107_OAF

Operational Amplifier Fundamentals

Microchip Analog FAE
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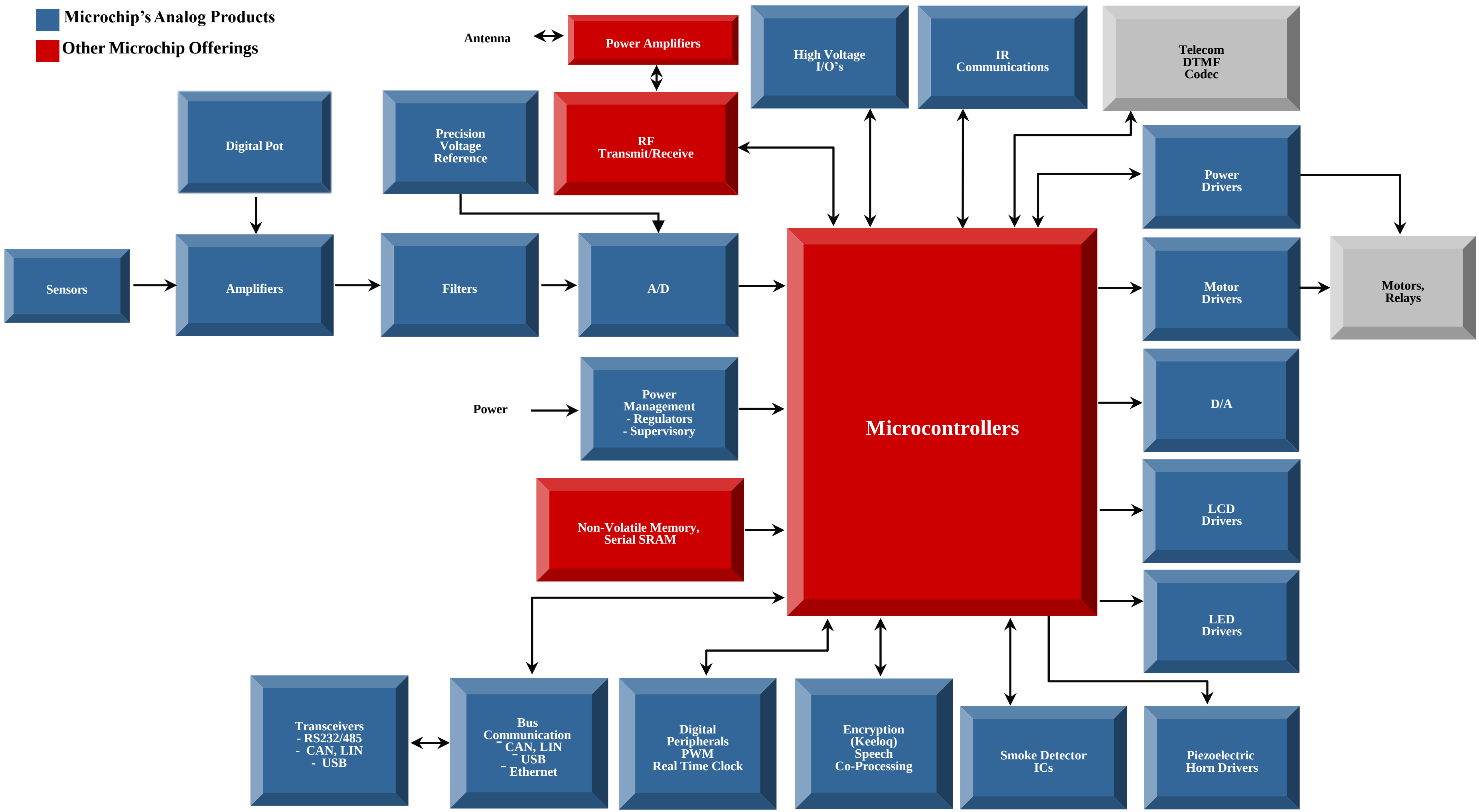
Universe of Embedded Control Systems



Overview

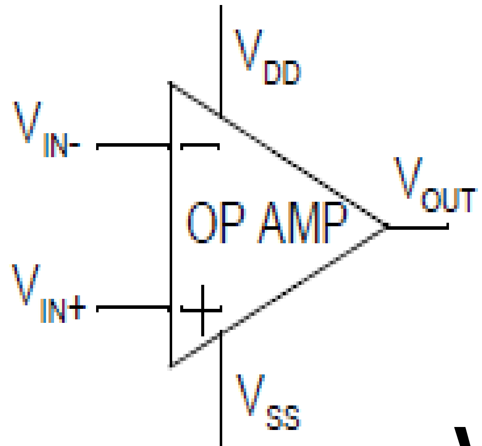
- The class will begin with basic Operational Amplifier Concepts and Terminology.
- Primary DC and AC characteristics found in an op amp data sheet will be defined and discussed, with Examples to enhance understanding.
- **Microchip Analog and Interface Product Introduction – TreeLink Application/ Product Selection Guide**
- Examples and analysis of Op Amp application circuits will be provided—Demo Boards

POWER SUPPLY

- No min or max Voltage (V_{DD}, V_{SS})
- I_{SUPPLY} = 0 Amps
- Power Supply Rejection Ratio (PSRR) = ∞

INPUT

- Input Current (I_B) = 0
- Input Impedance (Z_{IN}) = ∞
- Input Voltage Range (V_{IN}) $\rightarrow$ no limits
- Zero Input Voltage and Current Noise
- Zero DC offset error (V_{OS})
- Common-Mode Rejection = ∞



OUTPUT

- V_{OUT} = V_{SS} to V_{DD}
- I_{OUT} =
- Slew Rate (SR) = ∞
- Z_{OUT} = 0Ω

$$V_{OUT} = A(V_{IN+} - V_{IN-})$$

SIGNAL TRANSFER

- Open Loop Gain (A_{OL})= ∞
- Bandwidth = 0 $\rightarrow$ ∞
- Zero Harmonic Distortion (THD)

FIGURE 1: The ideal op amp description can be separated into four basic categories: input, power supply, output, and signal transfer.

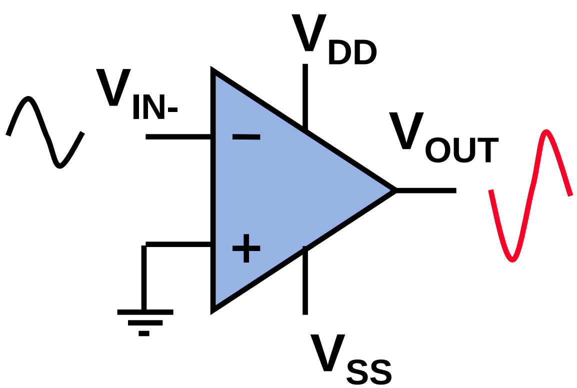
AN722_DC_OP

Op Amp Basics

Signal Input Modes

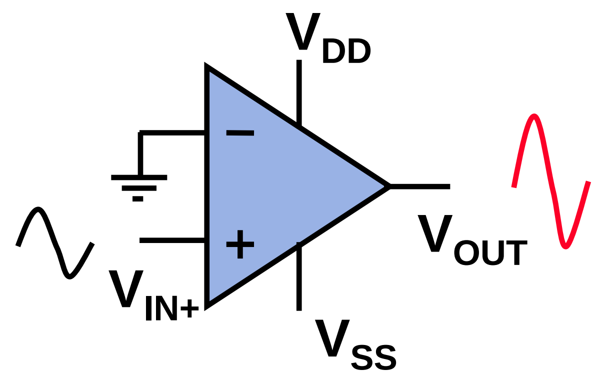
- <u>Single-input mode</u>

Inverting input



- Input signal is applied to the inverting input terminal
- V_{OUT} is 180° out of phase with V_{IN-}

Non-inverting input

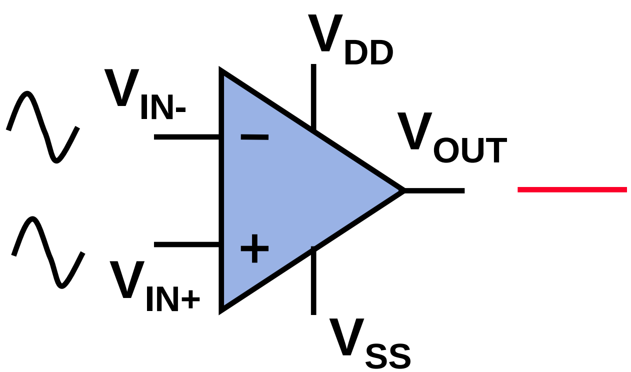


- Input signal is applied to the non-inverting input terminal
- V_{OUT} is in phase with V_{IN+}

Op Amp Basics

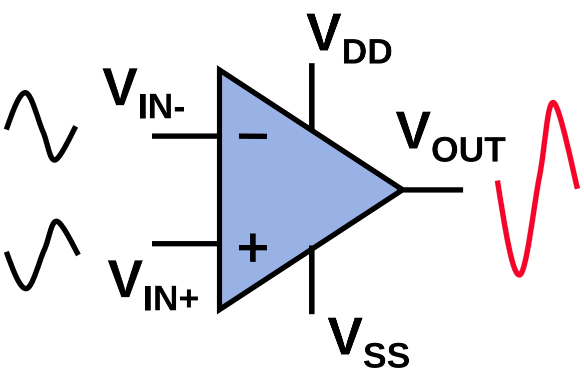
- **Dual-input mode**

Common mode inputs



- **The input signals are in phase and their amplitudes are equal**
- **V_{OUT} is zero**

Differential mode inputs



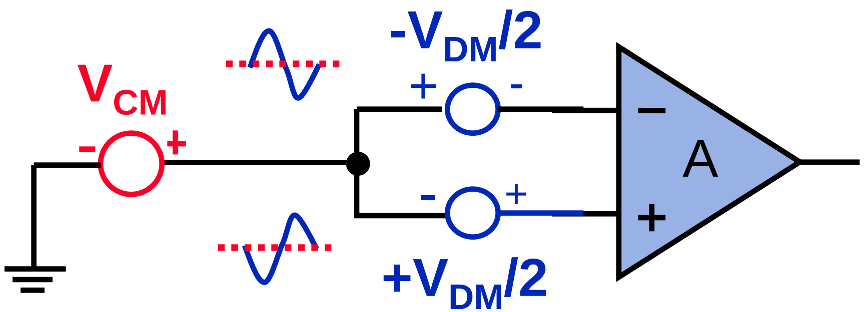
- **The input signals are 180° out of phase and their amplitudes are equal**
- **V_{OUT} is in phase with V_{IN+}**

Op Amp Basics

– **Emphasis: Representation of the input signals**

$$V_{CM} = (V_{IN-} + V_{IN+})/2$$
$$V_{DM} = V_{IN+} - V_{IN-}$$

$$V_{IN+} = V_{CM} + V_{DM}/2$$
$$V_{IN-} = V_{CM} - V_{DM/2}$$



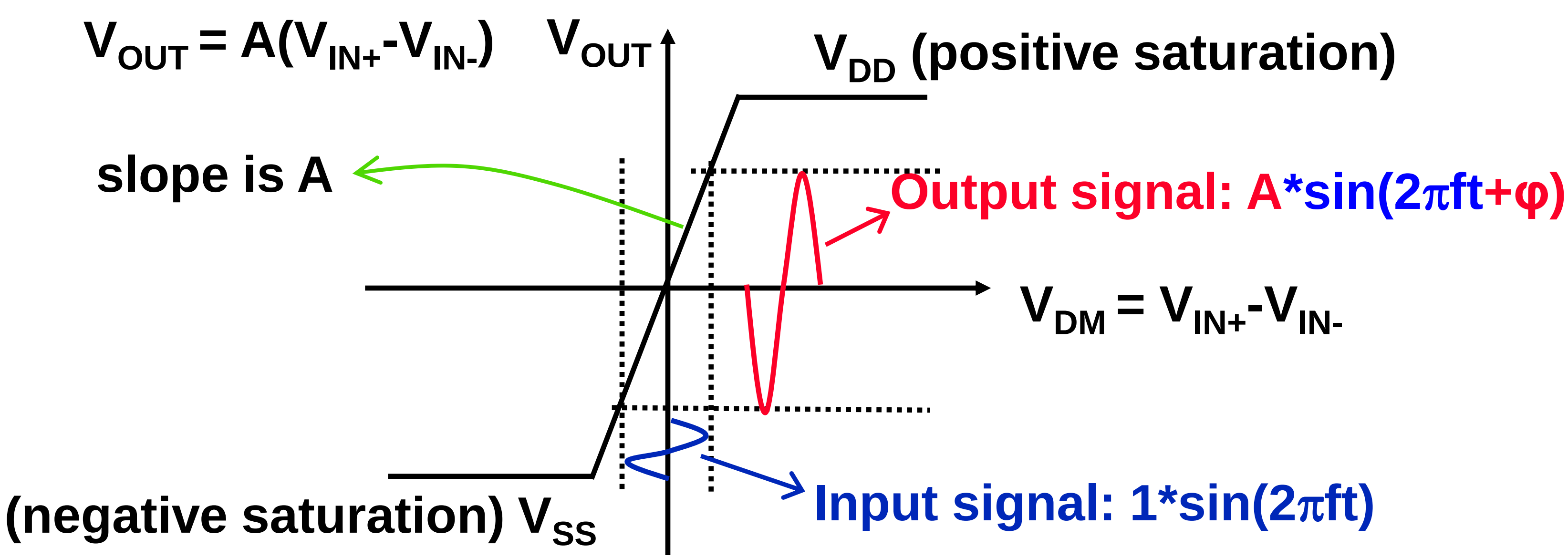
$$V_{OUT} = A(V_{IN+} - V_{IN-})$$

- Op amps **reject** common mode input (V_{CM}) and **only amplify** differential mode input (V_{DM})

Basic Op-Amp Concepts and Terminology

Op Amp Linearity

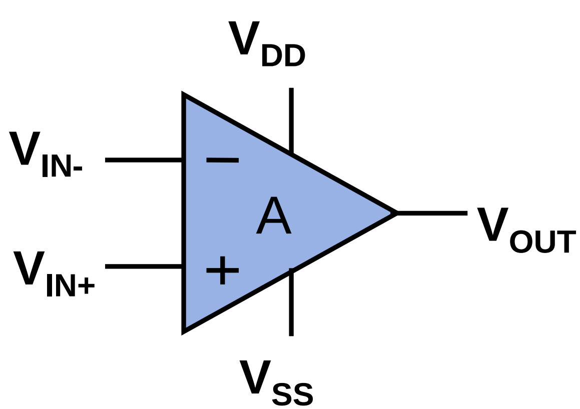
– When amplifying a signal, linearity means the information contained in the signal is not changed.
  - **The frequency of signal is same.**
  - **The amplitude and phase of signal can be different.**

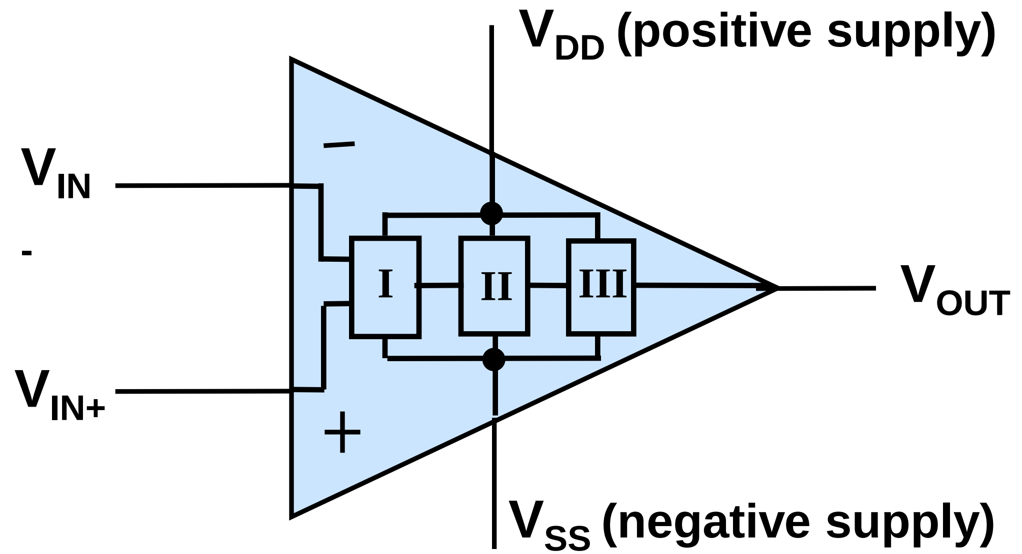


Basic Op-Amp Concepts and Terminology

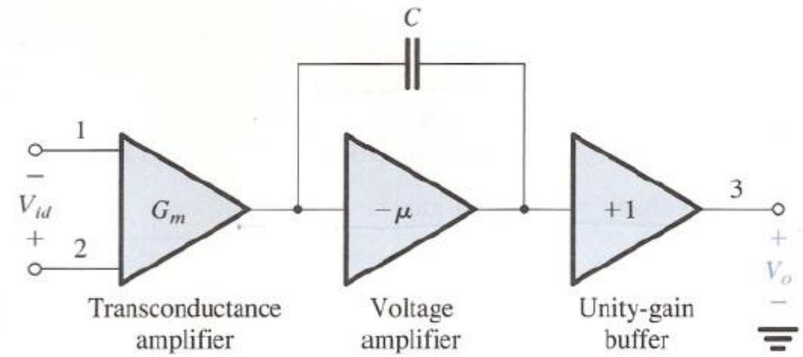
Op Amp Block Diagram

– The classical three stages inside an op amp.
- I: Differential input stage
- II: High voltage gain stage
- III: Output stage



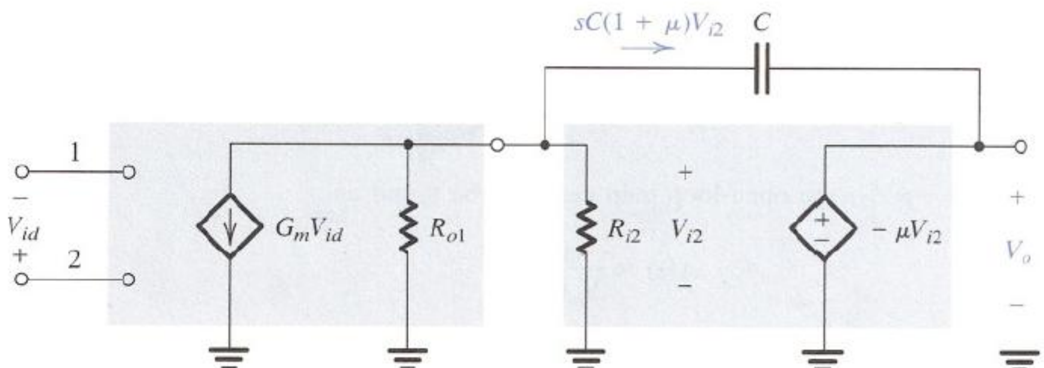


OP Amp Equivalent Circuit



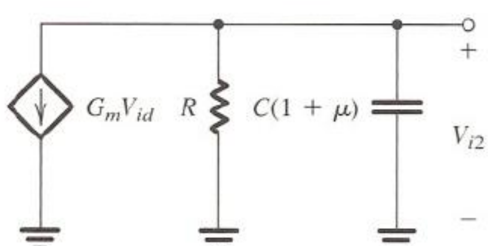
$$V_{i2} = -V_{id}\frac{G_m R}{1 + sC(1+\mu)R}$$

$$A(s) \equiv \frac{V_o(s)}{V_{id}(s)} = \frac{\mu G_m R}{1 + sC(1+\mu)R}$$



$$A_0 = \mu G_m R$$

$$\omega_b = \frac{1}{C(1+\mu)R}$$



$R = R_{o1} \parallel R_{i2}$

$$\boxed{A(s) = \frac{A_0}{1 + s/\omega_b}}$$

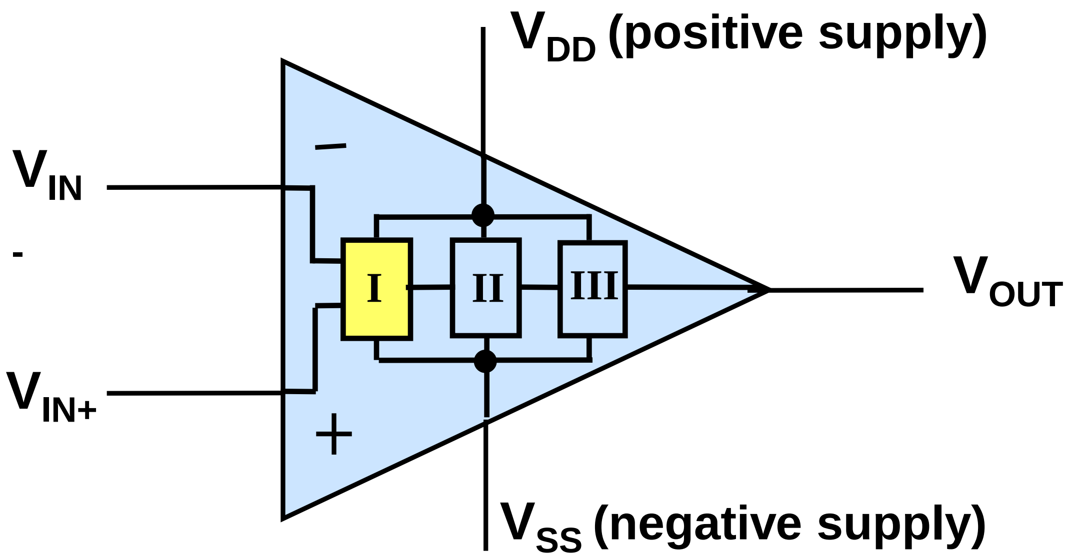
$$\boxed{A(j\omega) = \frac{A_0}{1 + j\omega/\omega_b}}$$

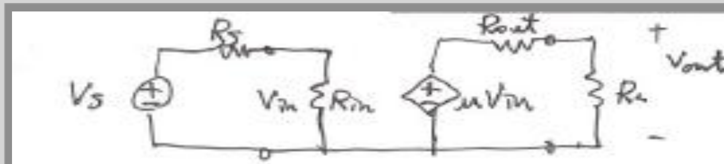
Basic Op-Amp Concepts and Terminology

Op Amp Basic Ideal Characteristics

Differential Input Stage

- Provides differential input for the op amp
- Has very high input impedance → Infinity
  - **Draws negligible input current → Zero**





$$A_V' = \frac{V_{out}}{V_s} = \frac{V_{in}}{V_s} \cdot \frac{V_{out}}{V_{in}}$$

$$= \frac{R_{in}}{R_s + R_{in}} \cdot \mu \cdot \frac{R_L}{R_{out} + R_L}$$

輸入負載效應. 輸出負載效應.

$R_{in} \to \infty$ $R_L \to \infty$

∴設計電壓放大器.

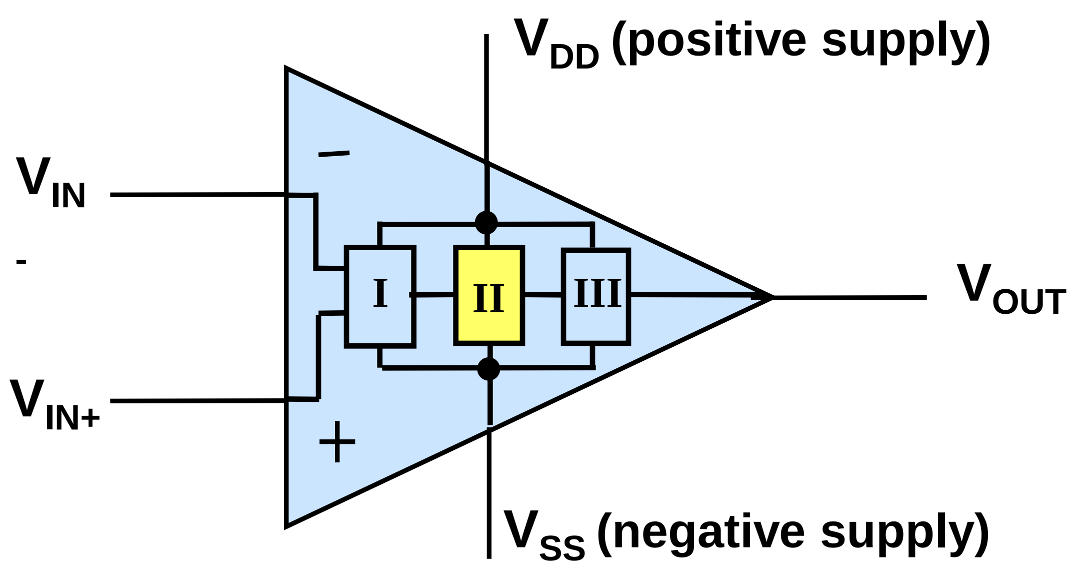
$R_L >> R_{out}$

$R_s << R_{in}$.

Basic Op-Amp Concepts and Terminology

High Voltage Gain Stage

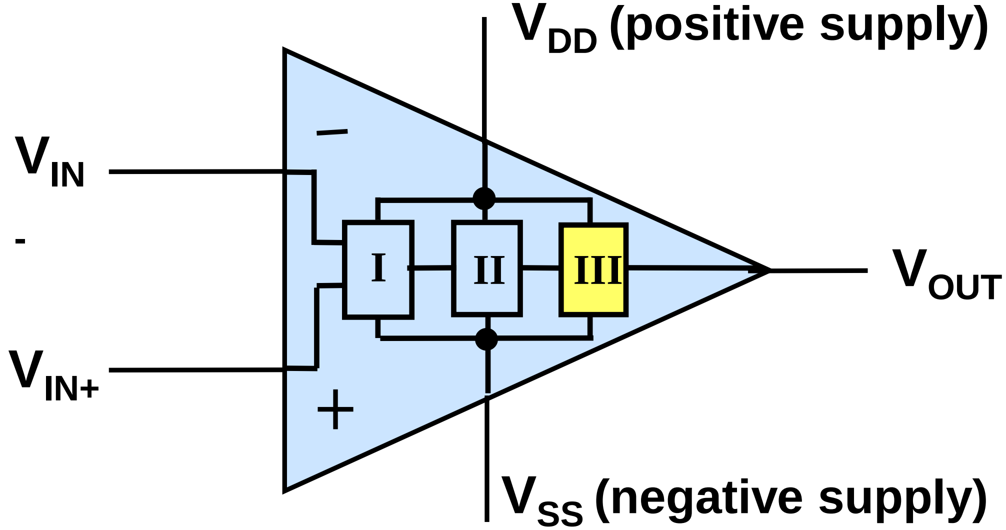
- Provides very high open loop gain →Infinity
- Gains up the differential input signal and conveys it to the output stage.



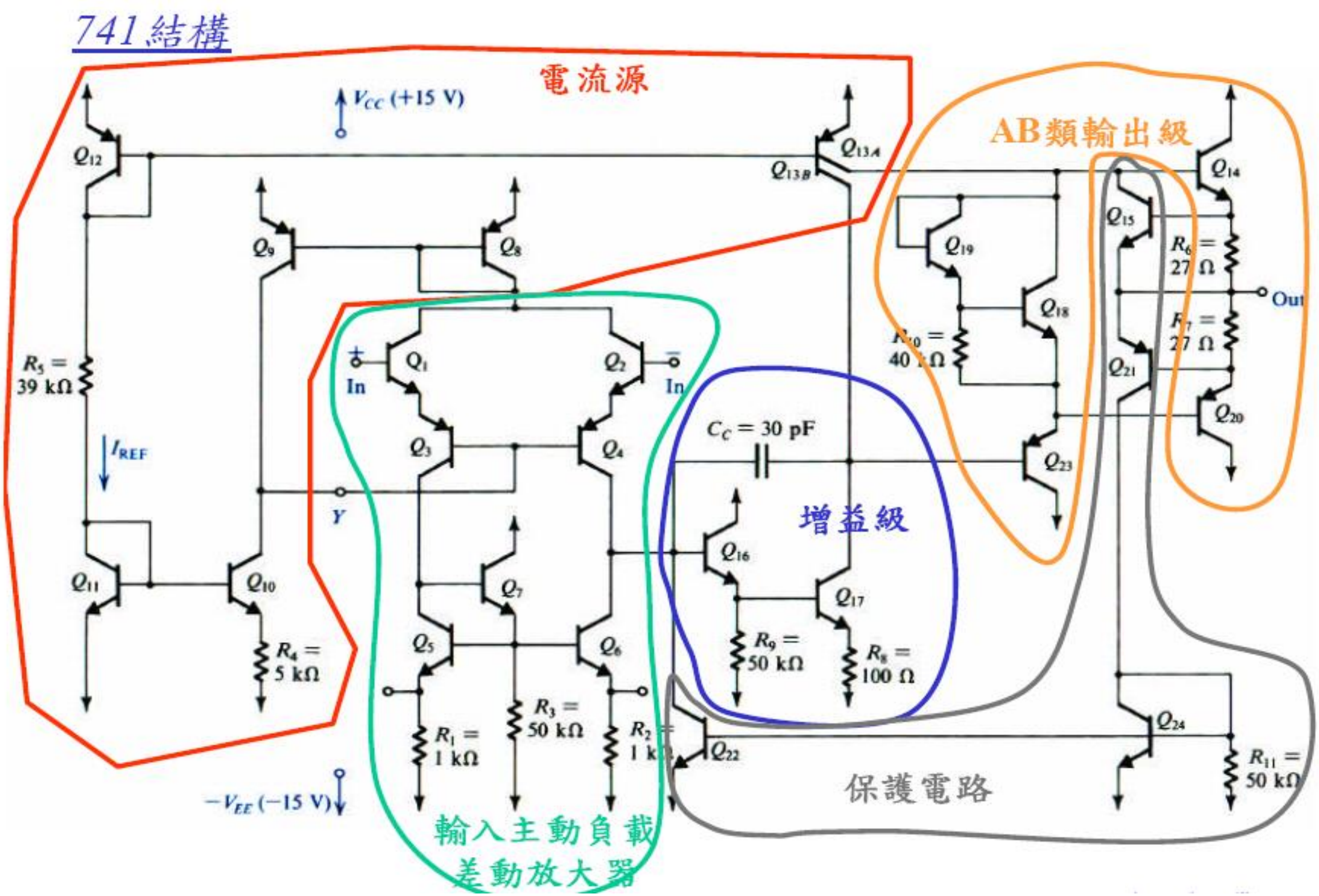
Basic Op-Amp Concepts and Terminology

Output Stage

- Has very low output impedance →Zero
  - **This minimizes the loading effect of the op amp output stage.**
- Delivers current to the load of op amp.



運算放大器內部結構



741結構
電流源
V_{CC} (+15 V)
AB類輸出級
Q_{12}
Q_{13A}
Q_{13B}
Q_{14}
Q_{15}
Q_9
Q_8
Q_{19}
R_6 = 27 Ω
Out
Q_{18}
R_{10} = 40 kΩ
R_7 = 27 Ω
R_5 = 39 kΩ
In
Q_1
Q_2
In
Q_{21}
Q_{20}
C_C = 30 pF
Q_3
Q_4
Q_{23}
I_{REF}
Y
增益級
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
R_1 = 1 kΩ
R_2 = 1 kΩ
Q_{22}
Q_{24}
R_{11} = 50 kΩ
保護電路
$-V_{EE}$ (−15 V)
輸入主動負載
差動放大器

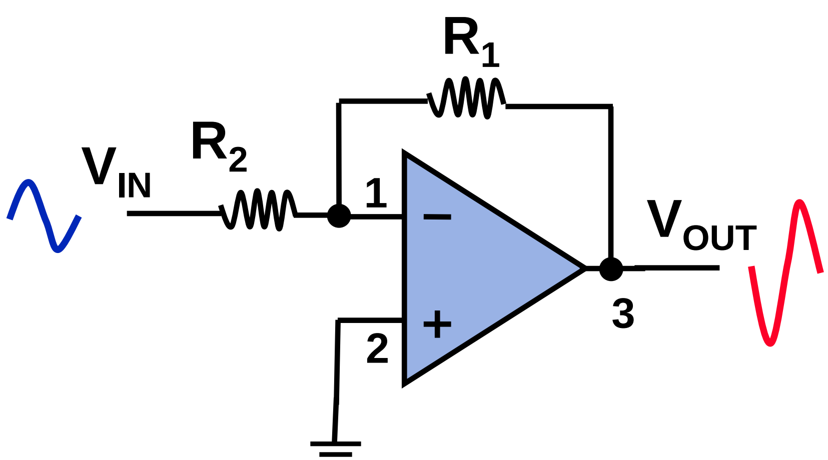
Basic Op-Amp Concepts and Terminology

Analysis of Circuits Containing Ideal Op Amps

- Open Loop Configuration
  - Open loop gain is very large. Ideally, it is infinite. Op amp is normally **not used** in the open loop mode.
  - A typical application: Comparator (will be discussed later at the section of Applications Circuit) .
- Closed Loop Configuration
  - Inverting Amplifier
  - Non-inverting Amplifier
  - Voltage Follower
  - Differential Amplifier

Fundamental Op Amp Circuits

- **Emphasis: The Concept of the Virtual Short Circuit**
  - In a closed loop configuration, the virtual short circuit means that
    - **Whatever voltage is at 2 will automatically appear at 1** (due to the infinite open loop gain A_{OL})



For ideal op amp: $V_1 = V_2$

For real op amp: $V_1 \approx V_2$

$V_2 - V_1 = \frac{V_o}{A} \approx 0$ (workable)

$\Rightarrow V_2 \approx V_1$

Assume $A \to \infty$ and this circuit works at all

→ Tracking each other in potential

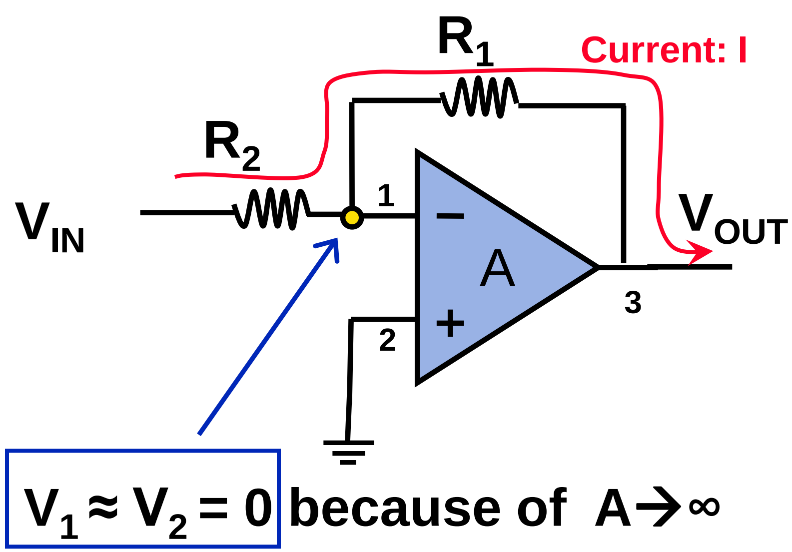
→ Virtual short.

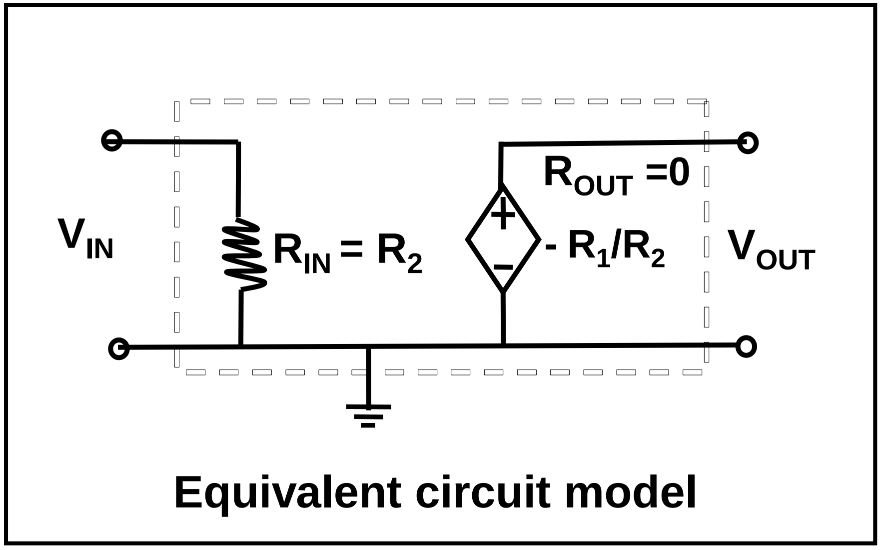
※ Virtual Ground.

Basic Op-Amp Concepts and Terminology

Inverting Amplifier

- Closed loop gain $G = V_{OUT}/V_{IN} = -R_1/R_2$
- Input resistance $R_{IN} = R_2$, Output resistance $R_{OUT} = 0$



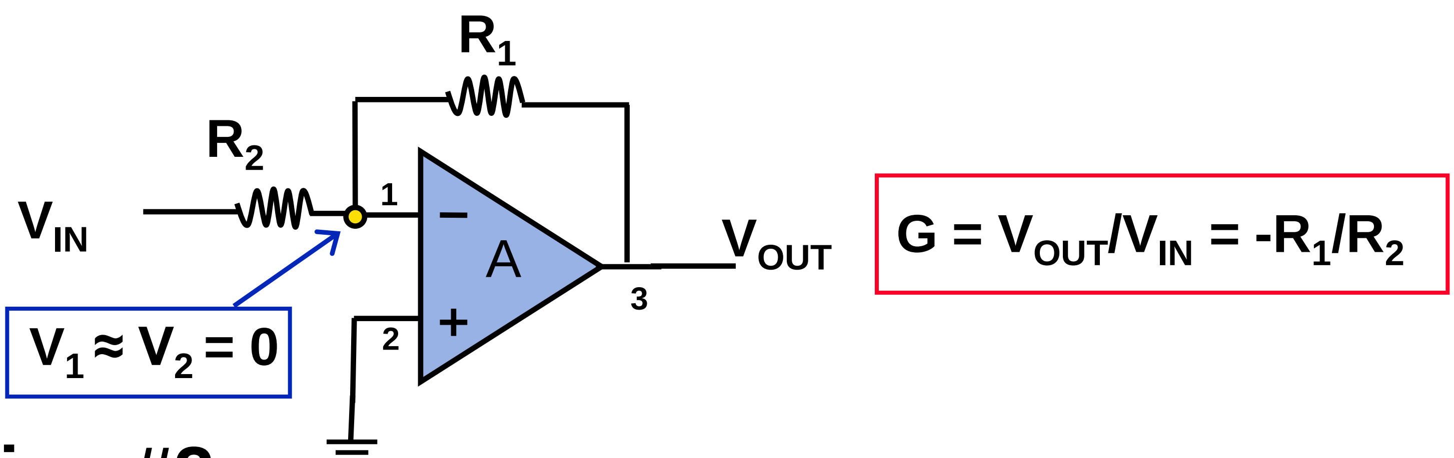


$I = (V_{IN} - V_1)/R_2 = (V_1 - V_{OUT})/R_1 \rightarrow V_{IN}/R_2 = -V_{OUT}/R_1 \rightarrow V_{OUT}/V_{IN} = -R_1/R_2$

Basic Op-Amp Concepts and Terminology

Exercise #2

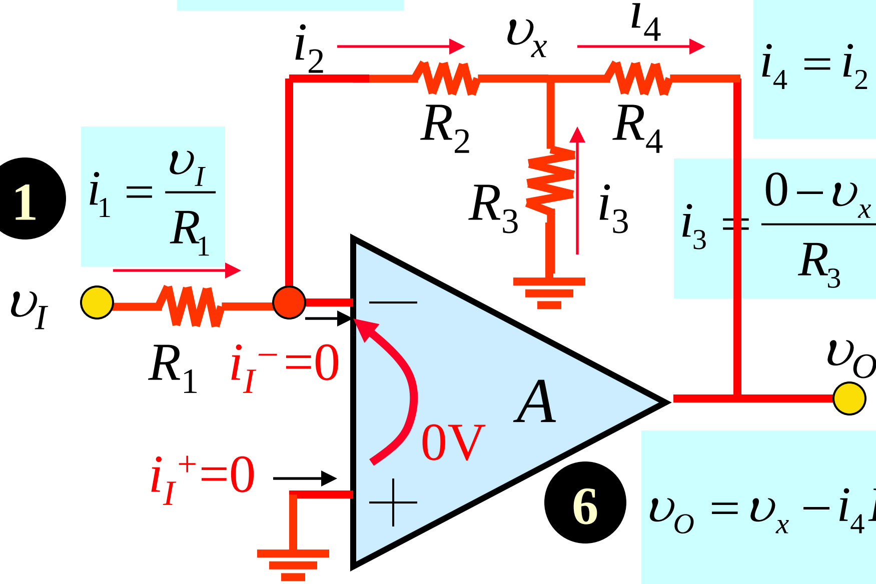
- Design an inverting amplifier having a gain of -10 and input resistance is1kΩ. Give the values of R_1 and R_2.
- If V_{IN} = 0.2V, what is the current that goes through R_2? And what is V_{OUT}?



