil peaking in the interstages. The T-coil design was based on a lossless virtual capacitance, a very big approximation. This virtual capacitance at the base was dominated by the transformation of the emitter feedback admittance into the base. The emitter feedback cascode connection made two transistors function more like a pentode. The initial use of transistors in the early '60s showed us that, most of the time, vacuum tube techniques didn't work with "those blasted transistors." After all, vacuum tubes had a physical capacitance that was measurable on an "off" tube; transistors had this "virtual capacitance thing"! The conventional thinking in the design groups at Tek in the early and mid '60s was that inductive peaking and transistor high-fidelity pulse amplifiers were not compatible. Despite this, the T-coils and transistors did work, the 454 worked, and the 454 was a "cash cow" for Tektronix for several years. Since then, ICs have displaced discrete transistors and the 'scope bandwidths translated upwards, with and without T-coils. The fastest amplifiers, however, are always produced with the aid of some T-coil configuration.

Figure 10–9. Tektronix 454 Vertical-Output Amplifier and Interstage T-coil.



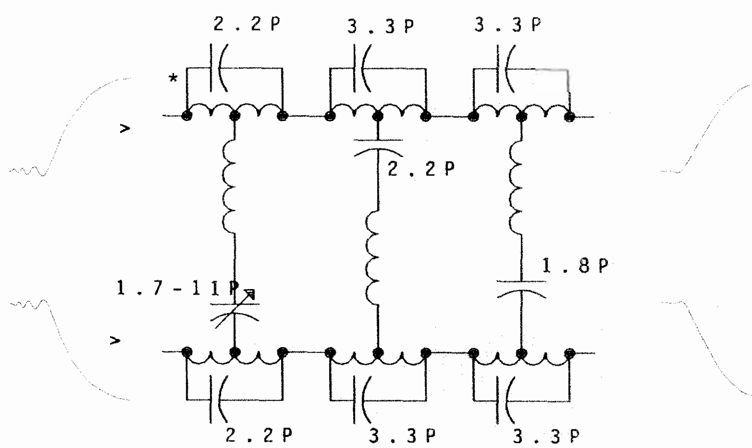
Phase Compensation with T-Coils

The portable 453 needed a compact delay line for the vertical system that didn't require tuning. Kobbe had designed and developed a balanced-counterwound delay line for the 580 series of 'scopes. We made it still smaller. This delay line worked well at 50MHz, and had reasonably low loss at 150MHz. Unfortunately, the step response revealed a preshoot problem. The explanation in the frequency domain is nonlinear phase response. High-frequency delay was insufficient, and one could see it as preshoot in the step response. Three sections of a constant-resistance-balanced T-coil structure added enough high-frequency delay to clean up the preshoot, and even speed the risetime by moving high frequencies into their "proper time slot." T-coil sections can provide delay boost at high frequencies if the T-coil section is proportioned differently from that of the peaking application. A negative value for "k" is usually appropriate and is realized by adding a separate inductor in the common leg.

Integrated Circuits

In the late '60s, when the 454A was being developed, George Wilson, head of the new Tektronix Integrated Circuits Group at that time, wanted to promote the design of an integrated circuit vertical amplifier. I rebuffed him, saying, "We can never use ICs in vertical amplifiers because they have too much substrate capacitance, too much collector resistance, and too low an f_t." I was correct at the time, but dead wrong in the long run. In the '70s, Tektronix pushed IC development in parallel with the high-bandwidth 7000 series oscilloscopes.

Figure 10–10. Correcting Insufficient High-Frequency Delay.



I stopped my slide into obsolescence in 1971 by doing a little downward mobility. I left the small portable oscilloscope group I headed, and joined George Wilson in the IC group as a designer. This foresight on my part was most uncharacteristic.

T-Coils with Integrated Circuit Vertical Amplifiers

The initial use of integrated circuits in the vertical amplifiers of Tektronix 'scopes supplied a huge bandwidth boost, but not just because of the high f_t. New processes included thin film resistors that allowed designers to put the small value emitter feedback resistors on the chip, thus eliminating the connection inductance in the emitters of transistors. That emitter inductance had made a brick wall limit in bandwidth for discrete transistor amplifiers. That wall was pretty steep, starting in the 150–200MHz area. In order to have flat, non ripple, frequency response at VHF and UHF, the separately packaged vertical amplifier stages needed to operate in a terminated transmission line environment. T-coils were vital to achieve this environment. Thor Hallen derived formulas for a minimum VSWR T-coil. Packaging and bond wire layout made constant-resistance T-coil design impossible. Hallen's T-coil incorporated and enhanced the base connection inductance. The Tektronix 7904 achieved 500MHz bandwidth by using all of the above, along with 3GHz transistors and an ft-doubler amplifier circuit configuration.

In 1979, the 1GHz 7104 employed many of the 7904 techniques but, in addition, had 8GHz f_t transistors, thin film conductors on substrates, and a package design having transmission line interconnects. It also had a much more sensitive cathode ray tube. Robert Ross had earlier developed formulas for a constant-resistance T-coil to drive a non-pure capacitor (a series capacitor-resistance combination). John Addis and Winthrop Gross made use of the Ross type T-coils (patterned with the thin film conductor) to successfully peak the stages and terminate the inter-chip transmission lines.

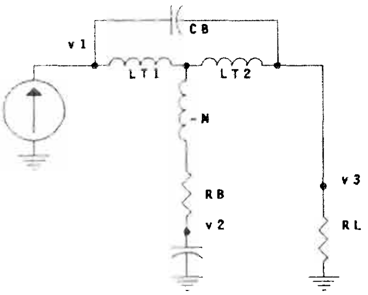
I have lumped Thor Hallen's and Bob Ross's T-coils together in a class I call "lossy capacitor T-coils."

Dual Channel Hybrid with T-Coils

In 1988, the digitizing 1GHz Tektronix 11402 was introduced. A fast real-time cathode ray tube deflection amplifier was no longer needed. T-coils were employed, however, in the 11A72 dual-channel plug-in preamp hybrid (Figure 10–12), where all of the two-channel analog signal processing took place. The T-coils peaked frequency response and minimized input reflections in the 50 Ohm input system. As in the 7904 'scope, Hallen used a design technique for the T-coils that minimized VSWR. To realize this schematic, a T-coil was needed which had

Two Types of Lossy Capacitor T-coils

ROSS CONSTANT-RESISTANCE T-COIL



$$L_{T1}=\frac{R_L^2C}{2}\left(1-\frac{R_B}{R_L}\right)$$

$$L_{T2}=\frac{R_L^2C}{2}\left(1+\frac{R_B}{R_L}\right)$$

$$C_B=\frac{C}{16\delta^2}\left(1+\frac{R_B}{R_L}\right)^2$$

$$M=\frac{R_L^2C}{4}\left[1-\left(\frac{R_B}{R_L}\right)^2-\frac{1}{4\delta^2}\left(1+\frac{R_B}{R_L}\right)^2\right]$$

$\delta = damping factor$ of quadratic response

$\frac{v1}{i}=R_L$ The Constant-Resistance property

$$\frac{v2}{iin}=\frac{R_L}{1+\frac{(R_L+R_B)}{2}Cs+R_L^2CC_Bs^2}$$

Two Pole Response

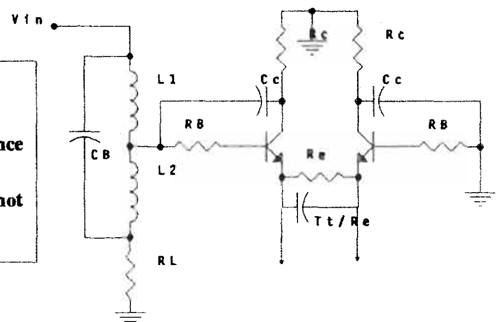
HALLEN MINIMUM VSWR T-COIL

For the Hallen and the Ross T-coils

$L_{total}=R_L^2C_{total}$

As R_B gets bigger, the input coil inductance gets smaller.

With a finite R_B, the response at R_L is not allpass



$$L_{total}=R_L^2\left[\frac{T_T}{R_e}+\left(\frac{R_c}{R_e}+1\right)C_c\right]$$

$$L_1=\frac{L_{total}}{2}\left[1+\frac{1}{R_L}\left(\frac{R_eC_cT_t(R_c+2R_B)}{(T_t+R_eC_c+R_cC_c)^2}-\frac{2R_BT_t+R_eR_cC_c}{T_t+R_eC_c+R_cC_c}\right)\right]$$

$$L_2=L_{total}-L_1$$

$$C_B=\frac{1}{R_L^2}\left[\frac{R_LC_cT_t(R_c+2R_B)(L_1-L_2)}{(T_t+R_eC_c+R_cC_c)(L_1+L_2)}+\frac{2R_BR_cC_cT_t}{T_t+R_eC_c+R_cC_c}+\frac{L_1L_2}{L_1+L_2}\right]$$

Figure 10–11.
Two Types of Lossy Capacitor T-coils.

enough mutual inductance to cancel the bond wire inductance that would be in series with its center tap. The remaining net branch inductances then had to match Hallen's values. To guide the physical layout of this coil, I used a three-dimensional inductance calculation program. This program was used iteratively. The two "G" patterns on the multilayer thick film hybrid are the top layer of these input T-coils. The major dimension of these coils is 0.05 inches. In between the chips are coils which "tune out" the collector capacitance of the transistor of each output channel. These coils are formed by multiple-layer runs and bond wire "loopbacks."

Afterglow

Conspicuous by its absence is a discussion of wideband amplifier configurations and how they operate. I have referred to f_t-doublers and current doublers without explanation. I had to really restrain myself to avoid that topic for the sake of brevity. The ultimate bandwidth limit of high-fidelity pulse amplifiers depends on the power gain capability (expressed by an f_{MAX}, for example) of the devices, and the power gain requirements of the amplifier. To approach this ultimate goal requires the sophisticated use of inductors to shape the response. For bipolar transistors, the f_t-doubler configurations and single-stage feedback amplifiers, combined with inductive peaking, do a very good job.

I hope this chapter has raised your curiosity about the circuit applications of the T-coil section. I have not written this chapter like a textbook

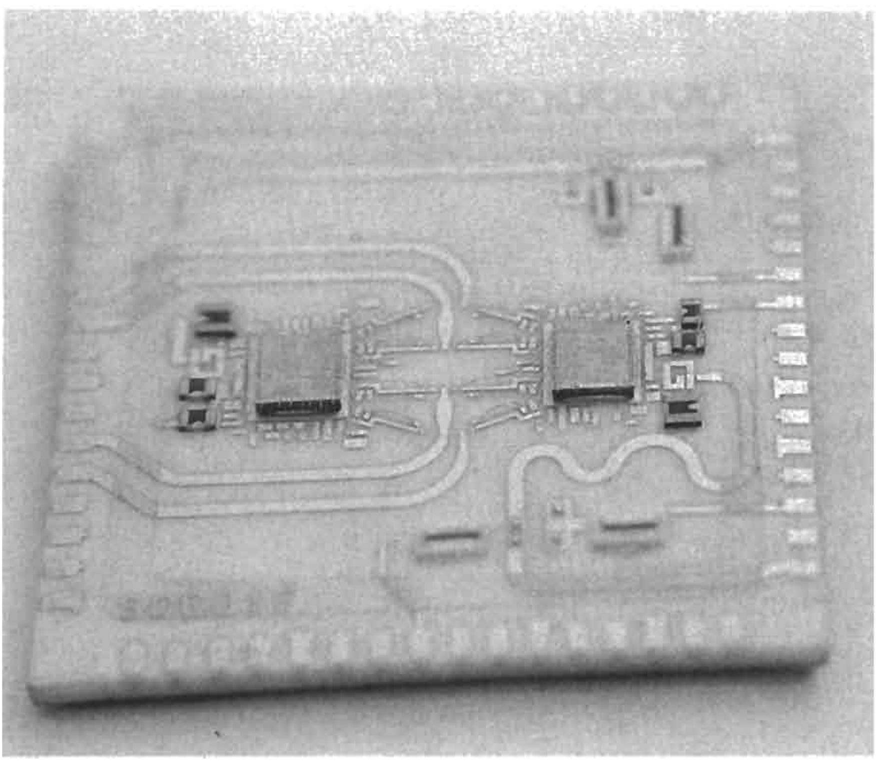


Figure 10–12. 11A72 1.5GHz Multilayer Hybrid with Thick Film T-coils.

and I am hoping that my assertions and derivation results are challenged by the reader. To get really radical, breadboard a real circuit! A less fun but easier way to verify circuit behavior is via SPICE or a similar simulator program. Keep in mind, while you are doing this, that most of the very early design took place without digital computer simulators. Frequency- and impedance-scaled simulations took place though, with physical analog models.

I'm grateful to the many knowledgeable folks who talked with me recently and added considerable information, both technical and historical. These included Gene Andrews, Phil Crosby, Logan Belleville, Dean Kidd, John Kobbe, Jim Lamb, Cliff Moulton, Oscar Olson, Ron Olson, and Richard Rhiger. If this chapter has errors, however, don't blame these guys; any mistakes are my own.

Bob Ross and Thor Hallen have been sources of insight on these topics over many years and have been ruthless in their rigorous analyses, helping me in my work immensely.

Finally, I leave you with my mother's and Socrates' advice, "Moderation in all things." Might I add, "Just do it!" If these Tek guys had waited for proper models of all known effects and proper theory before doing something, we would still be waiting. Everything can be tidied up in hindsight but, in fact, the real circuits in the real products are often more complicated than our simple schematics and were realized by a lot of theory, intuition, and especially smart, hard, and sometimes long work. I am proud of all of this heritage and the small part I played in it.

11. Tripping the Light Fantastic

Introduction

Where do good circuits come from, and what is a good circuit? Do they only arrive as lightning bolts in the minds of a privileged few? Are they synthesized, or derived after careful analysis? Do they simply evolve? What is the role of skill? Of experience? Of luck? I can't answer these weighty questions, but I do know how the best circuit I ever designed came to be.

What is a good circuit, anyway? Again, that's a fairly difficult question, but I can suggest a few guidelines. Its appearance should be fundamentally simple, although it may embody complex and powerful theoretical elements and interactions. That, to me, is the essence of elegance. The circuit should also be widely utilized. An important measure of a circuit's value is if lots of people use it, and are satisfied after they have done so. Finally, the circuit should also generate substantial revenue. The last time I checked, they still charge money at the grocery store. My employer is similarly faithful about paying me, and, in both cases, it's my obligation to hold up my end of the bargain.

So, those are my thoughts on good circuits, but I never addressed the statement at the end of the first paragraph. How did my best circuit come to be? That's a long story. Here it is.

The Postpartum Blues

Towards the end of 1991 I was in a rut. I had finished a large high-speed amplifier project in August. It had required a year of constant, intense, and sometimes ferocious effort right up to its conclusion. Then it was over, and I suddenly had nothing to do. I have found myself abruptly disconnected from an absorbing task before, and the result is always the same. I go into this funky kind of rut, and wonder if I'll ever find anything else interesting to do, and if I'm even capable of doing anything anymore.

Portions of this text have appeared in the January 6, 1994 issue of *EDN* magazine and publications of Linear Technology Corporation. They are used here with permission.

I've been dating me a long time, so this state of mind doesn't promote quite the panic and urgency it used to. The treatment is always the same. Keep busy with mundane chores at work, read, cruise electronic junk stores, fix things and, in general, look available so that some interesting problem might ask me to dance. During this time I can do some of the stuff I completely let go while I was immersed in whatever problem owned me. The treatment always seems to work, and usually takes a period of months. In this case it took exactly three.

What's a Backlight?

Around Christmas my boss, Bob Dobkin, asked me if I ever thought about the liquid crystal display (LCD) backlights used in portable computers. I had to admit I didn't know what a backlight was. He explained that LCD displays require an illumination source to make the display readable, and that this source consumed about half the power in the machine. Additionally, the light source, a form of fluorescent lamp, requires high-voltage, high-frequency AC drive. Bob was wondering how this was done, with what efficiency, and if we couldn't come up with a better way and peddle it. The thing sounded remotely interesting. I enjoy transducer work, and that's what a light bulb is. I thought it might be useful to get my hands on some computers and take a look at the backlights. Then I went off to return some phone calls, attend to other housekeeping type items, and, basically, maintain my funk.

A Call from Some Guy Named Steve

Three days later the phone rang. The caller, a guy named Steve Young from Apple Computer, had seen a cartoon (Figure 11–1) I stuck on the back page of an application note in 1989. Since the cartoon invited calls, he was doing just that. Steve outlined several classes of switching power supply problems he was interested in. The application was portable computers, and a more efficient backlight circuit was a priority. Dobkin's interest in backlights suddenly sounded a lot less academic.

This guy seemed like a fairly senior type, and Apple was obviously a prominent computer company. Also, he was enthusiastic, seemed easy to work with and quite knowledgeable. This potential customer also knew what he wanted, and was willing to put a lot of front end thinking and time in to get it. It was clear he wasn't interested in a quick fix; he wanted true, "end-to-end" system oriented thinking.

What a customer! He knew what he wanted. He was open and anxious to work, had time and money, and was willing to sweat to get better solutions. On top of all that, Apple was a large and successful company with excellent engineering resources. I set up a meeting to introduce him to Dobkin and, hopefully, get something started.

Application Note 35

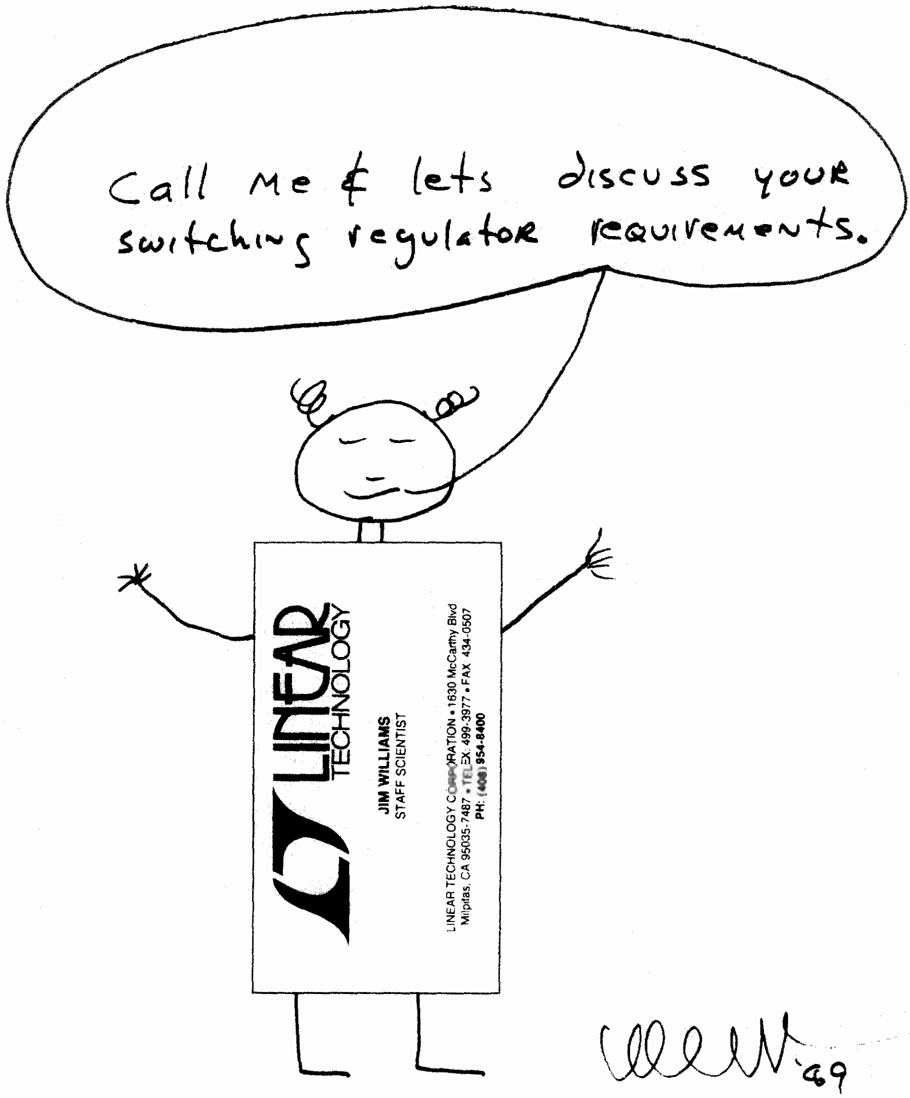


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Figure 11–1.
This invitation appeared in a 1989 application note. Some guy named Steve Young from Apple Computer took me up on it. (Reproduced with permission of Linear Technology Corporation)

The meeting went well, things got defined, and I took the backlight problem. I still wasn't enthralled with backlights, but here was an almost ideal customer falling in through the roof so there really wasn't any choice.

