BE IT EVER SO HIGH-TECH, THERE'S NO PLACE LIKE HOME

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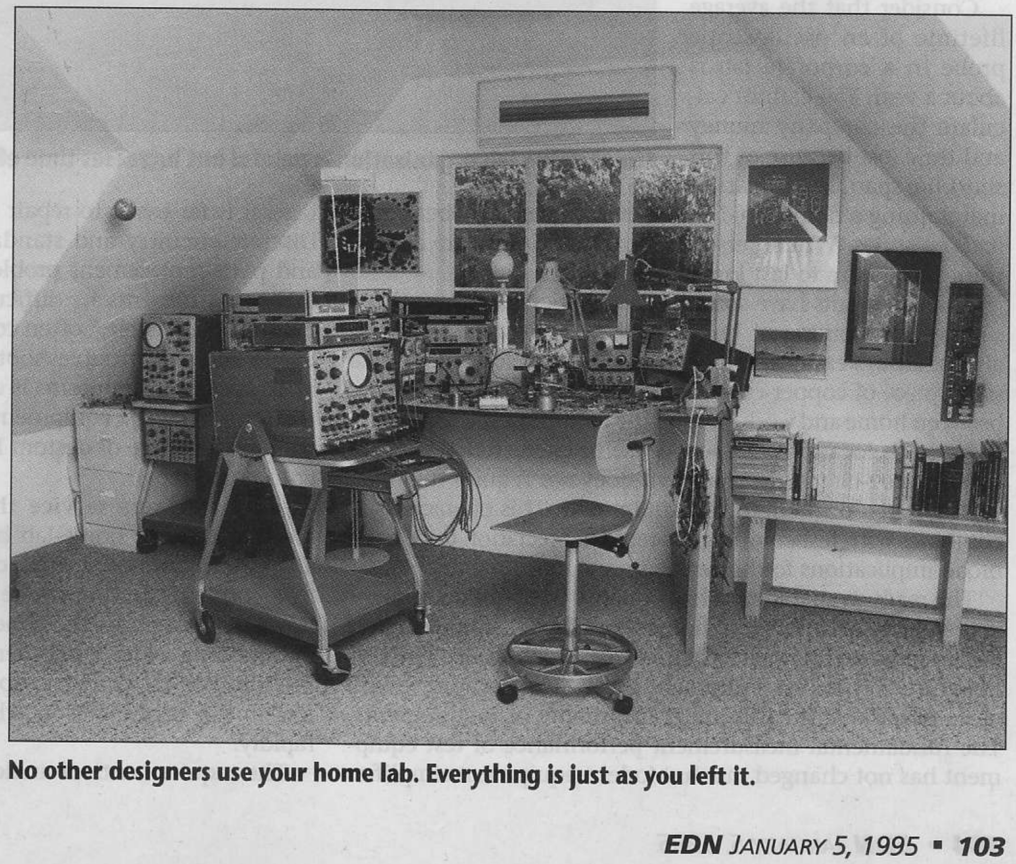
The ready availability of inexpensive used test equipment makes it practical for you to configure a home laboratory, a great timesaver and boon to your circuit-design productivity.

What's your choice for the single best aid to an interesting and productive circuit-design career? A PhD? An IQ of 250? A CAD workstation? Getting a paper into the International Solid State Circuits Conference? Befriending the boss? All these are of some value, but none even comes close to something else. In fact, their combined benefit isn't worth a fraction of the something else. This something else even has potential economic rewards. What is this wondrous thing that outshines all the other candidates? It is, simply, a laboratory in your home. Nothing matches the productivity advantage a home lab provides. As for economic benefits, no stock tip, no real-estate deal, and no raise can match the long-term investment yield a home lab can produce. The laboratory is, after all, an investment in yourself. It is almost an unfair advantage.

The magic of a home lab is that it effectively creates time. Over the past 20 years, about 90% of my work output has occurred in a home lab. The ability to grab a few hours here and there and occasional marathon five- to 20-hour sessions produces a huge accumulated time benefit. Perhaps more important, the time is highly leveraged. An hour in the lab at home is worth a day at work.

