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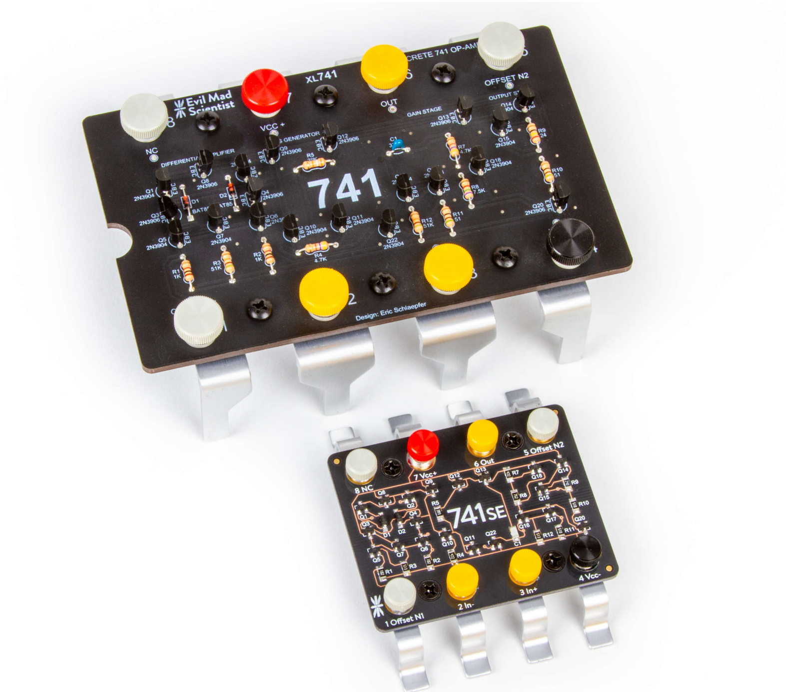
Educational Supplement



The 741 Op-Amp: Principles of Operation

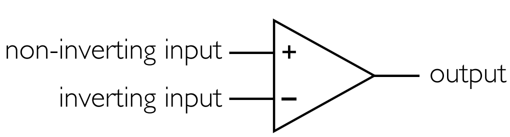
What's inside a '741 integrated circuit, and how does it work?

Supplementary documentation for the XL741 & 741SE Discrete Operational Amplifier Kits

§1.0 Introduction: Op-amps and the '741

An operational amplifier, or "op-amp" as they are more commonly known, is one of the most useful and common types of building blocks for making analog electronic circuits.

Op-amps are two-input devices – almost always integrated circuits – that perform mathematical operations upon their inputs. Placed in properly designed circuits, they are commonly used to amplify, add, subtract, differentiate, integrate, filter, compare, regulate, mix, and control electronic signals. If you look inside just about anything electronic, you'll find opamps hard at work.



The schematic symbol for an op-amp has two inputs: the "non-inverting" input (**+**) and the "inverting" input (**–**), as well as one output. The opamp takes the signal from the **+** input, subtracts the signal from the **–** input, and then multiplies the result by a large factor called the gain.

As an analog circuit element, an op-amp performs these operations on the electrical signal itself – the voltage, or electrical potential, at its terminals – and not on a digital representation of that signal.

A real op-amp has additional pins for power supply connections, and sometimes for additional external adjustment as well.

The most popular op-amp of all time – the quintessential op-amp – is the μA741, designed by Dave Fullagar while working for Fairchild in 1967. While it was not the first integrated circuit opamp (the μA702 holds that title), it became a smash hit thanks to its built-in frequency compensation which made it the easiest and simplest to use. Previous opamps needed carefully designed resistor and capacitor circuits to control the bandwidth and stability of the amplifier. Imagine having to do all that work even before connecting the inputs and the outputs!

While newer op-amp designs may outperform it in just about every possible respect (speed, noise, voltage range, and so on), the original '741 remains widely beloved and in active production today — over 45 years later.

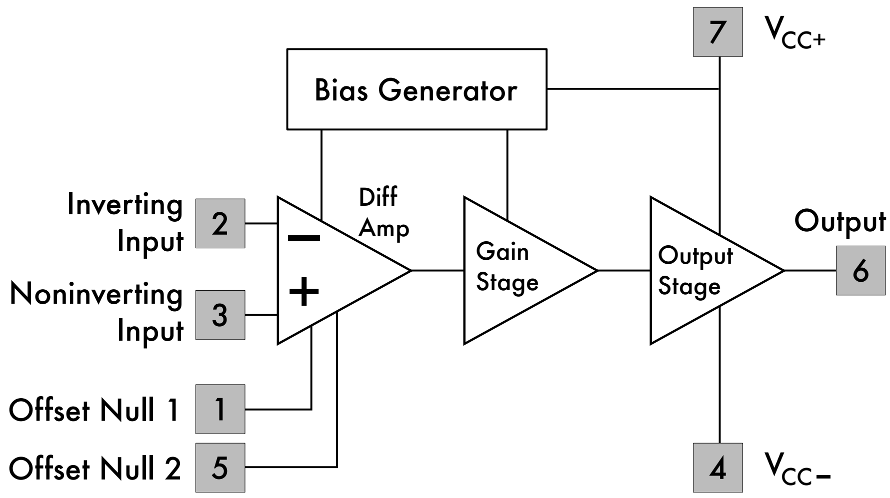


Figure 1: 741 op-amp block diagram

§1.1 *The XL741 and 741SE*

The XL741 and 741SE Discrete Operational Amplifier kits are functional transistor-scale replicas of the µA741 integrated circuit. Both kits implements the "equivalent circuit" from the original Fairchild µA741 datasheet, using discrete components such as resistors and individual transistors. These are, so to speak, a "dis-integrated circuits," containing essentially the same components that you might find on the die of a '741 IC.

As with an integrated circuit '741, you can build working amplifiers, oscillators, and other analog circuits with the discrete versions, and hook up with solder connections, test probes, or alligator clips to monitor what happens at the pins. However, unlike the chip version, it's also easy to insert your own probes *inside* the circuit, to monitor what happens at any point inside what would otherwise just be a black box.

This ability to peek inside the circuit makes the XL741 and 741SE kits a unique educational tool. In what follows, we'll work through the circuit diagram, discuss the theory of operation of the '741 op-amp, and present some opportunities for experiments and further exploration.

