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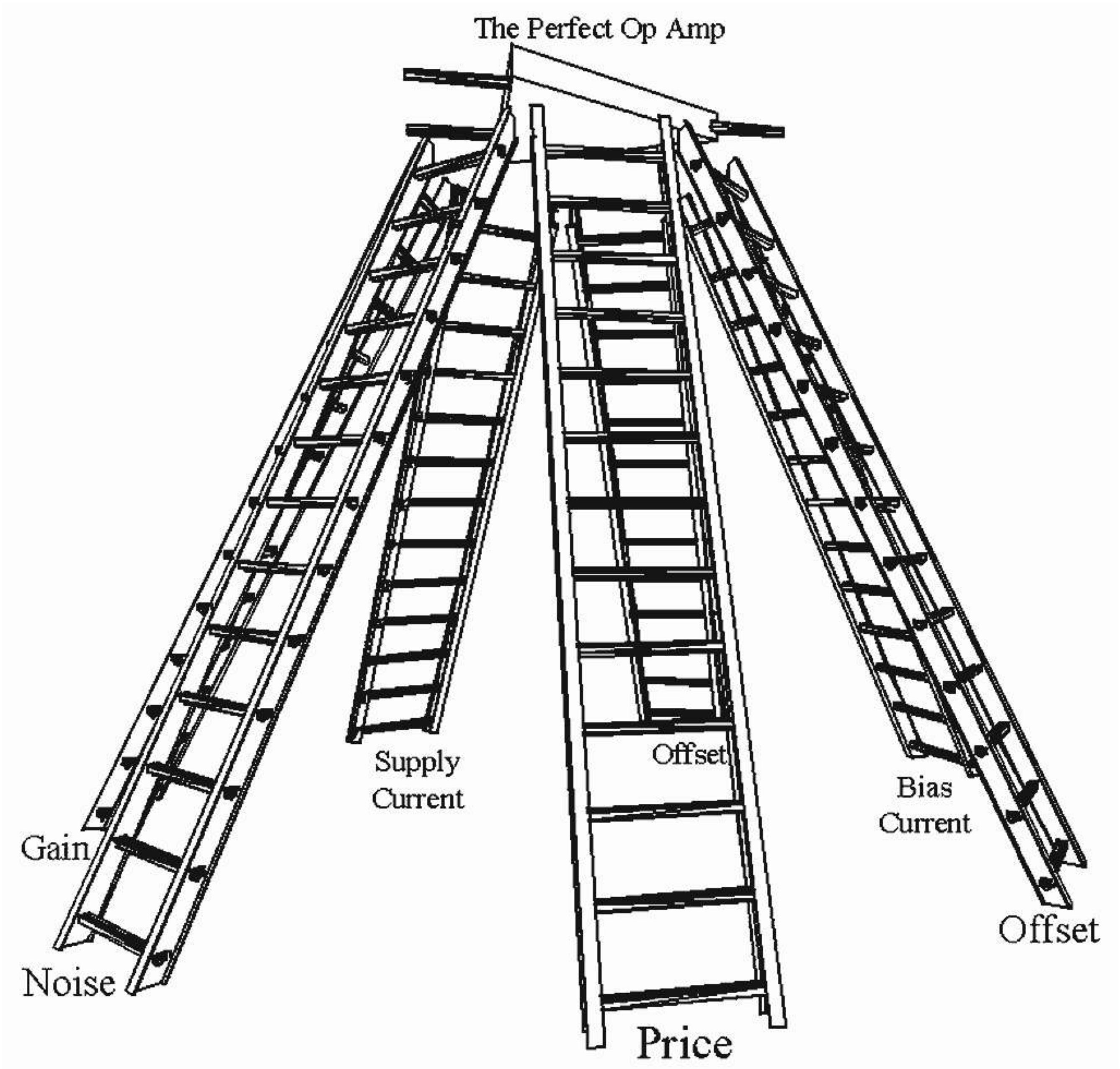