Solution #2

- $R_2 = 1k\Omega$, $R_1 = 10k\Omega$; $I_{R2} = (V_{IN} - V_1)/R_2 = V_{IN}/R_2 = 0.2mA$, $V_{OUT} = -(R_1/R_2)*V_{IN} = -2.0V$

用T型回授網路的反相放大器（inverting amplifier with a T-network)



1 $$i_1 = \frac{\upsilon_I}{R_1}$$

2 $$i_2 = i_1 = \frac{\upsilon_I}{R_1}$$

3 $$\upsilon_x = 0 - \frac{\upsilon_I}{R_1} R_2 = -\frac{R_2}{R_1}\upsilon_I$$

4 $$i_3 = \frac{0 - \upsilon_x}{R_3} = \frac{R_2}{R_1 R_3}\upsilon_I$$

5 $$i_4 = i_2 + i_3 = \frac{\upsilon_I}{R_1} + \frac{R_2}{R_1 R_3}\upsilon_I$$

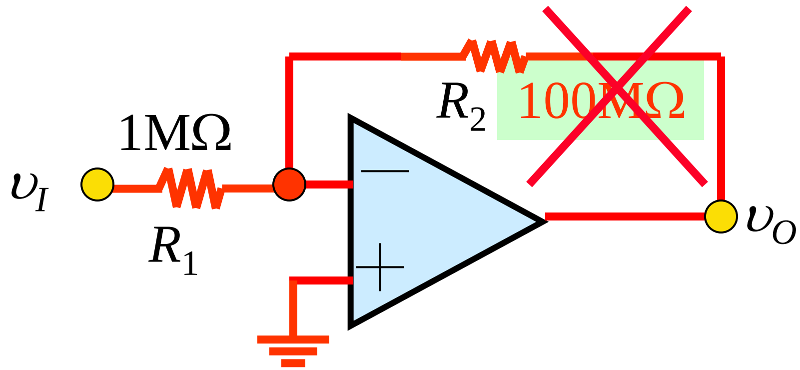
6 $$\upsilon_O = \upsilon_x - i_4 R_4 = -\frac{R_2}{R_1}\upsilon_I - \left(\frac{\upsilon_I}{R_1} + \frac{R_2}{R_1 R_3}\upsilon_I\right) R_4$$

$$G = \frac{\upsilon_O}{\upsilon_I} = -\frac{R_2}{R_1} - \frac{R_4}{R_1}\left(1 + \frac{R_2}{R_3}\right) = -\frac{R_2}{R_1}\left(1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right)$$

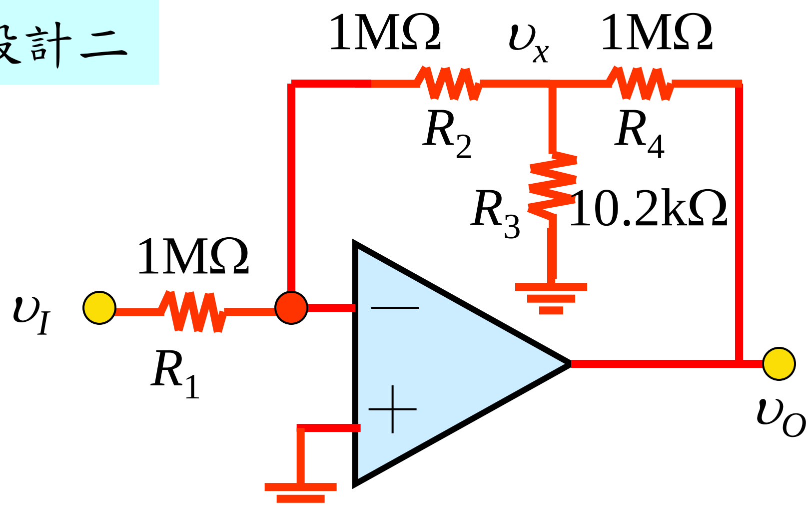
例題

利用運算放大器設計一個反相放大器，輸入阻抗1MΩ，增益100，但電路中不得使用大於1MΩ的電阻。

設計一



設計二



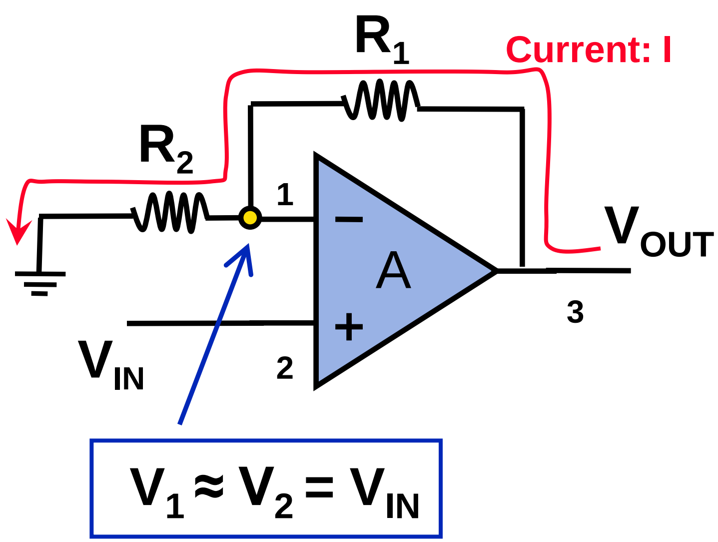
$$G=\frac{v_O}{v_I}=-\underbrace{\boxed{\frac{R_2}{R_1}}}_{1}\left(\underbrace{1+\underbrace{\boxed{\frac{R_4}{R_2}}}_{1}+\overset{98}{\frac{R_4}{R_3}}}_{100}\right)$$

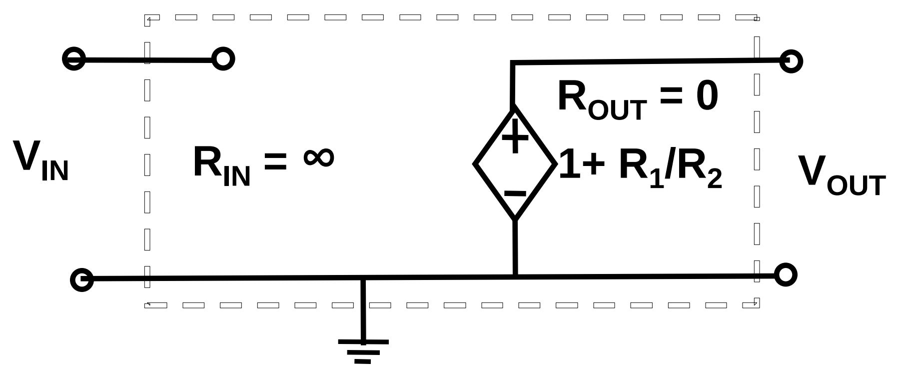
R_3 =1MΩ/98=10.2kΩ

Basic Op-Amp Concepts and Terminology

Non-inverting Amplifier

- Closed loop gain $G = V_{OUT}/V_{IN} = 1+R_1/R_2$
- Input resistance $R_{IN} = \infty$, Output resistance $R_{OUT} = 0$





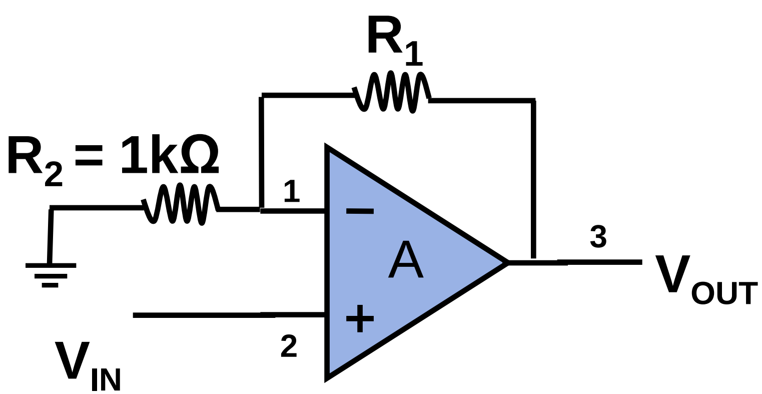
Equivalent circuit model

$I = V_1/R_2 = (V_{OUT}-V_1)/R_1 \rightarrow V_{IN}/R_2 = (V_{OUT}-V_{IN})/R_1 \rightarrow V_{OUT}/V_{IN} = 1+R_1/R_2$

Basic Op-Amp Concepts and Terminology

Exercise #3

- Design a non-inverting amplifier having a gain of 10. Give the value of R_1.
- If V_{IN} = 0.1V, what is the current that goes through R_2? And what is V_{OUT}?



$$G = V_{OUT}/V_{IN} = 1+R_1/R_2$$

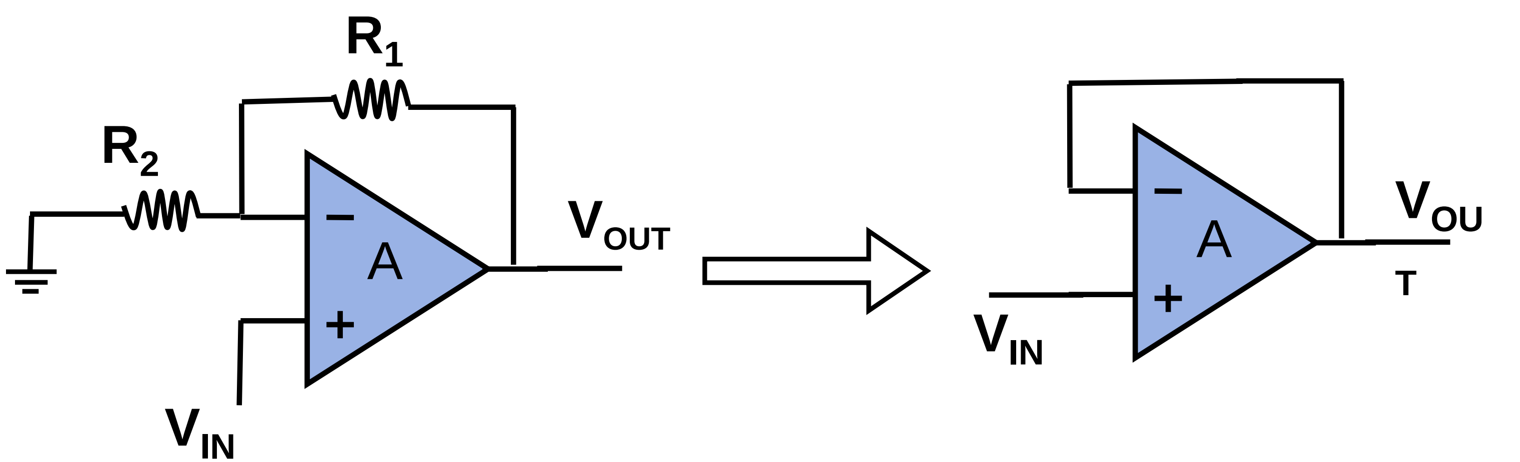
Solution #3

- $R_2 = 1k\Omega$, $R_1 = 9k\Omega$; $I_{R2} = V_1/R_2 = V_{IN}/R_2 = 0.1mA$,
  $V_{OUT} = (1+R_1/R_2)*V_{IN} = 10*V_{IN} = 1.0V$

Basic Op-Amp Concepts and Terminology

Voltage Follower (Buffer Amplifier)

- **Refer to the non-inverting amplifier configuration**
  - Make $R_2 = \infty$ and $R_1 = 0$ to obtain the unity gain amplifier.

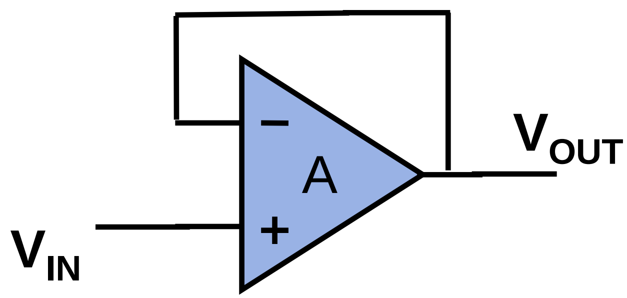


$$V_{OUT} = (1+R_1/R_2)*V_{IN} \longrightarrow V_{OUT} = V_{IN}$$

Basic Op-Amp Concepts and Terminology

– **In the ideal case, $V_{OUT} = V_{IN}$, $R_{IN} = \infty$, $R_{OUT} = 0$**

- $V_{OUT} = V_{IN}$; Used as a voltage follower.
- $R_{IN} = \infty$, $R_{OUT} = 0$; Used as a buffer amplifier for impedance matching and signal isolation.

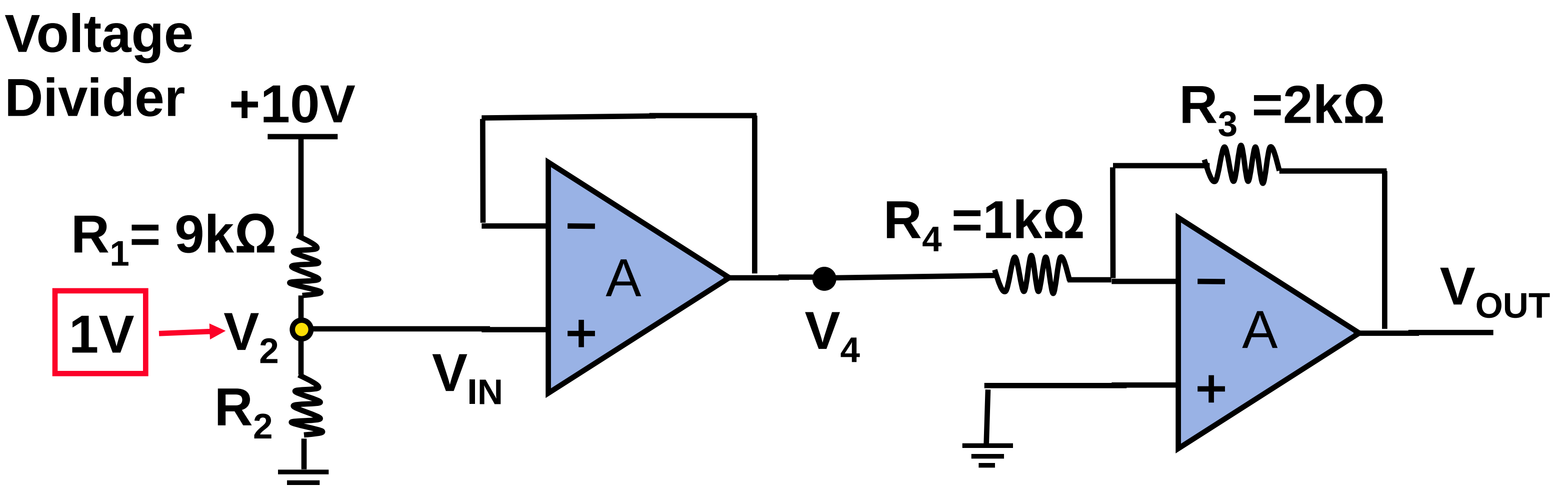


Example: **Buffer amplifiers are often used between the analog inputs/outputs of microcontroller and the outside circuits.**

Basic Op-Amp Concepts and Terminology

Exercise #4

- Refer to the circuit, a buffer amplifier is connected with an inverting amplifier and a voltage divider. If V_2 = 1V, R_2 = ? And V_{OUT} = ?
- If don't use buffer amplifier and connect them directly, can V_2 still keep 1V? Give the value of V_2 and V_{OUT}.



Basic Op-Amp Concepts and Terminology

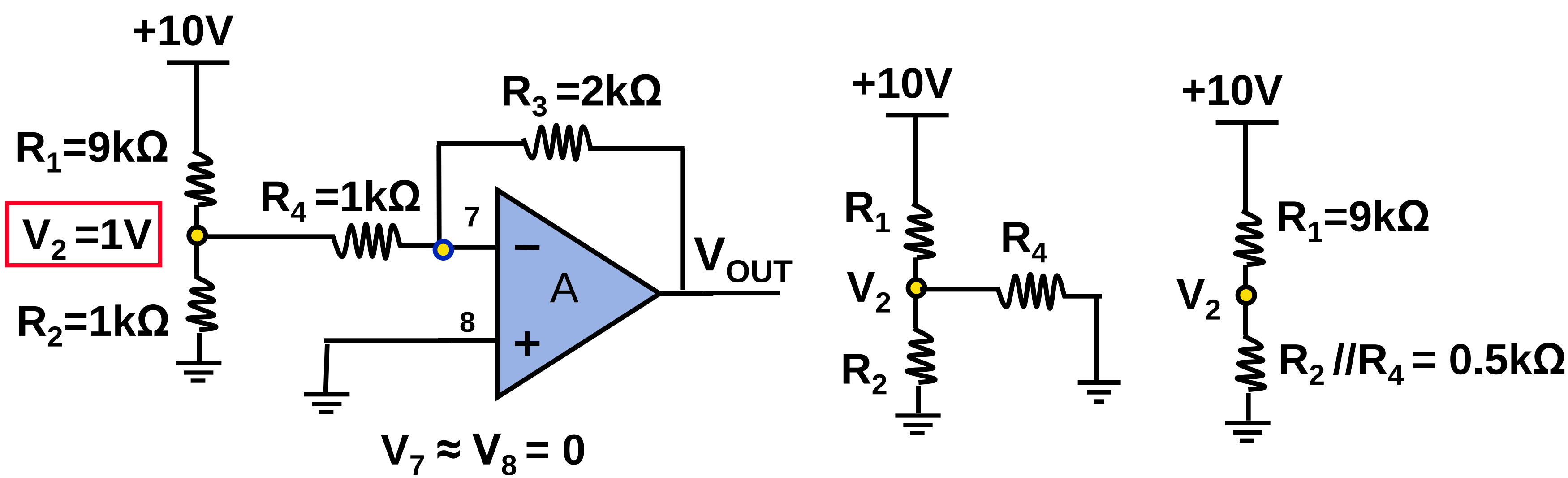
Solution #4

- For $V_2 = 1V$, $R_2 = 1k\Omega$, $V_2 = V_4$

  $V_{OUT} = -(R_3/R_4)*V_4 = -(R_3/R_4)*V_2 = -2*1V = -2V$
- If don't use buffer amplifier, V_2 can not keep 1.0V.

  $V_2 = [10V/(9k\Omega+0.5k\Omega)]*0.5k\Omega \approx 0.53V$ and $V_{OUT} = -1.06V$

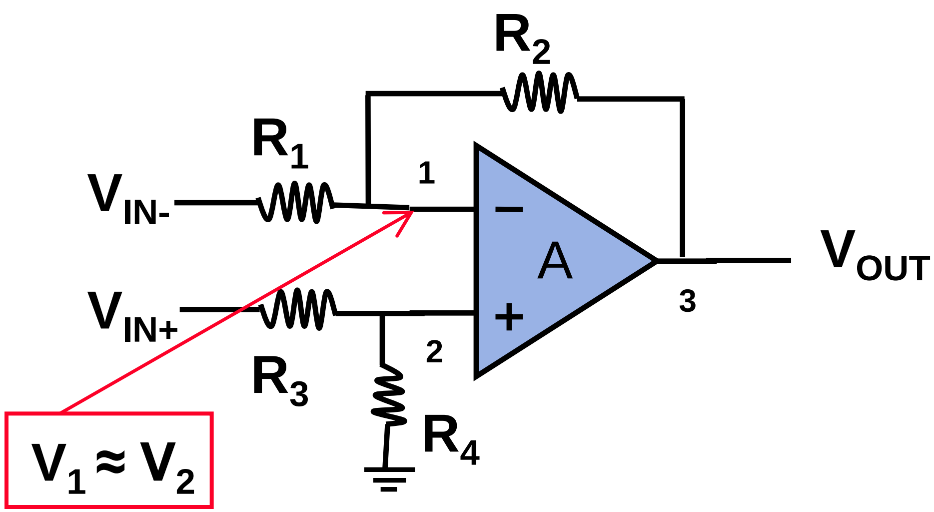
Voltage Divider



Basic Op-Amp Concepts and Terminology

Difference Amplifier

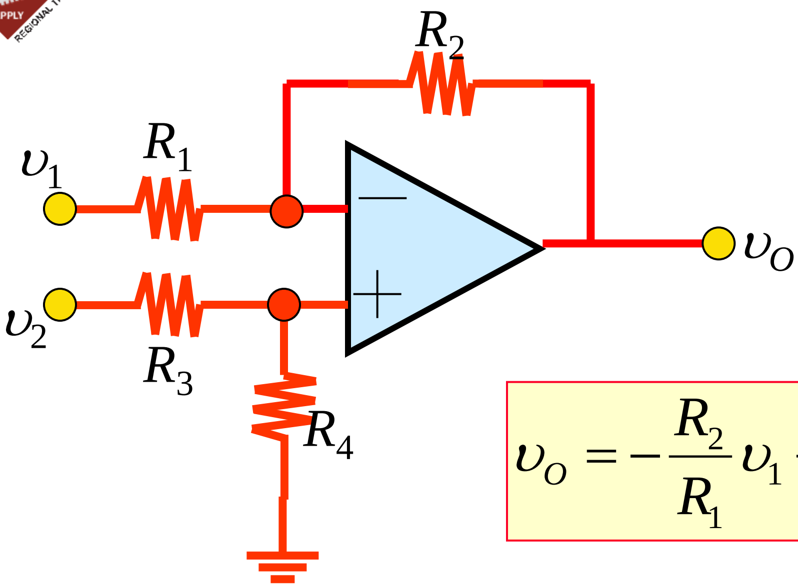
- The circuit shown is used for finding the difference of two voltages each multiplied by some constant (determined by the resistors).



$R_{IN} = R_1 + R_3$

- When $R_1 = R_3$ and $R_2 = R_4$, $V_{OUT} = (R_2/R_1)*(V_{IN+}-V_{IN-})$, it becomes a **Difference Amplifier**.

差動放大器（difference amplifier)



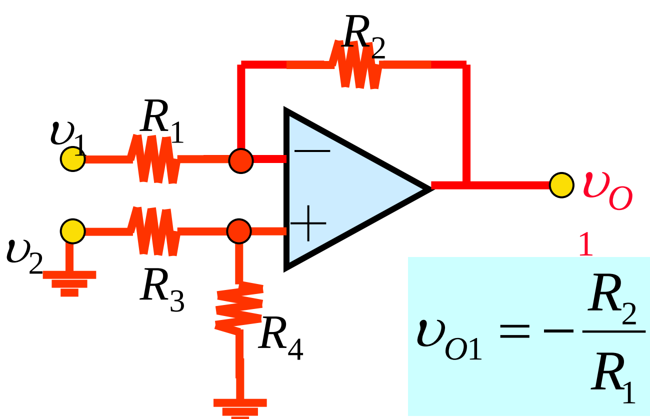
差動放大器有兩個輸入訊號，利用線性疊加法：

先令 $v_2=0$，得輸出 v_{O1}

再令 $v_1=0$，得輸出 v_{O2}

然後 $v_O=v_{O1}+v_{O2}$

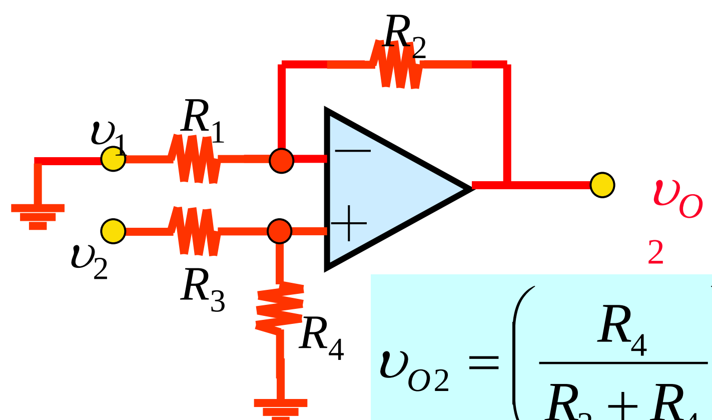
$$v_O=-\frac{R_2}{R_1}v_1+\frac{1+R_2/R_1}{1+R_3/R_4}v_2$$



1

$$v_{O1}=-\frac{R_2}{R_1}v_1$$

$$R_{in1}=R_1$$



2

$$v_{O2}=\left(\frac{R_4}{R_3+R_4}\right)\left(1+\frac{R_2}{R_1}\right)v_2$$

$$R_{in2}=R_3+R_4$$

$$\upsilon_O = -\frac{R_2}{R_1}\upsilon_1 + \frac{1+R_2/R_1}{1+R_3/R_4}\upsilon_2$$

我們希望輸入只有共模訊號υ_{CM}，無差模訊號υ_d時，輸出愈小愈好。

令 $\upsilon_1 = \upsilon_2 = \upsilon_{CM}$

$$\upsilon_O = \left(-\frac{R_2}{R_1} + \frac{1+R_2/R_1}{1+R_3/R_4}\right)\upsilon_{CM} \rightarrow 0$$

共模增益為0

CMRR→∞

$$\Rightarrow \boxed{\frac{R_2}{R_1} = \frac{R_4}{R_3}}$$

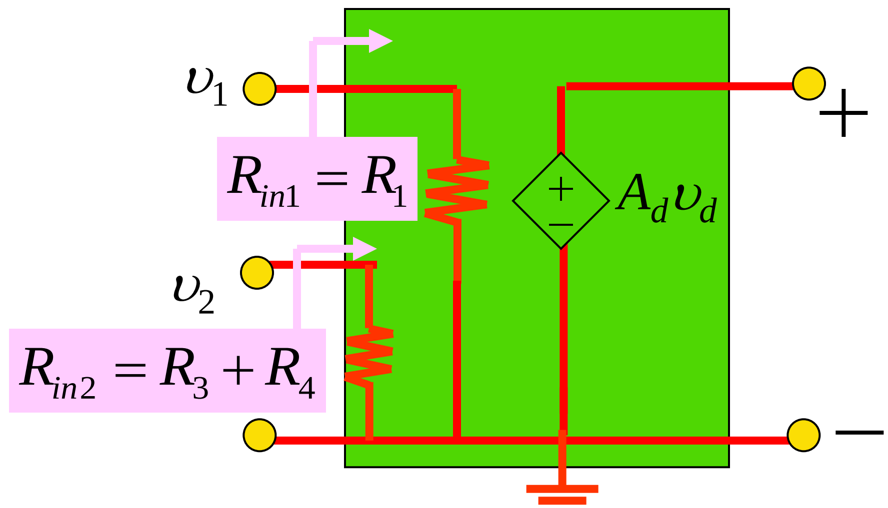
一般選擇R_1=R_3，R_2=R_4

此差動放大器的缺點：
1. 增益不容易調整
2. 輸入阻抗小
3. 正負輸入端不對稱

$$\boxed{\begin{aligned}&\Rightarrow \upsilon_O = -\frac{R_2}{R_1}\upsilon_1 + \frac{1+R_2/R_1}{1+R_1/R_2}\upsilon_2\\ &\upsilon_O = \frac{R_2}{R_1}(\upsilon_2 - \upsilon_1)\end{aligned}}$$

適當的選擇電阻後，

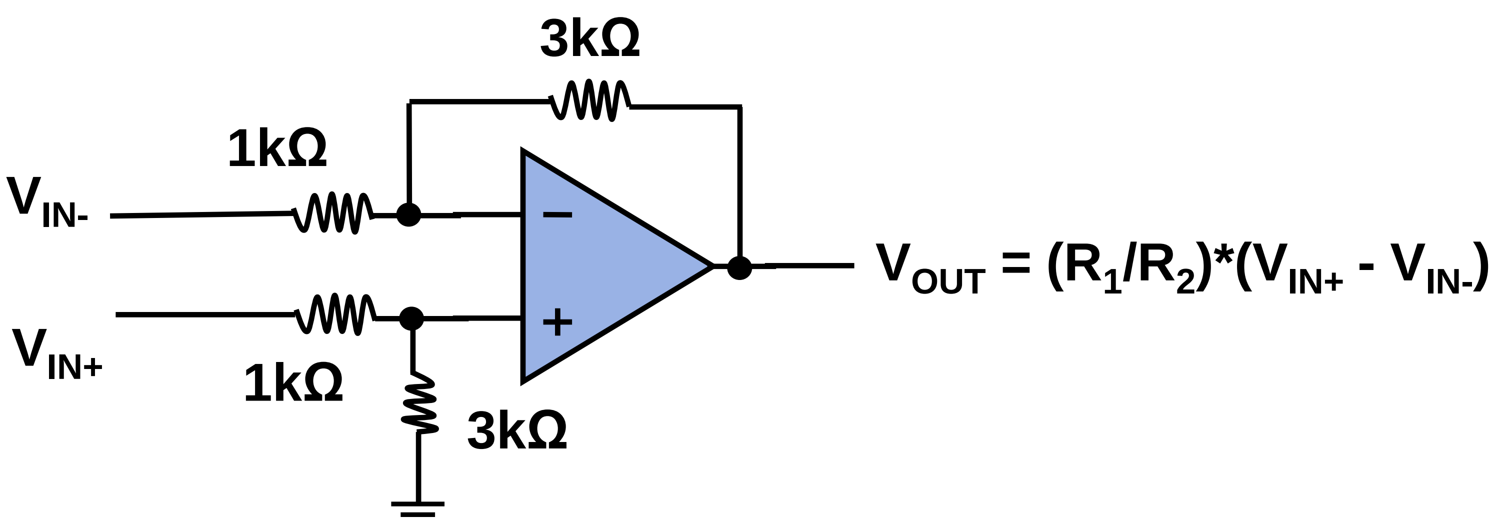
A_c=0，A_d= R_2/R_1



Fundamental Op Amp Circuits

Exercise #5

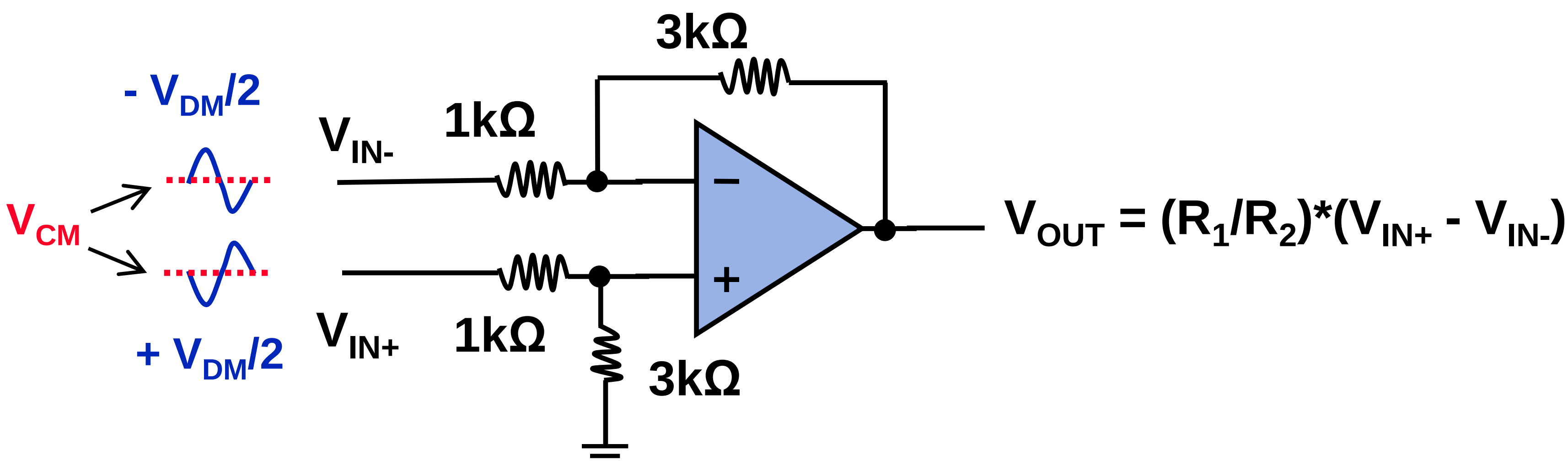
- Refer to the differential amplifier.
- $V_{IN+} = 1V + 0.5V*\sin 2\pi ft$; $V_{IN-} = 1V – 0.5V*\sin 2\pi ft$
  - **What is the closed loop gain G?**
  - **What is V_{CM} , V_{DM} and V_{OUT} ?**



Fundamental Op Amp Circuits

Solution

- Closed loop gain: G = 3 V/V
- We have $V_{IN+} = 1V + 0.5V*\sin 2\pi ft$; $V_{IN-} = 1V - 0.5V*\sin 2\pi ft$
  - $V_{CM} = (V_{IN-} + V_{IN+})/2 = 1V$
  - $V_{DM} = V_{IN+} - V_{IN-} = 1V*\sin 2\pi ft$
  - $V_{OUT} = 3*(V_{IN+} - V_{IN-}) = 3*V_{DM} = 3V*\sin 2\pi ft$



The Real World

In reality, there is no ideal op amp.

- How to choose an op amp for your application?
  - *Various performance specifications need to be taken into consideration*

    1. **Absolute Maximum Ratings**
    2. **Operating Condition Ratings**
    3. **Op Amp DC Specifications**
    4. **Op Amp AC Specifications**

(Note: MCP601 data sheet is selected as an example in the class)

Absolute Maximum Ratings

First electrical table in our op amp data sheets

- **Absolute maximum ratings** are those limits beyond which the life of individual devices may be impaired.
  - **Example: MCP601 data sheet**

Absolute Maximum Ratings †

$V_{DD} - V_{SS}$	7.0V
All inputs and outputs	V_{SS} - 0.3V to V_{DD} + 0.3V
Difference Input voltage	$\lvert V_{DD} - V_{SS} \rvert$
Output Short Circuit Current	continuous
Current at Input Pin	±2 mA
Current at Output and Supply Pins	±30 mA
Storage temperature	-65°C to +150°C
Junction temperature	+150°C
ESD protection on all pins (HBM; MM)	≥ 3 kV; 200V

Operating Condition Ratings

Operating Condition Ratings

– The op amp DC/AC specs are measured under the operating conditions

- **Beyond the operating conditions, op amp could have unsatisfactory performance.**

DC ELECTRICAL SPECIFICATIONS

Electrical Characteristics: Unless otherwise indicated, V_{DD} = +1.8V to +5.5V, V_{SS}=GND, T_A= +25°C, V_{CM} = V_{DD}/2, $V_{OUT} \approx V_{DD}/2$, $V_L = V_{DD}/2$, R_L = 1 MΩ to V_L and $\overline{CS}$ is tied low. (Refer to Figure 1-2 and Figure 1-3).

Parameters	Sym	Min	Typ	Max	Units	Conditions
Input Offset						
Input Offset Voltage	V_{OS}	-150	—	+150	µV	V_{DD} = 3.0V, $V_{CM} = V_{DD}/3$
Input Offset Drift with Temperature	$\Delta V_{OS}/\Delta T_A$	—	±3.0	—	µV/°C	T_A= -40°C to +125°C, V_{DD} = 3.0V, $V_{CM} = V_{DD}/3$
Power Supply Rejection Ratio	PSRR	70	88	—	dB	$V_{CM} = V_{SS}$
Input Bias Current and Impedance						
Input Bias Current	I_B	—	±1.0	100	pA	

Op Amp DC Specifications

Primary DC specifications

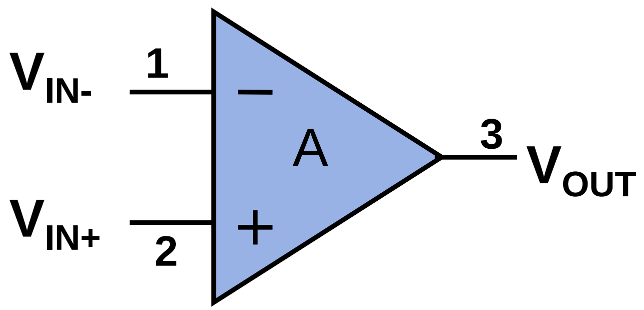
- **Voltage Ranges**
  - Input Voltage Range (V_{IN} or V_{CM} or V_{DM})
  - Output Voltage Swing (V_{OH} or V_{OL})
- **Input Errors**
  - Open Loop Gain (A) /Closed Loop Gain (G)
  - Input Offset Voltage (V_{OS})/Drift($\Delta V_{OS}/ \Delta T_A$)
  - Common-Mode Rejection Ratio (CMRR)
  - Power Supply Rejection Ratio (PSRR or PSR)
  - Input Bias Current (I_B)
- **Others**
  - Power Supply Requirements (V_{SS}, V_{DD}, I_Q)
  - Input/Output Impedance (Z_{IN} and Z_{OUT})

Op Amp DC Specifications

Input Voltage Range (V_{IN} , V_{DM} or V_{CM})

– The inputs of op amp must stay within a certain voltage range for proper operation.

- Op amps are subject to drastic gain changes and bizarre behavior if these ranges are exceeded.
- Limited by the input stage transistors.



Op Amp DC Specifications

– **Input Voltage Range**

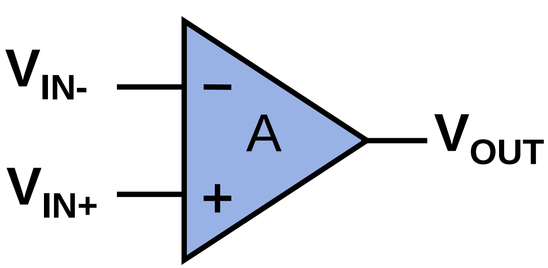
  The range of acceptable voltages applied to EITHER of the input pins.

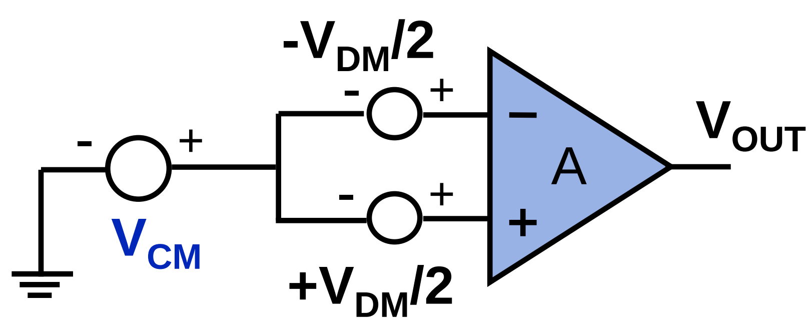
– **Difference Voltage Range** $V_{DM} = V_{IN+} - V_{IN-}$

  The range of maximum voltage difference between the two inputs.

– **Common Mode Voltage Range** $V_{CM} = (V_{IN+} + V_{IN-})/2$

  The range of acceptable common voltages applied to BOTH inputs simultaneously.





Op Amp DC Specifications

- **Example: MCP601 data sheet**

Electrical Specifications: Unless otherwise specified, T_A = +25°C, V_{DD} = +2.7V to +5.5V, V_{SS} = GND, $V_{CM} = V_{DD}/2$, $V_{OUT} = V_{DD}/2$ and R_L = 100 kΩ to $V_{DD}/2$.

Parameters	Sym	Min	Typ	Max	Units	Conditions
Common Mode Input Range	V_{CMR}	$V_{SS} - 0.3$	—	$V_{DD} - 1.2$	V	

Absolute Maximum Ratings

All Inputs and Outputs .... V_{SS} – 0.3V to V_{DD} + 0.3V
Difference Input Voltage .... $|V_{DD} - V_{SS}|$

– **Emphasis**
  - Stresses above those listed under "Maximum Ratings" may cause permanent damage to the device.
  - Op amp is supposed to reject V_{CM} (common mode voltages) and amplify V_{DM} (difference voltage).