§2.0 The High-Level Overview

Let's begin by looking at the '741 block diagram, Figure 1. Here, we simplify the many individual components into a much smaller set of functional blocks:

- A *differential amplifier*,
- a *bias generator*,
- a *gain stage*, and
- an *output stage.*

The differential amplifier:
The input differential amplifier subtracts the **–** input voltage from the **+** input voltage. Thus, it finds the difference between the two signals. Another part of the circuit controls the tiny currents (input bias currents) that need to flow into the inputs so that the input transistors can function.

The bias generator:
The bias generator is the "power plant" of the circuit. Using the V_{CC+} and V_{CC-} supply voltages, it generates an internal reference current which provides power to many of the other transistors.†

The gain stage:
The gain stage performs the multiplication function. At its heart, it is a simple transistor amplifier which multiplies the voltage difference between the **+** and **–** terminals by a factor of about 200,000. This helps the opamp react to very tiny changes in the input voltages.

Most opamp circuits operate by creating a balance such that the opamp tries to make both input voltages exactly equal. The output signal of the op-amp usually feeds back into a node in the external circuit that surrounds the '741. Typically, this external circuit connection involves the **–** input to create negative feedback.

The output stage:
Finally, the output stage takes the low-current signal from the gain stage and puts some muscle behind it, allowing the opamp to provide more current to the outside world.

† The names "V_{CC+}" and "V_{CC-}" mean the positive and negative power supply inputs to the '741, respectively. In this case, DC voltages up to 18 V (for V_{CC+}) and down to -18 V (for V_{CC-}).

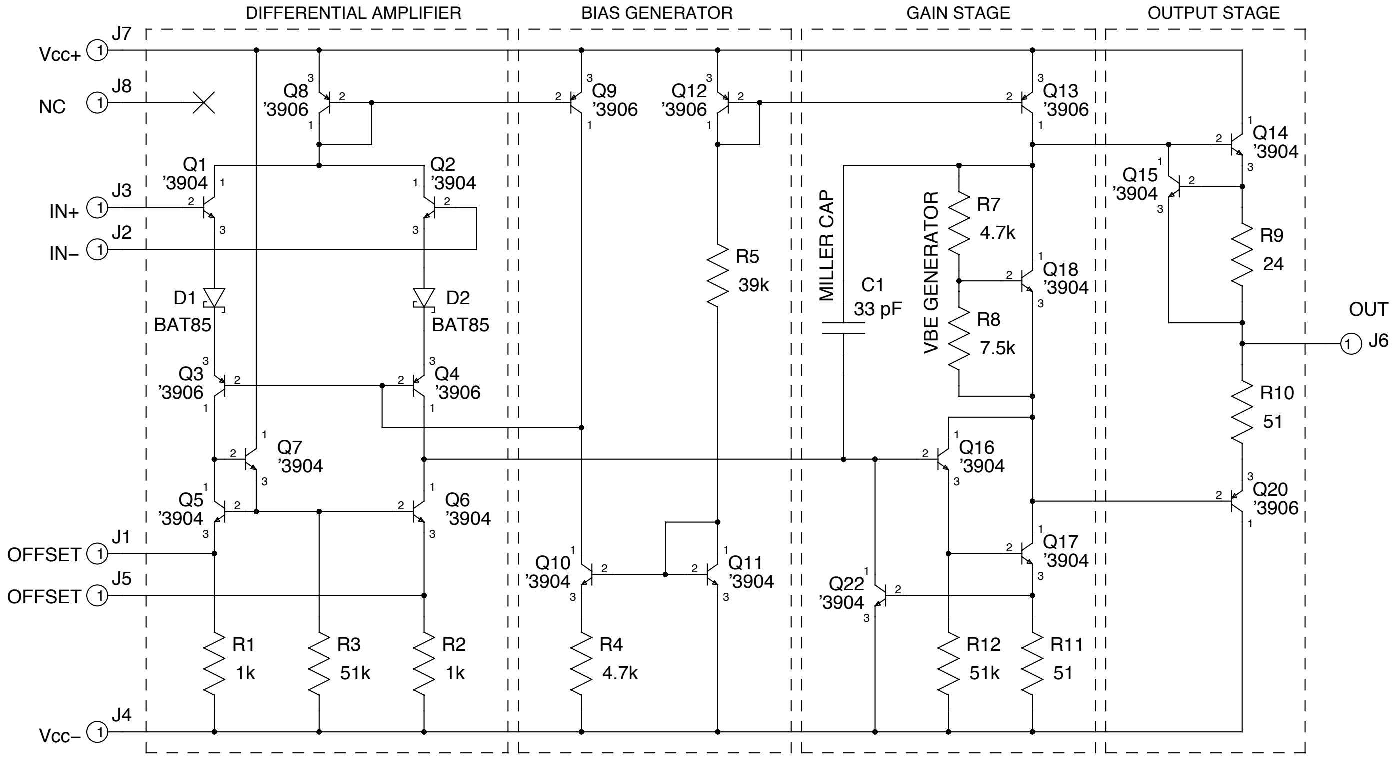


Figure 2: Detailed schematic diagram

§2.1 *The Overall Schematic*

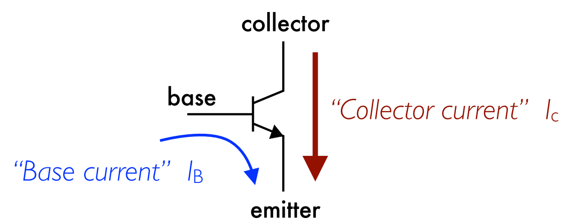
The detailed schematic for the XL741 and 741SE circuit boards is shown in Figure 2. As we walk through the details of the different blocks that make up the circuit, it will help to keep this overall diagram nearby.

You may notice – from this schematic or the parts included with the kit – that the electronic components in the circuit consist primarily of resistors and transistors. We'll briefly review these two components before we dive into the circuit diagram.

§2.2 *Component review*

Review: Resistors
The defining property of resistors is that they are circuit elements that follow Ohm's law, which is $V = I \times R$, where V is the voltage across the resistor, I is the current through the resistor, and R is the value of the resistor (measured in ohms). For example, if a 51 Ω resistor has current of 1 mA through it, then the voltage difference between its two ends is 51 mV.

Review: Transistors
While there are many types of transistors, the ones in this circuit are bipolar transistors, in which a small current controls a larger one, acting as amplifiers or switches. There are two flavors of these, NPN and PNP; we'll pick NPN to look at first: The three terminals of an NPN bipolar transistor are named "base," "collector," and "emitter." The base and emitter pins comprise a diode, indicated by the little arrow on its schematic symbol. A diode is a unidirectional circuit element, so under normal circumstances, current can only be made to flow from the base to the emitter, and not from the emitter to the base.