Steve introduced me to Paul Donovan, who would become my primary Apple contact. Donovan outlined the ideal backlight. It should have the highest possible efficiency, that is, the highest possible display luminosity with the lowest possible battery drain. Lamp intensity should be smoothly and continuously variable over a wide range with no hysteresis, or "pop-on," and should not be affected by supply voltage changes. RF emissions should meet FCC and system requirements. Finally, parts count and board space should be minimal. There was a board height requirement of .25".

Getting Started—The Luddite Approach to Learning

I got started by getting a bunch of portable computers and taking them apart. I must admit that the Luddite in me enjoyed throwing away most of the computers while saving only their display sections. One thing I immediately noticed was that almost all of them utilized a purchased, board-level solution to backlight driving. Almost no one actually built the function. The circuits invariably took the form of an adjustable output step-down switching regulator driving a high voltage DC-AC inverter (Figure 11–2). The AC high-voltage output was often about 50kHz, and approximately sinusoidal. The circuits seemed to operate on the assumption that a constant voltage input to the DC-AC inverter would produce a fixed, high voltage output. This fixed output would, in turn, produce constant lamp light emission. The ballast capacitor's function was not entirely clear, but I suspected it was related to lamp characteristics. There was no form of feedback from the lamp to the drive circuitry.

Was there something magic about the 50kHz frequency? To see, I built up a variable-frequency high voltage generator (Figure 11–3) and drove the displays. I varied frequency while comparing electrical drive power

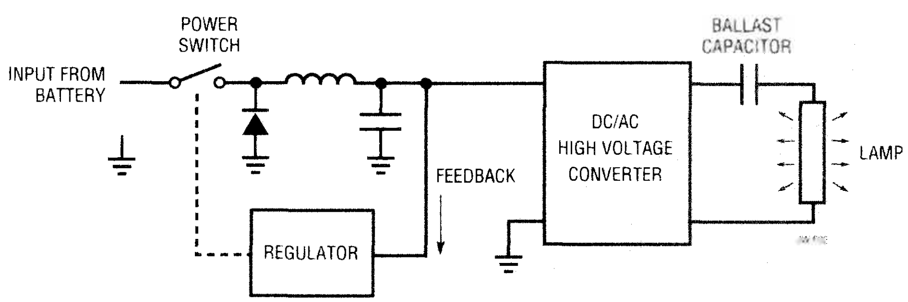


Figure 11–2. Architecture of a typical lamp driver board. There is no form of feedback from the lamp.

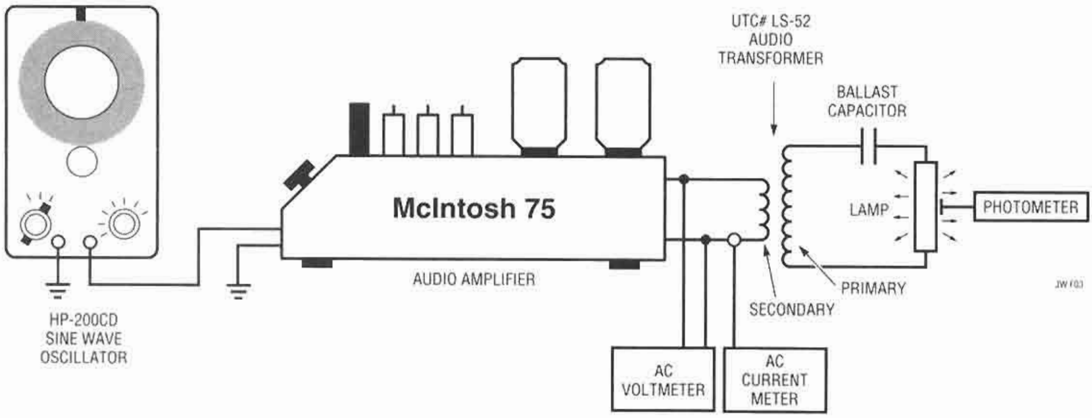


Figure 11–3. Variable frequency high-voltage test setup for evaluating lamp frequency sensitivity.

to optical emission. Lamp conversion efficiency seemed independent of frequency over a fairly wide range. I did, however, notice that higher frequencies tended to introduce losses in the wiring running to the lamp. These losses occurred at all frequencies, but became pronounced above about 100kHz or so. Deliberately introducing parasitic capacitances from the wiring or lamp to ground substantially increased the losses. The lesson was clear. The lamp wiring was an inherent and parasitic part of the circuit, and any stray capacitive path was similarly parasitic.

Armed with this information I returned to the computer displays. I modified things so that the wire length between the inverter board and display was minimized. I also removed the metal display housing in the lamp area. The result was a measurable decrease in inverter drive power for a given display intensity. In two machines the improvement approached 20%! My modifications weren't very practical from a mechanical integrity viewpoint, but that wasn't relevant. Why hadn't these computers been originally designed to take advantage of this "free" efficiency gain?

Playing around with Light Bulbs

I removed lamps from the displays. They all appeared to have been installed by the display vendor, as opposed to being selected and purchased by the computer manufacturer. Even more interesting was that I found identical backlight boards in different computers driving different types of lamps. There didn't seem to be any board changes made to accommodate the various lamps. Now, I turned my attention to the lamps.

The lamps seemed to be pretty complex and wild animals. I noticed that many of them took noticeable time to arrive at maximum intensity. Some types seemed to emit more light than others for a given input power. Still others had a wider dynamic range of intensities than the rest, although all had a seemingly narrow range of intensity control. Most striking was that every lamp's emissivity varied with ambient temperature. Experimenting with a hair dryer, a can of "cold spray" and a photometer, I found that each lamp seemed to have an optimum operating temperature range. Excursions above or below this region caused emittance to fall.

I put a lamp into a reassembled display. With the display warmed up in a 25°C environment I was able to increase light output by slightly ventilating the lamp enclosure. This increased steady-state thermal losses, allowing the lamp to run in its optimum temperature range. I also saw screen illumination shifts due to the distance between the light entry point at the display edge and the lamp. There seemed to be some optimum distance between the lamp and the entry point. Simply coupling the lamp as closely as possible did not provide the best results. Similarly, the metallic reflective foil used to concentrate the lamp's output seemed to be sensitive to placement. Additionally, there was clearly a trade-off between benefits from the foil's optical reflection and its absorption of high voltage field energy. Removing the foil decreased input energy for a given lamp emission level. I could watch input power rise as I slipped the foil back along the lamp's length. In some cases, with the foil fully replaced, I could draw sparks from it with my finger!

I also assembled lamps, displays, and inverter boards in various unoriginal combinations. In some cases I was able to increase light output, at lower input power drain, over the original "as shipped" configuration.

Grandpa Would Have Liked It

I tried a lot of similarly simple experiments and slowly developed a growing suspicion that nobody, at least in my sample of computers, was making any serious attempt at optimizing (or they did not know how to optimize) the backlight. It appeared that most people making lamps were simply filling tubes up with gas and shipping them. Display manufacturers were dropping these lamps into displays and shipping them. Computer vendors bought some "backlight power supply" board, wired it up to the display, took whatever electrical and optical efficiency they got, and shipped the computer.

If I allowed this conclusion, several things became clear. Development of an efficient backlight required an interdisciplinary approach to address a complex problem. There was worthwhile work to be done. I could contribute to the electronic portion, and perhaps the thermal design, but the optical engineering was beyond me. It was not, however, beyond Apple's resources. Apple had some very good optical types. Working together, it seemed we had a chance to build a better backlight with its attendant display quality and battery life advantages. Apple would get a more saleable product and my company would develop a valued customer. And, because the whole thing was beginning to get interesting, I could get out of my rut. The business school types would call this "synergistic" or "win-win." Other people who "do lunch" a lot on company money would call it "strategic partnering." My grandfather would have called it "such a deal."

Goals for the backlight began to emerge. For best overall efficiency, the display enclosure, optical design, lamp, and electronics had to be simultaneously considered. My job was the electronics, although I met regularly with Paul Donovan, who was working on the other issues. In particular, I was actively involved in setting lamp specifications and evaluating lamp vendors.

The electronics should obviously be as efficient as possible. The circuit should be physically compact, have a low parts count, and assemble easily. It should have a wide, continuous dimming range with no hysteresis or "pop-on," and should meet all RF and system emission requirements. Finally, it must regulate lamp intensity against wide power supply shifts, such as when the computer's AC adapter is plugged in.

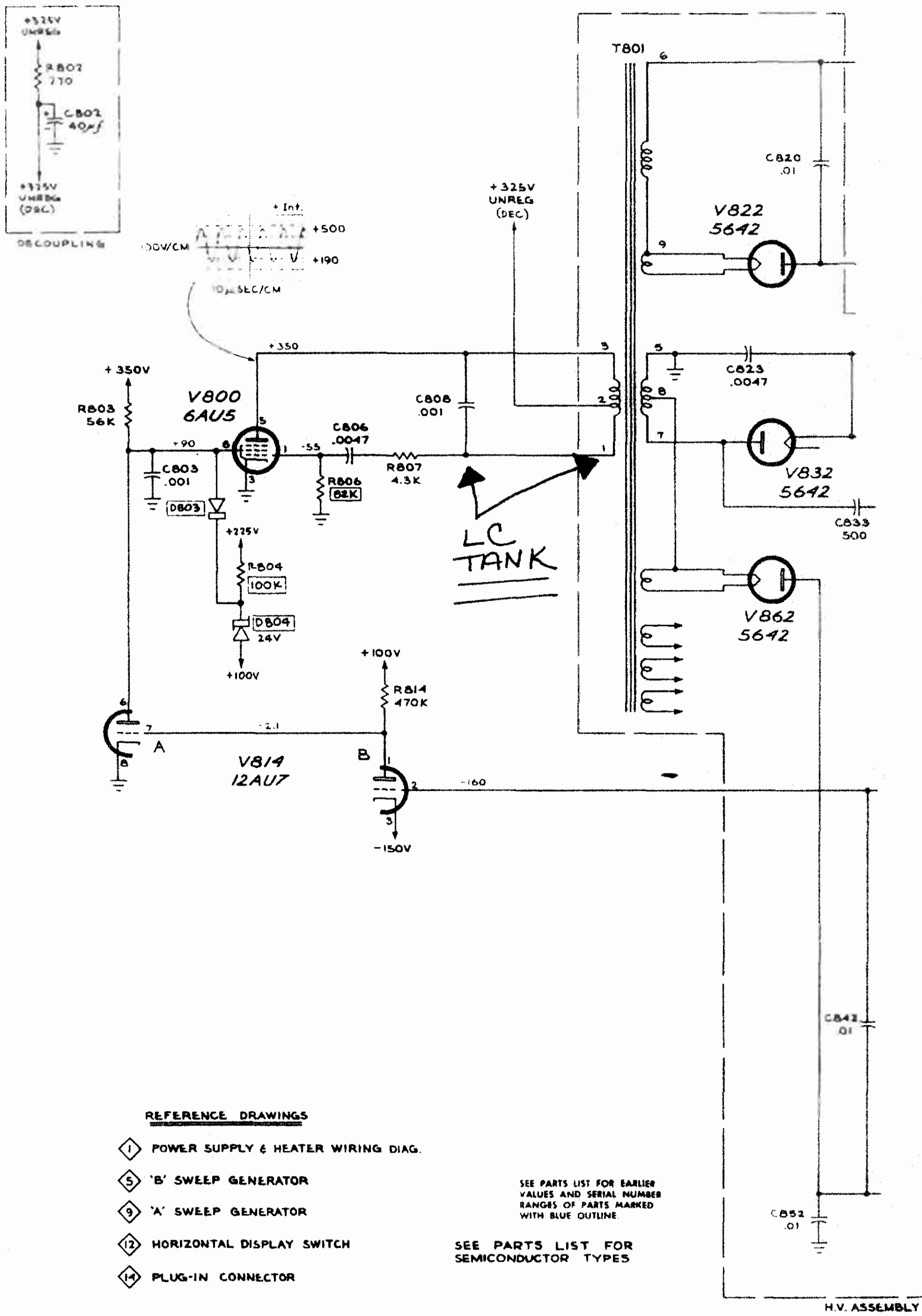
Help from Dusty Circuits

Where, I wondered, had I seen circuitry which contained any or all of these characteristics? Nowhere. But, one place to start looking was oscilloscopes. Although oscilloscope circuits do not accomplish what I needed to do, oscilloscope designers use high frequency sine wave conversion to generate the high voltage CRT supply. This technique minimizes noise and reduces transformer and capacitor size. Additionally, by doing the conversion at the CRT, long high voltage runs from the main power supply are eliminated.

I looked at the schematic of the high voltage converter in a Tektronix 547 (Figure 11–4). The manual's explanation (Figure 11–5) says the capacitor (C808) and transformer primary form a resonant tank circuit. More subtly, the "transformer primary" also includes the complex impedance reflected back from the secondary and its load. But that's a detail for this circuit and for now. A CRT is a relatively linear and benign load. The backlight's loading characteristics would have to be evaluated and matched to the circuit.

This CRT circuit could not be used to drive a fluorescent backlight tube in a laptop computer. For one reason, this circuit is not very efficient. It does not have to be. A 547 pulls over 500 watts, so efficiency in this circuit was not a big priority. Latter versions of this configuration were transistorized (Figure 11–6, Tektronix 453), but used basically the same architecture. In both circuits the resonating technique is employed, and a feedback loop enforces voltage regulation. For another reason, the CRT requires the high voltage to be rectified to DC. The backlight requires AC, eliminating the rectifier and filter. And, the CRT circuit had no feedback. Some form of feedback for the fluorescent lamp seemed desirable.

The jewel in the CRT circuit, however, was the resonating technique used to create the sine wave. The transformer does double duty. It helps create the sine wave while simultaneously generating the high voltage.



TYPE 547 OSCILLOSCOPE

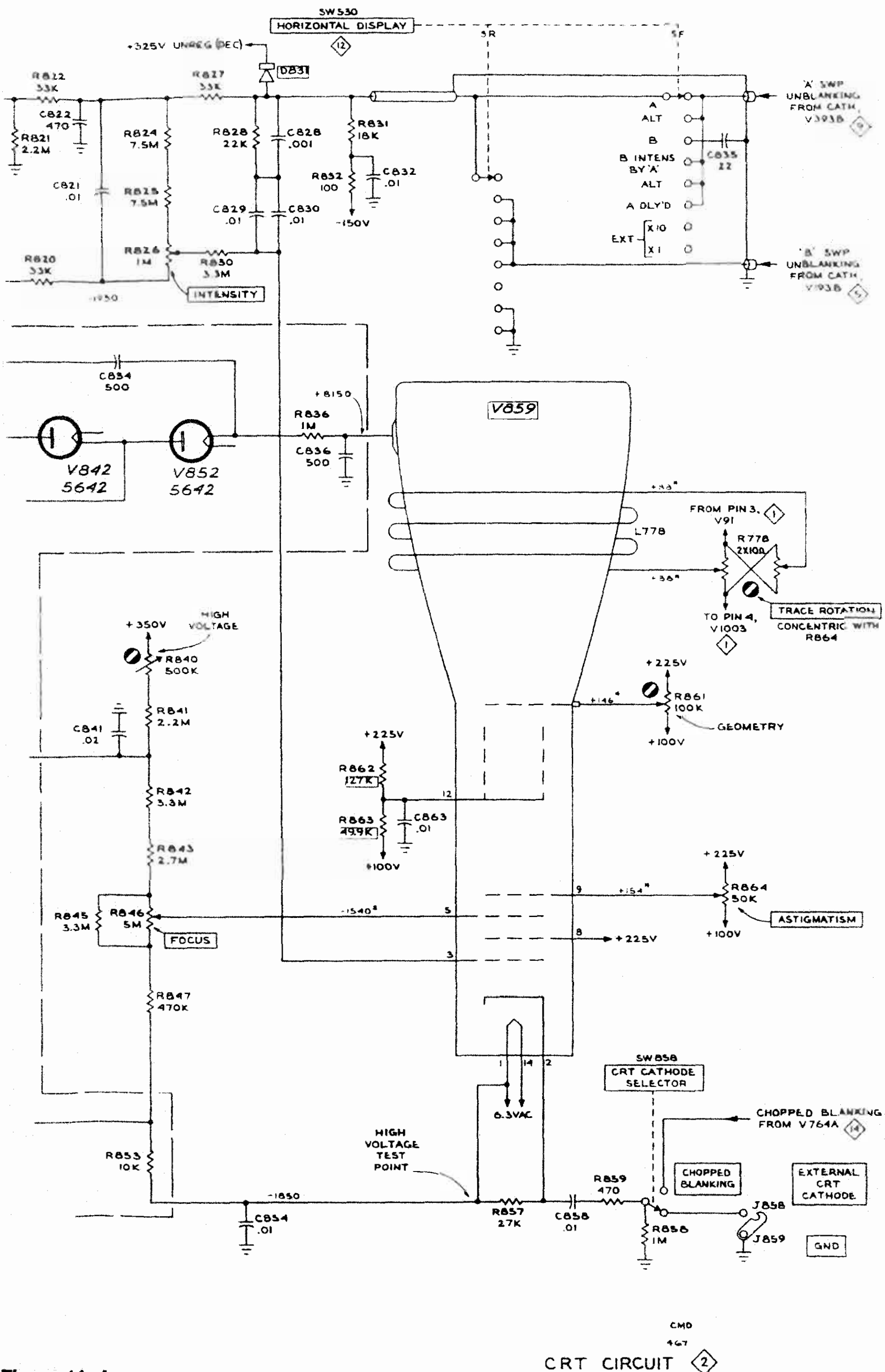


Figure 11–4.
CRT supply used in Tektronix 547. C808 resonates with transformer, creating sine wave drive. (Figure reproduced with permission of Tektronix, Inc.)

Figure 11–5. Tektronix 547 manual explains resonant operation. (Figure reproduced with permission of Tektronix, Inc.)

Crt Circuit

The crt circuit (see Crt schematic) includes the crt, the high-voltage power supply, and the controls necessary to focus and orient the display. The crt (Tektronix Type T5470-31-2) is an aluminized, 5-inch, flat-faced, glass crt with a helical post-accelerator and electrostatic focus and deflection. The crt circuit provides connections for externally modulating the crt cathode. The high-voltage power supply is composed of a dc-to-50-kc power converter, a voltage-regulator circuit, and three high-voltage outputs. Front-panel controls in the crt circuit adjust the trace rotation (screwdriver adjustment), intensity, focus, and astigmatism. Internal controls adjust the geometry and high-voltage output level.

High-Voltage Power Supply. The high-voltage power supply is a dc-to-ac converter operating at approximately 50 kc with the transformer providing three high-voltage outputs. The use of a 50-kc input to the high-voltage transformer permits the size of the transformer and filter components to be kept small. A modified Hartley oscillator converts dc from the +325-volt unregulated supply to the 50-kc input required by high-voltage transformer T801. C808 and the primary of T801 form the oscillator resonant tank circuit. No provisions are made for precise tuning of the oscillator tank since the exact frequency of oscillation is not important.

Voltage Regulation. Voltage regulation of the high-voltage outputs is accomplished by regulating the amplitude of oscillations in the Hartley oscillator. The —1850-volt output is referenced to the +350-volt regulated supply through a voltage divider composed of R841, R842, R843, R845, R846, R847, R853, and variable resistors R840 and R846. Through a tap on the voltage divider, the regulator circuit samples the —1850-volt output of the supply, amplifies any errors and uses the amplified error voltage to adjust the screen voltage of Hartley oscillator V800. If the —1850-volt output changes, the change is detected at the grid of V814B. The detected error is amplified by V814B and V814A. The error signal at the plate of V814A is direct coupled to the screen of V800 by making the plate-load resistor of V814A serve as

How could I combine this circuit's desirable resonating characteristics with other techniques to meet the backlight's requirements? One key was a simple, more efficient transformer drive. I knew just where to find it.

In December 1954 the paper "Transistors as On-Off Switches in Saturable-Core Circuits" appeared in *Electrical Manufacturing*. George H. Royer, one of the authors, described a "d-c to a-c converter" as part of this paper. Using Westinghouse 2N74 transistors, Royer reported 90% efficiency for his circuit. The operation of Royer's circuit is well described in this paper. The Royer converter was widely adopted, and used in designs from watts to kilowatts. It is still the basis for a wide variety of power conversion.

Royer's circuit is not an LC resonant type. The transformer is the sole energy storage element and the output is a square wave. Figure 11–7 is a conceptual schematic of a typical converter. The input is applied to a self-oscillating configuration composed of transistors, a transformer, and a biasing network. The transistors conduct out of phase switching (Figure 11–8: Traces A and C are Q1's collector and base, while Traces B and D are Q2's collector and base) each time the transformer saturates. Transformer saturation causes a quickly rising, high current to flow (Trace E).

