Understanding Operational Amplifiers

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Outline

- Cheng - History
- Pat - OP AMP Construction/design
- Alex - OP Amp Application Circuits
- Ken - Effect of Input offset voltage
- Nan - Effect of Slew Rate, Packaging, Conclusion

History

1941	First vacuum tube op-amp	Karl D. Swartzel Jr.
1947	First op-amp with non-inverting input	John R. Ragazzini
1949	First chopper-stabilized op-amp	Edwin A. Goldberg
1961	Discrete IC op-amp	

History Continued

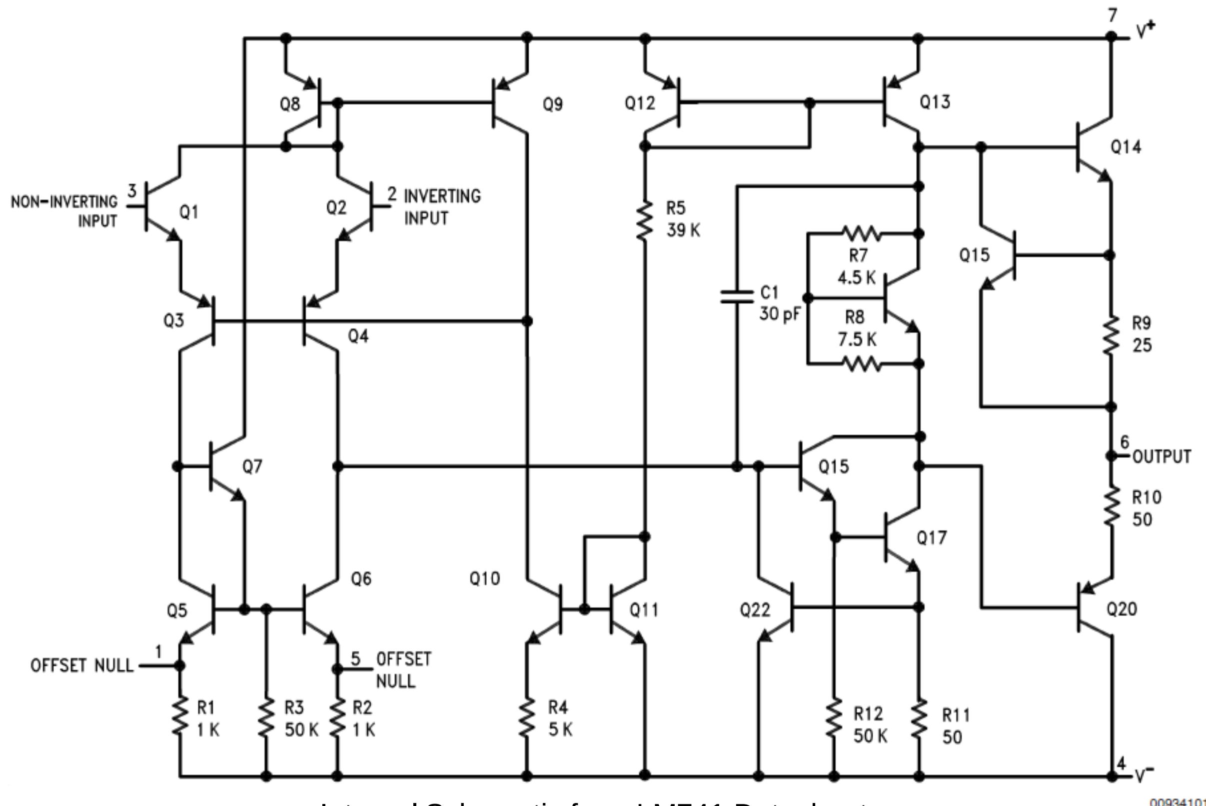
1963	First monolithic IC op-amp	Bob Widlar
1970	First high-speed, low-input current FET design	
1972	Single sided supply op-amps being produced	

Op Amp Construction

- Integrated Circuit(IC) Main Categories:
  - Linear ICs
    - Performs amplification or linear operations on signals.
  - Monolithic (“one stone”) Circuits
    - The entire circuit is embedded upon a single piece of semiconductor.

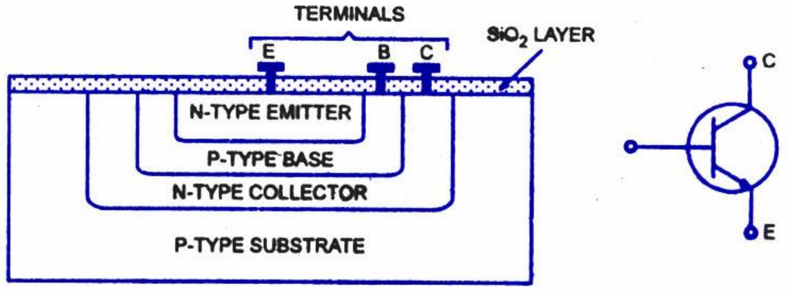
µA741 Op-Amp

- Bias Circuit
- Input Stage
- Intermediate Stage
- Output Stage
- Short-circuit Protection

