Operational Amplifiers (OpAmps) and Comparators

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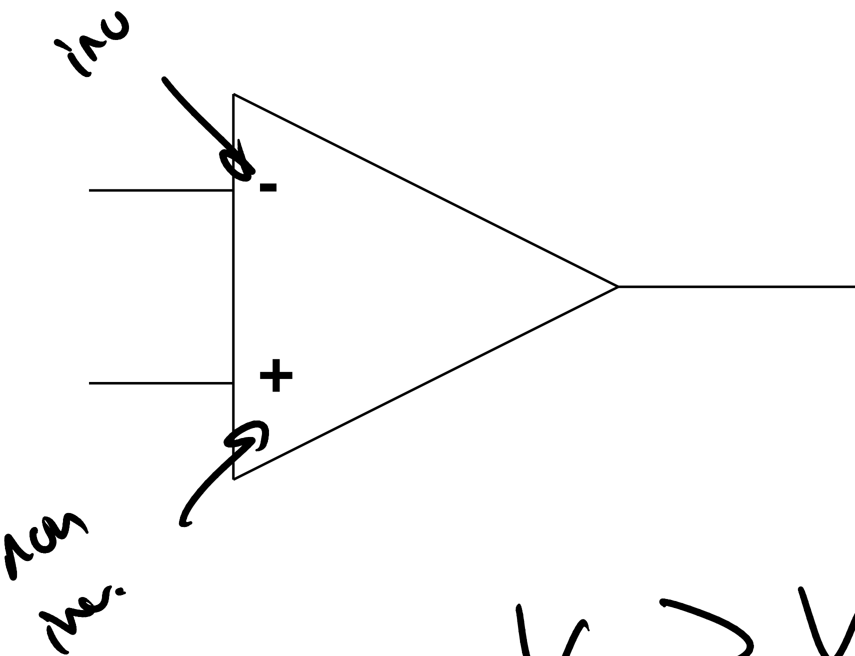
Winter 2010

Operational Amplifier



$V_{out} = G(V_+ - V_-)$

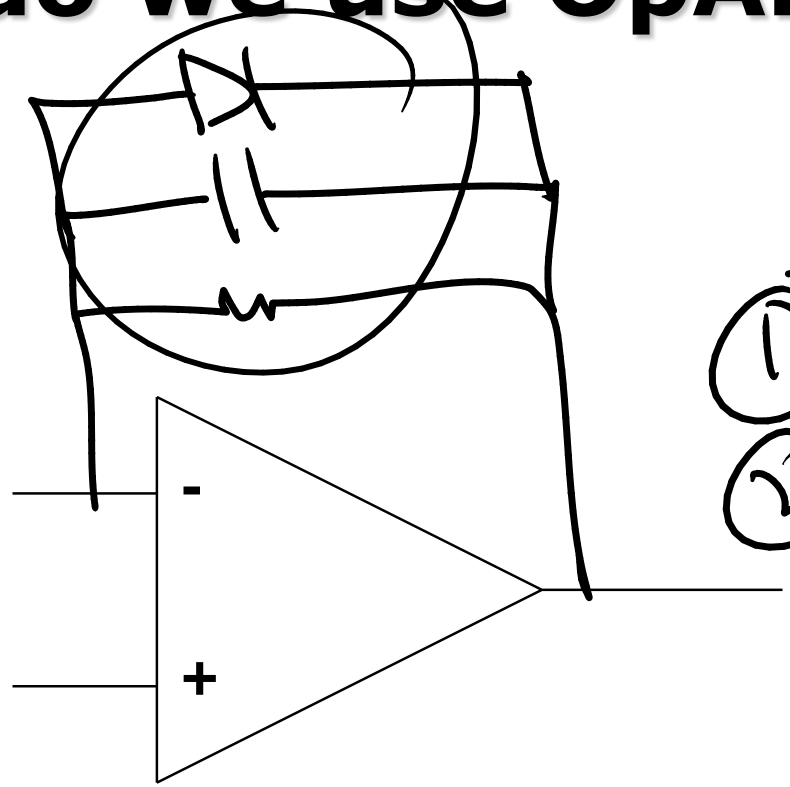
* where $G \to \infty$
  100k

* inputs draw no current

$V_+ > V_-$ ↑ V_{out}

$V_+ < V_-$ ↓ V_{out}

How do we use OpAmps?



