The Father of Analog Integrated Circuits: Robert J. Widlar

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At a time when even discrete solid-state op-amps had not yet succeeded in displacing their vacuum tube counterparts, and the very value of the integrated circuit idea was still a legitimate topic of debate, Bob Widlar ("wide-lar") almost single-handedly established the discipline of analog IC design. After receiving his bachelor's degree in 1962 from the University of Colorado at Boulder, he took a job with Ball Brothers Research, where his virtuosity at circuit design attracted the attention of engineers at one of their components suppliers. Despite the breach in protocol inherent in aggressively recruiting a customer's key employee, Fairchild induced Widlar to leave Ball in late 1963. In an amazing debut, abetted by Dave Talbert's brilliant process engineering, Widlar was able to put the world's first integrated circuit op-amp into production by 1964. Development of the µA702, as Fairchild called it, proceeded despite a general lack of enthusiasm for the project at the company.

The Fairchild µA702

Like the K2-W, this op-amp consists of two primary voltage gain stages (Figure 2). As in most differential designs, there is the problem of how to convert to a single-ended output without sacrificing half of the gain (the K2-W simply makes that sacrifice). Here the young Widlar solves this problem with a circuit that presages his later use of current-mirror loads. To the extent that Q3 and R3 behave as a high-gain amplifier (an "op-amp within the op-amp," if you will), the voltage at the base of Q3 moves much less than that at the collector. As an idealization, assume that the base voltage of Q3 simply doesn't move at all.

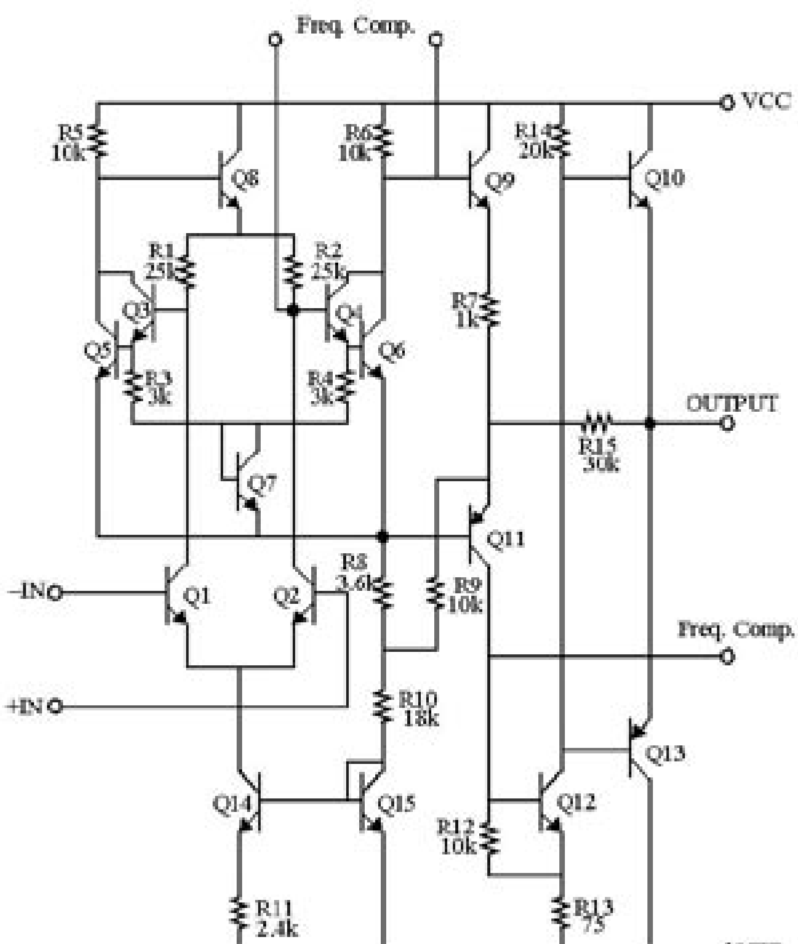

Figure 2: µA702A

If an applied signal increases the collector current of Q1 by some amount, the drop across R1 then also increases. Since the base voltage of Q3 doesn't move much, the increased voltage drop across R1 shows up as an increased voltage at the top of R1. Now, differential symmetry says that an increase in Q1's collector current is accompanied by an identical decrease in Q2's collector current. The voltage drop across R2 consequently diminishes, supplementing the effect of the increased voltage at the top of R1. Hence, both halves of the differential pair contribute an increase in the signal that ultimately drives Q4, so that the differential-to-single ended conversion takes place (ideally) with no loss in gain.