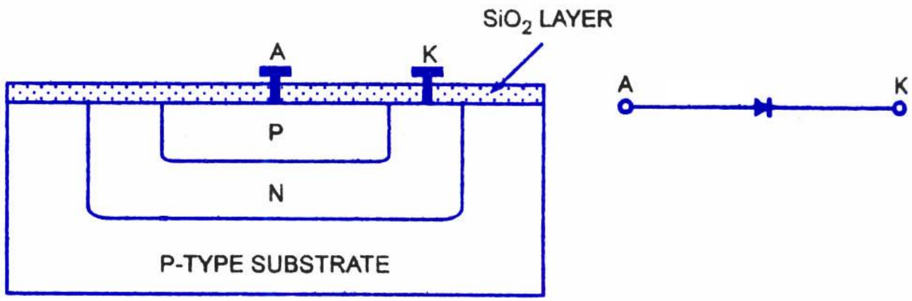


Internal Schematic from LM741 Datasheet

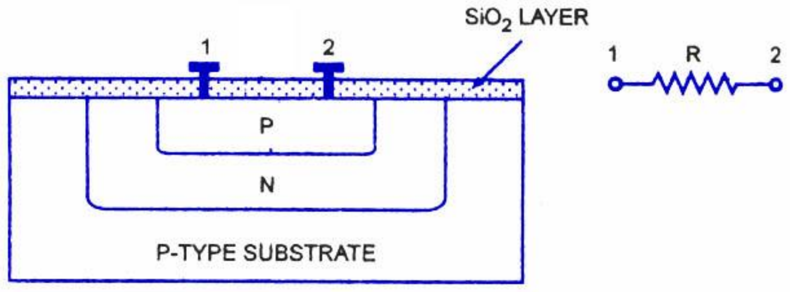
Monolithic Building Blocks



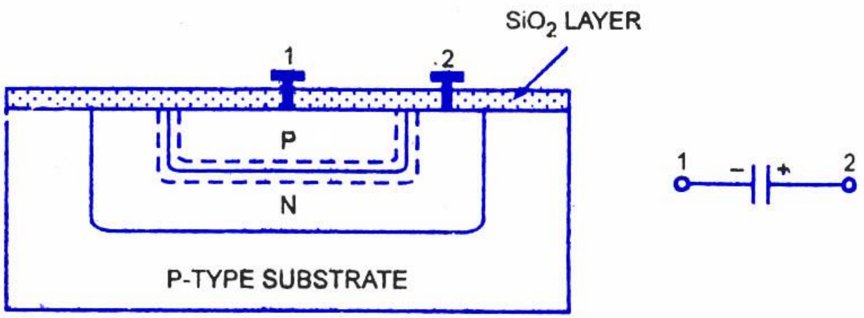
Transistor



Diode

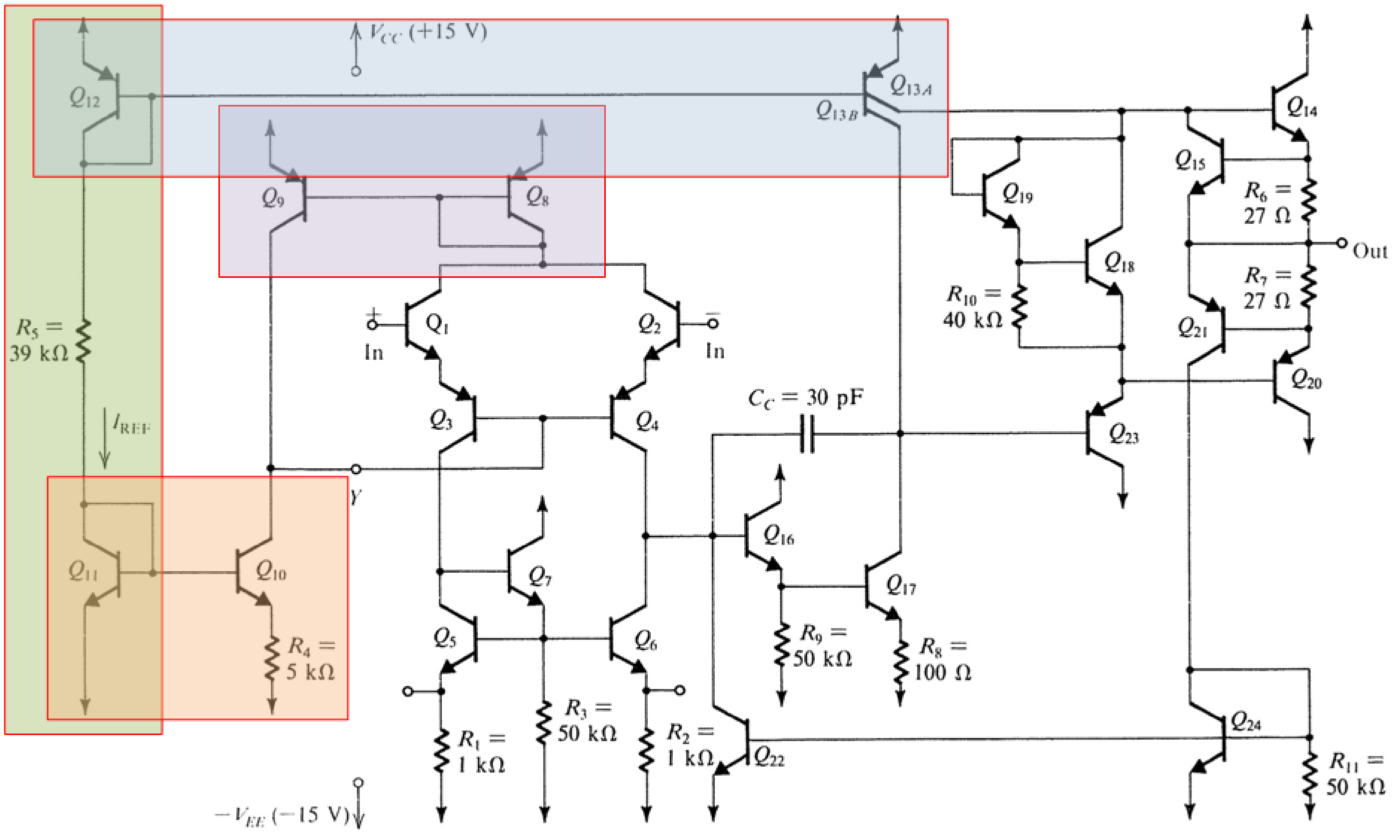


IC Diffused Resistor

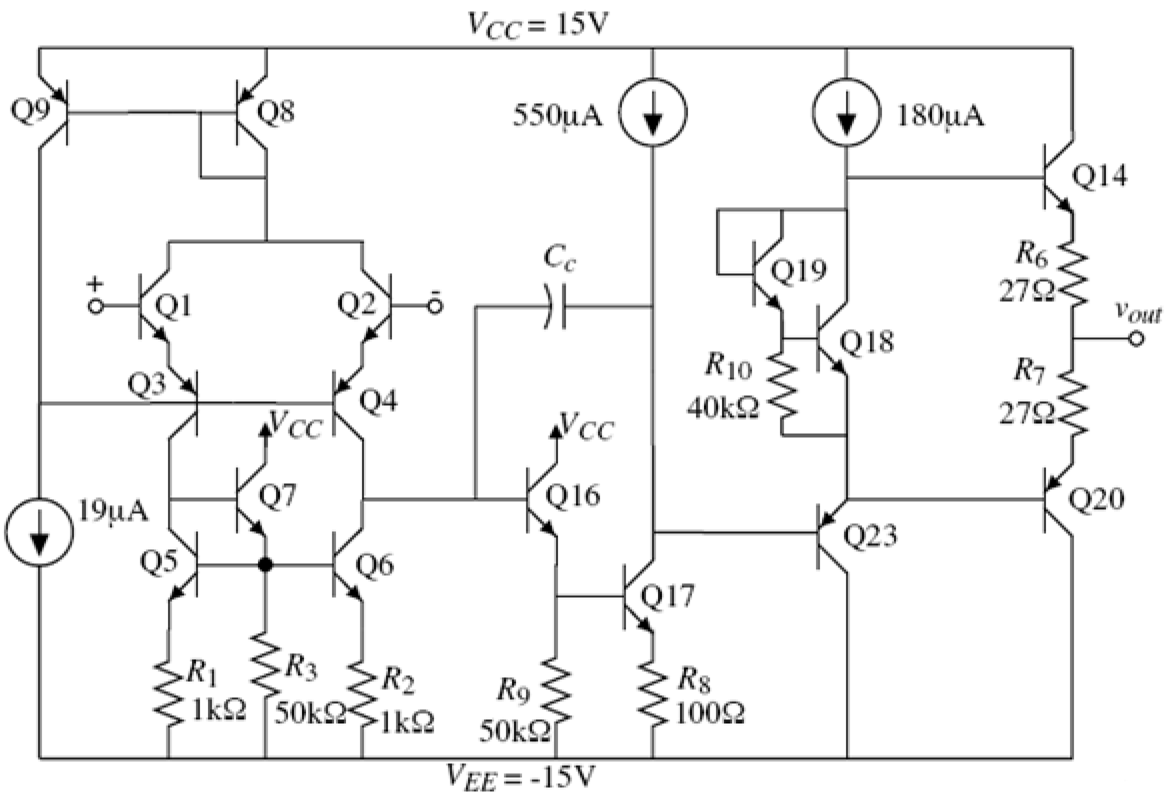


IC Diffused Capacitor

Biasing Circuit



Biasing Circuit



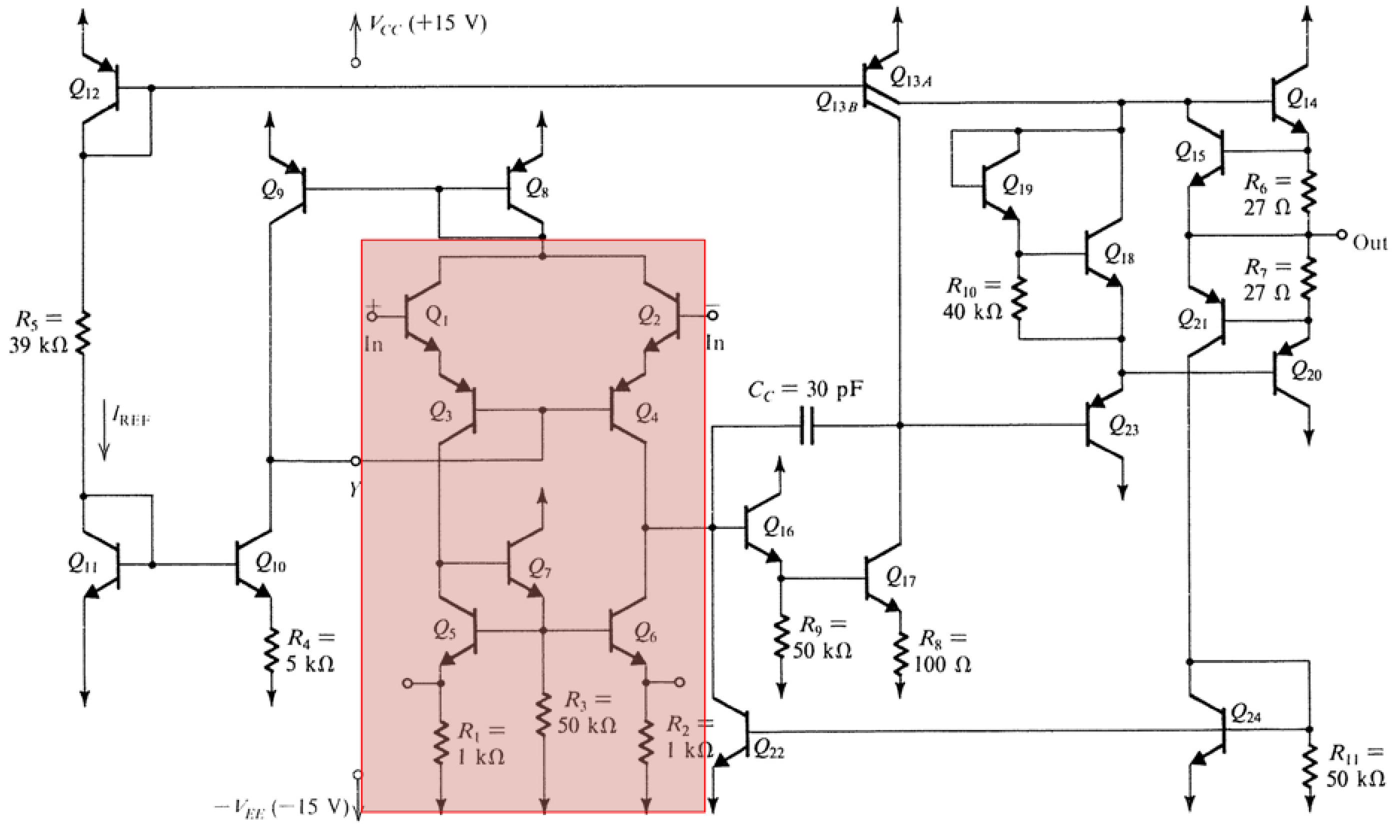
$$I_{ref} = \frac{V_{CC} - V_{EE} - 2V_{BE}}{R_5} = 733\mu A$$