This current spike, picked up by the base drive winding, switches the transistors. This phase opposed switching causes the transistors to exchange states. Current abruptly drops in the formerly conducting transistor and then slowly rises in the newly conducting transistor until saturation again forces switching. This alternating operation sets transistor duty cycle at 50%.

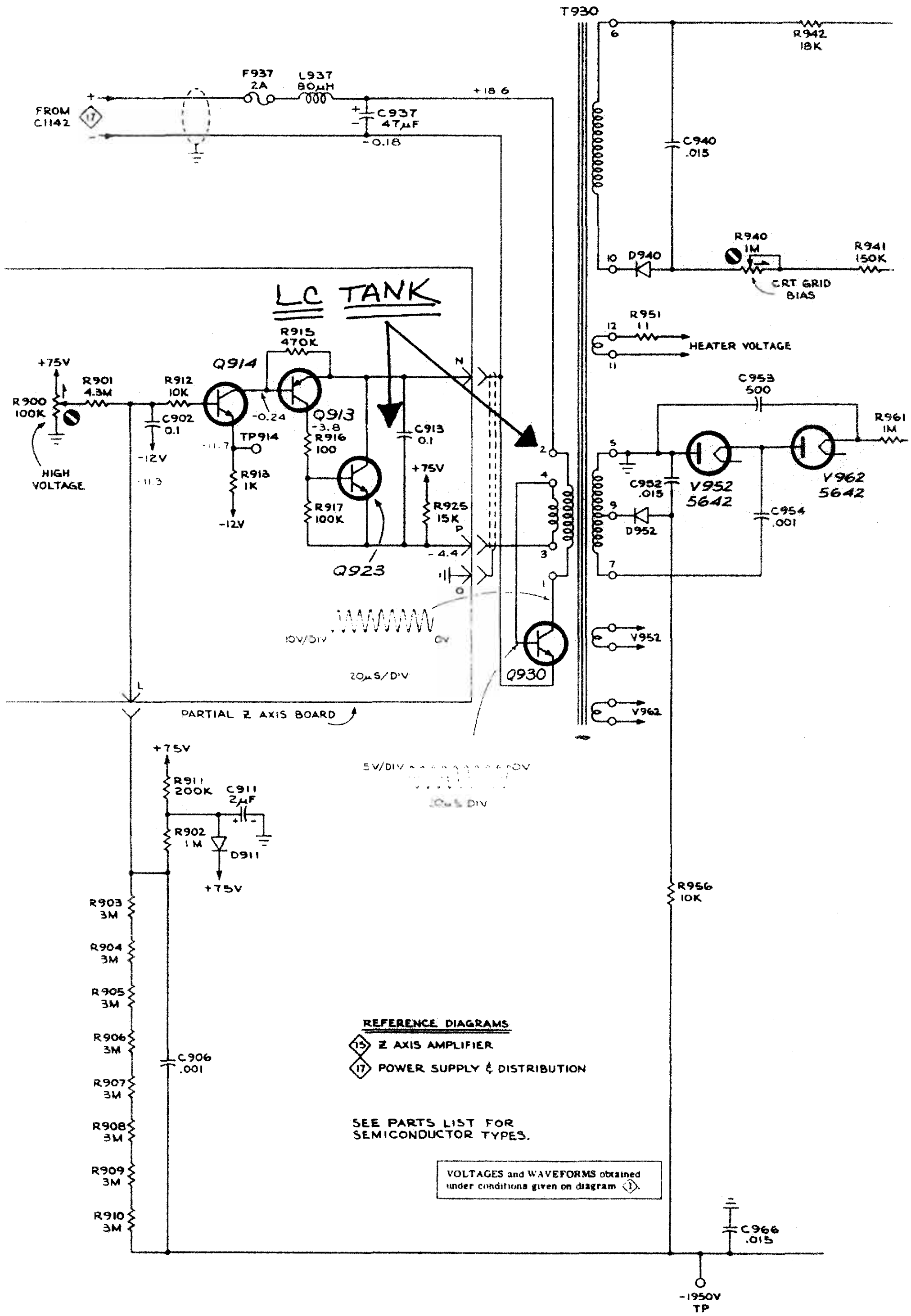
The photograph in Figure 11–9 is a time and amplitude expansion of Figure 11–8's Traces B and E. It clearly shows the relationship between transformer current (Trace B, Figure 11–9) and transistor collector voltage (Trace A, Figure 11–9).[1]

The Royer has many desirable elements which are applicable to backlight driving. Transformer size is small because core utilization is efficient. Parts count is low, the circuit self-oscillates, it is efficient, and output power may be varied over a wide range. The inherent nature of operation produces a square wave output, which is not permissible for backlight driving.

Adding a capacitor to the primary drive (Figure 11–10) should have the same resonating effect as in the Tektronix CRT circuits. The beauty of this configuration is its utter simplicity and high efficiency. As loading (e.g., lamp intensity) is varied the reflected secondary impedance changes, causing some frequency shift, but efficiency remains high.

The Royer's output power is controllable by varying the primary drive current. Figure 11–11 shows a way to investigate this. This circuit works well, except that the transistor current sink operates in its linear region, wasting power. Figure 11–12 converts the current sink to switch mode operation, maintaining high efficiency. This is obviously advantageous to the user, but also a good deal for my employer. I had spent the last six months playing with light bulbs, reminiscing over old oscilloscope circuits, taking arcane thermal measurements, and similar dalliances. All the while faithfully collecting my employer's money. Finally, I had found a place to actually sell something we made. Linear Technology (my employer) builds a switching regulator called the LT1172. Its features include a high power open collector switch, trimmed reference, low quiescent current, and shutdown capability. Additionally, it is available in an 8 pin surface-mount package, a must for board space considerations. It was also an ideal candidate for the circuit's current sink portion.

1. The bottom traces in both photographs are not germane and are not referenced in the discussion.



TYPE 453 OSCILLOSCOPE

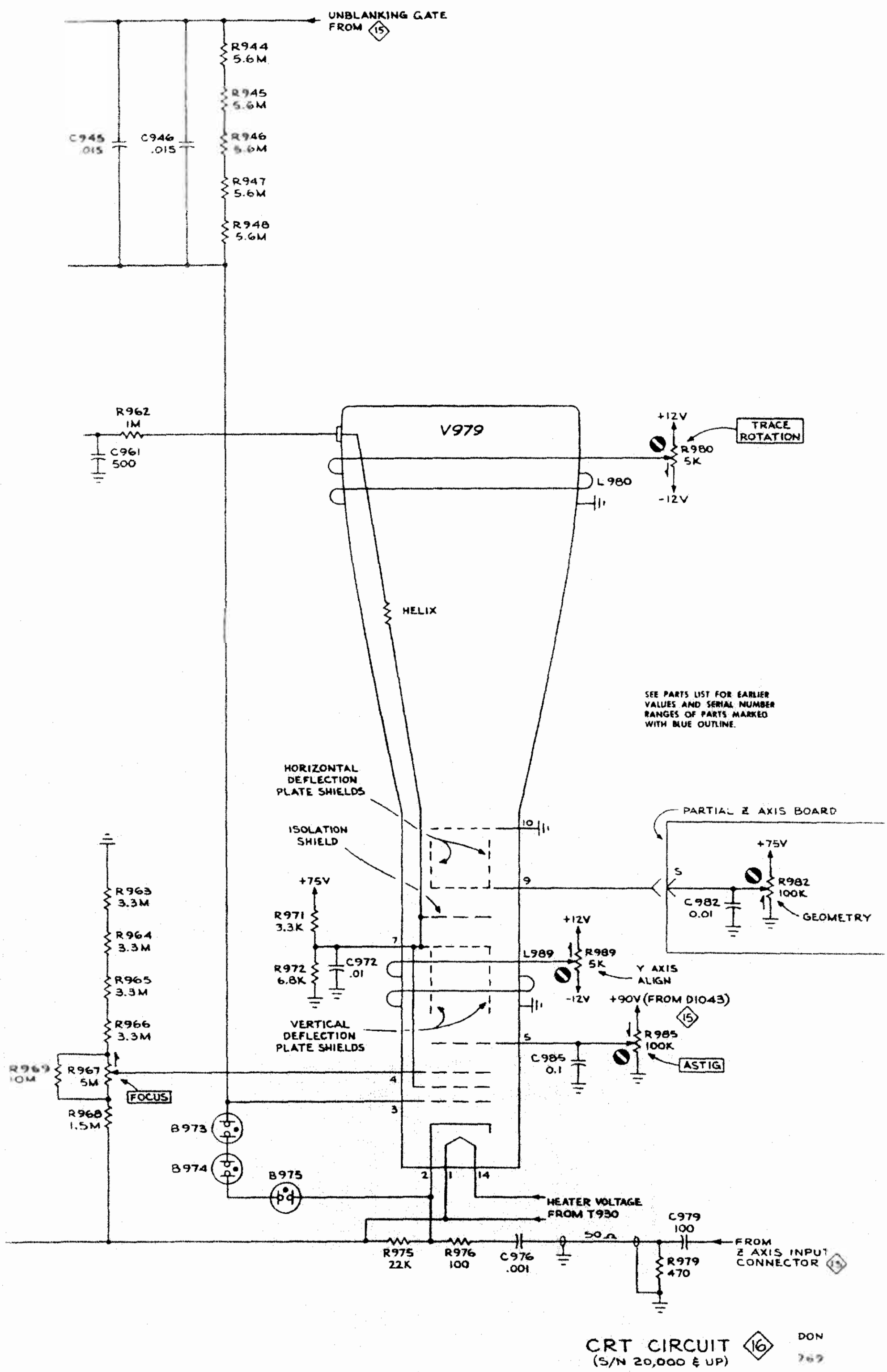


Figure 11–6.
Later model Tektronix 453 is transistorized version of 547's resonant approach. (Figure reproduced with permission of Tektronix, Inc.)

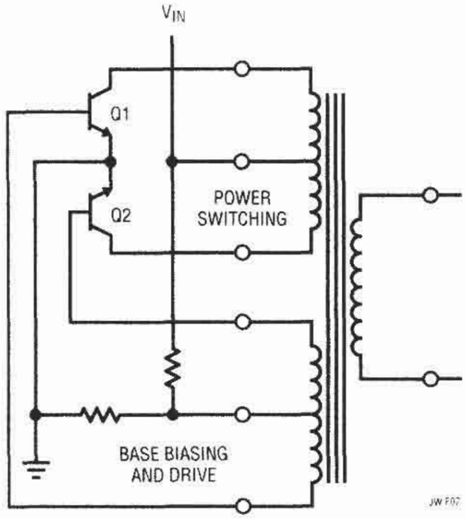


Figure 11–7. Conceptual classic Royer converter. Transformer approaching saturation causes switching.

Of Rafts and Paddles

At about this stage I sat back and stared at the wall. There comes a time in every project where you have to gamble. At some point the analytics and theorizing must stop and you have to commit to an approach and start actually doing something. This is often painful, because you never really have enough information and preparation to be confidently decisive. There are never any answers, only choices. But there comes this time when your gut tells you to put down the pencil and pick up the soldering iron.

Physicist Richard Feynman said, "If you're not confused when you start, you're not doing it right." Somebody else, I think it was an artist, said, "Inspiration comes while working." Wow, are they right. With circuits, as in life, never wait for your ship to come in. Build a raft and start paddling.

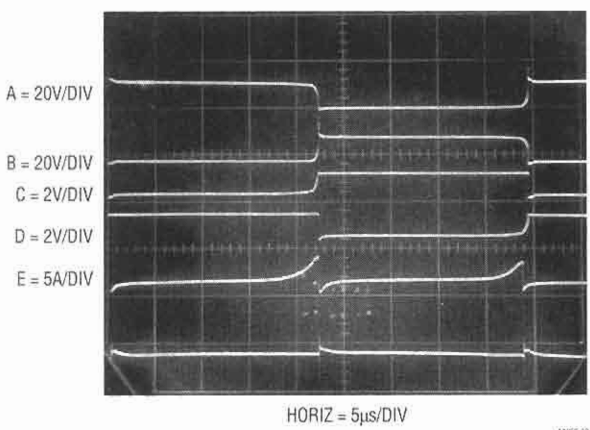


Figure 11–8. Waveforms for the classic Royer circuit.

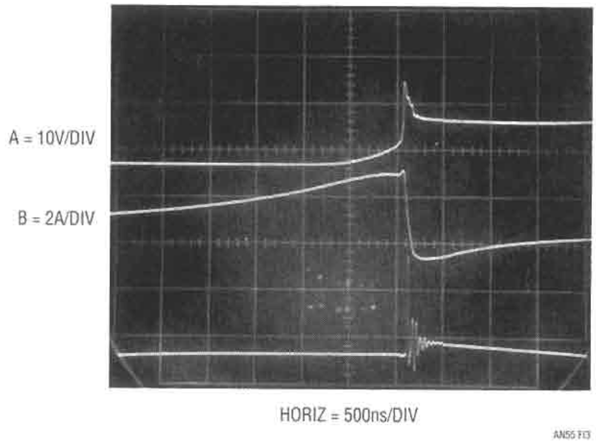


Figure 11–9. Detail of transistor switching. Turn-off (Trace A) occurs just as transformer heads into saturation (Trace B).

Everything was still pretty fuzzy, but I had learned a few things. A practical, highly efficient LCD backlight design is a classic study of compromise in a transduced electronic system. Every aspect of the design is interrelated, and the physical embodiment is an integral part of the electrical circuit. The choice and location of the lamp, wires, display housing, and other items have a major effect on electrical characteristics. The greatest care in every detail is required to achieve a practical, high efficiency LCD backlight. Getting the lamp to light is just the beginning!

A good place to start was to reconsider the lamps. These "Cold Cathode Fluorescent Lamps" (CCFL) provide the highest available efficiency for converting electrical energy to light. Unfortunately, they are optically and electrically highly nonlinear devices.

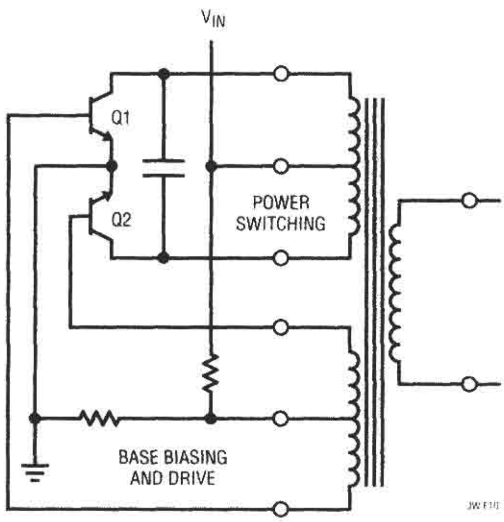


Figure 11–10. Adding the resonating capacitor to the Royer.

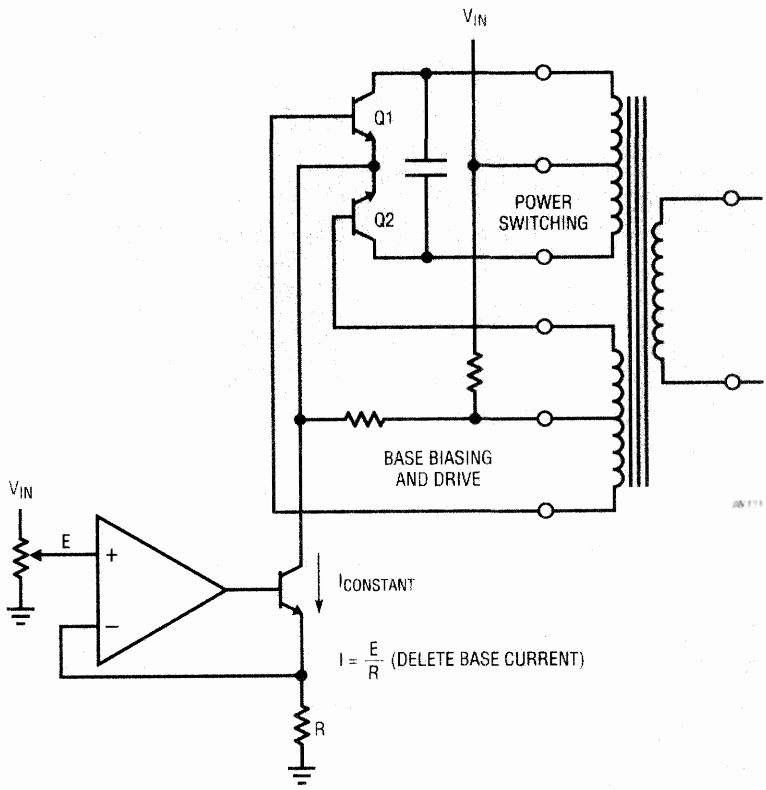


Figure 11–11. Current sink permits controlling Royer power, but is inefficient.

Cold Cathode Fluorescent Lamps (CCFLs)

Any discussion of CCFL power supplies must consider lamp characteristics. These lamps are complex transducers, with many variables affecting their ability to convert electrical current to light. Factors influencing conversion efficiency include the lamp's current, temperature, drive waveform characteristics, length, width, gas constituents, and the proximity to nearby conductors.

These and other factors are interdependent, resulting in a complex overall response. Figures 11–13 through 11–16 show some typical characteristics. A review of these curves hints at the difficulty in predicting lamp behavior as operating conditions vary. The lamp's current and temperature are clearly critical to emission, although electrical efficiency may not necessarily correspond to the best optical efficiency point. Because of this, both electrical and photometric evaluation of a circuit is often required. It is possible, for example, to construct a CCFL circuit with 94% electrical efficiency which produces less light output than an approach with 80% electrical efficiency (see Appendix C, "A Lot of Cut-off Ears and No Van Goghs—Some Not-So-Great Ideas"). Similarly, the performance of a very well matched lamp-circuit combination can be

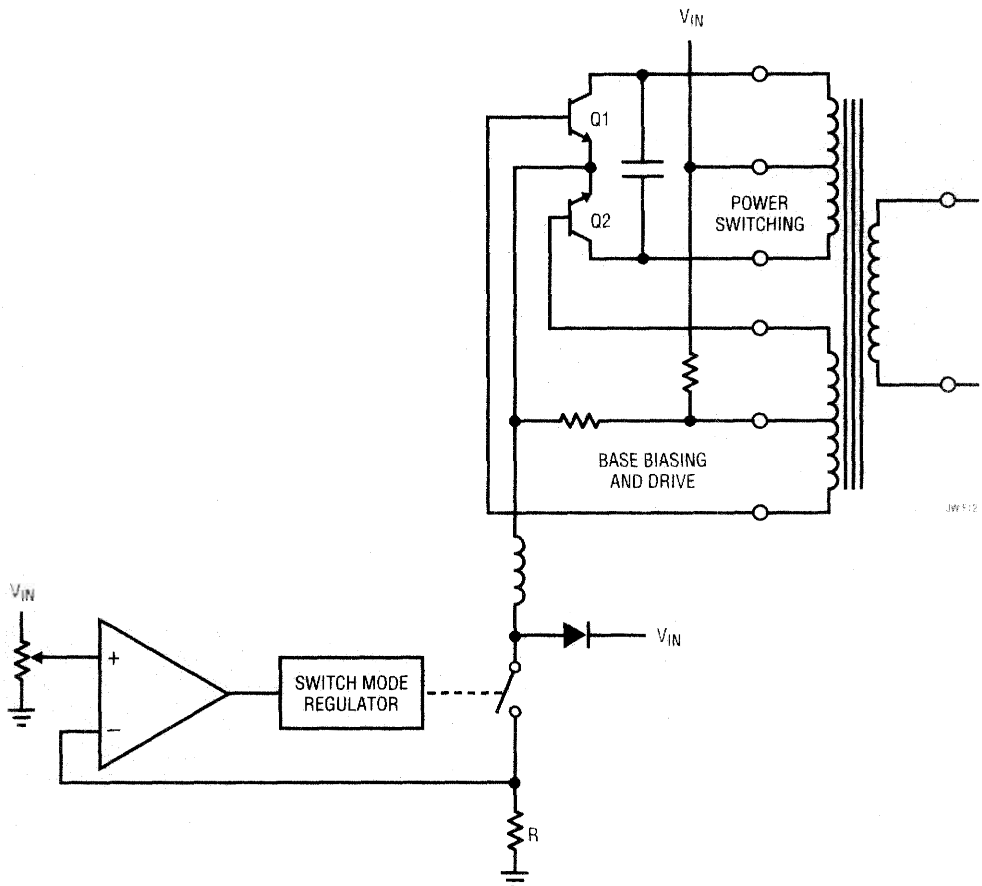


Figure 11–12. Switched mode current sink restores efficiency.

severely degraded by a lossy display enclosure or excessive high voltage wire lengths. Display enclosures with too much conducting material near the lamp have huge losses due to capacitive coupling. A poorly designed display enclosure can easily degrade efficiency by 20%. High voltage wire runs typically cause 1% loss per inch of wire.