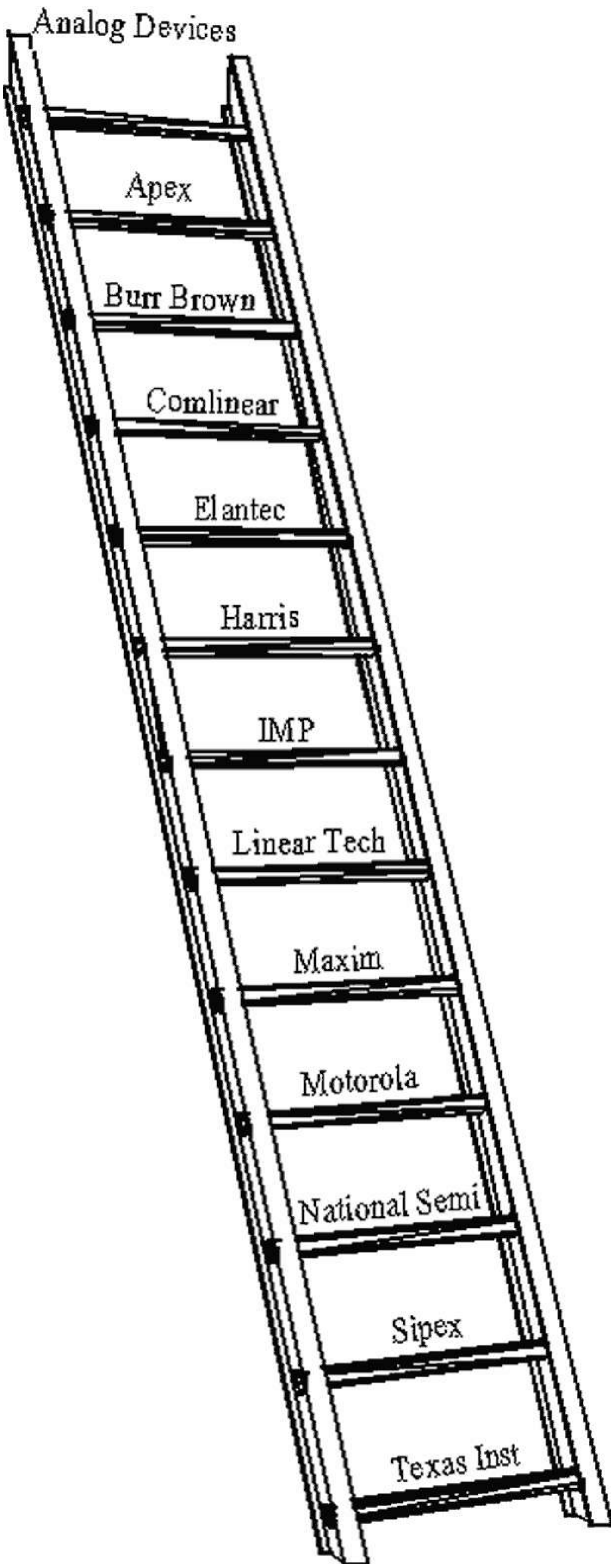
The various specs of op-amps