$$I_{13B} = 0.75 I_{ref} = 550\mu A$$

$$I_{13A} = 0.25 I_{ref} = 180\mu A$$

$$I_{10} = \frac{V_t}{R_4}\left[ln(I_{ref}) - ln(I_{10})\right] = 19\mu A$$

Input Stage

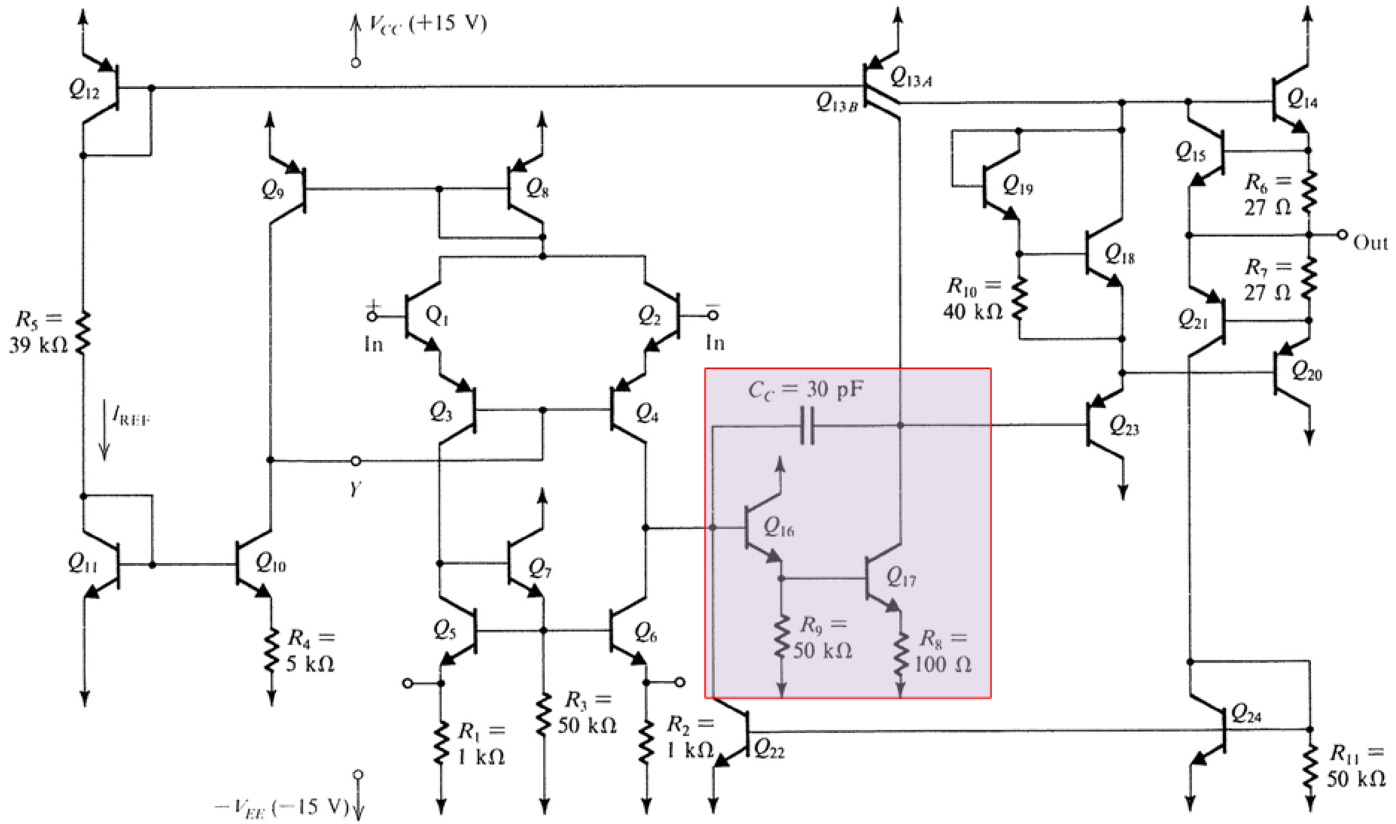


V_{CC} (+15 V)
Q_{12}
Q_{13A}
Q_{13B}
Q_{14}
Q_9
Q_8
Q_{15}
Q_{19}
$R_6 =$ 27 Ω
Out
Q_{18}
$R_{10} =$ 40 kΩ
$R_7 =$ 27 Ω
Q_1
Q_2
+ In
− In
$R_5 =$ 39 kΩ
Q_{21}
Q_{20}
$C_C =$ 30 pF
Q_3
Q_4
Q_{23}
I_{REF}
Y
Q_{16}
Q_{11}
Q_{10}
Q_7
Q_{17}
Q_5
Q_6
$R_4 =$ 5 kΩ
$R_9 =$ 50 kΩ
$R_8 =$ 100 Ω
$R_3 =$ 50 kΩ
Q_{24}
$R_1 =$ 1 kΩ
$R_2 =$ 1 kΩ
Q_{22}
$R_{11} =$ 50 kΩ
$-V_{EE}$ (−15 V)

Input Stage

- Q1, Q2 are emitter followers.
- Q3, Q4 in common-base configuration serve as differential amplifier, level shifters and protect Q1, Q2 against emitter-base junction breakdown.
- Q5, Q6, Q7 and R1, R2, R3 provide the load (active load) for the differential amplifier.

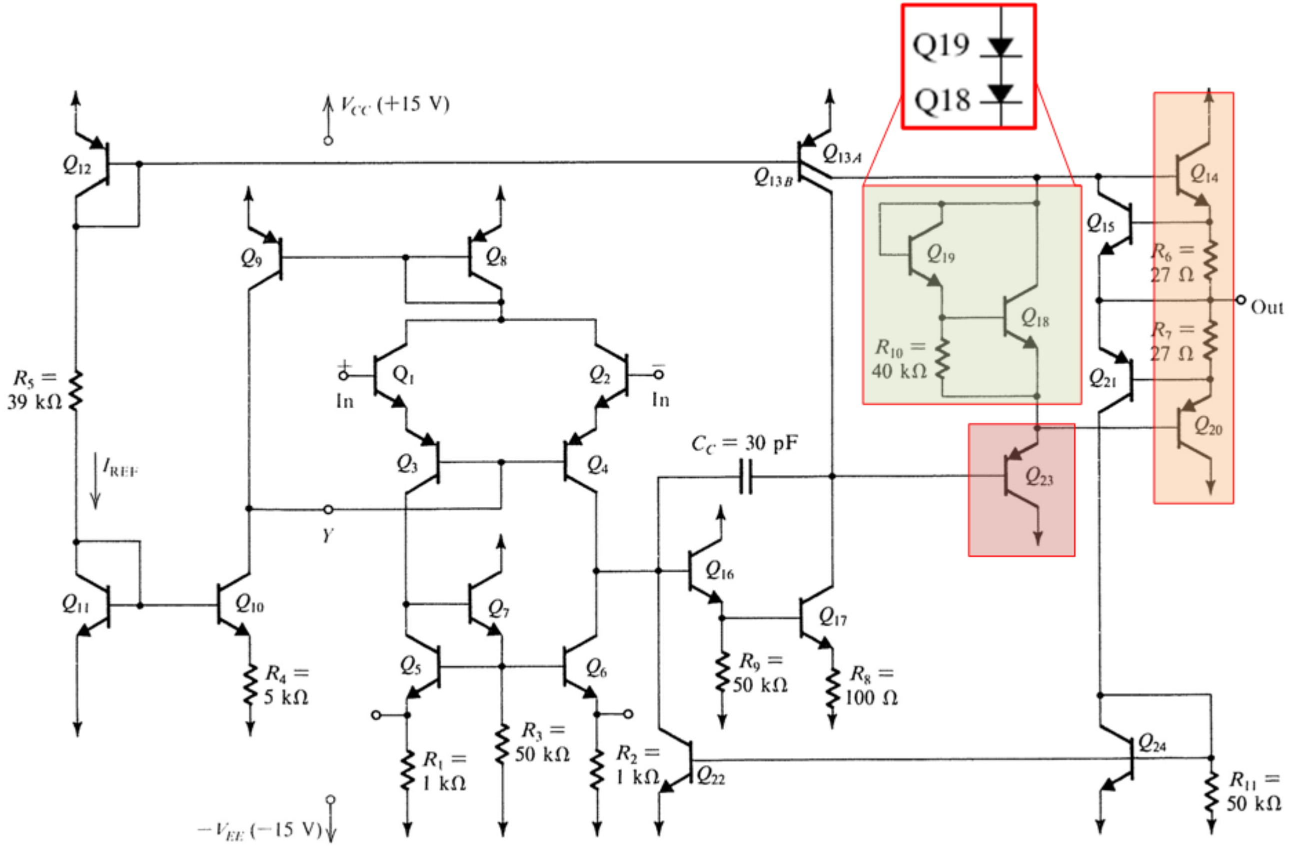
Intermediate Stage



Intermediate Stage

- Q16 is an emitter follower.
- Q17 is a common-emitter amplifier, loaded by Q13B.
  - GAIN $\approx (g_{m\text{-}Q17})(r_{0\text{-}Q13B})$
- Cc is the internal compensation cap used to maintain stability when the op-amp is used in a feedback configuration.