The second gain stage is a textbook common-emitter stage.

As with the K2-W, the all-NPN 709 presents a level shift challenge; each successive gain stage tends to drive swings ever closer to the positive voltage rail. Widlar solves this problem with a resistor (R5) in series with a current source (Q9), rather than a neon-bulb network, to implement the downward-level shifting "battery." Widlar being Widlar, however, the level shifter is not quite a simple as that: the battery voltage is not constant.

A second emitter follower (Q6) provides reasonable output drive capability. The loop it forms with R6/R10/R11 and Q9 is a positive feedback loop (an homage to the K2-W). Thanks to the voltage gain boost provided by the positive feedback, typical gain exceeds 3,000.

Later versions of the op-amp provide access to the emitter of Q5 (as shown in the figure), allowing the user to shunt R5 with a small capacitance. This connection counteracts the effect of any capacitance present at the bottom end of R5, boosting stable closed-loop bandwidths to as high as 30MHz. This remarkable achievement would not be matched by IC op-amps for another decade.

The μA709 (1965)
Despite its innovations, the 702 was not a commercial success. Its initial price of approximately $150-$300 limited potential sales to military and aerospace customers. The relatively low gain and limited output drive capability, the somewhat peculiar power supply voltages (e.g., +12V/-6V), and the uncomfortably small input common-mode range (forced in part by the grounding of the emitters of Q3 and Q4), further constrained the part's appeal.

Widlar responded by developing the first analog IC that was a certified "smash hit." The 709 op-amp's generous open-loop gain (~ 60,000), respectable bandwidths (~1MHz) and an input common-mode range that accommodates positive voltages, made it a credible competitor to the K2-W in many applications (Figure 3). It was also the first IC op-amp to use the +/-15V supply voltages that had recently emerged as a standard for many discrete solid-state op-amps (e.g., the GAP/R P65).

The 709 clearly shares a great deal with its progenitor, the 702, while going well beyond it. The resistively-loaded differential input stage (Q1/Q2, biased by current source Q14 which, in turn, is slaved to Q15), performs a differential-to-single ended conversion with a slightly more sophisticated implementation of the same idea used in the 702 (here, Darlington-connected Q3/Q5 and emitter follower Q8 together comprise the "op-amp within the op-amp"). Transistors Q3 and Q4 are biased to a low current without the use of large-value area-consumptive resistors by making the voltage across current-setting resistor R3 depend on the small difference between two diode voltages (those of Q5 and Q7). This same trick synthesizes a low current in Q14 without requiring absurdly large resistor values. This clever circuit (known, sensibly enough, as a Widlar current source) is an early expression of a Widlar IC-design rule: "Replace passives by transistors wherever and whenever possible". This philosophy remains an important guiding principle of analog IC design.

The second gain stage is a resistively-loaded common-emitter amplifier using Darlington pair Q4/Q6. Emitter follower Q9 participates in a downward level shift, in conjunction with common-base lateral PNP transistor

