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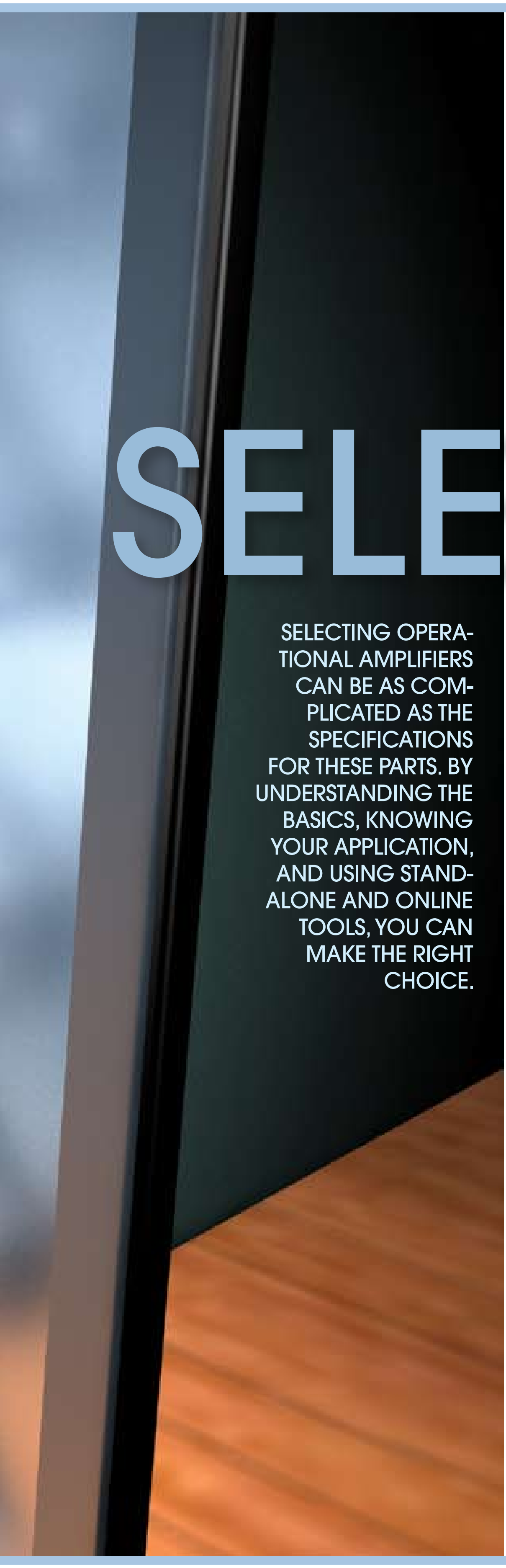


SELECTING OP AMPS

SELECTING OPERATIONAL AMPLIFIERS CAN BE AS COMPLICATED AS THE SPECIFICATIONS FOR THESE PARTS. BY UNDERSTANDING THE BASICS, KNOWING YOUR APPLICATION, AND USING STANDALONE AND ONLINE TOOLS, YOU CAN MAKE THE RIGHT CHOICE.

BY PAUL RAKO • TECHNICAL EDITOR

You would think that selecting operational amplifiers would be easy. After all, they have only three important pins: two inputs and one output. In designing a typical op amp, however, you must also consider the two power pins, and this total of five pins has a bewildering array of specifications. Given that fact, amplifier design and selection can be among the most daunting tasks that analog-system engineers face.

In selecting an amplifier, you must determine the maximum and minimum voltage for the part's operation, its quiescent current, the current the op amp must deliver to the load, and any other current it uses. You might, for example, set up the two power pins for bipolar operation on split supplies or for single-ended operation by hooking the negative power pin to ground (**Figure 1**). Although you can connect any amplifier in a bipolar or single-ended circuit, other factors often make the part suitable for single-ended operation. In addition, the input pins almost always include ground in their input range or provide for rail-to-rail inputs, in which the input pins can operate at either extreme of the power-supply voltage. Further complicating the design is the fact that op-amp data sheets typically express specifications for single-ended operation, despite the possibility that a test engineer could change the part's operating conditions and restate the specs to reflect bipolar operation.