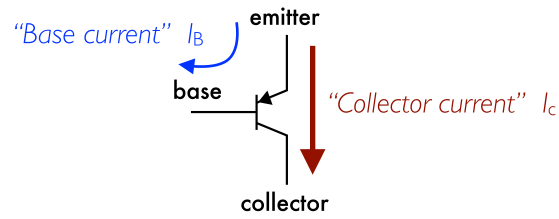
NPN Transistor

Aside: An NPN transistor also has a *second* internal diode, which conducts (only) from the base to the collector. In most use cases, a circuit that uses this kind of transistor is designed to always keep (or "bias") the collector at a higher voltage than the base, so that the base-collector diode does not conduct current. So long as this bias is maintained, we can usually ignore the presence of the second diode.

An important detail is that there is a small voltage loss across a diode, usually *about* 0.7 V. (The exact loss depends on the type of device and the operating conditions). This means that (a) when current is flowing from the base to the emitter, the voltage at the emitter pin is usually about 0.7 V below that at the base and (b) current does not begin to flow from the base to the emitter until the voltage of the base is about 0.7 V above that of the emitter. This typical voltage difference of 0.7 V is usually referred to as a "diode drop."

Finally, there is the matter of switching and amplification. When current flows from the base to emitter, that current ("base current," symbol I_B) is said to "switch on" the transistor: it allows current to flow from the collector to the emitter. The maximum current that can flow from the collector to the emitter is given (to good approximation) by $I_C = h \times I_B$, where I_C is the "collector current" (the current flowing from the collector to the emitter) and h is a gain factor that depends on the particular transistor. If h has a value of, say, 30, then the transistor acts as an amplifier where a small change in I_B causes a change 30 times larger in I_C.

The other flavor of transistor, PNP, works almost exactly the same way. Its schematic symbol is similar, with the major change that the little arrow is pointing in. (Mnemonics! PNP: **P**ointing i**N** **P**lease, NPN: **N**ot **P**ointing i**N**.) In a PNP, the emitter and base form a diode where current can only flow one way, but this time only *from emitter to base* (again, in the direction of the



PNP Transistor

arrow). And, when current flows through that diode, it allows a current $I_C = h \times I_B$ to flow from the emitter to collector.

The particular components that we are using are type 2N3904 or MMBT3904 for our NPN transistors and 2N3906 or MMBT3906 for our PNP transistors. These are some of the most common and well known types of bipolar transistors.

§3.0 The Differential Amplifier

Now that we've reviewed the basics, let's dive right into the 741 schematic. The non-inverting input and the inverting input are connected to the bases of NPN transistors Q1 and Q2, respectively. The collectors of these two transistors are connected to the positive power supply V_{CC+} through PNP transistor Q8. Because its collector and base are connected together, Q8 acts like a simple diode here (we say that it is "wired as a diode"). The collectors of Q1 and Q2 are thus normally kept at a voltage of one diode drop (about 0.7 V) below V_{CC+}.

Q1 and Q2 act as "voltage followers" that buffer the input signal voltage. They amplify the input current, increasing the input impedance. That is to say, they provide amplification such that the **+** and **–** inputs work well, even while drawing only a very small amount of input current.

Q3 and Q4 are common-base amplifiers – amplifiers with their bases connected together – that act as level shifters. The signal that controls them comes from the bias generator block; we will come back to this (and its function) when we discuss that block.

If the **–** terminal's voltage is higher than the **+** terminal's voltage, then transistors Q2,Q4 conduct more current down and out through Q4's collector and transistors Q1,Q3 conduct less. This causes the differential amplifier's output voltage to increase. We will work through how this works in greater detail in the next section (§3.1).

Aside 1: Output polarity
Ultimately, when the **–** terminal input is at a higher voltage than the **+** terminal, the '741's output voltage should decrease, so the paragraph above might seem backwards. However, everything works out: the gain stage will later invert the signal back to the proper polarity.

Aside 2: Transistor gain
The PNP transistors in the original µA741 had very poor current gain (less than a factor of ten), but that was all that was available at the time. The combination of a NPN transistor followed by a PNP transistor (as in Q1,Q3 or Q2,Q4) creates a sort of "super PNP" transistor that more or less made up for that problem.

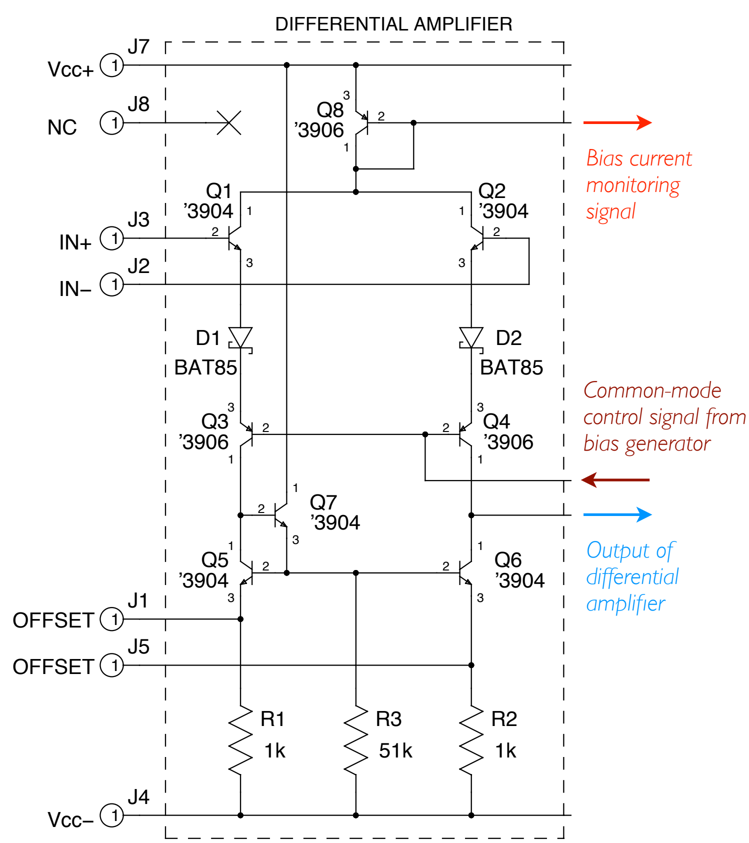


Figure 3: Differential Amplifier

Aside 3: D1 and D2

We have glossed over something else here. Between Q1 and Q3, and between Q2 and Q4 are diodes D1 and D2, respectively. These two diodes are *not present* in the original µA741 circuit.

