Introduction to Operational Amplifiers (Op Amp)

In this revision of the Semiconductors course, we have not built any discrete transistor amplifiers. These amplifiers are hard to design, finicky, usually have poor input and output impedances, can't handle DC signals or very high frequency signals, and usually give you the choice between stability and high gain -- one or the other, but not both. Consequently, these amplifiers are almost never used anymore.

For years, the goal of analog electronics was to come up with the "perfect" amplifier-in-a-box, a device that could be used for practically any application without needing to know "what's in the box". This was referred to as an "operational amplifier" -- a pre-packaged device for which you just needed to know how to make it work, not why it worked the way it did. Here were some of the design goals:

- infinite input impedance
- zero output impedance
- really high, or infinite, gain
- differential inputs (and maybe even differential outputs)
- bandwidth from zero (DC) to infinity

With ***infinite input impedance***, the amplifier could be connected to any source, ideal or non-ideal, without any loss of signal due to loading. In other words, the amplifier would draw no current from the source, and would be completely undetectable. V_{in} would always equal V_S in the "black box model" of an ideal amplifier.

With ***zero output impedance***, the output signal would be unaffected by any load that could be attached, except for a dead short to ground. V_o would always equal V_{oc}.

With ***infinite gain*** the actual gain could be brought down to anything you wanted using negative feedback.

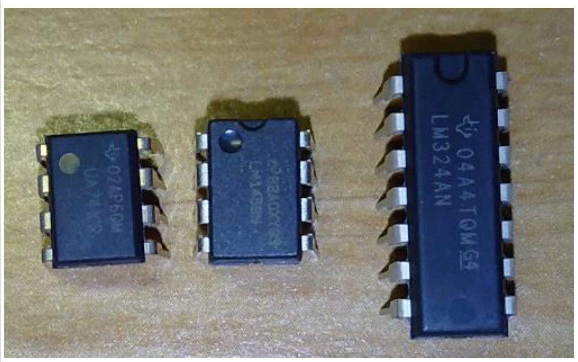
With ***differential inputs*** the amplifier would amplify the ***difference*** between the signals on its two inputs. This would allow for the amplifier to be inverting or non-inverting, or to use a differential two-wire signal referenced to itself rather than to ground. Also, any signal that appeared equally on both inputs would be automatically eliminated by superposition.

And of course, if the amplifier came with ***DC to infinity bandwidth***, you could add your own filters to pass only the frequencies you wanted, and you'd be able to manipulate super-slow signals (practically DC, often called "pseudo DC") like those generated by temperature sensors and other real-world sensors.

The first attempts at building operational amplifiers were promising in terms of approaching the design specifications, but they were completely impractical in terms of size, complexity, and cost. An early design involved dozens of vacuum tubes and high voltages; another design involved dozens of transistors. Then, in 1958, Jack Kilby came up with a way of building multiple transistors on a single piece of silicon, which he patented as "integrated circuit" technology, and suddenly there was a practical way to build an operational amplifier.

The operational amplifiers (OK, let's start calling them op amps) in your parts kit cost only pennies and can be tiny -- the ones in your kit have been cast in plastic to make them big enough to handle and work with, and so you can mount them on your breadboards. Surface mount versions of these can be really tiny.

Here are the three op amp ICs in your kit.



The one on the left is a single op amp -- the 741. The one in the middle has two op amps in it (dual op amp) -- the 1458. The one on the right has four op amps in it (quad op amp) -- the 324. You'll notice other characters before and after the numbers -- the ones in front indicate the manufacturer or designer, and the ones after specify things like grade of design and packaging. Often if you see an 'N' or a 'P' at the end it means it's dual inline pin (DIP) and can be used on a breadboard; 'D' usually means surface mount in an SOIC-style package -- not a good choice for breadboarding (keep that in mind when you get to courses where you order the components you'll be using!).

The 741 Op Amp

An old standby design, the 741 is an inexpensive and not very fancy IC; however, it's good enough for most of what we will need it to do. The 1458 and 324 op amps have pretty similar characteristics to the 741, just with multiples per IC. If you want better characteristics, and you'll soon be learning about some of the things you might need to improve upon, you'll end up paying more and having more difficulty sourcing the components.

Let's see how the 741 stacks up against the design standards discussed above. Look up the 741 Specification Sheet (https://www.ti.com/lit/ds/symlink/lm741.pdf?ts=1603937430839&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FLM741%253Futm_source%253Dgoogle%2526utm_medium%253Dcpc%2526utm_campaign%253Dasc-null-null-GPN_EN-cpc-pf-google-wwe%2526utm_content%253DLM741%2526ds_k%253DLM741%2526DCM%253Dyes%2526gclsrc%253Daw.ds%2526%2526gclid%253DEAIaIQobChMIju-ovNzY7AIVIgnnCh1bjwrKEAAYASAAEgJjPfD_BwE) and answer the following questions, based on the first set of specs labelled "LM741".

1. What is the stated typical input impedance? [2] [MΩ] . A fairly typical single-transistor amplifier has an input impedance in the 5 kΩ to 10 kΩ range, so that's a significant improvement! We'll soon discover that, in an actual circuit with negative feedback, the input impedance is much, much higher than the specified open-circuit input impedance.
2. The output impedance isn't stated on the specification sheet, but from an Internet search, it appears to be 75 Ω for the open-circuit device. That same fairly typical single-transistor amplifier has an output impedance in the 1 kΩ to 5 kΩ range, so this is again a big improvement. As with the input impedance, when we add negative feedback to the op amp, its output impedance improves dramatically.
3. Look up the average Large signal voltage gain. [200] [V/mV] . Convert that into a simple ratio: [200000] . The single transistor amplifier we've been comparing to has a gain of about 20, so the op amp's gain is huge!
4. Take a look at the two input pins on the schematic symbol for the op amp. This tells us that the amplifier has [Differential inputs]
5. Last, and unfortunately the biggest issue: In the 741 chart they don't even mention bandwidth, so look in the 741A chart to find the typical bandwidth [1.5] MHz.

   Since this is a real sticking point for the op amp, let's also look at its minimum value, converted to kilohertz: [437] kHz. Given that FM radio stations are from 88

MHz to 108 MHz, clearly this amplifier can't even touch signals like that. And, unfortunately, things get worse when we try to do any kind of actual signal amplification with the op amp -- the listed bandwidth is for when its gain is just 1, or no amplification at all, and it decreases with gain.

So the operational amplifier provides us with some interesting and close to ideal characteristics that make it easy to work with, but it has some limitations that must be considered when using it for certain applications, particularly those where speed and bandwidth are concerned.