Presentation at a 1997 EETimes analog conference. The myriad specifications of an op amp and how you can decipher them.



Op-anp features and selection

The methods marketing people use to differentiate products are best described in Trout and Reis's famous books "Positioning" and "Marketing Warfare".



These books describe how marketers try to create a good image for their products and bad image for their competitors' products. The analogy Trout and Reis use is one of "ladders" in the mind of the consumer. The job is to move your product up the ladder or, if possible, create a new ladder with your product at the top of that ladder.

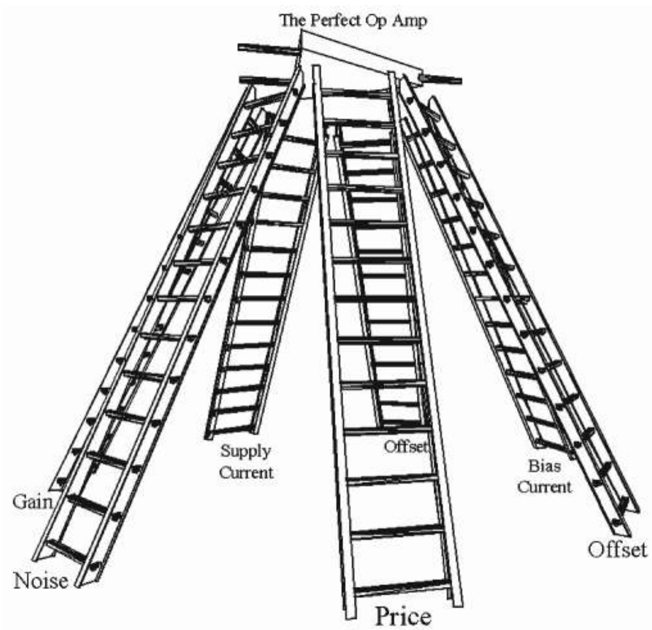
This is perhaps possible for rather generic products like dish soap and even automobiles. For complex analog electronic devices the approach can be problematic. One factor that can be disconcerting is that manufacturers try to simplify their job by trying to create the image that the companies are what's on the ladder and not individual products. This is an approach doomed to failure.

Analog Devices and people who order things alphabetically would have you believe that the ladder is something like **Figure 1**. The marketing people try to take a short cut by convincing you that if you buy from their company you will get the best op amp (or other analog product). After all, believing in a company is a lot easier then sifting through all those data sheets with their tedious and oftentimes incomprehensible specs.

Why on earth does it take 5 or 10 or 30 pages to describe a little blob of plastic with 8 little metal tabs on it? What a wonderful world it would be if life were this simple. In reality the 30 page data sheet doesn't even begin to tell you every thing you need to know about the part. The ladder is not some simple affair with 5 or 10 companies on it. In reality there is not one ladder at all but rather a dozen or more ladders all set up and pointing to that lofty goal: *the perfect op amp*.

The specification ladders

In fact, companies are not on the ladder at all. Certainly companies matter for things like availability and trust to deliver on time. But let purchasing worry about that. We have to give something to do to those poor wretches who did not pursue a technical career. The ladders that



we are concerned with are specification ladders. As I have said there are many of them. **Figure 2** shows how the perfect op amp would sit at the top of these specification ladders. You needn't feel daunted by the specs. Even if you are a digital, software or systems engineer the concepts are easy enough to grasp qualitatively.

I have yet to meet a software engineer who was not able to grasp the concepts of amplifier specs. I doubt that I will ever understand the concept of "coding" in C++. So don't be frustrated or intimidated by analog design. We can now go over the most important specs of op amps and build a set of ladders that will give you an intuitive feel for the range of values.

Intuitive feel is good. It's why I can make a lot of money as a consultant. Get to know these op amp spec ladders and you too can make a lot of money as a Silicon Valley Consultant. More importantly, your designs will work. Lets begin by considering the perfect op amp. We will look at op amp specs in rough order of their importance. Then we will establish a range for these specs in real life parts and use these values as ranges for the ladders in our mind that define the "goodness" of an op amp.

The perfect operational amplifier

The first and most important spec is price. The perfect op amp would not be free. Rather, large multinational companies would send over brilliant, engaging people like Jim Williams and Bob Pease. They would pay you to take large Hefty® bags full of perfect parts, but only after a pleasant afternoon discussing Jaguars and video cameras. Other specs of interest and what they are follows:

Gain

The gain of an amp is the amount of multiplication that the amp provides. The spec sheet shows open loop gain. It can be expressed as a simple number (100,000, 1 million) or as a decibel value. The decibel is one tenth of a bel, so named for Alexander Graham Bell, the inventor of the telephone. The decibel is a logarithmic scale value that is useful to represent wildly divergent values.

