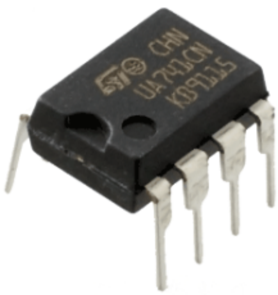
Physics 364, Fall 2014, Lab #9 **Name:** ____________

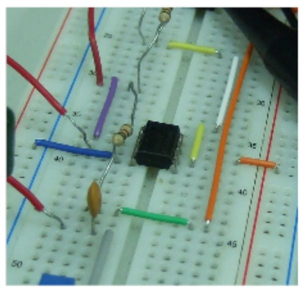
(opamps III: departures from ideal behavior)

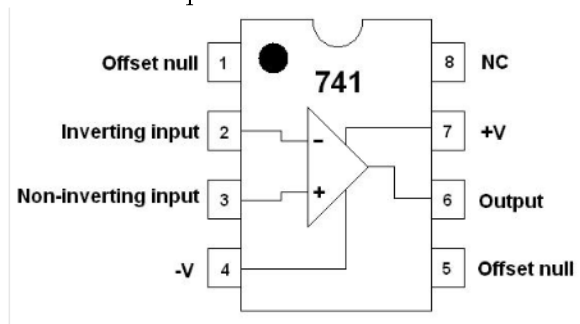
Monday, September 29 (section 401); Tuesday, September 30 (section 402)

Course materials and schedule are at `positron.hep.upenn.edu/p364`

Today we study the real-world imperfections of opamps, i.e. departures from the ideal behavior described by the Golden Rules. A new circuit (the AC amplifier) illustrates a simple work-around for one common consequence of these imperfections.



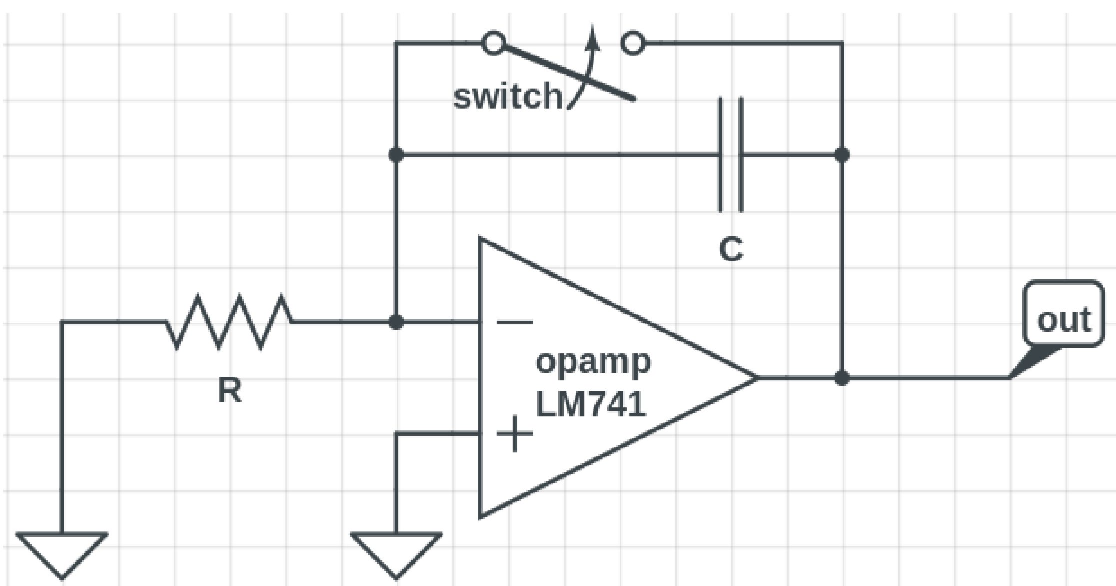




Part 1 **Start Time:** ____________

effect of I_{bias} and V_{offset} on opamp integrator (time estimate: 45 minutes)

Wire up the now-familiar opamp integrator, but without a bleeder resistor. Use $R = 1\ \text{k}\Omega$, $C = 1\ \mu\text{F}$, $V_{S\pm} = \pm 15$ V. Use a blue polyester capacitor so that you don't need to worry about polarity. Ground the integrator's input (the left side of the resistor), as shown below. You can find a push-button (momentary contact, normally open) switch in the back room, or you can just momentarily connect a piece of wire whenever you need to zero the charge on the capacitor.