The output current is a key spec. Rail-to-rail-output parts provide usable drive current even when the output pin is less than 0.6V from either power-supply rail. Parts that use FET outputs can swing closer to the rails than parts with bipolar outputs. For example, the Intersil 30-mA EL5020 can swing to within 15 mV of either rail at 5 mA. To ensure accurate, low-distortion performance, you must also understand output-pin impedance, which varies with frequency. In addition, the output pin must drive some level of capacitive loads. Some parts, such as Na-

AT A GLANCE

- All five pins of an amplifier have important specs.
- The application often drives the selection process.
- Understand the data-sheet sections to better choose parts.
- The semiconductor process affects amplifier specifications.
- Online tools and selector guides can help you find the right part.
- Consider using specialty amplifiers.

tional Semiconductor's LM8272, drive unlimited capacitive loads, whereas typical video amplifiers oscillate with just tens of picofarads of load capacitance.

Dave Kress, director of applications engineering for Analog Devices, sees five important elements in amplifier selection (**Figure 2**): bandwidth, power supply, the requirement for multiple parts in a package, application, and cost. On the other hand, Tim Green, linear-applications manager at Texas Instruments' Burr-Brown division, narrows down the criteria to three: voltage, current, and bandwidth.

However, Paul Grohe, an applications engineer at National Semiconductor, thinks more about the inside of the amp. "Bias current and bandwidth—the two Bs—are what matters," he says. "A fast part will use more current, and a low-noise part will use more current. And, if you have a high source impedance, the input-bias current is the most important spec."

Bob Pease, staff scientist at National Semiconductor, in a jab at the company's competitors, notes that the spec doesn't matter if the supplier can't deliver the parts on time. He also says that noise is an often-overlooked, yet critically vital parameter. "There are no easy answers; you have to use your judgment," he says. "In every application, there are one or two key parameters, and you have to figure out what they are. You can't have everything."

Tim Regan, application manager for Linear Technology's signal-conditioning unit, uses the acronym SNAP (supply voltage and current/need for ac or dc performance/amplifier count/packaging) to help engineers remember the important trade-offs. Patrick Long, business-marketing manager for op amps and comparators at Maxim, also mentions packaging as an important criterion. If the part targets cell phones, for example, you would want to use a flip-chip or solder-bump package. These ultrasmall packages provide high performance analog functions with a board area the size of a silicon die.

One way to understand the scope of selecting an op amp is to look at the structure of the data sheet. The first page is a valuable tool that reveals key features and the intended application. By ignoring marketing adjectives, such as "slow" and "fast," and looking for the actual speed figure, you can quickly see whether the amplifier is in the right ballpark for your application. The first page may describe the process that the manufacturer used to make the op amp (see **sidebar** "Op-amp processes").

A section on absolute-maximum ratings typically follows the first page in an op-amp data sheet. This section always covers the highest voltage and temperature that you can subject the part to. It should be obvious from the prominence of this section that these parameters are critical in your selection because they are absolute-maximum values. The part cannot exceed these limits for a nanosecond.

Data sheets also include tables on dc and ac performance and on operating voltage. The tables clearly state the operating voltage that the part was running on when the designers created the tables. The first page may claim that the part works at voltages as low as 2.7V, yet the tables may show that the part can run at 3V. Although it may be acceptable to run a 3V part at 2.7V, you cannot use the specification in the 3V-data-sheet table. Either you have to ask the manufacturer to characterize the part at the lower voltages, or you have to do it yourself. The values in the tables are contractual obligations that the manufacturer must meet.