Op Amp DC Specs: Input

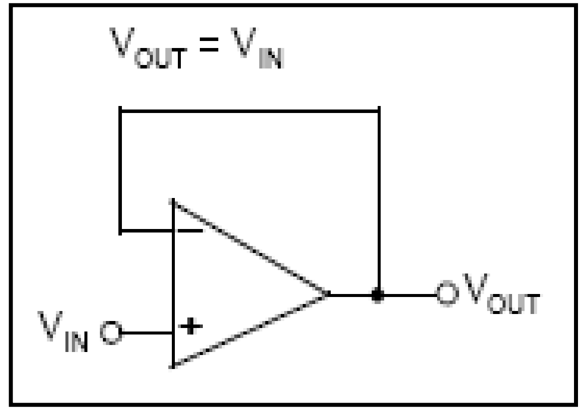
- **What Does “Rail-to-Rail Input” Mean?**
  - It means the common mode input range (V_{CMR}) can <u>exceed</u> the rails by several hundred millivolts
    - **Rail means supply voltage (V_{DD} and V_{SS})**

MCP6031 Datasheet

Parameters	Sym	Min	Typ	Max	Units	Conditions
Common Mode Input Voltage Range	V_{CMR}	$V_{SS} - 0.3$	—	$V_{DD} + 0.3$	V	

Op Amp DC Specs: Input

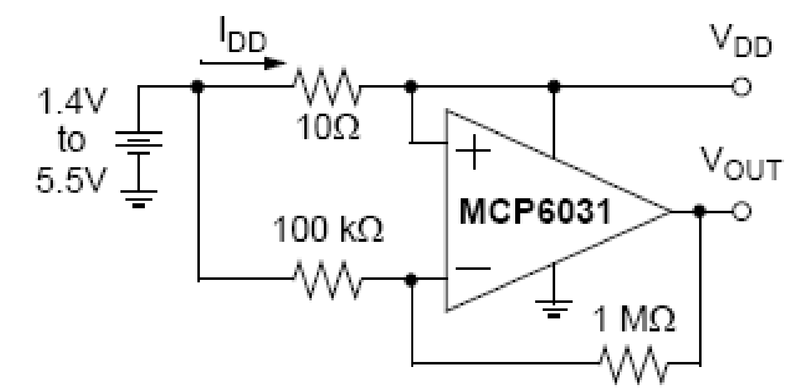
- **Application Examples**
  - Voltage follower usually requires rail to rail operations at its inputs as well as its output
  - For high-side battery



$$\frac{V_B - V_{DD}}{100k} = \frac{V_{DD} - V_{out}}{1000k}$$

to

$$I_{DD} = \frac{V_B - V_{DD}}{10} = \frac{V_{DD} - V_{out}}{10(V/V) \cdot 10\Omega}$$



$$I_{DD} = \frac{V_{DD} - V_{OUT}}{(10\ V/V) \cdot (10\ \Omega)}$$

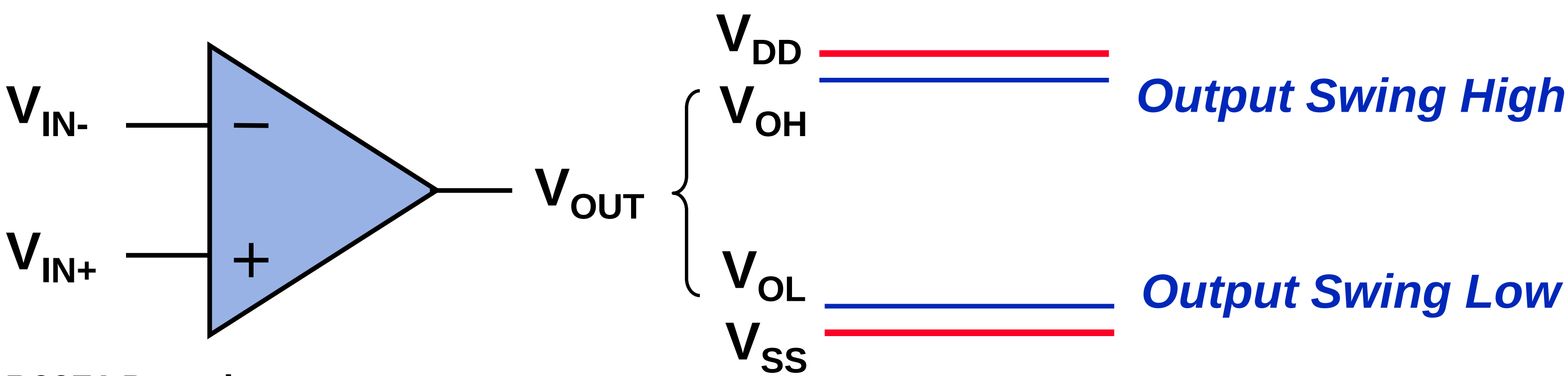
High Side Battery Current Sensor

Output Related Specs

Voltage Output Swing (V_{OH}, V_{OL})

– Defines how close the op amp output can be driven to either power rail

- **Rail-to-rail output means the V_{OUT} can <u>almost</u> , not exactly, reach the power supply rails.**

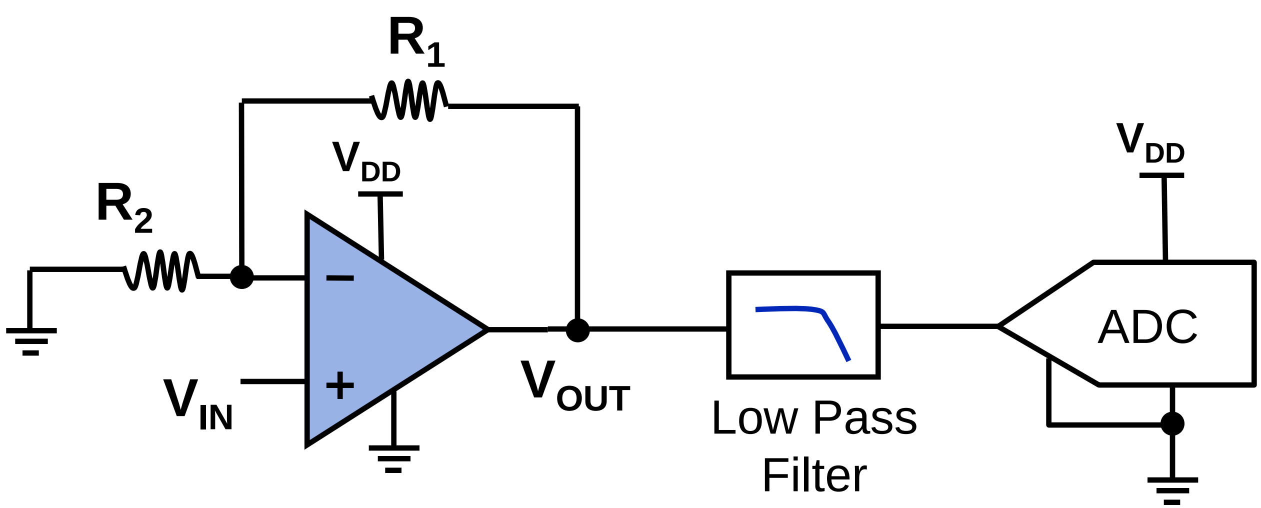


MCP6071 Datasheet

Parameters	Sym	Min	Typ	Max	Units	Conditions
Maximum Output Voltage Swing	V_{OL}, V_{OH}	V_{SS}+15	—	V_{DD}−15	mV	G = +2 V/V, 0.5V input overdrive

Output Related Specs

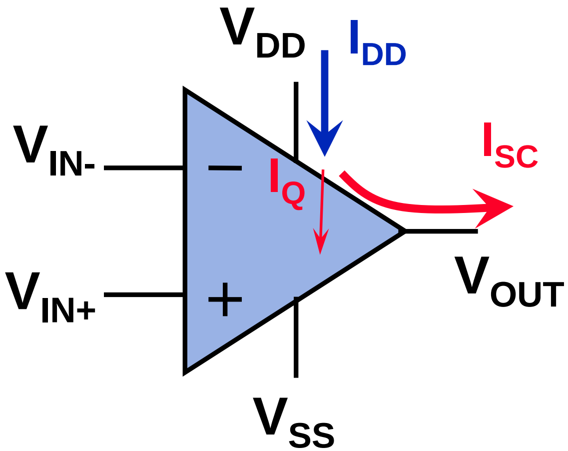
- **Application Challenge**
  - Rail-to-rail output is preferred in order to maximize the output dynamic performance
    - **Example: op amp is used to drive the input of ADC, which is configured for full scale input voltage between V_{SS} and V_{DD}**



Output Related Specs

Output Short Circuit Current (I_{SC})

– It is the maximum output current that the op amp can deliver to a load



MCP6071 Datasheet

Parameters	Sym	Min	Typ	Max	Units	Conditions
Output Short-Circuit Current	I_{SC}	—	±7	—	mA	V_{DD} = 1.8V
		—	±28	—	mA	V_{DD} = 6.0V

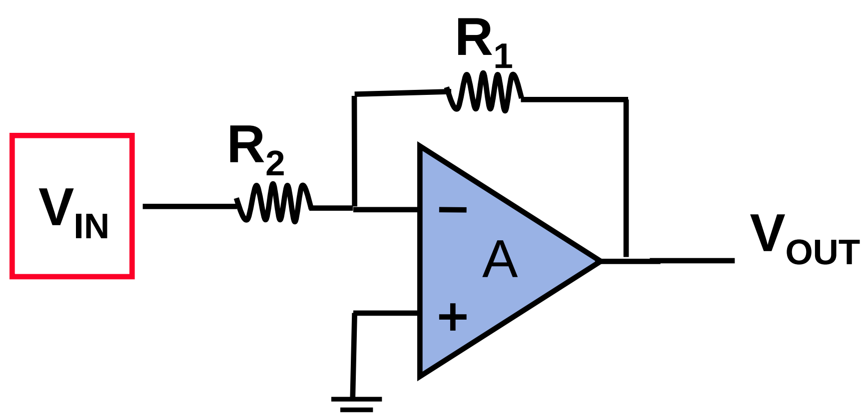
Output Related Specs

- **Application Challenge**
  - Power dissipation issue
    - **Continued short-circuit operation can cause internal junction temperature rise**
  - Limited power drive capability
    - **May not be able to drive too heavy load**
  - Output distortion when I_{OUT} is close to I_{SC}

Op Amp DC Specifications

– **Application Challenge**

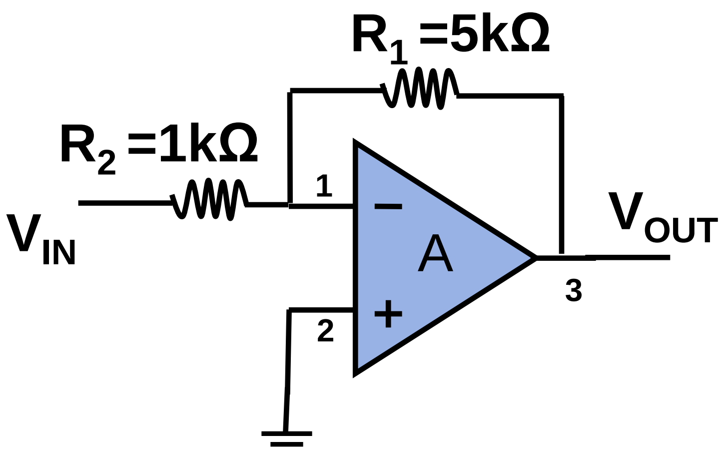
- In a closed loop configuration, the signal input voltage range is normally much **smaller** than the op amp input voltage range.
- Using the voltage beyond the V_{IN} range, the amplifier's output will suffer from clipping.



Op Amp DC Specifications

Exercise #8

- Refer to the inverting amplifier, assume V_{DD} = +2.52V, V_{SS} = -2.52V, V_{OH} = +2.5V, V_{OL} = -2.5V.
- What is the corresponding input voltage range?
  For V_{IN}= 0.1V, -0.2V, 0.6V, what is the V_{OUT} respectively?

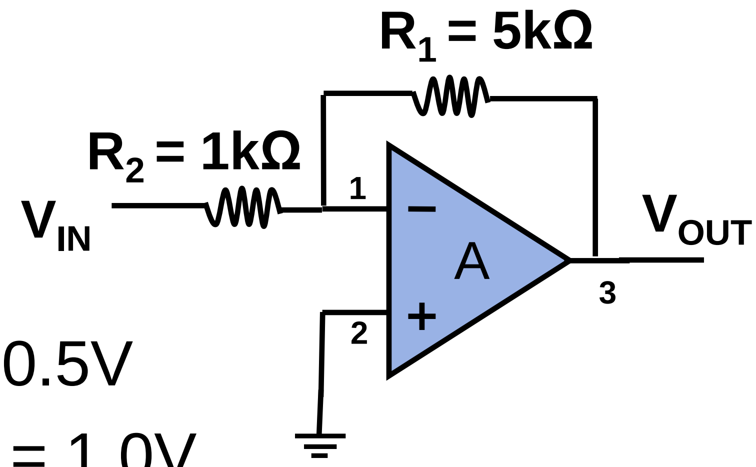


$$V_{OUT}/V_{IN} = - R_1/R_2$$

Op Amp DC Specifications

Solution #8

- $V_{OUT} = -(R_1/R_2)*V_{IN} = -5V_{IN}$
  $-2.5V \leq V_{OUT} \leq +2.5V$
  So, $-0.5V \leq V_{IN} \leq +0.5V$



- $V_{IN} = 0.1V \rightarrow V_{OUT} = -5*0.1V = -0.5V$
  $V_{IN} = -0.2V \rightarrow V_{OUT} = -5*(-0.2V) = 1.0V$

- $V_{IN} = -0.6V \rightarrow V_{OUT} = -5*(-0.6V) =$ 3.0V? Right or Wrong?

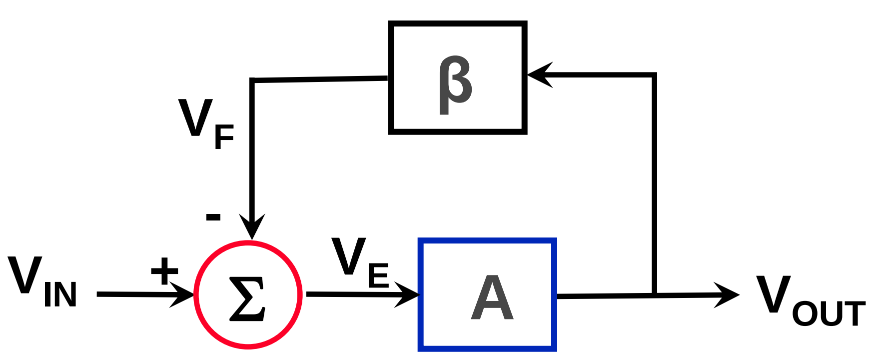
Answer: Wrong. V_{OUT} will be in positive saturation 2.5V (output clipping).

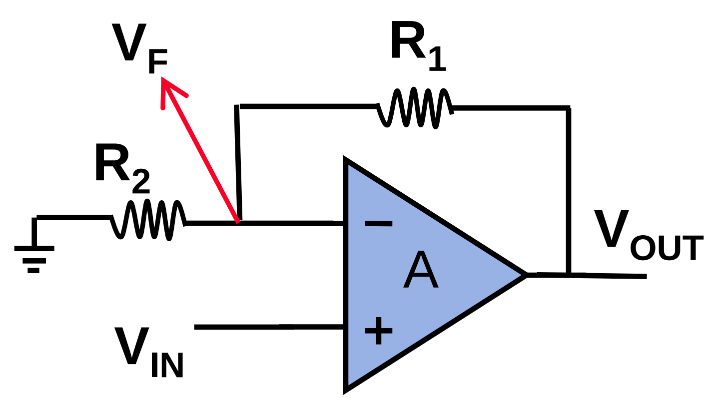
Op Amp DC Specifications

Issue : Open Loop Gain and Closed Loop Gain

- **Feedback** is a process whereby a fraction of the output signal is sensed ($V_F = \beta V_{OUT}$) and compared with the input (V_{IN}), generating a very small feedback error term ($V_E = V_{IN} - V_F$), thereby making the output feedback an accurate replica of the input.

- General feedback system





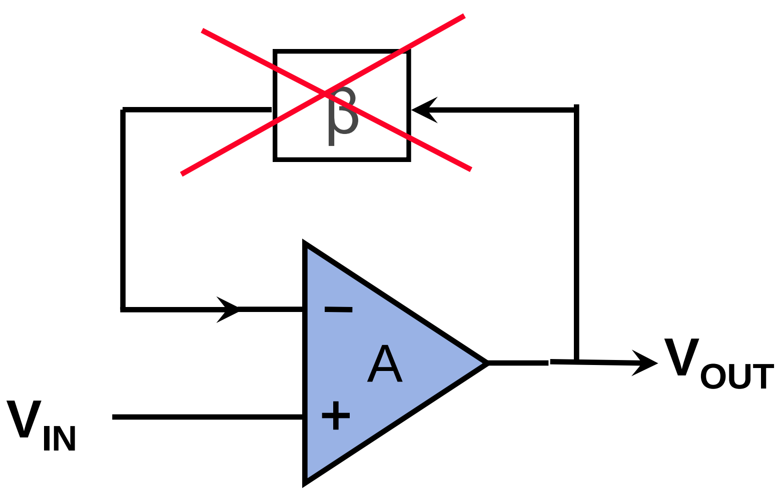
$$V_E = V_{IN} - V_F$$

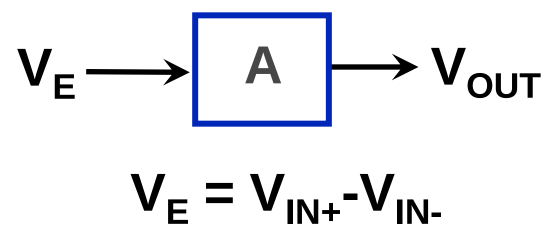
Op Amp DC Specifications

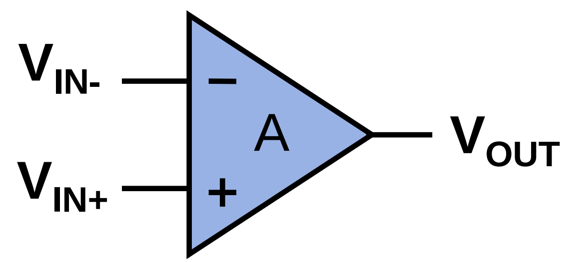
Open Loop Gain (A)

– Open loop gain of an op amp is the gain obtained when **no feedback** is used in the circuit.

- $A = V_{OUT}/V_E$ where $V_E = V_{IN+} - V_{IN-}$

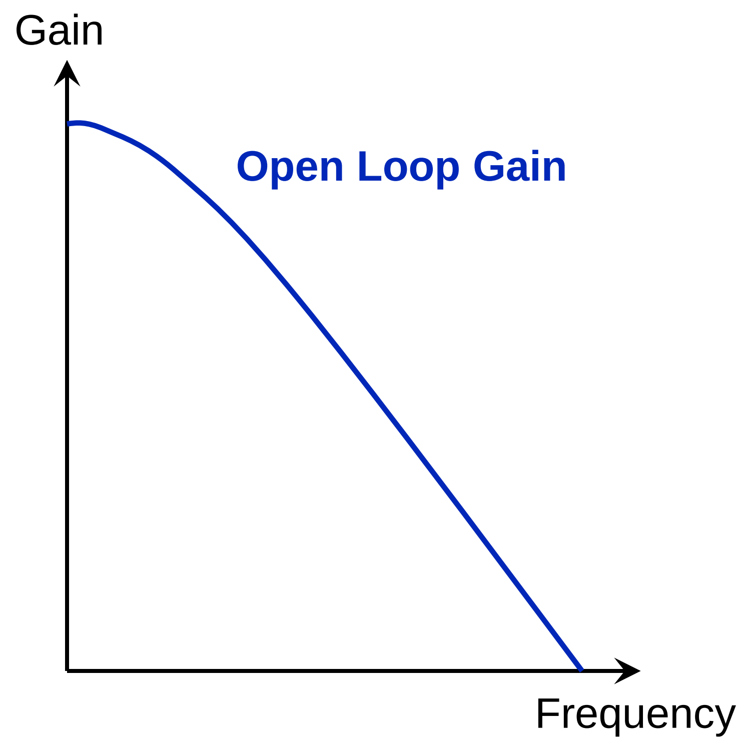






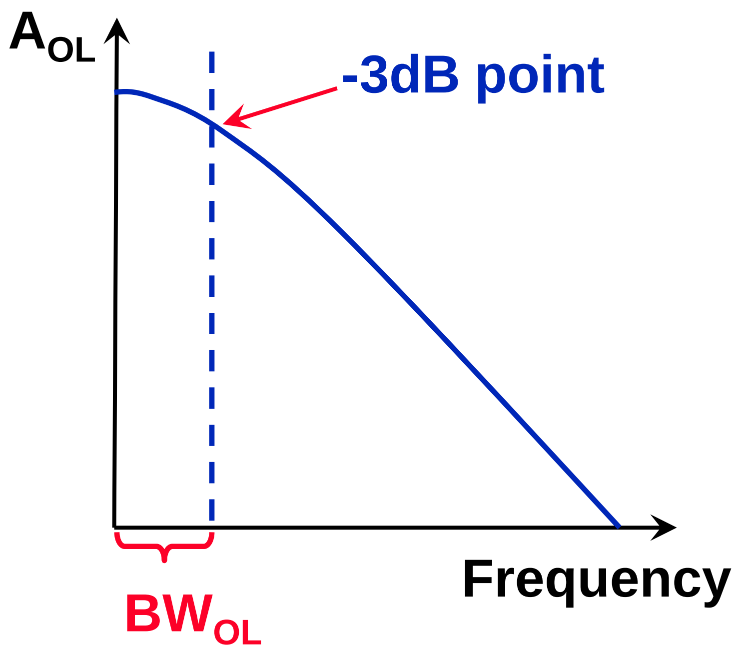
Op Amp DC Specifications

- Ideally, the open loop gain should be infinite.
  - **In reality, the open loop gain is less than ideal at DC ranging from 95dB to 120dB. (10^5 to 10^6)**
- Open loop gain will decrease when the frequency of the input signal increases.
  - **It is a function of frequency.**



Op Amp DC Specs: Output

- **Emphasis**
  - Open Loop Gain Bandwidth (BW_{OL})
    - **It is measured at the point where gain falls to 0.707 of maximum gain (-3dB bandwidth)**
    - **-3dB bandwidth is also called half-power bandwidth**



Op Amp DC Specifications

- **Example: MCP601 data sheet**

Electrical Characteristics: Unless otherwise indicated, all limits are specified for V_{DD} = +1.4 V to +5.5 V, V_{SS} = GND, T_A = 25 °C, $V_{CM} = V_{DD}/2$, R_L = 1 MΩ to $V_{DD}/2$, and $V_{OUT} \sim V_{DD}/2$						
Parameters	Sym	Min	Typ	Max	Units	Conditions
Open Loop Gain:						
DC Open Loop Gain (large signal)	A_{OL}	95	115	—	dB	R_L = 50 kΩ to $V_{DD}/2$, 100 mV < V_{OUT} < (V_{DD} – 100 mV)

– Decibel (dB) can be translated into volts per volts with the formula

$$A(dB) = 20\log\left(\frac{V_{OUT}}{V_{IN}}\right)$$

Op Amp DC Specifications

Example:

- If the open loop gain is 100dB, then

$$100\,\mathrm{dB} = 20\log\left(\frac{V_{OUT}}{V_{IN}}\right) \Longrightarrow \frac{V_{OUT}}{V_{IN}} = 10^{\left(100/20\right)} = 10^{5}$$

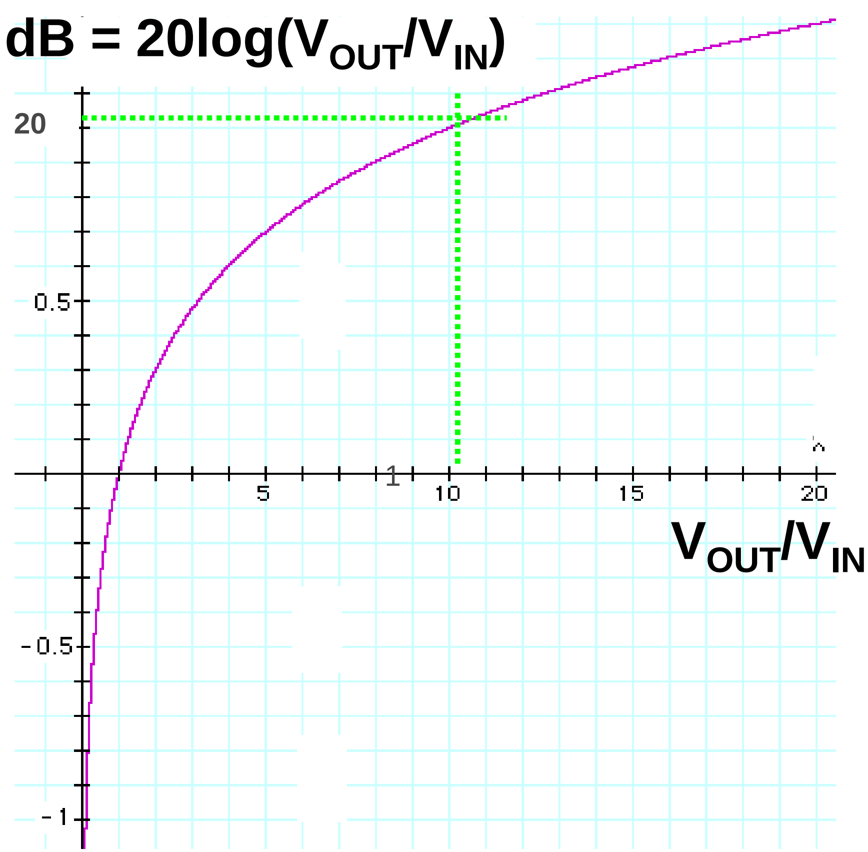
- If the open loop gain is 10^6, then

$$20\log\left(\frac{V_{OUT}}{V_{IN}}\right) = 20\log\left(10^{6}\right) = 120\mathrm{dB}$$

- Decibels are useful because they allow even very large or small ratios to be represented with a conveniently small number (similar to scientific notation).

Op Amp DC Specifications

– Graph: how dB relates to the linear response



dB level	Ratio (V/V)
-60dB	1/1000
-40dB	1/100
-20dB	1/10
0dB	1
20dB	10
40dB	100
80dB	1.0×10^4
120dB	1.0×10^6

Op Amp DC Specifications

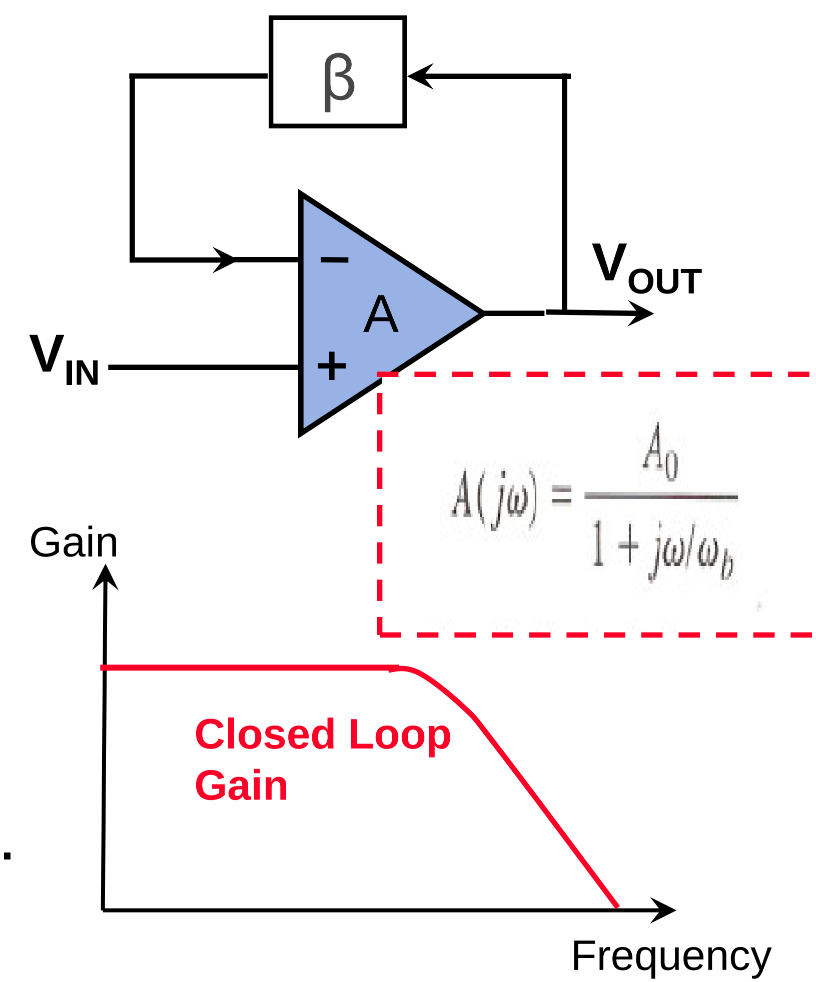
Closed Loop Gain (G)

– It, a transfer function, represents the relation between the input and output of a system.

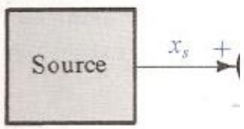
$$G = \frac{A}{1+\beta A}$$

- **A: open loop gain**
- **β: feedback factor**
- **βA: loop gain**

– G is a function of frequency.



Feedback System Merits



負回饋之優點

1.增益的穩定性提高

2.帶寬的增大.

3.失真率的降低.

4.輸出.輸入電阻的改善.

Gain Desensi

Bandwidth Exten

$$A_f = \frac{x_o}{x_s} = \frac{A}{1 + A\beta}$$

Impendence Improvement

βAV_i

$$R_{if} = R_i(1 + A\beta)$$

$$R_{of} = \frac{R_o}{1 + A\beta}$$

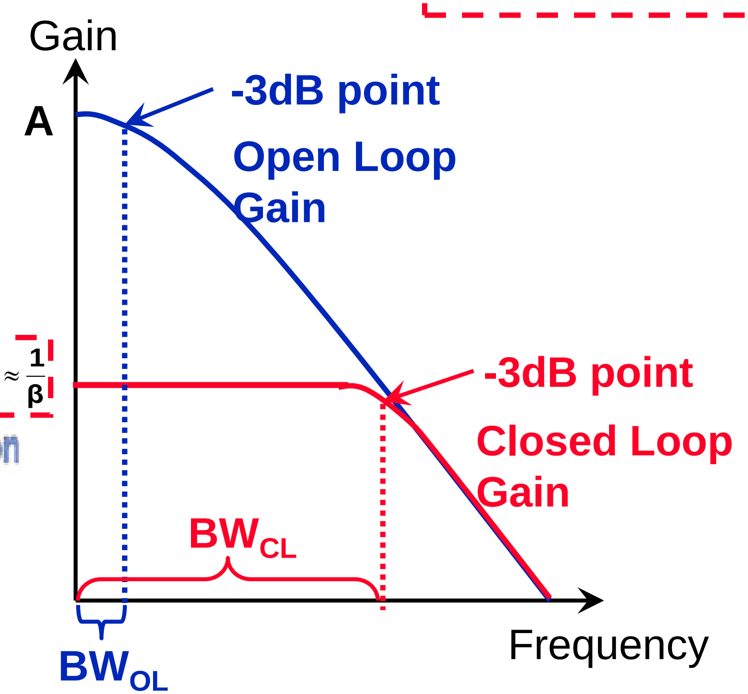
$$A_f(s) = \frac{A(s)}{1 + \beta A(s)} = \frac{A_M/(1 + A_M\beta)}{1 + s/\omega_H(1 + A_M\beta)}$$

$$|G| = \left|\frac{A}{1+\beta A}\right| \approx \frac{1}{\beta}$$

Reduction in Nonlinear Distortion

Noise Reduction

$$\frac{S}{N} = \frac{V_s}{V_n} A_2$$



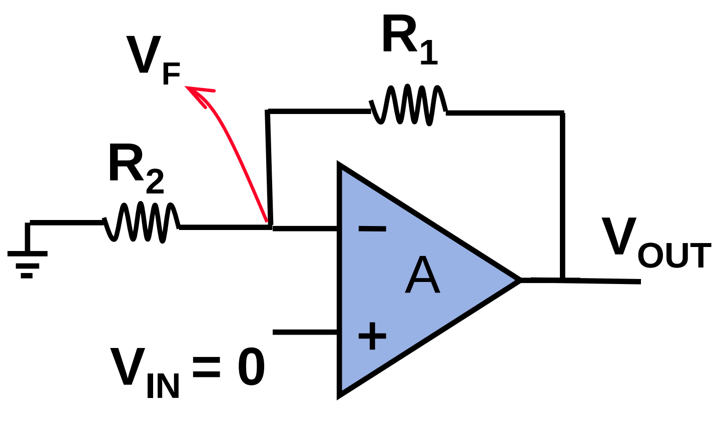
Op Amp DC Specifications

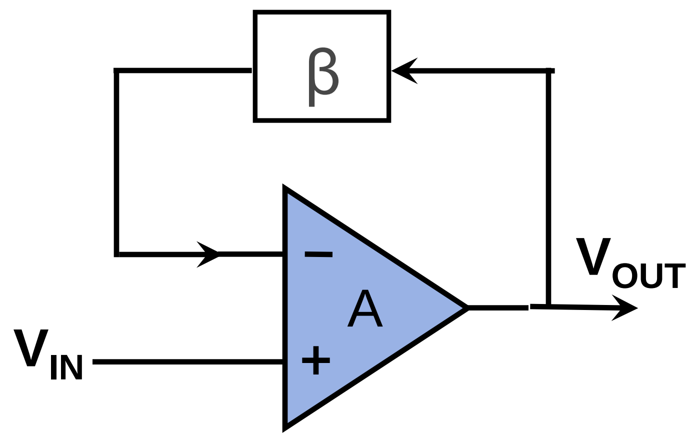
- **Open Loop vs. Close Loop (Comparison)**
  - **Open Loop**
    - Very high gain and poor stability.
    - Internal "noise" are amplified by the same gain factor.
    - Used in comparators and oscillators.
  - **Closed Loop**
    - Reduces and desensitizes the gain, good stability.
    - Internal "noise" amplified by the noise gain ($G_N = 1/\beta$).
    - Most amplifiers are used in this configuration.
  - **Op amps are normally <u>not used</u> in open loop mode.**

Op Amp DC Specifications

Discussion: Feedback Factor β

- Feedback factor is the fraction of the amplifier output signal fed back to the amplifier input.
- It is determined by the feedback network that is connected around the amplifier.

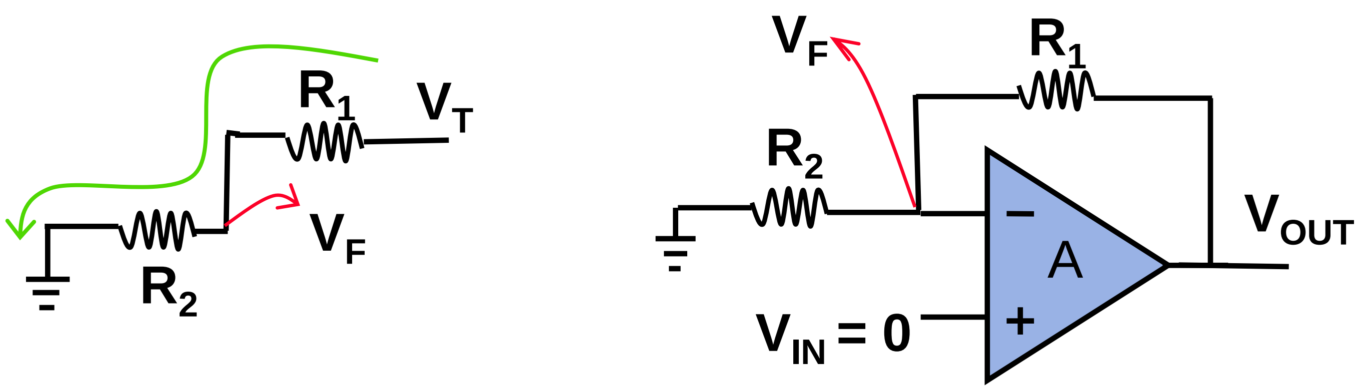




Op Amp DC Specifications

– **Feedback factor calculation**

- Break the loop at some points, only consider feedback network.
- Set $V_{IN} = 0$, inject a test signal V_T, then get the value of feedback signal V_F, $\beta = V_F/V_T$.

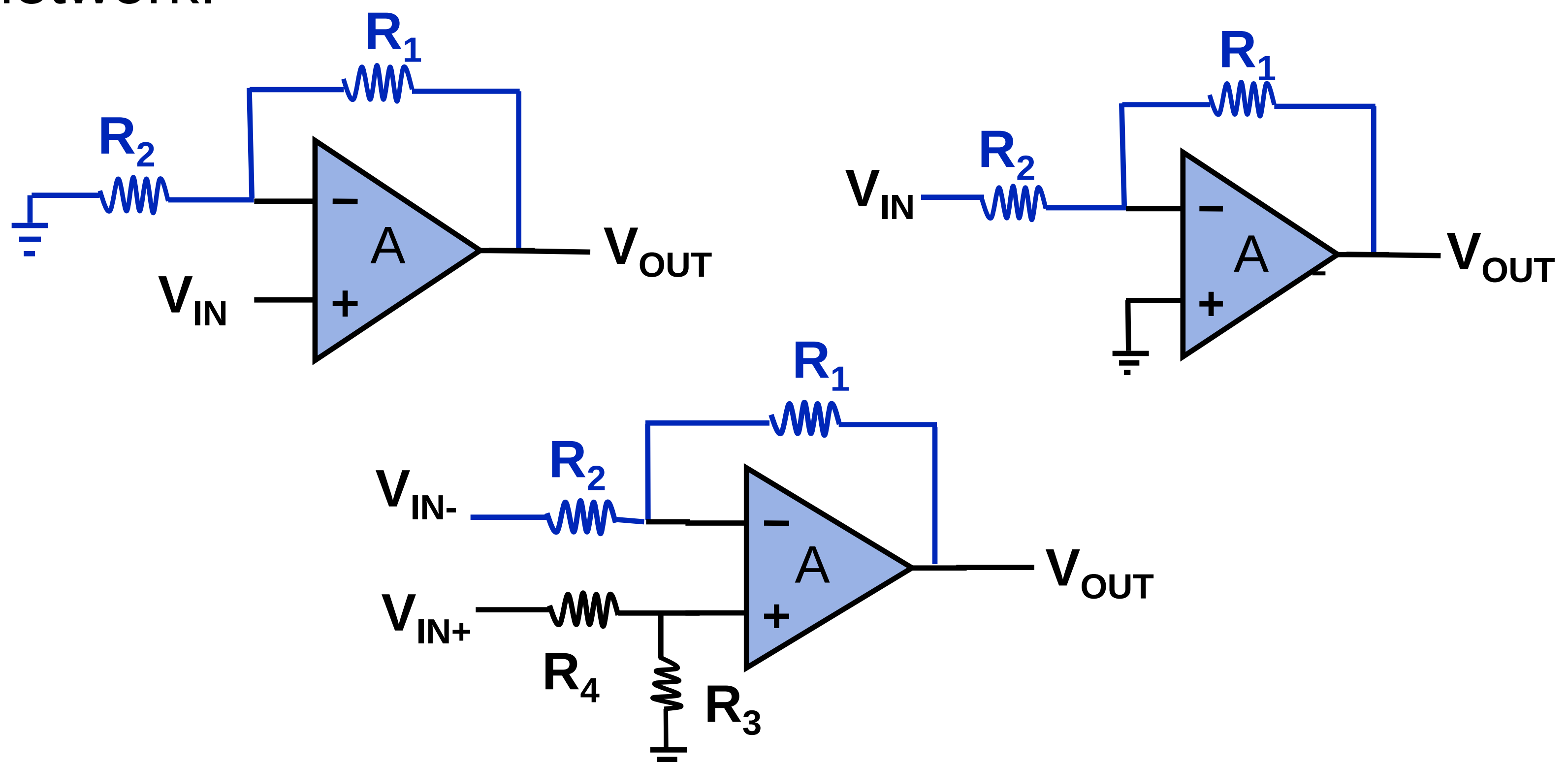


– As a general guideline, the feedback factor of an op amp circuit equals the **voltage divider ratio** of the feedback network.

Op Amp DC Specifications

Summary

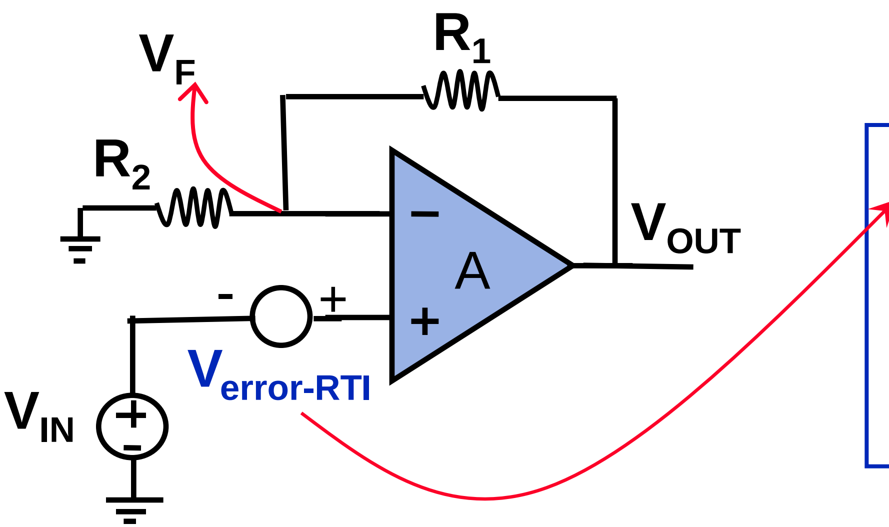
- **General guideline**: The feedback factor (**β**) of an op amp circuit **equals** the **voltage divider ratio** of the feedback network.



