# Tripping the light fantastic: a case study in circuit design

**Jim Williams, Linear Technology Corp** - March 16, 1995

Where do good circuits come from? Do they arrive as lightning bolts in the minds of a privileged few? Are they products of synthesis or derivation based on careful analysis-or do they simply evolve? Where do skill, experience, and luck fit into the equation? I cannot answer all of these weighty questions, but I can recount how the best circuit I ever designed came to be.

Deciding what makes a good circuit is a fairly difficult task, but I can suggest a few guidelines. Its appearance should be fundamentally simple, although it may embody complex and powerful theoretical elements and interactions. For me, that combination is the essence of elegance. The circuit should also find wide use. An important measure of a circuit's value is if lots of people use it and are satisfied with their decision afterward. Finally, the circuit should also generate substantial revenue. My employer is faithful about paying me, so I should hold up my end of the bargain, too. Those are a few general guidelines. Now for the circuit story.

### The postpartum blues

Toward the end of 1991, I was in a rut. In August, I finished a large high-speed-amplifier project, which had required a year of constant, intense, and sometimes ferocious effort, right up to its conclusion. Then it was over. I suddenly had nothing to do. The strange feeling of being abruptly disconnected from an absorbing task had hit me before, and the result was always the same. I go into this funky kind of rut, and I wonder if I'll ever find anything else interesting to do. I also begin to question if I'm even capable of doing anything anymore.

I've known myself 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 a bit, 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 take care of the stuff I completely let go while I was immersed in whatever problem owned me. The treatment always seems to work; it usually takes a period of months. In this case it took exactly three.

### What's a backlight?

At Christmas time, 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 LCDs require an illumination source to make the display readable, and that this source consumes about half the power in the machine. In addition, 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 could devise a better way-and then market it.

The idea 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 housekeeping chores, and basically maintain my funk.

**Figure 1** This doodle, circa 1989, was instrumental in getting the collaboration on the backlight project started with Apple Computer.

Three days later, the phone rang. A guy named Steve Young from Apple Computer had seen a cartoon (**Fig 1**) I'd stuck on the back page of an application note back in 1989. Steve outlined several classes of switching-power-supply problems he was interested in. His application was portable computers, and a more efficient backlight circuit was a priority. Bob Dobkin's interest in backlights suddenly sounded a lot less academic.

The guy on the phone 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 invest a lot of front-end thinking and time to achieve it. It was clear Young wasn't interested in a quick fix; he wanted true, "end-to-end," system-oriented solutions.

What a customer! He knew what he wanted, was open and eager to work, had time and money, and was willing to sweat to find better solutions. On top of all that, Apple had excellent engineering resources. I set up a meeting to introduce him to Dobkin.

The meeting went well. I took the backlight problem. I still wasn't enthralled with backlights, but Young was an almost ideal customer, so I really had no choice.

Steve Young introduced me to Paul Donovan, my primary 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 susceptible to supply-voltage changes. RF emissions should meet FCC and system requirements. Finally, parts count and board space should be minimal. The board-height limit was 0.25 in.

**Learning, Luddite-style**

**Figure 2** This configuration is most popular for driving backlights in portable computers. The circuit incorporates no feedback from the lamp.

I began 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. I immediately noticed that almost all of them used a purchased, board-level solution to backlight driving. Almost no computer maker 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 (**Fig 2**). The ac high-voltage output often ran at about 50 kHz and was approximately sinusodial.

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 light emission from the lamp. 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.

**Figure 3** A hi-fi amplifier helped to prove that lamp efficiency is relatively independent of drive frequency, but wiring parasitics can lead to losses at high frequencies.

Was there something magic about the 50-kHz frequency? To see, I built up a variable-frequency, high-voltage generator (**Fig 3**) and drove the displays. I varied frequency while comparing electrical drive power to optical emission. Lamp conversion efficiency seemed independent of frequency over a fairly wide range. I did notice, however, that higher frequencies tended to introduce losses in the wiring running to the lamp. These losses occurred at all frequencies but became pronounced above approximately 100 kHz 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 to minimize the wire length between the inverter board and display. 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 the mechanical-integrity viewpoint, but that wasn't relevant. I wondered why these computers hadn't been originally designed to take advantage of this "free" efficiency gain.

### Playing with light bulbs

I removed lamps from the displays; 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 the fact that I found identical backlight boards in different computers driving different types of lamps. It appeared that no board changes were made to accommodate various lamps. I then turned my attention to the lamps.

The lamps seemed to be pretty complex, 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 fairly narrow range of intensity control. Most striking was the fact 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 move increased steady-state thermal losses, allowing the lamp to run in its optimum temperature range. I also saw screen-illumination shifts arising from 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, I noted a distinct tradeoff between benefits from the foil's optical reflection and its absorption of high-voltage field energy. Removing the foil reduced 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 nonoriginal 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 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. In turn, display manufacturers just dropped these lamps into displays and shipped 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, 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 endeavor was getting interesting, I saw it as my way out of a rut. Business-school types call this a "synergistiwin-win" situation. Other people who "do lunch" on company money might call it "strategic partnering." My grandfather would have called it "such a deal."

Goals for the backlight began to emerge. For best overall efficiency, it was necessary to simultaneously consider the display enclosure, optical design, lamp, and electronics. My job involved 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.