Pages of charts follow the tables in the data sheet. Although these charts do not represent a legal obligation, they are important. For example, the tables may claim a huge PSRR (power-supply-rejection ratio), whereas the charts show that this specification decreases drastically with increasing frequency. If an amplifier is operating from a 1-MHz switcher that has a 1-MHz output ripple, you must evaluate the PSRR at 1 MHz from the appropriate chart and remember that designers created the chart at a certain operating voltage that may produce more beneficial results than your circuit will produce. Similarly, the tables base voltage noise on the flat-band noise at higher frequencies. For dc or low-frequency applications, you must con-

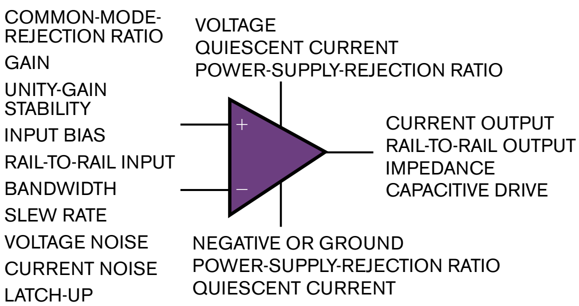


Figure 1 An op amp has only five pins, but each has a variety of specifications.

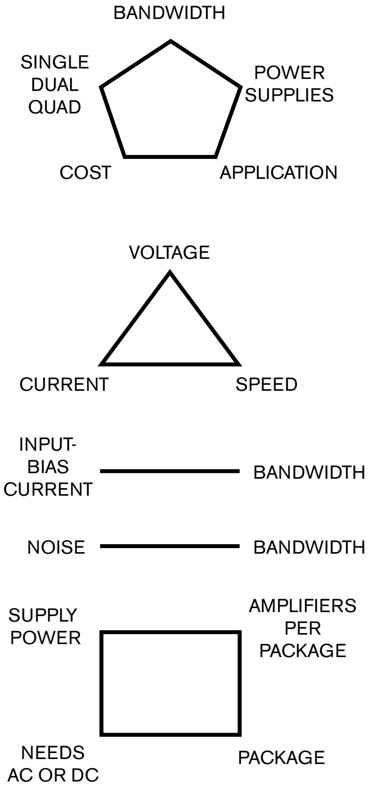
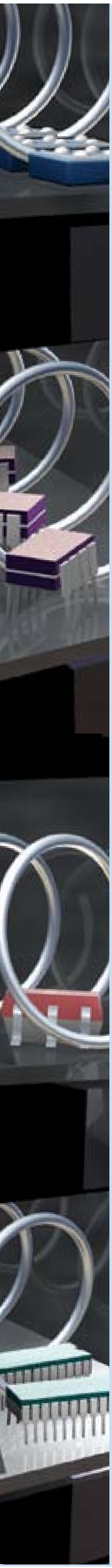


Figure 2 There are many ways to look at the trade-offs in selecting an op amp.



OP-AMP PROCESSES

Some amplifier manufacturers think that you should judge a part purely on its specifications without worrying about the process that went into its manufacture. Although this attitude has some validity, almost every IC designer and application engineer must consider the semiconductor process as well as the specs. Doing so helps them to broadly categorize their parts and to make certain assumptions about the specifications.

The original process that manufacturers used was bipolar, employing conventional transistors rather than FETs (field-effect transistors) or MOSFETs (metal-oxide-semiconductor FETs). Using bipolar processes means that the part can operate on higher voltages and is generally faster. Bipolar transistors have higher transconductance, easing design. If you use an isolated process, the design can work at much higher frequencies because the internal stray capacitance is often one-tenth that of a conventional process. This type of process often uses dielectric isolation, meaning that each transistor is in its own glass-isolated bowl. Some processes are only trench-isolated, meaning that the side of the transistors is glass-isolated but the bottom is junction-isolated as in a conventional bipolar process. The speeds for trench-isolated parts are better than those for plain bipolar but not as good as full dielectric isolation. The approach also prevents latch-up, in which the substrate forms a parasitic SCR (silicon-controlled rectifier). Because the parts do not latch up, you can exceed the common-mode range and have voltage at the inputs before you apply power to the part. Like all things analog, there is a downside to dielectric isolation, even beyond its greater cost. The glass walls around all the transistors have 10 times lower thermal conductivity than with junction isolation. As a result, designers rarely use dielectric isolation for higher output-current amplification.