1.1 Once the switch has been open (or the wire removed) for many seconds, what output do you see?

Use your pushbutton switch (or piece of wire) to discharge the capacitor (by momentarily shorting its leads together). What output do you expect **immediately** after opening the switch (or removing the wire)? What do you see?

How quickly does V_{out} reach saturation near the power supply rails? (What is $\mathrm{d}V_{\mathrm{out}}/\mathrm{d}t$? If it is too fast, you can set up the scope to trigger when V_{out} is about halfway to saturation.)

And how close to ± 15 V does it reach?

If you take the data sheet values for V_{os} (≈ 1 mV) and I_{bias} (≈ 100 nA) at face value, roughly how large do you expect the contributions of I_{bias} and V_{os} to $\mathrm{d}V_{\mathrm{out}}/\mathrm{d}t$ to be? (Note that in general you can estimate the magnitudes of these effects, but the precise values and even the signs can vary from opamp to opamp, so you can't say *a priori* whether the two effects will add to or subtract from each other.)

It takes some effort to think this through. Be sure to take the time to understand it, and ask us to help you check your reasoning. Also, I've enclosed my own analysis below (a few pages in) for you to look at.

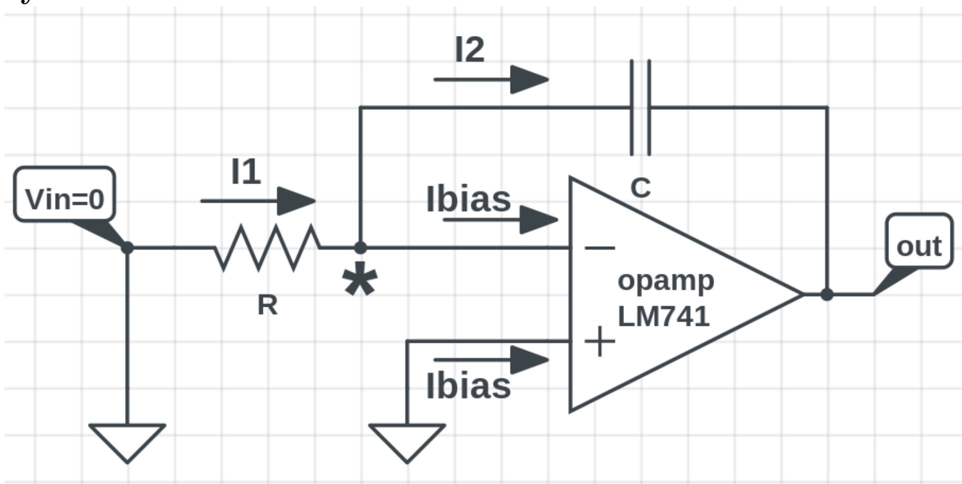
1.2 To see the effect of I_{bias} alone, let the input float (i.e. remove the ground connection to the resistor). Now I_{bias} must charge the capacitor, and V_{os} will not cause any current to flow through the resistor.

What is $\mathrm{d}V_{\text{out}}/\mathrm{d}t$ now?

Estimate I_{bias} and V_{offset} by combining the results from part 1.1 [which is affected by both I_{bias} and V_{os}] and 1.2 [which is affected by only I_{bias}]. Compare your measured (or estimated) values with the specifications from the '741 data sheet.

