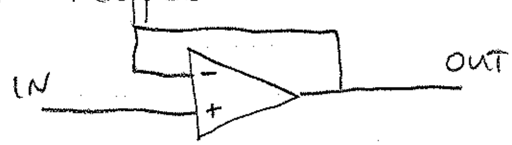
OPAMPS II

Last week, we used the "Golden Rules" of idealized opamps to analyze many useful opamp circuits: followers, (non)-inverting amplifiers, integrators, summing amp, etc.

Rule #2 (that inputs draw ≈ 0 current) is easy to understand as a consequence of the opamp's very high (typically $10^6 \sim 10^{12}\ \Omega$) input resistance. When we study transistor circuits, we will see how the large input resistance of transistor-based amplifiers arises.

Rule #1 (that negative feedback will adjust V_{out} such that $V_{in}^{+} \simeq V_{in}^{-}$) is less obvious. I said last week that Rule #1 was a consequence of the opamp's very high (typically ~ 10^6 or more) gain, but I gave no more details.

Let's analyze a few opamp circuits for an opamp of large but finite gain G, and then see what happens as $G \to \infty$.



FOLLOWER: $V_{OUT} = G \cdot (V_+ - V_-) = G \cdot (V_{IN} - V_{OUT})$

$V_{OUT}\,(1+G) = G \cdot V_{IN}$

~~$V_{OUT} = V_{IN} \cdot \frac{G+1}{G} = V_{IN}\left(1 + \frac{1}{G}\right)$~~

clearly $V_{OUT} \to V_{IN}$ as $G \to \infty$, which is the same result we got by using the Golden Rules.

oops: Vout = Vin * G/(G+1)

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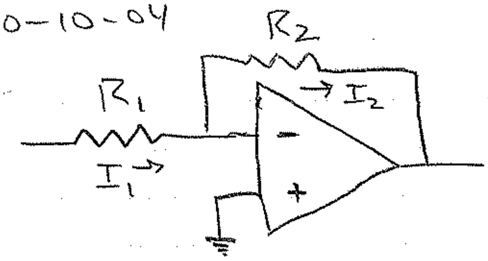
INVERTING AMP:



$$V_{OUT} = G \cdot (V_+ - V_-) = -G \cdot V_- \Rightarrow V_- = -\frac{V_{OUT}}{G}$$

using very large R_{IN} of opamp, $I_1 = I_2$

$$\Rightarrow (V_{IN} - V_-)/R_1 = (V_- - V_{OUT})/R_2$$

$$\Rightarrow \frac{1}{R_1}\left(V_{IN} + \frac{V_{OUT}}{G}\right) = -\frac{1}{R_2}\left(\frac{V_{OUT}}{G} + V_{OUT}\right)$$

some rearranging $\Rightarrow \frac{V_{OUT}}{V_{IN}} = -\frac{R_2}{R_1} \Big/ \left(1 + \frac{1}{G}\left(1 + \frac{R_2}{R_1}\right)\right)$

So $\frac{V_{OUT}}{V_{IN}} \rightarrow -\frac{R_2}{R_1}$ as $G \rightarrow \infty$

which again matches the Golden Rule result.

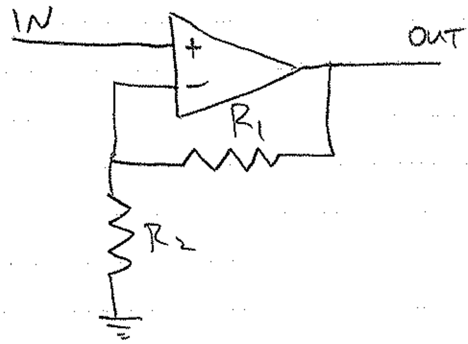
By the way, what is V_- now?

$$V_- = -\frac{V_{OUT}}{G} = -\frac{R_2}{R_1} V_{IN} \Big/ \left(G + 1 + \frac{R_2}{R_1}\right)$$

so as $G \rightarrow \infty$, $V_- \rightarrow 0$ ("virtual ground"),

as the Golden Rules imply.