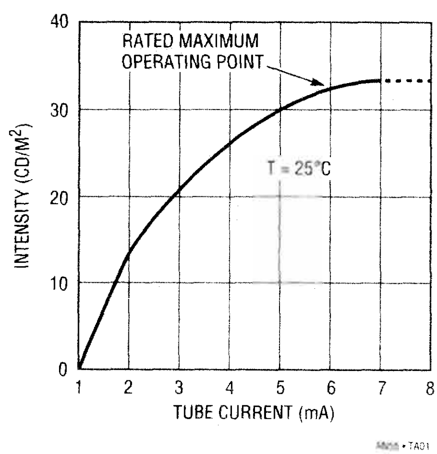


Figure 11–13. Emissivity for a typical 6mA lamp; curve flattens badly above 6mA.

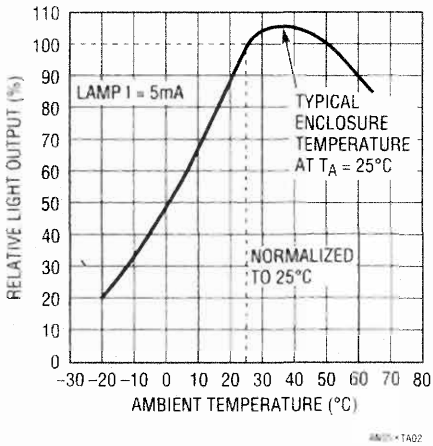


Figure 11–14. Ambient temperature effects on emissivity of a typical 5mA lamp. Lamp and enclosure must come to thermal steady state before measurements are made.

CCFL Load Characteristics

These lamps are a difficult load to drive, particularly for a switching regulator. They have a "negative resistance" characteristic; the starting voltage is significantly higher than the operating voltage. Typically, the start voltage is about 1000V, although higher and lower voltage lamps are common. Operating voltage is usually 300V to 400V, although other lamps may require different potentials. The lamps will operate from DC, but migration effects within the lamp will quickly damage it. As such, the waveform must be AC. No DC content should be present.

Figure 11–17A shows an AC driven lamp's characteristics on a curve tracer. The negative resistance induced "snapback" is apparent. In Figure 11–17B, another lamp, acting against the curve tracer's drive, produces oscillation. These tendencies, combined with the frequency compensation problems associated with switching regulators, can cause severe loop instabilities, particularly on start-up. Once the lamp is in its operating region it assumes a linear load characteristic, easing stability criteria. Lamp operating frequencies are typically 20kHz to 100kHz and a sine-

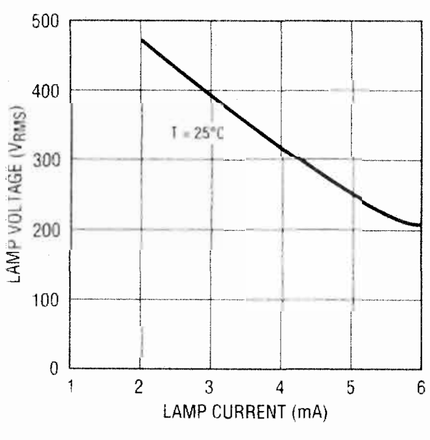


Figure 11–15. Current vs. voltage for a lamp in the operating region.

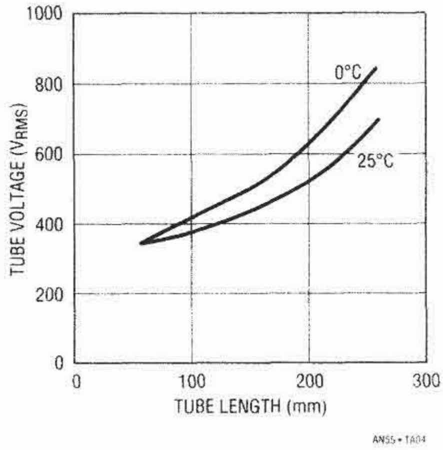


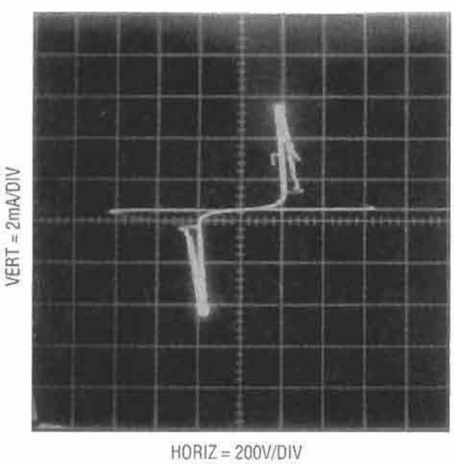
Figure 11–16. Running voltage vs. lamp length at two temperatures. Start-up voltages are usually 50% to 200% higher over temperature.

like waveform is preferred. The sine drive's low harmonic content minimizes RF emissions, which could cause interference and efficiency degradation. A further benefit of the continuous sine drive is its low crest factor and controlled risetimes, which are easily handled by the CCFL. CCFL's RMS current-to-light output efficiency is degraded by high crest factor drive waveforms.[2]

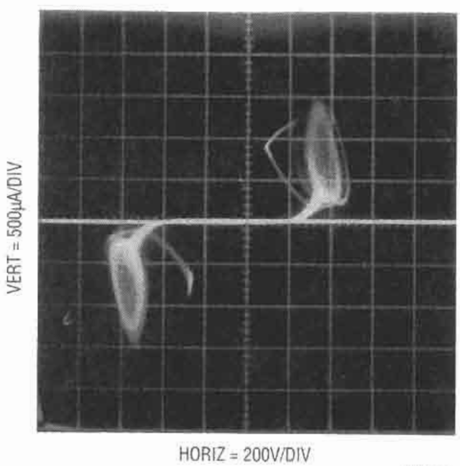
CCFL Power Supply Circuits

Figure 11–18's circuit meets CCFL drive requirements. Efficiency is 88% with an input voltage range of 4.5V to 20V. This efficiency figure will be degraded by about 3% if the LT1172 V_{IN} pin is powered from the same supply as the main circuit V_{IN} terminal. Lamp intensity is continuously and smoothly variable from zero to full intensity. When power is

Figure 11–17. Negative resistance characteristic for two CCFL lamps. "Snap-back" is readily apparent, causing oscillation in 11–17B. These characteristics complicate power supply design.



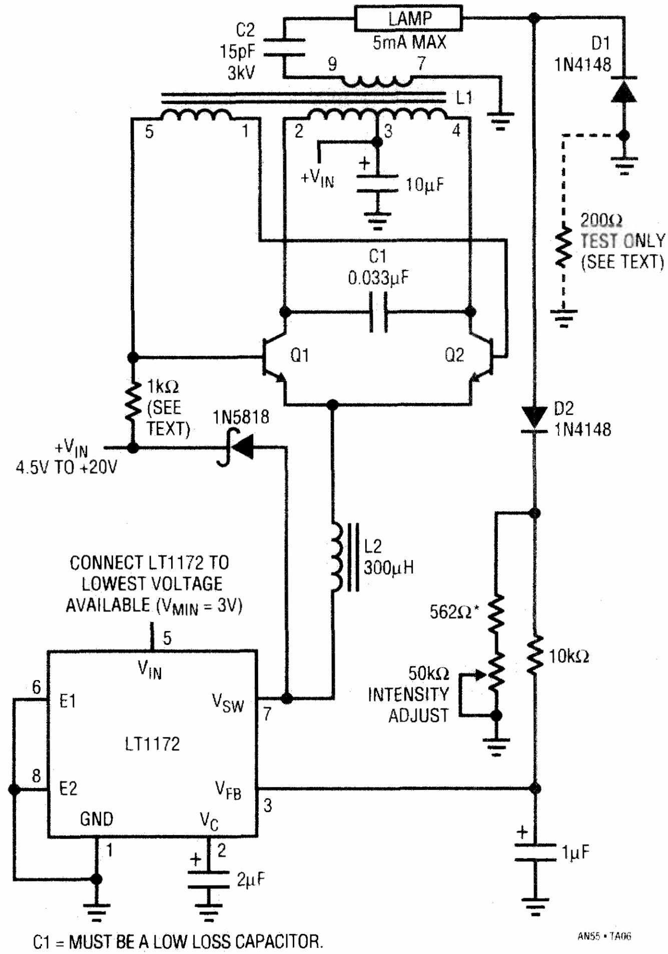
17A



17B

2. See Appendix C, "A Lot of Cut-off Ears and No Van Goghs—Some Not-So-Great Ideas."

Figure 11–18. An 88% efficiency cold cathode fluorescent lamp (CCFL) power supply.



C1 = MUST BE A LOW LOSS CAPACITOR.
METALIZED POLYCARB
WIMA FKP2 OR MKP-20 (GERMAN) RECOMMENDED
L1 = SUMIDA 6345-020 OR COILTRONICS CTX110092-1
PIN NUMBERS SHOWN FOR COILTRONICS UNIT
L2 = COILTRONICS CTX300-4
Q1, Q2 = ZETEX ZTX849 OR ROHM 2SC5001
* = 1% FILM RESISTOR
DO NOT SUBSTITUTE COMPONENTS

COILTRONICS (305) 781-8900, SUMIDA (708) 956-0666

applied the LT1172 switching regulator's feedback pin is below the device's internal 1.2V reference, causing full duty cycle modulation at the V_{SW} pin (Trace A, Figure 11–19). L2 conducts current (Trace B) which flows from L1's center tap, through the transistors, into L2. L2's current is deposited in switched fashion to ground by the regulator's action.

L1 and the transistors comprise a current driven Royer class converter which oscillates at a frequency primarily set by L1's characteristics (including its load) and the .033µF capacitor. LT1172 driven L2 sets the magnitude of the Q1-Q2 tail current, and hence L1's drive level. The 1N5818 diode maintains L2's current flow when the LT1172 is off. The LT1172's 100kHz clock rate is asynchronous with respect to the push-pull converter's (60kHz) rate, accounting for Trace B's waveform thickening.

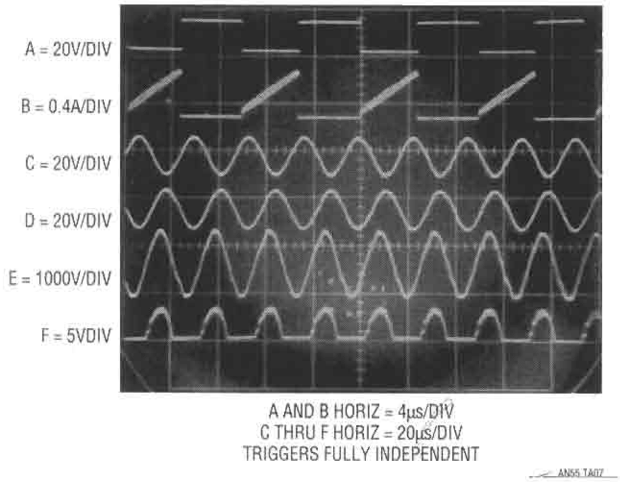


Figure 11–19. Waveforms for the cold cathode fluorescent lamp power supply. Note independent triggering on Traces A and B, and C through F.

The .033µF capacitor combines with L1's characteristics to produce sine wave voltage drive at the Q1 and Q2 collectors (Traces C and D, respectively). L1 furnishes voltage step-up, and about 1400V p-p appears at its secondary (Trace E). Current flows through the 15pF capacitor into the lamp. On negative waveform cycles the lamp's current is steered to ground via D1. Positive waveform cycles are directed, via D2, to the ground referred 562Ω–50k potentiometer chain. The positive half-sine appearing across the resistors (Trace F) represents ½ the lamp current. This signal is filtered by the 10k–1µF pair and presented to the LT1172's feedback pin. This connection closes a control loop which regulates lamp current. The 2µF capacitor at the LT1172's V_C pin provides stable loop compensation. The loop forces the LT1172 to switch-mode modulate L2's average current to whatever value is required to maintain a constant current in the lamp. The constant current's value, and hence lamp intensity, may be varied with the potentiometer. The constant current drive allows full 0%–100% intensity control with no lamp dead zones or "pop-on" at low intensities. Additionally, lamp life is enhanced because current cannot increase as the lamp ages. This constant current feedback approach contrasts with the open loop, voltage type drive used by other approaches. It greatly improves control over the lamp under all conditions.

This circuit's 0.1% line regulation is notably better than some other approaches. This tight regulation prevents lamp intensity variation when abrupt line changes occur. This typically happens when battery powered apparatus is connected to an AC powered charger. The circuit's excellent line regulation derives from the fact that L1's drive waveform never changes shape as input voltage varies. This characteristic permits the simple 10kΩ–1µF RC to produce a consistent response. The RC averaging characteristic has serious error compared to a true RMS conversion, but the error is constant and "disappears" in the 562Ω shunt's value. The base drive resistor's value (nominally 1kΩ) should be selected to provide full V_{CE} saturation without inducing base overdrive or beta starvation. A procedure for doing this is described in the following section, "General Measurement and Optimization Considerations."

Figure 11–20's circuit is similar, but uses a transformer with lower copper and core losses to increase efficiency to 91%. The trade-off is slightly larger transformer size. Value shifts in C1, L2, and the base drive resistor reflect different transformer characteristics. This circuit also features shutdown via Q3 and a DC or pulse width controlled dimming input. Figure 11–21, directly derived from Figure 11–20, produces 10mA output to drive color LCDs at 92% efficiency. The slight efficiency improvement comes from a reduction in LT1172 "housekeeping" current as a percentage

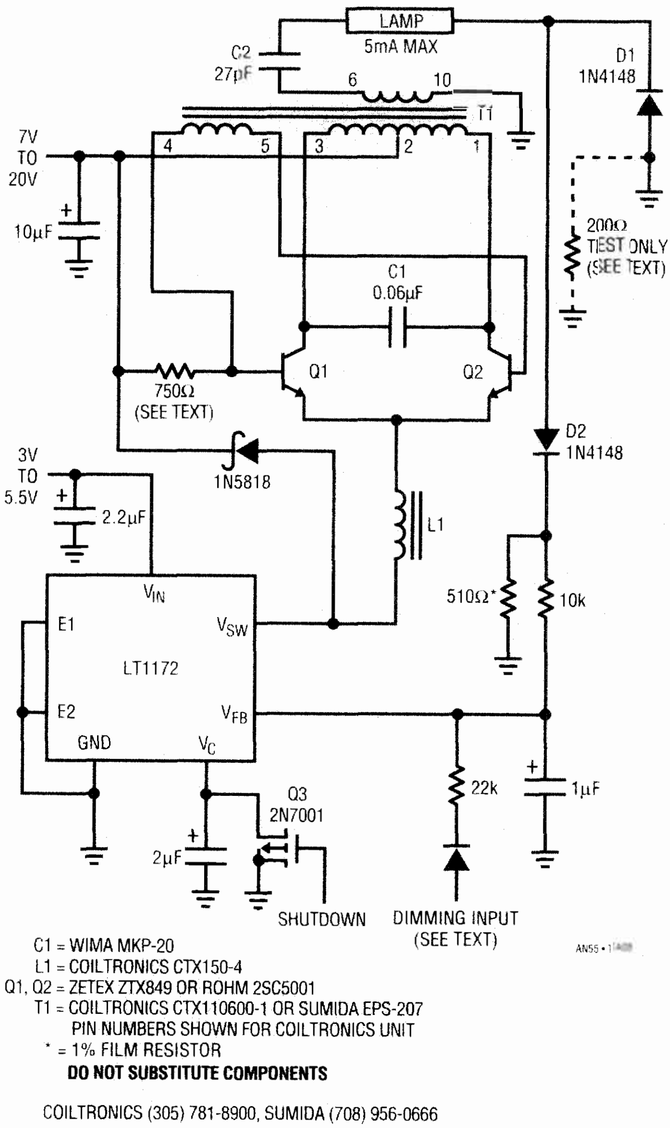
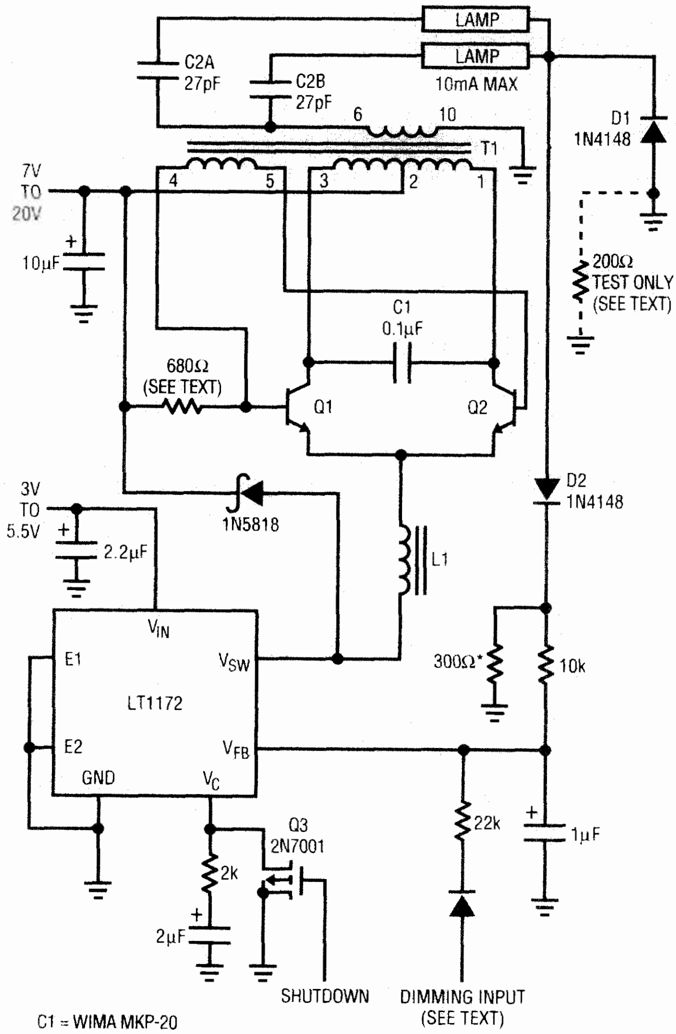


Figure 11–20. A 91% efficient CCFL supply for 5mA loads features shutdown and dimming inputs.

of total current drain. Value changes in components are the result of higher power operation. The most significant change involves driving two tubes. Accommodating two lamps involves separate ballast capacitors but circuit operation is similar. Two lamp designs reflect slightly different loading back through the transformer's primary. C2 usually ends up in the 10pF to 47pF range. Note that C2A and B appear with their lamp loads in parallel across the transformer's secondary. As such, C2's value is often smaller than in a single tube circuit using the same type lamp. Ideally the transformer's secondary current splits evenly between the C2-lamp branches, with the total load current being regulated. In practice, differences between C2A and B and differences in lamps and lamp wiring layout preclude a perfect current split. Practically, these differences are small, and the



C1 = WIMA MKP-20
L1 = COILTRONICS CTX150-4
Q1, Q2 = ZETEX ZTX849 OR ROHM 2SC5001
T1 = COILTRONICS CTX110600-1 OR SUMIDA EPS-207
PIN NUMBERS SHOWN FOR COILTRONICS UNIT
* = 1% FILM RESISTOR
DO NOT SUBSTITUTE COMPONENTS

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Figure 11–21. A 92% efficient CCFL supply for 10mA loads features shutdown and dimming inputs. Two lamps are typical of color displays.

lamps appear to emit equal amounts of light. Layout and lamp matching can influence C2's value. Some techniques for dealing with these issues appear in the section "Layout Issues."

General Measurement and Optimization Considerations

Several points should be kept in mind when observing operation of these circuits. L1's high voltage secondary can only be monitored with a wide-band, high voltage probe fully specified for this type of measurement. *The vast majority of oscilloscope probes will break down and fail if used for this measurement.* Tektronix probe types P6007 and P6009 (acceptable) or types P6013A and P6015 (preferred) must be used to read L1's output.

Another consideration involves observing waveforms. The LT1172's switching frequency is completely asynchronous from the Q1-Q2 Royer converter's switching. As such, most oscilloscopes cannot simultaneously trigger and display all the circuit's waveforms. Figure 11–19 was obtained using a dual beam oscilloscope (Tektronix 556). LT1172 related Traces A and B are triggered on one beam, while the remaining traces are triggered on the other beam. Single beam instruments with alternate sweep and trigger switching (e.g., Tektronix 547) can also be used, but are less versatile and restricted to four traces.