1.3 Connect a 10 kΩ potentiometer between pins 1 and 5, with the wiper (the center pin) connected to −15 V. Ground the integrator's input again (through R). Try to adjust the "trim" potentiometer such that $V_{\rm os}$ is zeroed. The goal is to get $|\mathrm{d}V_{\rm out}/\mathrm{d}t|$ as close to zero as possible. (This adjustment is called "trimming" the opamp.) How well do you do? Does your offset stay properly trimmed even if you try to heat up or cool down the opamp? (You can blow on it to cool it or hold your thumb on it to heat it a bit.)

Bill's analysis for Part 1



Including the offset voltage V_{os} in the opamp gain definition gives

$$V_{\mathrm{out}} = A \cdot (V_+ - V_- + V_{\mathrm{os}}) \;\Rightarrow\; \frac{V_{\mathrm{out}}}{A} = V_{\mathrm{os}} - V_- \;\Rightarrow\; V_- = V_{\mathrm{os}} - \frac{V_{\mathrm{out}}}{A}.$$

Using K.C.L. at node $*$ gives $I_1 - I_2 - I_{\mathrm{bias}} = 0$. Then substituting for I_1 and I_2,

$$\frac{V_{\mathrm{in}} - V_-}{R} + C\frac{\mathrm{d}}{\mathrm{d}t}(V_{\mathrm{out}} - V_-) - I_{\mathrm{bias}} = 0.$$

Plugging in the above value for V_- gives

$$\frac{V_{\mathrm{in}}}{R} - \frac{V_{\mathrm{os}}}{R} + \frac{V_{\mathrm{out}}}{AR} + C\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}t} + \frac{C}{A}\,\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}t} - I_{\mathrm{bias}} = 0$$

which in the limit $A \to \infty$ becomes

$$\frac{V_{\mathrm{in}}}{R} - \frac{V_{\mathrm{os}}}{R} + C\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}t} - I_{\mathrm{bias}} = 0$$

which we can rearrange to get

$$\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}t} = \frac{V_{\mathrm{os}}}{RC} - \frac{V_{\mathrm{in}}}{RC} + \frac{I_{\mathrm{bias}}}{C}.$$

Finally, using $V_{\mathrm{in}} = 0$, we have

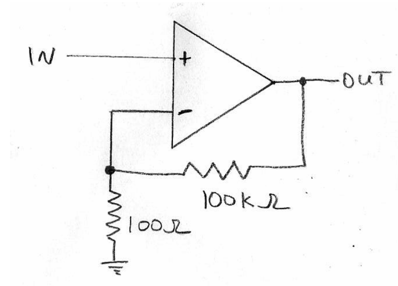
$$\boxed{\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}t} = \frac{V_{\mathrm{os}}}{RC} + \frac{I_{\mathrm{bias}}}{C}}\,.$$

When you let the resistor's ground connection float (for part 1.2), you can use the same equation with $R = \infty$.

Part 2 **Start Time:** ____________

non-inverting amplifier reveals imperfections (time estimate: 45 minutes)

2.1 Build the amplifier shown at right. What do you expect its gain to be? (When the gain is so large, is it easy to measure what the gain really is?)



Now remove whatever input signal source (if any) you might have been using to try to measure the gain, and connect V_{in} to ground through a 100 Ω resistor. This provides a balanced (and low-resistance) path to ground at both opamp inputs, which cancels the effect of I_{bias} and makes the effect of I_{os} very small. How small an effect do you expect, if I_{os} is expected to be ≈ 10 nA? Hint: compare the IR drop for $I_{os} \approx 10$ nA flowing across a 100 Ω resistor with $V_{os} \approx 1$ mV. Also look at my analysis below — a few pages in.

Measure V_{out}. What do you infer about V_{os}? Compare your measured V_{os} with the '741 specification and with your estimated V_{os} from Part 1. Make this measurement with your **trim pot disconnected** from your opamp, but note that you will reconnect the trim pot for part 2.2.