NON-INVERTING AMP:



$$V_{OUT} = G \cdot (V_+ - V_-) = G \cdot (V_{IN} - V_-)$$

(and here we again use the fact that inputs draw negligible current)

$$= G \cdot \left(V_{IN} - \frac{R_2 V_{OUT}}{R_1 + R_2} \right)$$

$$V_{OUT} \cdot \left(1 + \frac{G R_2}{R_1 + R_2} \right) = G \cdot V_{IN}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{G}{1 + \frac{G R_2}{R_1 + R_2}} = \frac{G \cdot (R_1 + R_2)}{R_1 + R_2 + G R_2}$$

as $G \to \infty$, $\frac{V_{OUT}}{V_{IN}} \to \frac{R_1 + R_2}{R_2} = 1 + \frac{R_1}{R_2}$

as we got from Golden Rules

what is V_- ?

$$V_- = \frac{R_2 V_{OUT}}{R_1 + R_2} = \frac{R_2 V_{IN}}{\cancel{R_1 + R_2}} \cdot \frac{G \cdot \cancel{(R_1 + R_2)}}{R_1 + R_2 + G R_2}$$

$$\xrightarrow{\text{as } G \to \infty} \frac{R_2 \cdot V_{IN} \cdot G}{G \cdot R_2} = V_{IN}$$

as Golden Rules imply, $V_- \to V_{IN}$ as $G \to \infty$

So you can see that G.R. are just a shorthand for limit $G \to \infty$, $R_{IN} \to \infty$

Let's look at LM741 data sheet. It quotes these parameters:

		(typical)	(maximum)
"Input Offset Voltage" @ 25°C		1 mV	5 mV
"Input Bias Current"		80 nA	500 nA
"Input Offset Current"		20 nA	200 nA
"Input Resistance"		2 MΩ	300 kΩ (min)
"Voltage Gain"		2×10^5	5×10^4 (min)
"Output Voltage Swing"	($V_{supply} = \pm 15V$)	±14 V	±10 (min) V
"Output Short-Circuit Current"		25 mA	
"Bandwidth"		1.5 MHz	
"Slew Rate"		0.5 V/μs	

It is important to know what these numbers mean when you select an opamp for your own project, and it is helpful to be aware of these limitations (and how to work around them) when you build or study a circuit using a given opamp.

The 741 is a cheap ($0.75) and simple opamp — like an old Dodge Dart. You can get far better performance from newer components.

We can explore the 741's limitations to understand the ideas for real-life opamp use.

August 2000

National Semiconductor

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.

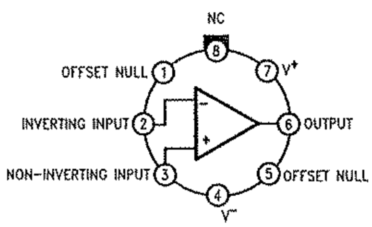
The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

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



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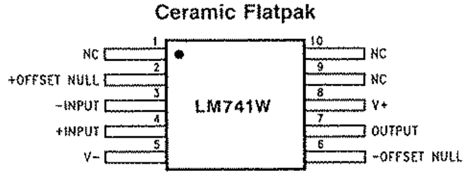
Note 1: LM741H is available per JM38510/10101

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

Ceramic Flatpak



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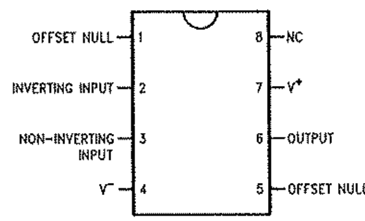
Order Number LM741W/883
See NS Package Number W10A

Dual-In-Line or S.O. Package



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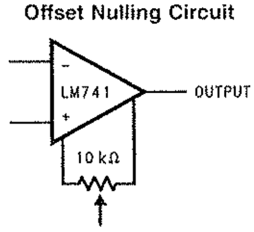
Order Number LM741J, LM741J/883, LM741CN
See NS Package Number J08A, M08A or N08E

Typical Application

Offset Nulling Circuit



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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.

	LM741A	LM741	LM741C
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	$T_A = 25°C$										
	$R_S \leq 10\ k\Omega$					1.0	5.0		2.0	6.0	mV
	$R_S \leq 50\Omega$		0.8	3.0							mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$										
	$R_S \leq 50\Omega$			4.0							mV
	$R_S \leq 10\ k\Omega$						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
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			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
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			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
	$T_{AMIN} \leq T_A \leq T_{AMAX}$, $V_S = \pm 20V$	0.5									MΩ
Input Voltage Range	$T_A = 25°C$							±12	±13		V
	$T_{AMIN} \leq T_A \leq T_{AMAX}$				±12	±13					V

Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A Min	LM741A Typ	LM741A Max	LM741 Min	LM741 Typ	LM741 Max	LM741C Min	LM741C Typ	LM741C Max	Units
Large Signal Voltage Gain	$T_A = 25°C$, $R_L \geq 2\ k\Omega$										
	$V_S = \pm 20V$, $V_O = \pm 15V$	50									V/mV
	$V_S = \pm 15V$, $V_O = \pm 10V$				50	200		20	200		V/mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$R_L \geq 2\ k\Omega$,										
	$V_S = \pm 20V$, $V_O = \pm 15V$	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	$V_S = \pm 20V$										
	$R_L \geq 10\ k\Omega$	±16									V
	$R_L \geq 2\ k\Omega$	±15									V
	$V_S = \pm 15V$										
	$R_L \geq 10\ k\Omega$				±12	±14		±12	±14		V
	$R_L \geq 2\ k\Omega$				±10	±13		±10	±13		V
Output Short Circuit Current	$T_A = 25°C$	10	25	35		25			25		mA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$	10		40							mA
Common-Mode Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$										
	$R_S \leq 10\ k\Omega$, $V_{CM} = \pm 12V$				70	90		70	90		dB
	$R_S \leq 50\Omega$, $V_{CM} = \pm 12V$	80	95								dB
Supply Voltage Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$V_S = \pm 20V$ to $V_S = \pm 5V$										
	$R_S \leq 50\Omega$	86	96								dB
	$R_S \leq 10\ k\Omega$				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.

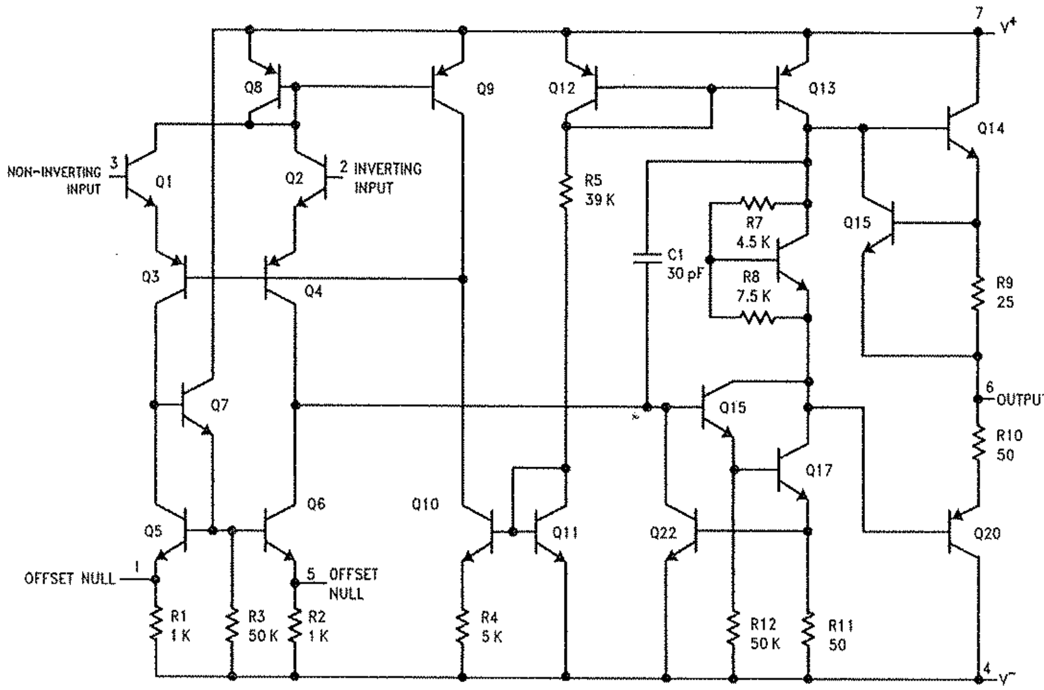
Note 5: Unless otherwise specified, these specifications apply for V_S = ±15V, −55°C ≤ T_A ≤ +125°C (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to 0°C ≤ T_A ≤ +70°C.

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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- $V_{offset} \equiv \Delta V$ (between + and − inputs) needed to make $V_{OUT} = 0$ (a few mV for 1741)

- I_{bias}, I_{offset} } finite DC current drawn by + and − inputs

  Note $I_{bias} \equiv \frac{1}{2}(I_+ + I_-)$, while

  $$I_{offset} \equiv |I_+ - I_-|$$

  I_{os} is typically smaller than I_b by ×2 − ×10

  (these are $\mathcal{O}$(100 nA) for '741)