Op Amp DC Specifications

Emphasis: General Error Analysis

- 1/β is called **Noise Gain (G_N)**
  - Internal noise is amplified by noise gain G_N.
  - Internal noise manifests itself as input error signal.



***Error Source*: the error signals generated by non-ideal op amp specifications, such as V_{OS}, I_B, CMRR, etc.**

Op Amp DC Specifications

$$\beta = \frac{R_2}{R_1+R_2} \Rightarrow \frac{1}{\beta} = 1 + \frac{R_1}{R_2}$$

Non-Inverting $G = 1 + \frac{R_1}{R_2} = \frac{1}{\beta}$

Inverting $G = -\frac{R_1}{R_2} = 1 - \frac{1}{\beta}$

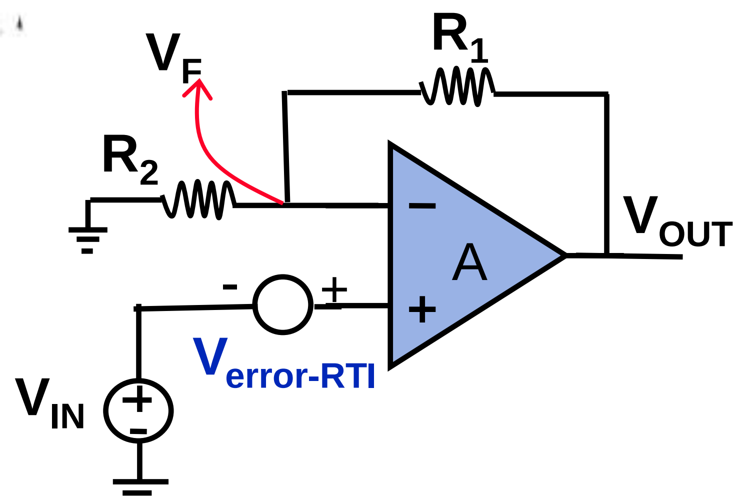
Difference $G = \frac{R_1}{R_2} = \frac{1}{\beta} - 1$

Feedback Factor

用Gain表示之關係.

ıd output errors

ɘrror-RTI



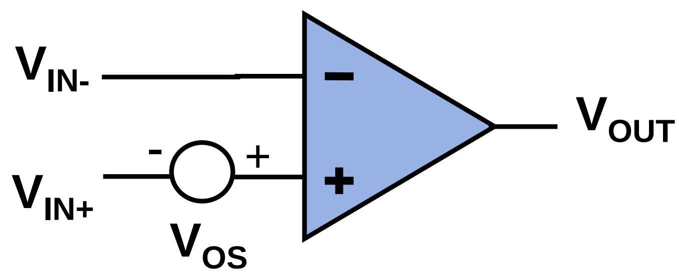
Recall:

Non-inverting amplifier: G = 1/β
Inverting amplifier: |G| = (1/β) - 1
Difference amplifier: G = (1/β) - 1

Input Related Specs

Input Offset Voltage (V_{OS})

- Defines the DC error voltage which exists in the input stage of an op amp and can be either polarity.
- Circuit model for an op amp with V_{OS}
  - **A dc source of value V_{OS} is placed in series with the <u>non-inverting</u> input of an offset-free op amp**



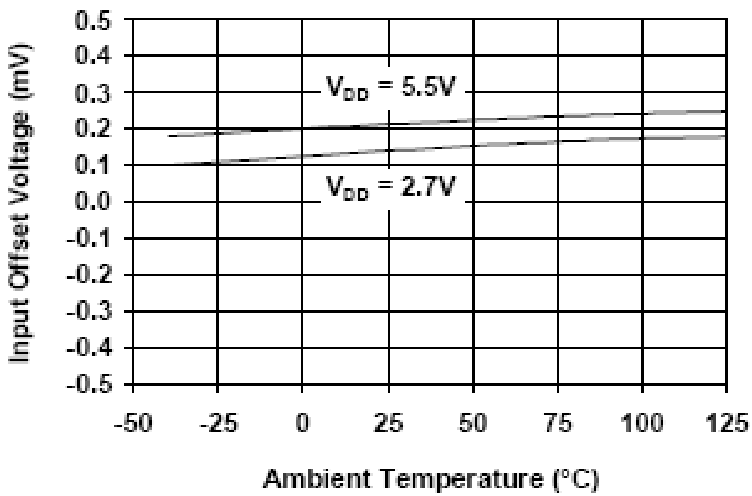
MCP6V01 Auto-zeroed Op Amp Datasheet

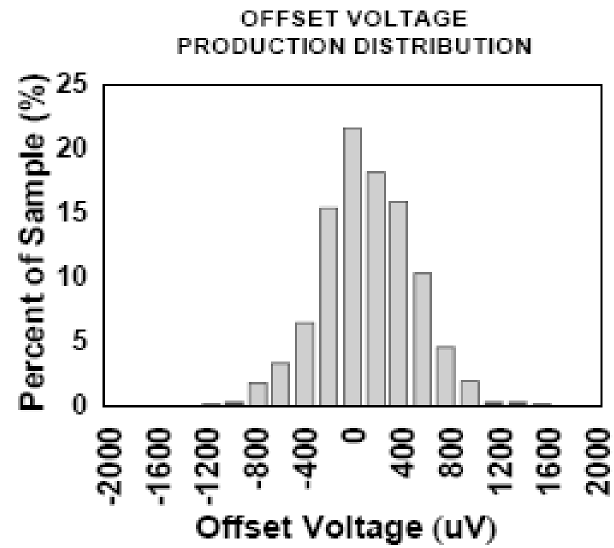
Parameters	Sym	Min	Typ	Max	Units	Conditions
Input Offset Voltage	V_{OS}	-2.0	—	+2.0	µV	T_A = +25°C (Note 1)

Op Amp DC Specifications

– V_{OS} varies with ambient temperature.

- V_{OS} typical value is the mean value of the normal distribution.





- **Example: MCP601 data sheet**

Electrical Specifications: Unless otherwise indicated, T_A = +25°C, V_{DD} = +2.7V to +5.5V, V_{SS} = GND, V_{CM} = $V_{DD}/2$, $V_{OUT} \approx V_{DD}/2$, R_L = 100 kΩ to $V_{DD}/2$ and C_L = 50 pF.

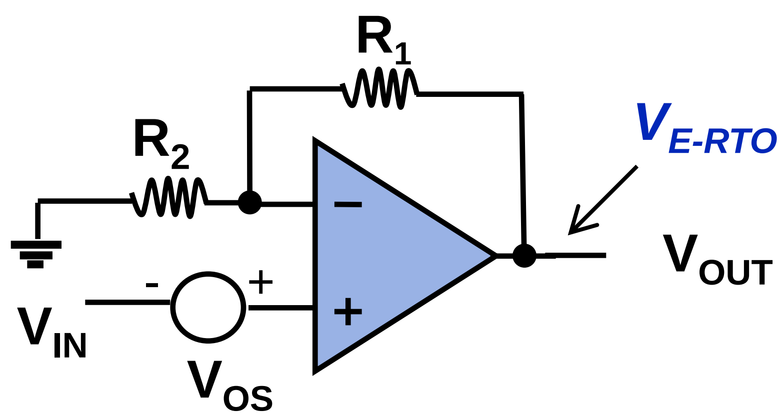
Parameters	Sym	Min	Typ	Max	Units	Conditions
Input Offset Voltage	V_{OS}	-2	±0.7	+2	mV	
Input Offset Temperature Drift	$\Delta V_{OS}/\Delta T_A$	—	±2.5	—	µV/°C	T_A = -40°C to +125°C

Input Related Specs

- **DC Error Analysis (due to V_{OS})**
  - In a closed loop system, the input offset voltage V_{OS} will be amplified by noise gain G_N .

$$V_{E\text{-}RTO} = G_N * V_{OS}$$

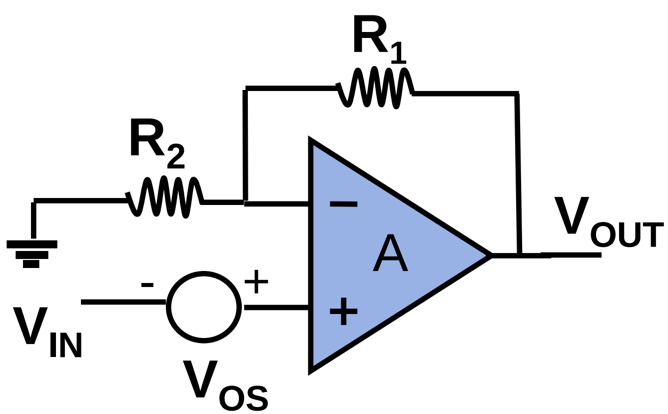
    - **The lower the V_{OS}, the smaller the $V_{E\text{-}RTO}$**



Op Amp DC Specifications

- **Application Challenge**
  - Low V_{OS} is preferred in an high gain amplifier
    - **good accuracy and maximizing the output dynamic range**
- Assume input offset voltage is 1mv, $R_1 = 10k\Omega$, $R_2 = 100\Omega$. Express V_{OUT} by using V_{IN} and V_{OS}.
- What is the DC error at the output?

High Gain ex. $\frac{10000}{100} = 100$



Hint:

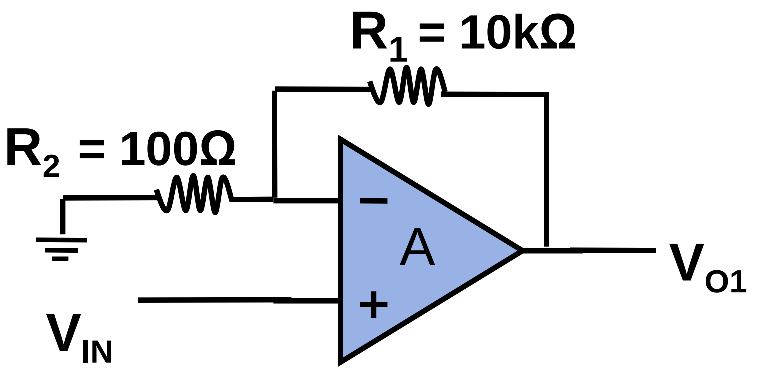
$V_{error\text{-}RTO} = G_N{*}V_{OS}$

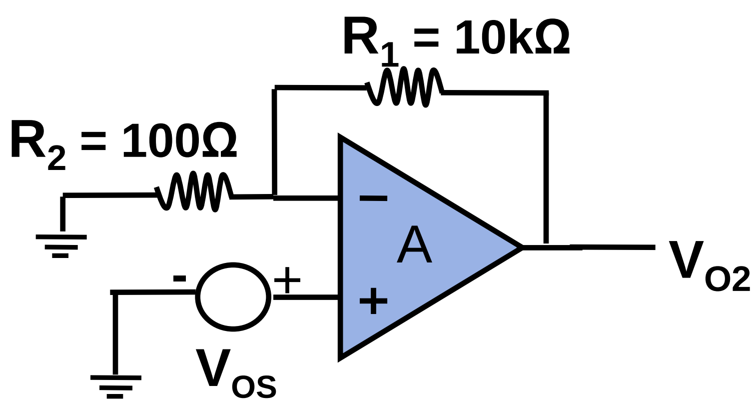
G_N = G for non-inverting amplifier

$G = 1+R_1/R_2$

Solution #15

- *Superposition Principle*
  - First, let $V_{OS} = 0$
    - Find the corresponding output voltage V_{O1}
    - $V_{O1} = V_{IN}(1+R_1/R_2)$
  - Next, let $V_{IN} = 0$,
    - Find the corresponding output voltage V_{O2}
    - $V_{O2} = V_{OS}(1+R_1/R_2)$

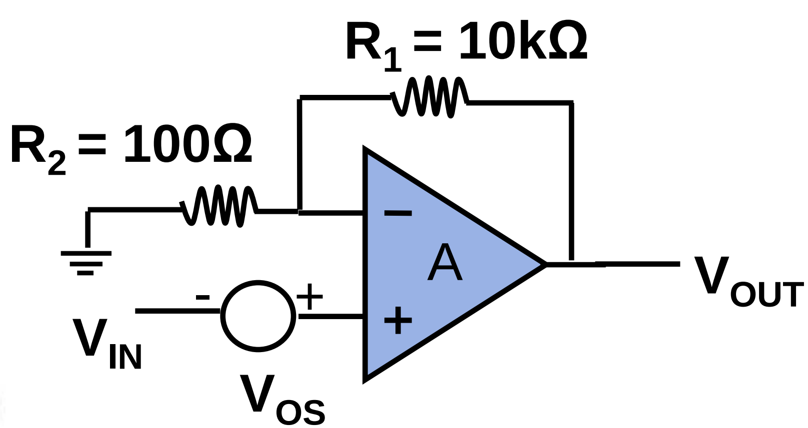




Op Amp DC Specifications

– Finally, $V_{OUT} = V_{O1}+V_{O2} = (1+R_1/R_2)*(V_{IN}+V_{OS})$

- For V_{OS} = 1mV, we have V_{O2} = 1mV*(1+100) = 101mV
- In a 5V system, the DC error 101mV lessens the output dynamic range by 101mV/5V ≈ 2%.



$\frac{5V}{1024} = 5mV$

$\frac{101mV}{5mV} = 20$ (steps or LSB)

考慮 ADC 造成之誤差

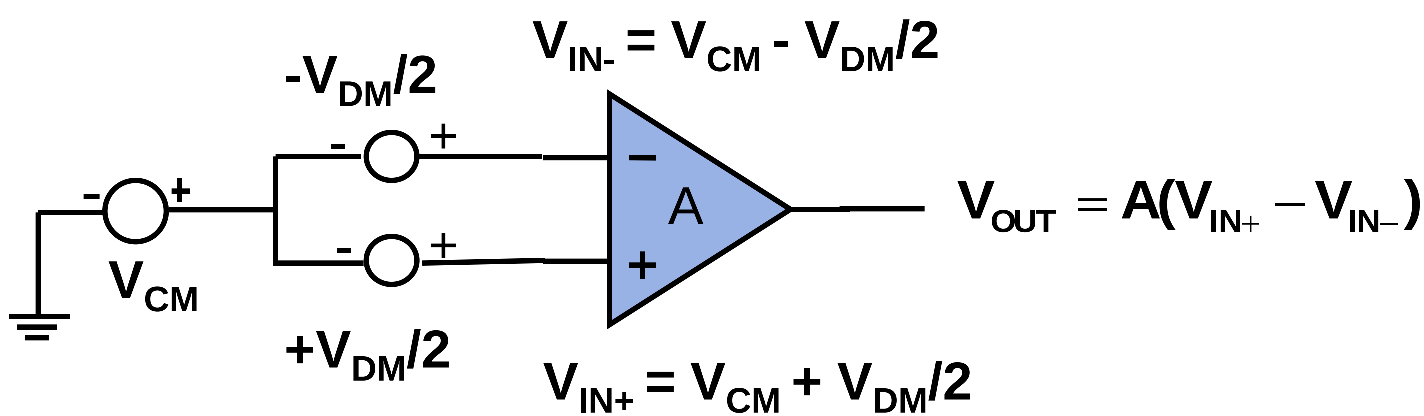
Take a Break

http://ezphysics.nchu.edu.tw/prophys/electron/new_page_7.htm

Op Amp DC Specifications

Common Mode Rejection Ratio (CMRR)

- CMRR is the ratio of differential gain (A_{DM}) to common mode gain (A_{CM}) .
  - It is a measure of the capability of an op amp to reject a signal that is common to both inputs.
  - Ideally, CMRR is infinite.



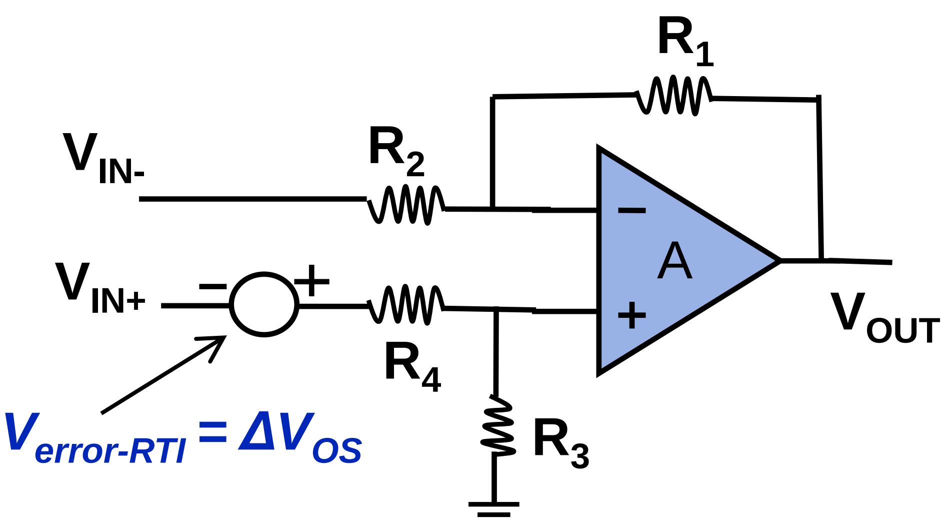
Op Amp DC Specifications

– **Refer To Input**

- Practically, CMRR is not infinite. In a closed loop system, an amplifier manifests ΔV_{CM} as input voltage error ΔV_{OS}.
- This error is described by the formula:

$$\text{CMRR (dB)} = 20\log(A_{DM}/A_{CM}) = 20\log(\Delta V_{CM}/\Delta V_{OS})$$

where $A_{DM} = \Delta V_{OUT}/\Delta V_{OS}$, $A_{CM} = \Delta V_{OUT}/\Delta V_{CM}$



$$V_{error\text{-}RTO} = G_N * V_{error\text{-}RTI}$$
$$= (1+G) * V_{error\text{-}RTI}$$
$$= (1+R_1/R_2)*V_{error\text{-}RTI}$$

Op Amp DC Specifications

- **Example: MCP601 data sheet**

Electrical Characteristics: Unless otherwise indicated, all limits are specified for V_{DD} = +1.4 V to +5.5 V, V_{SS} = GND, T_A = 25 °C, $V_{CM} = V_{DD}/2$, R_L = 1 MΩ to $V_{DD}/2$, and $V_{OUT} \sim V_{DD}/2$

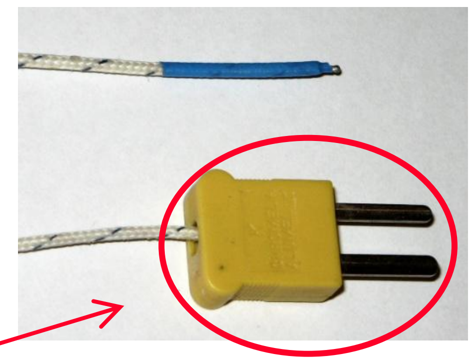
Parameters	Sym	Min	Typ	Max	Units	Conditions
Common Mode Rejection Ratio	CMRR	75	90	—	dB	V_{DD} = 5.0V, V_{CM} = -0.3V to 3.8V

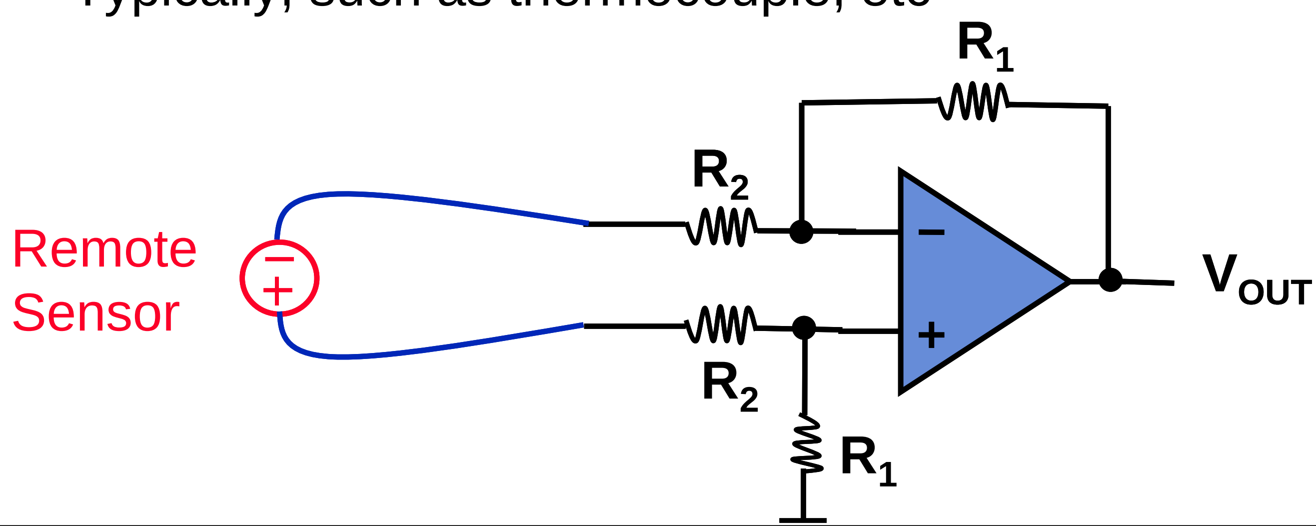
– **Application Challenge**

- The lower the CMRR, the larger the effect on the output signal.
- A value of 70dB is adequate for most of applications.

Input Related Specs

- **Application Challenge**
  - High CMRR is preferred for most applications with remote sensors
    - **Remote sensors with differential output are subject to high common mode noise.**
    - Typically, such as thermocouple, etc

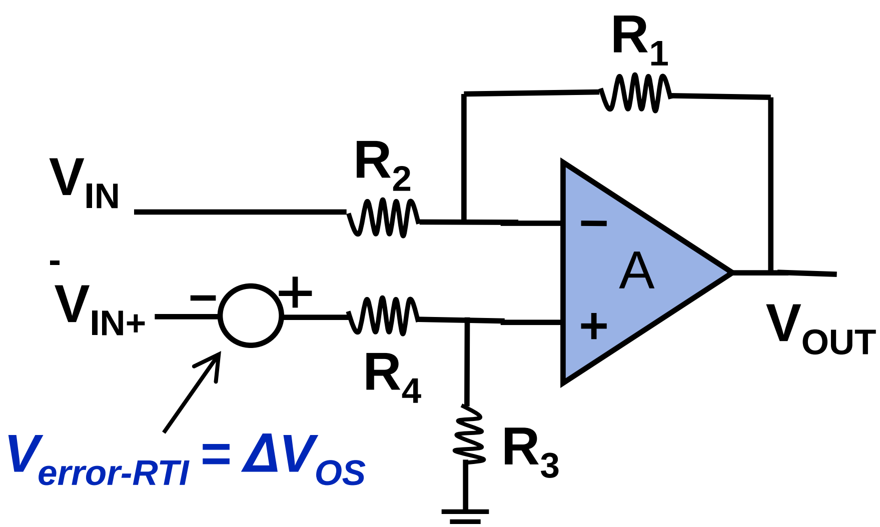




Op Amp DC Specifications

Exercise #16

- Refer to the difference amplifier. Assume closed loop gain G = 100, CMRR = 80dB. ΔV_{CM}, the change of the amplifier input CM level, is 1.0V.
- What is the error at the output? Repeat the calculation for CMRR = 60dB. **Recall: CMRR(dB) = 20log($\Delta V_{CM}/\Delta V_{OS}$)**



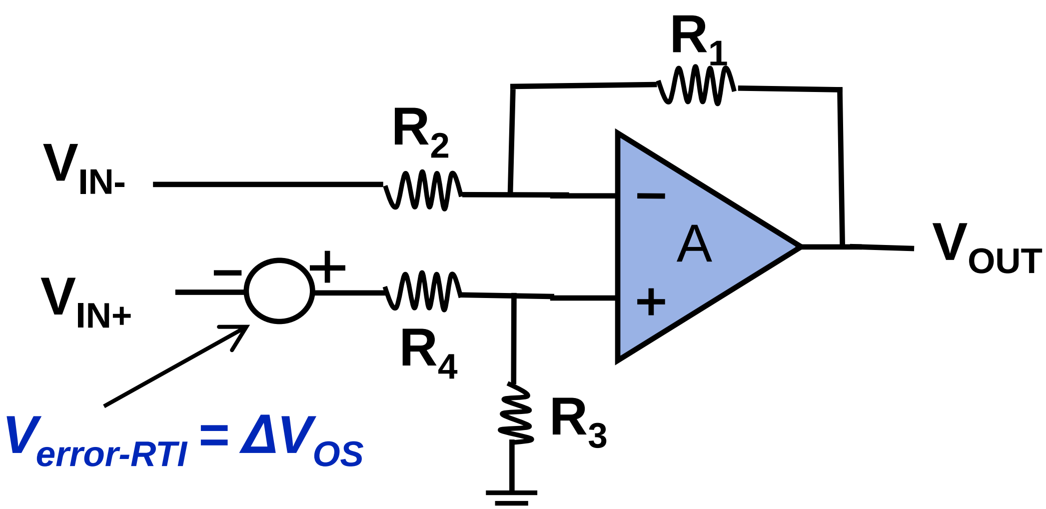
$$
\begin{aligned}
V_{error\text{-}RTO} &= G_N * V_{error\text{-}RTI} \\
&= (1+G) * V_{error\text{-}RTI} \\
&= (1+R_1/R_2)*V_{error\text{-}RTI}
\end{aligned}
$$

Op Amp DC Specifications

Solution #16

- $CMRR = 20\log(\Delta V_{CM}/\Delta V_{OS})$, CMRR = 80dB, $\Delta V_{CM} = 1.0V$
  $\rightarrow$ $80dB = 20\log(1.0V/\Delta V_{OS}) \rightarrow \Delta V_{OS} = 0.1mV$.
- $V_{error\text{-}RTO} = G_N * V_{error\text{-}RTI} = (1+R_1/R_2) * V_{error\_RTI}$
  $= 101 * 0.1mV =$ **10.1mV.**

The output range will be decreased by 10.1mV.

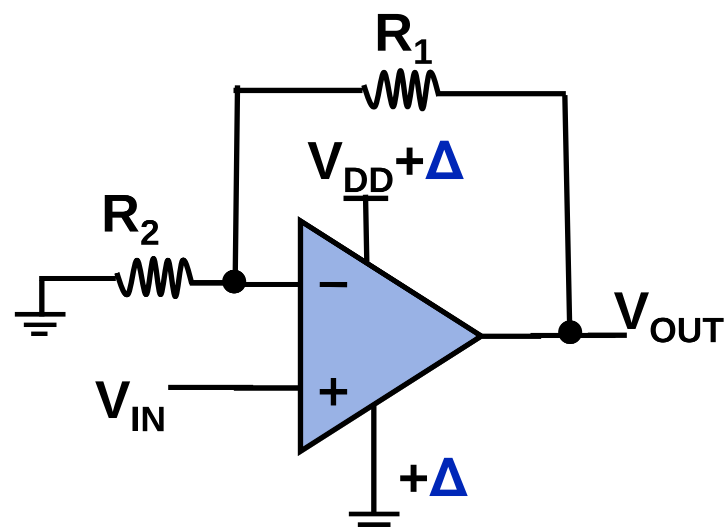


If CMRR = 60dB, the output range will be decreased by 101mV.

Power Supply Related Specs

Power Supply Rejection Ratio

- Quantifies an op amp's capability to reject a change on power supply.
  - **Such as power drift (from batteries)**



MCP6071 Datasheet

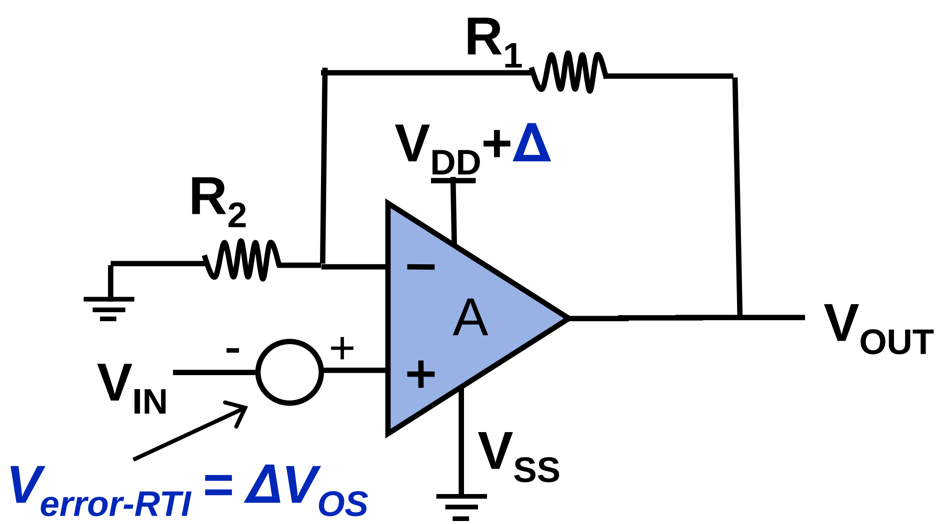
Parameters	Sym	Min	Typ	Max	Units	Conditions
Power Supply Rejection Ratio	PSRR	70	87	—	dB	$V_{CM} = V_{SS}$

Op Amp DC Specifications

– **Refer To Input**

- Practically, PSRR is not infinite. In a closed loop system, an amplifier manifests ΔV_{SUPPLY} as offset voltage error ΔV_{OS} at the input.
- This error is described with the formula:

$$\text{PSRR (dB)} = 20\log[(\Delta V_{OUT}/\Delta V_{OS})/(\Delta V_{OUT}/\Delta V_{SUPPLY})]$$
$$= 20\log(\Delta V_{SUPPLY}/\Delta V_{OS})$$



$$V_{error\text{-}RTO} = G_N * V_{error\text{-}RTI}$$
$$= G * V_{error\text{-}RTI}$$
$$= (1+R_1/R_2)*V_{error\text{-}RTI}$$

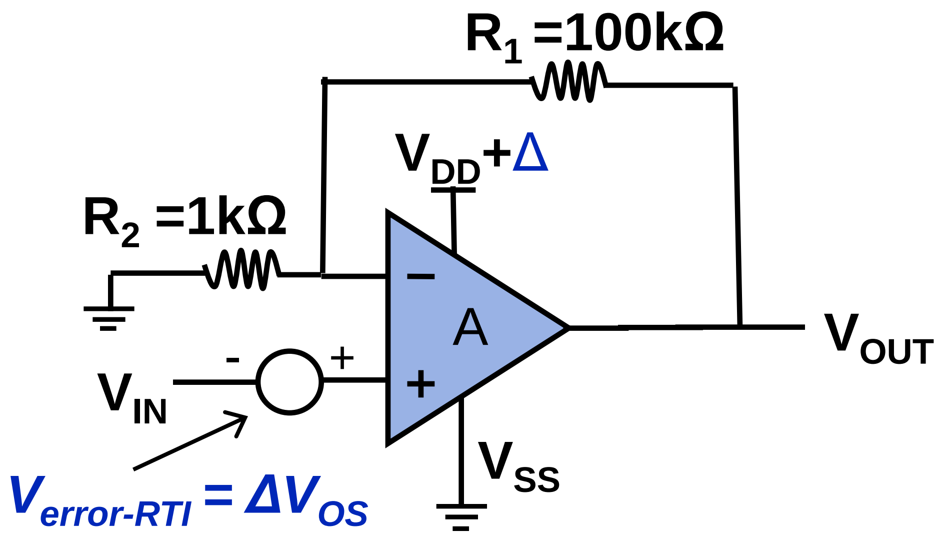
Op Amp DC Specifications

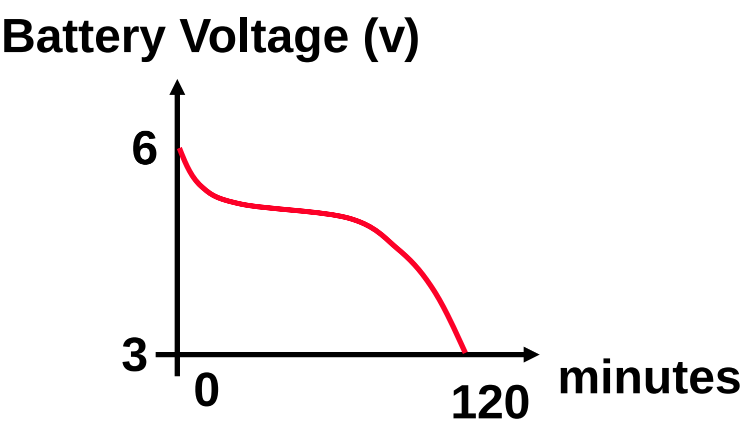
Exercise #17

A Battery Powered Application

- During the life of the battery, the output voltage ranges from 6.0V to 3.0V, PSRR = 80dB.
- What is the error at the output of the amplifier over time?

Recall: **PSRR (dB) = 20log(ΔV_{SUPPLY} /ΔV_{OS})**

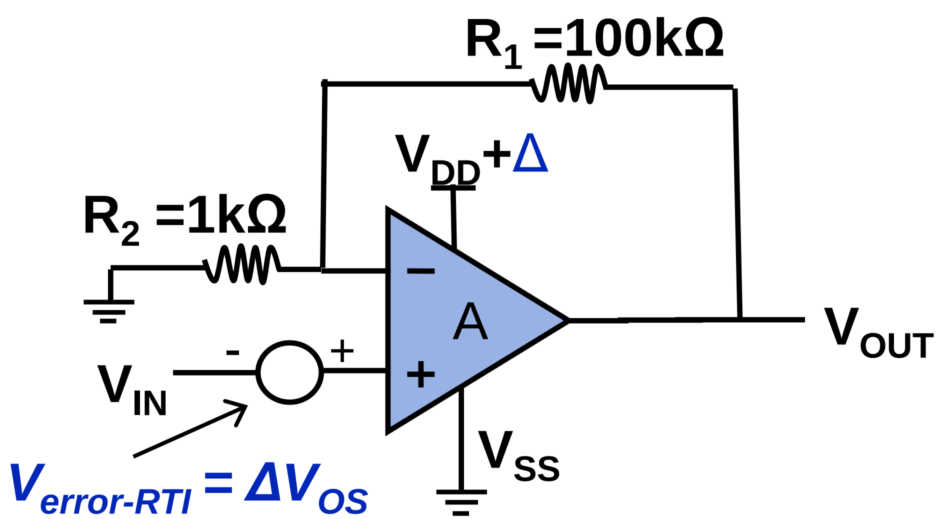


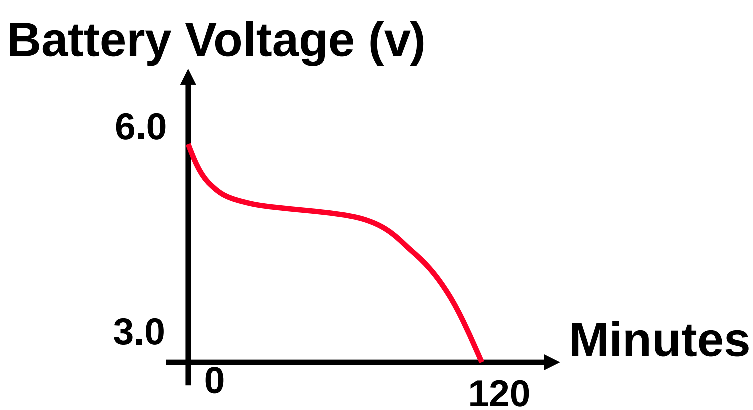


Op Amp DC Specifications

Solution #17

- PSRR = 80dB, ΔV_{supply} = 6.0V - 3.0V = 3.0V,
  PSRR (dB) = $20\log(\Delta V_{supply}/\Delta V_{os}) \rightarrow \Delta V_{os} = 0.3mV$.
- The error at the output is
  $V_{error\text{-}RTO} = G_N * V_{error\text{-}RTI} = (1+R_1/R_2) * \Delta V_{OS}$,
  $\rightarrow V_{error\text{-}RTO} = (1+100)*(0.3mV) \approx 30.3mV$





Power Supply Related Specs

- **Application Challenge**
  - High DC PSRR is needed when
    - **Using battery power**
    - **Using unregulated power**
  - High AC PSRR is required when
    - **Using line power** *(50 Hz to 400 Hz)*
    - **Using switched mode power supply**
    - **Using an op amp with digital logic** *(which typically causes a lot of power supply noise)*

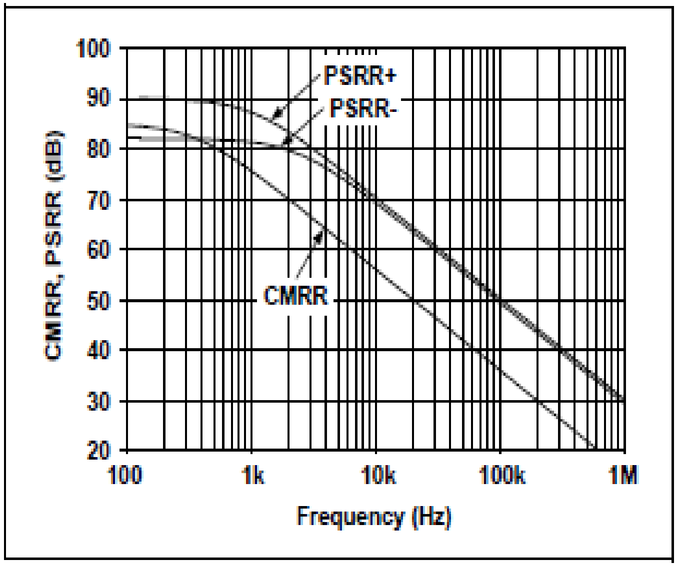


FIGURE 2-9: CMRR, PSRR vs. Frequency.

Op Amp DC Specifications

Input Bias Current (I_B, I_{B+}, I_{B-}, and I_{OS})

– **Input bias current (I_B)**

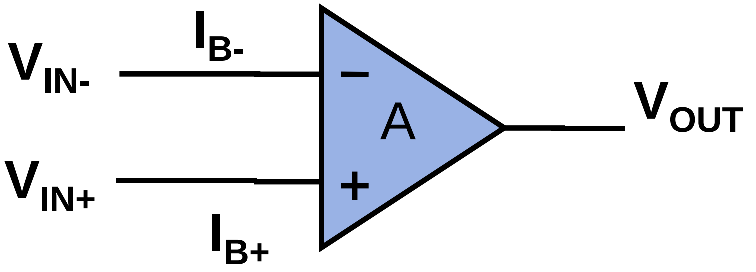
- The input bias current is the average current drawn by the input terminals.
- Depending on the type of input transistor, the bias current can flow in or out of the input terminals.

– **Input offset current (I_{OS})**

- It is equal to the difference between I_{B+} and I_{B-}. It will be either positive or negative.

$$I_B = (I_{B+} + I_{B-})/2$$

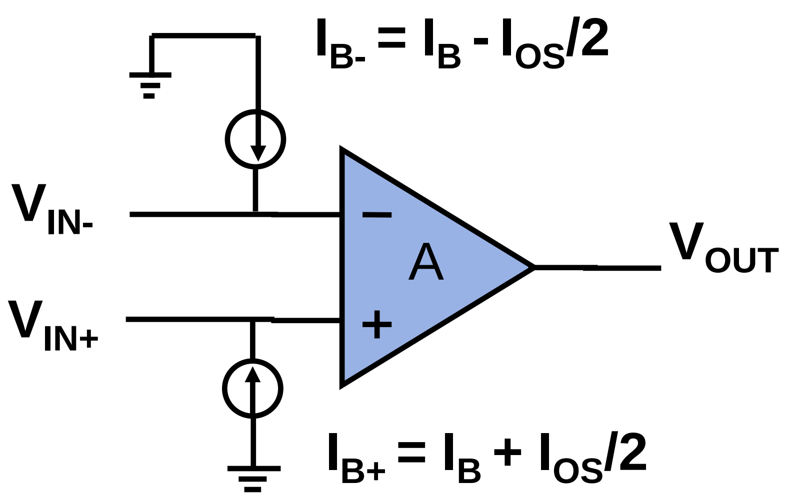
$$I_{OS} = I_{B+} - I_{B-}$$



Op Amp DC Specifications

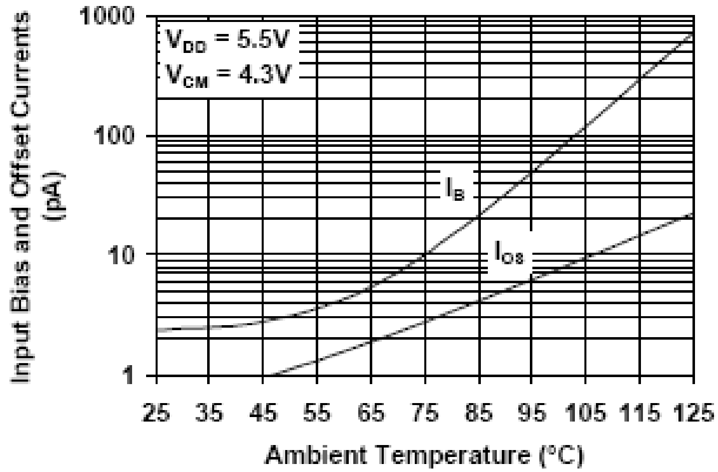
– **Circuit Model** for an op amp with I_B

- The input current is modeled as current sources, I_{B+} and I_{B-}, in parallel with the positive and negative input terminals.