2.2 Now connect a 10 kΩ trim pot between pins 1 and 5, with the wiper (the center pin) connected to −15 V, and zero $V_{\rm os}$ as best you can. Then replace the 100 Ω input resistor with 10 kΩ, so that the bias current at the opamp's non-inverting input flows through a fairly large resistor. Measure $V_{\rm out}$ now. Then try 100 kΩ, and measure $V_{\rm out}$ again. What do you infer about $I_{\rm bias}$? Is your measured $I_{\rm bias}$ consistent with the '741 data sheet?

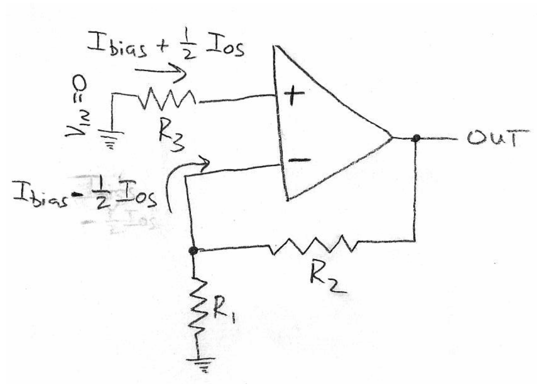
2.3 Choose components to change the amplifier's gain to (approximately) $\times 100$. (For this part, it shouldn't matter too much whether you keep your trim pot in place or remove it.) Drive V_{in} with a 1 kHz sine wave, about 1 V_{pp}. How close does V_{out} get to ± 15 V before saturating? Try using ± 20 V supply voltages. (What range of supply voltages does the '741 data sheet allow?) Now where is the limit on V_{out}?

Reduce the amplitude until V_{out} no longer saturates. Vary the frequency to measure f_{3dB}: that's the frequency at which $\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right|$ is reduced by a factor $\frac{1}{\sqrt{2}}$ from its maximum value (which in this case is at low frequency, since the opamp contains an internal low-pass filter).

Now change the amplifier's gain to approximately $\times 10$. (What resistors did you choose? You may find that $\times 11$ is a more practical choice than $\times 10$ exactly.) What is f_{3dB} now?

How can you change the gain to $\times 1$? (This is somewhat tricky.) What is f_{3dB} for gain=1? What is the gain$\times$bandwidth product that you measure for the '741? This product should be about the same for your $\times 1$, $\times 10$, and $\times 100$ amplifiers. How does it compare with the data sheet's value?

Bill's analysis for Part 2



We start with the equation for an opamp with finite gain A and offset voltage $V_{\rm os}$:

$$V_{\rm out} = A \cdot (V_+ + V_- + V_{\rm os}).$$

As drawn above, current $I_{\rm bias} + \frac{1}{2}I_{\rm os}$ flows into the opamp's non-inverting (+) input, and current $I_{\rm bias} - \frac{1}{2}I_{\rm os}$ flows into the opamp's inverting (−) input. Using Ohm's law for R_3 and the fact that $V_{\rm in}$ is grounded, we find

$$V_+ = V_{\rm in} - R_3 \cdot (I_{\rm bias} + \frac{1}{2}I_{\rm os}) = -R_3 \cdot (I_{\rm bias} + \frac{1}{2}I_{\rm os}).$$

To find V_-, I'm going to do something tricky, which I think you should be able to follow. If the (−) input drew no current, we could use the voltage-divider equation to write $V_- = V_{\rm out}R_1/(R_1 + R_2)$. But then how do we correct V_- for the fact that current really does flow into the (−) terminal of the opamp? Well, we know that $R_{\rm thev}$ of a voltage divider is $R_1 \parallel R_2$, and we know that the whole point of $R_{\rm thev}$ is to tell us how much the voltage divider's output voltage changes in proportion to the current that we draw from the voltage divider's output: remember that $(-R_{\rm thev})$ is the slope of the $V_{\rm output}$-vs.-$I_{\rm output}$ curve for an imperfect voltage source. Using $R_{\rm thev} = R_1 \parallel R_2$, we have

$$V_- = V_{\rm out} \cdot \frac{R_1}{R_1 + R_2} - (R_1 \parallel R_2)(I_{\rm bias} - \frac{1}{2}I_{\rm os}).$$