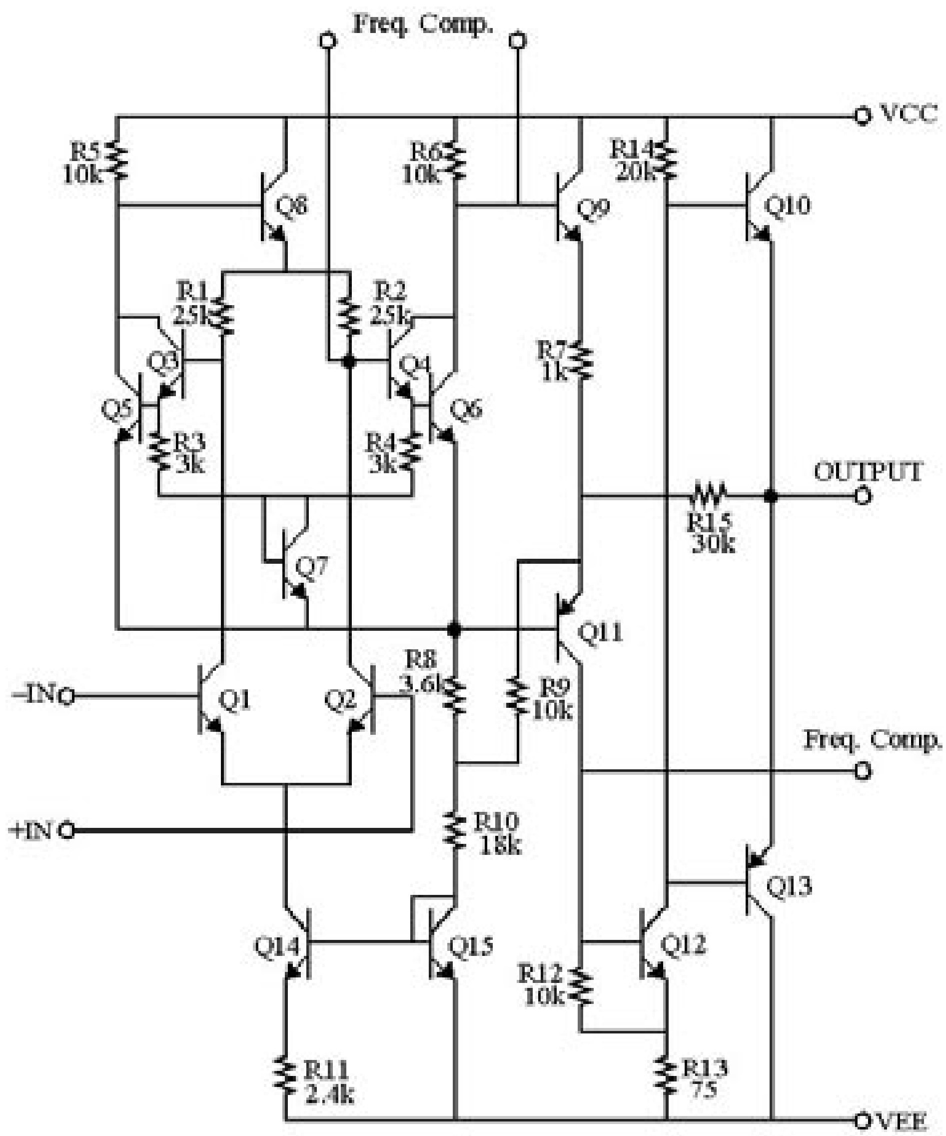

Figure 3: μA709

Q11. The 709 is the first commercial product in which a lateral PNP transistor makes an appearance (an IC for the Minuteman II missile had used one a bit earlier). Widlar's design accommodates the dreadful characteristics of these early devices (made out of re-purposed NPN parts), which include a β that is nominally two. Widlar's design allegedly continues to function (if one parses the word function generously) even if β is as small as 0.2.

To achieve the high open-loop gains demanded by users of op-amps, this design has a third gain stage, with Q12 in a resistively-loaded common-emitter amplifier. The presence of a third stage complicates using the 709, however, owing to the challenges of stabilizing a feedback amplifier that contains three cascaded stages. Widlar consequently makes externally accessible every high-impedance node in the op-amp to allow the user great flexibility in connecting a host of RC networks (many of them suggested by Fairchild in the 709's data sheet and applications notes) to achieve satisfactory stability, bandwidth and settling time. Sometimes, the user even succeeded.

The output of the third gain stage drives a textbook complementary emitter follower. The PNP transistor Q13 can be (and is) implemented as a vertical PNP device, whose characteristics are better matched to those of an

NPN than is a lateral PNP. A simple complementary buffer unfortunately possesses a well-known "dead zone" in its input-output transfer characteristic; there is roughly a 1.4V range of input voltages over which neither transistor conducts. Widlar employs local negative feedback around the output stage (through R15) in an effort to reduce the resulting distortion.

Fairchild's applications notes make a game (and unintentionally amusing) attempt at moderating a user's fears about the output driver's robustness:

Although it is not clear from the schematic, the output stage is actually short-circuit-proof for a short period of time [10].

Murphy guarantees that your short circuits will always persist just a little longer than that unspecified "short period of time."