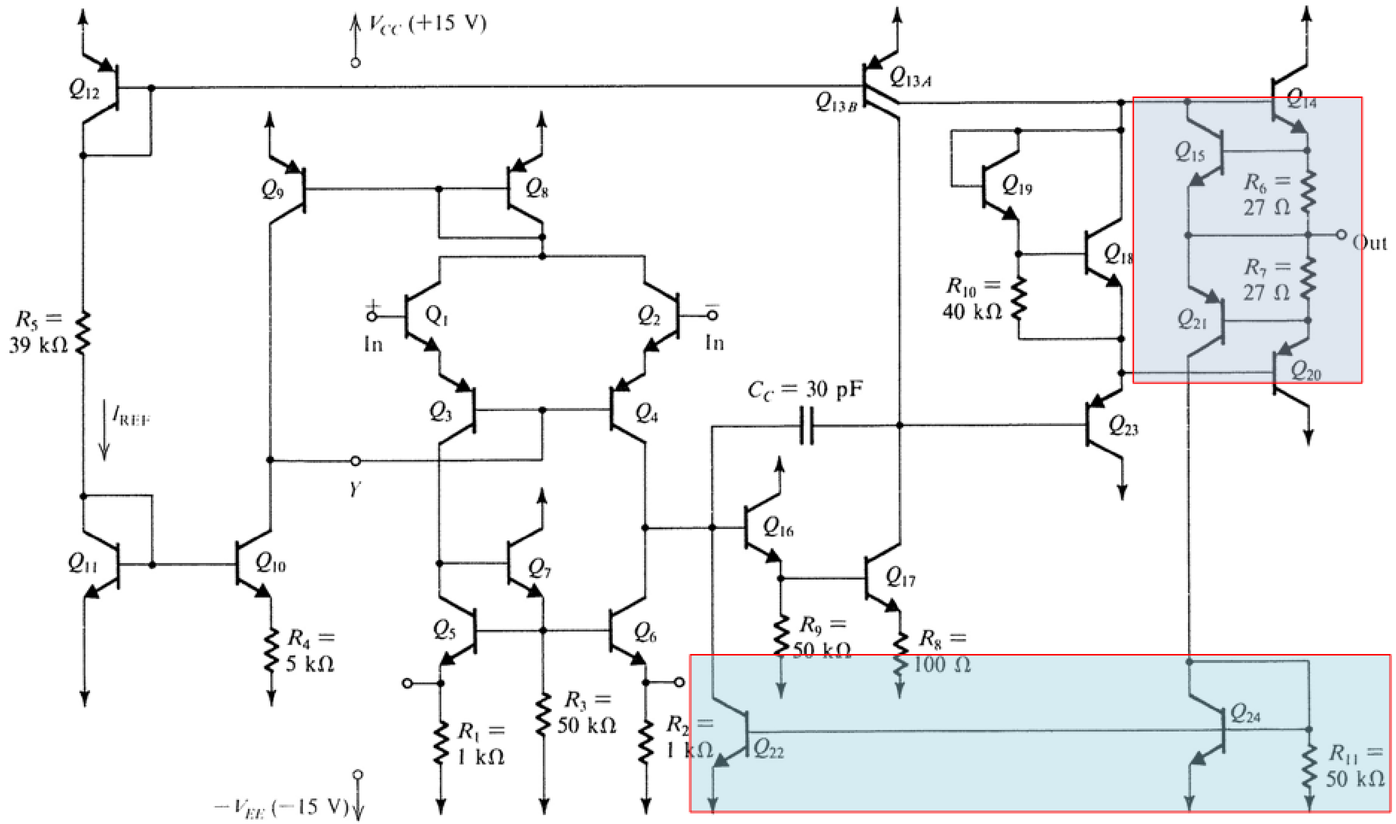
Output Stage



Output Stage

- Q23 is an emitter follower.
- Q14, Q20 are a complementary push-pull, or Class AB amplifier.
- Q19, Q18 are a Darlington-pair, but act similar to diodes. They maintain a V_{BE} drop to smooth out the crossover distortion of Q14, Q20.

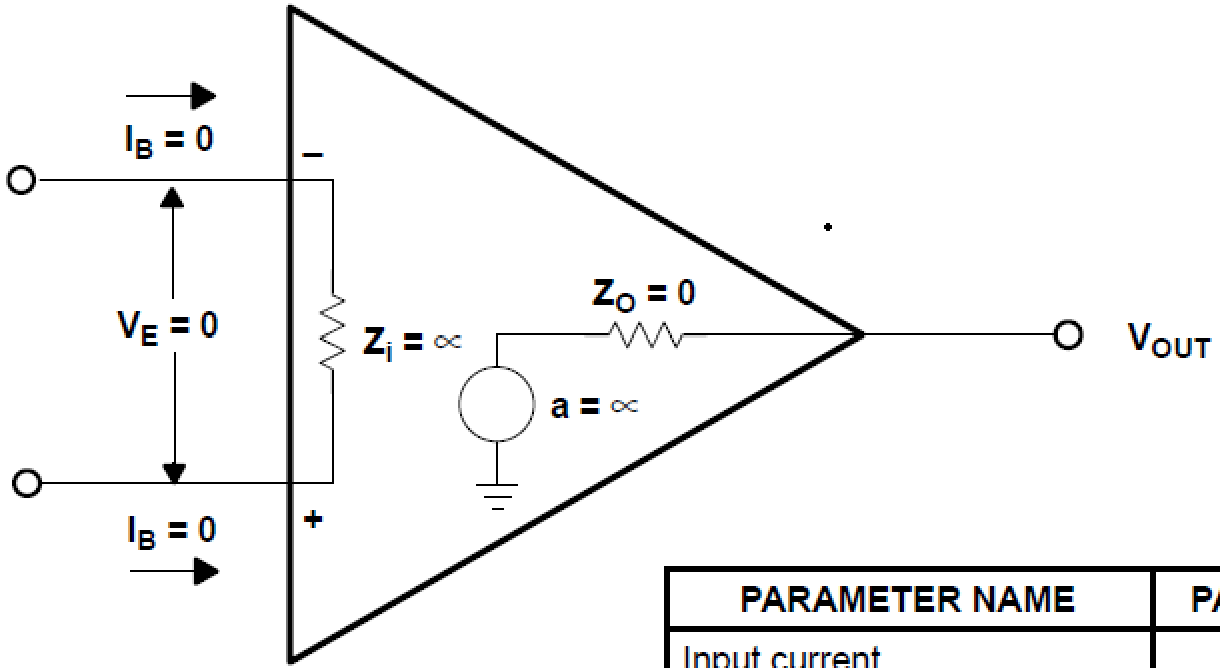
Short-circuit Protection



Short-circuit Protection

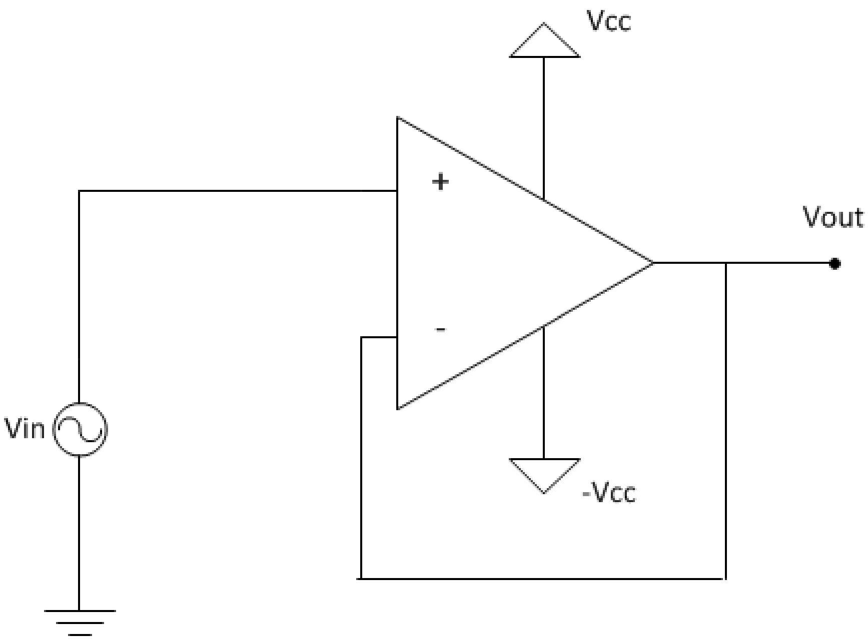
- Q15, Q21 are normally off.
- If too much current is being output (~25mA), the voltage drop across R6, R7 will turn Q15, Q21 on to bleed off the current via Q22, Q24 current mirror.

Op-amp Design Applications

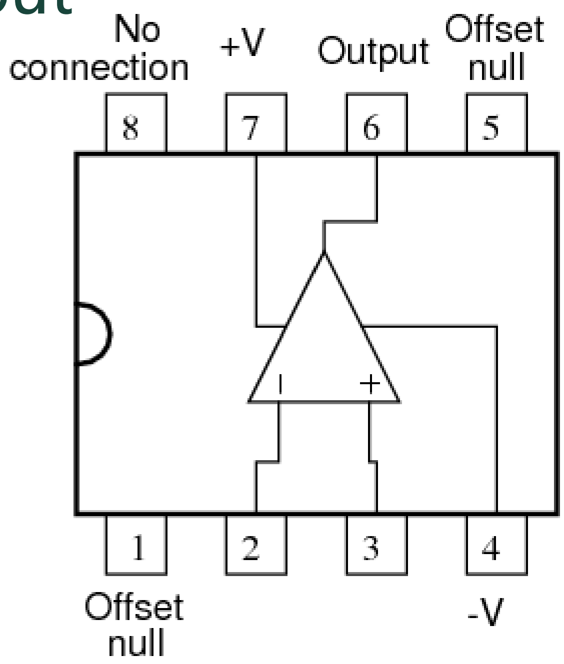


PARAMETER NAME	PARAMETERS SYMBOL	VALUE
Input current	I_{IN}	0
Input offset voltage	V_{OS}	0
Input impedance	Z_{IN}	∞
Output impedance	Z_{OUT}	0
Gain	a	∞