The formula for voltage gain expressed in decibels is:

$$decibel = 20 \times \log_{10} \frac{V_{IN}}{V_{OUT}}$$

A voltage gain of 1 is zero decibels (db). A gain of 100 is 40 db. A gain of 1 million is 120 db. The larger the gain the more accurate will be the circuit the op amp is used in.

If the amps open loop gain is one million, the high gain will insure an accurate output if there is negative feedback that is designed to give a closed loop gain of two or ten. A perfect gain would be infinite, but 200 or 300 db would be OK.

Bandwidth

The bandwidth of an amplifier is the frequency range over which it can produce gain. An amplifier with a bandwidth of 1 megahertz will have a open loop gain of one for an input sine wave of one million cycles per second (Hertz). A gain of one is not very useful, so this value is the extreme limit of the amp. Since the gain of all op amps falls as frequency increases, the benefit of all that open loop DC gain is not available as the frequency increases.

Hence, the accuracy (lack of distortion) declines the faster the op amp is performing. This just highlights the importance of the open loop gain mentioned above. If it starts out high, there might be enough for a good circuit at high frequencies. Perfect bandwidth would be in the hundreds of Gigahertz.

Noise

The perfect op amp would add no noise to the output. Noise specs are usually expressed as an input referred voltage or as a voltage or current per root hertz. All these are referred to the input so that you have to remember to multiply the gain of the circuit (not the open loop gain) to get the output noise.

Microvolts of input noise looks great until you need a gain of 1000. Then you have millivolts of output noise. That can turn your sixteen bit analog to digital converter into an eight bit one as far as the data is concerned. Perfect is, of course, zero noise.

Offset voltage & current, and drift

The two input pins of a perfect op amp should have zero volts across them and zero current difference between them when the open loop output is zero. Process variations make this unlikely.

Real world op amps are trimmed at the factory or have on chip compensation to reduce these offsets. Offsets ore most troublesome when trying to accurately measure or reproduce some DC value or AC wave form. Offsets can also cause non-linearity's and other problems. Drift is the change in offsets over time and temperature.

Bias current

The two input pins of real world op amps have some small current that must enter or exit the pins to keep the op amp biased (in its' linear range). Some designs use p-channel input transistors that causes current to flow out of the input pins. Some have currents that flow in. Some are corrected at the factory so the current is less, but the downside is that it can flow in either direction in either pin and will be different for every part in the same lot. There are CMOS input amps that have essentially zero bias current. At last, perfection realized.

Supply current

We will concede that even a perfect amp will need power supply pins. But this should be to deliver current (hence voltage) to the load. Supply current is the current that is used by the circuitry inside the amp to bias transistors and references and pout out the input pins as the dreaded bias current mentioned above. Zero supply current would be nice.

Output impedance, power, and voltage

The output of an op amp has impedance (think of it as varying resistance over frequency). Not good. There are power op amps that have low impedance to drive motors and speakers. Even driving a 50 ohm cable can be difficult with the wrong amp. Related concepts are the output power. Low output impedance is of little use if the op amp cant get the heat out of the die. The output voltage should also be able to swing the full range from the top power supply rail to the bottom (or ground).

Slew rate

Slew rate is like bandwidth for big signal changes. It's rated in volts per microsecond instead of megahertz. The bandwidth we discussed earlier was a small signal bandwidth.

A one megahertz bandwidth does not imply that the op amp can go from +15 to -15 volts one million times a second while maintaining a gain of at least one. These large signal swings are limited by the slew rate spec. This can be very important in applications where a multiplexor is switching different analog inputs to an op amp circuit.

Each signal could be moving very slowly, say ten hertz. When the multiplexor switches in the other signal there is a definite likelihood that the input of the amp suddenly snaps between, say, -10 and +10 volts. The operational amplifier slews at its slew rate to the new value, but if an A to D converter takes a sample before the amps has reached the new value, it gets a bad reading.