Obtaining and verifying high efficiency[3] requires some amount of diligence. The optimum efficiency values given for C1 and C2 are typical, and will vary for specific types of lamps. An important realization is that the term "lamp" includes the total load seen by the transformer's secondary. This load, reflected back to the primary, sets transformer input impedance. The transformer's input impedance forms an integral part of the LC tank that produces the high voltage drive. Because of this, circuit efficiency must be optimized with the wiring, display housing and physical layout arranged exactly the same way they will be built in production. Deviations from this procedure will result in lower efficiency than might otherwise be possible. In practice, a "first cut" efficiency optimization with "best guess" lead lengths and the intended lamp in its display housing usually produces results within 5% of the achievable figure. Final values for C1 and C2 may be established when the physical layout to be used in production has been decided on. C1 sets the circuit's resonance point, which varies to some

3. The term "efficiency" as used here applies to electrical efficiency. In fact, the ultimate concern centers around the efficient conversion of power supply energy into light. Unfortunately, lamp types show considerable deviation in their current-to-light conversion efficiency. Similarly, the emitted light for a given current varies over the life and history of any particular lamp. As such, this publication treats "efficiency" on an electrical basis; the ratio of power removed from the primary supply to the power delivered to the lamp. When a lamp has been selected, the ratio of primary supply power to lamp-emitted light energy may be measured with the aid of a photometer. This is covered in Appendix B, "Photometric Measurements." See also Appendix D, "Perspectives on Efficiency."

extent with the lamp's characteristics. C2 ballasts the lamp, effectively buffering its negative resistance characteristic. Small values of C2 provide the most load isolation, but require relatively large transformer output voltage for loop closure. Large C2 values minimize transformer output voltage, but degrade load buffering. Also, C1's "best" value is somewhat dependent on the lamp type used. Both C1 and C2 must be selected for given lamp types. Some interaction occurs, but generalized guidelines are possible. Typical values for C1 are 0.01μF to .15μF. C2 usually ends up in the 10pF to 47pF range. C1 must be a low-loss capacitor and substitution of the recommended devices is not recommended. A poor quality dielectric for C1 can easily degrade efficiency by 10%. C1 and C2 are selected by trying different values for each and iterating towards best efficiency. During this procedure, ensure that loop closure is maintained by monitoring the LT1172's feedback pin, which should be at 1.23V. Several trials usually produce the optimum C1 and C2 values. Note that the highest efficiencies are not necessarily associated with the most esthetically pleasing waveshapes, particularly at Q1, Q2, and the output.

Other issues influencing efficiency include lamp wire length and energy leakage from the lamp. The high voltage side of the lamp should have the smallest practical lead length. Excessive length results in radiative losses, which can easily reach 3% for a 3 inch wire. Similarly, no metal should contact or be in close proximity to the lamp. This prevents energy leakage, which can exceed 10%.[4]

It is worth noting that a custom designed lamp affords the best possible results. A jointly tailored lamp-circuit combination permits precise optimization of circuit operation, yielding highest efficiency.

Special attention should be given to the layout of the circuit board, since high voltage is generated at the output. The output coupling capacitor must be carefully located to minimize leakage paths on the circuit board. A slot in the board will further minimize leakage. Such leakage can permit current flow outside the feedback loop, wasting power. In the worst case, long term contamination build-up can increase leakage inside the loop, resulting in starved lamp drive or destructive arcing. It is good practice for minimization of leakage to break the silk screen line which outlines transformer T1. This prevents leakage from the high voltage secondary to the primary. Another technique for minimizing leakage is to evaluate and specify the silk screen ink for its ability to withstand high voltages.

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4. A very simple experiment quite nicely demonstrates the effects of energy leakage. Grasping the lamp at its low-voltage end (low field intensity) with thumb and forefinger produces almost no change in circuit input current. Sliding the thumb-forefinger combination towards the high-voltage (higher field intensity) lamp end produces progressively greater input currents. Don't touch the high-voltage lead or you may receive an electrical shock. Repeat: Do not touch the high-voltage lead or you may receive an electrical shock.

Efficiency Measurement

Once these procedures have been followed efficiency can be measured. Efficiency may be measured by determining lamp current and voltage. Measuring current involves measuring RMS voltage across a temporarily inserted 200Ω .1% resistor in the ground lead of the negative current steering diode. The lamp current is

$$\text{Ilamp} = \frac{\text{ERMS}}{200} \times 2$$

The ×2 factor is necessitated because the diode steering dumps the current to ground on negative cycles. The 200Ω value allows the RMS meter to read with a scale factor numerically identical to the total current. Once this measurement is complete, the 200Ω resistor may be deleted and the negative current steering diode again returned directly to ground. Lamp RMS voltage is measured at the lamp with a properly compensated high voltage probe. Multiplying these two results gives power in watts, which may be compared to the DC input supply E × I product. In practice, the lamp's current and voltage contain small out of phase components but their error contribution is negligible.

Both the current and voltage measurements require a wideband true RMS voltmeter. The meter must employ a thermal type RMS converter—the more common logarithmic computing type based instruments are inappropriate because their bandwidth is too low.

The previously recommended high voltage probes are designed to see a 1MΩ–10pF–22pF oscilloscope input. The RMS voltmeters have a 10 meg Ω input. This difference necessitates an impedance matching network between the probe and the voltmeter. Details on this and other efficiency measurement issues appear in Appendix A, "Achieving Meaningful Efficiency Measurements."

Layout

The physical layout of the lamp, its leads, the display housing, and other high voltage components, is an integral part of the circuit. Poor layout can easily degrade efficiency by 25%, and higher layout induced losses have been observed. Producing an optimal layout requires attention to how losses occur. Figure 11–22 begins our study by examining potential parasitic paths between the transformer's output and the lamp. Parasitic capacitance to AC ground from any point between the transformer output and the lamp creates a path for undesired current flow. Similarly, stray coupling from any point along the lamp's length to AC ground induces parasitic current flow. All parasitic current flow is wasted, causing the circuit to produce more energy to maintain the desired current flow in D1 and D2. The high-voltage path from the transformer to the display housing should be as short as possible to minimize losses. A good rule of thumb is

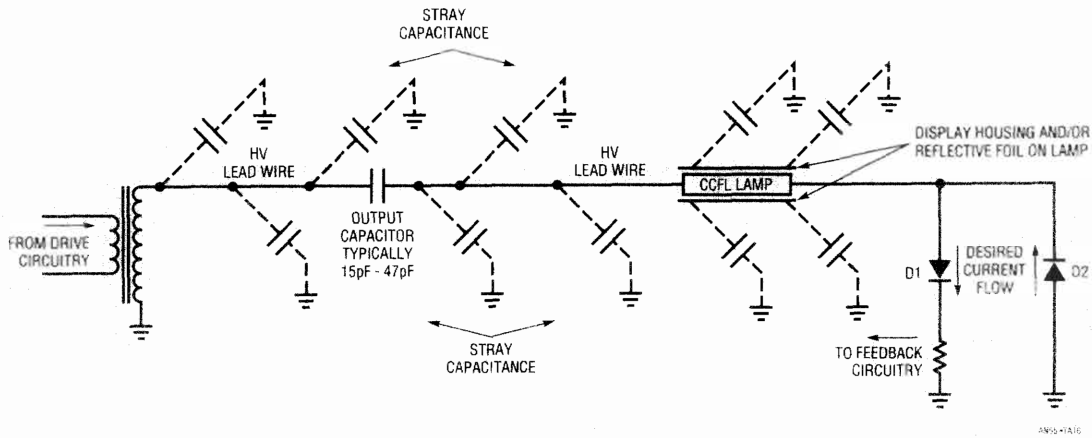


Figure 11–22. Loss paths due to stray capacitance in a practical LCD installation. Minimizing these paths is essential for good efficiency.

to assume 1% efficiency loss per inch of high voltage lead. Any PC board ground or power planes should be relieved by at least ¼" in the high voltage area. This not only prevents losses, but eliminates arcing paths.

Parasitic losses associated with lamp placement within the display housing require attention. High voltage wire length within the housing must be minimized, particularly for displays using metal construction. Ensure that the high voltage is applied to the shortest wire(s) in the display. This may require disassembling the display to verify wire length and layout. Another loss source is the reflective foil commonly used around lamps to direct light into the actual LCD. Some foil materials absorb considerably more field energy than others, creating loss. Finally, displays supplied in metal enclosures tend to be lossy. The metal absorbs significant energy and an AC path to ground is unavoidable. Direct grounding of a metal enclosed display further increases losses. Some display manufacturers have addressed this issue by relieving the metal in the lamp area with other materials.

The highest efficiency "in system" backlights have been produced by careful attention to these issues. In some cases the entire display enclosure was re-engineered for lowest losses.

Layout Considerations for Two-Lamp Designs

Systems using two lamps have some unique layout problems. Almost all two lamp displays are color units. The lower light transmission characteristics of color displays necessitate more light. Therefore, display manufacturers use two tubes to produce more light. The wiring layout of these two tube color displays affects efficiency and illumination balance in the lamps. Figure 11–23 shows an "x-ray" view of a typical display. This symmetrical arrangement presents equal parasitic losses. If C1 and C2 and the lamps are matched, the circuit's current output splits evenly and equal illumination occurs.

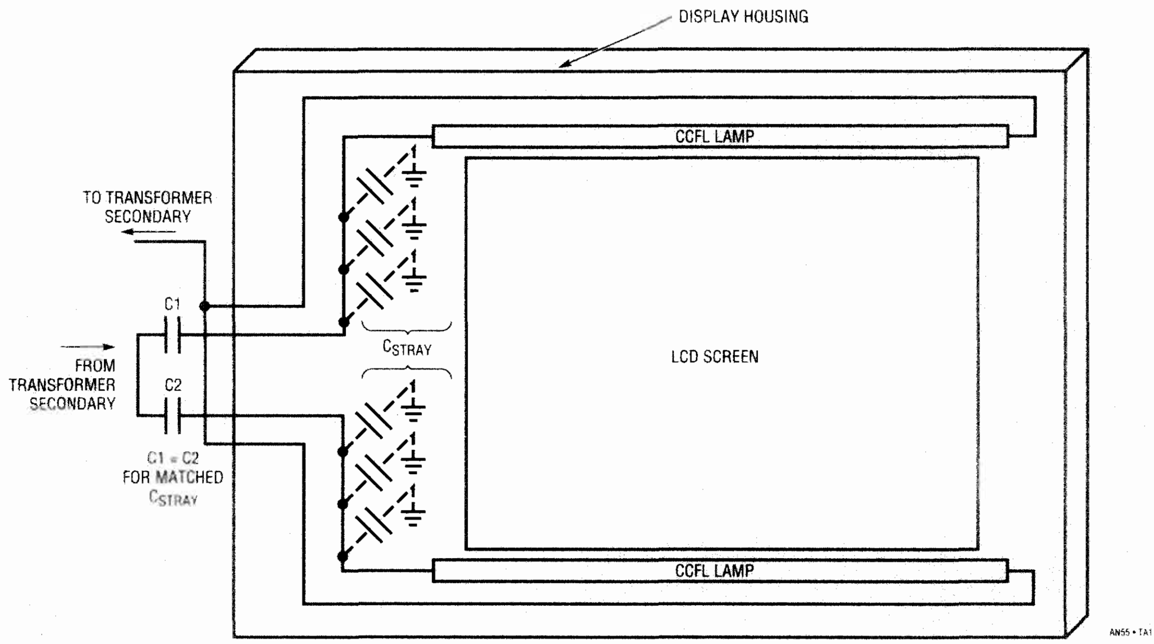


Figure 11–23. Loss paths for a "best case" dual lamp display. Symmetry promotes balanced illumination.

Figure 11–24's display arrangement is less friendly. The asymmetrical wiring forces unequal losses, and the lamps receive imbalanced current. Even with identical lamps, illumination may not be balanced. This condition is correctable by skewing C1's and C2's values. C1, because it drives greater parasitic capacitance, should be larger than C2. This tends to equalize the currents, promoting equal lamp drive. It is important to realize that this compensation does nothing to recapture the lost energy—efficiency is still compromised. There is no substitute for minimizing loss paths.

In general, imbalanced illumination causes fewer problems than might be supposed. The effect is very difficult for the eye to detect at high intensity levels. Unequal illumination is much more noticeable at lower levels. In the worst case, the dimmer lamp may only partially illuminate. This phenomenon is discussed in detail in the section "Thermometering."

Feedback Loop Stability Issues

The circuits shown to this point rely on closed loop feedback to maintain the operating point. All linear closed loop systems require some form of frequency compensation to achieve dynamic stability. Circuits operating with relatively low power lamps may be frequency compensated simply by overdamping the loop. Figures 11–18 and 11–20 use this approach. The higher power operation associated with color displays requires more attention to loop response. The transformer produces much higher output

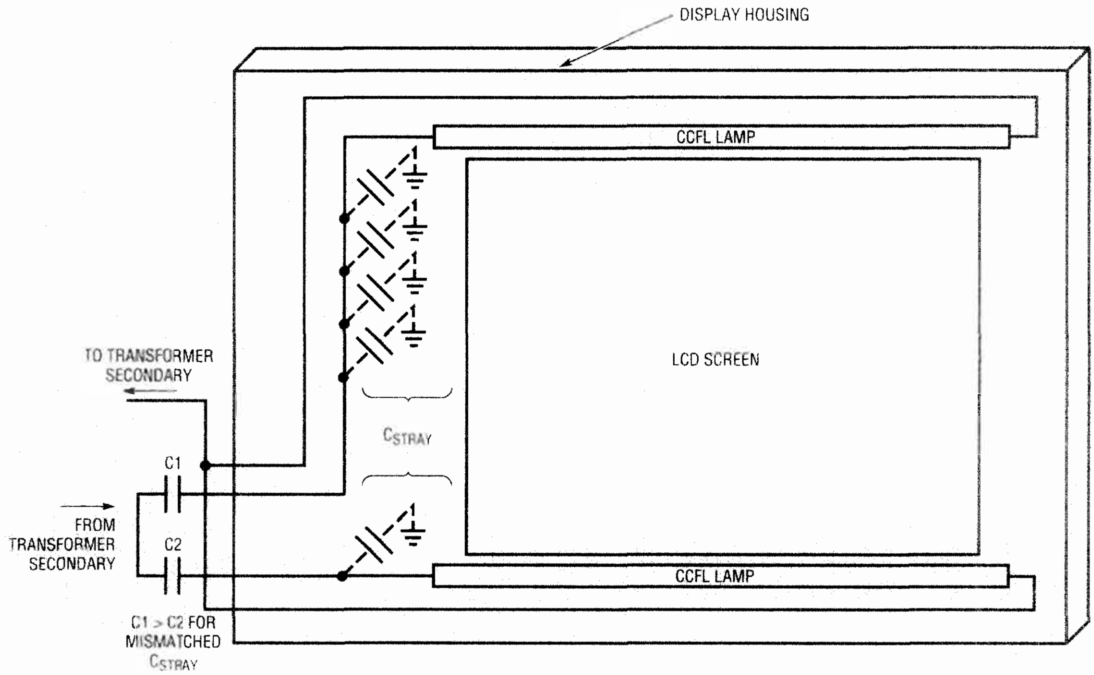


Figure 11–24. Symmetric losses in a dual lamp display. Skewing C1 and C2 values compensates imbalanced loss paths, but not wasted energy.

voltages, particularly at start-up. Poor loop damping can allow transformer voltage ratings to be exceeded, causing arcing and failure. As such, higher power designs may require optimization of transient response characteristics.

Figure 11–25 shows the significant contributors to loop transmission in these circuits. The resonant Royer converter delivers information at

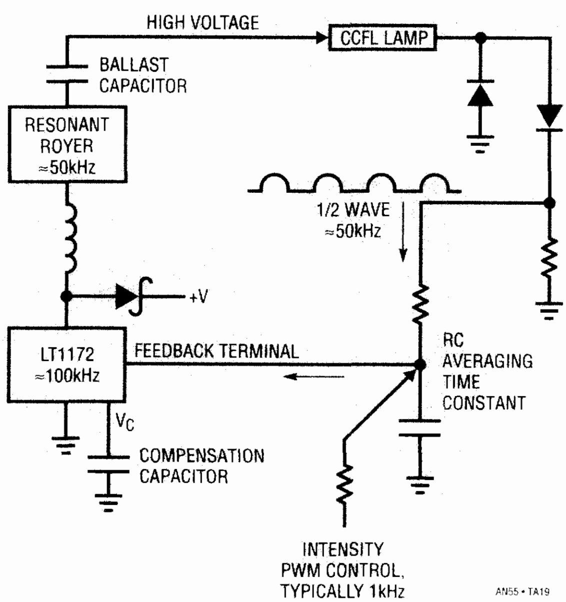


Figure 11–25. Delay terms in the feedback path. The RC time constant dominates loop transmission delay and must be compensated for stable operation.

about 50kHz to the lamp. This information is smoothed by the RC averaging time constant and delivered to the LT1172's feedback terminal as DC. The LT1172 controls the Royer converter at a 100kHz rate, closing the control loop. The capacitor at the LT1172 rolls off gain, nominally stabilizing the loop. This compensation capacitor must roll off the gain bandwidth at a low enough value to prevent the various loop delays from causing oscillation.

Which of these delays is the most significant? From a stability viewpoint, the LT1172's output repetition rate and the Royer's oscillation frequency are sampled data systems. Their information delivery rate is far above the RC averaging time constant's delay and is not significant. The RC time constant is the major contributor to loop delay. This time constant must be large enough to turn the half wave rectified waveform into DC. It also must be large enough to average any intensity control PWM signal to DC. Typically, these PWM intensity control signals come in at a 1kHz rate. The RC's resultant delay dominates loop transmission. It must be compensated by the capacitor at the LT1172. A large enough value for this capacitor rolls off loop gain at low enough frequency to provide stability. The loop simply does not have enough gain to oscillate at a frequency commensurate with the RC delay.

This form of compensation is simple and effective. It ensures stability over a wide range of operating conditions. It does, however, have poorly damped response at system turn-on. At turn-on, the RC lag delays feedback, allowing output excursions well above the normal operating point. When the RC acquires the feedback value, the loop stabilizes properly. This turn-on overshoot is not a concern if it is well within transformer breakdown ratings. Color displays, running at higher power, usually require large initial voltages. If loop damping is poor, the overshoot may be dangerously high. Figure 11–26 shows such a loop responding to turn-on. In this case the RC values are 10kΩ and 4.7µf, with a 2µf compensation capacitor. Turn-on overshoot exceeds 3500 volts for over 10

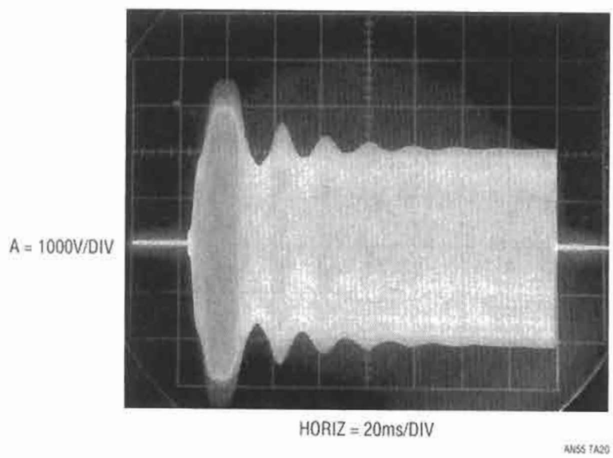
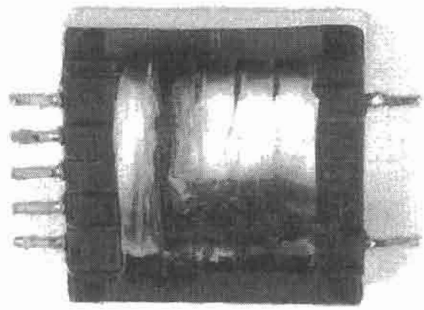


Figure 11–26. Destructive high voltage overshoot and ring-off due to poor loop compensation. Transformer failure and field recall are nearly certain. Job loss may also occur.



AN55 F21

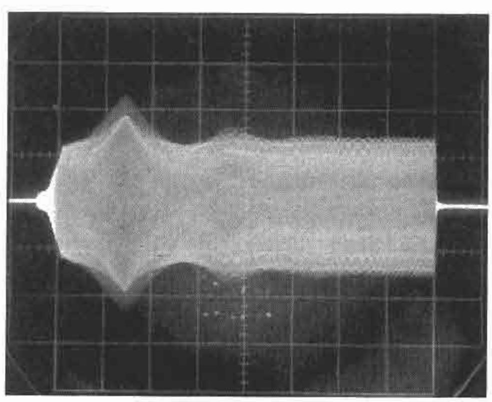
Figure 11–27. Poor loop compensation caused this transformer failure. Arc occurred in high voltage secondary (lower right). Resultant shorted turns caused overheating.

milliseconds! Ring-off takes over 100 milliseconds before settling occurs. Additionally, an inadequate (too small) ballast capacitor and excessively lossy layout force a 2000 volt output once loop settling occurs. This photo was taken with a transformer rated well below this figure. The resultant arcing caused transformer destruction, resulting in field failures. A typical destroyed transformer appears in Figure 11–27.