The other broad category of amplifier process is CMOS (complementary metal-oxide semiconductor). CMOS parts cost less because their manufacture involves fewer process steps. CMOS parts also usually have low operating current. One of the best features of CMOS is that it requires a minuscule amount of input-bias current on the input pins. For example, Texas Instruments' CMOS OPA2355 has 0.05 nA of input bias, second only to JFET (junction-FET)-input parts. CMOS parts are usually 5V parts, although some 12V CMOS processes exist. Because early CMOS parts took advantage of the low operating currents of CMOS, the parts exhibited voltage noise–not an inherent property of CMOS but rather a design decision to use low bias currents and small transistors in the input section. For example, National Semiconductor manufactures its LMV751 in CMOS, but it has low voltage noise because its designers used large input transistors and higher quiescent current in the input-differential-transistor pair. Another process, BIMOS (bipolar MOS), includes both bipolar and CMOS transistors.

The less popular but still-useful bipolar-JFET process adds mask steps to allow the creation of JFETs. Like CMOS transistors, the JFETs have low-input-bias current. Older JFET parts, such as National Semiconductor's LF411 and Analog Devices' AD549, provided low bias current before CMOS parts became prevalent. TI offers modern JFET parts that provide low bias current but are also fast. The TI OPA656, for example, has a bandwidth of 500 MHz. JFETs also have lower input-voltage noise than CMOS transistors because diffusions in the wafer substrate bury the JFETs. In contrast, CMOS transistors sit on the surface of the die where they are subject to the lattice defects and crystal impurities that cause noise. Again, this approach involves a trade-off: Diffusion during manufacturing controls the JFET parameters. CMOS-transistor properties depend more on lithography in manufacturing. Thus, CMOS parts have better input-pair matching, lower offset voltages, and less drift.

When an application requires higher speed than bipolar parts can provide, designers can turn to SiGe (silicon-germanium) processes. The higher electron mobility in the base area, thinner base regions, and higher emitter-current density of these processes give op amps bandwidths that exceed 1 GHz. The parts use more current and have the same stability issues as all other high-speed parts. SiGe processes are seeing use in differential-input amplifiers for high-speed ADCs and high-speed communications amplifiers.

Other processes include GaAs (gallium arsenide) and SOS (silicon on sapphire). The GaAs process is blazingly fast, with even higher electron mobility and thinner base regions than SiGe. The downside is that GaAs, unlike silicon, uses no easily formed insulating oxide. Silicon oxide is glass and can isolate different layers of metallization. Without this process feature, GaAs trails the silicon process but provides parts operating at 10 GHz and higher. Prices and operating currents are higher, as well. In SOS-process technology, the dielectrically isolated transistors are fast, just as in an oxide dielectric-isolation process. Because the transistors are isolated with sapphire instead of glass, however, the thermal conductivity is that of a crystal; glass, in contrast, has low thermal conductivity. SOS parts are thus fast and provide lots of power output. Manufacturers can build them with CMOS-process flows that have fewer mask layers than bipolar processes do.

sult the charts to determine the noise in your circuit's frequencies of interest (**Figure 3**).

Examine every chart and think of what your fellow engineer who measured the data is trying to tell you. Often, your fellow engineer at a semiconductor company includes a chart that highlights a less flattering specification of an amplifier. If a chart shows that an amplifier has 90% overshoot at 10 pF of output capacitance, the part is subject to instability.

The general description and application section follows the chart section of a typical data sheet. In this section, you can learn of appropriate applications and read about any peculiarities or special features of the amplifier. The application section may warn you that the part will burn up if you overdrive the outputs. In some older parts, the application section may warn that the part exhibits phase reversal—that is, when you bring the input pin past its common-mode range, the output of the amplifier suddenly inverts, even though the inputs never cross zero.

The part number, or suffix, section of the data sheet may be toward the end, but some manufacturers, such as TI, put this information on the front page. Every package and voltage rating of the part gets its own part number. The manufacturer may also include numbers for lead-free ROHS (restriction-of-hazardous-substances) parts. Part numbers also differ for parts in a rail or in a 4000-part reel. It is exasperating to lay out a board with a different package from the one you intended because you used an incomplete part number. Errors such as these can cost weeks or months in the development cycle.

One of the last sections of the data sheet is often the packages section, which includes drawings and suggested PCB (printed-circuit-board) patterns. If your PCB has a low profile, the overall height of the package may be the critical performance specification you must meet.