If this doesn't concern you, please don't get into medical equipment design if only for the sake of the rest of us.

A similar concept is settling time. This is an expression that accounts for both the slew rate and the "ringing" or small oscillations that occur as the amp settles down to a new value after a large change. Once again, this is critical for sampled data systems with large input swings. Our perfect amp has infinite slew rate and zero settling time.

Common-mode and power supply rejection

The two input pins to an op amp should only function with respect to each other. Common mode in this context refers to the fact that both pins might be exposed to the same voltage even though the pins have the same differential (between them) voltage. This is usually expressed as negative decibels.

From our gain calculations for decibels we can surmise that a -120 db common mode rejection implies that any voltage appearing simultaneously on both input pins will be one millionth the value at the output. The same concept applies to power supply rejection.

A noise or ripple on the power pins would also be one millionth at the out put for an amp with -120 db power supply rejection. The caveat here is that the rejections change over frequency (hence the need for those little graphs in the data sheet). Care should be taken that spurious high frequencies don't appear on the output due to amps selected on low frequency rejection specs.

Input capacitance

This spec is not mentioned on many data sheets but it can be important in high frequency applications and in circuits sensing frequency or acquiring frequency.

Fortunately it doesn't vary much from part to part of a given part number. If it's too high it can attenuate the input signal thus requiring more gain to compensate for. There are also phase and other issues. Once again, perfect is zero.

Minimum gain

The concept of minimum gain (Unity gain stable) is a little elusive. In this context the gain is referring to closed loop gain in your circuit. In order to get some op amps to work (have gain) at high bandwidths they are internally compensated with capacitors on circuit nodes.

This allows good high frequency performance with useful gain. The problem is that if the closed loop gain of your circuit is not large enough, the op amp will oscillate. Think of it as trying to shoot a very fast moving duck. You lead the shotgun so much that if the duck stops you shoot your buddy drinking beer next to you. A minimum gain of one is cool. This is also stated as "unity gain stable".

Delay

This is like gate delay in a digital circuit. It is of course related to bandwidth, slew rate and input capacitance. We would like zero delay.

Operating temperature

Of course we need this op amp to work in outer space and in down-hole oil well data logging. This means a temperature range of -170 to +300 degrees Celsius.

The perfect spec summary

Let's tabulate these perfect specs:

Specifications of the perfect op-amp

SPEC	PERFECT VALUE
Price	Free
Gain:	Infinite
Bandwidth	DC to Daylight
Noise	Unmeasurable
Offset Voltage	Zero
Offset Current	Zero
Bias Current	Zero
Supply Current	Zero
Output impedance	Zero
Output power	67 horsepower (50 KWatts)
Output voltage	1000 volts
Slew rate	1 million volts/ microsecond
Common mode rejection	500 Decibels
Power supply rejection	900 Decibels
Drift	Non-existent
Input capacitance	0 picofarads
Minimum Gain	Unity
Delay	0
Operating temperature	-170 to +300 degrees C
Settling time	0

Now, we've been considering what specs a perfect op amp would have. Of course perfection is impossible. Especially with government run schools. But let's admit it: Close to perfection is better then far from perfection.

Some parts do achieve near perfection. PMI's OP-27 started the trend to parts with so little noise that the noise of the input resistors would far exceed the noise of the amplifier. A National Semiconductor's LMC6001 op amp has essentially unmeasurable input bias currents (10 femtoAmps). Let's now assign reasonable values to these specs.