Op Amp DC Specifications

– I_B and I_{OS} vary with ambient temperature.



- **Example: MCP601 data sheet**

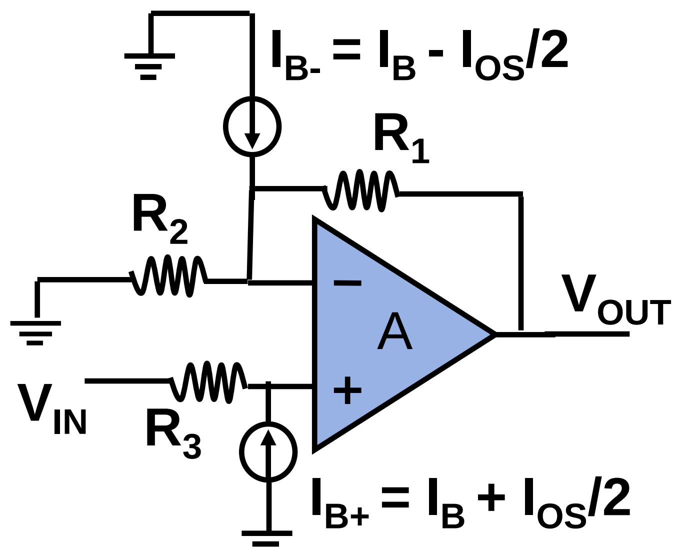
Electrical Characteristics: Unless otherwise indicated, all limits are specified for V_{DD} = +1.4 V to +5.5 V, V_{SS} = GND, T_A = 25 °C, $V_{CM} = V_{DD}/2$, R_L = 1 MΩ to $V_{DD}/2$, and $V_{OUT} \sim V_{DD}/2$

Parameters	Sym	Min	Typ	Max	Units	Conditions
Input Bias Current	I_B	—	1.0	—	pA	
Input Bias Current Over Temperature	I_B	—	—	100	pA	T_A= -40°C to+85°
Input Offset Current	I_{OS}	—	1.0	—	pA	

Op Amp DC Specifications

Application Challenge

- The lower the I_B, the smaller the effect on the output signal.
- The most sensitive configurations for the op amp's input bias current error.
  - **Circuits that use high value resistors at the input of the amplifier.**



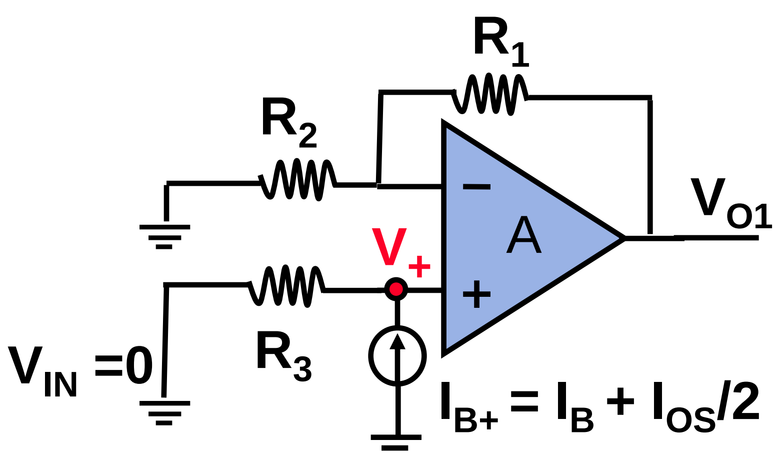
Op Amp DC Specifications

- **Effect of input bias current I_{B+} and I_{B-} on the output**
- **Using Superposition Principle**
  - **Effect of I_{B+} on the output**

    Let $V_{IN} = 0$, $I_{B-} = 0$

    $V_{O1} = V_+ * (1+R_1/R_2)$; $V_+ = I_{B+}R_3$

    So, $V_{O1} = (I_{B+}R_3) * (1+R_1/R_2)$



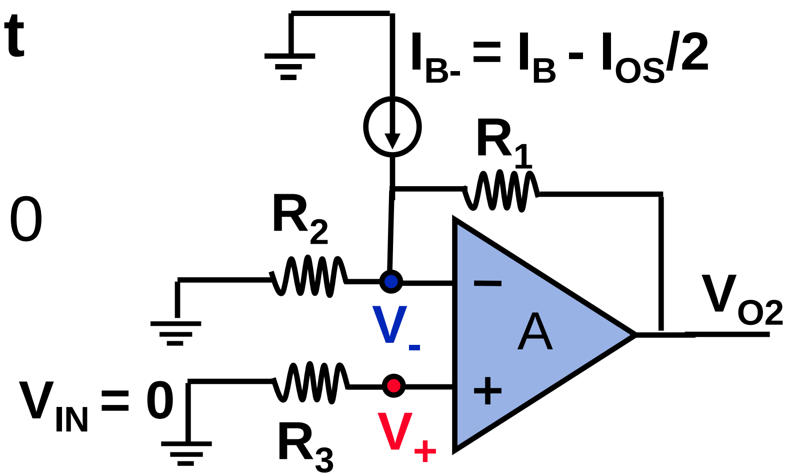
Op Amp DC Specifications

– **Effect of I_{B-} on the output**

Let $V_{IN} = 0$, $I_{B+} = 0$

$V_- - V_{O2} = I_{B-}R_1$; $V_- = V_+ = 0$

So, $V_{O2} = - I_{B-}R_1$



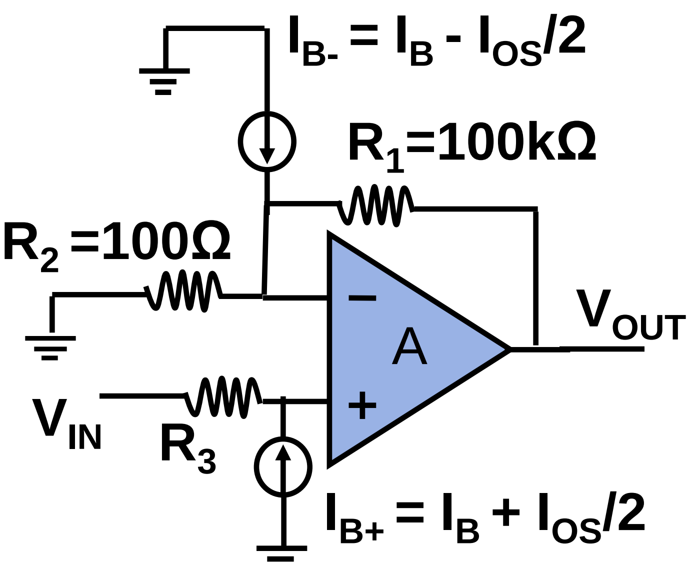
– **Total effect of input bias current I_{B+} and I_{B-} on the output**

$$\boxed{V_O = V_{O1} + V_{O2} = (I_{B+}R_3)*(1+R_1/R_2) - I_{B-}R_1}$$

Op Amp DC Specifications

Exercise #18

- Refer to the non-inverting amplifier, I_B =16nA, I_{OS} =1nA. Assume R_3 =100kΩ, what is the DC error at the output? If $R_3 = R_1//R_2 \approx 100\Omega$, repeat the calculation.



Hint:

Effect of I_{B+} on V_{OUT}: $V_{O1} = I_{B+}R_3(1+R_1/R_2)$

Effect of I_{B-} on V_{OUT}: $V_{O2} = -(I_{B-}R_1)$

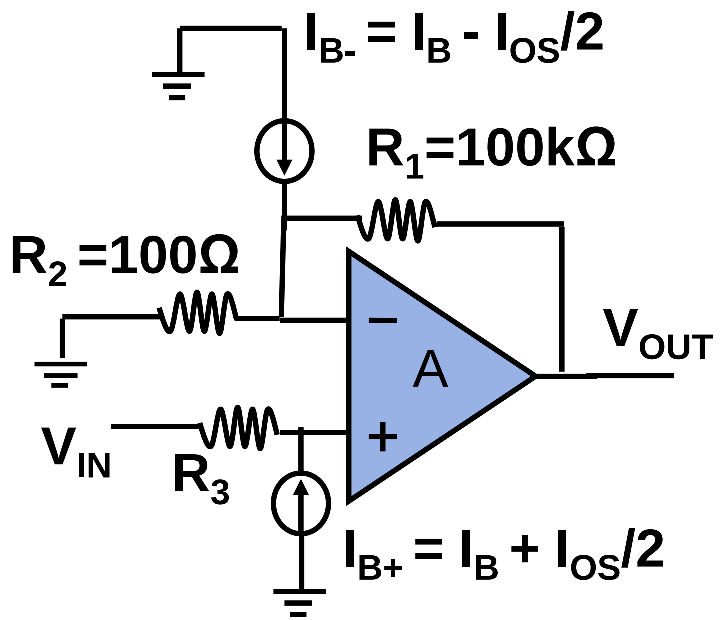
Total Effect: $V_o = I_{B+}R_3(1+R_1/R_2)-(I_{B-}R_1)$

Op Amp DC Specifications

Solution #18

- $I_B = 16nA$, $I_{OS} = 1nA$,
  $I_{B-} = I_B + I_{OS}/2$; $I_{B-} = I_B - I_{OS}/2$

  If $\mathbf{R_3 = R_1 = 100k\Omega}$,
  then
  $V_o = (I_{B+}R_3)*(1+R_1/R_2)-(I_{B-}R_1)$
  $= I_B*(100M\Omega-100k\Omega)+$
  $I_{OS}*(50M\Omega+50k\Omega)$
  ≈ 1.6V



Op A

Assume $I_{B+} = I_{B-} = I_B$

- If $\mathbf{R_3 = R_1//R_2 \approx 1}$

  then

  $V_o = (I_{B+}R_3)*(1+R$

  $\quad = (100k\Omega)*(I_B-$

  $\quad = (100k\Omega)*I_{OS}$

  $\quad =$ **0.1mV**

$\rightarrow V_o = I_B\left[R_2 - R_3\left(1 + R_2/R_1\right)\right]$

$\because V_o = 0$

$\Rightarrow R_3 = \dfrac{R_2}{1 + R_2/R_1} = \dfrac{R_2 R_1}{R_1 + R_2} = R_1//R_2$

R_3 is called a **balanced resistor.**

For minimum error due to the input bias current, R_3 should be equal to $R_1//R_2$.

Input Related Specs

- **For <u>CMOS and FET</u> input op amps**
  - I_B is low enough not to cause appreciable error
    - I_B: **~ 1pA to several nA** (from 25°C to 125°C)

- **For <u>BJT</u> input op amps**
  - I_B may become an issue
    - I_B: **~ 10nA to several thousand nA** (from 25°C to 125°C)

Op Amp DC Specs: Power

Power S

– It (... and V_S

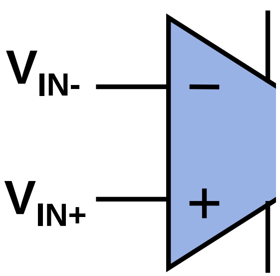
single (Positive) Power Supply.

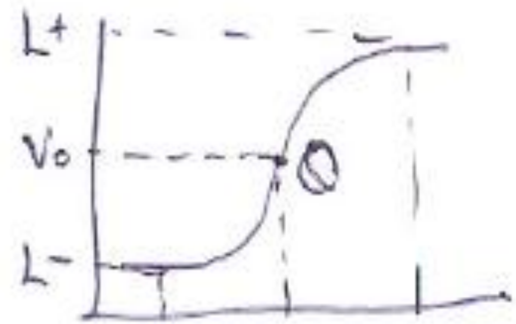
→ nonlinearity due to single supply operation.

not centered around the origin.

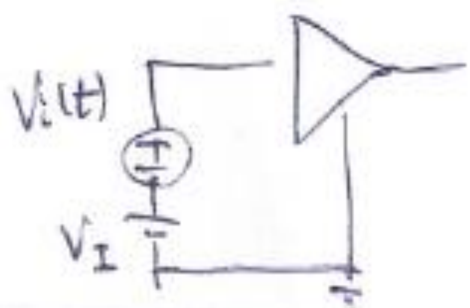
→ biasing → apply a DC voltage V_I.

$$A_v = \frac{dV_o}{dV_i}\Big|_{\text{at } Q}$$





V_{OUT}



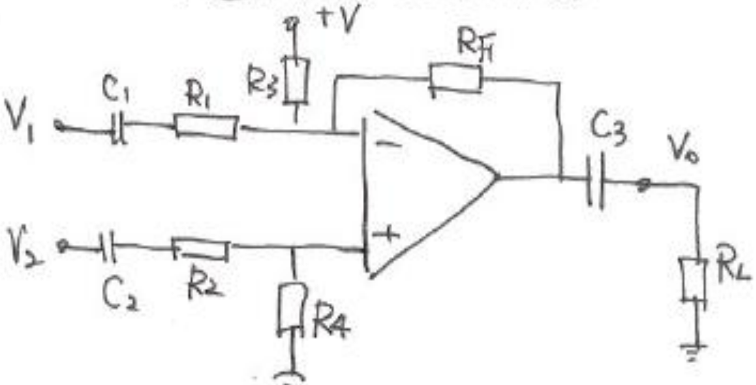
ply

MCP6031 Da

Parameters	Sym	Min	Typ	Max	Units	Conditions
Supply Voltage	V_{DD}	1.8	—	5.5	V	

Single Power Supply Amp Circuit

單電源供電之差分放大器



$V_o = \frac{R_F}{R_1}(V_2 - V_1)$, $\frac{R_F}{R_1} = \frac{R_3}{2R_2}$

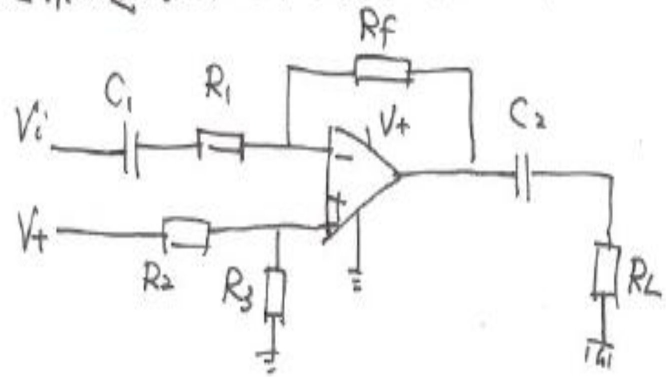
若 $R_F = R_1$ ⟹ 模擬減法器.

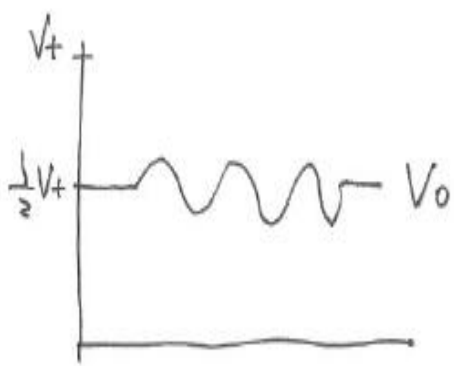
缺点：無信号輸入時,輸出為電源電壓之一半.

即所謂甲類放大器之輸出狀態

— 靜態功耗較大.

單電源供電的反相放大器(在輸入,輸出信号端加交流耦合電容.





$G = -\frac{R_f}{R_1}$

$C_1 = 1000/2\pi f_c R_1$ (μF)

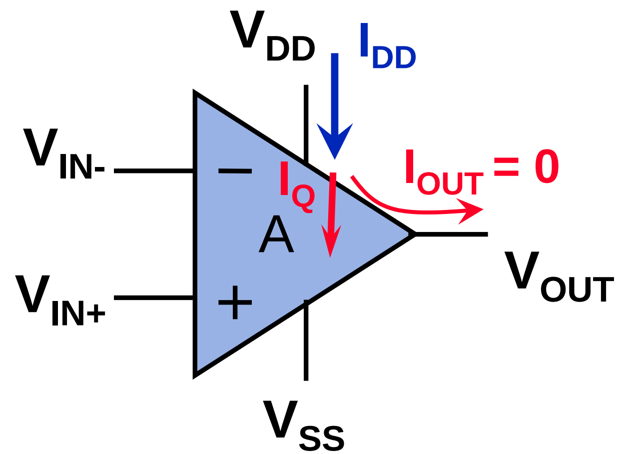
$C_2 = 1000/2\pi f_c R_L$ (μF)

一般 $R_2 = R_3 = 2R_f$.

Op Amp DC Specifications

Power Supply Requirements

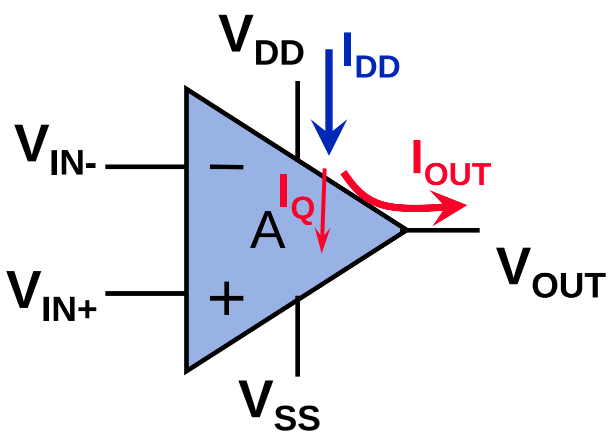
- Power Supply Voltage
  - It defines the acceptable difference between V_{DD} and V_{SS} which allows linear operation of the op amp.
- Quiescent Current (I_Q)
  - It is the amount of current consumed by op amp when it is not performing any work.
    - **Usually, the order of mA ~µA.**
    - **Low I_Q is preferred for power-saving .**



$$\boxed{I_{DD} = I_Q + I_{OUT}}$$

Op Amp DC Specifications

– Typically, if a load is applied to op amp, the current into V_{DD} pin will primarily goes through the op amp output stage, and then through the load.



$$\boxed{I_{DD} = I_Q + I_{OUT}}$$

- **Example: MCP601 data sheet**

Parameters	Sym	Min	Typ	Max	Units	Conditions
Power Supply						
Supply Voltage	V_{DD}	2.7	—	5.5	V	
Quiescent Current per Amplifier	I_Q	—	230	325	µA	$\boxed{I_O = 0}$

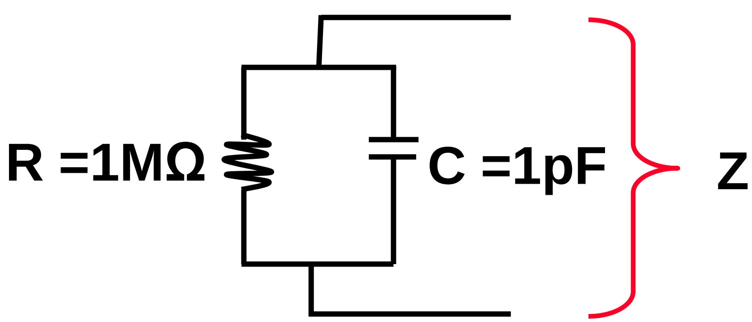
Op Amp DC Specifications

Input Impedance/Output Impedance (Z_{IN}, Z_{OUT})

- Impedance:

  Generalizes Ohm's law to AC circuit analysis. Unlike resistance, the impedance of an electric circuit is **a function of frequency.**

- **Example:** Impedance (Z) at different frequency.



f (Hz)	$\lvert Z_C \rvert$ (Ω)	$\lvert Z \rvert$ (Ω)
1	1.6×10^{11}	1M
0.1M	1.6M	0.85M
0.5M	0.32M	0.30M

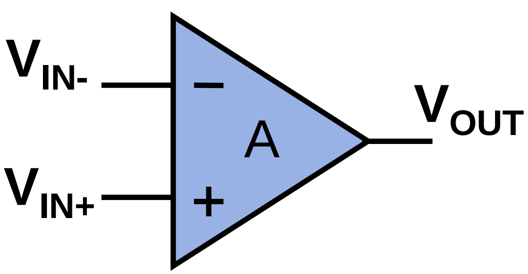
$Z = R // Z_C$, $Z_C = 1/(j\omega C)$, $\omega = 2\pi f$

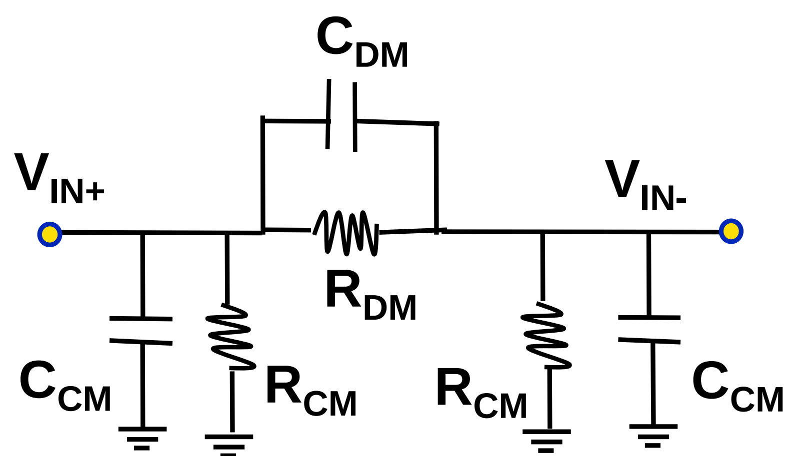
Op Amp DC Specifications

- **Example: MCP601 data sheet**

Parameters	Sym	Min	Typ	Max	Units
Common Mode Input Impedance	Z_{CM}	—	$10^{13}\|\|6$	—	$\Omega\|\|pF$
Differential Input Impedance	Z_{DIFF}	—	$10^{13}\|\|3$	—	$\Omega\|\|pF$

Recall: The input impedance of an ideal op amp is infinity.
For a real op amp, high input impedance is preferred.

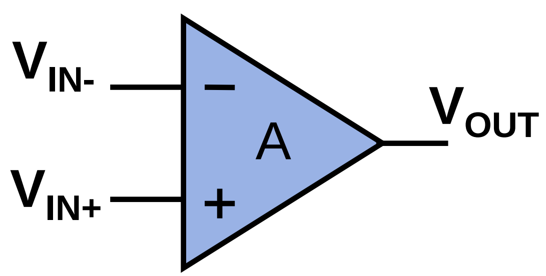




Op Amp DC Specifications

Output Impedance (Z_{OUT})

- **Low** output impedance of an op amp is an important characteristic.
  - Ideally, it should be zero and it is usually very small.
    - This minimizes the loading effect of the op amp output stage.
- Normally, it is not specified in our data sheet.



Op Amp

AC Specifications

Op Amp AC Specifications

Primary AC performance specifications

- **Frequency Domain Spec.**

  --- Describe the response to **Sine Wave Input** and **Bode Plot Analysis** method will be introduced.

  - **Gain Bandwidth Product (GBWP)**
  - **Phase Margin/Gain Margin (PM, GM)**
  - **Full Power Bandwidth (FPBW)**

- **Time Domain Spec.**

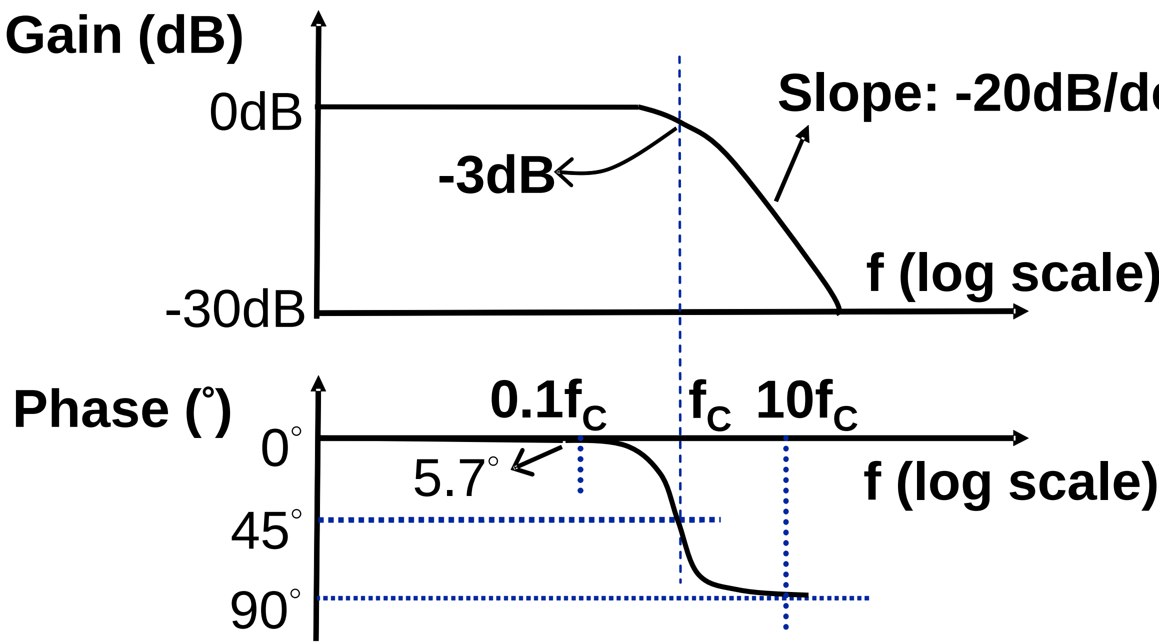
  --- Describe the response to a **Step Input**.

  - **Slew Rate (SR)**
  - **Settling Time**
  - **Overshoot**

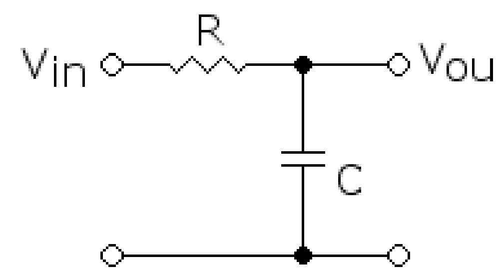
Op Amp AC Specifications

Bode Plot Analysis Method

- The Bode plot describes the output response of a frequency-dependent system for a sine wave input. It is a combination of **magnitude plot** and **phase plot.**



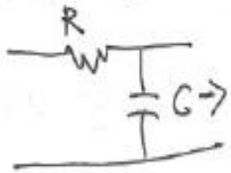
f_C: Cut-off frequency



Low Pass Filter

$G = V_{out} / V_{in}$

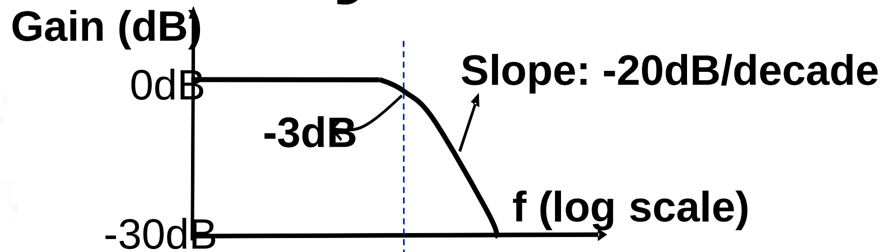
Bode Plot Analysis

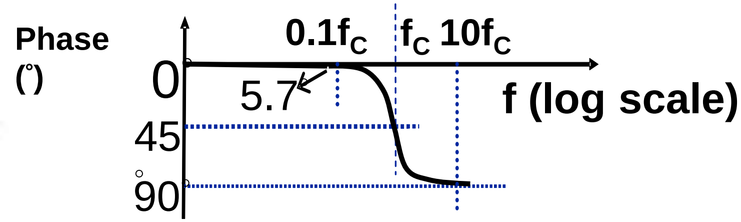


$C \to Z_c = \frac{1}{j\omega C} = \frac{1}{sC}$

$$\frac{V_o(s)}{V_i(s)} = \frac{Z_c}{R+Z_c} = \frac{\frac{1}{sC}}{R+\frac{1}{sC}} = \frac{1}{1+sCR} = \frac{1}{1+\frac{s}{\omega_0}}$$

$$\Rightarrow \frac{V_o(j\omega)}{V_i(j\omega)} = \frac{1}{1+j\frac{\omega}{\omega_0}}. \quad \left(\omega_0 = \frac{1}{RC}\right).$$





f_C: Cut-off frequency

$$|H(j\omega)| = \left|\frac{1}{1+j\frac{\omega}{\omega_0}}\right| = -20\log\left(\sqrt{1+\left(\frac{\omega}{\omega_0}\right)^2}\right) dB, \qquad \angle H(j\omega) = -\angle\left[1+j\frac{\omega}{\omega_0}\right] = -\tan^{-1}\left(\frac{\omega}{\omega_0}\right)$$

(i) $\omega \ll \omega_0$ $\quad |H(j\omega)| = -20\log(1) = 0\ dB$, $\quad \angle H(j\omega) \approx -\tan^{-1}(0) = 0^\circ = 0$ radian

(ii) $\omega \gg \omega_0$ $\quad |H(j\omega)| = -20\log\left(\frac{\omega}{\omega_0}\right) dB$, $\quad \angle H(j\omega) \approx -\tan^{-1}(\infty) = -90^\circ = -\frac{\pi}{2}$ (radian)

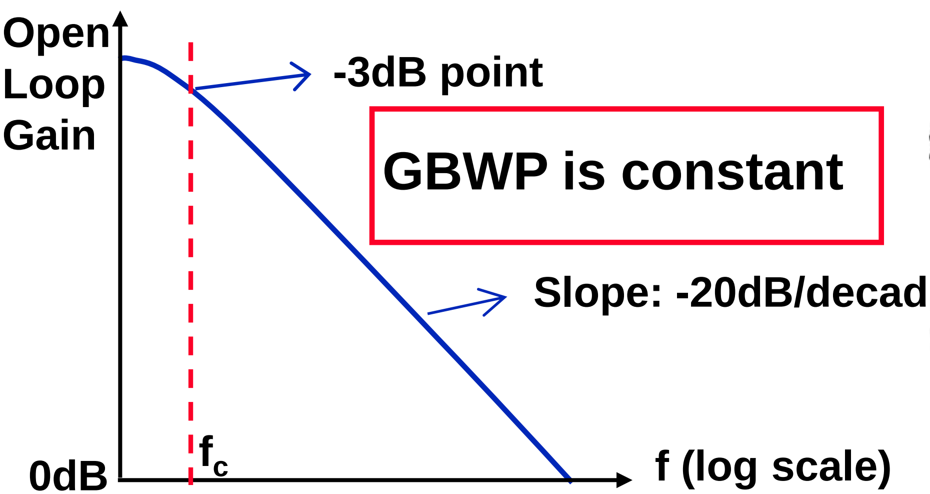
(iii) $\omega = \omega_0$ $\quad |H(j\omega)| = -20\log(\sqrt{2})\,dB = -3.01\ dB \doteq -3dB$ $\quad \angle H(j\omega) = -\tan^{-1}(1) = -45^\circ = -\frac{\pi}{4}$ (radian)

Bode Plot for magnitude at 0dB until the break frequency and then drop at 20 dB per decade.

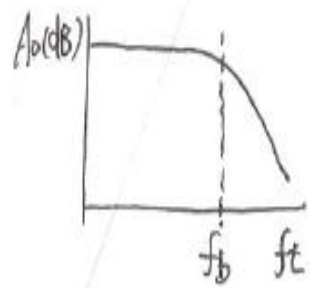
Op Amp AC Specifications

Gain Bandwidth Product (GBWP)

– GBWP is the product of op amp open loop gain times the frequency at any point where the amplifier response is attenuating at a rate of -20dB/decade of frequency.



★ Internal Compensated.



$$A(s) = \frac{A_0}{1+s/\omega_b}$$

$$A(j\omega) = \frac{A_0}{1+j\omega/\omega_b}$$

(i) $\omega = \omega_b$, $|A(j\omega)| = \frac{A_0}{\sqrt{2}}$, (-3dB point)

(ii) $\omega \gg \omega_b$. $A(j\omega) \approx \frac{A_0 \omega_b}{j\omega}$

if $\omega = \omega_t = A_0 \omega_b$

$|A(j\omega)| = 1 = 0$ dB.

→ Unit Gain Bandwidth

→ Gain Bandwidth Product.

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Op Amp AC Specifications

- GBWP is used to estimate closed loop gain bandwidth when the gain is known.

$$BW \approx GBWP/G_N$$

  - **BW: Closed loop gain bandwidth**
  - **G_N: Noise gain**
  - **Recall: For $|G| >> 1$, $G_N \approx |G|$.**

- The larger GBWP, the wider BW for a certain closed loop gain.

- **Example: MCP601 data sheet**

Parameters	Sym	Min	Typ	Max	Units	Conditions
Gain Bandwidth Product	GBWP	—	2.8	—	MHz	

BW ≈ GBWP/G_N

Frequency Response of Closed-Loop Amplifiers

finite op amp open-loop gain A,

the inverting circuit

$$\frac{V_o}{V_i} = \frac{-R_2/R_1}{1 + (1 + R_2/R_1)/A}$$

$$\frac{V_o(s)}{V_i(s)} = \frac{-R_2/R_1}{1 + \frac{1}{A_0}\left(1 + \frac{R_2}{R_1}\right) + \frac{s}{\omega_t/(1 + R_2/R_1)}}$$

For $A_0 \gg 1 + R_2/R_1$

$$\frac{V_o(s)}{V_i(s)} \simeq \frac{-R_2/R_1}{1 + \frac{s}{\omega_t/(1 + R_2/R_1)}}$$

noninverting circuit

$$\frac{V_o}{V_i} = \frac{1 + R_2/R_1}{1 + (1 + R_2/R_1)/A}$$

$$A(j\omega) = \frac{A_0}{1 + j\omega/\omega_b}$$

For $A_0 \gg 1 + R_2/R_1$

$$\frac{V_o(s)}{V_i(s)} \simeq \frac{1 + R_2/R_1}{1 + \frac{s}{\omega_t/(1 + R_2/R_1)}}$$

$$\omega_{3dB} = \frac{\omega_t}{1 + R_2/R_1}$$

Op Amp AC Specifications

Exercise #19

- Assume GBWP = 1MHz and unity gain stable, what is the closed loop gain bandwidth for G = 1, 11, -1, -10?

	G (closed loop gain)		G_N (noise gain)
R_1/R_2	Non-inverting	Inverting	$1/\beta$
0.1	1.1	- 0.1	1.1
1	2	-1	2
10	11	-10	11

Recall BW = GBWP/G_N, Inverting amplifier: G_N = 1+ |G|, Non-inverting amplifier: G_N = G.

Op Amp AC Specifications

Solution #19

- For G = 1 (unity gain stable) → G_N = G =1; BW = 1MHz/1 = 1MHz
- For G = 11 → G_N = G =11; BW = 1MHz/11 = 91 kHz
- For G = -1 → G_N = 1+ |G| = 2; BW = 1MHz/2 = 500 kHz
- For G = -10 → G_N = 1+ |G| = 11; BW = 1MHz/11 = 91 kHz

	G		G_N
R_1/R_2	Non-inverting	Inverting	$1/\beta$
0.1	1.1	- 0.1	1.1
1	2	-1	2
10	11	-10	11

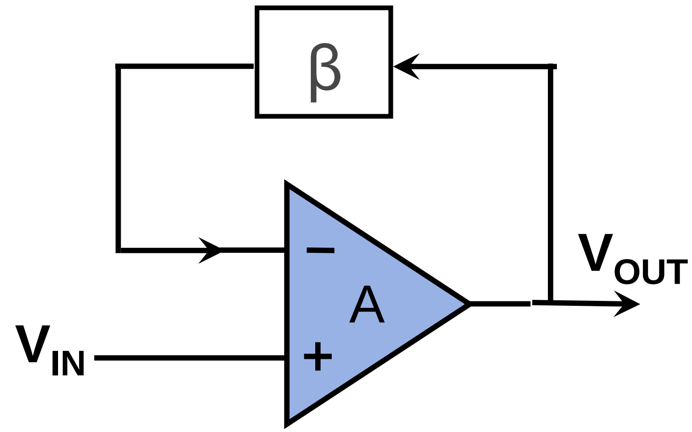
BW = GBWP/G_N
Non-inverting amplifier: G_N = G
Inverting amplifier: G_N = 1+ |G|

Op Amp AC Specifications

Stability of Op Amp and its Feedback Loop

$$G = \frac{A}{1 + \beta A}$$

G: closed loop gain
A: open loop gain
βA: loop gain



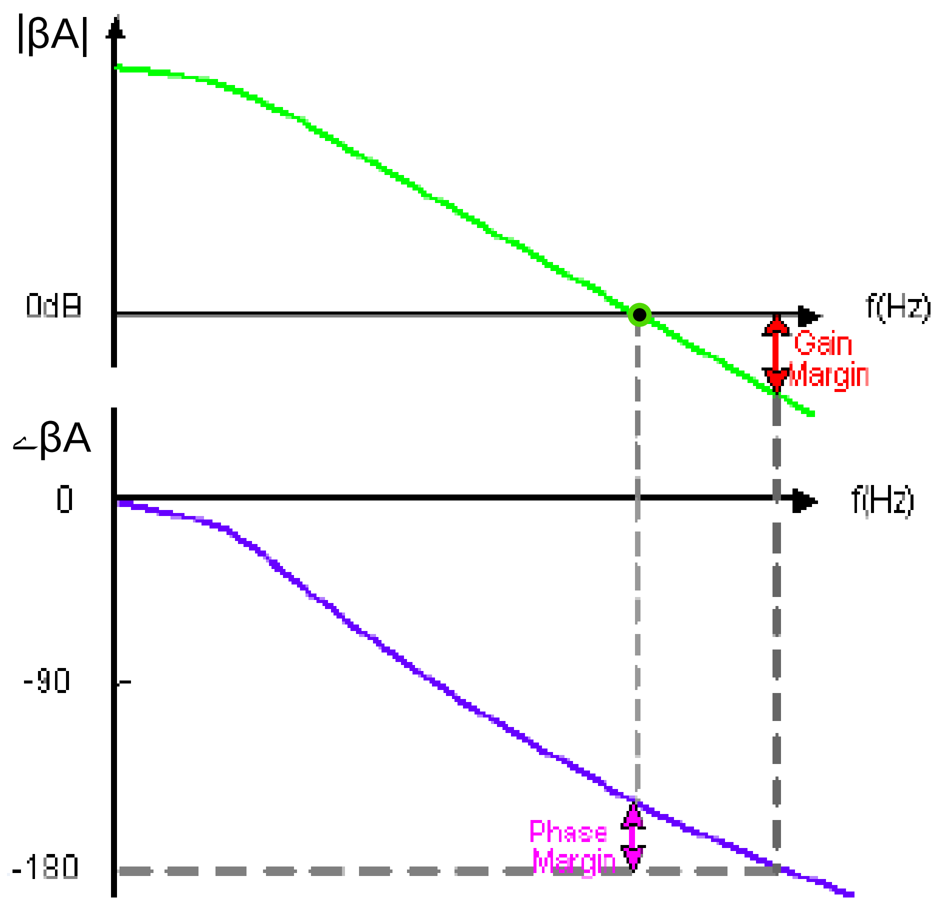
- If **$\beta A = -1$** at frequency f_0, $G = A/(1-1) = \infty$ → Instability.
  - $\beta A = -1$: $|\beta A| = 1$ and $\angle \beta A = -180^\circ$, at $f = f_0$
  - This observation leads us to the concepts "Phase Margin".

Op Amp AC Specifications

Phase Margin (PM) and Gain Margin (GM)

- **Phase Margin:**
  The phase difference between ∠βA(f_{0dB}) and -180°, where f_{0dB} is the frequency at which |βA|=1.

- **Gain Margin:**
  The difference between 0dB and |βA| where the loop gain phase is -180°.