In the original µA741, Q3 and Q4 are lateral PNP devices with a base-emitter breakdown voltage (V_{EBO}) greater than 30V. However, the 2N3906/MMBT3906 transistors in our discrete 741 circuit have a much lower V_{EBO}: an absolute maximum of 5V. This maximum would limit the differential mode range (the maximum voltage difference between the **+** and **–** inputs) to about ±11 V. The "obvious" fix of using a different transistor with a higher V_{EBO}, turns out to not be practical, as very few types are currently available.

A viable solution – added in version 2.0 of the XL741 kit and present in all 741SE kits – is to use two Schottky diodes which have a breakdown voltage above 30V. Added in series with the transistors, they protect the '3906 transistors with a very small impact on the offset voltage.

If you so choose, you could build up the kit without D1 and D2, by substituting a wire for each of them. Doing so is somewhat more authentic in terms of the device layout, but not in terms of performance. With the added diodes in series, the input transistors Q1 through Q4 are protected when excessive differential mode voltage is applied to the inputs. But without D1 and D2, it is critical to keep the **+** and **–** inputs within ± 11 V of one another.

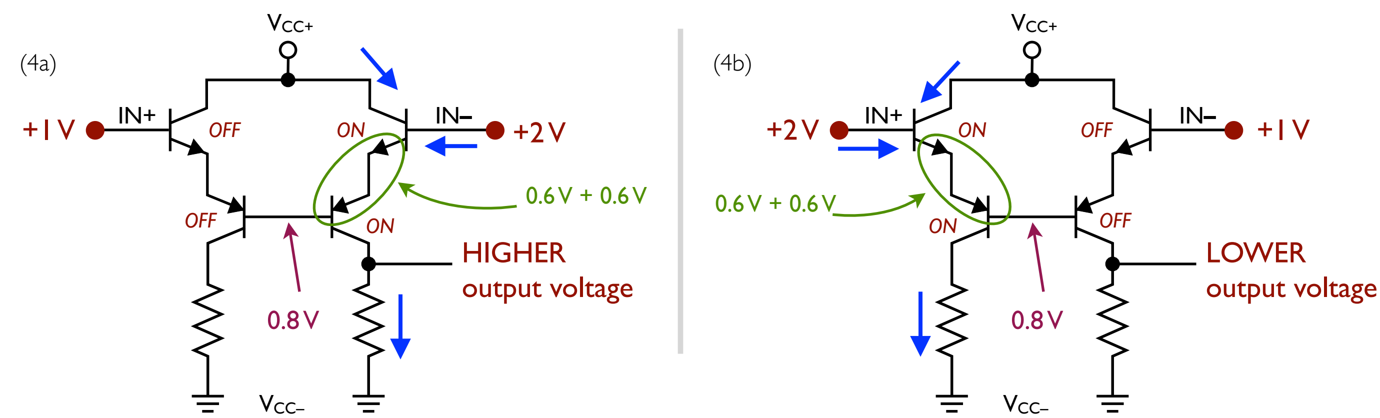


Figure 4: Simplified differential amplifier

§3.1 *A model differential amplifier*

In order to understand how the differential amplifier section of the '741 works, it is helpful to simplify the circuit to its core elements (Figure 4). We can use this model to visualize the path that the majority of the current takes, depending on the input voltages. We will show that the input with the higher voltage dominates the behavior of the circuit.

First consider the case of Figure 4a. The voltage at the **+** input is 1 V, and the voltage at the **–** input is 2 V. On the right side of the circuit, the 2V input voltage goes through the two base-emitter junctions in the two transistors (that is, two effective diodes, with two "diode drops" of voltage loss) losing 0.6 V + 0.6 V = 1.2 V along the way. This gives a voltage of 0.8 V (i.e., 2 V - 1.2 V) on the central circuit node (wire) that connects the bases of the two PNP transistors.

Now, note that the voltage between the **+** input and this central node is only 0.2 V (1 V - 0.8 V). That means that there is not enough voltage across the base-emitter junctions of the two left-hand transistors to turn them on. Thus, they stay off and no current flows through the the left-hand branch of the circuit.

As current flows through the branch on the right, the point above the "load" resistor in that branch develops a voltage. We know this because Ohm's law tells us that the voltage across a resistor depends on the current through it. We read out this voltage as the output of the amplifier.

Let us now consider the other case, in Figure 4b. The voltage at the **+** input is 2 V, and the voltage at the **–** input is 1 V. The behavior in this case is just the opposite: the two left-hand transistors are on, the two right-hand transistors are off, and current flows down the left branch of the circuit. The output voltage is lower, because less current (zero, for these input values) is flowing through the right-hand load resistor.

A valid question at this point is "If this is a differential amplifier, where is a difference actually being amplified?" The answer is that the difference between the input voltages controls an amplified current that predominantly flows through one of the two resistors near the bottom of the diagram, developing an also-amplified voltage. Thus, the output voltage is an amplified version of the difference between the two inputs.

The '741 does not use load resistors like the ones shown in Figure 4. Instead, Q5, Q6, and Q7 form a current-mirror circuit, which we will discuss in the next section. The current mirror acts as an *active load* that allows a higher gain than is possible with simple load resistors.

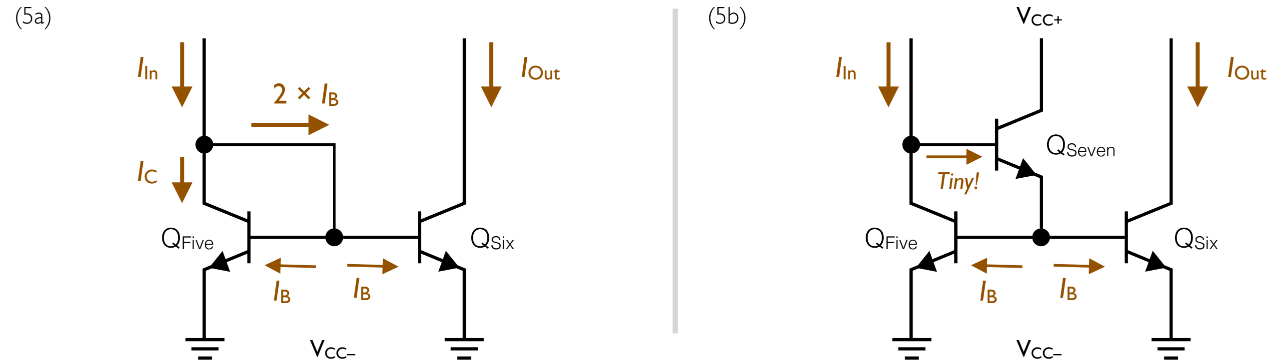


Figure 5: Simple and buffered current mirrors

§3.2 *Current Mirrors*

Transistors Q5, Q6, and Q7 form an active load *current mirror* circuit that increases the gain of our differential amplifier.