But now because $R_1 \ll R_2$ in this circuit, we can replace $R_1 \parallel R_2$ with R_1 alone:

$$V_- = V_{\rm out} \cdot \frac{R_1}{R_1 + R_2} - R_1 \cdot (I_{\rm bias} - \frac{1}{2}I_{\rm os}).$$

Then we can solve for $V_{\rm out}$ (in the $A \to \infty$ limit) and find (after some hidden work):

$$V_{\rm out} = \frac{R_2 + R_1}{R_1}\left(V_{\rm os} + (R_1 - R_3)I_{\rm bias} - \frac{R_1 + R_3}{2}I_{\rm os}\right).$$

The ×1001 gain of the amplifier circuit makes $V_{\rm os}$ measurable. We can see $I_{\rm bias}$ only if $R_1 - R_3$ is large. And we can see $I_{\rm os}$ if $R_1 + R_3$ is large.

Part 3 **Start Time:** ______________

slew-rate and output-current limitations (time estimate: 30 minutes)

3.1 Build an opamp follower. (Draw the schematic, to refresh your memory.) Drive it with a 1 kHz square wave. Look at V_{in} and V_{out} with the scope. Infer the slew rate from the slope of V_{out}. Compare the measured slopes of V_{in} and V_{out}, so that you are sure that you are looking at an effect of the amplifier and not of the scope or FG. Do you see a limit on the slope of V_{out}? Compare your measurement with the '741's slew-rate specification.

Now try changing the amplitude. Does the slope of V_{out} change? If you were looking at a linear low-pass effect, rather than a slew-rate effect, how would the slope change with amplitude? (Remember that for a linear circuit, multiplying the input by a constant always multiplies the output by that same constant.)

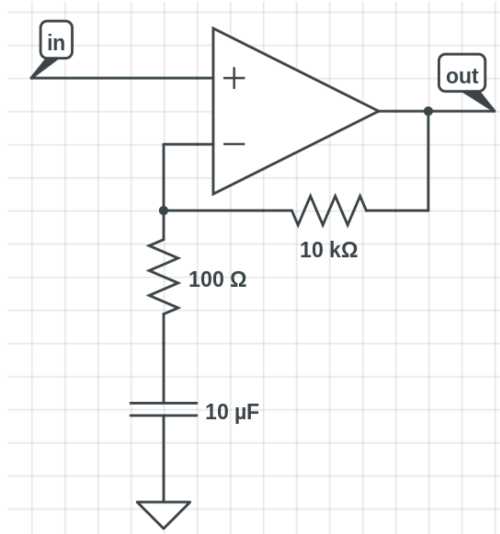
3.2 Try a 10 V_{pp} sine wave input now. Raise the frequency until you see the *shape* of the sine begin to distort. What is the maximum slope of a 10 V_{pp} sine wave of frequency f? What slew-rate limit do you infer? Compare again with the '741's slew-rate specification and with your measurement in 3.1.

3.3 Now load the follower's output with a 100 Ω resistor to ground. Try driving V_{in} with a 1 kHz sine wave of various amplitudes. Try 100 Hz sine waves, too. (Trying sine waves of the same amplitude but two different frequencies should help you to convince yourself that you're not looking at a slew-rate limit here.) Do you see a current limit on the opamp's output? (If there were such a limit, how would you see it?) Measure the maximum current. Now try a 200 Ω resistor (or two 100 Ω resistors in series). Do you measure the same current limit? Compare with the '741's specification (which is ≈ 25 mA).