Op Amp AC Specifications

Emphasis

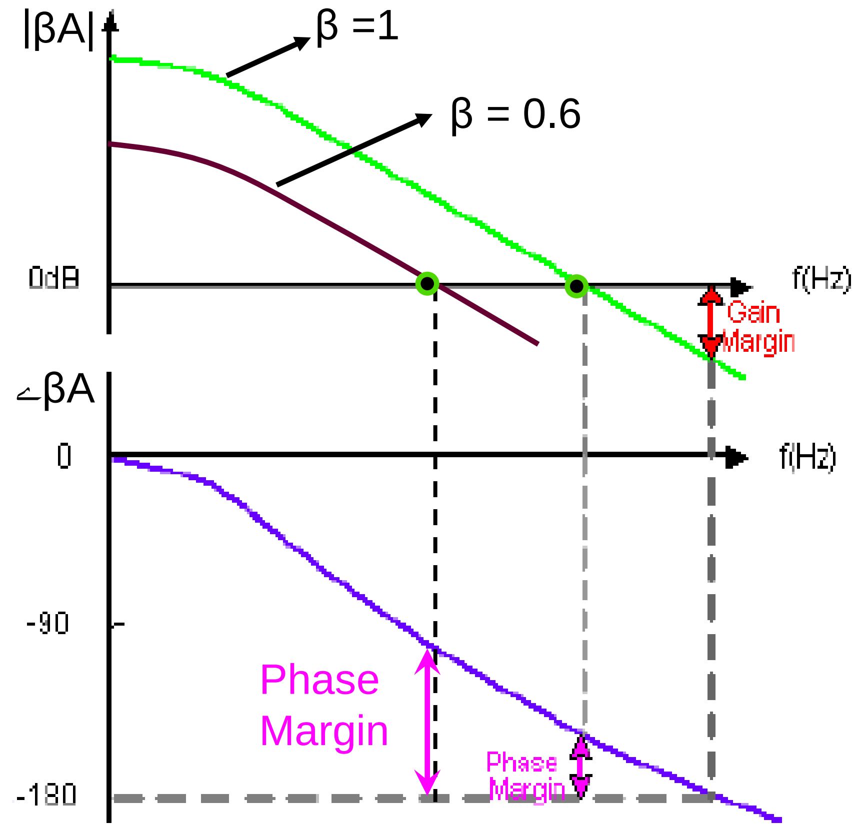
PM ≤ 0° indicates instability and oscillation.

PM > 0° indicates stability (in theory) .

– **Our data sheet specifies PM of the worst case stability. (G =1, β =1)**

➢ Recall: 0≤β≤1, when β =1, G= A/(1+βA)= A/(1+A) ≈1

➢ β<1, PM is bigger, which makes the feedback system more stable.



Op Amp AC Specifications

– **PM > 0°** indicates stability. How far from **0°** is enough?

- PM = 65° is adequate for the stability (at G=1).
- PM = 90° is more stable but it has slow time response.

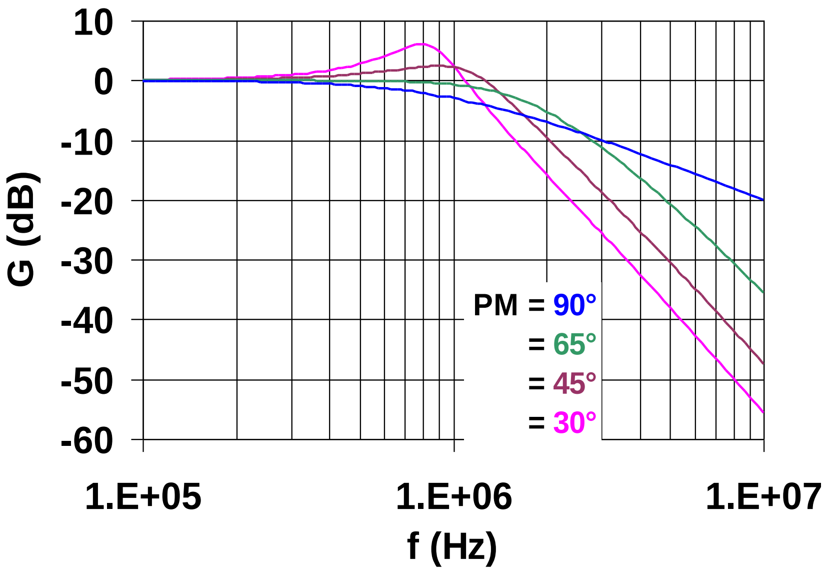


Figure: Frequency response for PM = 30°, 45°,65°, 90° at G = 1

$$\boxed{A(j\omega_1)\beta = 1 \times e^{-j\theta}} \qquad \theta = 180° - \text{phase margin}$$

$$A_f(j\omega_1) = \frac{A(j\omega_1)}{1 + A(j\omega_1)\beta} = \frac{(1/\beta)e^{-j\theta}}{1 + e^{-j\theta}}$$

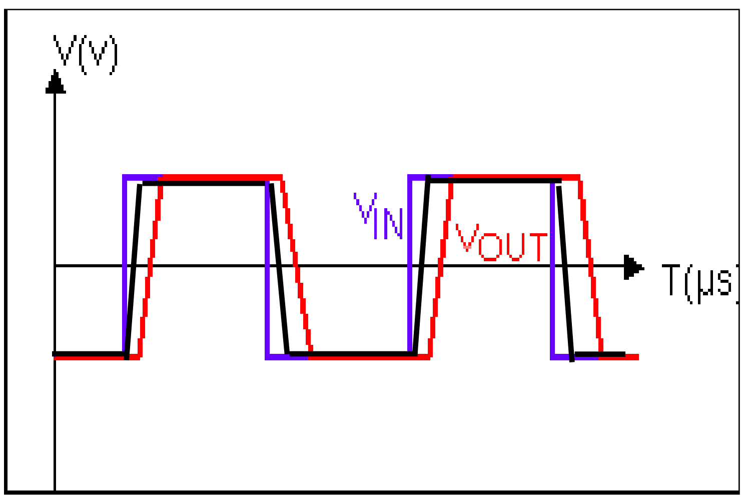
$$|A_f(j\omega_1)| = \frac{1/\beta}{|1 + e^{-j\theta}|}$$

phase margin of 45°, $\theta = 135°$ $\quad \boxed{|A_f(j\omega_1)| = 1.3\,\frac{1}{\beta}}$

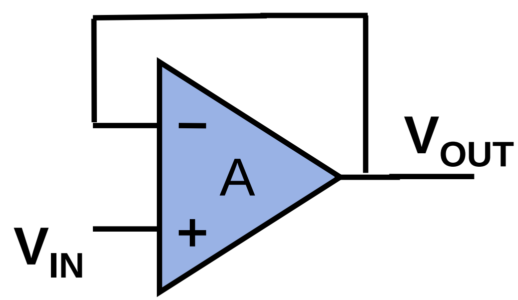
Op Amp AC Specifications-- SR

Emphasis (Slew-Rate Limiting on Output Transient Step)

- Slew Rate is the maximum rate of change at the output of an op amp. Basically says how fast the output can "follow" the input.
- The bigger the SR is, the faster the output of op amp can follow the input.



$$SR = \left.\frac{\Delta V_{OUT}}{\Delta t}\right|_{MAX}$$



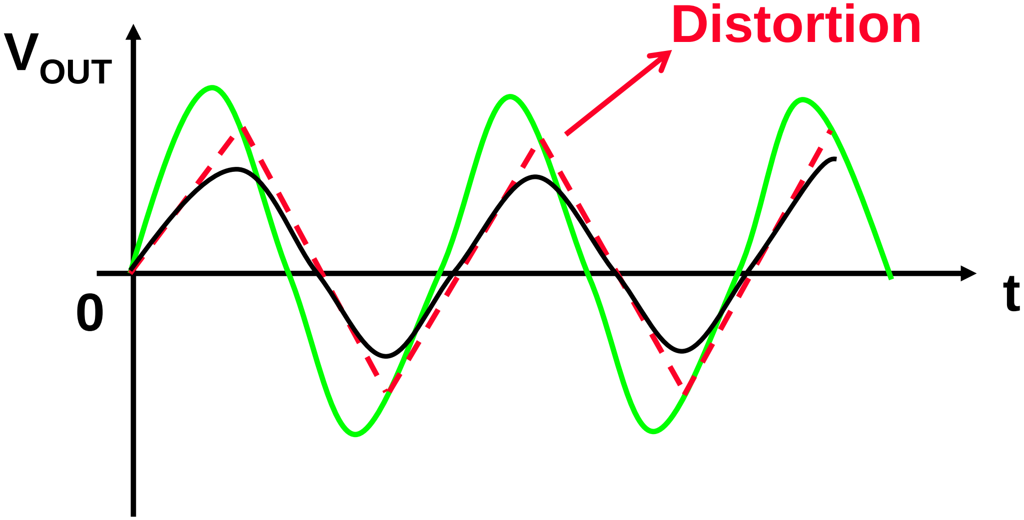
Example: MCP601 data sheet

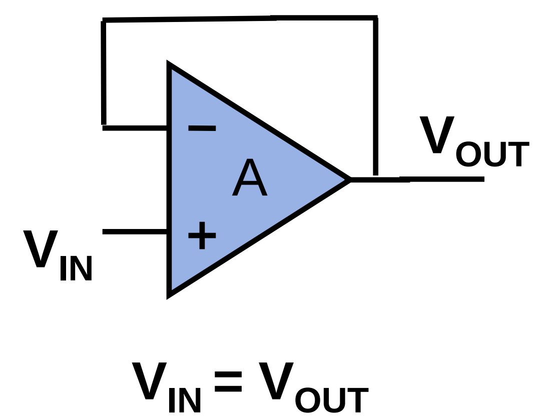
Parameters	Sym	Min	Typ	Max	Units	Conditions
Slew Rate	SR	—	2.3	—	V/µs	G = +1 V/V

Op Amp AC Specifications

Slew-Rate Limiting

- Effect of slew-rate limiting on output sine waveforms.
  - Theoretical output
  - Output when op amp is slew-rate limited
  - The fastest changing input signal without slew-rate limiting

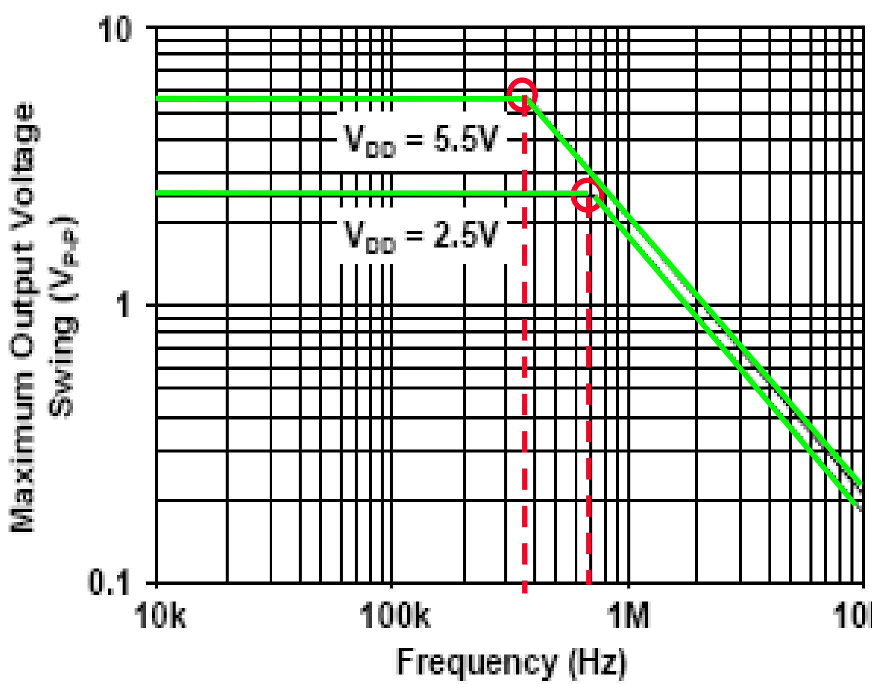




Op Amp AC Specifications

Full Power Bandwidth (FPBW)

– FPBW gives the highest frequency sine wave that will not be distorted by the slew rate limit and it is still at the maximum output voltage swing.



$$\boxed{FPBW = SR/(2\pi V_{OMAX})}$$

SR: slew rate

V_{OMAX}: maximum output voltage

$V_I = \hat{V}_i \sin \omega t$

$\omega_M V_{omax} = SR$ (Voltage follower)

$\frac{dV_o}{dt} = \frac{dV_I}{dt} = \omega \hat{V}_i \cos \omega t$

$\Rightarrow f_M = \frac{SR}{2\pi V_{omax}}$

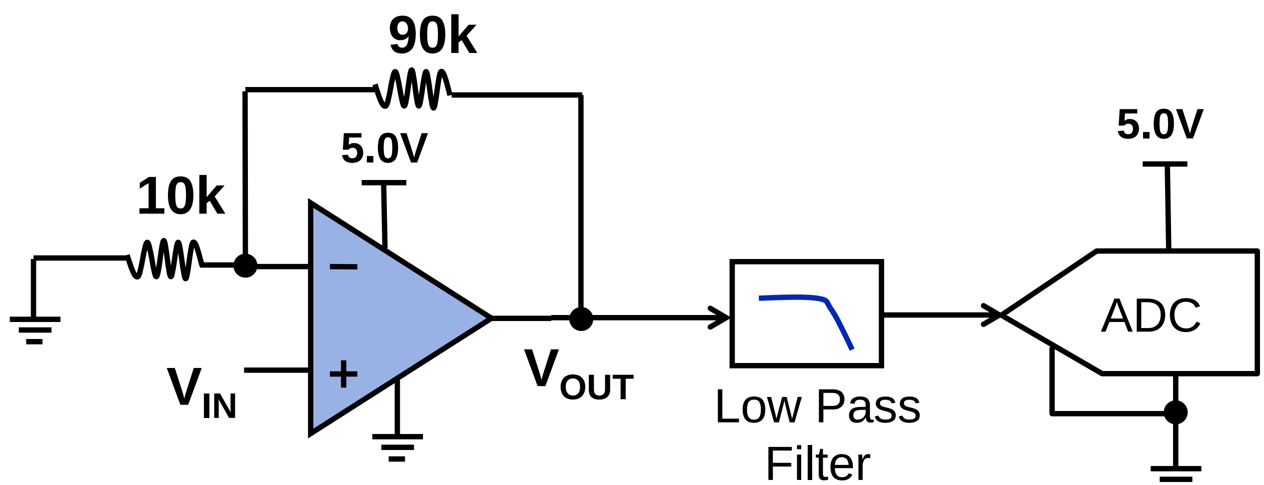
(Voltage Follower)

Speed Related Specs

- **Application Challenge**
  - FPBW is important when an amplifier drives the input of ADC which requires full dynamic range.
  - Example: FPBW = $SR/(2\pi * V_{OUT-PP})$
  - $= (0.6V/\mu s)/(2\pi * 5.0V_{P-P}) \approx 19kHz$
  - ***(Note: Small signal BW = GBWP/G_N = 1.0 MHz/10 = 100 kHz)***

Op amp:

Rail-to-rail Output
SR = 0.6 V/µs
GBWP = 1.0 MHz



Op Amp AC Specifications

CMOS製程 OP之特色.

優點: 1. 低 I_{bias}.

2. 低 I_{supply} < 1μA.

3. 易做到 Rail-to-Rail Input/Output

4. Low Noise, Small $nV/\sqrt{Hz}$.

適合 portable Application.

缺點: 1. 低 Supply 電压

2. 低 GBWP (10MHz)

3. 低 Slew Rate (5V/μs)

不適合高速放大或影像.

Audio is O.K. (~20kHz).

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Em

ent

F

0V

step

Time

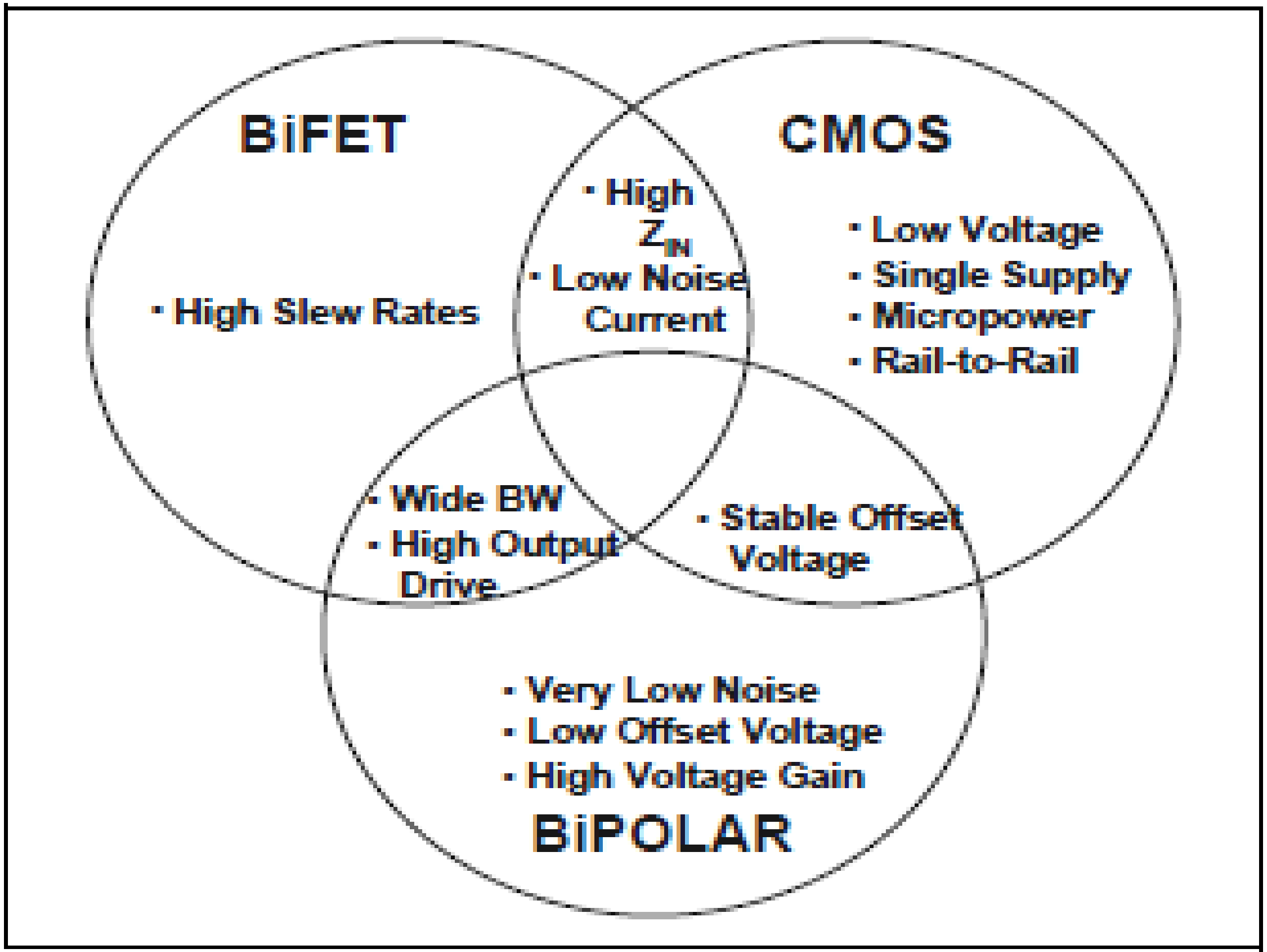
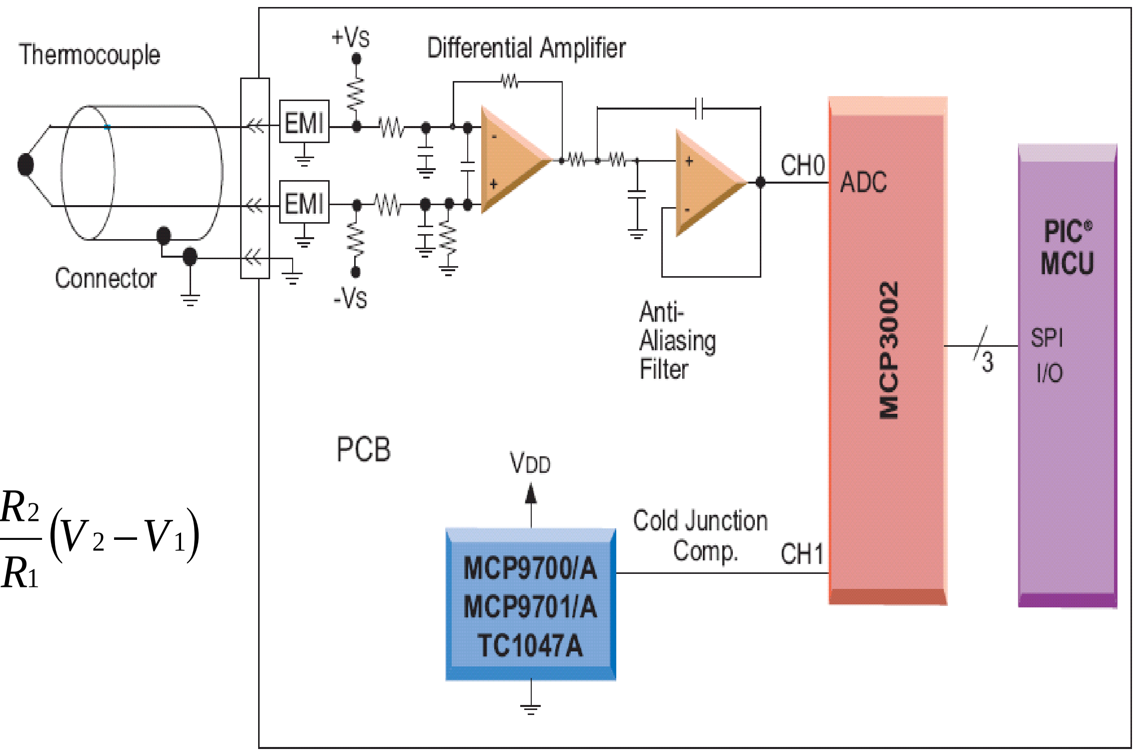


FIGURE 2: Different IC processes render different advantages for amplifiers. The choices in processes for single supply amplifiers are Bipolar, CMOS and BiFET, which is a combination of Field Effect Transistors (FET) and Bipolar transistors.

AN722_DC_OP

Example-Thermocouple Solution

- Filtered signal requires amplification
  - Thermocouple output typically ~40 µV/1˚C
  - A differential amplifier provides voltage gain and signal buffering
  - Gain may be on the order of 50x to 500x
- Critical design parameters:
  - Input offset voltage
  - Voltage offset drift
  - Input bias current



$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

Offset Voltage and Drift

- **Large offset will affect temperature measurement if not calibrated out**
  - **Thermocouple output typically ~40 µV/1˚C**
  - **Large offset limits ADC range which reduces sensing range**
- **Voltage offset drifts over temperature**
  - **Circuitry can experience wide temperature ranges**
- **Three architectures that address these issues**
  - EPROM **– Corrects input offset voltage through trimming algorithm completed at production final test**
  - mCal **– Implements onboard calibration circuit that calibrates input offset voltage at power up and by input on external pin**
  - Auto-zero **- Implements a nulling amplifier to continuously correct the input offset voltage of the main amplifier**

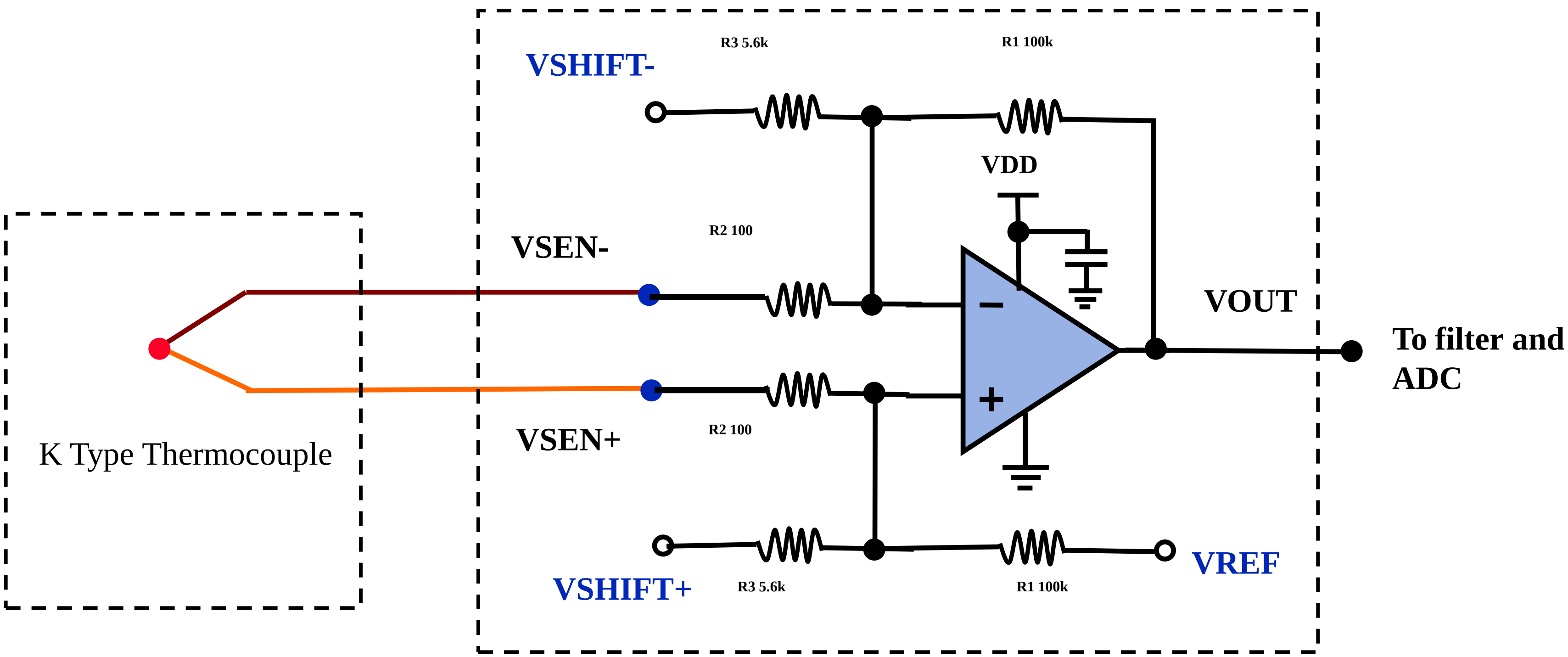
Microchip Solutions

Types	Families	Max V_{os}	Advantages (+) / Disadvantages (-)
EPROM Trim 	MCP603X, MCP605X, MCP607X	150 µV	+ Accurate initial offset + Competitive cost + Low power (0.9 µA – Ideal for portable) - Experiences Offset drift
mCal 	MCP62X, MCP65X	200 µV	+ External recalibration pin reduces drift + Accurate (initial and when recalibrated) + Very high GBWP (20-50 MHz) + User controlled recalibration - Higher current consumption
Auto-zero 	MCP6V0X	2-3 µV	+ Extremely accurate + Not subject to drift + Continuous calibration (10000/sec) + No 1/f noise - Higher cost

Thermocouple Conditioning Example

- Difference Amplifier
  - **It is implemented using the MCP6V01 auto-zeroed op amp and 0.1% tolerance resistors.**

VOUT = (R1/R2)*(VSEN+-VSEN-) + (R1/R3)*(VSHIFT+-VSHIFT-) + VREF

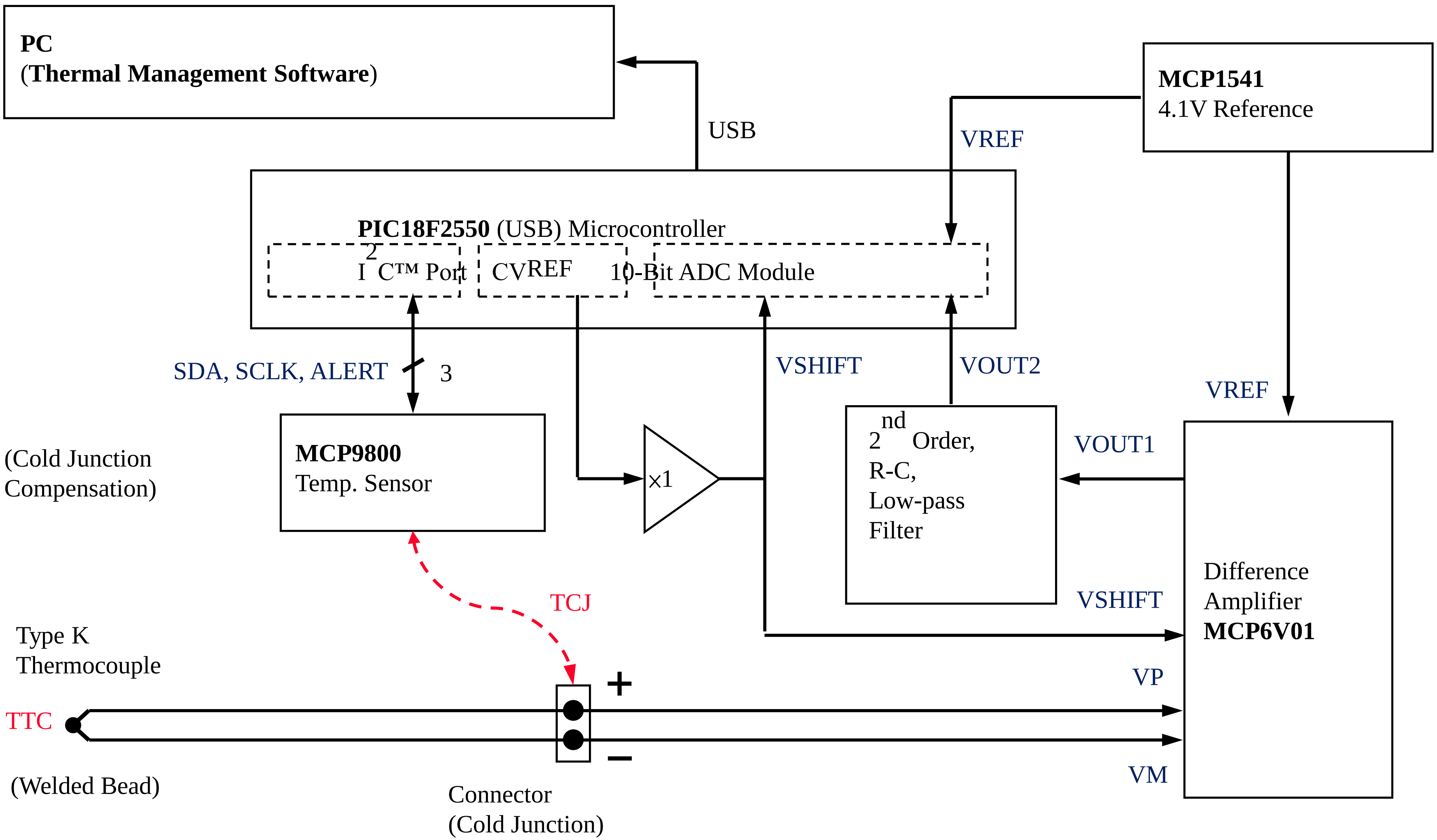


Note: Refer to the board User's Guide for details

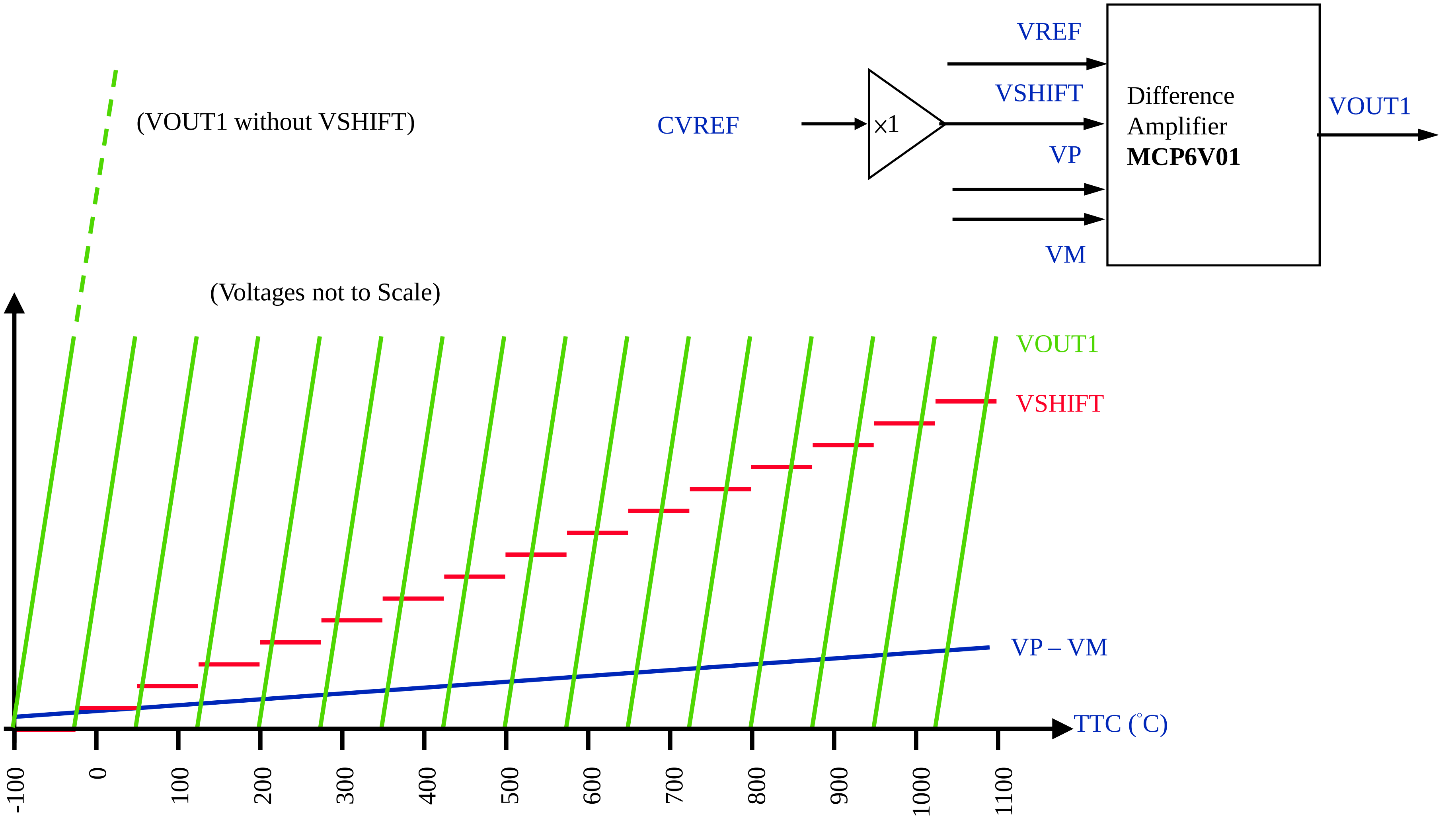
High Precision Circuits:
Thermocouple Reference Design

- **MCP6V01/2/3 & MCP6V06/7/8**
  - V_{OS} Drift ≤ ±50 nV/°C
  - V_{OS} ≤ ±2 µV
  - A_{OL}, CMRR, PSRR ≥ 130 dB
- **Reference Design Features**
  - AZ OA Provides Gain for Thermocouple Voltage
  - IC Temp Sensor for Cold Junction
  - 14-Bit Resolution, 10-Bit ADC
    - PIC® device's V_{REF} (16 levels) subdivides input ranges
    - PIC device's ADC (10-bit) converts result and calibrates PIC device's CV_{REF}
    - Automatically searches for correct CV_{REF} value

High Precision Circuits:
Thermocouple Reference Design



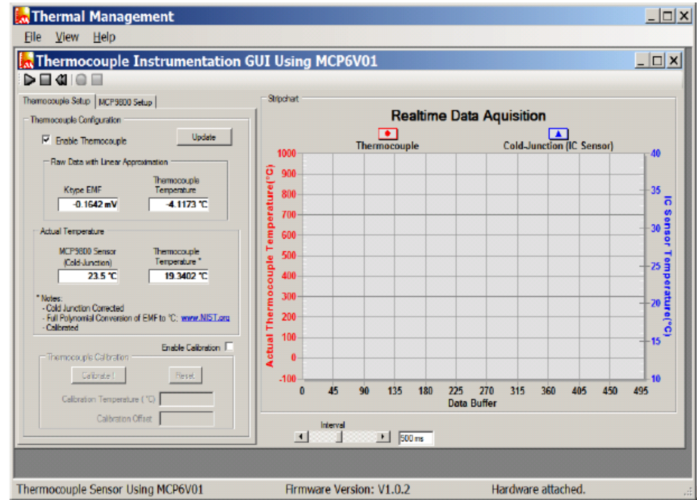
High Precision Circuits:
Thermocouple Reference Design

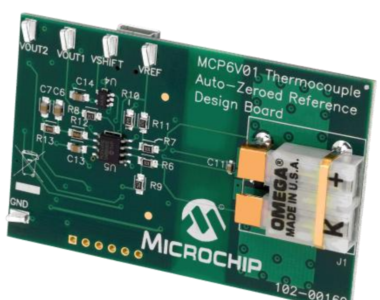


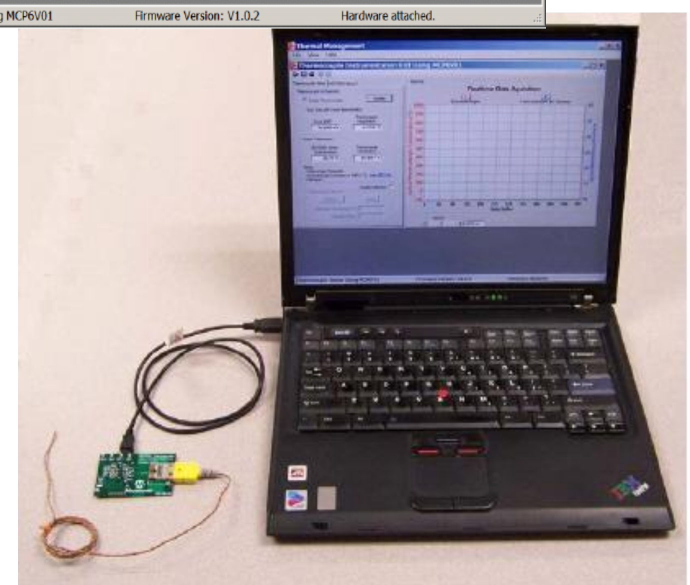
Auto-zero Thermocouple Reference Design

Features:

- Difference amplifier system for sensor conditioning
- Use the K-type thermocouple to sense temperature
- Temperature range is from -100°C to +1000°C
- MCP9800 Temp Sensor used for cold junction compensation
- USB interface to transfer data to PC
- Test points for bench work







www.microchip.com/MCP6V0X

MCP6V01RD-TCPL

Operational Amplifiers

- **GBWP < 1 MHz**
  - Precision
    - NVM
      - MCP606/7/8/9
      - MCP6031/2/3/4
      - MCP6051/2/4
      - MCP6061/2/4
    - Bipolar/NVM
      - MCP616/7/8/9
    - Zero-Drift
      - MCP6V11
      - MCP6V31
      - TC7652
    - Instrumentation
      - MCP6N11
  - General Purpose
    - MCP6441/2/4
    - MCP6041/2/3/4
    - MCP6141/2/3/4
    - MCP623x/4x
    - MCP6421
- **GBWP = 1 to 10 MHz**
  - Precision
    - NVM
      - MCP6071/2/4
    - Zero-Drift
      - MCP6V01/2/3
      - MCP6V06/7/8
      - MCP6V26/7/8
      - TC913A/B
      - TC7650
  - General Purpose
    - MCP601/2/3/4
    - MCP6L1/2/4
    - MCP6001/2/4
    - MCP6L01/2/4
    - MCP6401/2/4
    - MCP6271/2/3/4/5
    - MCP6L71/2/4
    - MCP6281/2/3/4/5
    - MCP6471
    - MCP6481
    - MCP6491
    - Low Noise
      - MCP6286
    - VDD max > 12V
      - MCP6H01/2/4
      - MCP6H71/2/4
      - MCP6H81/2/4
- **GBWP > 10MHz**
  - Precision
    - NVM
      - MCP6021/2/3/4
    - mCAL
      - MCP651/1S/2/3/4/5/9
      - MCP621/1S/2/3/4/5/9
  - General Purpose
    - MCP6291/2/3/4/5
    - MCP6L91/2/3/4/5
    - MCP631/2/3/4/5/9
    - MCP660/1/2/3/4/5/9
    - VDD max = 12V
      - MCP6H91/2/4

<< BACK

Linear
Demo & Eval Boards

High Speed Op Amps

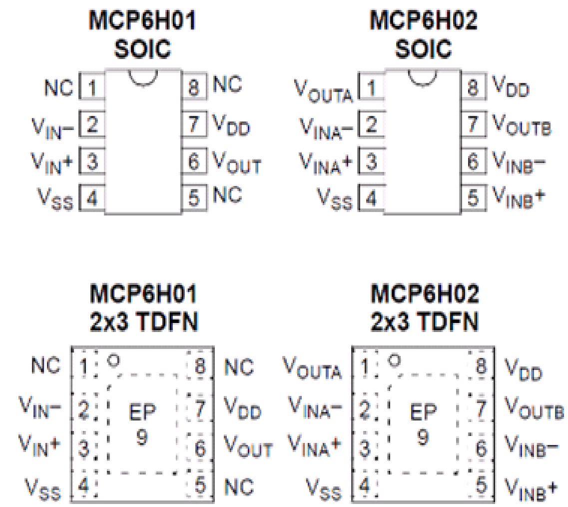
- **MCP62X/63X/65X/66X Key Specifications**
  - **I_{SC} = 70 to 100 mA (typ.)**
    - Drive heavy loads (e.g., H-bridge, Transmission Line Driver, Audio Speaker)
  - **GBWP = 20, 24, 50 and 60 MHz**
    - High speed (e.g., optical detector)
    - High gain (e.g., audio amplifier)
  - **e_{ni} = 13, 10, 7.5 and 6.8 nV/√Hz**
    - Very low white noise for CMOS (e.g., sensor amplifier)

MCP6H01/2

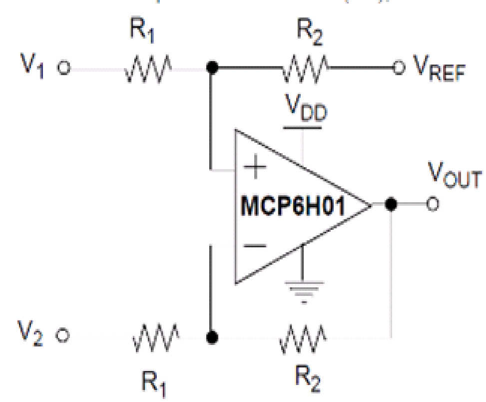
Online Datasheet

Features

- Gain Bandwidth Product: 1.2 MHz (typ.)
- Low Power and Supply Voltages:
  - I_Q: 135 μA/amplifier (typ.)
  - Wide Supply Voltage Range: 3.5V to 16V
- High DC Precision:
  - Input Offset Voltage: $\pm$3.5 mV (max.)
  - V_{OS} Drift: $\pm$2.5 uV/°C (max.)
  - PSRR: 87 dB (min.)
  - CMRR:78 dB (min.)
- Rail-to-Rail Output
- Unity Gain Stable
- Available in Single and Dual
- Extended Temperature Range: -40°C to 125°C



* Includes Exposed Thermal Pad (EP); see Table 3-1.