The real operational amplifier

A real world Operational Amplifier has specs that are tabulated as follows:

SPEC	REAL VALUE RANGE
Price	0.05 to 30 Dollars
Gain:	25,000 to 167 db
Bandwidth	1 KiloHertz to 1 GigaHertz
Noise	1000nV/Hz to 1nV/Hz
Offset Voltage	0.5 m V to 10 mV
Offset Current	30pA to 50 nA
Bias Current	10 fA to 250 nA
Supply Current	1 m A to 10 MmA
Output impedance	1 ohm to 1000 ohms
Output power	0.1W to 500W
Output voltage	1.2 to 600V
Slew rate	0.1 to 800V/ m S
Common mode rejection	50 to 130 db
Power supply rejection	50 to 145 db
Drift	0.01 to 30 m V/degreeC
Input capacitance	2 to 20 picofarads
Minimum Gain	Unity to 25
Delay	5.5nS to 100nS
Operating temperature	0-70 to -55 to 200 degC
Settling time	1000nS to 25nS

The amplifier ladders

Figure 3 shows a top view of our amplifier ladders with some real world numbers pasted in.

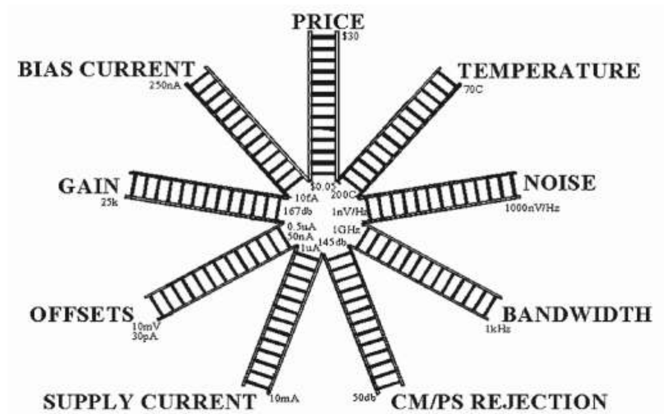
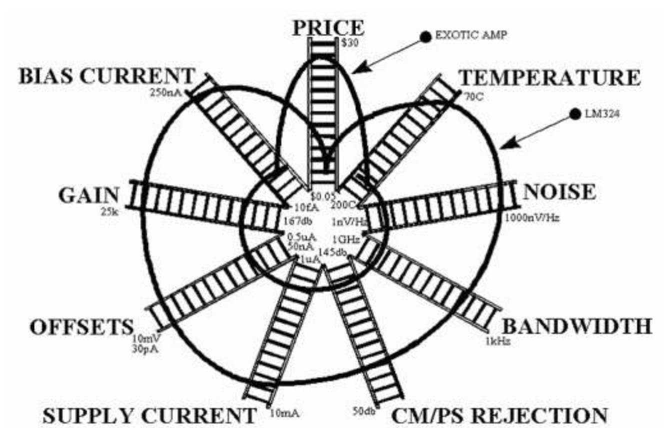


Figure 4 shows how different op amps can be mapped on the ladders by drawing a line through the specs that a real world part delivers. A low price usually compromises the other specs so a LM 324 is a heart shaped line.

A high price results in a pear shaped line that incorporates more improved specs.



Handy guidelines

Lastly, this table gives some handy guidelines to get you on the right track or help land that new job.

Key Words	Think	Disadvantages
Low Offset, low drift	Chopper Amp	Slow, cost
Low bias Current	CMOS, JFET Input amp	Noise, speed, temp dependent
Fast	Bipolar, Current feedback	Power consumption, cost
Cheap	LM324	Offset, speed
Inexpensive	OP27/37	Supply current, bias current
Low Power	CMOS	Noise, speed
Low Operating Voltage	CMOS	Noise, speed
Power	Apex, Burr Brown	Price, availability

One more thing, remember the most important tool an engineer owns. No, not a computer, not a data library, not a CAD package and certainly not a Spice package. It's a telephone. Call the manufactures' application engineers and take advantage of some of the finest minds on earth. They are patient, friendly and understanding. I've had several occasions where an apps engineer recommended a competitor's part because that is what was best for the job. They will provide you with the collective experience of an entire industry and it's free for the asking.