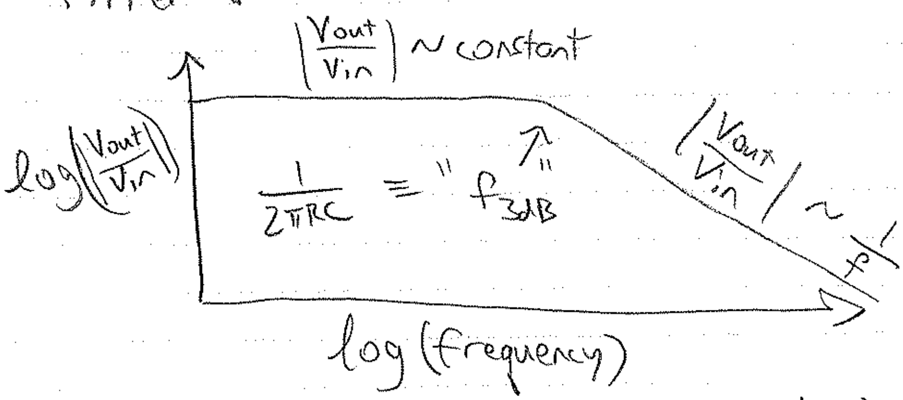
- R_{IN} and gain are large but of course finite. R_{IN} for FET-based opamps is enormously larger than R_{IN} for BJT-based opamps. Details in coming weeks.

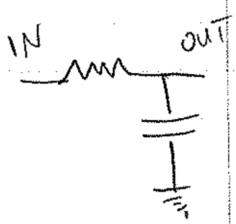
  ($\mathcal{O}(10^6 \Omega)$ and $\mathcal{O}(10^5)$ respectively for '741)

- As noted last week, V_{OUT} cannot swing beyond the power "rails." In fact, the '741 typically will only go to ±14V or less, if powered with ±15 V. Some opamps offer "rail-to-rail" output.

- The largest current a '741 will source or sink is about 25mA. This can be an issue when driving a big 8Ω speaker, charging a big capacitor, driving a long cable, driving a motor, etc. Sometimes one enlists the help of a high-current external transistor in these cases.

- Every opamp has some finite bandwidth, i.e. range of frequencies over which it can amplify. Usually the frequency response looks like that of an RC lowpass filter:





Remember that (for RC filter) $\left|\frac{V_{out}}{V_{in}}\right| = \left|\frac{(1/j\omega C)}{R + (1/j\omega C)}\right| = \frac{1}{\sqrt{1+(2\pi f RC)^2}}$

this expression $\longrightarrow 1$ for $f \ll \frac{1}{2\pi RC}$

and $\longrightarrow \frac{1}{2\pi RC} \cdot \frac{1}{f}$ for $f \gg \frac{1}{2\pi RC}$

So one often speaks of "gain · bandwidth product" when one is in the $1/f$ regime.

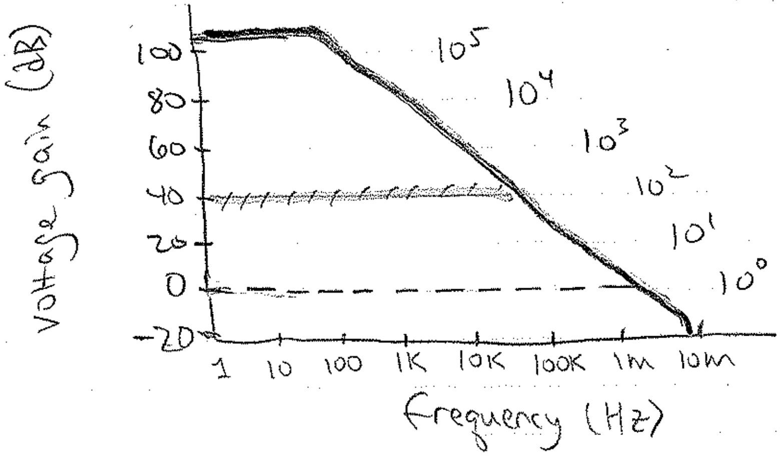
The product $f \cdot \left|\frac{V_{out}}{V_{in}}\right|$ is constant along the falling part of the curve.

(continued next page.)

— = open loop gain

Let's take '741 typical values

$BW = 1.5\ \text{MHz}, \quad G = 2 \times 10^5 \quad (\simeq 106\ \text{dB})$

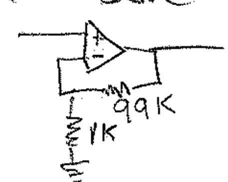


(from HH figure 4.80, page 243)

You can see that "bandwidth" for an opamp does not mean f_{3dB}. It means the frequency at which the gain = 1.

If I build a '741 follower

, its response will look like the - - - - curve above. If I build a ×100 amplifier



its response will resemble the ////// curve above.

You can see this from the finite-gain $|V_{out}/V_{in}|$ expression on page 3 of these notes.

Why the gain rolls off this way relates to the subtle topic "frequency compensation" that is beyond the scope of this course. You can read about it in HH if you're curious. The key idea is to get the gain below 1 well before internal phase shifts reach 180°, to prevent oscillations.