Figure 11–28 shows the same circuit, with the RC values reduced to 10kΩ and 1μf. The ballast capacitor and layout have also been optimized. Figure 11–28 shows peak voltage reduced to 2.2 kilovolts with duration down to about 2 milliseconds. Ring-off is also much quicker, with lower amplitude excursion. Increased ballast capacitor value and wiring layout optimization reduce running voltage to 1300 volts. Figure 11–29's results are even better. Changing the compensation capacitor to a 3kΩ–2μf network introduces a leading response into the loop, allowing faster acquisition. Now, turn-on excursion is slightly lower, but greatly reduced in duration. The running voltage remains the same.

The photos show that changes in compensation, ballast value, and layout result in dramatic reductions in overshoot amplitude and duration. Figure 11–26's performance almost guarantees field failures, while Figures 11–28 and 11–29 do not overstress the transformer. Even with

A = 1000V/DIV



HORIZ = 5ms/DIV

AN55 TA22

Figure 11–28. Reducing RC time constant improves transient response, although peaking, ring-off, and run voltage are still excessive.

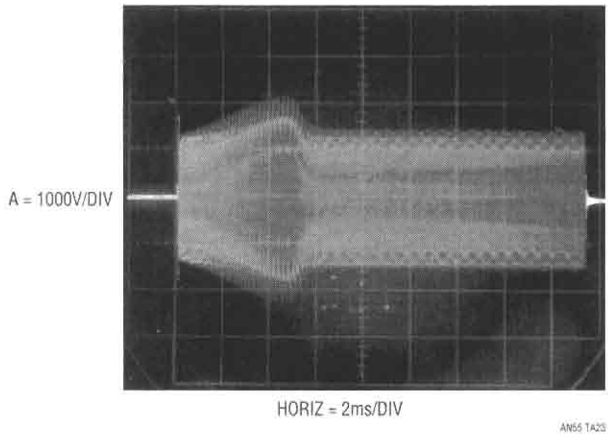


Figure 11–29. Additional optimization of RC time constant and compensation capacitor reduces turn-on transient. Run voltage is large, indicating possible lossy layout and display.

the improvements, more margin is possible if display losses can be controlled. Figures 11–26–11–29 were taken with an exceptionally lossy display. The metal enclosure was very close to the foil wrapped lamps, causing large losses with subsequent high turn-on and running voltages. If the display is selected for lower losses, performance can be greatly improved.

Figure 11–30 shows a low loss display responding to turn-on with a 2µf compensation capacitor and 10kΩ-1µf RC values. Trace A is the transformer's output while Traces B and C are the LT1172's Vcompensation and feedback pins, respectively. The output overshoots and rings badly, peaking to about 3000 volts. This activity is reflected by overshoots at the Vcompensation pin (the LT1172's error amplifier output) and the feedback pin. In Figure 11–31, the RC is reduced to 10kΩ–.1µf. This substantially reduces loop delay. Overshoot goes down to only 800 volts—a reduction of almost a factor of four. Duration is also much shorter. The Vcompensation and feedback pins reflect this tighter control. Damping is much better, with slight overshoot induced at turn-on. Further reduction of the RC to 10kΩ–.01µf (Figure 11–32) results in even faster loop capture, but a new problem appears. In Trace A, lamp turn on is so fast that the overshoot does not register in the photo. The

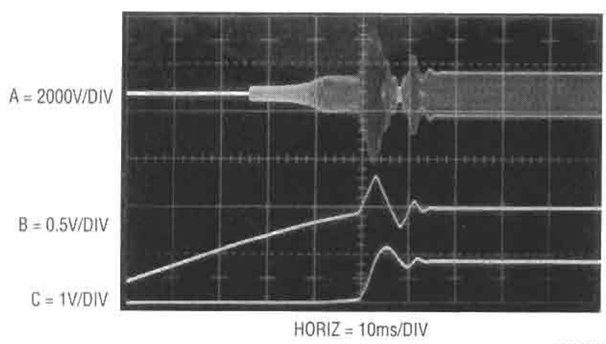


Figure 11–30. Waveforms for a lower loss layout and display. High voltage overshoot (Trace A) is reflected at compensation node (Trace B) and feedback pin (Trace C).

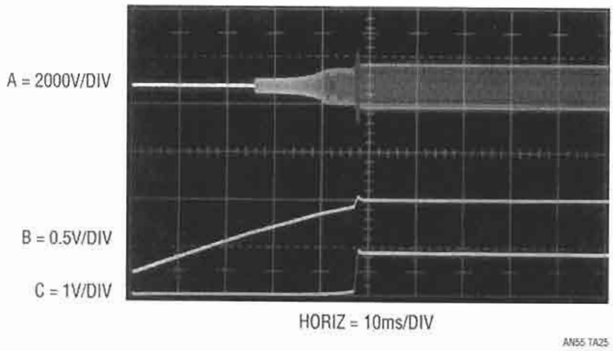


Figure 11–31. Reducing RC time constant produces quick, clean loop behavior. Low loss layout and display result in 650 VRMS running voltage.

Vcompensation (Trace B) and feedback nodes (Trace C) reflect this with exceptionally fast response. Unfortunately, the RC's light filtering causes ripple to appear when the feedback node settles. As such, Figure 11–31's RC values are probably more realistic for this situation.

The lesson from this exercise is clear. The higher voltages involved in color displays mandate attention to transformer outputs. Under running conditions, layout and display losses can cause higher loop compliance voltages, degrading efficiency and stressing the transformer. At turn-on, improper compensation causes huge overshoots, resulting in possible transformer destruction. Isn't a day of loop and layout optimization worth a field recall?

Extending Illumination Range

Lamps operating at relatively low currents may display the "thermometer effect," that is, light intensity may be nonuniformly distributed along lamp length. Figure 11–33 shows that although lamp current density is uniform, the associated field is imbalanced. The field's low intensity, combined with its imbalance, means that there is not enough energy to maintain uniform phosphor glow beyond some point. Lamps displaying the thermometer effect emit most of their light near the positive electrode, with rapid emission fall-off as distance from the electrode increases.

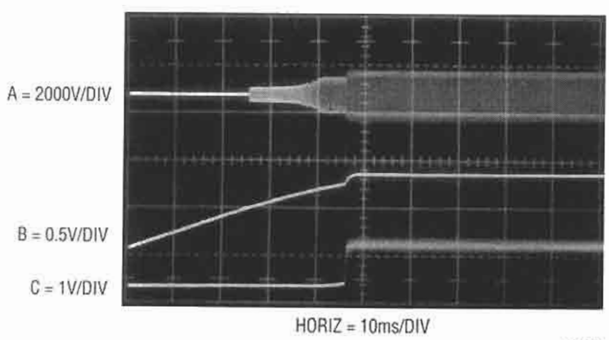


Figure 11–32. Very low RC value provides even faster response, but ripple at feedback pin (Trace C) is too high. Figure 11–31 is the best compromise.

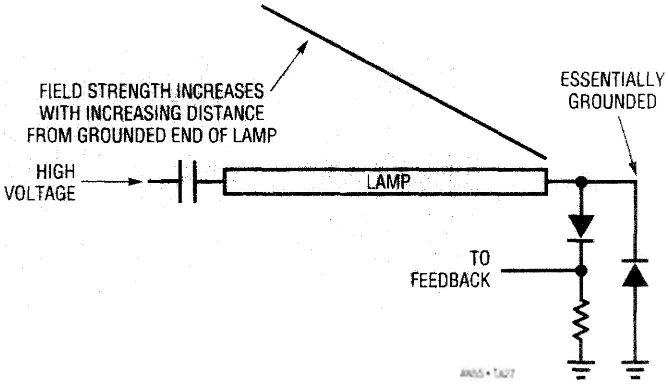
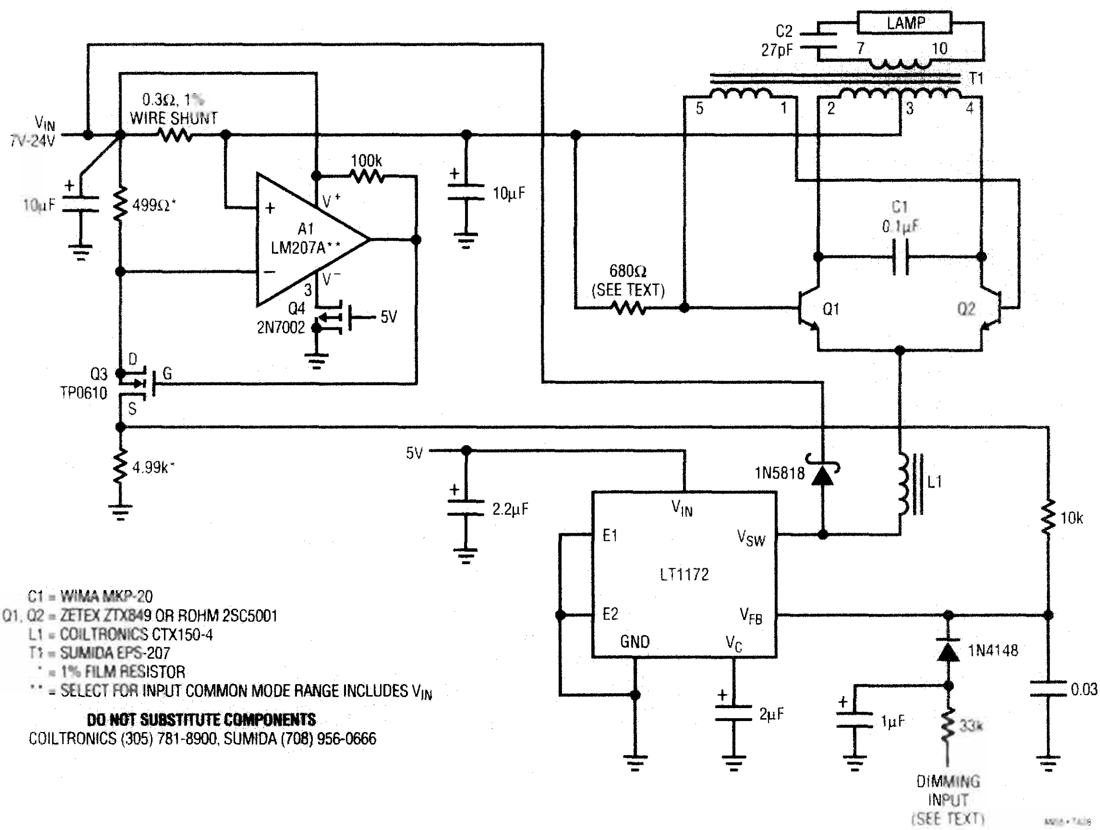


Figure 11–33. Field strength vs. distance for a ground referred lamp. Field imbalance promotes uneven illumination at low drive levels.

Figure 11–34. The "low thermometer" configuration. "Topside sensed" primary derived feedback balances lamp drive, extending dimming range.

Placing a conductor along the lamp's length largely alleviates "thermometering." The trade-off is decreased efficiency due to energy leakage (see Note 4 and associated text). It is worth noting that various lamp types have different degrees of susceptibility to the thermometer effect.

Some displays require an extended illumination range. "Thermometering" usually limits the lowest practical illumination level. One acceptable way to minimize "thermometering" is to eliminate the large



field imbalance. Figure 11–34's circuit does this. This circuit's most significant aspect is that the lamp is fully floating—there is no galvanic connection to ground as in the previous designs. This allows T1 to deliver symmetric, differential drive to the lamp. Such balanced drive eliminates field imbalance, reducing thermometering at low lamp currents. This approach precludes any feedback connection to the now floating output. Maintaining closed loop control necessitates deriving a feedback signal from some other point. In theory, lamp current proportions to T1's or L1's drive level, and some form of sensing this can be used to provide feedback. In practice, parasitics make a practical implementation difficult.[5]

Figure 11–34 derives the feedback signal by measuring Royer converter current and feeding this information back to the LT1172. The Royer's drive requirement closely proportions to lamp current under all conditions. A1 senses this current across the .3Ω shunt and biases Q3, closing a local feedback loop. Q3's drain voltage presents an amplified, single ended version of the shunt voltage to the feedback point, closing the main loop. The lamp current is not as tightly controlled as before, but .5% regulation over wide supply ranges is possible. The dimming in this circuit is controlled by a 1kHz PWM signal. Note the heavy filtering (33kΩ–2µf) outside the feedback loop. This allows a fast time constant, minimizing turn-on overshoot.[6]

In all other respects, operation is similar to the previous circuits. This circuit typically permits the lamp to operate over a 40:1 intensity range without "thermometering." The normal feedback connection is usually limited to a 10:1 range.

The losses introduced by the current shunt and A1 degrade overall efficiency by about 2%. As such, circuit efficiency is limited to about 90%. Most of the loss can be recovered at moderate cost in complexity. Figure 11–35's modifications reduce shunt and A1 losses. A1, a precision micropower type, cuts power drain and permits a smaller shunt value without performance degradation. Unfortunately, A1 does not function when its inputs reside at the V+ rail. Because the circuit's operation requires this, some accommodation must be made.[7]

At circuit start-up, A1's input is pulled to its supply pin potential (actually, slightly above it). Under these conditions, A1's input stage is shut off. Normally, A1's output state would be indeterminate but, for the amplifier specified, it will always be high. This turns off Q3, permitting the LT1172 to drive the Royer stage. The Royer's operation causes Q1's collector swing to exceed the supply rail. This turns on the 1N4148, the BAT-85 goes off, and A1's supply pin rises above the supply rail. This "bootstrapping" action results in A1's inputs being biased within the am-

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5. See Appendix C, "A Lot of Cut-Off-Ears and No Van Goghs—Some Not-So-Great Ideas," for details.
6. See section "Feedback Loop Stability Issues."
7. In other words, we need a hack.

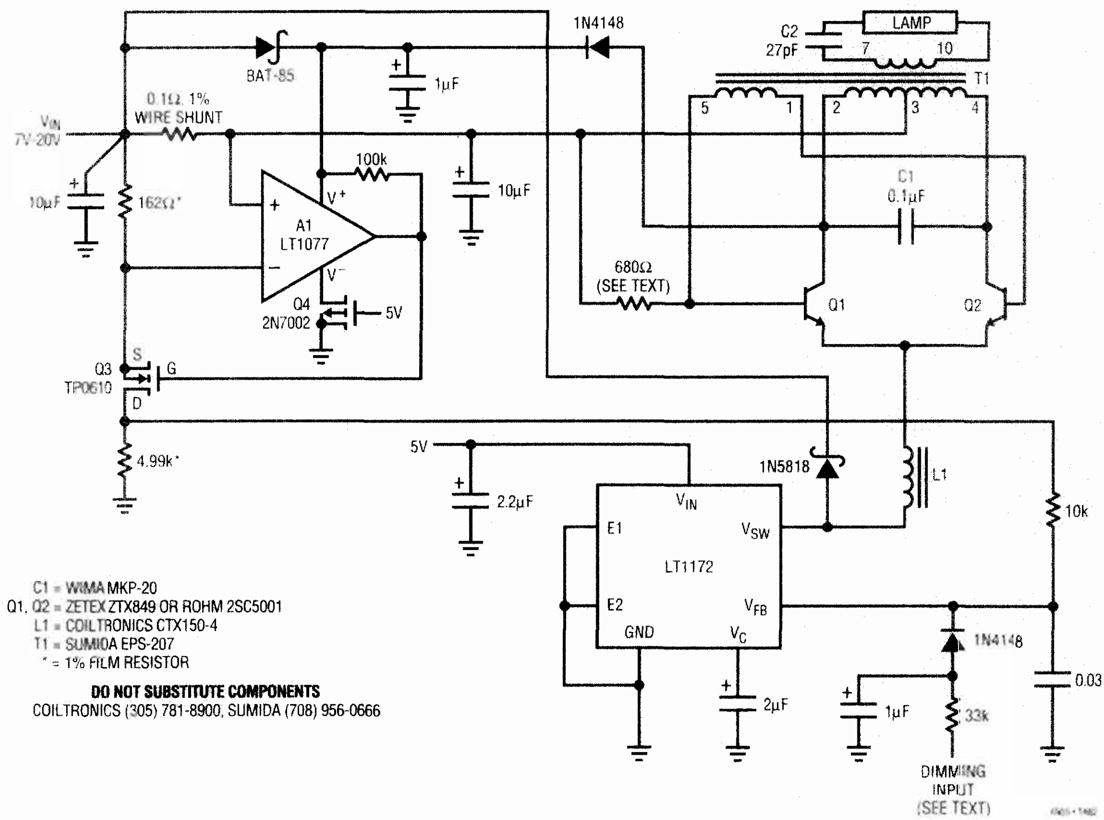

Figure 11–35. The "low thermometer" circuit using a micropower, precision topside sensing amplifier. Supply bootstrapping eliminates input common mode requirement, permitting a 1.6% efficiency gain.

plifier's common mode range, and normal circuit operation commences. The result of all this is a 1.6% efficiency gain, permitting an overall circuit efficiency of just below 92%.

Epilogue

Our understanding with Apple Computer gave them six months sole use of everything I learned while working with them. After that, we were free to disclose the circuit and most attendant details to anyone else, which we did. It found immediate use in other computers and applications, ranging from medical equipment to automobiles, gas pumps, retail terminals and anywhere else LCD displays are used. The development work consumed about 20 months, ending in August, 1993. Upon its completion I immediately fell into a rut, certain I would never do anything worthwhile again.

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Appendix A

Achieving Meaningful Efficiency Measurements

Obtaining reliable efficiency data for the CCFL circuits presents a high order difficulty measurement problem. Establishing and maintaining accurate AC measurements is a textbook example of attention to measurement technique. The combination of high frequency, harmonic laden waveforms and high voltage makes meaningful results difficult to obtain. The choice, understanding, and use of test instrumentation is crucial. Clear thinking is needed to avoid unpleasant surprises![1]

Probes

The probes employed must faithfully respond over a variety of conditions. Measuring across the resistor in series with the CCFL is the most favorable circumstance. This low voltage, low impedance measurement allows use of a standard 1X probe. The probe's relatively high input capacitance does not introduce significant error. A 10X probe may also be used, but frequency compensation issues (discussion to follow) must be attended to.

The high voltage measurement across the lamp is considerably more demanding on the probe. The waveform fundamental is at 20kHz to 100kHz, with harmonics into the MHz region. This activity occurs at peak voltages in the kilovolt range. The probe must have a high fidelity response under these conditions. Additionally, the probe should have low input capacitance to avoid loading effects which would corrupt the measurement. The design and construction of such a probe requires significant attention. Figure 11–A1 lists some recommended probes along with their characteristics. As stated in the text, almost all standard oscilloscope probes will fail[2] if used for this measurement. Attempting to circumvent the probe requirement by resistively dividing the lamp voltage also creates problems. Large value resistors often have significant voltage coefficients and their shunt capacitance is high and uncertain. As such, simple voltage dividing is not recommended. Similarly, common high voltage probes intended for DC measurement will have large errors because of AC effects. The P6013A and P6015 are the favored probes; their 100MΩ input and small capacitance introduces low loading error. The penalty for their 1000X attenuation is reduced output, but the recommended voltmeters (discussion to follow) can accommodate this.

All of the recommended probes are designed to work into an oscilloscope input. Such inputs are almost always 1MΩ paralleled by (typically)

1. It is worth considering that various constructors of Figure 11–18 have reported efficiencies ranging from 8% to 115%.
2. That's twice I've warned you nicely.

10pF–22pF. The recommended voltmeters, which will be discussed, have significantly different input characteristics. Figure 11–A2's table shows higher input resistances and a range of capacitances. Because of this the probe must be compensated for the voltmeter's input characteristics. Normally, the optimum compensation point is easily determined and adjusted by observing probe output on an oscilloscope. A known-amplitude square wave is fed in (usually from the oscilloscope calibrator) and the probe adjusted for correct response. Using the probe with the voltmeter presents an unknown impedance mismatch and raises the problem of determining when compensation is correct.

The impedance mismatch occurs at low and high frequency. The low frequency term is corrected by placing an appropriate value resistor in shunt with the probe's output. For a 10MΩ voltmeter input, a 1.1MΩ resistor is suitable. This resistor should be built into the smallest possible BNC equipped enclosure to maintain a coaxial environment. No cable connections should be employed; the enclosure should be placed directly between the probe output and the voltmeter input to minimize stray capacitance. This arrangement compensates the low frequency impedance mismatch. Figure 11–A4 shows the impedance-matching box attached to the high voltage probe.