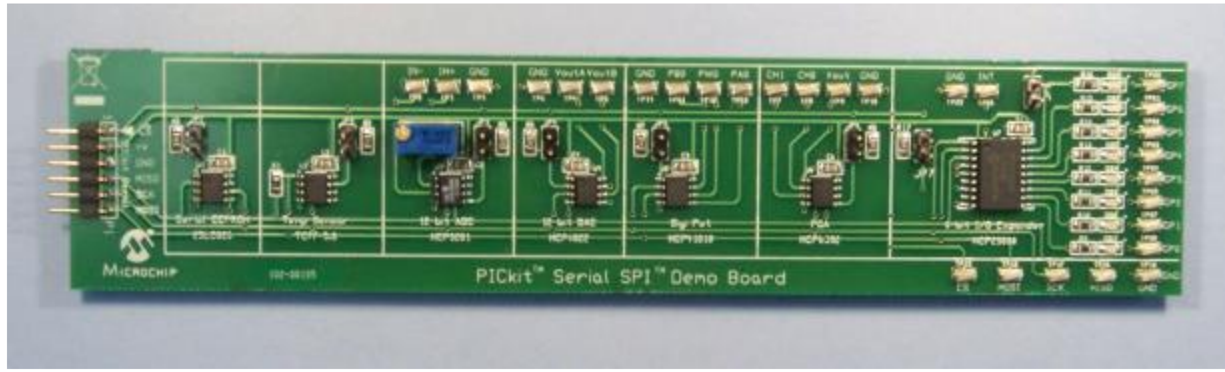


Difference Amplifier

<< BACK

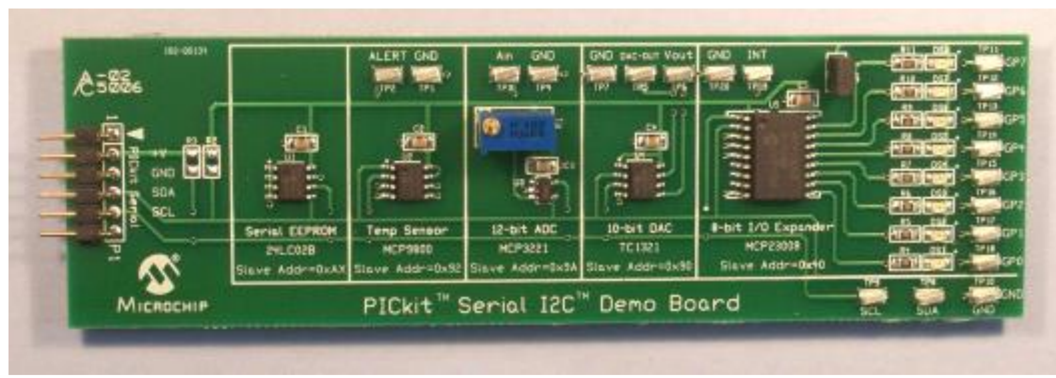
The Low Power Analog Solution

Reference Tools



SPI Demo Board

PICKit Serial Analyzer



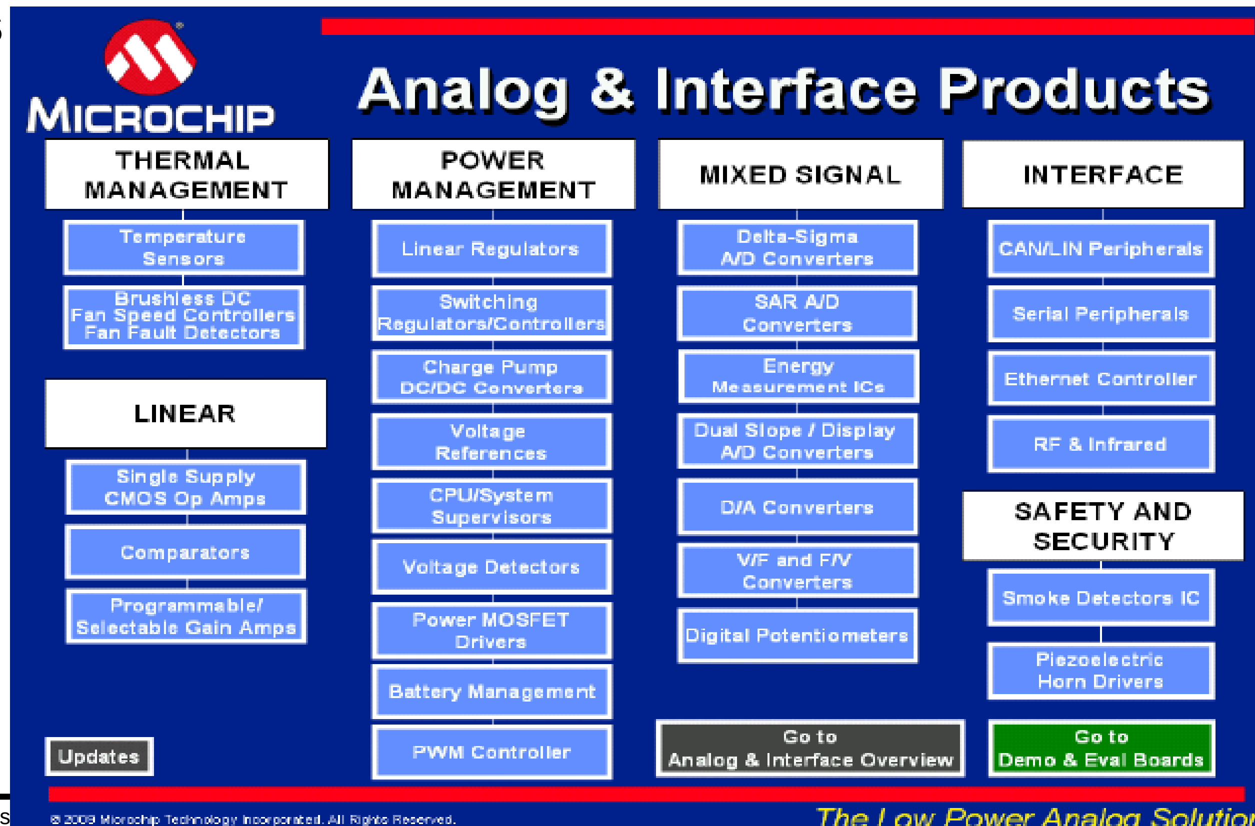
I2C Demo Board

Product Selector Tools

- **Treelink** www.microchip.com/treelink

(2014-MAR, All New AIPD Inside, R&E)

- **Gives brief overview of Microchip's Analog & Interface products**
- **View products of interest by clicking on dynamic links on the product trees**



Stand-Alone Analog and Interface Solutions

- **Analog and Interface Solutions Brochure**

  DS20001060AD➔Download from WEBSITE

- **Provides quick overview of critical parameters, features and packages**

THERMAL MANAGEMENT

Part #	Typical Accuracy (°C)	Maximum Accuracy @ 25°C (°C)	Maximum Temperature Range (°C)	Vcc Range (V)	Maximum Supply Current (µA)	Features	Packages
THERMAL MANAGEMENT PRODUCTS – Temperature Sensors							
Logic Output Temperature Sensors							
TC6501	±0.5	±3	-55 to +125	+2.7 to +5.5	40	Cross to MAX6501, Open-drain	5-pin SOT-23A
TC6502	±0.5	±3	-55 to +125	+2.7 to +5.5	40	Cross to MAX6502, Push-pull	5-pin SOT-23A
TC6503	±0.5	±3	-55 to +125	+2.7 to +5.5	40	Cross to MAX6503, Open-drain	5-pin SOT-23A
TC6504	±0.5	±3	-55 to +125	+2.7 to +5.5	40	Cross to MAX6504, Push-pull	5-pin SOT-23A
TC620	±1	±3	-40 to +125	+4.5 to +18	400	Two resistor-programmable trip points	8-pin PDIP, 8-pin SOIC
TC621	Note 1	Note 1	-40 to +85	+4.5 to +18	400	Requires external thermistor, resistor-programmable trip points	8-pin PDIP, 8-pin SOIC
TC622	±1	±5	-40 to +125	+4.5 to +18	600	Dual output, TO-220 for heat sink mounting, resistor-programmable trip points	8-pin PDIP, 8-pin SOIC, 5-pin TO-220
TC623	±1	±3	-40 to +125	+2.7 to +4.5	250	Two resistor-programmable trip points	8-pin PDIP, 8-pin SOIC
TC624	±1	±5	-40 to +125	+2.7 to +4.5	300	Dual output, resistor-programmable trip points	8-pin PDIP, 8-pin SOIC
Voltage Output Temperature Sensors							
MCP9700	±1	±4	-40 to +125	+2.3 to +5.5	12	Linear Active Thermistor® IC, Temperature slope: 10 mV/°C	3-pin TO-92, 5-pin SC-70, 3-pin SOT-23
MCP9701	±1	±4	-10 to +125	+3.1 to +5.5	12	Linear Active Thermistor® IC, Temperature slope: 19.53 mV/°C, cross to MAX6512	3-pin TO-92, 5-pin SC-70, 3-pin SOT-23
MCP9700A	±1	±2	-40 to +125	+2.3 to +5.5	12	Linear Active Thermistor® IC, Temperature slope: 10 mV/°C	3-pin TO-92, 5-pin SC-70, 3-pin SOT-23
MCP9701A	±1	±2	-40 to +125	+3.1 to +5.5	12	Linear Active Thermistor® IC, Temperature slope: 19.53 mV/°C, cross to MAX6512	3-pin TO-92, 5-pin SC-70, 3-pin SOT-23
TC1046	±0.5	±2	-40 to +125	+2.7 to +4.4	60	High precision temperature-to-voltage converter, 6.25 mV/°C	3-pin SOT-23B
TC1047	±0.5	±2	-40 to +125	+2.7 to +4.4	60	High precision temperature-to-voltage converter, 10 mV/°C	3-pin SOT-23B
TC1047A	±0.5	±2	-40 to +125	+2.5 to +5.5	60	High precision temperature-to-voltage converter, 10 mV/°C	3-pin SOT-23B
Serial Output Temperature Sensors							
MCP9800	±0.5	±1	-55 to +125	+2.7 to +5.5	400	SMbus/I²C™ compatible interface, 0.0625°C to 0.5°C adj. resolution, power-saving one-shot temperature measurement	5-pin SOT-23
MCP9801	±0.5	±1	-55 to +125	+2.7 to +5.5	400	SMbus/I²C™ compatible interface, 0.0625°C to 0.5°C adj. resolution, power-saving one-shot temperature measurement, multi-drop capability	8-pin MSOP, 8-pin SOIC
MCP9802	±0.5	±1	-55 to +125	+2.7 to +5.5	400	SMbus/I²C™ compatible interface with time out, 0.0625°C to 0.5°C adj. resolution, power-saving one-shot temperature measurement	5-pin SOT-23
MCP9803	±0.5	±1	-55 to +125	+2.7 to +5.5	400	SMbus/I²C™ compatible interface with time out, 0.0625°C to 0.5°C adj. resolution, power-saving one-shot temperature measurement, multi-drop capability	8-pin MSOP, 8-pin SOIC
MCP9805	±0.5	±1[2]	-20 to +125	+3.0 to +3.6	400	JEDEC compatible register set, SMbus/I²C™ compatible interface, programmable, shut-down modes and EVENT output	8-pin TSSOP, 8-pin 2x3 DFN
MCP98242	±0.5	±1[2]	-20 to +125	+3.0 to +3.6	400	Same temperature sensor as MCP9805 plus integrated DDR2 Serial Presence Detect EEPROM	8-pin TSSOP, 8-pin 2x3 DFN
TC77	±0.5	±1	-55 to +125	+2.7 to +5.5	400	SPI compatible interface, 0.0625°C temperature resolution	5-pin SOT-23A, 8-pin SOIC
TC72	±0.5	±1	-55 to +125	+2.65 to +5.5	400	SPI compatible interface, power-saving one-shot temperature measurement; 0.25°C temperature resolution	8-pin MSOP, 8-pin 3x3 DFN
TC74	±0.5	±2	-40 to +125	+2.7 to +5.5	350	SMbus/I²C™ compatible interface, 1°C temperature resolution	5-pin SOT-23A, 5-pin TO-220

Note 1: These devices use an external temperature sensor. Accuracy of the total solution is a function of the accuracy of the external sensor.
2: Maximum accuracy measured at 85°C.

Analog and Interface Solutions 4

Take a Break

Treelink for AIPD Introduction

1. Product Portfolio
2. Demo Board
3. Company profile

Op Amp

Application Circuits

Op Amp Application Circuits

Applications

- Inverting Amplifier / Non-inverting Amplifier / Voltage Follower / Difference Amplifier
- Instrumentation Amplifier
- Summing Amplifier
- Current to Voltage Amplifier
- Voltage to Current Amplifier
- Comparator
- Electronic Filters
- Others

Op Amp Application Circuits

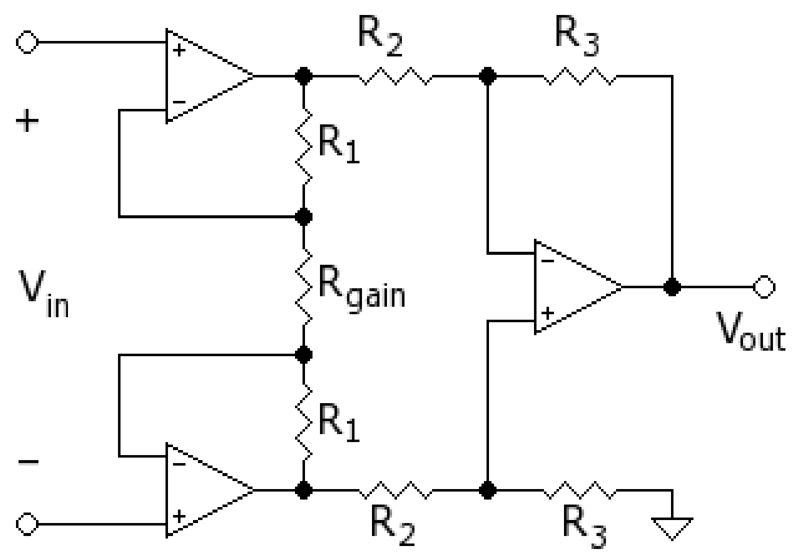
Instrumentation Amplifier (MCP6N11: New)

– It is widely used in the very accurate, low noise measurements because of the following properties:

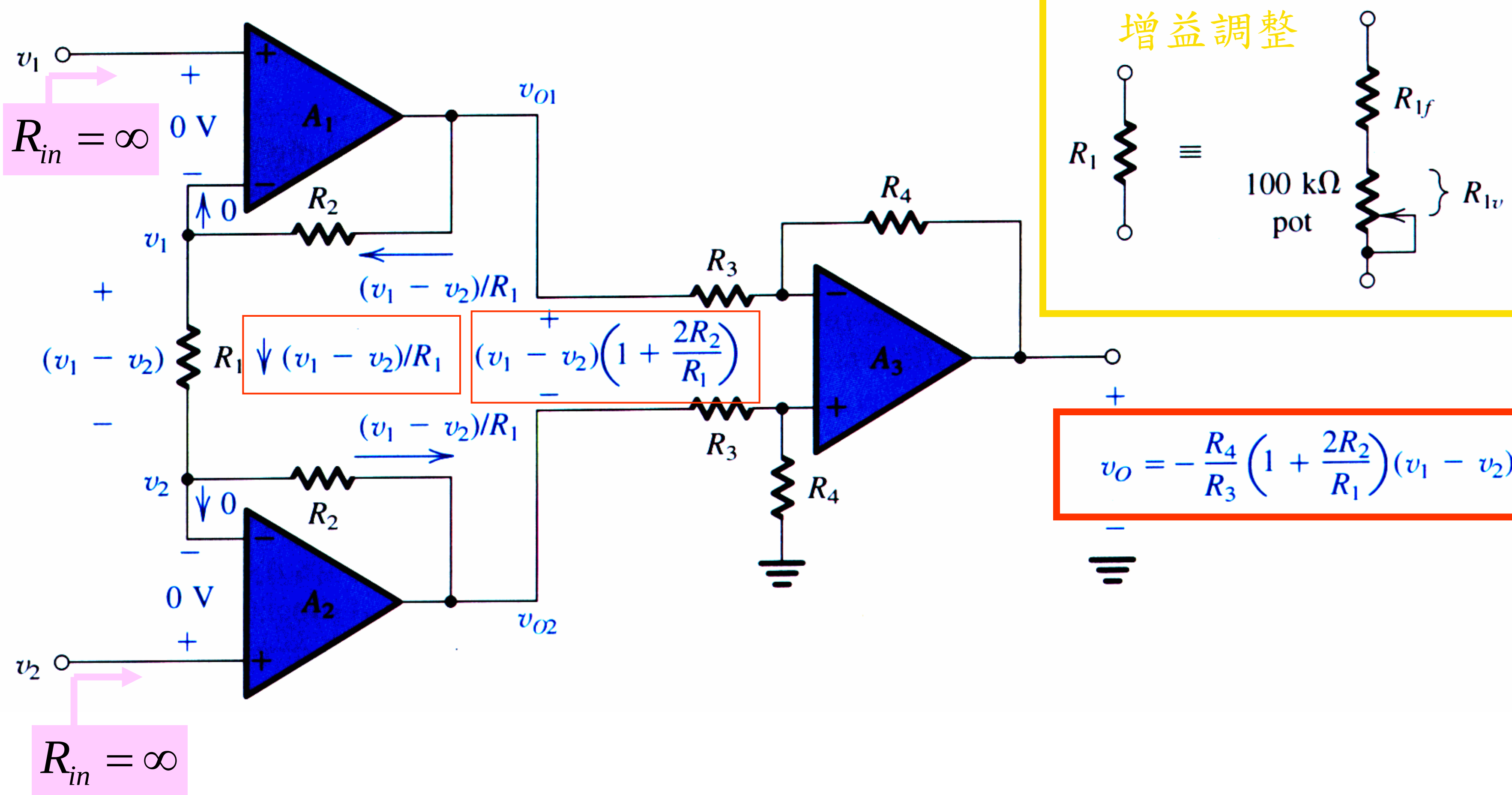
- **Very high input impedance**
- **High common-mode rejection ratio**
- **Low DC offset**

It is made by adding a non-inverting buffer to each input of the difference amplifier.

$$V_{OUT}/V_{IN} = (1+2R_1/R_{gain})(R_3/R_2)$$



儀器放大器（instrumentation amplifier)



$$v_O = -\frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)(v_1 - v_2)$$

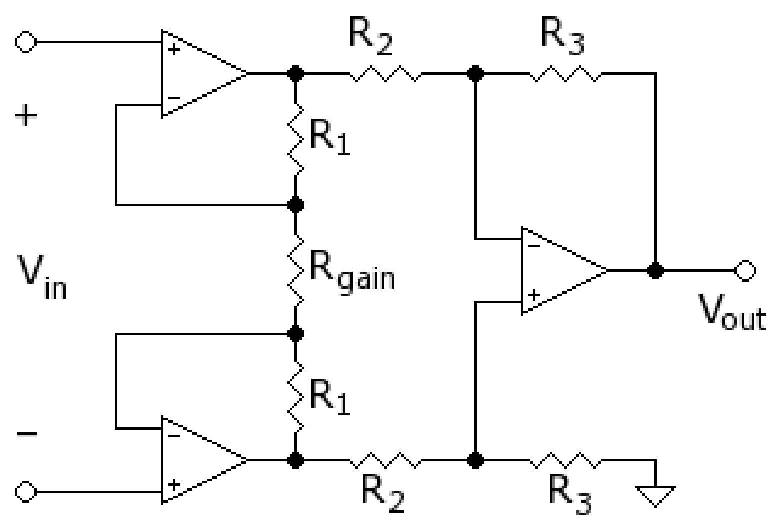
Op Amp Application Circuits

Exercise #22

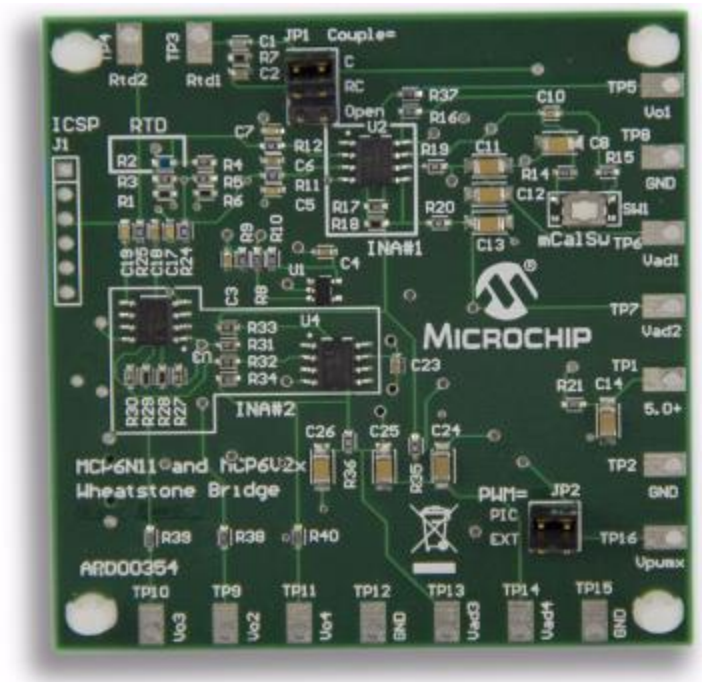
- The instrumentation amplifier has a differential gain, variable in the range 1 to 50, the second stage for a gain of 0.5, $R_1 = 50k\Omega$. Give the value range of variable resistor R_{gain}. [**Recall: $G = V_{OUT}/V_{IN} = (1+2R_1/R_{gain})(R_3/R_2)$**]

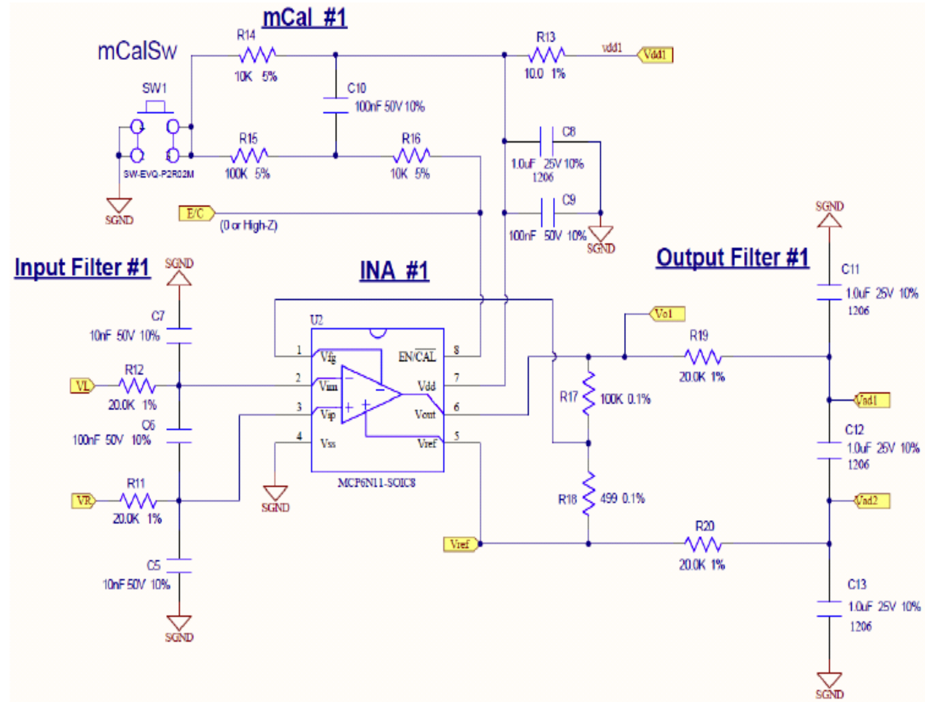
Solution #22

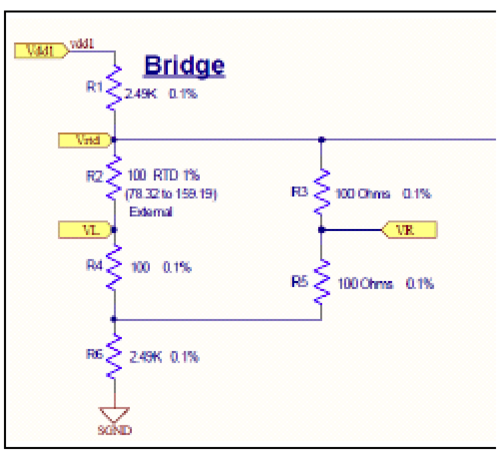
- $G = (1+2R_1/R_{gain})(R_3/R_2)$
  $= (1+100k\Omega/R_{gain})(0.5)$
- When $G = 1$, $R_{gain} = 100k\Omega$
  When $G = 50$, $R_{gain} \approx 1k\Omega$



MCP6N11 v.s. MCP6V0X Demo Board







$$G_{DM} = 1 + R_F / R_G$$

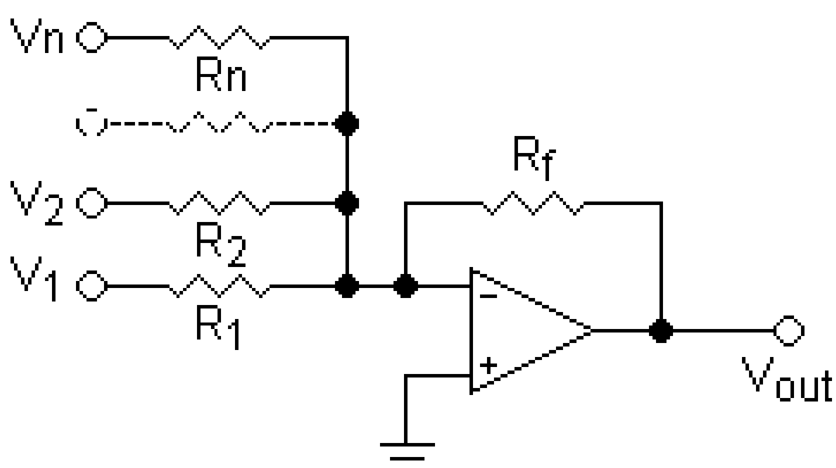
$$V_{OUT} = V_{CNT}$$

$$V_M = V_{REF} + G_{DM}(1 + g_E)V_E$$

Op Amp Application Circuits

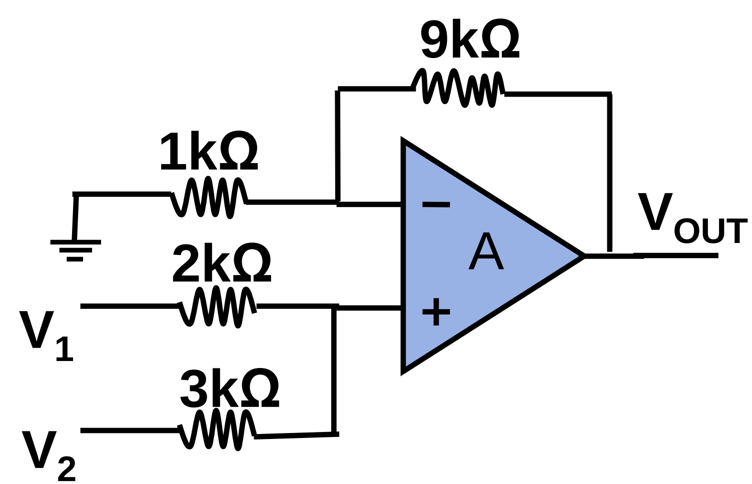
Summing Amplifier (Inverting/Non-Inverting)

– The output voltage is a weighted sum of the input signals V_1, V_2 , ……, V_n



$$V_{out} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \right)$$

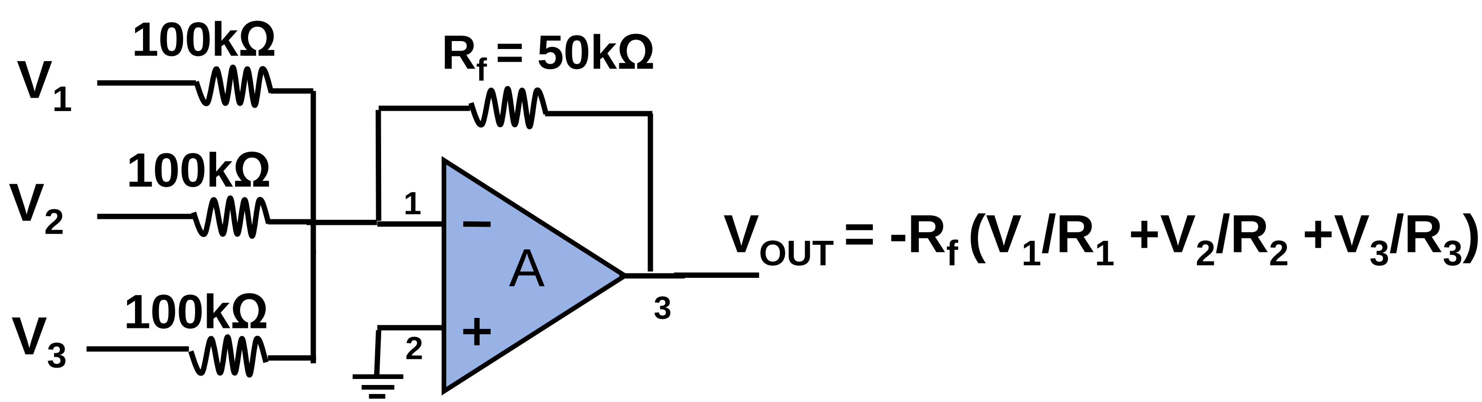
Hint: Superposition Principle
Let V1 = 0, calculate VO1
Let V2 = 0, calculate VO2
Finally, VOUT = VO1 + VO2



Op Amp Application Circuits

Exercise #23

- An inverting summing amplifier has three inputs using 100kΩ resistors and a feedback resistor of 50kΩ.
- Express V_{OUT} in terms of V_1, V_2, V_3.
- If $V_1 = V_2 = 2V$ and $V_3 = -1V$, what is V_{OUT} ?



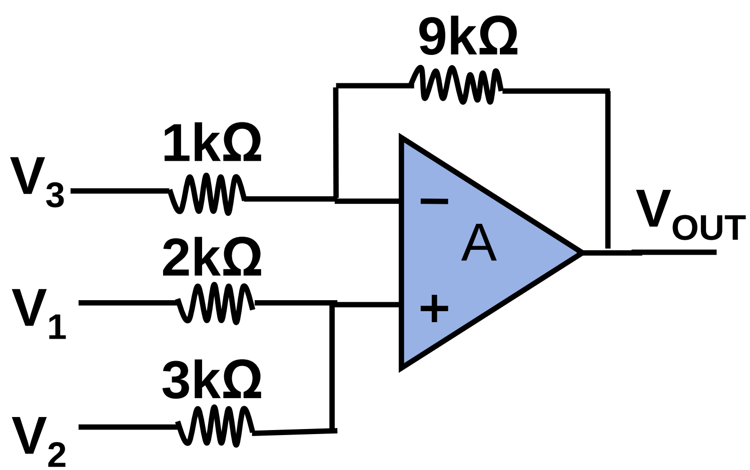
Solution #23

- $V_{OUT} = -50*(V_1/100 + V_2/100 + V_3/100) = -1.5V$

Op Amp Application Circuits

Exercise #24

- If the 1kΩ resistor is disconnected from ground and connected to a third signal source V_3, please use superposition to determine V_{OUT} in terms of V_1, V_2, and V_3.

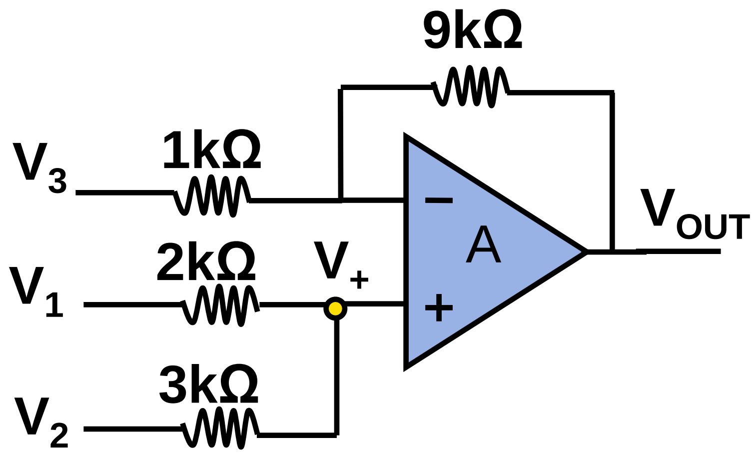


Hint: Superposition Principle

Op Amp Application Circuits

Solution #24

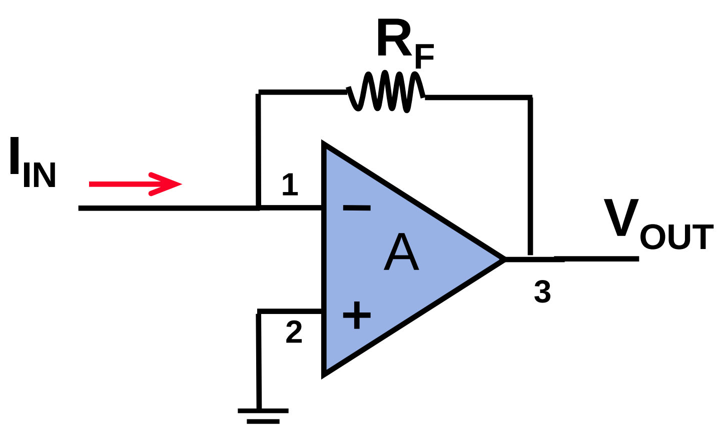
- For V_3, let $V_1 = 0$, $V_2 = 0 \rightarrow V_{O3} = -(9k/1k)*V_3 = -9V_3$
  From Exercise #23, we already got
  For $V_1 \rightarrow V_{O1} = 6V_1$; For $V_2 \rightarrow V_{O2} = 4V_2$
- Finally, $V_{OUT} = V_{O1}+V_{O2}+V_{O3} = 6V_1 + 4V_2 - 9V_3$



Op Amp Application Circuits

Current to Voltage Amplifier (Transimpedance Amplifier)

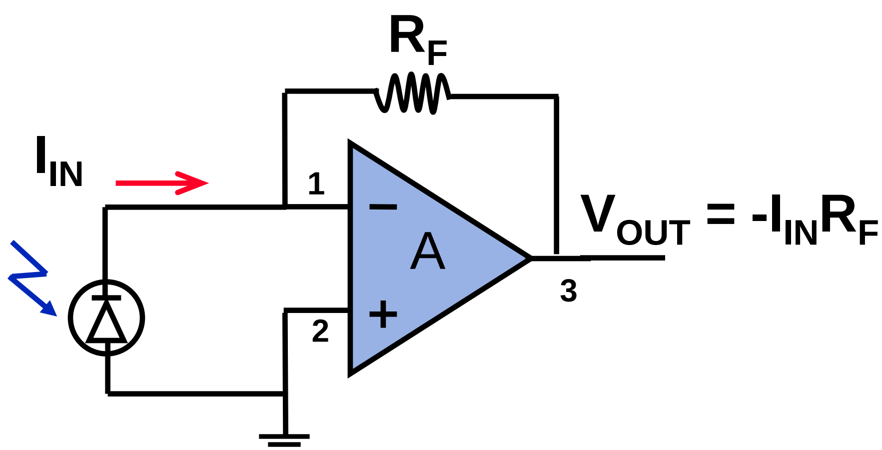
- A circuit for converting small current signals to a more easily measured proportional voltage signals.
- I_{IN} must flow through R_F and the output voltage is expressed by $V_{OUT} = -I_{IN}R_F$.



Op Amp Application Circuits

Example: Photodiode Light Detector

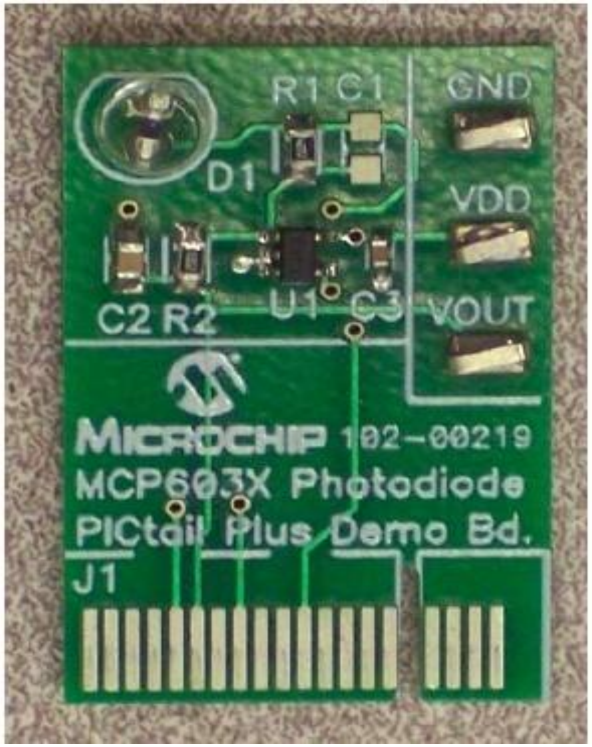
- This light detector is a current-to-voltage converter.
  - The generated photocurrent is proportional to incident light.
  - $V_{OUT} = -I_{IN}R_F$
  - **V_{OUT} is proportional to the incident light.**



The value of R_F should be chosen to ensure V_{OUT} swings within the maximum output voltage dynamic range.