The spectacular success of the 709 quickly drove prices down as it drove production volumes up (despite yields that were simply terrible for a long time; Dave Fullagar assumed the task of solving the yield problem). This op-amp, introduced in November of 1965 at approximately $70 ($50 in large quantities), was the first to break through the $10 barrier (and then the $5 barrier by 1967), guaranteeing extremely widespread use. By 1969, op-amps were selling for around $2. Unable to compete against exponential price reductions, the K2-W was retired in 1971, its twentieth year of continuous production.

Widlar didn't just work on op-amps at Fairchild, he also designed a popular pair of comparators (the 710 and the 711), whose 40ns response time represents an order-of-magnitude improvement over the speeds achieved by contemporary general-purpose op-amps reluctantly impressed into service as comparators.

Widlar's last design for Fairchild, the μA726, rolled out in 1965. The high-precision differential pair's on-chip temperature-controlled heater enables offset drifts of 0.2μV/°C over the entire military temperature range. In two years, Widlar had put five ICs into production and firmly established analog IC design as a legitimate (and profitable) discipline.

He was just warming up.

Analog epilogue: A bit more about Widlar

Widlar essentially created the analog IC business, and so perhaps it is appropriate to say a little more about him in this sidebar.

The individualism evident in his circuit designs reflects his independent, idiosyncratic personality. While still at Fairchild, he acquired a reputation as a hard-working, hard-drinking prankster. By the time he'd joined National Semiconductor, his antics were well on their way to becoming legendary, as is evident from a sidebar accompanying an August 1968 article by him in EEE ("Bob Widlar of National Semiconductor speaks out on what makes a good IC").

He was famous for total immersion when working on a design. He could work nonstop into a state of such exhaustion that he found relief by driving his beloved '66 Mercedes 280SL convertible to the airport and purchasing a ticket for "the next flight out."

The mere fact of his having a gun collection might have made some of his colleagues a bit nervous; knowing that he used, for target practice, beer cans with the names of those not in his esteem probably unnerved the rest.

The reporter who interviewed him noted that Widlar's apartment was stocked only with scotch, beer and glasses. "His refrigerator is bare if you don't count the ice cubes." This comment only hinted at the magnitude of Widlar's ability to imbibe.

When National, along with the rest of the electronics industry, suffered during a recession a couple of years later, the groundskeeping staff was eliminated as part of a corporate cost-cutting plan. Widlar didn't like the unkempt look of the facilities as the weeds grew. His response was to drive with Bob Dobkin to someplace south of San Jose and purchase a sheep (some say it was a goat, but look at the photo in Figure 17 and decide for yourself). Upon returning to National, "someone" called a reporter at the San Jose Mercury News, and a photographer appeared soon after to document National's new lawn-mowing technology in action.

The groundskeeping staff was rehired soon afterwards.

Later that day, Widlar took the sheep with him to Marchetti's, a popular National watering hole in those days. He left it with the bartender. History does not record what the bartender did with the sheep.

Only a few years after joining National, Widlar's stock options had appreciated sufficiently (thanks in large part to his designs) that he "retired" from National Semiconductor at about 10:30 PST, 21 December 1970. Not long after, he drove his Mercedes down to Puerto Vallarta, Mexico, where he lived the rest of his life. He had celebrated his 33rd birthday just the month before.

After a brief period of time in which he worked with a fledgling Linear Technology (co-founded by Bob Dobkin of the sheep adventure), he returned to designing for National Semiconductor on a contract basis. During this time he designed an op-amp (the LM10) that delivered 741-like specifications while operating off of a single 1.2V supply. If that weren't impressive enough, he included a bandgap voltage reference (the reader will note that the nominal supply voltage does not exceed a bandgap voltage). He followed that achievement with the LM11, a bipolar op-amp with 25pA input bias current. His next design represented a leap from one power extreme to the other: The LM12 is an operational amplifier capable of 10-ampere output currents and 80W continuous dissipation (800W peak). Its integral protection is so comprehensive that considerable effort is required to destroy it.

After a life of extreme habits, he eventually adopted a healthier lifestyle, and began jogging regularly. On one of these jogs in early 1991, he suffered a fatal heart attack near his home in Puerto Vallarta. He was only 53 years old.