Designers spend a lot of work time on un-planned and parasitic activities. Phone calls, in-terruptions, meetings and just plain gossiping eat time. These events may ultimately contribute toward good circuits but in an oblique way. Worse, they rob psychological momentum, breaking design time into chunks instead of allowing continuous periods of concentration. When I'm at work, I do my job. When I'm at home in the lab, the boss and stockholders get what they're paying for. It



No other designers use your home lab. Everything is just as you left it.

This article is part of a new book by Jim Williams. *The Art of Analog Circuit Design* will be published this spring by Butterworth-Heinemann as part of the *EDN* Series for Design Engineers. Contact (800) 366-2665 to order.

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sounds absurd, but I have sat in meetings praying for 6 pm to come so that I can go home and get to work. The uninterrupted time in a home lab permits persistence, one of the most powerful tools a designer has.

I favor long, uninterrupted lab sessions of at least five to 10 hours, but family time doesn't always allow this. However, I can almost always get in two to four hours per day. Few things can match the convenience and efficiency of getting an idea while washing dishes or putting my son to sleep and then being able to breadboard that idea immediately. The easy and instant availability of lab time makes even small amounts of time practical. You can get right to work. Over months, these small sessions produce spectacular gains in work output. The less frequent but more lengthy sessions contribute still more. Because no one else uses your lab, everything remains undisturbed and just as you left it after the last session. Nothing is missing or broken, and all test equipment is familiar.

Maintaining lab organization is painful but increases time efficiency.

Consider that the average lifetime of an oscilloscope probe in a corporate lab is about a year. You cannot calculate the company money and time lost because of this short life span. In 20 years of maintaining a home lab, I have never broken a probe or lost its accessories. When personal money and time are at risk, things just seem to last longer.

Analog circuits have some characteristics that make them suitable for working at home. First, they're small. You can almost always easily and quickly build an analog design on a small piece of copper-clad board. This board readily shuttles between home and work, permitting continuous design activity at both locations. A second useful characteristic is that most analog-circuit development does not require the most sophisticated or modern test equipment. This characteristic combines with test equipment's rapid depreciation to provide broad implications for home-lab financing.

The ready availability of high-quality used test equipment is the key to an affordable home lab. Clearly, serious circuit design requires high-performance instrumentation. The saving grace is that this equipment can be five, 20, or even 30 years old and still easily meet measurement requirements. The fundamental measurement performance of test equipment has not changed much. Modern equipment simplifies measurement and offers computational capability, lower parts count, smaller size, and cost advantages for new purchases. However, new equipment is vastly more expensive than used instrumentation. A 150-MHz Tektronix 454 portable oscilloscope is available on the surplus market for about $150. A new oscilloscope of equivalent capability costs at least 10 times this price.

Older equipment offers another subtle economic advantage: It is far easier to repair than are modern instruments. Discrete circuitry and standard-product ICs ease servicing and parts-replacement problems. Contemporary processor-driven instruments are difficult to fix because their software control is "invisible," often convoluted, and almost impervious to standard troubleshooting techniques. Accurate diagnosis based on symptoms is extremely difficult. You usually require special test equipment and fixtures. Additionally, the widespread usage of custom ICs presents a formidable barrier to home repair.

Manufacturers service their own products, but costs are too high for home-lab budgets. Modern computationally based equipment using custom ICs makes perfect sense in a corporate setting where economic realities differ from those in the home. The time and dollar costs of using and maintaining older equipment in an industrial setting are prohibitive—in diametric opposition to home-lab economics—and a prime reason why test equipment depreciates rapidly.

The requirements of analog design and these anomalies

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set guidelines for home-lab purchases. In general, instruments designed between about 1965 and 1980 meet most of the needs of home-lab work. Some of my opinions and prejudices about instruments follow.

Oscilloscopes are probably the most important instrument in analog laboratories. I favor Tektronix oscilloscopes manufactured between 1964 and 1969. Brilliantly conceived and stunning in their execution, they define excellence. Tektronix designed and manufactured these instruments to meet uncompromising standards under circumstances that are unlikely to recur. For example, the company built Types 547 and 556 for durability and easy maintenance. They are almost a privilege to own.

The widely available plug-in vertical amplifiers for the 547 and 556 provide broad measurement capability. The 1A4 4-trace and 1A5 and 1A7A differential plug-ins are particularly useful. A 547 with a 1A4 plug-in provides extensive triggering and display capability. The dual-beam 556 with two vertical plug-ins is an oscilloscope driver's dream. You can purchase these instruments for less than the price of dinner for two in San Francisco. The instruments' primary disadvantages are large size and 50-MHz bandwidth, although sampling plug-ins extend the bandwidth to 1 GHz.