Part 4 **Start Time:** ______________

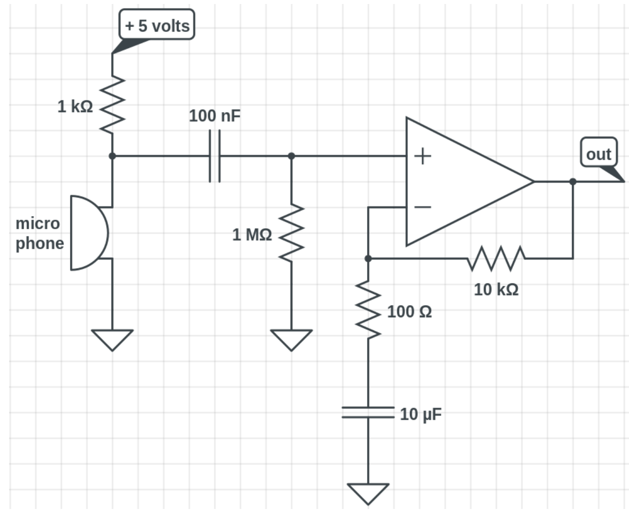
high-gain AC amplifier (time estimate: 30 minutes)

4.1 Calculate (making approximations to keep your calculations simple) the gain of the amplifier drawn in the figure. Make separate estimates at DC and at about 1.6 kHz. An answer good to ±10% is close enough. Notice that $(2\pi)(1.6) \approx 10$.



Now build it and check your calculation by measuring the gain at low frequency and at 1.6 kHz. The idea here is that V_{os} and I_{bias} are DC effects, whereas the signals that you want to amplify are often time-varying. The DC component of your time-varying signal may be arbitrary or uninteresting. So one easy way to make a high-gain amplifier that circumvents V_{os} and I_{bias} is to kill the gain of your amplifier at DC, as we do here, so that small DC offsets are not amplified. Keep this trick in mind, as you will see it again when we study transistor circuits.

4.2 Now let's connect a microphone, as shown below. You can google "Jameco 1950948" to see the microphone's specifications if you're curious. Feed various sounds into the microphone and try to see them with the oscilloscope. Adjust your amplifier's gain if necessary to see a good signal. We have speakers available, if you want to play sounds with the function generator. Also, if you have time, this is a great opportunity to try out the scope's FFT (fourier transform) display, to view the frequency content of your amplified sounds.



What happens to V_{out} if you remove the 1 MΩ input resistor? Why? (Think about I_{bias}.) Now put back the 1 MΩ resistor.

What happens to V_{out} if you connect the 100 Ω resistor directly to ground, eliminating the 10 μF capacitor? Why? (Think about V_{os}.)

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National Semiconductor

August 2000

LM741 Operational Amplifier

General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

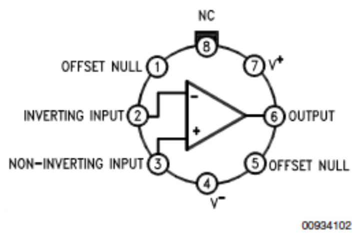
The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0°C to +70°C temperature range, instead of −55°C to +125°C.

Features

Connection Diagrams

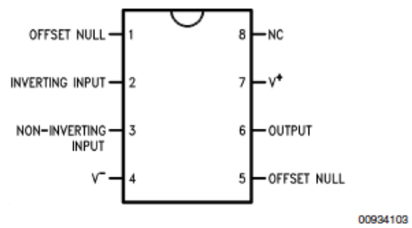
Metal Can Package



Note 1: LM741H is available per JM38510/10101

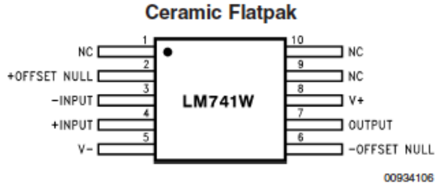
Order Number LM741H, LM741H/883 (Note 1), **LM741AH/883 or LM741CH**
See NS Package Number H08C

Dual-In-Line or S.O. Package



Order Number LM741J, LM741J/883, LM741CN
See NS Package Number J08A, M08A or N08E

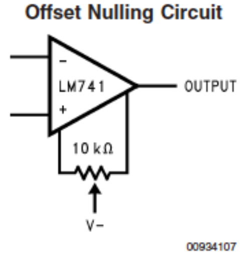
Ceramic Flatpak



Order Number LM741W/883
See NS Package Number W10A

Typical Application

Offset Nulling Circuit



 www.national.com

Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

(Note 7)