Correcting the high frequency mismatch term is more involved. The wide range of voltmeter input capacitances combined with the added shunt resistor's effects presents problems. How is the experimenter to know where to set the high frequency probe compensation adjustment? One solution is to feed a known value RMS signal to the probe-voltmeter combination and adjust compensation for a proper reading. Figure 11–A3 shows a way to generate a known RMS voltage. This scheme is simply a standard backlight circuit reconfigured for a constant voltage output. The op amp permits low RC loading of the 5.6K feedback termination without introducing bias current error. The 5.6kΩ value may be series or parallel trimmed for a 300V output. Stray parasitic capacitance in the feedback network affects output voltage. Because of this, all feedback associated nodes and components should be rigidly fixed and the entire circuit built into a small metal box. This prevents any significant change in the parasitic terms. The result is a known $300V_{RMS}$ output.

Now, the probe's compensation is adjusted for a 300V voltmeter indication, using the shortest possible connection (e.g., BNC-to-probe adapter) to the calibrator box. This procedure, combined with the added resistor, completes the probe-to-voltmeter impedance match. If the probe compensation is altered (e.g., for proper response on an oscilloscope) the voltmeter's reading will be erroneous.[3] It is good practice to verify the

3. The translation of this statement is to hide the probe when you are not using it. If anyone wants to borrow it, look straight at them, shrug your shoulders, and say you don't know where it is. This is decidedly dishonest, but eminently practical. Those finding this morally questionable may wish to reexamine their attitude after producing a day's worth of worthless data with a probe that was unknowingly readjusted.

Figure 11–A1. Characteristics of some wideband high voltage probes. Output impedances are designed for oscilloscope inputs.

TEKTRONIX PROBE TYPE	ATTENUATION FACTOR	ACCURACY	INPUT RESISTANCE	INPUT CAPACITANCE	RISE TIME	BAND-WIDTH	MAXIMUM VOLTAGE	DERATED ABOVE	DERATED TO AT FREQUENCY	COMPENSATION RANGE	ASSUMED TERMINATION RESISTANCE
P6007	100X	3%	10MΩ	2.2pF	14ns	25MHz	1.5kV	200kHz	$700V_{RMS}$ at 10MHz	15-55pF	1M
P6009	100X	3%	10MΩ	2.5pF	2.9ns	120MHz	1.5kV	200kHz	$450V_{RMS}$ at 40MHz	15-47pF	1M
P6013A	1000X	Adjustable	100MΩ	3pF	7ns	50MHz	12kV	100kHz	$800V_{RMS}$ at 20MHz	12-60pF	1M
P6015	1000X	Adjustable	100MΩ	3pF	1.4ns	250MHz	20kV	100kHz	$2000V_{RMS}$ at 20MHz	12-47pF	1M

Figure 11–A2. Pertinent characteristics of some thermally based RMS voltmeters. Input impedances necessitate matching network and compensation for high voltage probes.

MANUFACTURER AND MODEL	FULL SCALE RANGES	ACCURACY AT 1MHz	ACCURACY AT 100kHz	INPUT RESISTANCE AND CAPACITANCE	MAXIMUM BANDWIDTH	CREST FACTOR
Hewlett-Packard 3400 Meter Display	1mV to 300V, 12 Ranges	1%	1%	0.001V to 0.3V Range = 10M and < 50pF, 1V to 300V Range = 10M and < 20pF	10MHz	10:1 At Full Scale, 100:1 At 0.1 Scale
Hewlett-Packard 3403C Digital Display	10mV to 1000V, 6 Ranges	0.5%	0.2%	10mV and 100mV Range = 20M and 20pF ±10%, 1V to 1000V Range = 10M and 24pF ±10%	100MHz	10:1 At Full Scale, 100:1 At 0.1 Scale
Fluke 8920A Digital Display	2mV to 700V, 7 Ranges	0.7%	0.5%	10M and < 30pF	20MHz	7:1 At Full Scale, 70:1 At 0.1 Scale

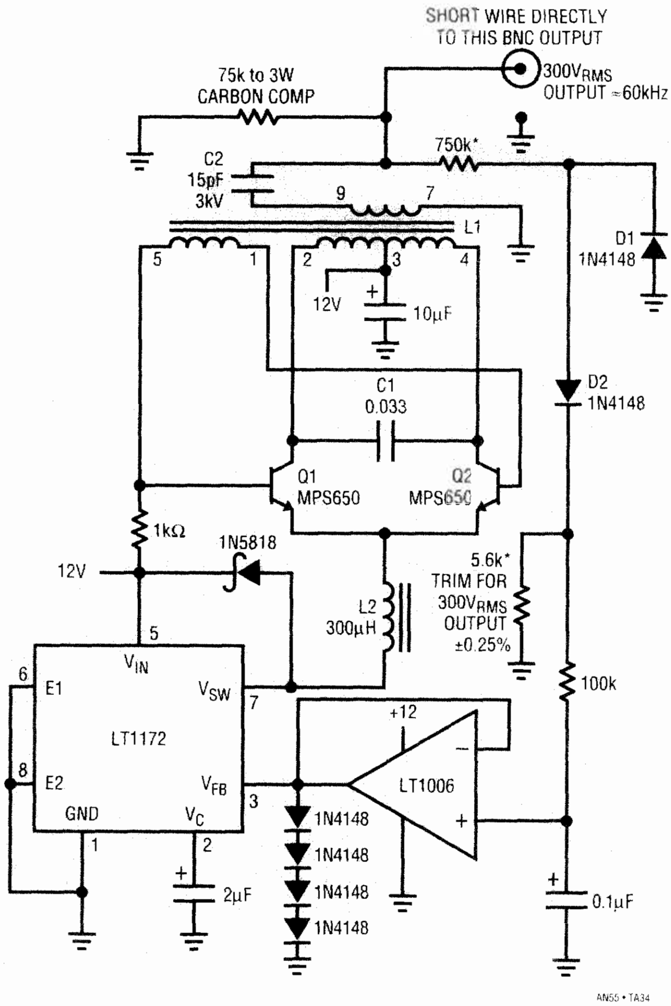


Figure 11–A3. High voltage RMS calibrator is voltage output version of CCFL circuit.

C1 = MUST BE A LOW LOSS CAPACITOR.
METALIZED POLYCARB
WIMA FKP2 OR MKP-20 (GERMAN) RECOMMENDED
L1 = SUMIDA 6345-020 OR COILTRONICS CTX110092-1
PIN NUMBERS SHOWN FOR COILTRONICS UNIT
L2 = COILTRONICS CTX300-4
Q1, Q2 = AS SHOWN OR BCP 56 (PHILLIPS SO PACKAGE)
* = 1% FILM RESISTOR (10kΩ TO 75kΩ RESISTORS IN SERIES)
DO NOT SUBSTITUTE COMPONENTS

COILTRONICS (305) 781-8900, SUMIDA (708) 956-0666

calibrator box output before and after every set of efficiency measurements. This is done by directly connecting, via BNC adapters, the calibrator box to the RMS voltmeter on the 1000V range.

RMS Voltmeters

The efficiency measurements require an RMS responding voltmeter. This instrument must respond accurately at high frequency to irregular and harmonically loaded waveforms. These considerations eliminate almost all AC voltmeters, including DVMs with AC ranges.

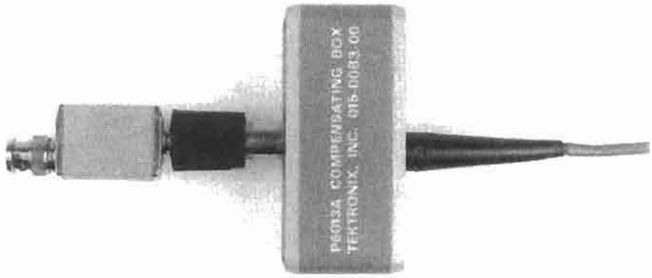


Figure 11–A4. The impedance matching box (extreme left) mated to the high voltage probe. Note direct connection. No cable is used.

There are a number of ways to measure RMS AC voltage. Three of the most common include average, logarithmic, and thermally responding. Averaging instruments are calibrated to respond to the average value of the input waveform, which is almost always assumed to be a sine wave. Deviation from an ideal sine wave input produces errors. Logarithmically based voltmeters attempt to overcome this limitation by continuously computing the input's true RMS value. Although these instruments are "real time" analog computers, their 1% error bandwidth is well below 300kHz and crest factor capability is limited. Almost all general purpose DVMs use such a logarithmically based approach and, as such, are not suitable for CCFL efficiency measurements. Thermally based RMS voltmeters are direct acting thermo-electronic analog computers. They respond to the input's RMS heating value. This technique is explicit, relying on the very definition of RMS (e.g., the heating power of the waveform). By turning the input into heat, thermally based instruments achieve vastly higher bandwidth than other techniques.[4] Additionally, they are insensitive to waveform shape and easily accommodate large crest factors. These characteristics are necessary for the CCFL efficiency measurements.

Figure 11–A5 shows a conceptual thermal RMS-DC converter. The input waveform warms a heater, resulting in increased output from its associated temperature sensor. A DC amplifier forces a second, identical, heater-sensor pair to the same thermal conditions as the input driven pair. This differentially sensed, feedback enforced loop makes ambient temperature shifts a common mode term, eliminating their effect. Also, although the voltage and thermal interaction is non-linear, the input-output RMS voltage relationship is linear with unity gain.

The ability of this arrangement to reject ambient temperature shifts depends on the heater-sensor pairs being isothermal. This is achievable by thermally insulating them with a time constant well below that of ambient shifts. If the time constants to the heater-sensor pairs are matched, ambient temperature terms will affect the pairs equally in phase and amplitude.

4. Those finding these descriptions intolerably brief are commended to references 4, 5, and 6.

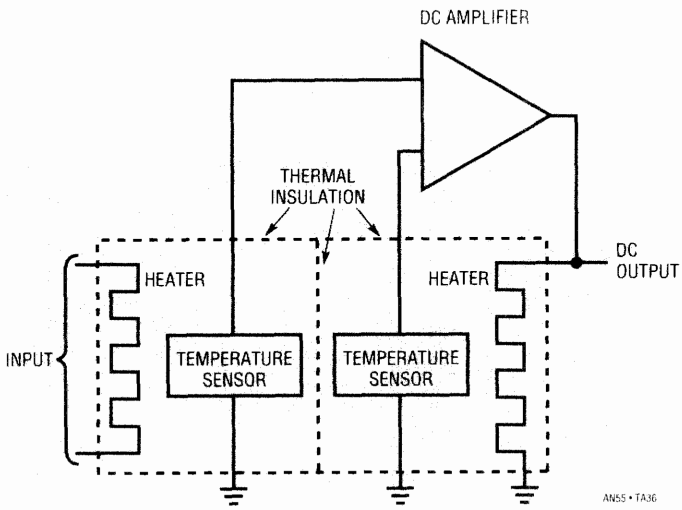


Figure 11–A5. Conceptual thermal RMS-DC converter.

The DC amplifier rejects this common mode term. Note that, although the pairs are isothermal, they are insulated from each other. Any thermal interaction between the pairs reduces the system's thermally based gain terms. This would cause unfavorable signal-to-noise performance, limiting dynamic operating range.

Figure 11–A5's output is linear because the matched thermal pair's nonlinear voltage-temperature relationships cancel each other.

The advantages of this approach have made its use popular in thermally based RMS-DC measurements.

The instruments listed in Figure 11–A2, while considerably more expensive than other options, are typical of what is required for meaningful results. The HP3400A and the Fluke 8920A are currently available from their manufacturers. The HP3403C, an exotic and highly desirable instrument, is no longer produced but readily available on the secondary market.

Figure 11–A6 shows equipment in a typical efficiency test setup. The RMS voltmeters (photo center and left) read output voltage and current via high voltage (left) and standard 1X probes (lower left). Input voltage is read on a DVM (upper right). A low loss clip-on ammeter (lower right) determines input current. The CCFL circuit and LCD display are in the foreground. Efficiency, the ratio of input to output power, is computed with a hand held calculator (lower right).

Calorimetric Correlation of Electrical Efficiency Measurements

Careful measurement technique permits a high degree of confidence in the accuracy of the efficiency measurements. It is, however, a good idea to check the method's integrity by measuring in a completely different domain. Figure 11–A7 does this by calorimetric techniques. This arrangement, identical to the thermal RMS voltmeter's operation (Figure 11–A5),

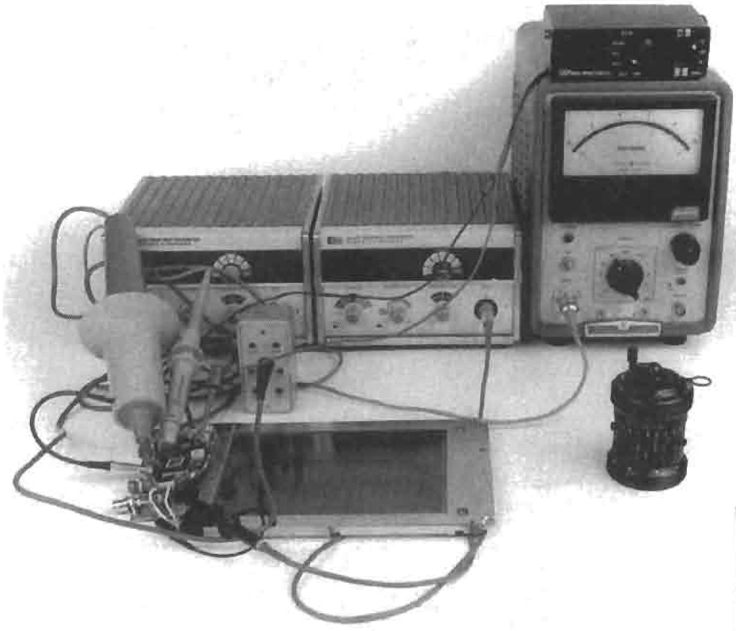
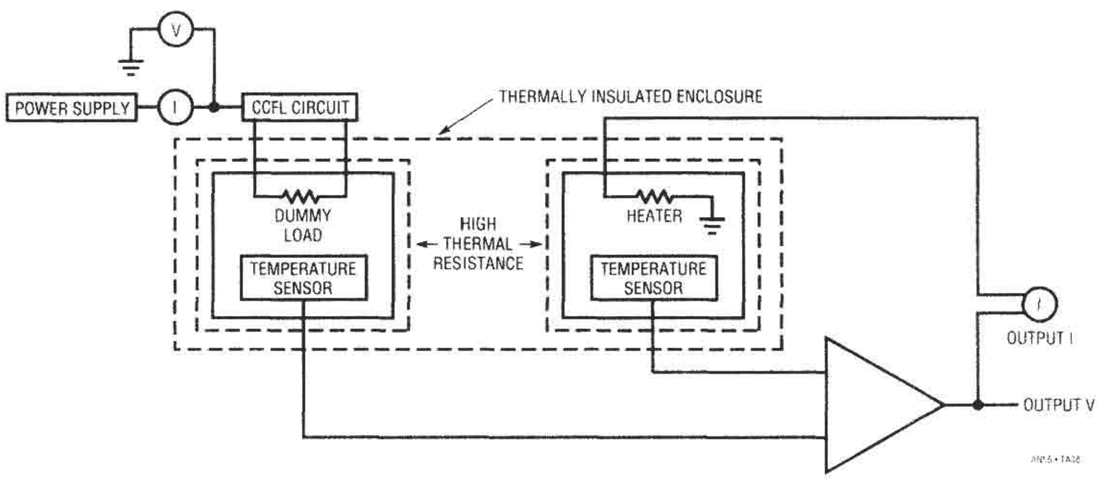


Figure 11–A6. Typical efficiency measurement instrumentation. RMS voltmeters (center left) measure output voltage and current via appropriate probes. Clip-on ammeter (right) gives low loss input current readings. DVM (upper right) measures input voltage. Hand calculator (lower right) is used to compute efficiency.

determines power delivered by the CCFL circuit by measuring its load temperature rise. As in the thermal RMS voltmeter, a differential approach eliminates ambient temperature as an error term. The differential amplifier's output, assuming a high degree of matching in the two thermal enclosures, proportions to load power. The ratio of the two cells' E × I products yields efficiency information. In a 100% efficient system, the amplifier's output energy would equal the power supplies' output. Practically it is always less, as the CCFL circuit has losses. This term represents the desired efficiency information.

Figure 11–A8 is similar except that the CCFL circuit board is placed within the calorimeter. This arrangement nominally yields the same information, but is a much more demanding measurement because far less heat is generated. The signal-to-noise (heat rise above ambient) ratio is unfavorable, requiring almost fanatical attention to thermal and instru-

Figure 11–A7. Efficiency determination via calorimetric measurement. Ratio of power supply to output energy gives efficiency information.



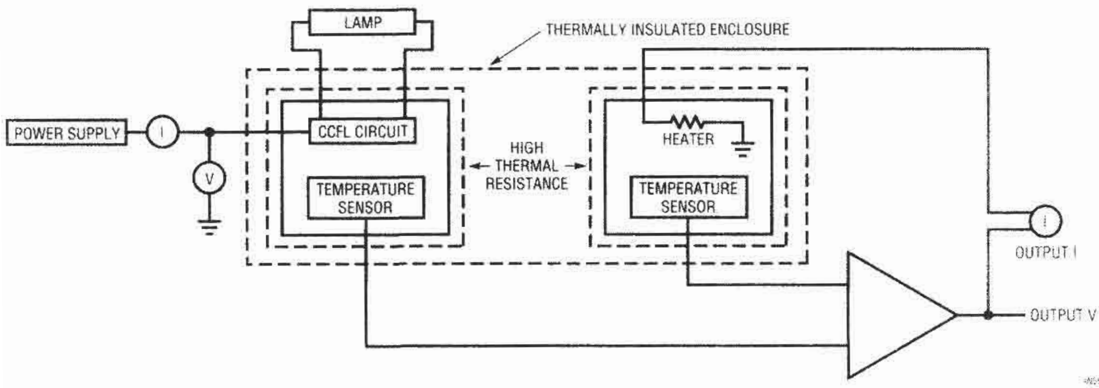


Figure 11–A8. The calorimeter measures efficiency by determining circuit heating losses.

mentation considerations.[5] It is significant that the total uncertainty between electrical and both calorimetric efficiency determinations was 3.3%. The two thermal approaches differed by about 2%. Figure 11–A9 shows the calorimeter and its electronic instrumentation. Descriptions of this instrumentation and thermal measurements can be found in the References section following the main text.

5. Calorimetric measurements are not recommended for readers who are short on time or sanity.

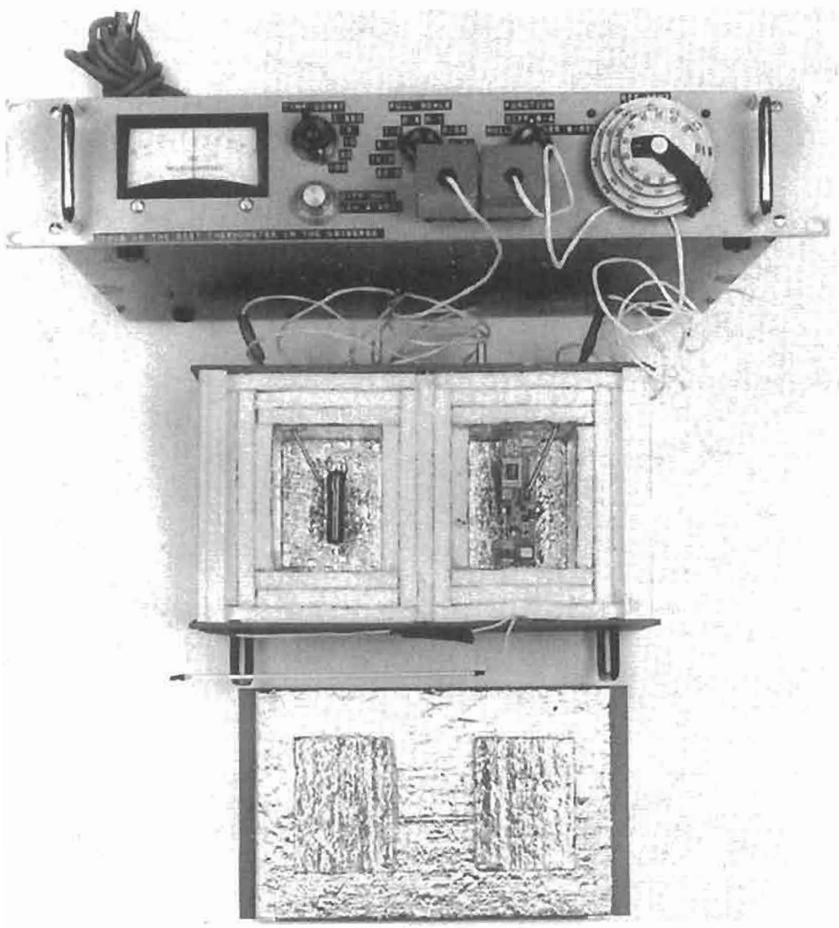


Figure 11–A9. The calorimeter (center) and its instrumentation (top). Calorimeter's high degree of thermal symmetry combined with sensitive servo instrumentation produces accurate efficiency measurements. Lower portion of photo is calorimeter's top cover.