Not working

① PWR/GND

② Feedback

Always use in negative feedback

The Golden Rules

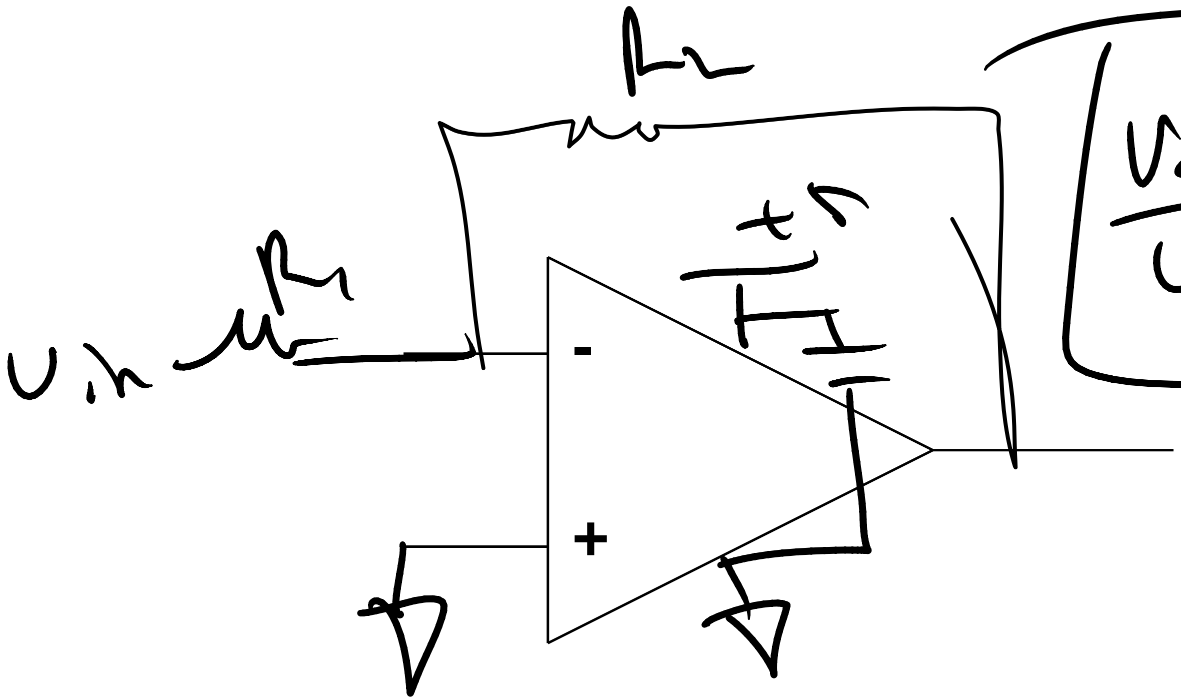
ideal

(1) inputs drawn no current
(2) V_- V_+ are the same voltage

applies only when

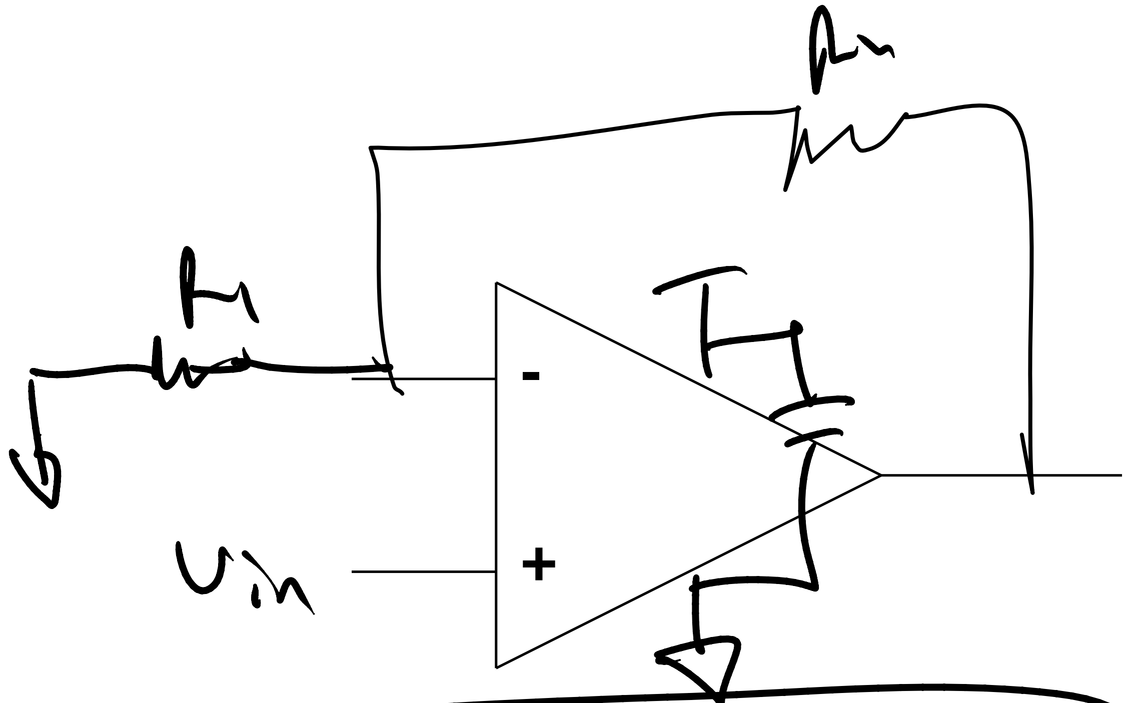
+ negative feedback
+ within op. specs

Inverting Amplifier



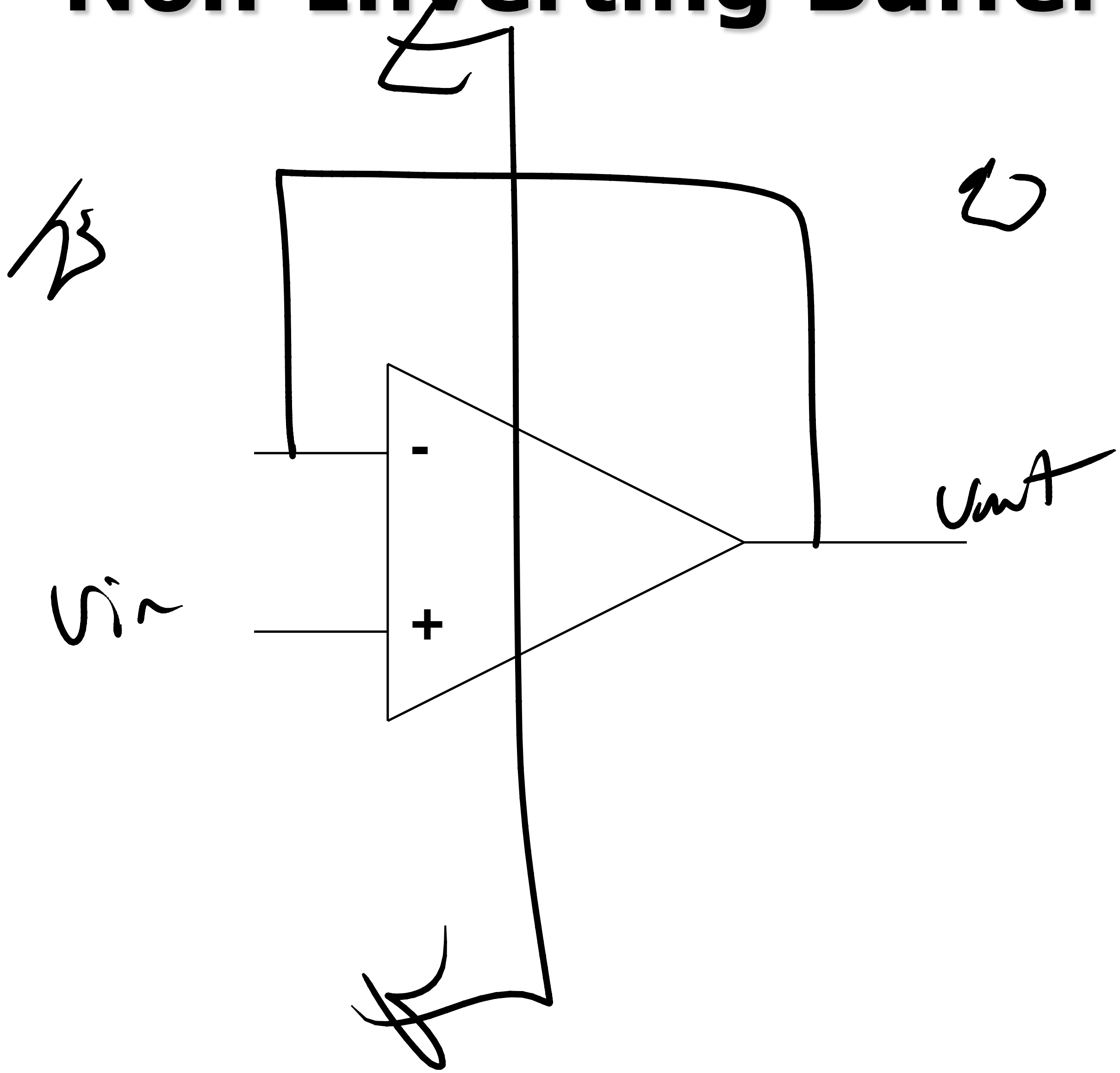
$$\frac{V_{out}}{V_{in}} = \frac{-R_2}{R_1}$$

Non-Inverting Amplifier

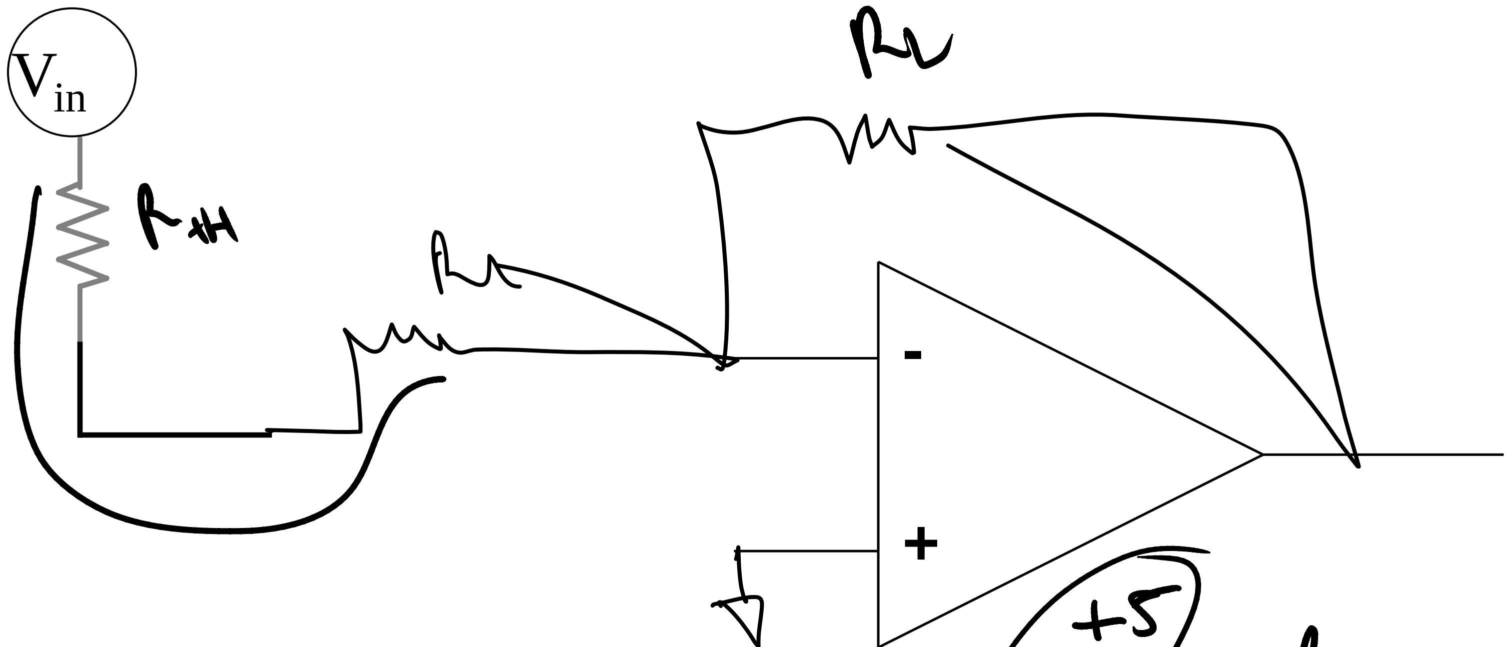


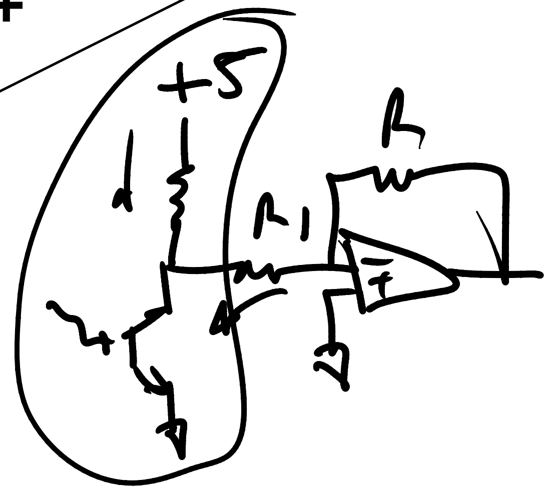
$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

Non-Inverting Buffer



What about a real source?