	LM741A	LM741	LM741C
Supply Voltage	±22V	±22V	±18V
Power Dissipation (Note 3)	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V
Input Voltage (Note 4)	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous
Operating Temperature Range	−55°C to +125°C	−55°C to +125°C	0°C to +70°C
Storage Temperature Range	−65°C to +150°C	−65°C to +150°C	−65°C to +150°C
Junction Temperature	150°C	150°C	100°C
Soldering Information			
N-Package (10 seconds)	260°C	260°C	260°C
J- or H-Package (10 seconds)	300°C	300°C	300°C
M-Package			
Vapor Phase (60 seconds)	215°C	215°C	215°C
Infrared (15 seconds)	215°C	215°C	215°C

See AN-450 “Surface Mounting Methods and Their Effect on Product Reliability” for other methods of soldering surface mount devices.

ESD Tolerance (Note 8)	400V	400V	400V

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25°C$										
	$R_S \le 10\ k\Omega$					1.0	5.0		2.0	6.0	mV
	$R_S \le 50\Omega$		0.8	3.0							mV
	$T_{AMIN} \le T_A \le T_{AMAX}$										
	$R_S \le 50\Omega$			4.0							mV
	$R_S \le 10\ k\Omega$						6.0			7.5	mV
Average Input Offset Voltage Drift				15							μV/°C
Input Offset Voltage Adjustment Range	$T_A = 25°C$, $V_S = \pm 20V$	±10				±15			±15		mV
Input Offset Current	$T_A = 25°C$		3.0	30		20	200		20	200	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							nA/°C
Input Bias Current	$T_A = 25°C$		30	80		80	500		80	500	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			0.210			1.5			0.8	μA
Input Resistance	$T_A = 25°C$, $V_S = \pm 20V$	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \le T_A \le T_{AMAX}$, $V_S = \pm 20V$	0.5									MΩ
Input Voltage Range	$T_A = 25°C$							±12	±13		V
	$T_{AMIN} \le T_A \le T_{AMAX}$				±12	±13					V

Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain	$T_A = 25°C$, $R_L \ge 2$ kΩ										
	$V_S = \pm 20V$, $V_O = \pm 15V$	50									V/mV
	$V_S = \pm 15V$, $V_O = \pm 10V$				50	200		20	200		V/mV
	$T_{AMIN} \le T_A \le T_{AMAX}$,										
	$R_L \ge 2$ kΩ,										
	$V_S = \pm 20V$, $V_O = \pm 15V$	32									V/mV
	$V_S = \pm 15V$, $V_O = \pm 10V$				25			15			V/mV
	$V_S = \pm 5V$, $V_O = \pm 2V$	10									V/mV
Output Voltage Swing	$V_S = \pm 20V$										
	$R_L \ge 10$ kΩ	±16									V
	$R_L \ge 2$ kΩ	±15									V
	$V_S = \pm 15V$										
	$R_L \ge 10$ kΩ				±12	±14		±12	±14		V
	$R_L \ge 2$ kΩ				±10	±13		±10	±13		V
Output Short Circuit	$T_A = 25°C$	10	25	35		25			25		mA
Current	$T_{AMIN} \le T_A \le T_{AMAX}$	10		40							mA
Common-Mode	$T_{AMIN} \le T_A \le T_{AMAX}$										
Rejection Ratio	$R_S \le 10$ kΩ, $V_{CM} = \pm 12V$				70	90		70	90		dB
	$R_S \le 50Ω$, $V_{CM} = \pm 12V$	80	95								dB
Supply Voltage Rejection	$T_{AMIN} \le T_A \le T_{AMAX}$,										
Ratio	$V_S = \pm 20V$ to $V_S = \pm 5V$										
	$R_S \le 50Ω$	86	96								dB
	$R_S \le 10$ kΩ				77	96		77	96		dB
Transient Response	$T_A = 25°C$, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		µs
Overshoot			6.0	20		5			5		%
Bandwidth (Note 6)	$T_A = 25°C$	0.437	1.5								MHz
Slew Rate	$T_A = 25°C$, Unity Gain	0.3	0.7			0.5			0.5		V/µs
Supply Current	$T_A = 25°C$					1.7	2.8		1.7	2.8	mA
Power Consumption	$T_A = 25°C$										
	$V_S = \pm 20V$		80	150							mW
	$V_S = \pm 15V$					50	85		50	85	mW
LM741A	$V_S = \pm 20V$										
	$T_A = T_{AMIN}$			165							mW
	$T_A = T_{AMAX}$			135							mW
LM741	$V_S = \pm 15V$										
	$T_A = T_{AMIN}$					60	100				mW
	$T_A = T_{AMAX}$					45	75				mW