Finally, a maximum slew rate is quoted. A slew-rate limit is a saturation of dV_{OUT}/dt. It may arise, for instance, if an internal amplifier stage has a current limit and is charging an internal capacitance.

For a '741, the maximum $\left|\frac{dV_{out}}{dt}\right|$ (slew rate) is $0.5\,V/\mu s$.

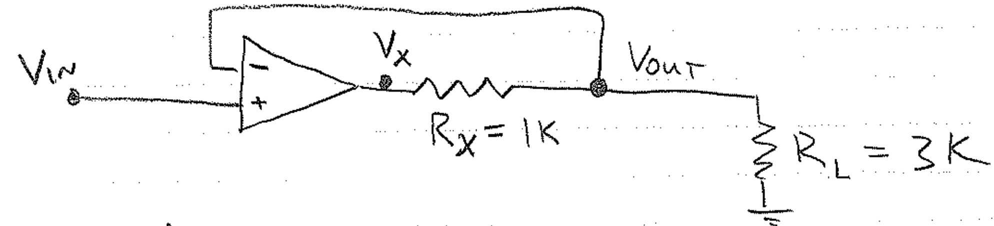
As a form of saturation, this is a non-linear effect, i.e. it is a frequency limit that depends upon amplitude. Thus, driving an opamp close to a slew-rate limit can distort your signal — e.g. introducing fourier components not present in your input signal.

Slewing is also pertinent when you need to get from V_{OUT} (min) to V_{OUT} (max) as quickly as possible — something we will discuss when we introduce the comparator below.

NOTES WILL CONTINUE FROM HERE ON WEB

See blackboard or see positron.hep.upenn.edu/p364

To illustrate the effect of feedback on output impedance, let's analyze for finite gain the Lab 3 (part 1) example in which we artificially gave the '741 an output resistance of 1K.



$$V_X = G\cdot(V_+ - V_-) = G\cdot(V_{IN} - V_{OUT})$$

$$V_X \cdot \frac{R_L}{R_X+R_L} = V_{OUT} \implies V_{OUT}\cdot\frac{R_X+R_L}{R_L} = V_X = G\cdot(V_{IN}-V_{OUT})$$

after rearranging, $V_{OUT} = V_{IN}\cdot\dfrac{G}{G+1+\frac{R_X}{R_L}} = V_{IN}\cdot\dfrac{1}{1+\frac{1}{G}+\frac{R_X}{GR_L}}$

"output impedance" R_{OUT} measures how much V_{OUT} will droop as we increase I_{OUT}, i.e. $dV_{OUT}/dI_{OUT} = -R_{OUT}$.

let's define $\gamma \equiv \frac{1}{R_L}$, so $I_{OUT} = V_{OUT}/R_L = \gamma V_{OUT}$

then $\dfrac{-1}{R_{OUT}} = \dfrac{dI_{OUT}}{dV_{OUT}} = \dfrac{d(\gamma V_{OUT})}{dV_{OUT}} = \gamma + \dfrac{V_{OUT}\,d\gamma}{dV_{OUT}} = \gamma + V_{OUT}\Big/\dfrac{dV_{OUT}}{d\gamma}$

$$V_{OUT} = V_{IN}\left[1+\frac{1}{G}+\frac{\gamma R_X}{G}\right]^{-1} \implies \frac{dV_{OUT}}{d\gamma} = \frac{-V_{IN}\cdot R_X/G}{\left(1+\frac{1}{G}+\frac{\gamma R_X}{G}\right)^2} = -\frac{V_{OUT}R_X}{G+1+\gamma R_X}$$

$$\frac{-1}{R_{OUT}} = \gamma - V_{OUT}\cdot\frac{G+1+\gamma R_X}{V_{OUT}R_X} = \gamma - \frac{G+1}{R_X} - \gamma$$