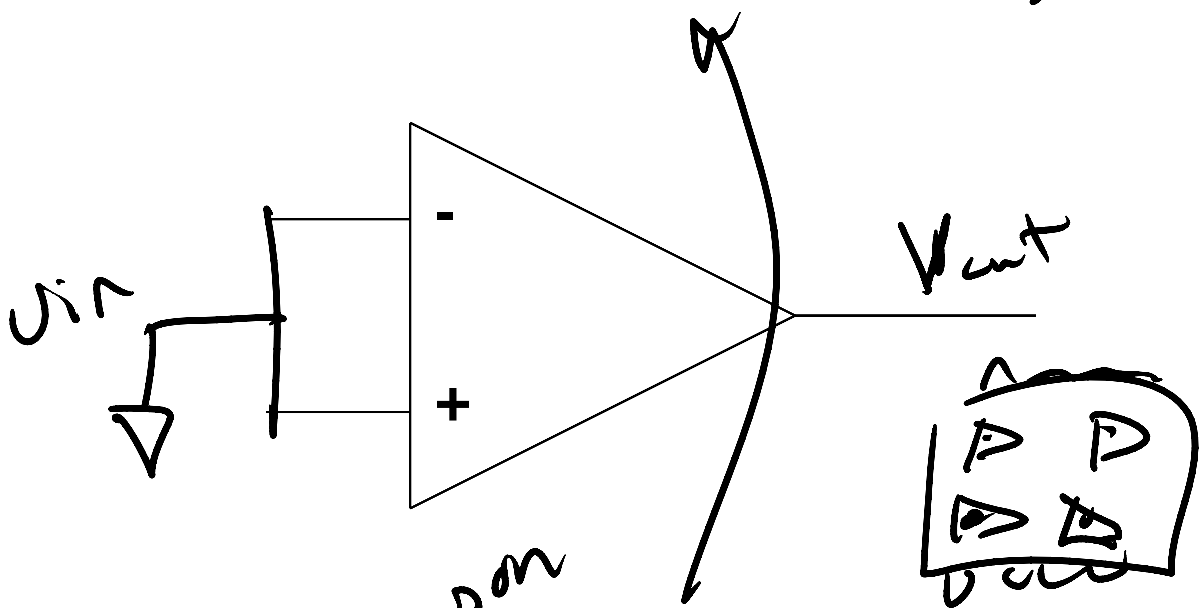


$(R_1)_{eff} > R_1$

What if I connect the two inputs?

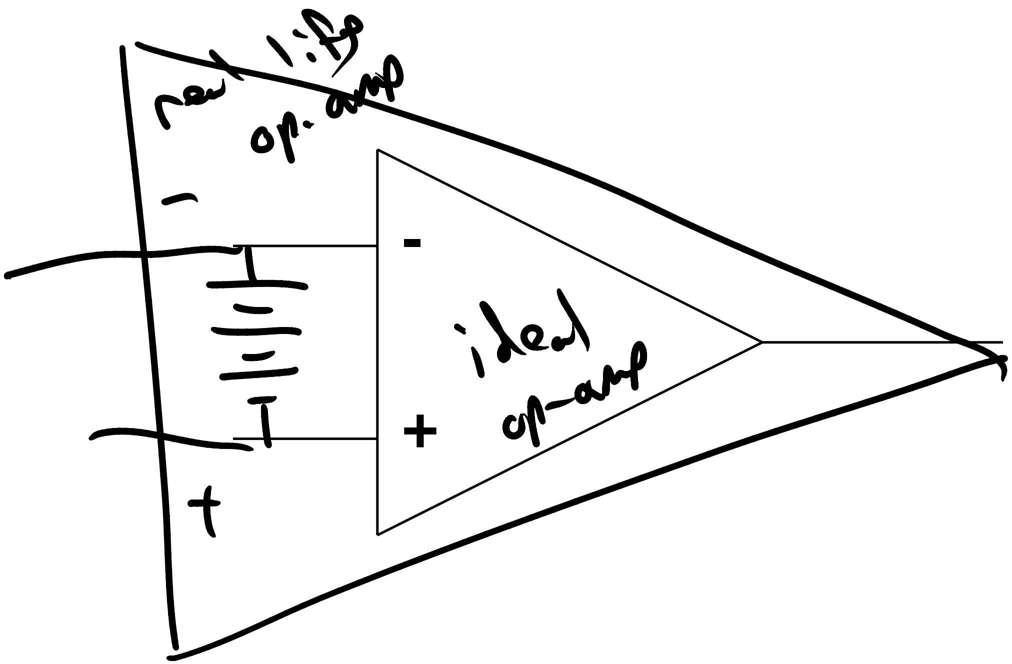
ideal op amp: Vout = 0

real Life: rail one way or the other



reason: input offset voltage

Input Offset Voltage?

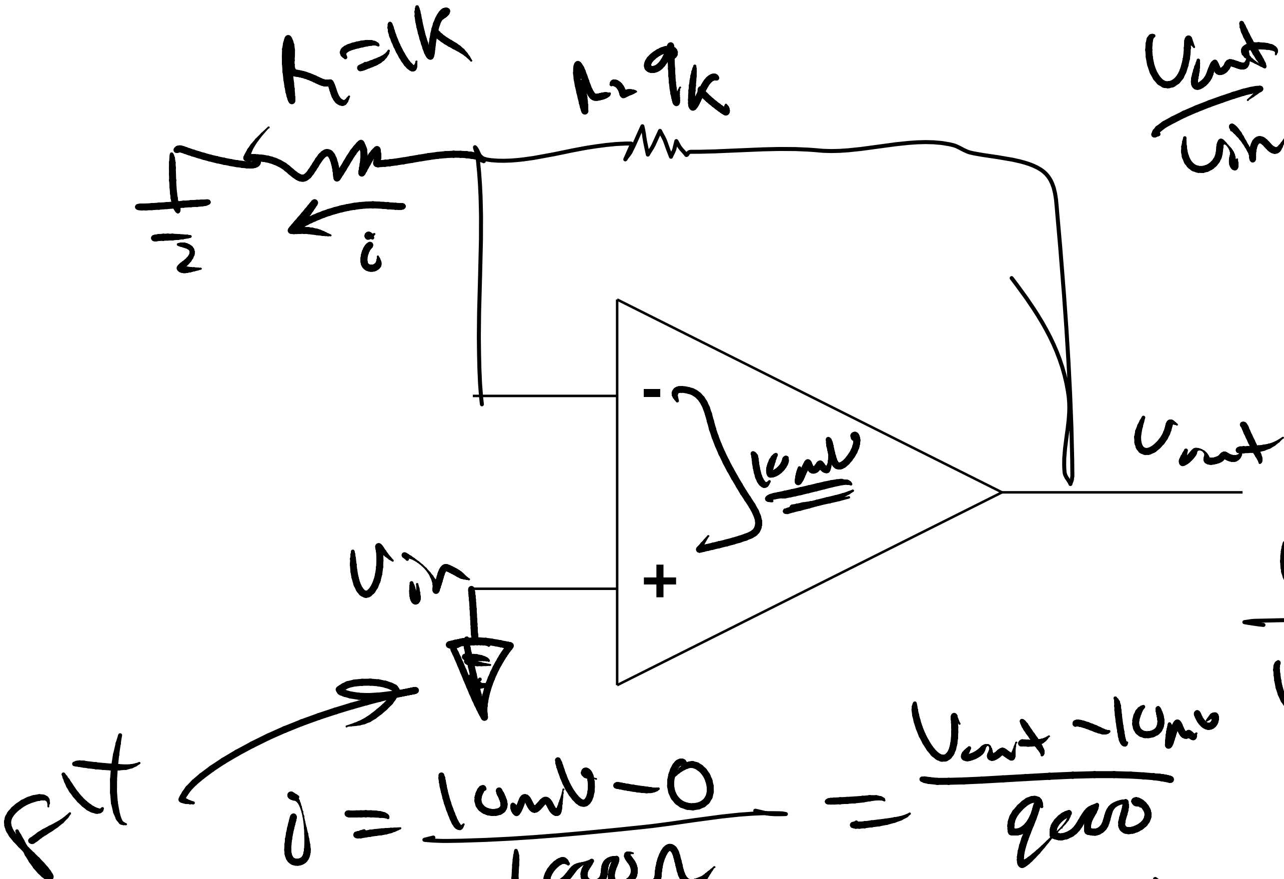


Input Offset Voltage Specifications

ELECTRICAL CHARACTERISTICS (V_{CC} = 5.0 V, V_{EE} = Gnd, T_A = 25°C, unless otherwise noted.)

