I recall excitedly listening to one of my early tech mentors explain the concept of analog computing: “You can easily use op amps to sum and scale any signals, do calculus, or any math you can think of.” As a physics student I was instantly intrigued at the idea of representing various quantities as voltages and currents. “So I can use simple circuits to, say, take the inverse-square of a signal?” He replied with his usual drawn out, disappointment inducing “Well ...”

The truth is that precision analog multiplication of signals in all four quadrants (meaning both inputs can be either positive or negative and the sign of the result of the multiplication will be correct) is by no means trivial. Dissatisfied with existing circuits, it quickly became one of my go-to, pencil-t-paper design challenges whilst sitting at a diner or on the train: multiply two signals together and do it cleanly. That means from DC to as high a frequency as possible. The whole audio band is the bare minimum.

I’ve come up with a dozen or so schemes and implemented many of them in various projects over the years, but few came close to rivaling key performance aspects of commercially available analog multipliers (pride and the limitations of a student’s budget are the mother of invention).

I finally arrived upon the circuit depicted below, and it has suited my purposes quite well in all contexts in which I’ve applied it. It is a simple, modern take on a very old and very slick idea: balanced ring modulation.

The circuit has three stages: A mode converter/isolator, the diode ring, and the output decoder. Two inputs, whose signals get converted to common and differential mode respectively, are used to bias a ring of matched Schottky diodes. The output is decoded with a differential virtual ground. The diode ring acts to shuttle the input signals to either or both virtual grounds to achieve positive, negative, or zero “gain.”

A bandwidth of a few MHz is easily attainable, dependent on components, but the real trick is to maintain good isolation at higher frequency. It’s fairly economical to buy 0.1% resistors and bin out another decade. For diodes, I use a pair of the wonderful BAT54S, each of which contain a very well matched pair, simplifying things a fair bit. In practice, getting all the way to 80dB of isolation is virtually impossible without trimming, due to amplifier offset voltage. I’ve had great results with TSV914, LMV344, and particularly TSV714.

Start with a circuit we all know and love:
And consider concocting a differential equivalent:

The A amp’s output sees an inverting unity gain amp. This is a nice setup, because I can put any number of diodes into either virtual ground and build any arbitrary superposition of exponentials. I smell a multiplier.

Connecting the two inputs together with one diode reversed yields a hyperbola, or indeed, any superposition of hyperbolas:

For small signals, the hyperbolic characteristic is indistinguishable from a parabola or square-law relationship. This is because all constant and odd terms of the Taylor series expansion disappear,
leaving the first term a quadratic with respect to input voltage.

From arbitrary superpositions of squares to a multiplier is fairly easy. The first one I stumbled upon is this:

\[(a+b)^2 - (a-b)^2 = 4ab\]

Aesthetically pleasing drawing, but I had a hard time fitting it on a quad op amp.

Here’s another:

\[(a+b)^2 - (a-b)^2 = 4ab\]

A little better. The “sum of squarers” part is already done with a circuit depicted above. All I need to do is feed a signal into the common mode of the inputs, and another signal into the differential mode of the inputs and it spits out the product like magic.

So the entirety of the remaining design challenge is to build some sort of device like this:
I bet someone can come up with a slicker version but here's mine:

I use this circuit to balance and unbalance all kinds of things. It will even convert common and differential mode signals back to single ended.
The circuit mock-up was done on one of my early op amp breakout boards (blue) that I still had tons of kicking around.

The through hole resistor wiring kinda reminds me of the Marine Corps War memorial for some reason.
She worked like a charm, so I moved on to a PCB prototype shown below.

A multiplier in situ
The following is a real picture from my bench. That image is from the through-hole proto.

This fast, square-ish wave is multiplied by a slower triangle wave.

You can see this multiplier in action in a musical context on YouTube:
If anyone is walking around with a better/more economical multiplier idea in their back pocket, I’d love to hear all about it. Multiply and conquer!

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