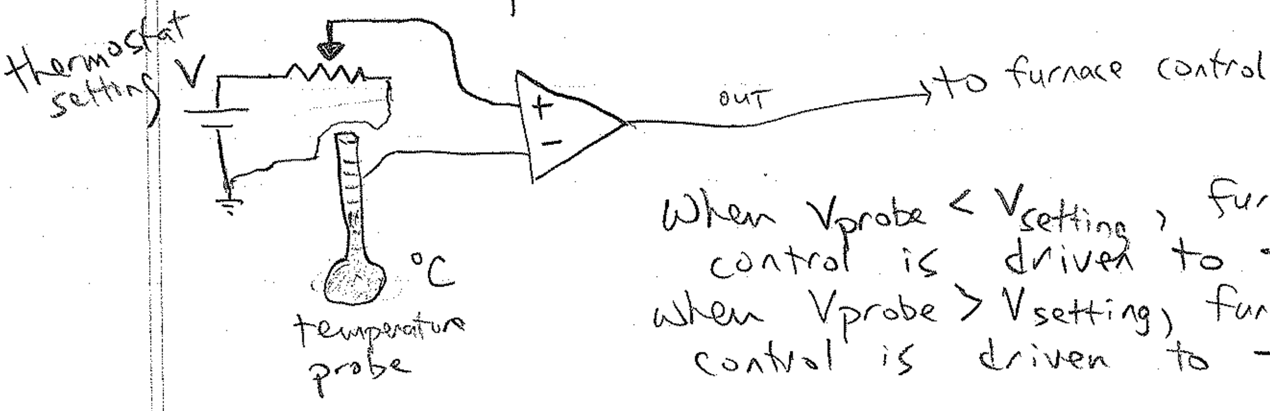
$$\implies \boxed{R_{OUT} = \frac{R_X}{1+G}}$$

Probably $\exists$ a less laborious way to prove this, but you can see that the feedback reduces the output resistance from R_X to $R_X/(1+G)$

Similar analysis is possible for input resistance w/ feedback.

Now for something rather different: comparators and positive feedback.

Suppose you just want to compare two signals: for instance, compare your room temperature to the thermostat setting.

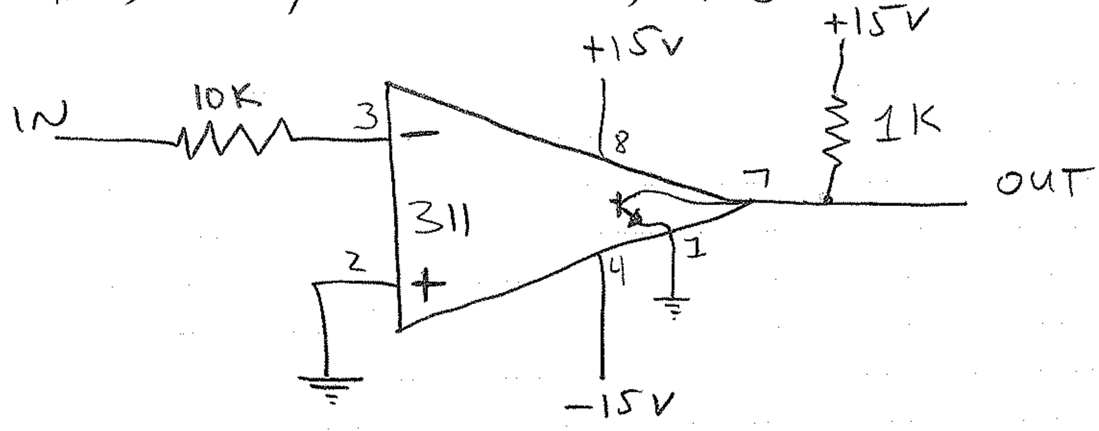


When $V_{probe} < V_{setting}$, furnace control is driven to $+V_{supply}$; when $V_{probe} > V_{setting}$, furnace control is driven to $-V_{supply}$.

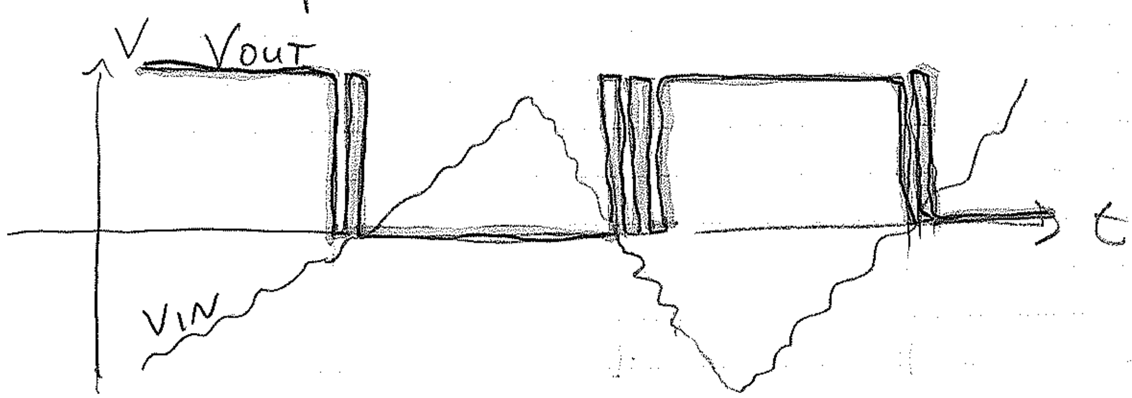
We could do this with an opamp. But ...