Characteristics	Symbol	LM224			LM324A			LM324			LM2902			LM2902V/NCV2902			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage V_{CC} = 5.0 V to 30 V (26 V for LM2902, V), V_{ICR} = 0 V to V_{CC} −1.7 V, V_O = 1.4 V, R_S = 0 Ω	V_{IO}																mV
T_A = 25°C		–	2.0	5.0	–	2.0	3.0	–	2.0	7.0	–	2.0	7.0	–	2.0	7.0	
T_A = T_{high} (Note 2)		–	–	7.0	–	–	5.0	–		9.0	–	–	10	–	–	13	
T_A = T_{low} (Note 2)		–	–	7.0	–	–	5.0	–	–	9.0	–	–	10	–	–	10	
Average Temperature Coefficient of Input Offset Voltage T_A = T_{high} to T_{low} (Notes 2 and 4)	$\Delta V_{IO}/\Delta T$	–	7.0	–	–	7.0	30	–	7.0	–	–	7.0	–	–	7.0	–	µV/°C

Effects of Input Offset Voltage



$$\frac{V_{out}}{V_{in}} = 1 + \frac{9}{1} = 10$$

10mV

V_{in} 0–1V

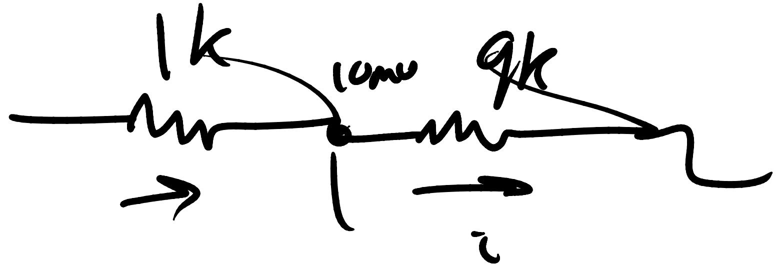
V_{in} 0–20mV

$$i = \frac{10mV - 0}{1000\Omega} = \frac{V_{out} - 10mV}{9000}$$

$\therefore V_{out} = 100mV$

How to fix

① V_{os}.



V_{out} ← want to be 0

$$i = \frac{10mv - 0}{9k} = 11.1\,\mu A$$

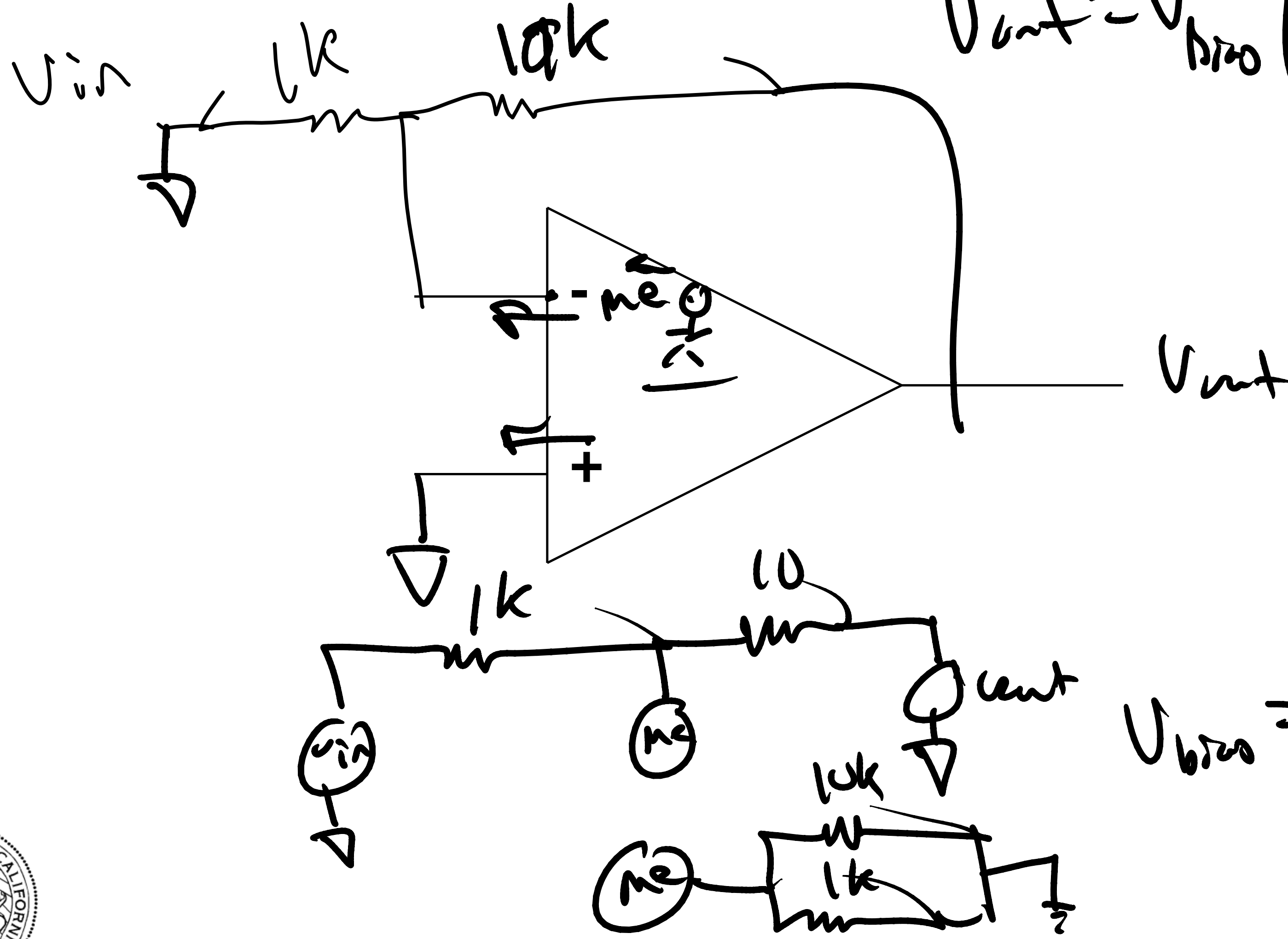
$$11.1\,\mu A = \frac{V_{os} - 10mv}{1K}$$