Simple Buffer Circuit or Voltage Follower

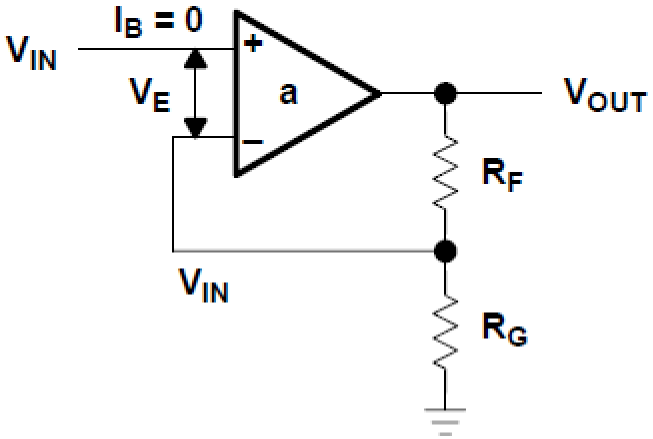


Typical 8-pin Op-Amp Layout



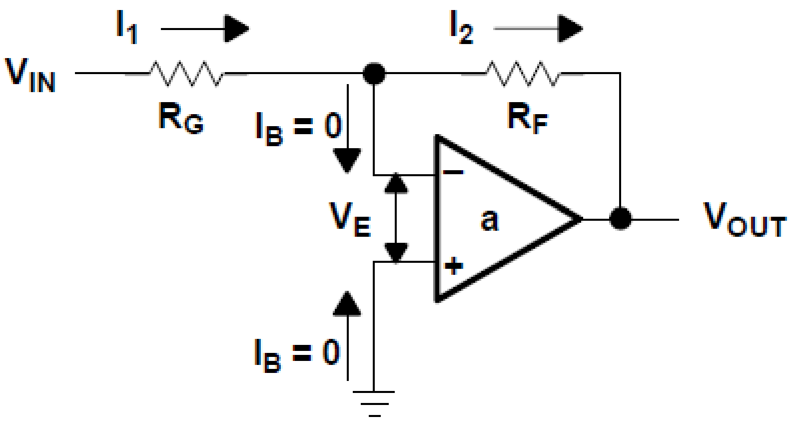
Amplifier Circuits

Non-Inverting



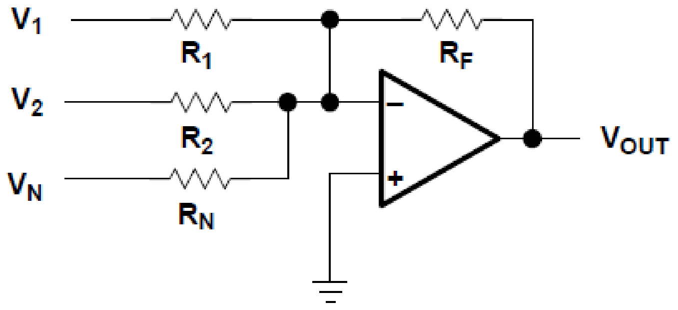
$$\frac{V_{OUT}}{V_{IN}} = \frac{R_G + R_F}{R_G} = 1 + \frac{R_F}{R_G}$$

Inverting



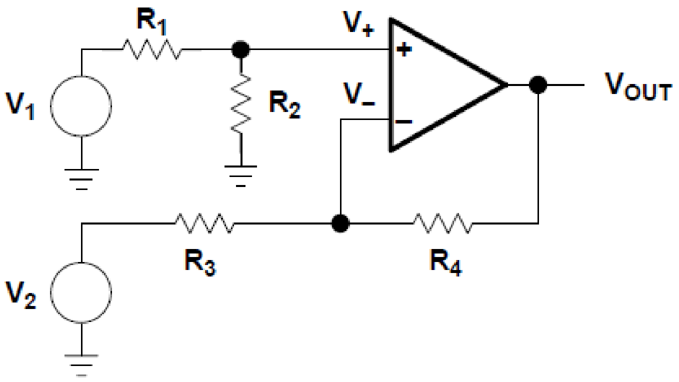
$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_F}{R_G}$$

Adder



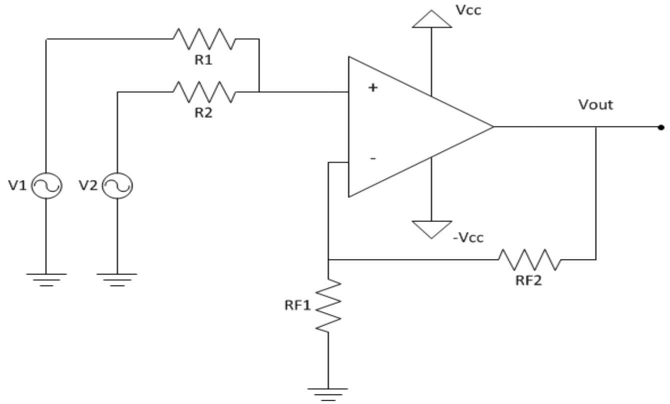
$$V_{OUT} = -\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2 + \frac{R_F}{R_N}V_N\right)$$

Differential



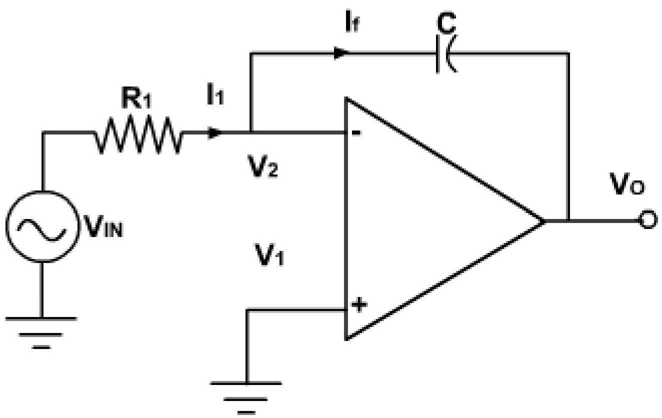
$$V_{OUT} = (V_1 - V_2)\frac{R_4}{R_3}$$

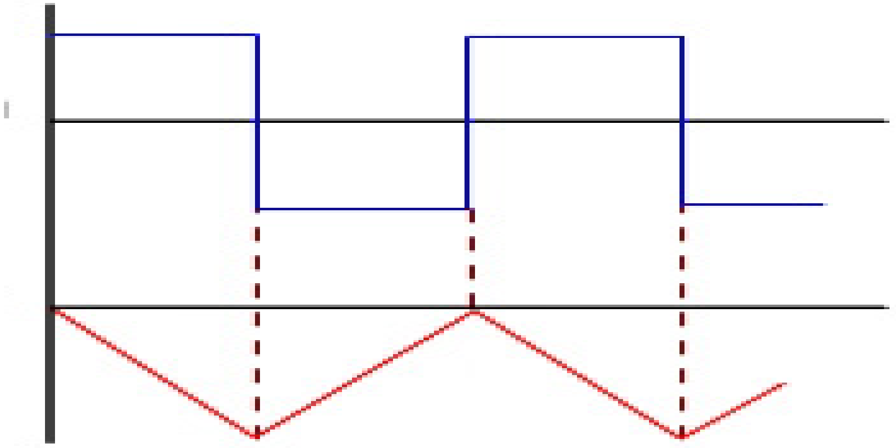
Non-Inverting Summing Amplifier



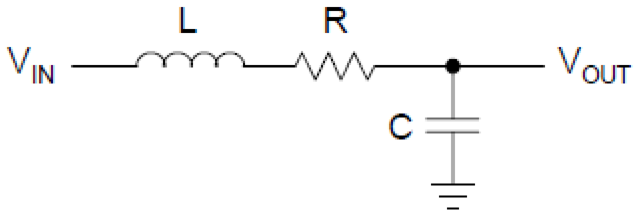
$$Vout = \left(1 + \frac{Rf2}{Rf1}\right) \cdot \left(V1 \cdot \frac{R2}{R1 + R2} + V2 \cdot \frac{R1}{R1 + R2}\right)$$

Integrator

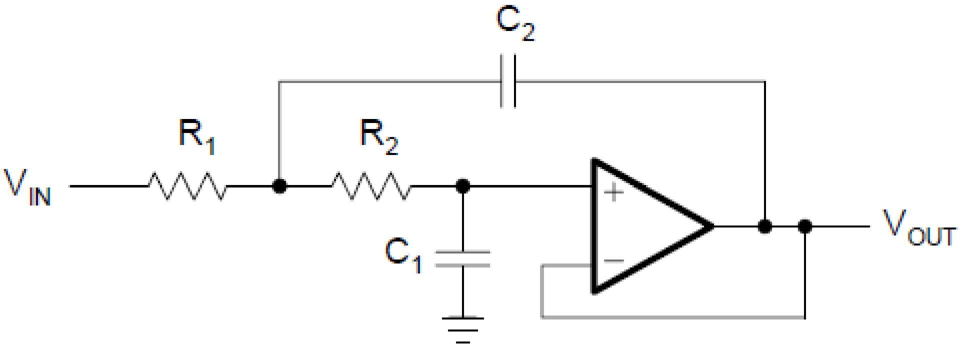




Active Filter Design



Passive



Active

OP AMP Specifications

Some Specifications to be aware of when using Operational Amplifiers in your circuits.