You can never have enough power supplies.

The Tektronix 453 and 454 portables extend bandwidth to 150 MHz and cut size. The trade-off is a lack of plug-in capability. The later (1972) Tektronix 485 portable has 350-MHz bandwidth but uses custom ICs, is less rugged, and is difficult to repair. Similarly, the high-performance Tektronix 7000 Series plug-in instruments (1970s and '80s) have custom ICs and are less well-constructed than earlier types. They are also more difficult to fix. The price-risk/performance ratio is, however, becoming almost irresistible. A 500-MHz 7904 with plug-in amplifiers brings only $1000 today, and the price will continue to drop.

Sampling scopes and plug-ins attain bandwidths into the gigahertz range at low cost. The Tektronix 661 with a 4S2 plug-in has 3.9-GHz bandwidth but costs less than $100. The high bandwidths, sensitivity, and overload immunity of sampling instruments are attractive, but their wideband sections are tricky to maintain.

Other scopes worthy of mention include the Hewlett-Packard 180 Series, featuring small size, plug-in capability, and 250-MHz bandwidth. HP also built the portable 1725A, a 275-MHz instrument with many good attributes. Both these instruments use custom ICs and hybrids, raising the maintenance-cost risk factor.

In addition to oscilloscopes, a home lab must have a curve tracer. The Tektronix 575 is an excellent choice. It is the same size as older Tektronix lab scopes and is indispensable for device characterization. The more modern, fully solid-state 576 has more features but is still fairly expensive (about $1500). I winced when I finally bought one, but the pain fades quickly. A 575 is adequate; the 576 is the one you really want.

Oscilloscopes also require probes. There are many kinds of probes; as a probe fanatic, I am too embarrassed to reveal how many probes I own. Because there are many subtleties in probe design and construction, particularly in high-frequency probes, you should purchase only high-quality, name-brand probes. Many off-brand types give poor results. You need passive, differential, high-voltage, and other probes. In addition, 50Ω systems use probes that give clean results at high frequencies.

Your lab also needs active probes, including FET and current probes. FET probes provide low capacitive loading at high frequency. The 230-MHz Tektronix P-6045 is noteworthy because it is easy to repair compared with other FET probes. Another type of FET probe, the differential probe, is basically two matched FET probes in a common housing. This probe brings the advantages of a differential-input oscilloscope to circuit boards. The Tektronix P-6046 is excellent, and usually quite inexpensive because nobody knows what it is. Make sure it works when you buy it, because these probes are extraordinarily tricky to trim up for CMRR after repair.

Finally, you can buy clip-on current probes. These are really a must, and the one to have is the dc to 50-MHz Tektronix P-6042. It is not difficult to fix, but the Hall-effect-based sensor in the head is expensive. Clip-on probes that are ac-only are less versatile but still useful. Tektronix has several versions, for which the type 131 and 134 amplifiers extend probe capability and eliminate scale-factor calculations. The Hewlett-Packard 428B, essentially a dc-only clip-on probe, features high accuracy over a 50-μA to 10A range.

Moving on to power supplies and signal sources

You can never have enough power supplies. For analog work, supplies should be metered, linear regulators with fully adjustable voltage output and current limiting. The HP 6216 is small and serves well. The Lambda LK Series supplies are excellent for higher currents (10A, for example). These SCR-preregulated linear regulators are reasonably compact, very rugged, and can handle any load I have ever seen without introducing odd dynamics. The SCR preregulator delivers high power over a wide output-voltage range with the low-noise characteristics of a linear regulator.

A lab also needs a variety of signal sources. HP's 200 Series sine-wave oscillators are inexpensive and easy to repair. The later versions are solid-state and small. The HP 8601A sweep generator suits high frequencies and offers fully settable and leveled output to 100 MHz. The size, high performance, and versatility make this a desirable instru-

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ment. It does, however, have a couple of custom hybrid circuits, raising its cost to repair.

Function generators are sometimes useful, and you can easily find and repair the old Wavetek 100 Series. Pulse generators are a must; I favor the Datapulse 101. It is compact, fast, and has a full complement of features. It has fully discrete construction and is easy to maintain. The HP214A suits high power output, although it is large.