Appendix B

Photometric Measurements

In the final analysis the ultimate concern centers around the efficient conversion of power supply energy to light. Emitted light varies monotonically with power supply energy,[1] but certainly not linearly. In particular, bulb luminosity may be highly nonlinear, particularly at high power, vs. drive power. There are complex trade-offs involving the amount of emitted light vs. power consumption and battery life. Evaluating these trade-offs requires some form of photometer. The relative luminosity of lamps may be evaluated by placing the lamp in a light tight tube and sampling its output with photodiodes. The photodiodes are placed along the lamp's length and their outputs electrically summed. This sampling technique is an uncalibrated measurement, providing relative data only. It is, however, quite useful in determining relative bulb emittance under various drive conditions. Figure 11–B1 shows this "glometer," with its uncalibrated output appropriately scaled in "brights." The switches allow various sampling diodes along the lamp's length to be disabled. The photodiode signal conditioning electronics are mounted behind the switch panel.

Calibrated light measurements call for a true photometer. The Tektronix J-17/J1803 photometer is such an instrument. It has been found

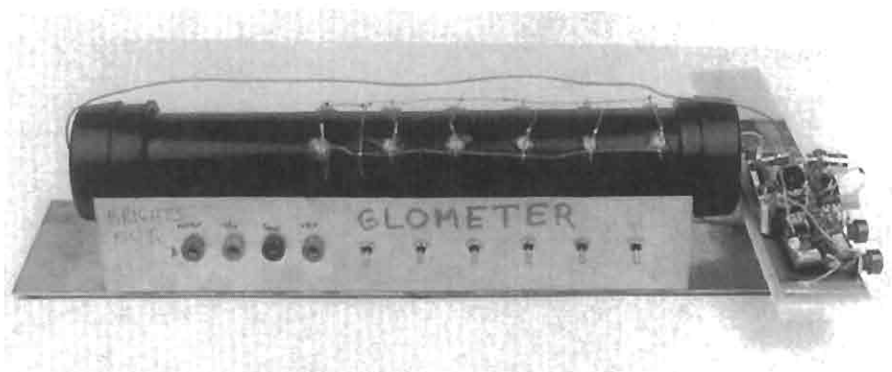


Figure 11–B1.
The "glometer" measures relative lamp emissivity. CCFL circuit mounts to the right. Lamp is inside cylindrical housing. Photodiodes (center) convert light to electrical output (lower left) via amplifiers (not visible in photo).

1. But not always! It is possible to build highly electrically efficient circuits that emit less light than "less efficient" designs. See Appendix C, "A Lot of Cut-Off Ears and No Van Goghs—Some Not-So-Great Ideas."

particularly useful in evaluating display (as opposed to simply the lamp) luminosity under various drive conditions. The calibrated output permits reliable correlation with customer results.[2] The light tight measuring head allows evaluation of emittance evenness at various display locations. This capability is invaluable when optimizing lamp location and/or ballast capacitor values in dual lamp displays.

Figure 11–B2 shows the photometer in use evaluating a display.

2. It is unlikely that customers would be enthusiastic about correlating the "brights" units produced by the aforementioned glometer.

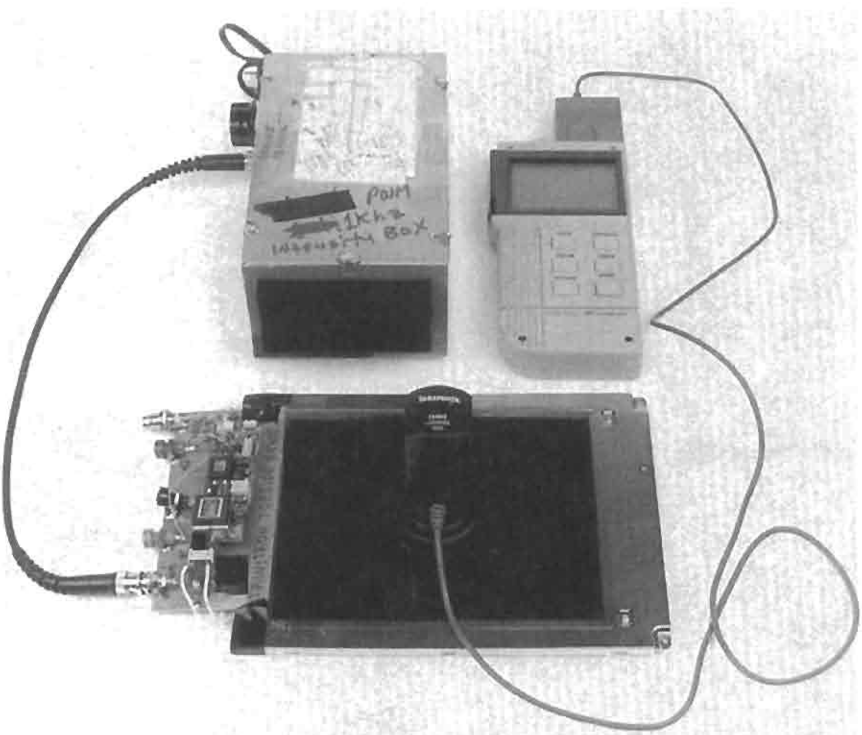


Figure 11–B2.
Apparatus for calibrated photometric display evaluation. Photometer (upper right) indicates display luminosity via sensing head (center). CCFL circuit (left) intensity is controlled by a calibrated pulse width generator (upper left).

Appendix C

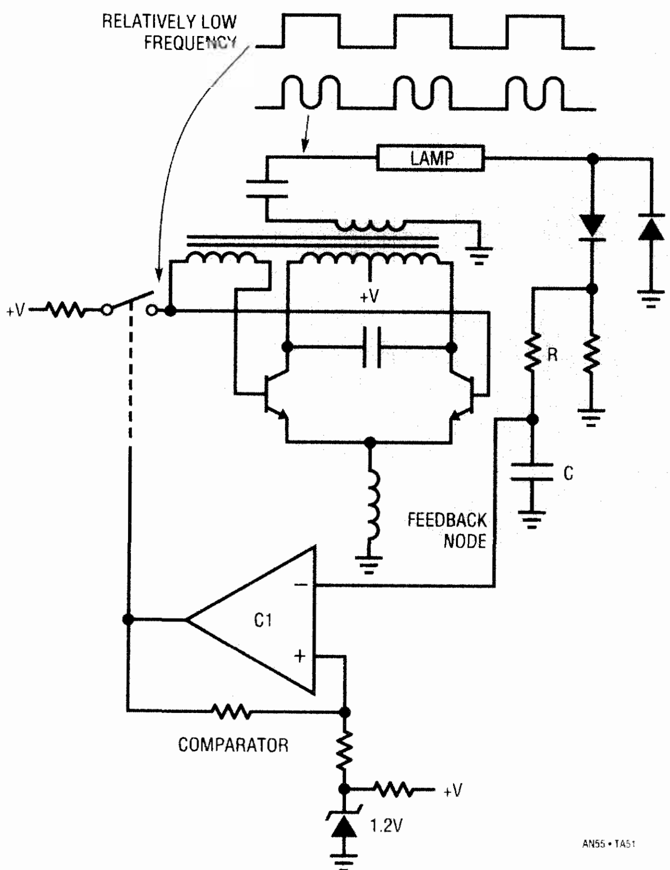
A Lot of Cut-Off Ears and No Van Goghs—Some Not-So-Great Ideas

The hunt for a practical CCFL power supply covered (and is still covering) a lot of territory. The wide range of conflicting requirements combined with ill-defined lamp characteristics produces plenty of unpleasant surprises. This section presents a selection of ideas that turned into disappointing breadboards. Backlight circuits are one of the deadliest places for theoretically interesting circuits the author has ever encountered.

Not-So-Great Backlight Circuits

Figure 11–C1 seeks to boost efficiency by eliminating the LT1172's saturation loss. Comparator C1 controls a free running loop around the Royer by on-off modulation of the transistor base drive. The circuit delivers bursts of high voltage sine drive to the lamp to maintain the feedback

Figure 11–C1. A first attempt at improving the basic circuit. Irregular Royer drive promotes losses and poor regulation.



node. The scheme worked, but had poor line rejection, due to the varying waveform vs. supply seen by the RC averaging pair. Also, the "burst" modulation forces the loop to constantly re-start the bulb at the burst rate, wasting energy. Finally, bulb power is delivered by a high crest factor waveform, causing inefficient current-to-light conversion in the bulb.

Figure 11–C2 attempts to deal with some of these issues. It converts the previous circuit to an amplifier-controlled current mode regulator. Also, the Royer base drive is controlled by a clocked, high frequency pulse width modulator. This arrangement provides a more regular waveform to the averaging RC, improving line rejection. Unfortunately the improvement was not adequate. 1% line rejection is required to avoid annoying flicker when the line moves abruptly, such as when a charger is activated. Another difficulty is that, although reduced by the higher frequency PWM, crest factor is still non-optimal. Finally, the lamp is still forced to restart at each PWM cycle, wasting power.

Figure 11–C3 adds a "keep alive" function to prevent the Royer from turning off. This aspect worked well. When the PWM goes low, the Royer is kept running, maintaining low level lamp conduction. This eliminates the continuous lamp restarting, saving power. The "supply correc-

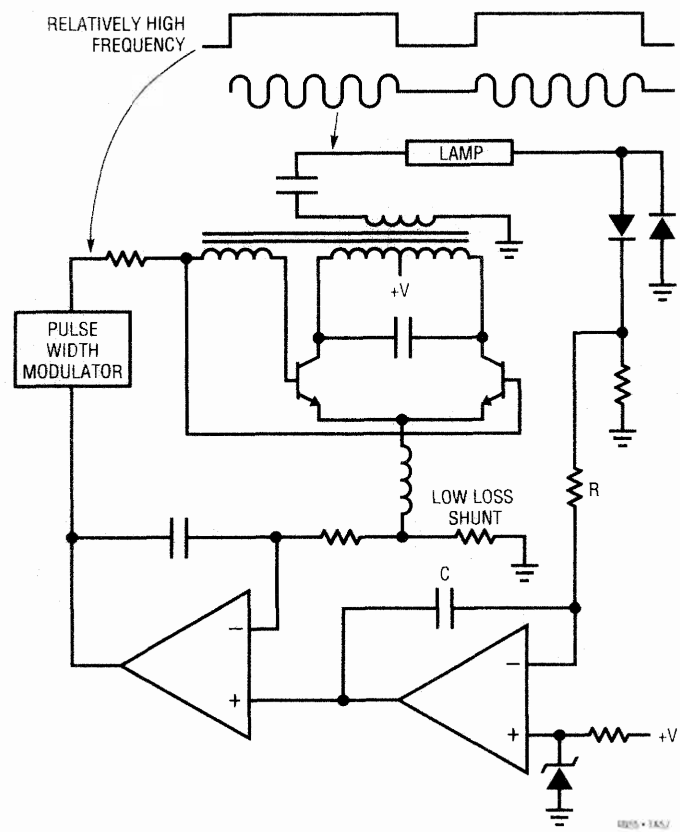


Figure 11–C2. A more sophisticated failure still has losses and poor line regulation.

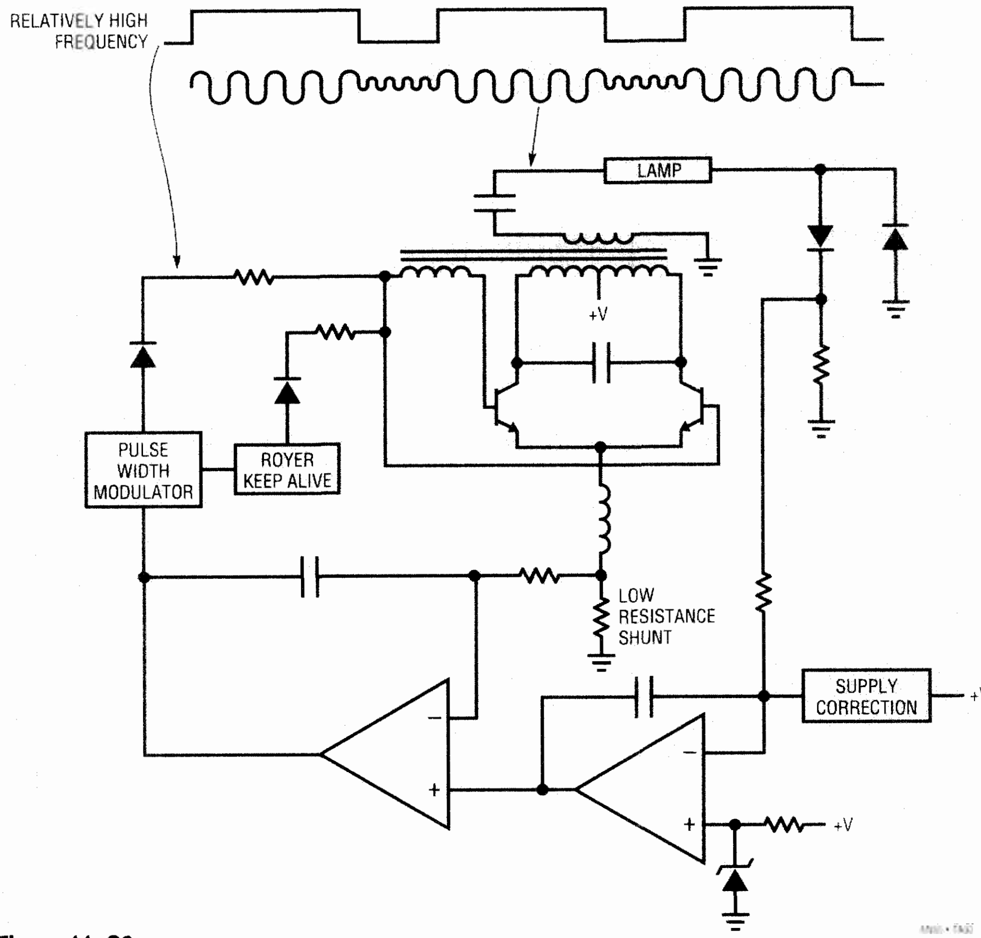


Figure 11–C3. "Keep alive" circuit eliminates turn-on losses and has 94% efficiency. Light emission is lower than "less efficient" circuits.

tion" block feeds a portion of the supply into the RC averager, improving line rejection to acceptable levels.

This circuit, after considerable fiddling, achieved almost 94% efficiency but produced less output light than a "less efficient" version of Figure 11–18! The villain is lamp waveform crest factor. The keep alive circuit helps, but the lamp still cannot handle even moderate crest factors.

Figure 11–C4 is a very different approach. This circuit is a driven square wave converter. The resonating capacitor is eliminated. The base drive generator shapes the edges, minimizing harmonics for low noise operation. This circuit works well, but relatively low operating frequencies are required to get good efficiency. This is so because the sloped drive must be a small percentage of the fundamental to maintain low losses. This mandates relatively large magnetics—a crucial disadvantage. Also, square waves have a different crest factor and rise time than sines, forcing inefficient lamp transduction.

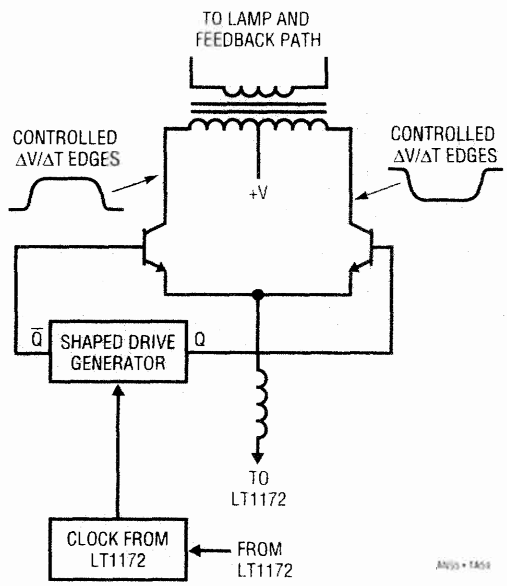


Figure 11–C4. A non-resonant approach. Slew retarded edges minimize harmonics, but transformer size goes up. Output waveform is also non-optimal, causing lamp losses.

Not-So-Great Primary Side Sensing Ideas

Figures 11–34 and 11–35 use primary side current sensing to control bulb intensity. This permits the bulb to fully float, extending its dynamic operating range. A number of primary side sensing approaches were tried before the "topside sense" won the contest.

Figure 11–C5's ground referred current sensing is the most obvious way to detect Royer current. It offers the advantage of simple signal conditioning—there is no common mode voltage. The assumption that essentially all Royer current derives from the LT1172 emitter pin path is true. Also true, however, is that the waveshape of this path's current

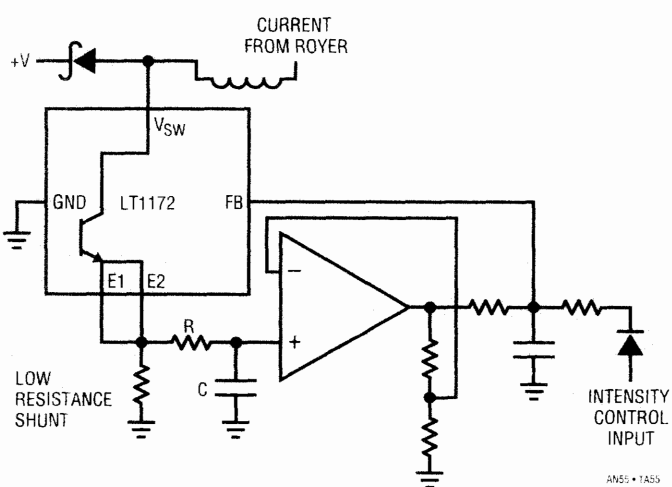


Figure 11–C5. "Bottom side" current sensing has poor line regulation due to RC averaging characteristics.

varies widely with input voltage and lamp operating current. The RMS voltage across the shunt (e.g., the Royer current) is unaffected by this, but the simple RC averager produces different outputs for the various waveforms. This causes this approach to have very poor line rejection, rendering it impractical. Figure 11–C6 senses inductor flux, which should correlate with Royer current. This approach promises attractive simplicity. It gives better line regulation but still has some trouble giving reliable feedback as waveshape changes. It also, in keeping with most flux sampling schemes, regulates poorly under low current conditions.

Figure 11–C7 senses flux in the transformer. This takes advantage of the transformer's more regular waveform. Line regulation is reasonably good because of this, but low current regulation is still poor. Figure 11–C8 samples Royer collector voltage capacitively, but the feedback signal does not accurately represent start-up, transient, and low current conditions.

Figure 11–C9 uses optical feedback to eliminate all feedback integrity problems. The photodiode-amplifier combination provides a DC feedback signal which is a function of actual lamp emission. It forces the lamp to constant emissivity, regardless of environmental or aging factors.

This approach works quite nicely, but introduces some evil problems. The lamp comes up to constant emission immediately at turn-on. There is no warm-up time required because the loop forces emission, instead of current. Unfortunately, it does this by driving huge overcurrents through the lamp, stressing it and shortening life. Typically, 2 to 5 times rated current flows for many seconds before lamp temperature rises, allowing the loop to back down drive. A subtle result of this effect occurs with lamp aging. When lamp emissivity begins to fall off, the loop increases current to correct the condition. This increase in current accelerates lamp aging, causing further emissivity degradation. The resultant downward spiral continues, resulting in dramatically shortened lamp life.

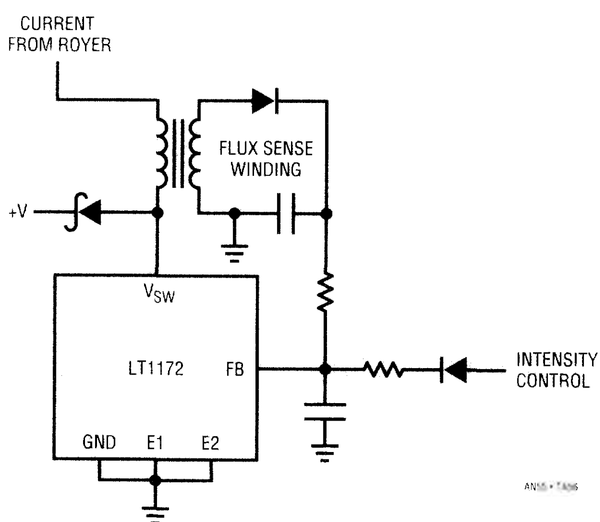


Figure 11–C6. Flux sensing has irregular outputs, particularly at low currents.