$$V_{os} = 21.1\,mV$$

②

Input Bias Current

$$V_{out} = V_{bias}\left(1 + \frac{R_2}{R_1}\right)$$



$$V_{bias} = i_B\left(R_1 \| R_2\right)$$

Input Bias Current Specifications

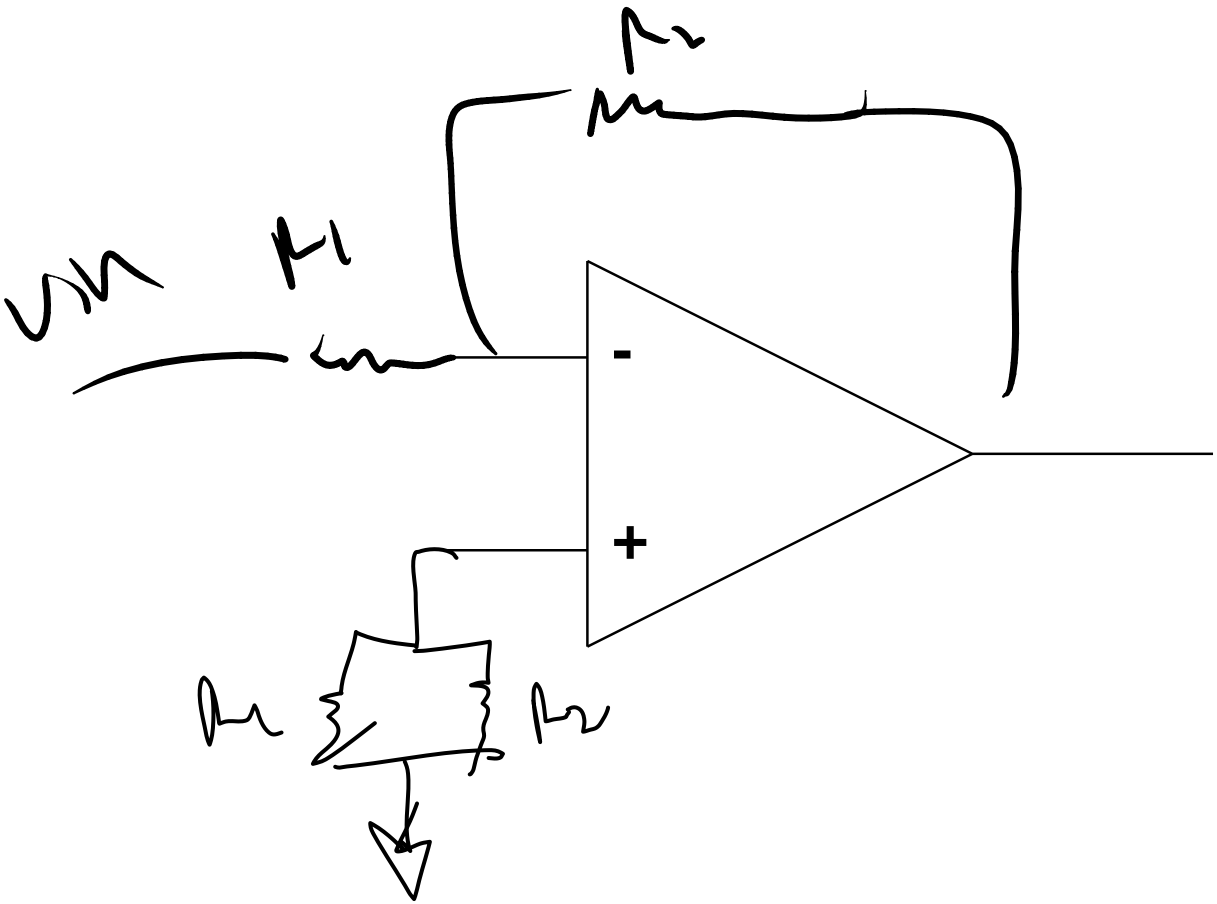
min 324 max

Input Offset Current $T_A = T_{high}$ to T_{low} (Note 2)	I_{IO}	– –	3.0 –	30 100	– –	5.0 –	30 75	– –	5.0 –	50 150	– –	5.0 –	50 200	– –	5.0 –	50 200	nA
Average Temperature Coefficient of Input Offset Current $T_A = T_{high}$ to T_{low} (Notes 2 and 4)	$\Delta I_{IO}/\Delta T$	–	10	–	–	10	300	–	10	–	–	10	–	–	10	–	pA/°C
Input Bias Current $T_A = T_{high}$ to T_{low} (Note 2)	I_{IB}	– –	–90 –	–150 –300	– –	–45 –	–100 –200	– –	–90 –	–250 –500	– –	–90 –	–250 –500	– –	–90 –	–250 –500	nA
Input Common Mode	V_{ICR}																V

–90nA → 250nA

500nA @ HT

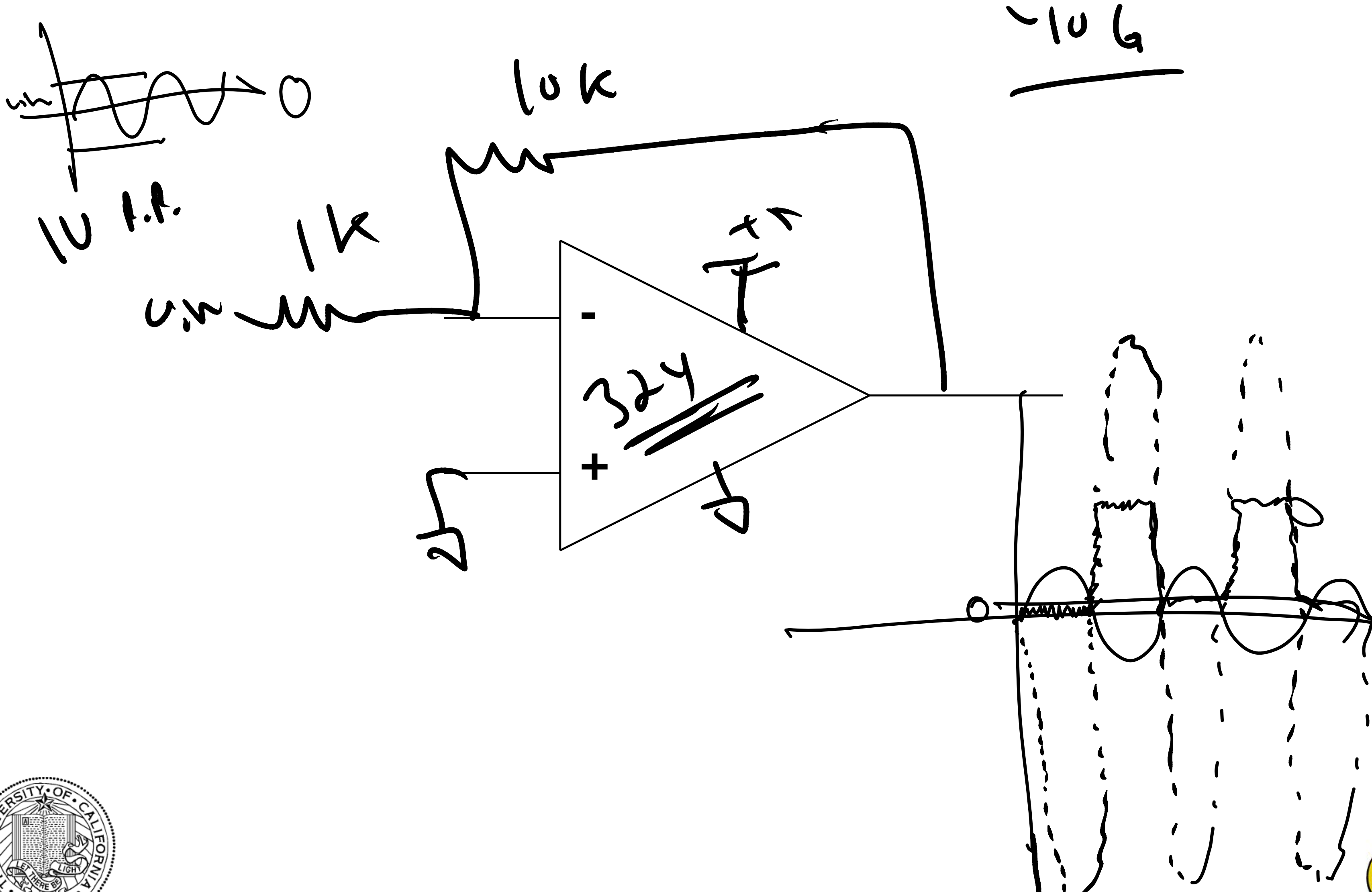
Can We Correct for Input Bias Current



Does this fix the bias current problem?

Input Offset Current	I_{IO}	–	3.0	30	–	5.0	30	–	5.0	50	–	5.0	50	–	5.0	50	nA
$T_A = T_{high}$ to T_{low} (Note 2)		–	–	100	–	–	75	–	–	150	–	–	200	–	–	200	
Average Temperature Coefficient of Input Offset Current $T_A = T_{high}$ to T_{low} (Notes 2 and 4)	$\Delta I_{IO}/\Delta T$	–	10	–	–	10	300	–	10	–	–	10	–	–	10	–	pA/°C
Input Bias Current	I_{IB}	–	–90	–150	–	–45	–100	–	–90	–250	–	–90	–250	–	–90	–250	nA
$T_A = T_{high}$ to T_{low} (Note 2)		–	–	–300	–	–	–200	–	–	–500	–	–	–500	–	–	–500	
Input Common Mode	V_{ICR}																V

Output Voltage Limitations



Does that fix the bias current problem?