I'm willing to take a risk on processor-driven equipment when selecting DVMs because they are low-cost. For example, Fluke's handheld DVMs are inexpensive, and they work well. The Fluke $5\frac{1}{2}$-digit 8800A provides good value but lacks current ranges of the $4\frac{1}{2}$-digit HP3465. Another older DVM, the Data Precision 245-248 series $4\frac{1}{2}$-digit meters, are small and low-cost. Their construction is acceptable, although their compactness sometimes makes repair challenging.

A home lab ensures that my vocation and hobby remain happily mixed.

If you use ac wideband true-rms voltmeters, you also need thermal converters, which are indispensable for measuring root-mean-square quantities. For years, HP has manufactured the widely available metered 3400A, which provides accuracy to 10 MHz. All 3400s look the same, but HP has periodically updated the design. If possible, avoid the photochopped version in favor of the later models. The HP3403C goes out to 100 MHz, has higher accuracy, and features an autoranging digital display. However, it is also more difficult to find and repair and more expensive than other models.

Dozens of other instruments are also useful and practical. Tektronix plug-in spectrum analyzers make sense once you commit to a scope mainframe. Types 1L5, 1L10, and 1L20 cover a wide frequency range but are more difficult to use than are modern instruments. Distortion analyzers are also useful. For example, the HP334A offers a distortion floor of about 0.01%, and the considerably more expensive HP339A goes down to about 0.002% and has a built-in low-distortion oscillator. Both models are "autonulling" types, which saves much knob twiddling. Some labs require frequency counters; the small HP5300 series are a good general-purpose unit. The old 5245L is larger but can be versatile if you incorporate the device's extensive line of plug-ins.

You may occasionally need a chart recorder, such as the HP7000A (XY) and HP680 (strip) models. The 7000A has well-designed input amplifiers and sweep capabilities. Other instruments finding occasional use are variable voltage references and picoammeters. The Fluke 332 variable voltage reference is huge, but there is no substitute when you need it. Keithley picoammeters, such as the Model 610, are relatively difficult to find but read into the femtoampere range. Precision and nonprecision "diddle boxes" for resistance and capacitance are also useful. General Radio and ESI built excellent precision types (for example, General Radio's 1400 Series), but many are worn out: Look inside before you buy. Nonprecision types from EICO and Heathkit are widely available and cost little. The 722D and the later 1422D precision variable air capacitors from General Radio suit transducer simulation.

You'll need oscilloscope cameras to document displays. Modern data-recording techniques are relegating scope cameras to almost antique status, which has fortunately reduced prices. My work involves much waveform documentation, so I have specialized camera equipment. The Tektronix C-30 is a good general-purpose camera that fits, via adapters, a variety of oscilloscopes. It is probably the best choice for occasional work. The larger Tektronix C27 and C12 for plug-in scopes offer ease of use. However, I do not recommend them unless you do a lot of photographic documentation or require repeatable results.

Finally, you must have cables, connectors, and adapters. You need a variety of BNC connectors; banana jacks; and other terminator, connector, adapter, and cable hardware. This stuff is not cheap—in fact, it is outrageously expensive, but you have no choice. You can't work without it.

No discussion of a home laboratory is complete without comments on its location. You will spend many hours in this lab; it should be as comfortable and pleasant as possible. Consider the use of space, lighting, and furnishings. My lab is in a large, bright, and colorful room on the second floor, overlooking a quiet park. Some of my favorite pictures and art hang on the walls, and I keep the place clean. In short, I do what I can to promote an environment conducive to working.

Over the last 20 years, I have found a home lab the best career friend. It provides a time-efficiency advantage, and it ensures that my vocation and hobby remain happily mixed. At 45, I view engineering as good a career choice as I did when I was 8 years old. To get that from a room full of old equipment has got to be the world's best bargain. EDN

Author's biography

Jim Williams, staff scientist at Linear Technology Corp, Milpitas, CA, specializes in analog-circuit and instrumentation design. He has served in similar capacities at National Semiconductor, Arthur D Little, and the Instrumentation Lab at the Massachusetts Institute of Technology. A former student at Wayne State University, Detroit, Williams enjoys art, collecting antique scientific instruments, and restoring old Tektronix oscilloscopes.