A current mirror is called that because it "copies" a current through one circuit element to a current in another element. To illustrate how that works, Figure 5 shows two current mirror circuits similar to those in the '741. We have named the transistors here Q_{Five}, Q_{Six}, and Q_{Seven} to note their correspondence to those in the '741.

Figure 5a shows a basic current mirror. Notice how Q_{Five} and Q_{Six} are connected. Transistor Q_{Five} is wired up *as a diode*, with its collector connected to its base, allowing current to flow through its emitter. Part of the input current I_{In} provides the base current I_B that turns on the two transistors. Since their bases and emitters have the same voltages, symmetry dictates that the same amount of current flows from the base to the emitter in both transistors. Furthermore, since both transistors have the same gain, they will also have the same collector current. (Recall that $I_C = h \times I_B$ from §2.2.) In this sense, the output current I_{Out} through the collector of Q_{Six} "mirrors" the collector current through Q_{Five}.

Aside: Matched transistors
We have just relied on two properties of the transistors being equal: the current-voltage curve of the base-emitter junction and the transistor gain. This generally requires excellent matching between the two transistors. *Ideally*, the two transistors should be fabricated as part of the same IC die for the best possible performance. There are other places on the '741 where matched transistor pairs are needed as well – notably differential input transistors Q1 and Q2 should be matched as should Q3 and Q4.

While the collector currents are mirrored, there is some subtlety since the base currents for both transistors are supplied by the input current: $I_{In} = I_C + 2 \times I_B$. Given that the output current I_{Out} is equal to I_C, we have $I_{Out} = I_{In} - 2 \times I_B$. Thus, the output current is a bit less than the input current.

Since even a small current difference puts the differential amplifier off balance and creates offset errors, the '741 has an enhanced current mirror, of the type shown in Figure 5b.

In this case, a third "buffer" transistor (Q_{Seven}) provides most of the base current directly from the power supply, sipping only a tiny fraction of current from the input current I_{In} to drive its base. This allows the output current to be much closer in value to the input current than it would without the third transistor.

§3.3 *The Offset Null Pins*

Inputs 1 and 5 of a '741 are "offset nulling" pins. These inputs allow the bias currents in each side of the differential amplifier to be adjusted so that any remaining offset voltage can be zeroed out.

When the **+** and **–** inputs of a '741 are equal (connected together) the output voltage at pin 6 should ideally be zero. In the real world, thanks to imperfect component matching, the output is never exactly zero. Typically there is an *input offset voltage*, such that a slightly different voltage (perhaps as much as 10 mV) needs to be applied to the two inputs in order to make the output zero. To compensate for this with the nulling inputs, hook a 10 kΩ potentiometer between the two pins (pin 1 and pin 5), with the potentiometer's wiper connected to V_{CC-}. Then, adjust the pot until the output is zeroed.†

It is worth noting that *most* circuits that incorporate a '741 are not particularly sensitive to input offsets. Accordingly, most '741 circuits leave these two terminals permanently unconnected.

† When the two inputs are connected together and the output is disconnected, the output "prefers" to be fully positive or negative, as it amplifies even tiny differences between the inputs. However, one can always trim the pot until the *offset* is almost exactly zero.

§3.4 *The Common Mode Control Loop*

Much as the differential input voltage refers to the difference between the input voltages, the *common mode voltage* is the average voltage of that on the **+** and **–** input terminals. See Figure 6 for an illustration. If both inputs change in value such that the difference between the two stays the same — for example if both inputs rise by 2 V — then we say that their common-mode voltage has changed but their differential voltage has not.

An ideal op-amp should be sensitive only to the differential input voltage. Its output should *ignore* any common-mode voltage, whether steady or changing. The '741 has a rather clever circuit, the "common mode control loop" to help manage this.

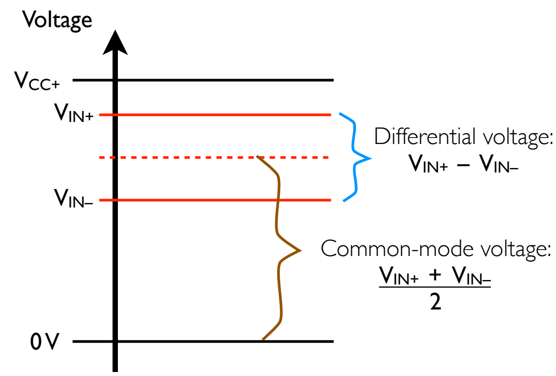


Figure 6: Differential vs common-mode voltages

Transistors Q8 and Q9 form a current mirror similar to the one in §3.2. Unlike the previous example this current mirror uses PNP instead of NPN transistors. However, it works in essentially the same way, and Q9 "mirrors" Q8. You could also say that the Q9's collector current represents a measurement of the sum total bias current (amplified by the transistor gain) that flows into the differential amplifier.

Separately, in the Bias Generator block, transistor Q10 generates a fixed reference current through its collector. (We will discuss this further in §4.) Thus the measured bias current from the collector of Q9 flows into the circuit node (wire) that connects Q9 and Q10, while a fixed reference current flows out of it. The difference between these two current values must be taken up by current that flows into or out of the node connecting the bases of Q3 and Q4.

> *Aside:* The statement above is true because total amount of current that flows into and out of a given circuit node must sum to zero. If this does not seem intuitive to you, you might want to learn about or review Kirchhoff's circuit laws.

If the bias current is larger than the reference current, then the extra current must flow towards the differential amplifier, increasing the voltage at the bases of Q3 and Q4. This decreases the voltage across the base emitter junctions of the transistors Q1, Q2, Q3, and Q4, reducing the input current and therefore the measured bias current.

If the bias current is smaller than the reference current, then current must flow out of the differential amplifier into Q10. Thus the voltage at the bases of Q3 and Q4 decreases, increasing the voltage across the base emitter junctions of transistors Q1, Q2, Q3, and Q4, and increasing the input current. See Figure 7.