ONLINE TOOLS CAN HELP

Never hesitate to call the local field-application engineer or the factory-applications group. Analog Devices and Texas Instruments sell almost every type of op amp, so they have no reason to steer you to a specific part. One exception to this rule is that manufacturers often want to promote their newest parts in the hope of recovering the costs of designing them. For this reason, National Semiconductor's Grohe likes to use selector guides. "A parametric search will return all the parts that meet your required specifications, whether the part was designed yesterday or 20 years ago," he says. Grohe developed the downloadable selector guide you can get from the company's amplifier Web page. TI, Analog Devices, STMicroelectronics, and others also provide online selector guides.

Linear Technology developed another helpful, free, fully functional, downloadable tool, LTSPICE, which Mike Engelhardt designed. He assures that the program converges, even with magnetic elements. Texas Instruments also offers the downloadable, node-limited, fully functional Tiny TI SPICE program, which provides accurate results when you use it with accurate models. Analog Devices' Web site also has a downloadable simulator and the ADIsim op-amp-evaluation tool. The program does a simple evaluation using National Instruments' LabView engine. Once you select a part, the tool switches to using National Instruments' MultiSIM full-SPICE engine if a part model is available. In addition to the SPICE tools, Analog Devices, National Semiconductor, and TI also offer Web tools to help design instrumentation amps or to properly bias a single-ended amplifier, as well as for scores of other applications.

For designing filter chains, TI offers its FilterPro software. This downloadable software performs the math calculations to show you the response of multipole filters. National Semiconductor offers its Webench online environment for designing filters. It runs SPICE simulations online to show you the response of the part.

Selecting op amps can be daunting. In addition to conventional voltage-feedback amplifiers, many specialty amplifiers exist (see **sidebar** "Specialty op amps," pg 48). You may need to read relevant trade magazines and books before you understand all the subtleties of amplifier selection. Application engineers can be a great help in getting you to understand the right specifications and amplifier types at which you should be looking. Once you know those facts, you can use the variety of downloadable selector guides and online guides. You can then simulate your circuit online or through the downloadable tools, as well as use the vendor-supplied SPICE models to simulate you circuit in Orcad, Altium, PADS, or Electronics Workbench. **EDN**

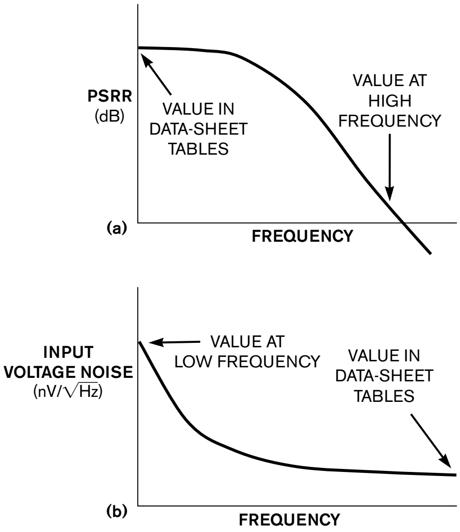


Figure 3 Data-sheet tables often overstate performance. The data-sheet tables list PSRR at dc, at which it is rarely an issue. The data-sheet chart shows where PSRR falls off drastically at high frequencies (a). Similarly, the tables list the input-voltage noise at higher frequencies where the noise is in the flat band (b).

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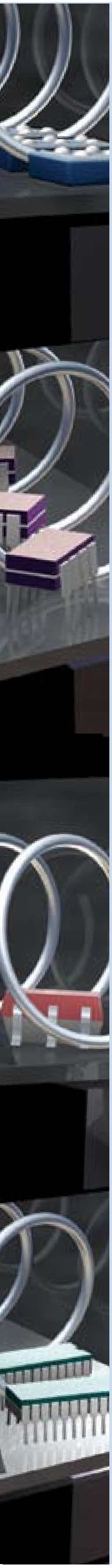

SPECIALTY OP AMPS

Designers often predicate their selection criteria for operational amplifiers on the use of a mainstream amplifier. Several specialty types of amplifiers are available. The most common are current-feedback amplifiers, which find use in video and DSL (digital-subscriber-line) applications requiring high slew rates (Figure A). Another unique benefit is that higher gains do not reduce the bandwidth. An amplifier that can provide the same gain to the higher bandwidth components of a signal has less distortion than one that does not. Current-feedback amps thus suit use in applications requiring high speed and low distortion.