- Input Offset Voltage- Input Offset Null Pins
- Slew Rate

LM741 Datasheet

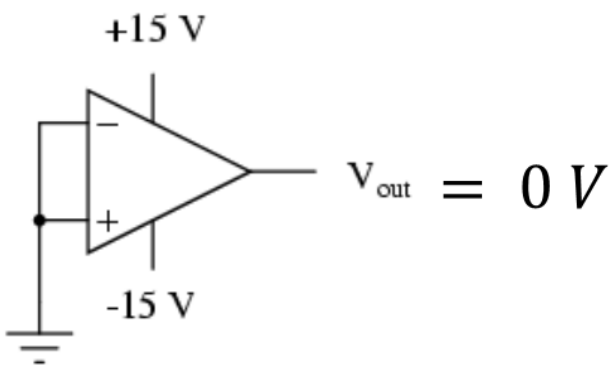
Electrical Characteristics (Note 5)

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)

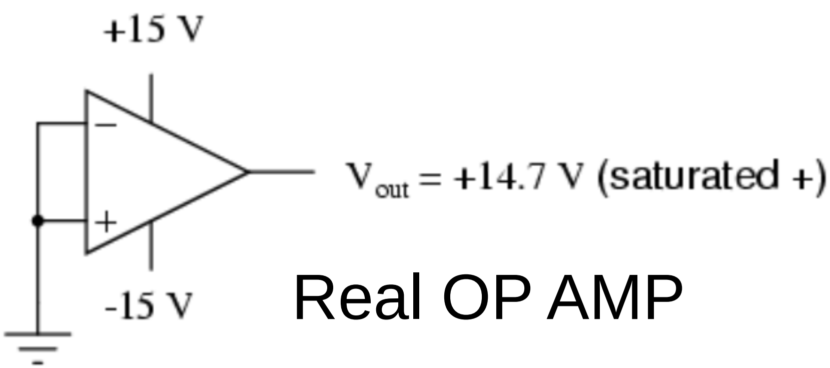
Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain	$T_A = 25°C$, $R_L \geq 2\ k\Omega$										
	$V_S = \pm 20V$, $V_O = \pm 15V$	50									V/mV
	$V_S = \pm 15V$, $V_O = \pm 10V$				50	200		20	200		V/mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$R_L \geq 2\ k\Omega$,										
	$V_S = \pm 20V$, $V_O = \pm 15V$	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

What is Input Offset Voltage?



Ideal OP AMP

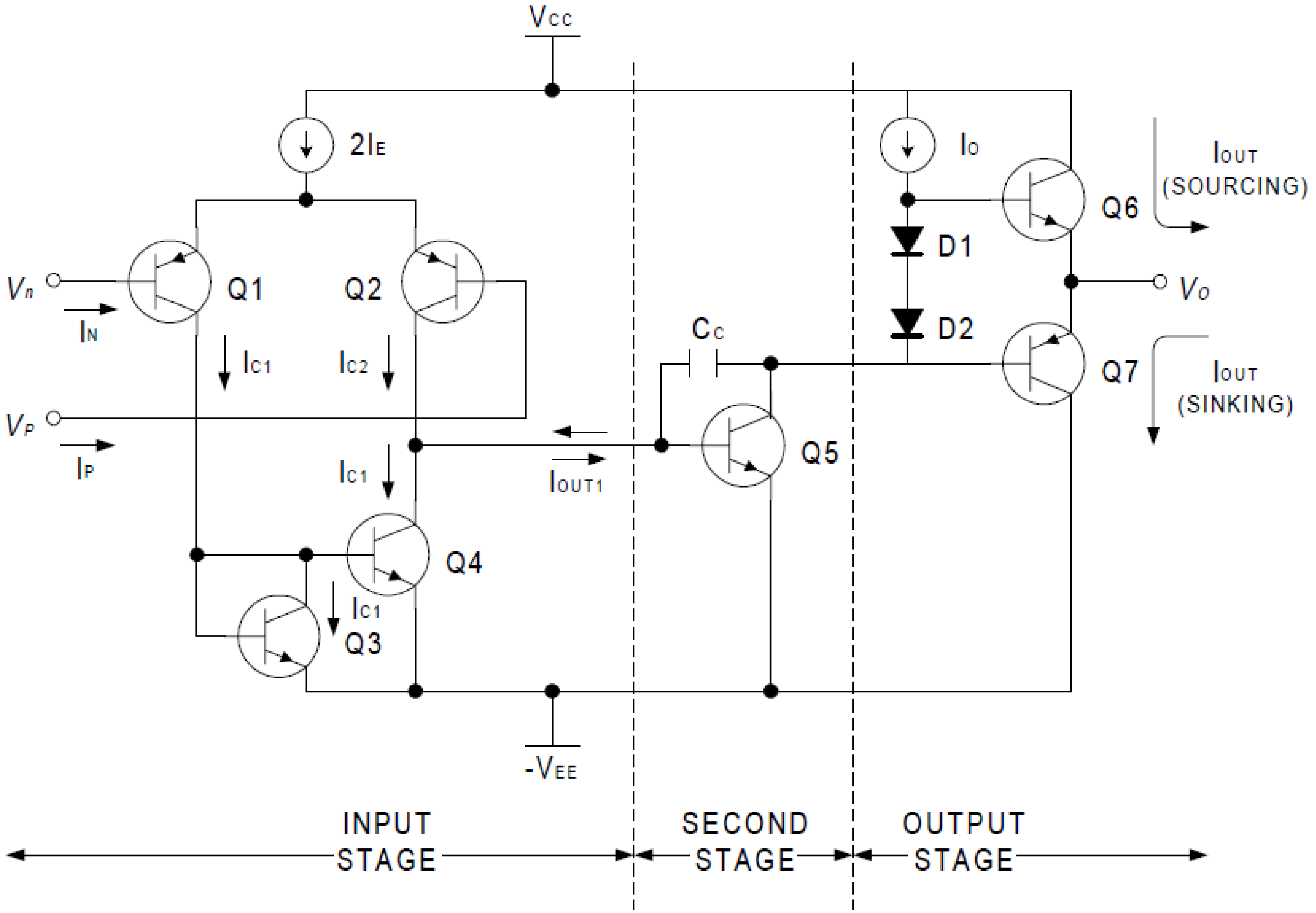
In an Ideal Op Amp the output should be exactly 0v with inputs shorted.

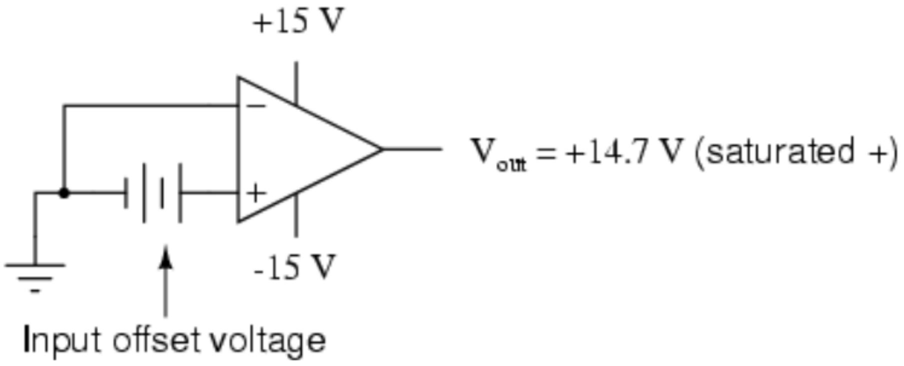


Real OP AMP

However In a real OP Amp there will be some output voltage when the inputs are shorted due to slight differences in the internal OP Amp transistors

What Causes Input Offset Voltage?



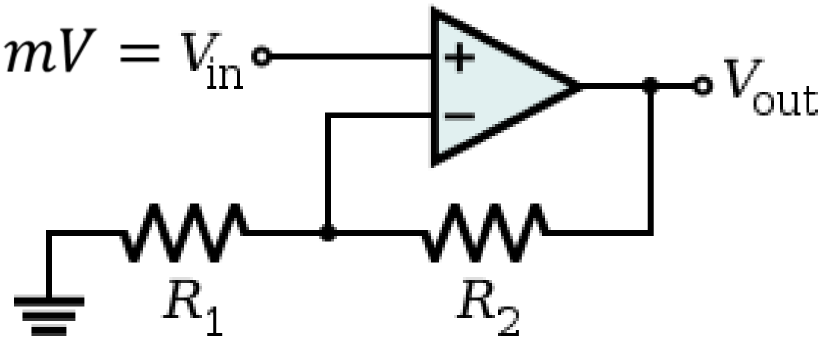


Typically 0 to 10 mV

The Input Offset Voltage can be modeled as a small voltage always present at one of the inputs to an Ideal Op Amp.