Obviously, the electronics should 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 those that occur when the computer's ac adapter is plugged in.

Where, I wondered, had I seen circuitry that contained any or all of these characteristics? Nowhere. But, one area to start looking was oscilloscope design. 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. Handling the conversion locally at the CRT eliminates long high-voltage runs from the main power supply.

I examined the schematic of the high-voltage converter in a Tektronix 547 (**Fig 4**). The manual explains that capacitor C and the 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 the scope circuit, in which the CRT is a relatively linear and benign load. It would be necessary to evaluate the backlight's loading characteristics and match them to the circuit.

**Figure 4** The perhaps-unfamiliar symbols in this diagram for the high-voltage section in the Tektronix 547 oscilloscope are vacuum tubes. The capacitor and primary inductance form a resonant tank circuit.

This CRT circuit could not be used to drive a fluorescent backlight tube in a laptop computer. For one reason, this circuit isn't very efficient. It doesn't need to be. A 547 pulls over 500W, so efficiency in this circuit wasn't a big priority. Latter versions of this configuration used transistors (**Fig 5**, Tektronix 453) but basically had the same architecture. Both circuits use the resonating technique and a feedback loop to enforce voltage regulation. For another reason, the CRT requires rectifying the high voltage 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.

**Figure 5** Except for the vacuum-tube diodes in the secondary, this high-voltage circuit is the solid-state version of the circuit in **Fig 4**.

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. So I needed to figure out how to 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 1954, "Transistors as On-Off Switches in Saturable-Core Circuits" (Ref 3) appeared in Electrical Manufacturing magazine. George Royer, one of the authors, described a "dc-to-ac 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 the paper. The Royer converter was widely adopted and used in designs from watts to kilowatts; it is still the basis for a variety of power-conversion systems.

**Figure 6** Transformer saturation produces the switching in this circuit from Ref 3. The transistors conduct out of phase, switching each time the transformer saturates.

Royer's circuit is not an LC resonant type. The transformer is the sole energy-storage element, and the output is a square wave. **Fig 6** is a conceptual schematic of a typical converter. The input connects to a self-oscillating configuration comprising transistors, a transformer, and a biasing network. The transistors conduct out of phase, switching each time the transformer saturates. In **Fig 7**, Traces A and C are $Q_1$'s collector and base waveforms; Traces B and D are $Q_2$'s collector and base waveforms. Transformer saturation causes a rapidly rising, high current to flow (Trace E).

This current spike, picked up by the base-drive winding, switches the transistors. 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 photo in **Fig 8** is a time and amplitude expansion of Traces B and E of **Fig 7**. It clearly shows the relationship between transformer current (Trace B) and transistor collector voltage (Trace A).

**Figure 7** (left) The first and third and second and fourth traces are the collector and base waveforms, respectively, for the Royer circuit in Fig 6. The base-drive winding delivers the current spike in Trace E to the switching transistors.

**Figure 8** (right) This expanded display shows the relationship between transformer current (Trace B) and transistor collector voltage (Trace A) in the Royer circuit.

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

**Figure 9** The op amp and transistor provide a means to control the output power of the modified Royer circuit in Fig 9. The transistor current sink operates in the linear region and thus wastes power.

Adding a capacitor to the primary drive (Fig 9) should have the same resonating effect that exists in the Tektronix CRT circuits. The beauty of this configuration is its utter simplicity and high efficiency. As the loading (viz, lamp intensity) varies, the reflected secondary impedance changes, causing some frequency shift, but efficiency remains high.

You can control the Royer's output power by varying the primary drive current. Fig 10 shows a way to investigate this relationship. This circuit works well, except that the transistor current sink operates in its linear region, wasting power. Fig 11 converts the current sink to switch-mode operation, which yields high efficiency. Obviously, this enhanced efficiency is an advantage for the user; but it's also a good deal for my employer.

**Figure 10** Adding a capacitor to the primary drive in the Royer circuit produces the same LC-tank resonance as exists in the Tektronix high-voltage circuits.

**Figure 11** The switch-mode regulator eliminates the power waste inherent in the linear regulator of **Fig 10**.

I had spent the previous six months playing with light bulbs, reminiscing over old oscilloscope circuits, taking arcane thermal measurements, and pursuing similar dalliances-all the while collecting a paycheck. Finally, I had found an application where I could actually sell something my company manufactured. Linear Technology 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, the LT1172 is available in an eight-pin, surface-mount package, a must for board-space considerations. It was also an ideal candidate for the circuit's current-sink portion.

In the design effort, I gained insight not only from the Tektronix scope manuals and the Royer circuit in Ref 3, but also from every document in the long list of references at the end of this article.

### Dive right in

At about this stage, I sat back and stared at the wall. At some point in every project, you have to gamble. It's time to halt the analytics and theorizing and commit to an approach-and start actually doing something. This realization is often painful, because you never really have enough information and preparation to be confidently decisive. Answers are rare, and choices abound. But, at some point, your gut tells you to put down the pencil and pick up the soldering iron. Physicist Richard Feynman once said "If you're not confused when you start, you're not doing it right." And I think it was an artist who said "Inspiration comes while working." They were both right. It was now obvious to me that you cannot wait for your perfect circuit to design itself.

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!

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### Author's biography

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