Note 2: "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.

Electrical Characteristics (Note 5) (Continued)

Note 3: For operation at elevated temperatures, these devices must be derated based on thermal resistance, and T_j max. (listed under "Absolute Maximum Ratings"). $T_j = T_A + (\theta_{jA} P_D)$.

Thermal Resistance	Cerdip (J)	DIP (N)	HO8 (H)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100˚C/W	100˚C/W	170˚C/W	195˚C/W
θ_{jC} (Junction to Case)	N/A	N/A	25˚C/W	N/A

Note 4: For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

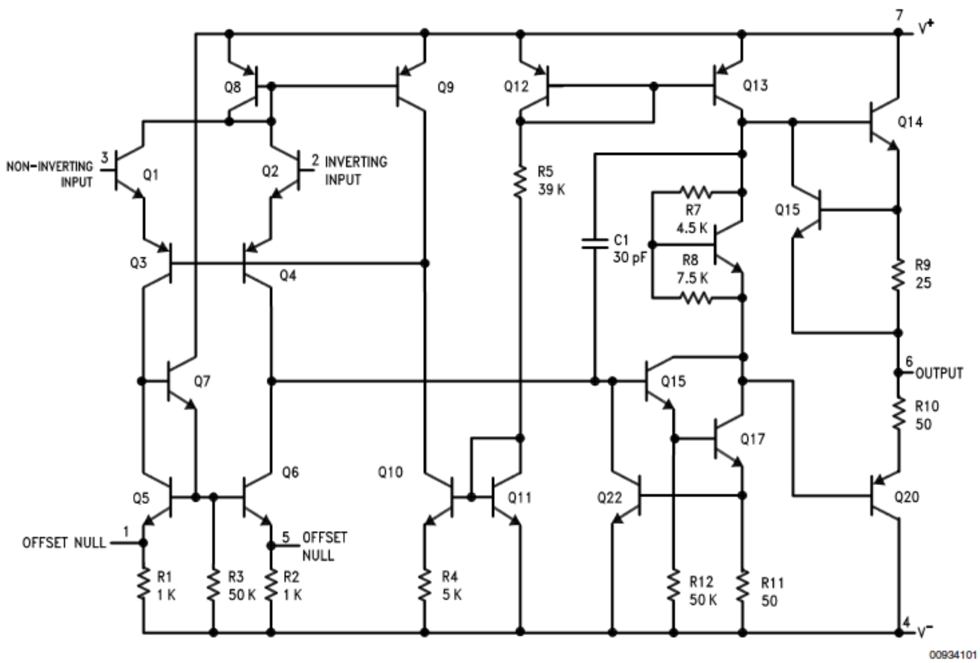
Note 5: Unless otherwise specified, these specifications apply for V_S = ±15V, −55˚C ≤ T_A ≤ +125˚C (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to 0˚C ≤ T_A ≤ +70˚C.

Note 6: Calculated value from: BW (MHz) = 0.35/Rise Time(µs).

Note 7: For military specifications see RETS741X for LM741 and RETS741AX for LM741A.

Note 8: Human body model, 1.5 kΩ in series with 100 pF.

Schematic Diagram



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