Effect of Input Offset Voltage

$50\ mV = V_{in}$



$1\ K$ $99\ K$

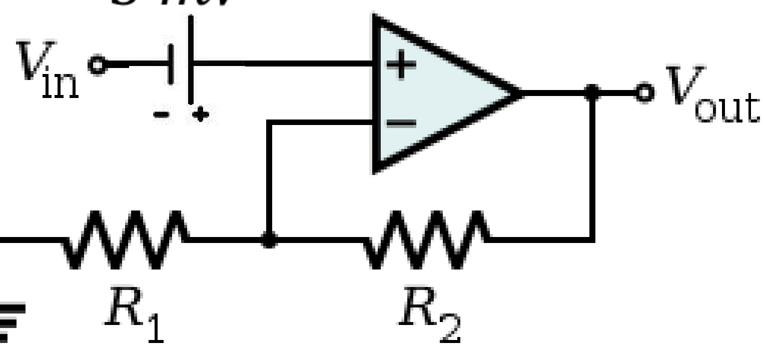
$$= Vin * \left(1 + \frac{R2}{R1}\right)$$

$$= 50\ mV * (1 + 99)$$

$$= 5\ V$$

$3\ mV$

$50\ mV =$



$1\ K$ $99\ K$

$$= (Vin + 3\ mV) * \left(1 + \frac{R2}{R1}\right)$$

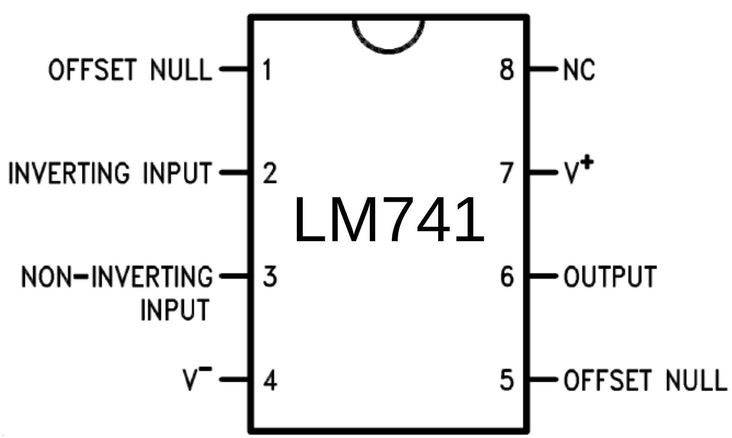
$$= 53\ mV * (1 + 99)$$

$$= 5.3\ V\ \ OR\ \ 4.7V$$

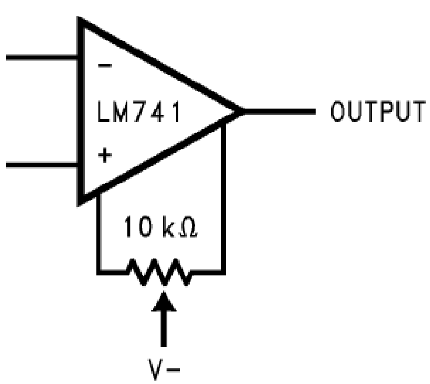
LM741 Null Pins

Some Op Amps have NULL Pins which allow adjustment to compensate for Input Offset Voltage.

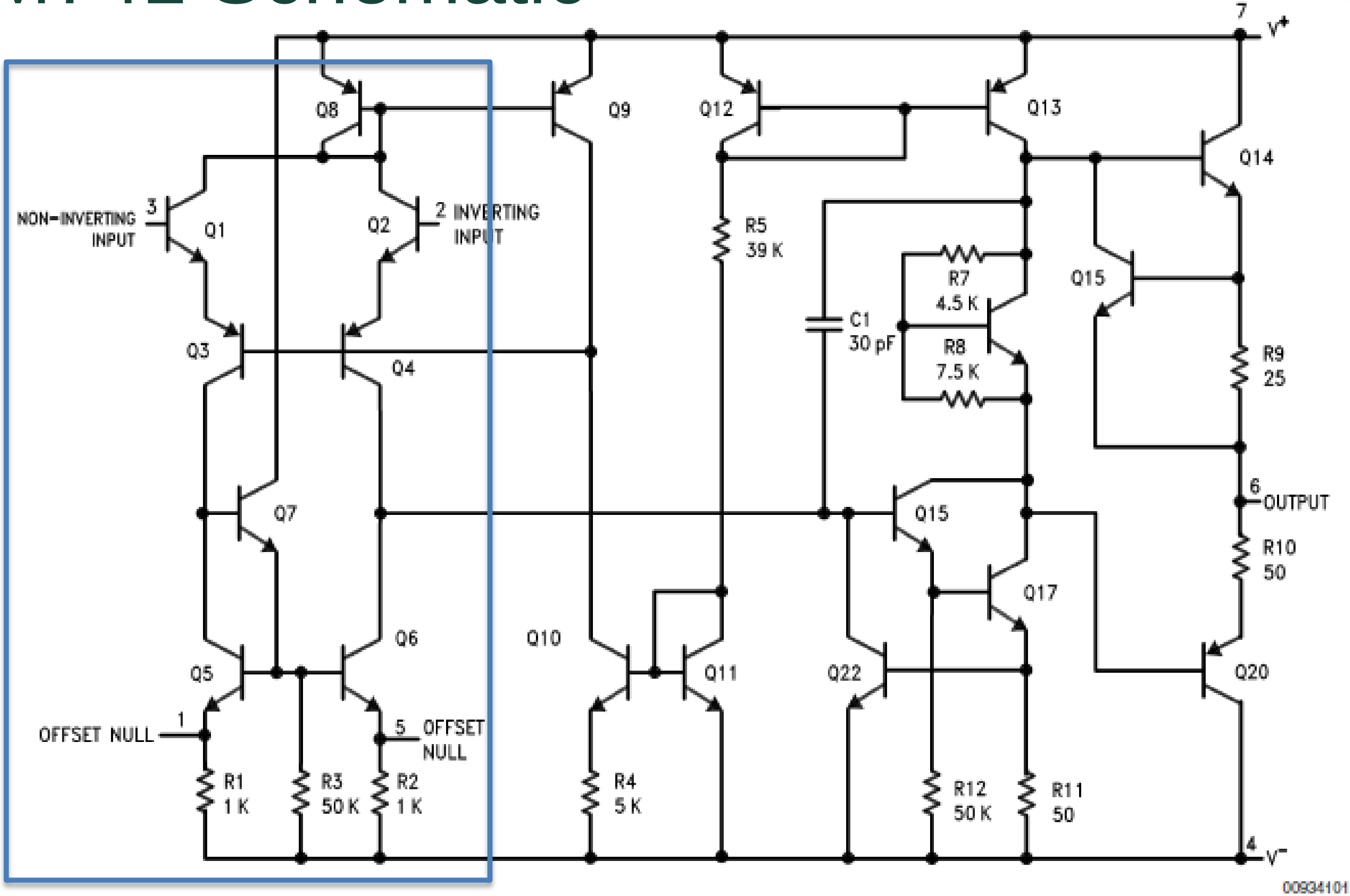
- LM741 Has Null Pins
- LM324 Does NOT have Null Pins