Output Voltage Specifications

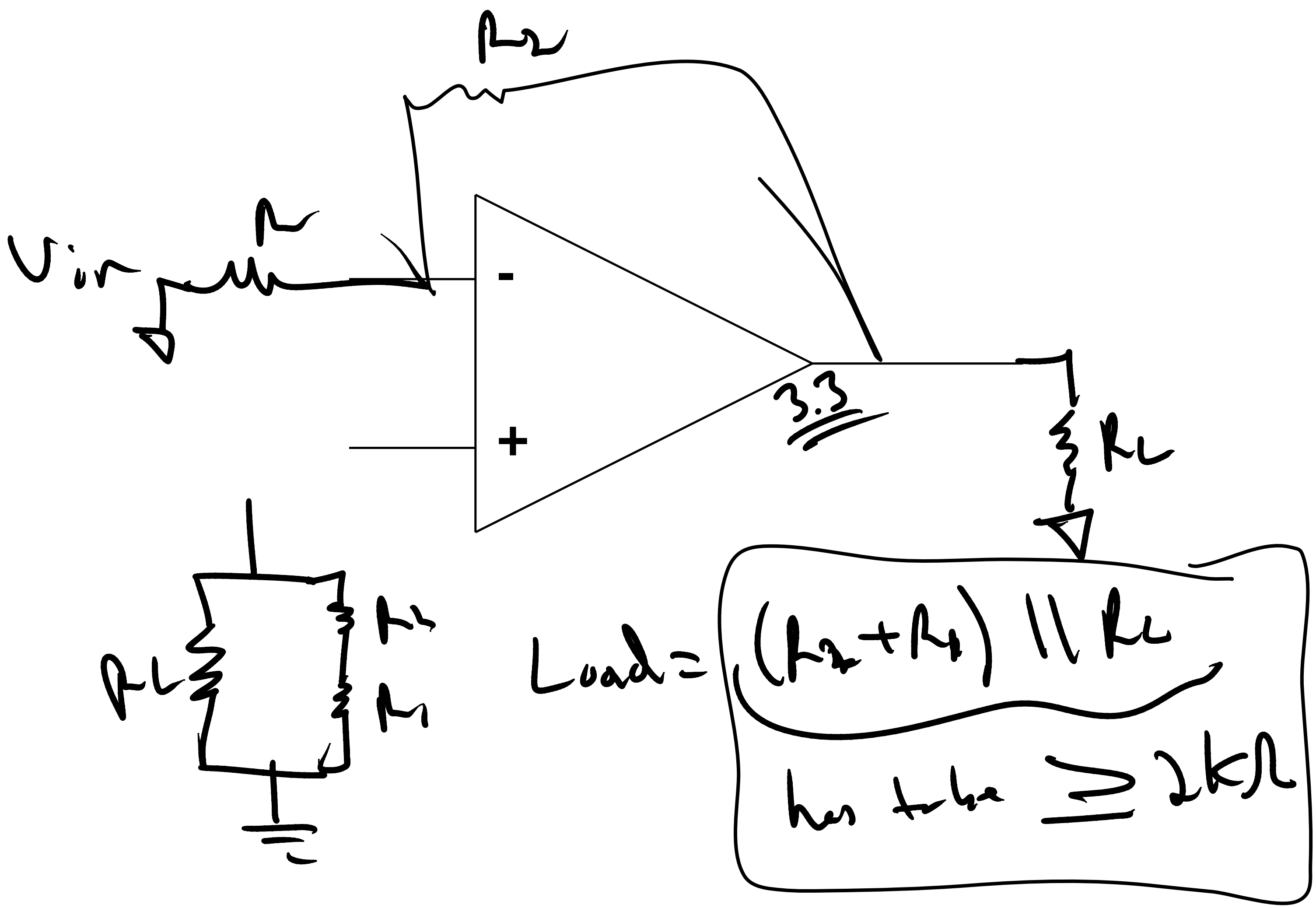
ELECTRICAL CHARACTERISTICS (V_{CC} = 5.0 V, V_{EE} = Gnd, T_A = 25°C, unless otherwise noted.)

Characteristics	Symbol	LM224			LM324A			LM324			LM2902			LM2902V/NCV2902			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Output Voltage– High Limit (T_A = T_{high} to T_{low}) (Note 5)	V_{OH}																V
V_{CC} = 5.0 V, R_L = 2.0 kΩ, T_A = 25°C		3.3	3.5	–	3.3	3.5	–	3.3	3.5	–	3.3	3.5	–	3.3	3.5	–	
V_{CC} = 30 V (26 V for LM2902, V), R_L = 2.0 kΩ		26	–	–	26	–	–	26	–	–	22	–	–	22	–	–	
V_{CC} = 30 V (26 V for LM2902, V), R_L = 10 kΩ		27	28	–	27	28	–	27	28	–	23	24	–	23	24	–	
Output Voltage – Low Limit, V_{CC} = 5.0 V, R_L = 10 kΩ, T_A = T_{high} to T_{low} (Note 5)	V_{OL}	–	5.0	20	–	5.0	20	–	5.0	20	–	5.0	100	–	5.0	100	mV
Output Source Current	I_{O+}																mA

$R_L = 2.0 k\Omega$

not very close to rails at all

The Importance of Test Conditions



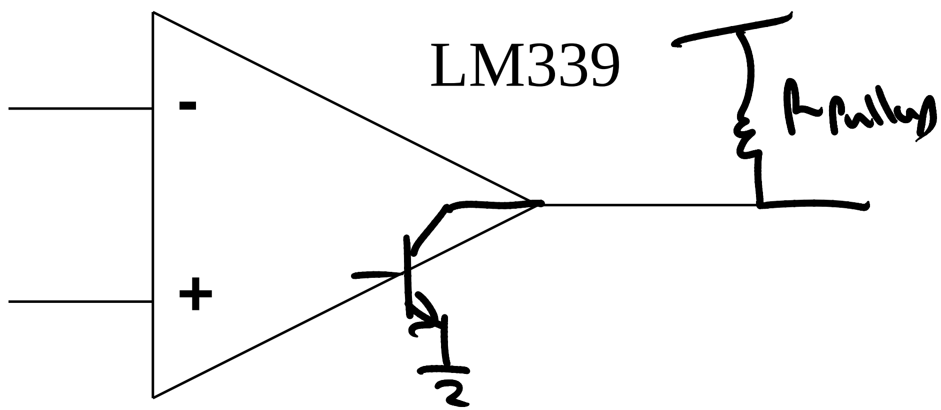
A Comparison of Some Op-Amps

Parameter	LM324	LM6144	LMC6484	LMC6494
Input Offset Voltage	7mV	3.3mV	3.7mV	6.8mV
Input Bias Current	250nA	526nA	4pA	200pA
Input Offset Current	50nA	80nA	2pA	100pA
Output Voltage Hi @10KΩ	3.5V	4.87V		
Output Voltage Lo @10KΩ	0.02V	0.05V		
Output Voltage Hi @2KΩ	3V	4.8V	4.7V	4.7V
Output Voltage Lo @2KΩ		0.13	0.24V	0.24V
Output Voltage Hi @600Ω			4.24V	4.24V
Output Voltage Lo @600Ω			0.65V	0.65V
Unity Gain Bandwidth	1MHz	6MHz	1.5MHz	1.5MHz
Slew Rate	0.42V/μS	11V/μS	0.63V/μS	0.5V/μS
Input Common Mode Range	0-3.5V	0-5V	0-5V	0-5V
Cost @ 1k	$0.088	$2.80	$1.39	$1.59
Temperature Range	0° – 70° C	-40° – 85° C	-40° – 85° C	-40° – 125° C

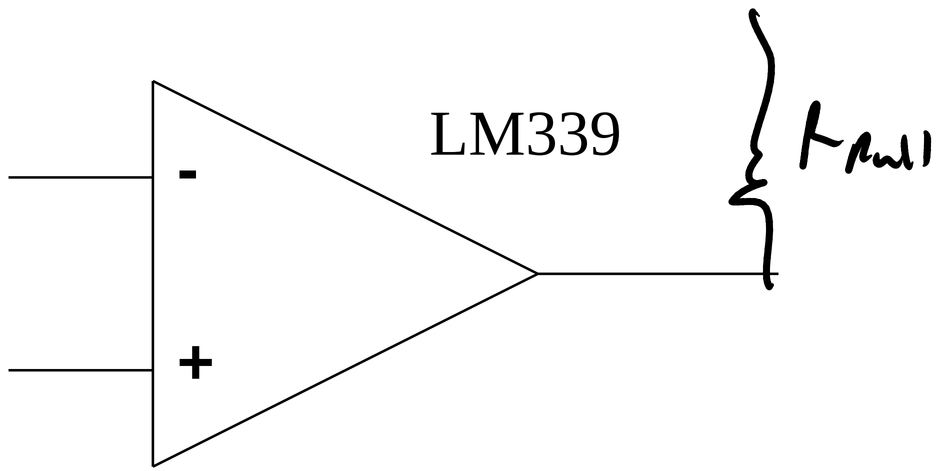
What is this?