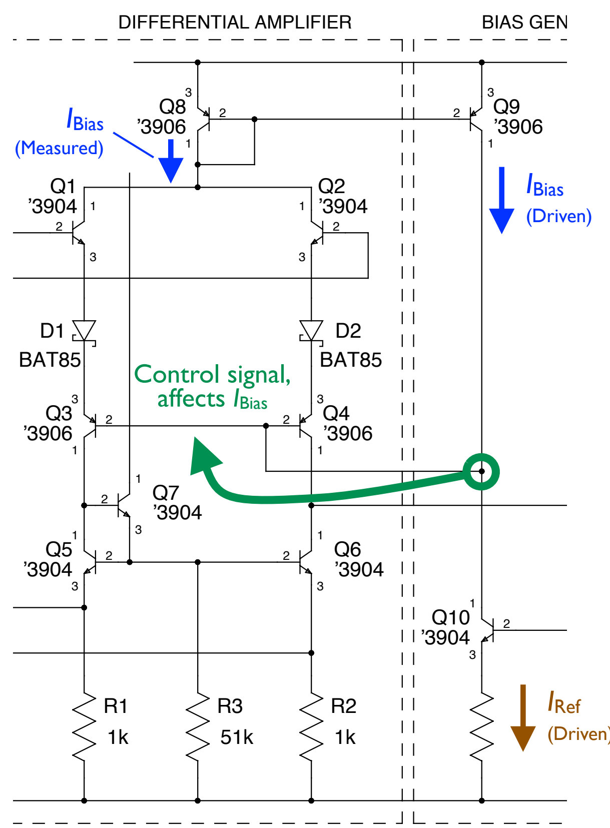


Figure 7: The common-mode control loop

The end result is that this circuit sets the base voltage of Q3 and Q4 to follow the optimal common mode input voltage of the opamp, and at the same time, it controls the maximum input bias current.

§3.5 *Questions and Experiments I*

1. Short the base and emitter terminals of Q7. How does this change the performance?

2. On a real (integrated circuit) '741, try measuring the values of R1 and R2. You can do this with an ohmmeter connected to V_{CC-} and one or the other offset null pins (while disconnected from power). How close are they to the nominal specification of 1 kΩ?

3. Measure the voltage on the two offset pins of a real (integrated circuit) '741 and compare them with the same measurements on the discrete '741. Measure the resistance between that terminal and the negative rail (with the op-amp powered off), and calculate the bias current in the differential amplifier. Try adjusting the common mode voltage to see if it changes the bias current. The easiest way to control the common mode voltage is by connecting the amplifier as a voltage follower and manipulating the voltage supplied to the noninverting input.

4. How can you disable the common mode control loop? Don't forget about the bias current mirror Q8,Q9; the changes might be more extensive than you think.

5. How precisely do the transistors need to be matched? What happens if the transistor matching is poor?

6. The XL741 and 741SE kits use discrete transistors that are separately manufactured and do not come in matched pairs. Why does this still work? How does the input offset voltage (for example) compare to that on an integrated circuit '741?

7. How does an active load compare to a traditional passive load – i.e., a resistor? Could an op-amp be made with a resistive load instead?

8. What purpose does R3 serve? What would be different if it were not there?

§4.0 The Bias Generator

The core of the bias generator circuit is formed by diode-connected transistors Q11 and Q12. These create a reference current set by the supply voltages and by R5. Q12 and Q13 act as a current mirror that provides bias current to the gain stage.

Transistors Q10, Q11, and resistor R4 form what is called a Widlar current source. The output current of the Widlar source is the reference current divided by a fixed ratio determined by R4. A small fraction of the reference current flows into the collector of Q10, and this reference current is used by the common mode control loop.

Unlike most modern analog ICs which have a reference current that depends only on temperature (PTAT, or Proportional To Absolute Temperature), the '741 reference current changes when the supply voltage changes. This is probably why the datasheet specifies performance for supply voltages of +/15V only. Modern opamps use internal compensated current sources which make them operate consistently over a wide supply voltage range.

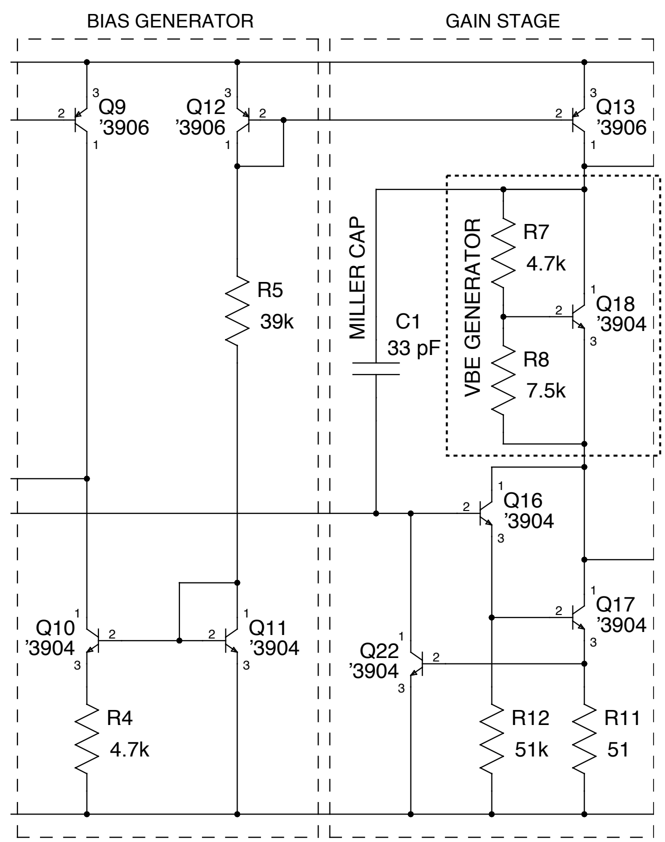


Figure 8: Bias Generator

§4.1 *Questions and Experiments II*

1. Try changing the value of R5. How does this impact the performance? How about the supply current?

§5.0 The Gain Stage

The gain stage performs the multiplication function on the the signal coming from the differential amplifier. Before we get into the heart of it, let's look at a couple of the building blocks that we'll use.

§5.1 *Background: Darlington transistors*

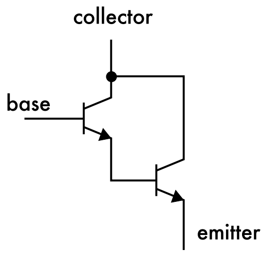


Figure 9:
The Darlington

Two of the transistors in the gain stage, Q16 and Q17 are wired together emitter-to-base in what is known as the Darlington configuration.

In the Darlington configuration, the emitter of one transistor is hooked to the base of another. This effectively makes one new "super transistor" out of the two, since it is the amplified current out of the first collector that serves as the base current for the second transistor. If the gain of a single transistor were 30, then the effective gain of the Darlington pair would be 30 × 30 = 900.