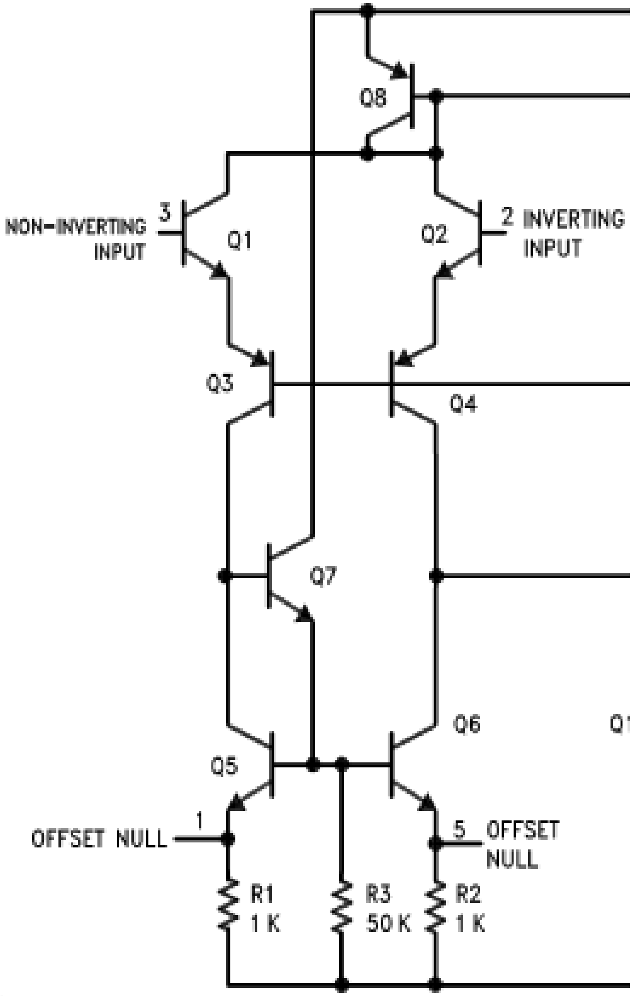
Offset Nulling Circuit



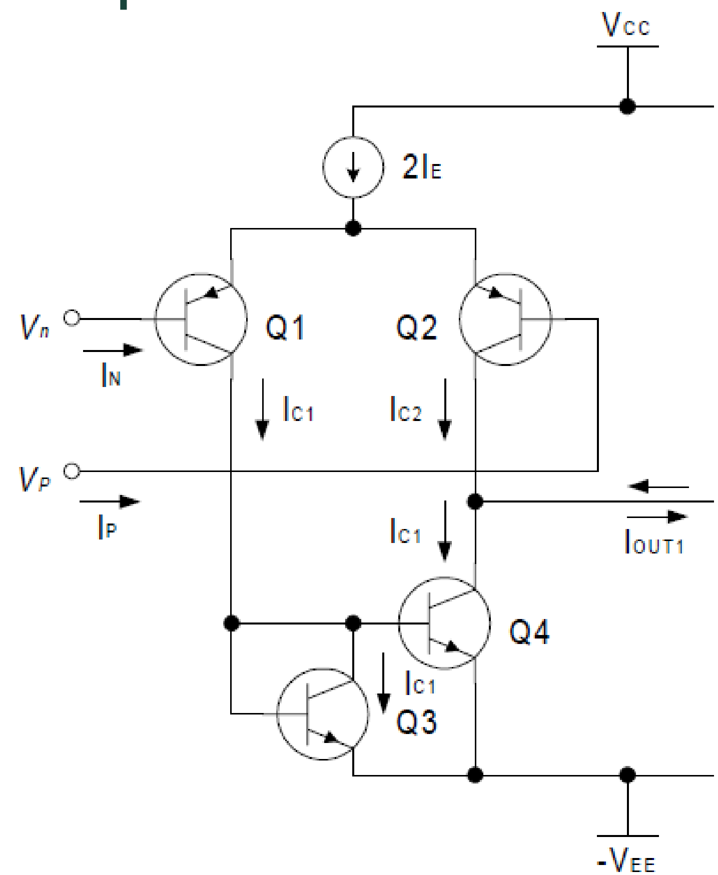
LM741 Schematic



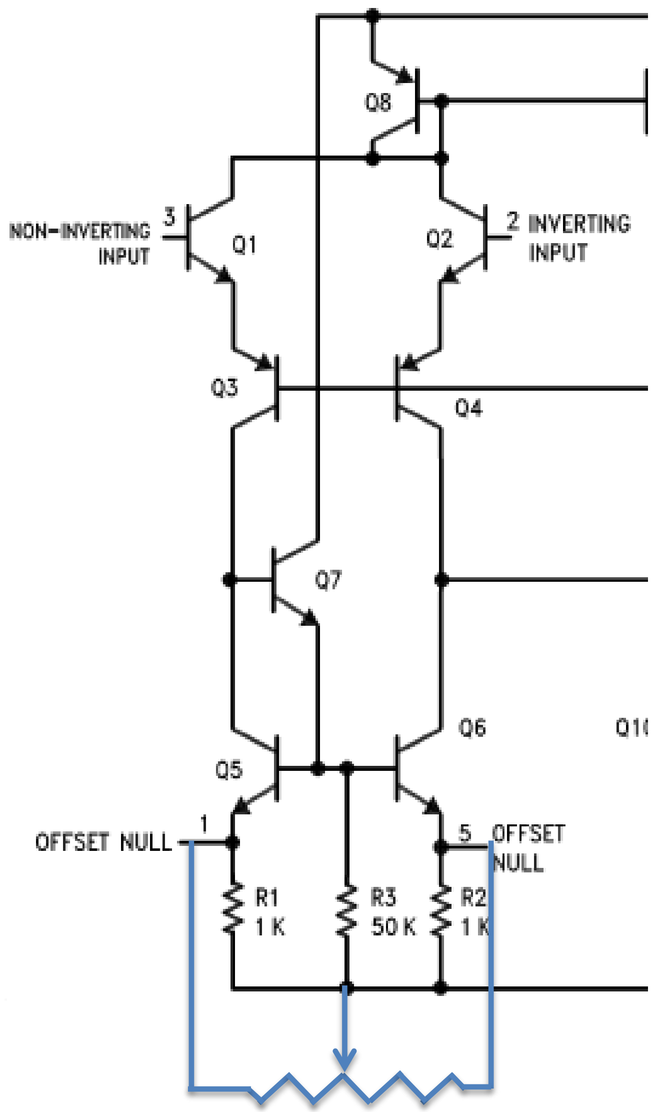
LM741 Input



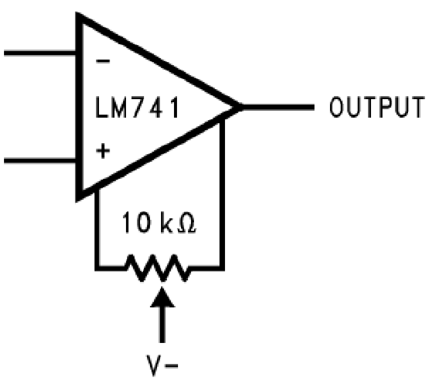
Generalized Op Amp Input- similar to LM324



LM741 Input



Offset Nulling Circuit



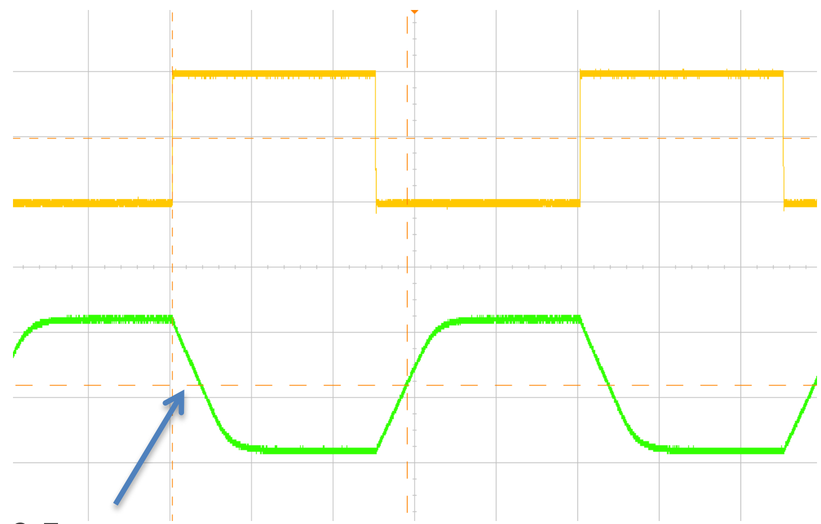
Slew Rate

The Slew Rate of an Op Amp is the maximum rate of change in the output voltage expressed in volts/µs

The LM741 has a slew rate of 0.5 volts/µs

Inpu
t

Outpu
t



0.5
volts/µs

The maximum frequency input sine which can be applied before slew rate distortion is seen-

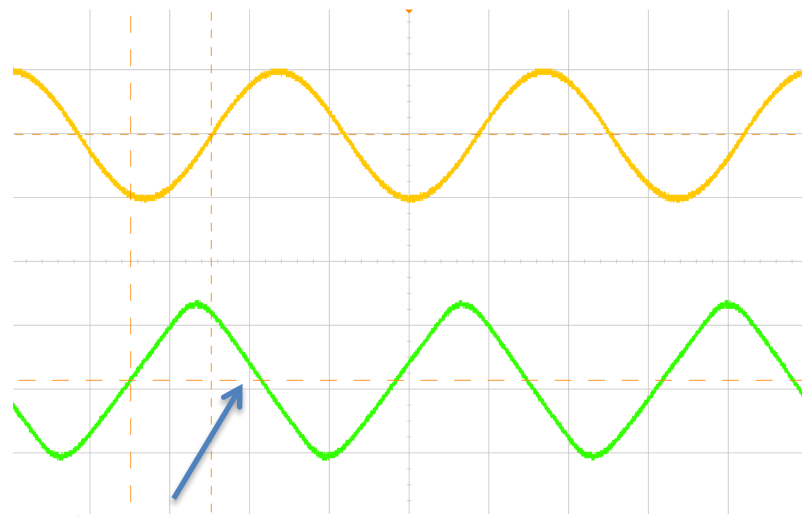
$$\frac{dV}{dt}(\sin(2\pi f t)) = 2\pi f\cos(2\pi f t)$$

$$\frac{dV}{dt}(max) = \ 2\pi f$$

$$f_{max} = \frac{10^6 * Slew\ Rate}{2\pi}$$

Input

Output



0.5 volts/µs

Purchasing an Op-amp

- Package
  - DIP
  - TSSOP
  - MSOP
- Mount Type
  - Surface Mount
  - Through Hole

1. Package

- Dual in-line-package (DIP):

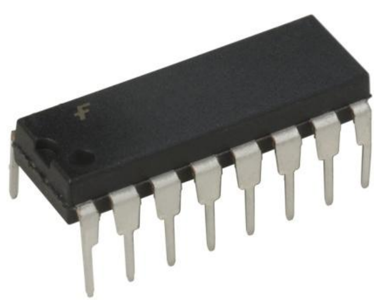
  Regular sized op amp.

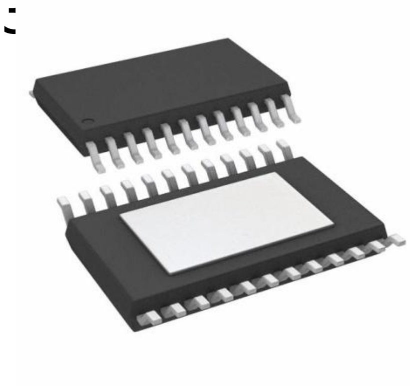
- Thin Shrink Small outline package (TSSOP):

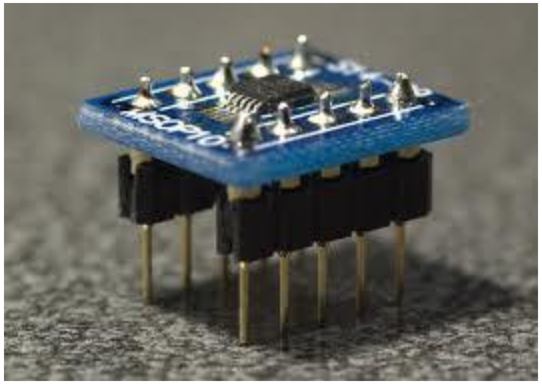
  Smaller body size & lead pitches (0.9mm thick).

- Micro small outline package (MSOP):

  Only 3mm * 3







2. Mount type

- Surface mount

  SOPs are surface mount. Need sockets to solder on the PCB.

- Through hole

  DIPs are though hole. Sockets will help to remove or switch the op amp.

Conclusion

Cheng - History

Pat - OP AMP Construction/design

Alex - OP Amp Application Circuits

Ken - Effect of Input offset voltage

Nan - Effect of Slew Rate, Packaging, Conclusion

Thank you