- opamps don't like to be slammed from rail to rail, and can take some time to recover from each transition
- we may want to slew from OFF to ON and back faster than limited opamp slew rate
- Opamp $\pm V_{supply}$ may not be what we want for output (e.g. to furnace control). We may want more flexibility in output voltages for ON and OFF states.

For these reasons, the comparator exists.



LM311 comparator (no feedback yet)

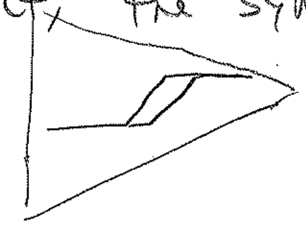


The problem with this circuit is that any noise makes it indecisive.

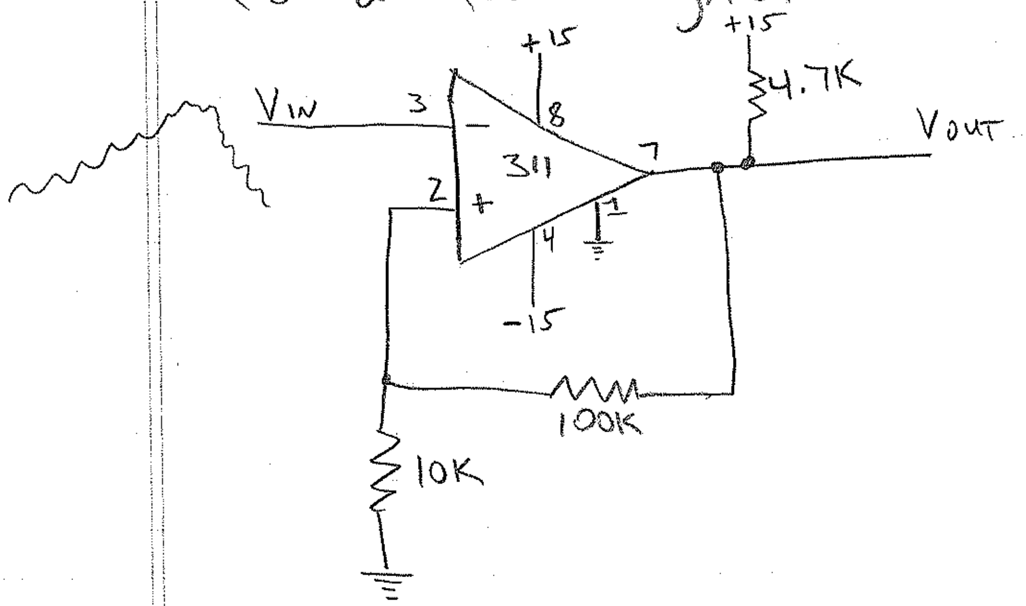
By the way, the mysterious-looking output is called an "open collector" output. When the output is in the LOW state, it looks like a short circuit to ground. When it is in the HIGH state, it looks like an open circuit. This gives the user considerable flexibility in using the output. An open collector output requires a "pull up" resistor to reach the proper HIGH voltage.

The solution to the open-loop comparator's indecisiveness is called a Schmitt Trigger. It adds hysteresis to the circuit.

In fact, the symbol for a Schmitt Trigger is



which resembles the M vs. H curve for a ferromagnet.



When VOUT is driven to ground by comparator (in low state), $V_+ = 0$, so the low-to-high threshold is at 0V.

When VOUT is pulled up to +15 (in HIGH state),

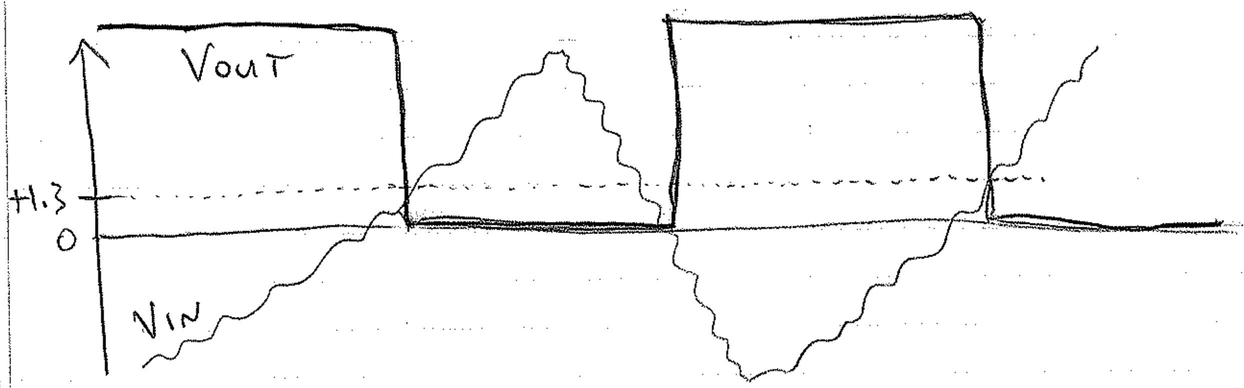
$$V_{OUT} = 15V \cdot \frac{110K}{110K + 5K} \simeq 14.4V.$$