This huge improvement in gain is not without cost. Since there are two transistors, there are also two diode drops to be overcome; the Darlington pair will not begin to turn on until its base is at least 1.4 V above the emitter.

§5.2 *Background: The common-emitter amplifier*

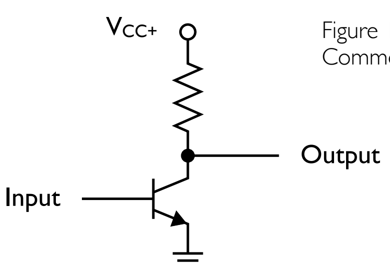


Figure 10:
Common emitter

The transistor circuit snippet above is called a *common emitter* amplifier. "Common" in this context means that the emitter is shared reference point between the input and output of the circuit. In this particular instance, common is also ground, and this configuration is sometimes called a "grounded emitter" amplifier.

Thanks to the gain of the transistor, a small current into the input causes a larger current to flow from V_{CC+} to ground, going through the "load" resistor along the way. Since the voltage drop across the resistor increases as the current through it increases, the voltage on the output *decreases* as the input current increases. That is to say, this is an *inverting* amplifier.

§5.3 *Inside the gain stage*

The Darlington pair Q16,Q17 form the heart of the gain stage. It amplifies the signal coming from the differential amplifier. Since it is arranged as a common-emitter amplifier, it also inverts the input signal. Remember how the differential amplifier output seemed backwards? The gain stage takes this inverted output and changes the polarity back to the intended one.

Q13, which mirrors Q12, is the load of the amplifier. It is an active load to maximize the gain of the circuit. You can think of an active load as a current source (it is a current mirror, after all) in parallel with a large, fixed resistor. This effective resistor plays the role of the load resistor in the common-emitter amplifier shown in §5.2. However, as an active load, it has a very high impedance (meaning that the voltage across it varies strongly as a function of current) while maintaining a relatively constant amount of bias current through it.

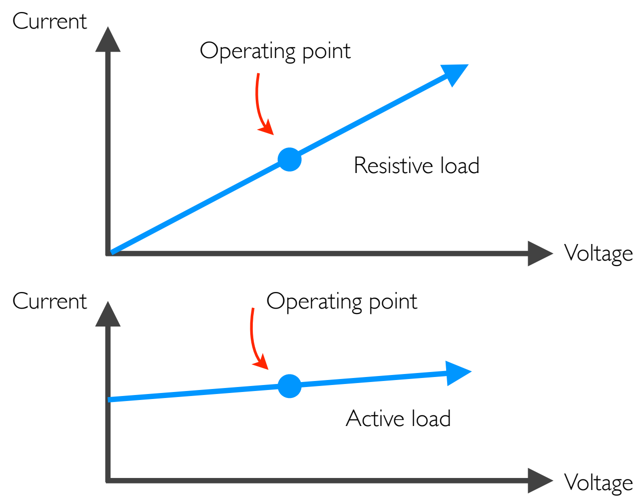


Figure 11: Resistor versus active load

Q18, working with R7 and R8, is called a V_{BE} generator. It generates a fixed voltage drop of roughly 1.2 V regardless of what the amplifier is doing. The gain stage therefore has two outputs: one is the signal directly coming from the collector of Q17, and the other is the same voltage shifted up by 1.2 V. If the V_{BE} generator were not there, the output would exhibit crossover distortion.

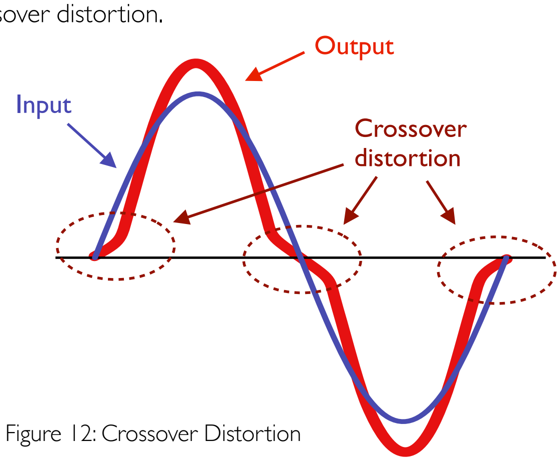


Figure 12: Crossover Distortion

This distortion happens when the output voltage crosses 0 V (either rising or falling) and both transistors are shut off or close to being shut off. If the V_{BE} generated too much voltage, then both transistors could be on at the same time, which would waste power.

C1 is the compensation capacitor (and the only capacitor in the '741), also known as a Miller capacitor. This capacitor stabilizes the behavior of the op-amp at the cost of some gain. The introduction of this capacitor into the op-amp itself was the key innovation that led to the success of the '741. At the time of its introduction, all other opamp ICs required an external compensation network and thus were harder to use.

Aside: Frequency compensation

An analysis of the ac performance of the '741 is outside of the bounds of this discussion, but we can mention the broad strokes as they relate to the capacitor. (We will use some new terms that you might want to research separately!)

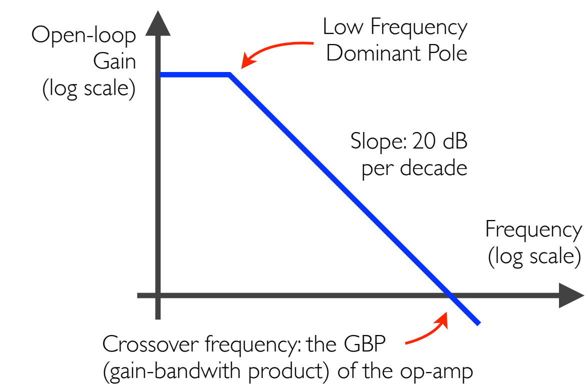


Figure 13: Frequency Response

The addition of the C1 creates a lowfrequency "pole" in the frequency response that dominates all the other effects caused by parasitics. That is to say (in essence, and glossing over some details) that we add one large capacitor, which overwhelms various stray capacitances from all of the components within the op-amp, and leaves the output performance (gain as a function of frequency) instead constrained by an *intentionally* chosen component.

This method is known as dominant pole compensation. It is very much the same thing as adding a large RC low-pass filter within the circuit, which costs gain at higher input frequencies, but makes the opamp's characteristics predictable and easy to work with.

§6.0 The Output Stage

The output stage uses two transistors configured as emitter followers. Q14 can source current to the output, and Q20 can sink current from the output. This allows the opamp to drive current in either direction depending on the needs of the circuit connected to the output terminal.