Comparator

Very fast, not linear



The Comparator

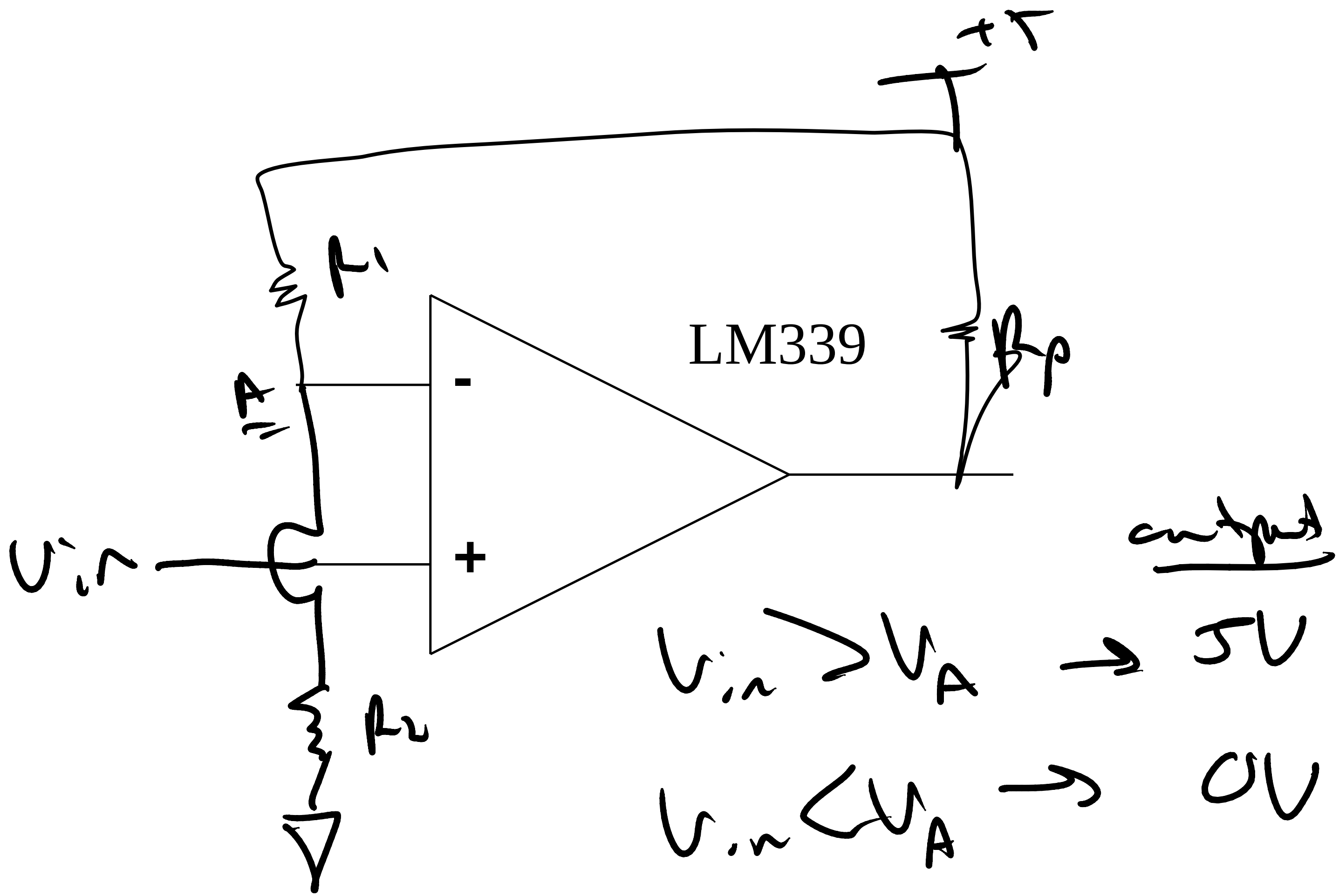


outputs!

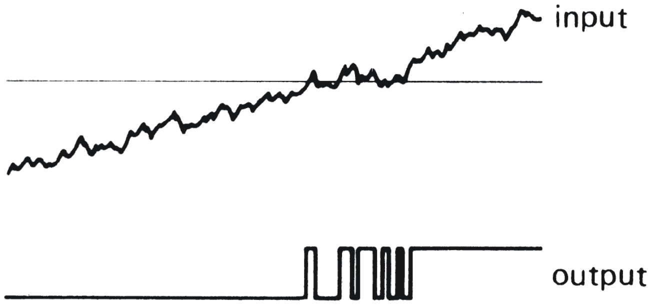
Comparator : open collector

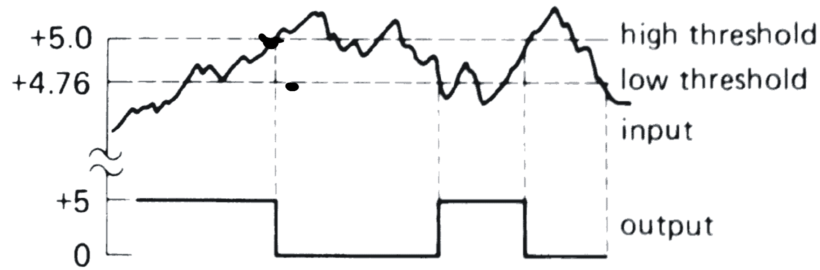
op amp : push-pull (totem pole)

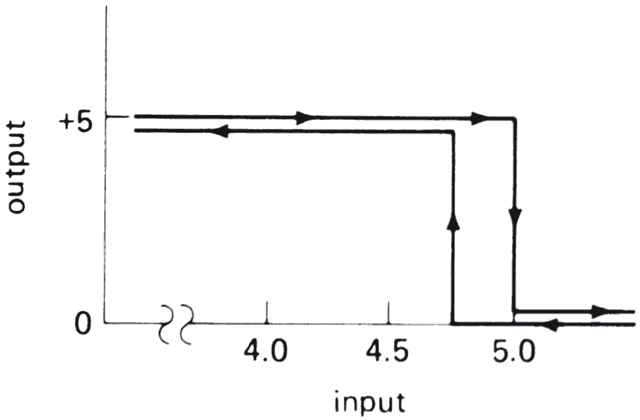
How might you use it?



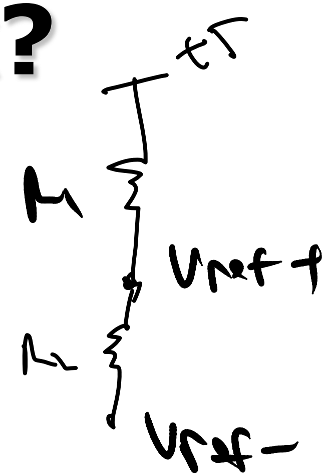
Implementing Hysteresis

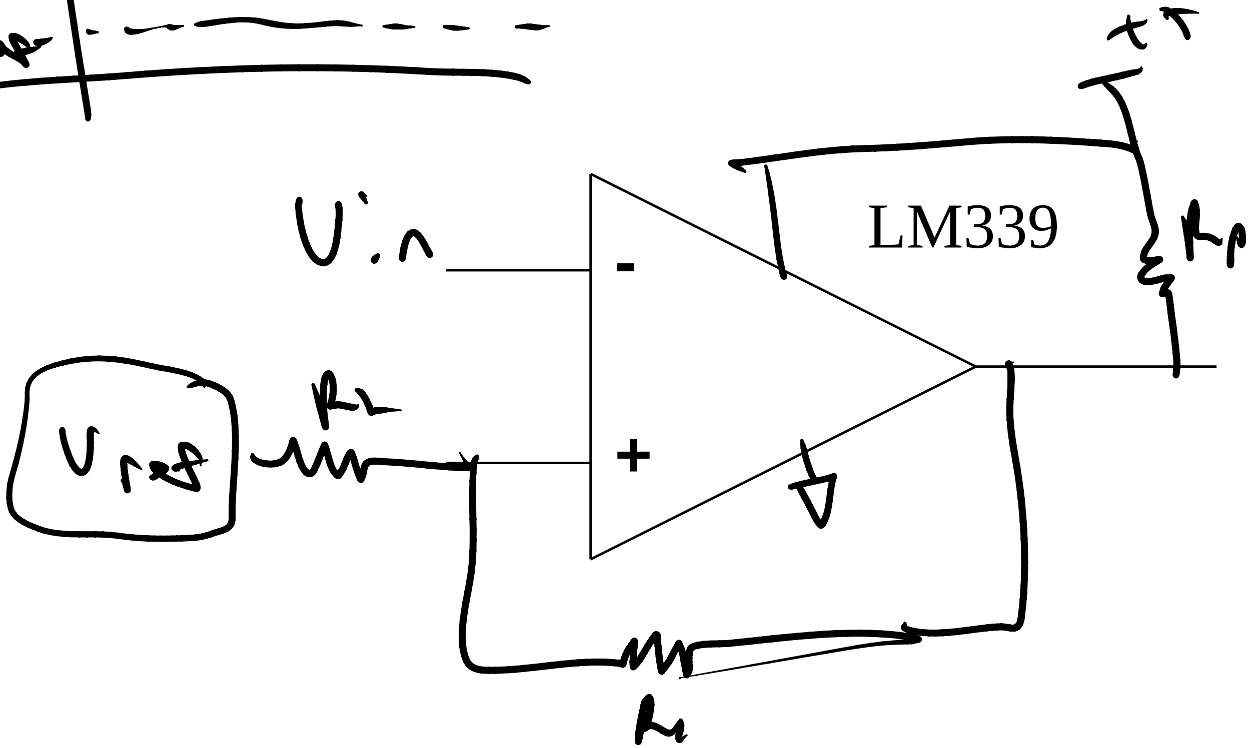


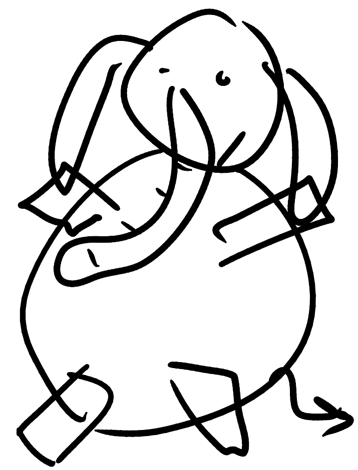




How does this work?