$$V_+ = 14.4V \cdot \frac{10K}{10K + 100K} \simeq 1.3V$$

so the high-to-low threshold is at +1.3V.

(This sounds backward, but note that V_{IN} is at the inverting (−) input in this example.)

The resulting hysteresis looks like this:

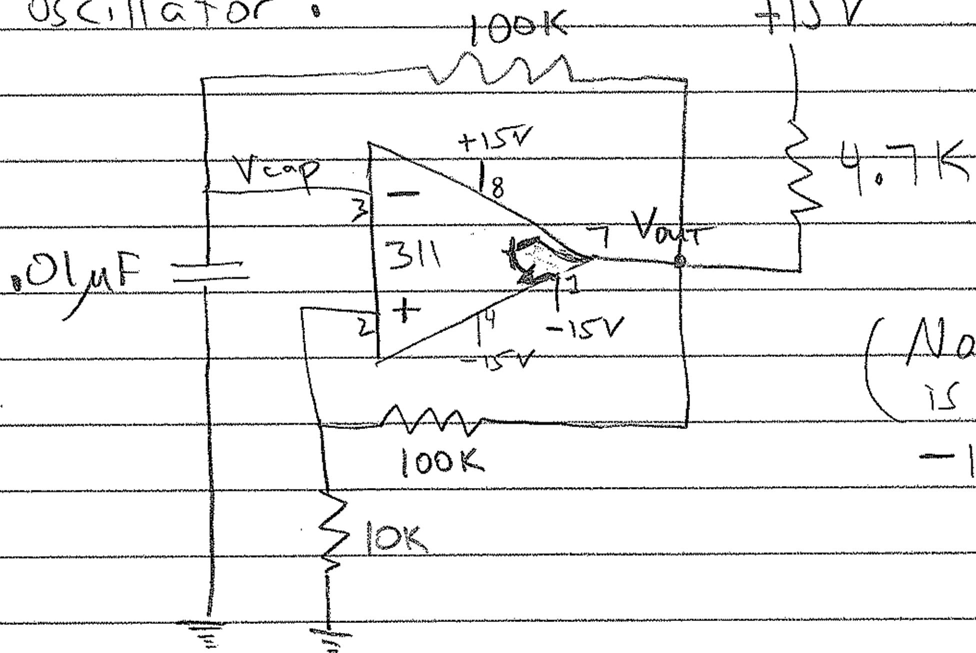


This is an example of positive feedback: once the output moves into a given state, the threshold changes so that it becomes relatively difficult to leave that state.

(Sun Tsu writes that upon sailing to the enemy's beach, you must order your soldiers to burn their own boats.)

Clearly, once your thermostat has switched on the furnace, you want to leave it on for several minutes, not just long enough to raise the temperature ~ 0.1 degree. Thermostat contains something analogous to a Schmitt Trigger.

One handy thing you can build with a Schmitt trigger is an oscillator:



(Note that pin 1 is connected to −15V here.)

Suppose $V_{cap} = 0$ at $t = 0$. If V_{OUT} is low, it is driven to −15V, which reduces V_{cap} with initial $dV_{cap}/dt = \frac{I}{C} = -\frac{15V}{100K} \cdot \frac{1}{.01\mu F} = -15V/ms$.
Threshold in LOW state is $-15V \cdot \frac{10K}{10K+100K} \simeq -1.36V$.

Once V_{cap} reaches −1.36V, V_{OUT} goes to HIGH state, pulled up to $+15V \cdot \frac{110K}{114.7K} \simeq 14.4V$. Then threshold is $+14.4V \cdot \frac{10K}{110K} \simeq +1.31V$. Initial $dV_{cap}/dt = \frac{I}{C} = \frac{+14.4V + 1.36V}{100K} \cdot \frac{1}{.01\mu F} \simeq +16V/ms$.

When V_{cap} reaches +1.31V, it turns around again. Period $\simeq 2 \times \frac{2.6V}{15V/ms} \simeq .35ms$, i.e. frequency ≈ 3 KHz.