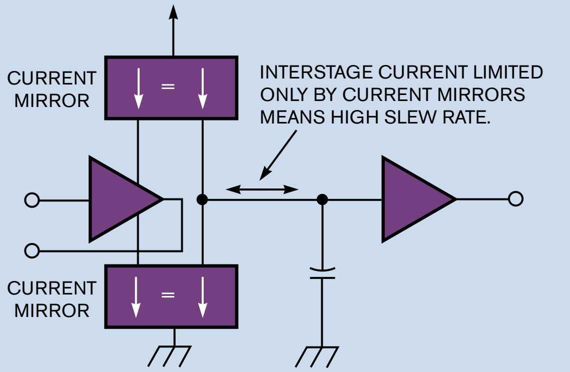

Figure A Current-feedback amplifiers find use in applications requiring high slew rates. The "tail" current of an input-differential pair does not limit the slew rate.

Another specialty amp, the compound amplifier, may use discrete transistors or have multiple amplifier stages inside–that is, several amps for one signal rather than multiple-part packages. For example, the Cirrus Logic CS3001 family has an open-loop gain of 1 trillion, or 300 dB–a sure sign that more than one amplifier is in the signal chain. The phase response indicates that this part is a compound amplifier, suitable for instrumentation. Huge gain means low distortion.

Another form of compound amplifier is the chopper, or autonulling, amplifier. These amps, also called autozero amplifiers, have a second amplifier that is constantly correcting the offset voltage. This feature suits the parts for dc-instrumentation uses, especially because the offset correction also removes low-frequency noise. The disadvantages are that these parts are slow, and their chopping frequency, typically in the 100- to 35,000-Hz range, bleeds into the outputs. This frequency is far beyond the intended frequency of interest, and subsequent circuit stages filter it out. One notable exception is National Semiconductor's LMP2011, which has the microvolt offsets associated with chopper amps yet also has a 3-MHz bandwidth. This device also provides better transient response and slew rates than other chopper amps.

Differential-output amplifiers provide an audio-signal path that is immune to ground loops or to buffering differential-input ADCs. Differential-output audio amplifiers operate in the kilohertz range, and ADC buffers operate in the gigahertz range.

Instrumentation amplifiers are often compound amplifiers with three amplifiers to allow the inputs to work over a large common-mode range. When you change the voltage on the plus pin of a conventional amplifier, the output voltage tracks that input voltage, with the difference between the input pins providing output beyond that level. Instrumentation amplifiers, on the other hand, have reference pins that set the output reference to the desired voltage, which is usually ground. This feature makes them useful for measuring Wheatstone-bridge sensors, such as strain gauges, and for measuring high-side currents. The downsides are reduced speed and high cost. Instrumentation amps often target use for dc signals. Some, such as the PGA206 from Texas Instruments' Burr-Brown division, have bandwidths of 5 to 0.5 MHz, depending on gain. The parts have digitally programmable gain and use JFET (junction-field-effect-transistor)-input stages to provide low noise and high speed.

Other specialty amplifiers have fallen out of favor but are still useful to the analog gurus that know how to use them. Transimpedance amplifiers, such as National Semiconductor's LM13700, have variable gain. They multiply an input current on a control pin by the voltage across the amplifier inputs. The data sheet is worth reading just for the plethora of applications it covers (Reference A). The company's LM3900 Norton amp is obsolete, but its LM359 is still in production. The amplifiers employ Norton's current laws, which work on a current difference into current mirrors as opposed to the voltage-operated input-differential pair that almost all other amplifiers employ. The parts are fairly rare but can provide an interesting exercise in analysis and understanding (Reference B). On Semiconductor's MC33304 power-adaptable amplifier is also obsolete but is interesting because its quiescent current and frequency response would increase whenever the output sourced more current than a user-selectable threshold.

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