Q15, in combination with R9, acts as a current limit when the opamp is sourcing (outputting positive) current. When high current flows through R9, it increases the base-emitter voltage across Q15 enough that it can begin to conduct. As Q15 turns on more, it "steals" current from the base of Q14, reducing the amount of emitter (output) current.

§5.4 *Questions and Experiments III*

1. What happens to the supply current if you increase the voltage generated by Q18 by increasing R8? What happens if you decrease the voltage generated by Q18, or short out Q18's collector and emitter? Try configuring the opamp as a voltage follower driving a 1 kΩ load, with a sine wave input. Compare the input to the output on an oscilloscope.

2. What happens if you remove C1? What happens if you increase C1?

3. Can you measure and reproduce the curve in figure 13? This is easiest with a variable-frequency signal generator and an oscilloscope. At what frequency is the "knee" of the plot? What happens at the crossover frequency? Compare the results to that which you get with an integrated circuit '741.

4. Short Q16's base and emitter. What happens? Try building some high gain amplifier circuits and measure the actual gain.

5. What happens if you replace Q13 with a resistor? Try removing Q13 and connecting a 39 kΩ resistor from the collector connection to the emitter connection. You can test it with a voltage follower configuration and a pulse generator.

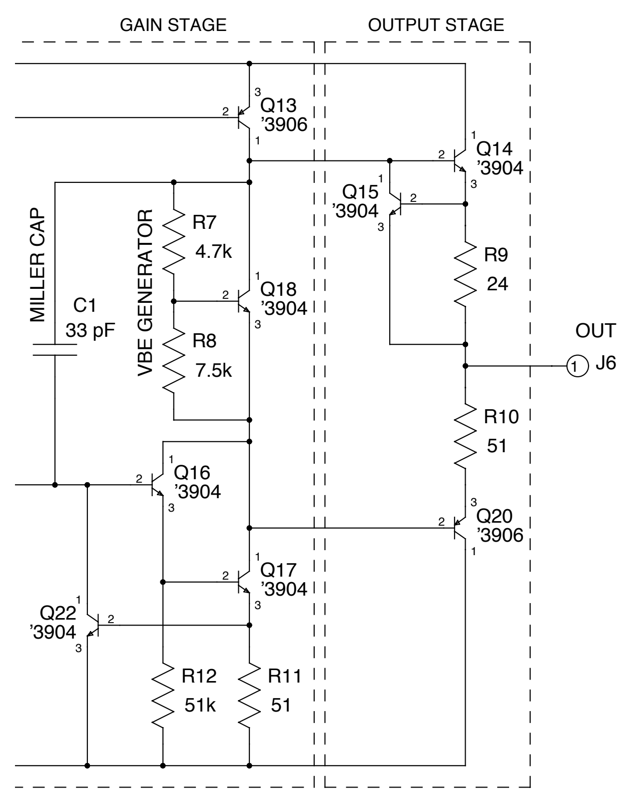


Figure 14: Output stage

When the opamp sinks (outputs negative) current, a fraction of this incoming current flows through R11. As the voltage on R11 increases, the current limit transistor Q22 begins to turn on and steal current from the Darlington pair Q16,Q17, which increases the output voltage, reducing the sink current. The XL741 and 741SE can sink much more current than a the original '741 because the '3906 PNP transistor has more gain than the lateral PNP used in a '741 integrated circuit.

§6.1 *Questions and Experiments IV*

1. Do Q14 and Q20 conduct current at the same time? In other words, does the V_{BE} generator create enough of a voltage drop that both transistors are on at the same time? Why might this be done?

2. What is the current limit of the discrete '741? Is it the same for sourcing and sinking current? How "sharp" is this limit? Compare its behavior to that of an integrated circuit '741.

3. Is it possible to change the current to limit at ± 50 mA? How would you go about doing this?

4. Suppose that you wanted to build a high-power '741, capable of sourcing or sinking 1 A of current by changing the components in the output stage. How would you go about doing this? What components, besides those that limit the current would need to be changed, and why?

5. What is the total range of the XL741/741SE output? How does it depend on the total power supply voltage? What sets this range?

6. Some op-amps have a "rail to rail" output feature, where the output voltage can get to within millivolts of the positive or negative power supply pins. How do these circuits work? Could you design an output stage for the discrete '741 that has a larger output range?

7. What sets the *minimum* power supply voltage required for a '741 to work properly?

FURTHER READING

1. Main XL741 and 741SE Documentation page: http://wiki.evilmadscientist.com/741

2. Main product pages for the kits XL741: https://emsl.us/762 741SE: https://emsl.us/923

3. Original Fairchild µA741 datasheet (scanned): https://cdn.evilmadscientist.com/wiki/741/ua741.pdf

4. A modern µA741 IC datasheet: http://www.ti.com/lit/ds/slos094g/slos094g.pdf

5. Tube Time, the web site of Eric Schlaepfer, designer of the XL741 circuit board: http://tubetime.us

6. Texas Instruments App Note 31 has a great number of basic op-amp example circuits: http://www.ti.com/lit/an/snla140c/snla140c.pdf

7. Wikipedia is an excellent resource for learning basic electronics. Some potential topics of interest include:
   https://en.wikipedia.org/wiki/Operational_amplifier
   http://en.wikipedia.org/wiki/Current_mirror
   http://en.wikipedia.org/wiki/Transistor
   http://en.wikipedia.org/wiki/Common_emitter
   http://en.wikipedia.org/wiki/Widlar_current_source
   https://en.wikipedia.org/wiki/Active_load
   https://en.wikipedia.org/wiki/Miller_effect

8. Analog Devices Op Amp History
   http://www.analog.com/library/analogDialogue/archives/39-05/Web_ChH_final.pdf (Short url: http://bit.ly/1Kfe4yX)
   A detailed history of operational amplifiers, beginning with vacuum tubes.

9. Huijsing, Johan H. Operational Amplifiers, Theory and Design. Boston: Klewer, 2001. Print. pp. 292294.
   A brief but more technical description of the µA741.

10. Grey, Paul R., Hurst, Paul J., Lewis, Stephen H., and Meyer, Robert G. Analysis and Design of Analog Integrated Circuits (4th Edition). New York: Wiley, 2001. Print. pp. 454472.
    A very good technical description of the µA741 with a lot of detail and mathematical analysis. Be sure to get the 4th edition; the section on the µA741 was removed from subsequent editions.

Your corrections and suggestions for this document are welcome.
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