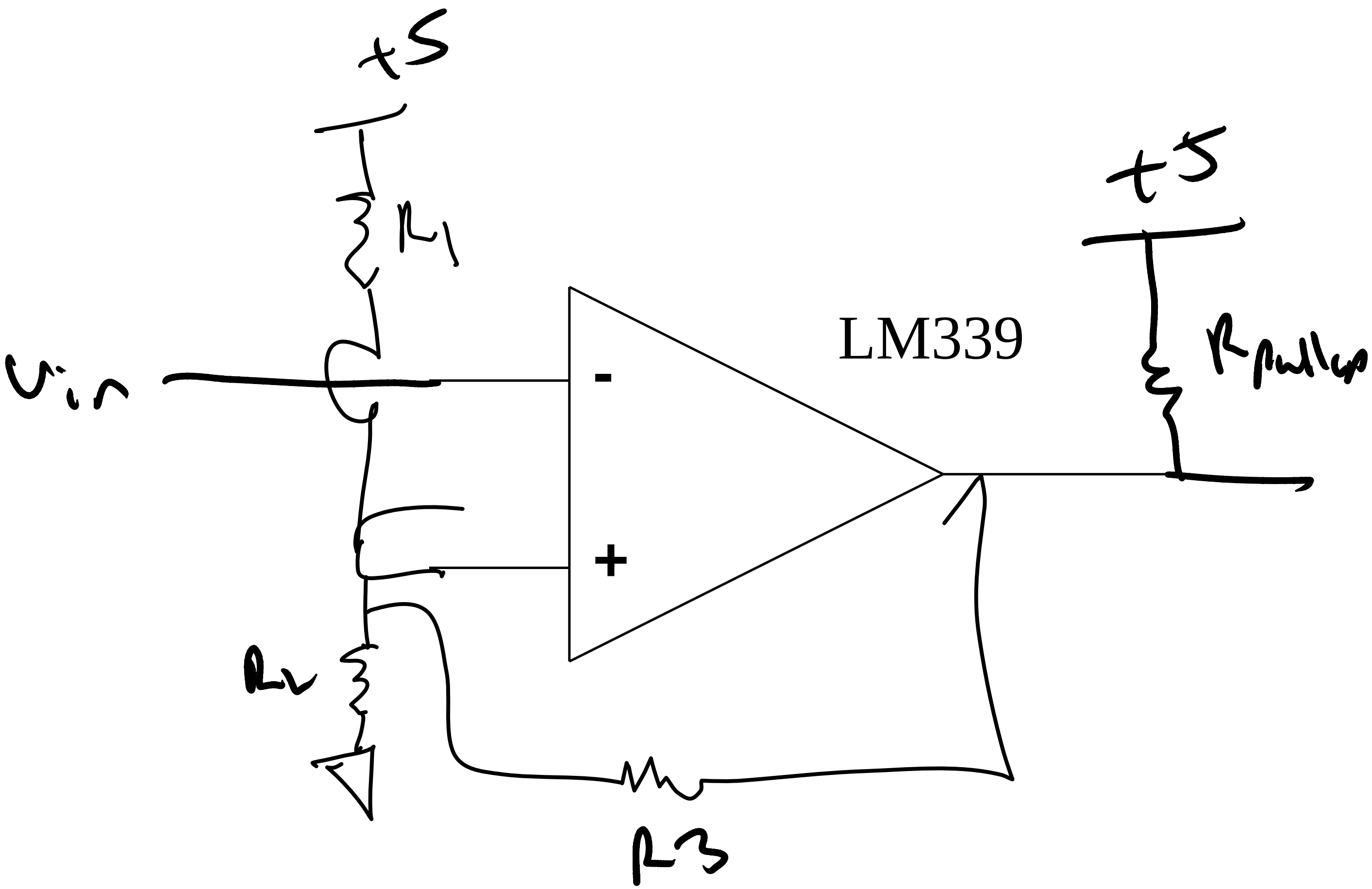






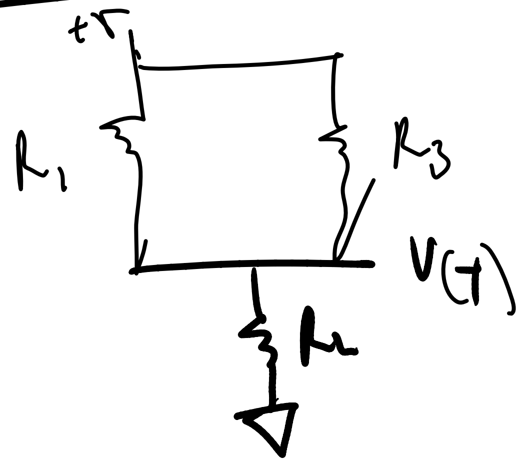
Same schmitt trigger

Eliminating the separate Vref?

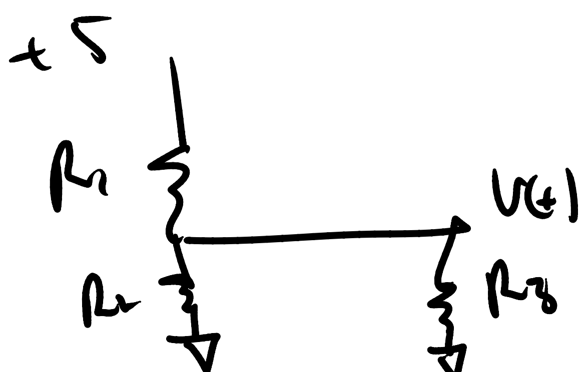


What is going on?

if output high



if output low



$R_3 \gg R_{pullup}$

Inverting Comparator Design Procedure (1.3)

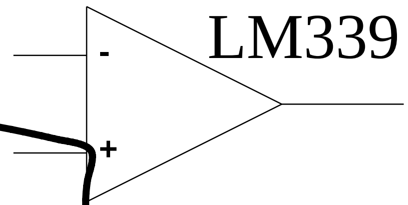
Cookbook on Comp.

V_{A1} = high threshold

V_{AL} = low threshold

$$\Delta V = V_{A1} - V_{A2}$$

$$N = \frac{\Delta V}{V_{A2}}$$



pick:

$R_3 = 1M\Omega$

$R_p = 3.9k\Omega$

$$R_1 = N R_3$$

$$R_2 = \frac{R_1 \parallel R_3}{\left(\frac{V_{cc}}{V_{A1}} - 1\right)}$$

if R_1 too big ($> 1M\Omega$) then reduce R_3 & try again

Inverting Comparator Design Procedure (2.3)

$V_{A1} = 1.625$

$V_{A2} = 1.375$

$\Delta V = 0.25$

$N = \frac{0.25}{1.375} = 0.182$

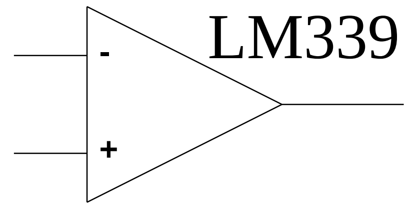
$R_3 = 1\,M\Omega$

$R_1 = N R_3 = 182\,k\Omega$

$R_2 = \frac{182\,k\Omega \,||\, 1\,M\Omega}{\frac{5}{1.625} - 1} \approx \frac{154\,k\Omega}{2} \approx 74\,k\Omega$

trip point @ 1.5V

ΔV 0.25V hyst.



The Non-Inverting Configuration