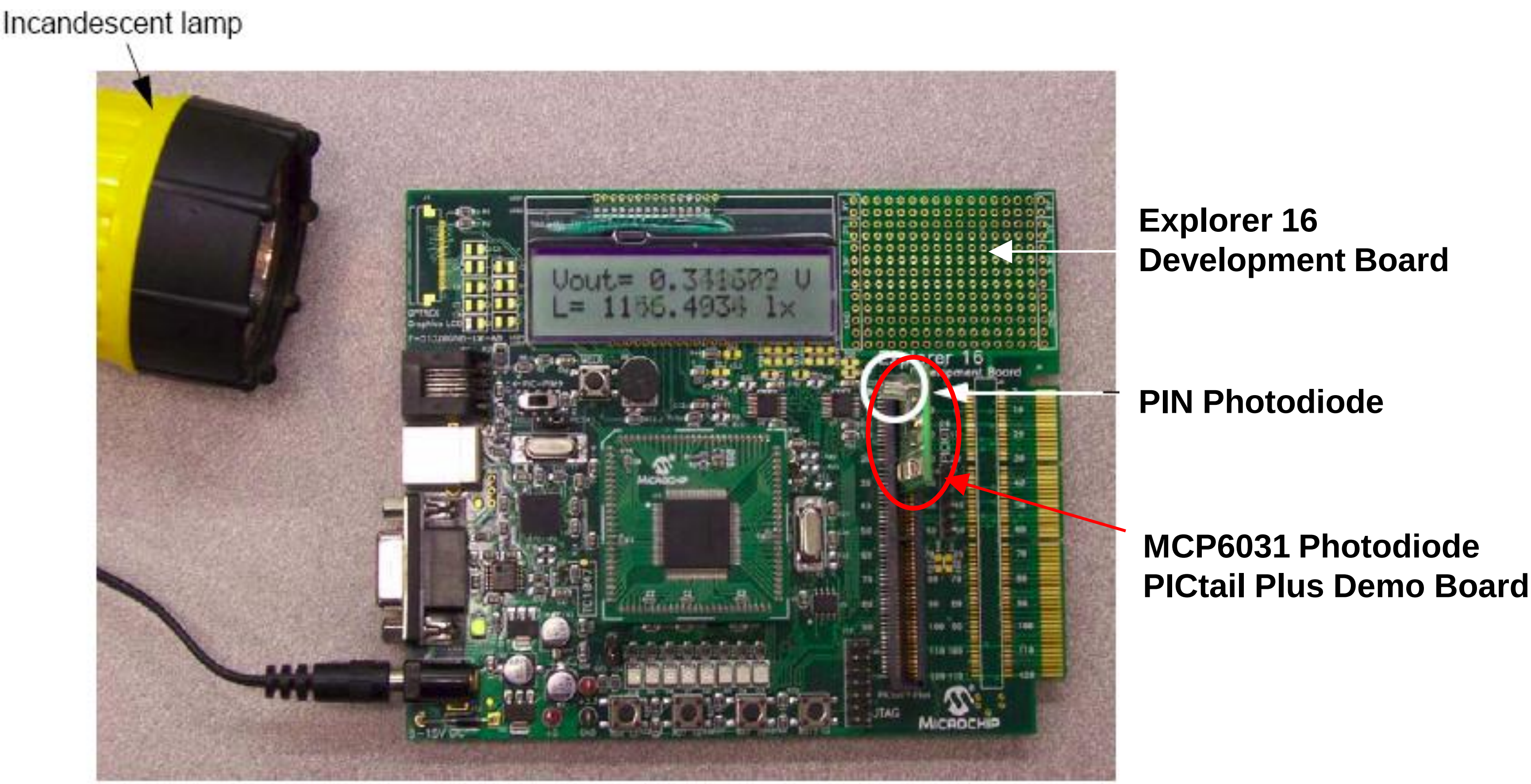
Technical Support

- **Documentation links**
  - User's Guide: MCP6031 Photodiode PICtail Plus Demo Board User's Guide
  - Product Datasheet: MCP6031
  - Application Note: AN951
  - Product Selection Tools



Board Operation

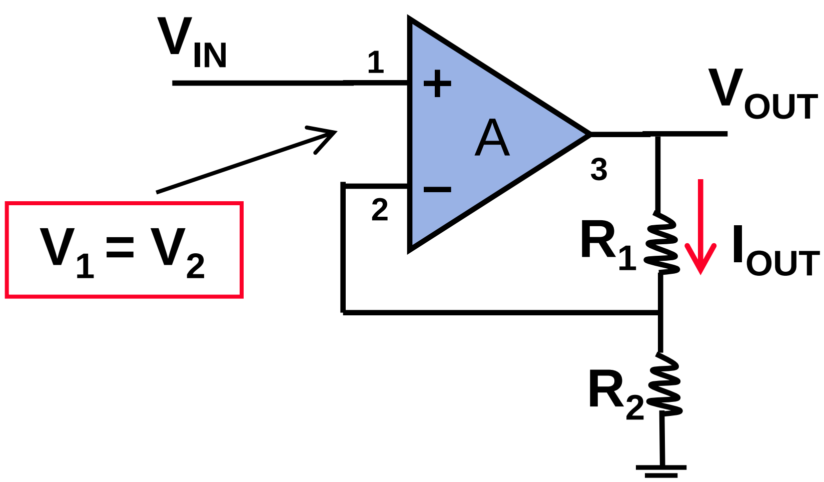
- **The figure shows data taken near an incandescent lamp powered by a battery**



Op Amp Application Circuits

Voltage to Current Amplifier

- The current output through the load resistor is proportional to the input voltage.
- $I_{OUT} = V_{IN}/R_2$, which is independent of R_1.

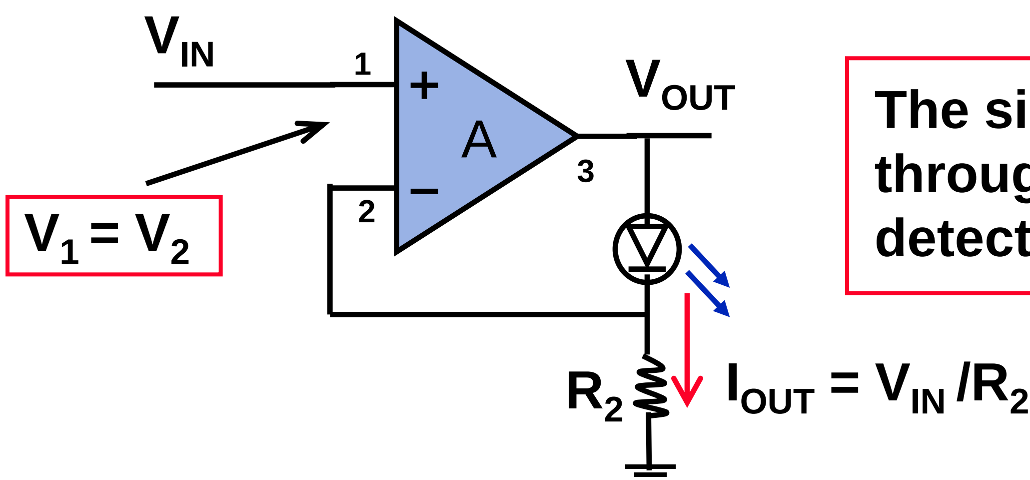


R_1 is the load and the current through it is the desired output signal.

Op Amp Application Circuits

Example: Light Emitting Diode (LED) Modulator

- The light output from an LED: Linearly proportional to the current (I_{OUT}) through the diode
- $I_{OUT} = V_{IN}/R_2$
- **The light level is proportional to input signal (V_{OUT}).**



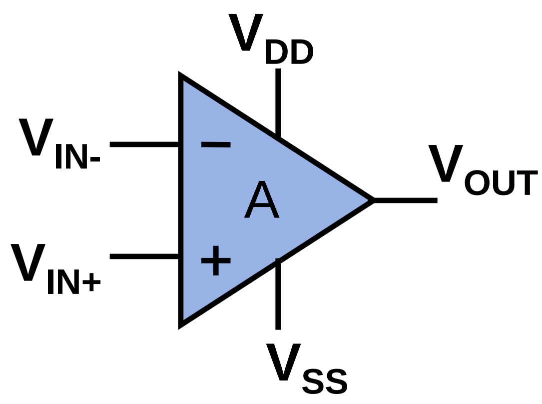
The signal can then be send through a fiber optic cable and detected on the other end.

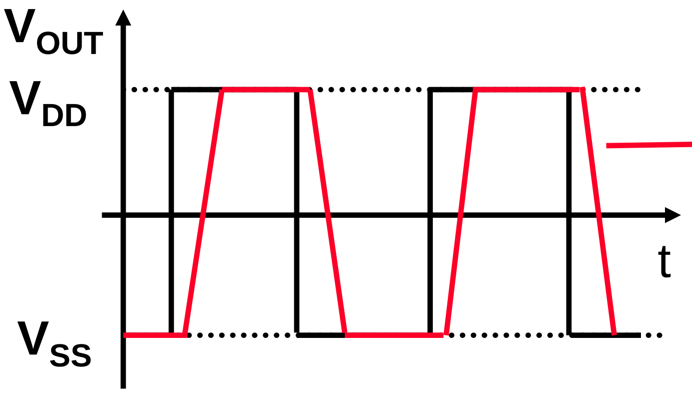
Op Amp Application Circuits

Comparator

– A standard op amp can be used as a comparator in open loop mode.

- $V_{OUT} = V_{DD}$ when $V_{IN+} > V_{IN-}$
- $V_{OUT} = V_{SS}$ when $V_{IN+} < V_{IN-}$



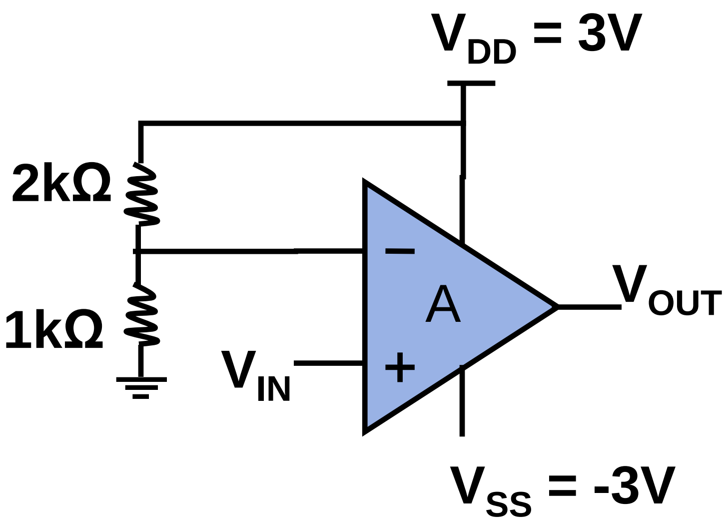


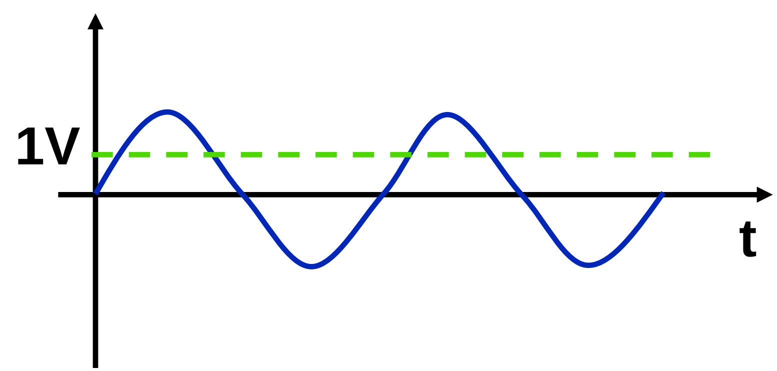
The switching time between V_{SS} and V_{DD} is limited by op amp slew rate. (Propagation Delay)

Op Amp Application Circuits

Exercise #25

- Level detector: another name for a comparator used to compare an input voltage to a fixed dc reference voltage.
  - For V_{IN} = 2V and 0.5V, what is V_{OUT} respectively?
  - If V_{IN} is a sine wave, what is the wave form of V_{OUT} ?

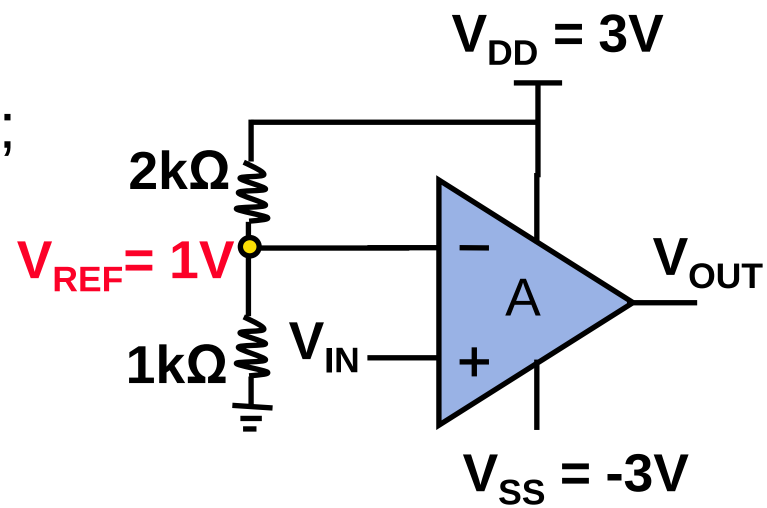




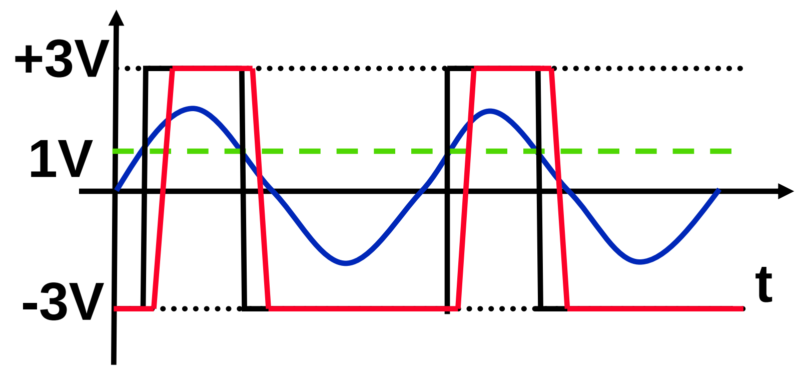
Op Amp Application Circuits

Solution #25

- V_{ref} = [3V/(2kΩ+1kΩ)]*1kΩ = 1V;
  V_{IN} =2V > V_{ref} =1V, V_{OUT} = 3V;
  V_{IN} =0.5V < V_{ref} =1V, V_{OUT} = -3V
- V_{IN} is a sine wave, V_{OUT}?



I. Slew rate limits switching time.
II. Open loop gain BW limits the sine wave frequency.
Recall: Open loop gain BW drops very fast with frequency.



- **Application: Pulse-width modulator.** That is, the DC reference voltage controls, or modulates the pulse width of the output voltage.

Comparators

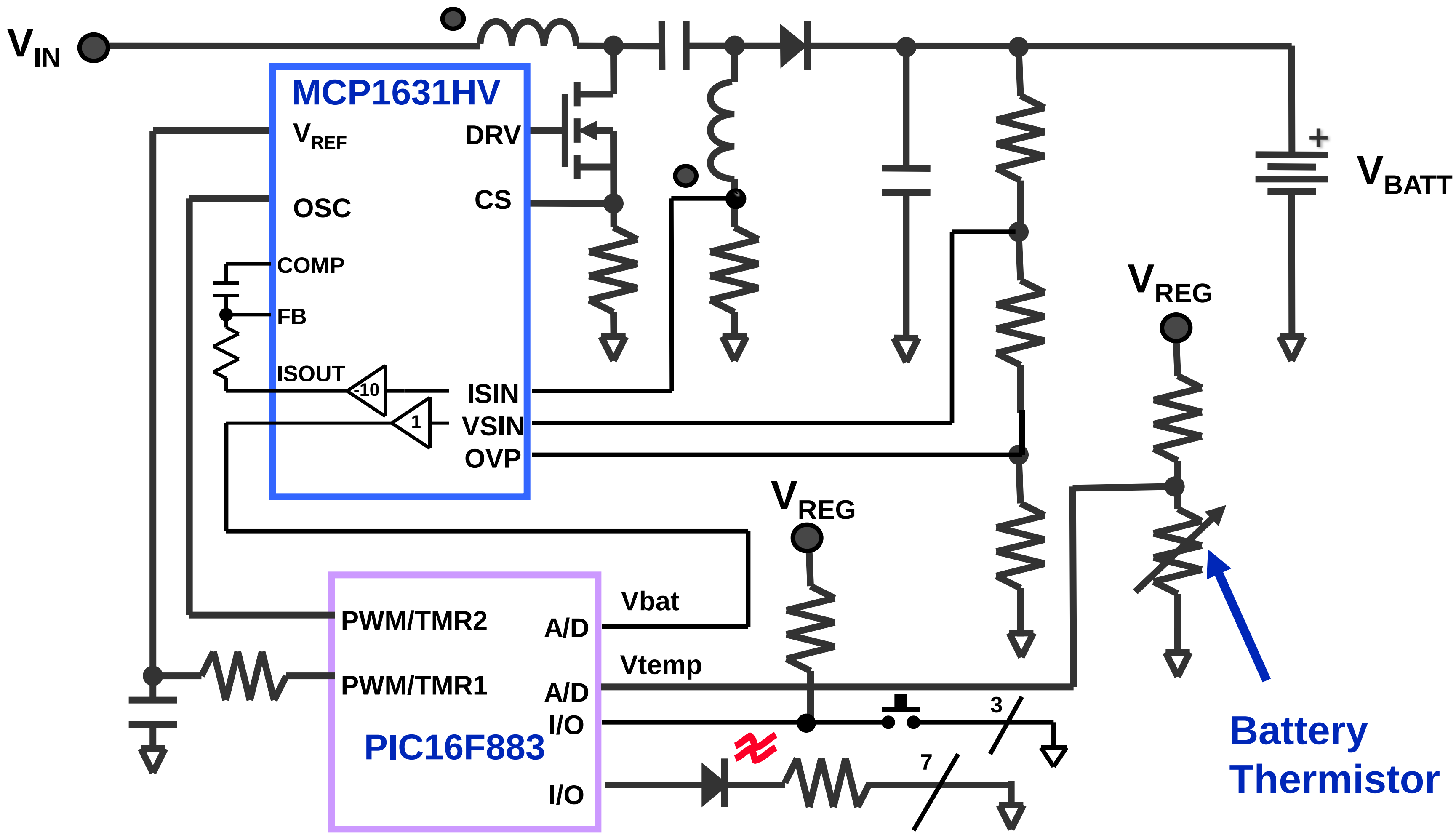
- **Push-Pull Output**
  - **4µs Prop Delay**
    - **MCP6541/2/3/4**
    - **MCP65R41**
  - **50ns Prop Delay**
    - **MCP6561/2/4**
- **Open Drain Output**
  - **4µs Prop Delay**
    - **MCP6546/7/8/9**
    - **MCP65R46**
  - **50ns Prop Delay**
    - **MCP6566/7/9**

<< BACK

General Purpose
Demo & Eval Boards

Multi-Chemistry Design

Charger Block Diagram



Op Amp Application Circuits

Electronic Filter

- Electronic filters perform signal processing functions
  - **Remove unwanted signal components and/or enhance wanted ones.**
- Classification by technology
  - **Passive filter**
  - **Active filter**

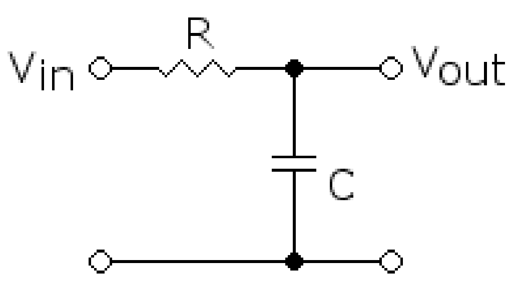
Op Amp Application Circuits

Passive Filter

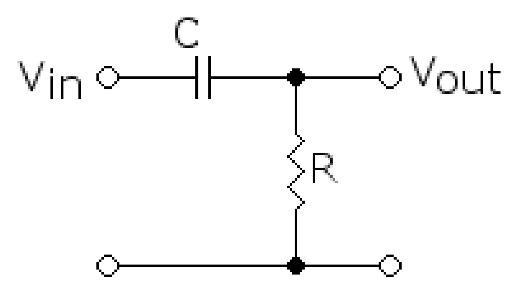
- A passive filter is an electronic filter made entirely from passive components.

A passive component does not require a source of energy to perform its intended function, such as resistors, capacitors, and inductors.

- These filters exist in so-called RC, RL, LC and RLC varieties.



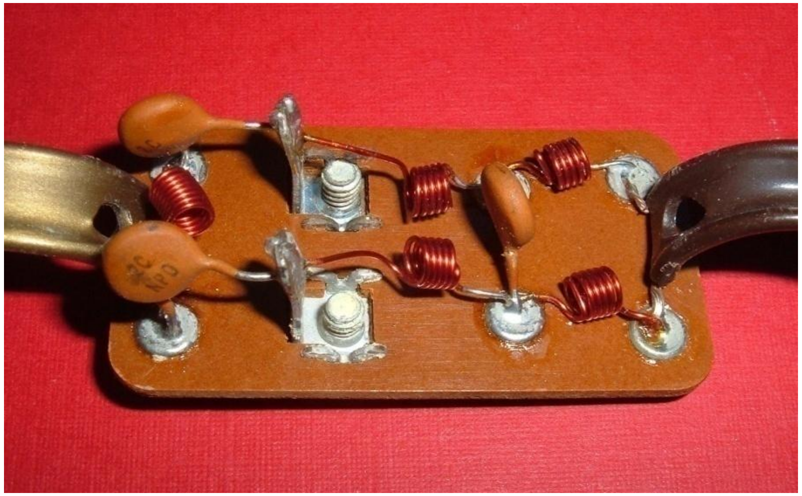
A passive low-pass filter



A passive high-pass filter

Op Amp Application Circuits

– **Example**



Television signal splitter consisting of a high-pass and a low-pass filter.

Some Drawbacks of Passive Filter:

- Very sensitive to the component value tolerances.
- For low frequencies, the values of R and C can be quite large, leading to physically large components.
- Cannot add gain to the filter itself.
- Potentially have a high output impedance.

Op Amp Application Circuits

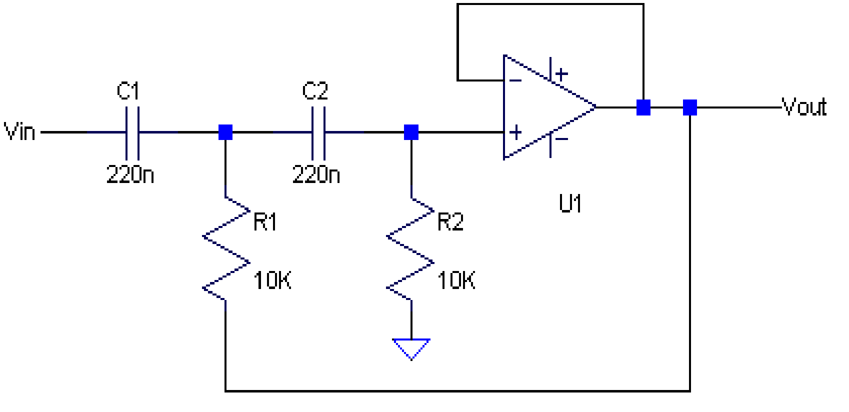
Active Filter

– Active filter is implemented using a combination of passive and active components.

An active component is one that require a source of energy to perform its intended function and can be used to provide gain in an electronic circuit, such as op amps.

– Example:

High-pass active filter



Op Amp Application Circuits

Principal reasons for the use of active filters

The op amps powering the active filter can be used to:

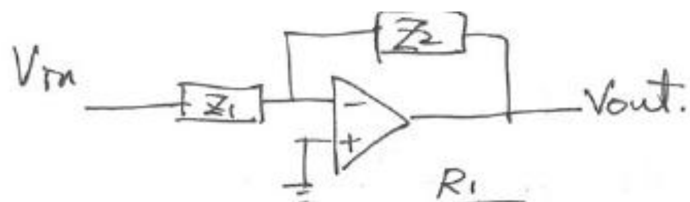
I. Shape the filter’s response
- **Add gain to the filter.**
- **Shape the filter how steeply it moves from its passband to stopband.** (To do this passively, one must use inductors, which are often quite physically large and tend to pick up surrounding noise.)

II. Buffer the filter from the electronic components it drives.
- **This is often necessary so that they do not affect the filter’s actions.**

Op Amp Application Circuits

Low Pass Active Filter

– It passes low frequencies well, but attenuates frequencies higher than the cut-off frequency f_c.



$$\frac{1}{R'} = \frac{1}{R_1} + \frac{1}{\frac{1}{SC}}$$

$$\Rightarrow R' = \frac{R_1}{1+SR_1C}$$

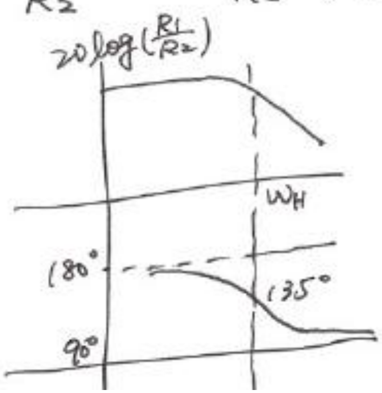
$$\frac{V_o}{V_i} = -\frac{Z_2}{Z_1} = -\frac{\frac{R_1}{1+SR_1C}}{R_2} = -\frac{R_1}{R_2}\cdot\frac{1}{1+SRC}$$

$$= -\frac{R_1}{R_2}\cdot\frac{1}{1+j\frac{\omega}{\omega_0}}$$

$$T = R_1C$$

$$\omega = \frac{1}{R_1C}$$

$$\Rightarrow f = \frac{1}{2\pi R_1C}$$

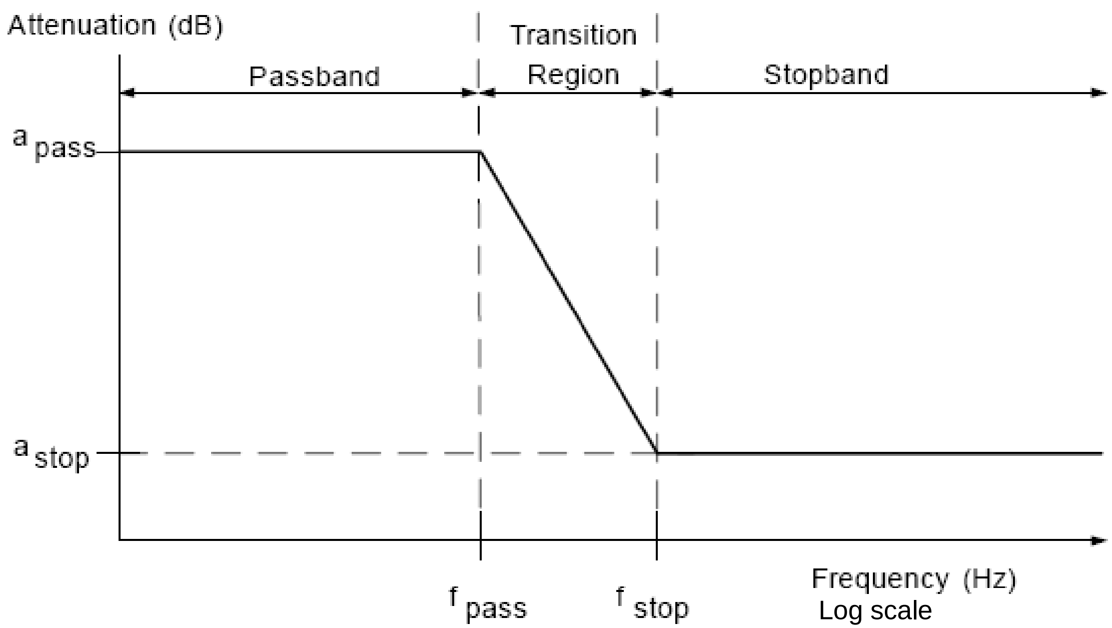


: V_o/V_i, $f_c = 1/(2\pi R_1C)$

- ***Unit: f in hertz (Hz), R in ohms (Ω), C in farads (F)***

Op Amp Application Circuits

– $f >> f_p$, $G \approx 0$; $f << f_p$, $G \approx -R_1/R_2$.
  - $f_p = f_{pass} = f_c = 1/(2\pi R_1 C)$
– f_{stop} must be greater than f_{pass}.



Op Amp Application Circuits

High Pass Active Filter

– It passes high frequencies well, but attenuates frequencies lower than the cut-off frequency f_c.

$$\frac{V_o(S)}{V_i(S)} = \frac{-Z_2(S)}{Z_1(S)} = -\frac{R_2}{R_1+\frac{1}{SC_1}} = -\frac{R_2SC_1}{1+SR_1C_1}$$

$$= -\frac{R_2}{R_1}\left[\frac{R_1SC_1}{1+SR_1C_1}\right]$$

$$T(j\omega) = \frac{V_o(j\omega)}{V_i(j\omega)} = A_\infty\left[\frac{j\omega R_1C_1}{1+j\omega R_1C_1}\right] = A_\infty\left[\frac{j\omega/\omega_L}{1+j\omega/\omega_L}\right]$$

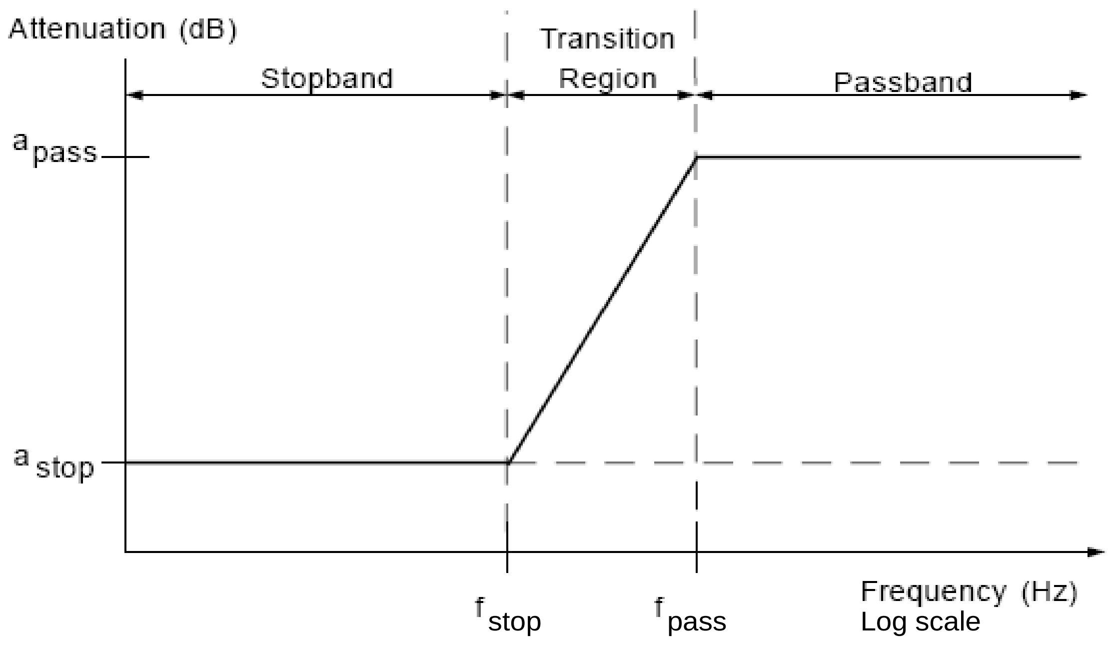
$$\omega_L = 1/R_1C_1$$

– Closed loop gain $G = V_o/V_i$, $f_c = 1/(2\pi R_2C)$

- ***Unit: f in hertz (Hz), R in ohms (Ω), C in farads (F)***

Op Amp Application Circuits

- $f << f_p$, $G \approx 0$; $f >> f_p$, $G \approx -R_1/R_2$
  - $f_p = f_{pass} = f_c = 1/(2\pi R_2 C)$
- f_{pass} must be greater than f_{stop}.



Op Amp Application Circuits

Band Pass Active Filter

– It 需注意運算放大器之帶寬特性. r low pass ar

Pole & Zero

$$Z_1 = Z_2 + R_2 = \frac{1}{j\omega C_2} + R_2$$

$$Z_2 = Z_{C_1} // R_1 = \frac{1}{j\omega C_1} // R_1$$

$$\frac{V_o}{V_i} = -\frac{Z_2}{Z_1} = -\frac{Z_1 // R_1}{Z_{C_2} + R_2}$$

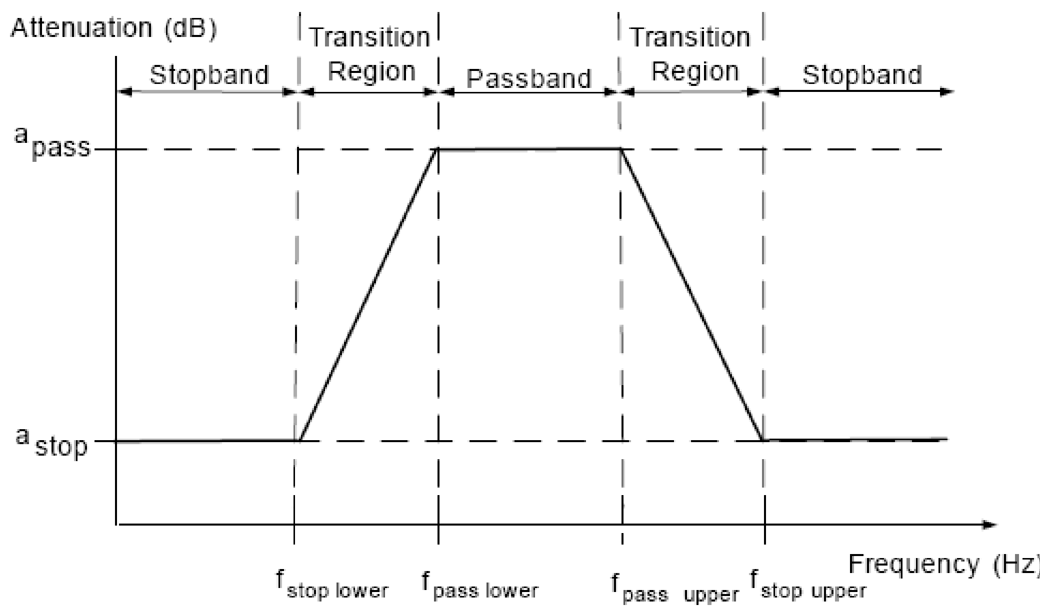
$$= \frac{\dfrac{R_1}{j\omega C_1 R_1 + 1}}{\dfrac{1 + j\omega C_2 R_2}{j\omega C_2 R_2}} = \frac{j\omega C_2 R_1}{(1 + j\omega C_1 R_1)(1 + j\omega C_2 R_2)}$$

– P ith a gain of -F

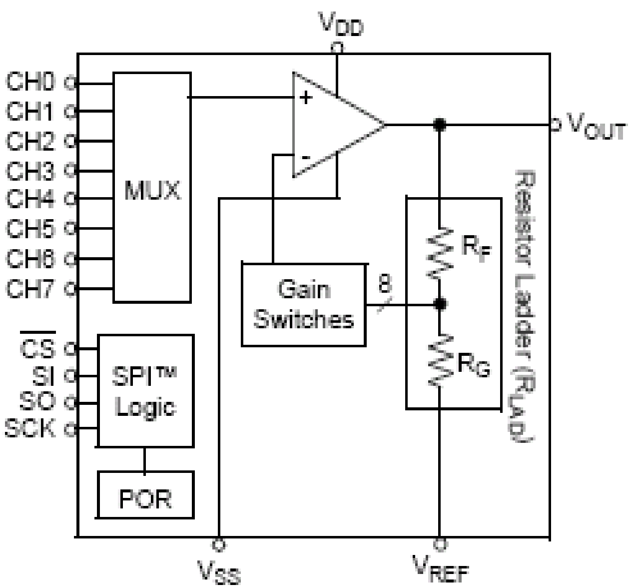
– **Where $f_{c1} = 1/(2\pi R_1 C_1)$, $f_{c2} = 1/(2\pi R_2 C_2)$.**

Op Amp Application Circuits

- Attenuate $f \ll f_{PL}$, $f \gg f_{PU}$; Pass $f_{PL} \le f \le f_{PU}$, $G = -R_1/R_2$
  - $f_{PL} = f_{pass\text{-}lower} = f_{c2} = 1/(2\pi R_2 C_2)$
  - $f_{PU} = f_{pass\text{-}upper} = f_{c1} = 1/(2\pi R_1 C_1)$
- $f_{stop\text{-}lower} < f_{pass\text{-}lower} < f_{pass\text{-}upper} < f_{stop\text{-}upper}$



Programmable Gain Amplifier MCP6S2X



MCP6S21–One input (CH0), no SO pin

MCP6S22–Two inputs (CH0, CH1), V_{REF} tied internally to V_{SS}, no SO pin

MCP6S26–Six inputs (CH0 to CH5)

MCP6S28–Eight inputs (CH0 to CH7)

Features

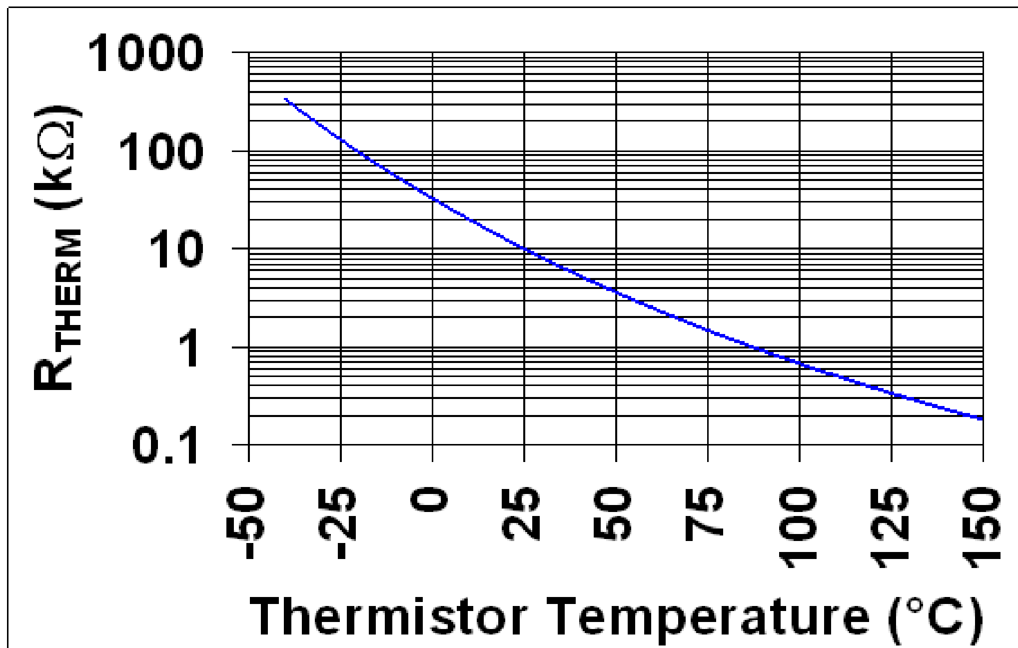
- Multiplexed Inputs: 1, 2, 6 or 8 channels
- 8 Gain Selections:
  - +1, +2, +4, +5, +8, +10, +16 or +32 V/V
- Serial Peripheral Interface (SPI™)
- Rail-to-Rail Input and Output
- Low Gain Error: ±1% (max)
- Low Offset: ±275 µV (max)
- High Bandwidth: 2 to 12 MHz (typ)
- Low Noise: 10 nV/√Hz @ 10 kHz (typ)
- Low Supply Current: 1.0 mA (typ)
- Single Supply: 2.5V to 5.5V

Resistive Sensors – Thermistor

Resistance vs. Temperature

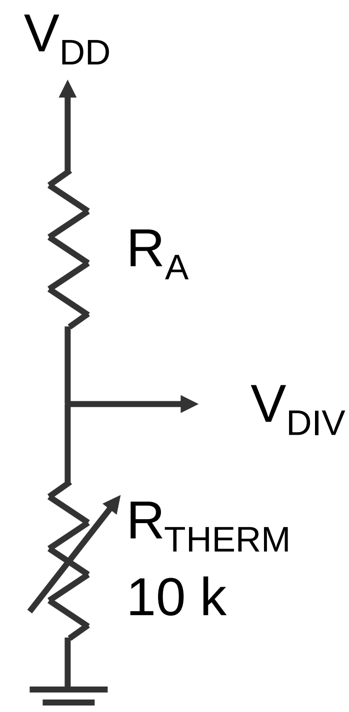
T_{THERM} (C)	T_{THERM} (F)	R_{THERM} (k)
-40	-40	332.1
0	32	32.56
25	77	10.00
70	158	1.753
125	257	0.3387
150	302	0.1826

BCcomponents P/N: 2381 640 55103



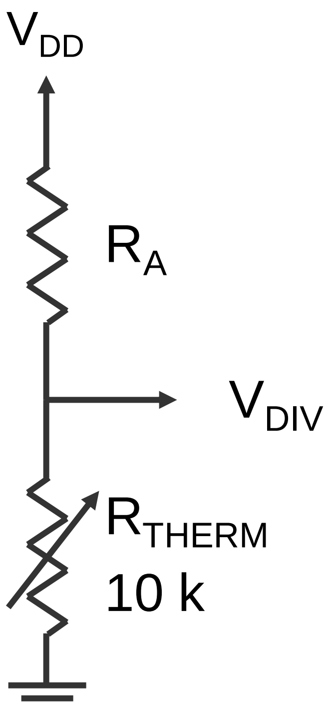
Resistive Sensors – Thermistor

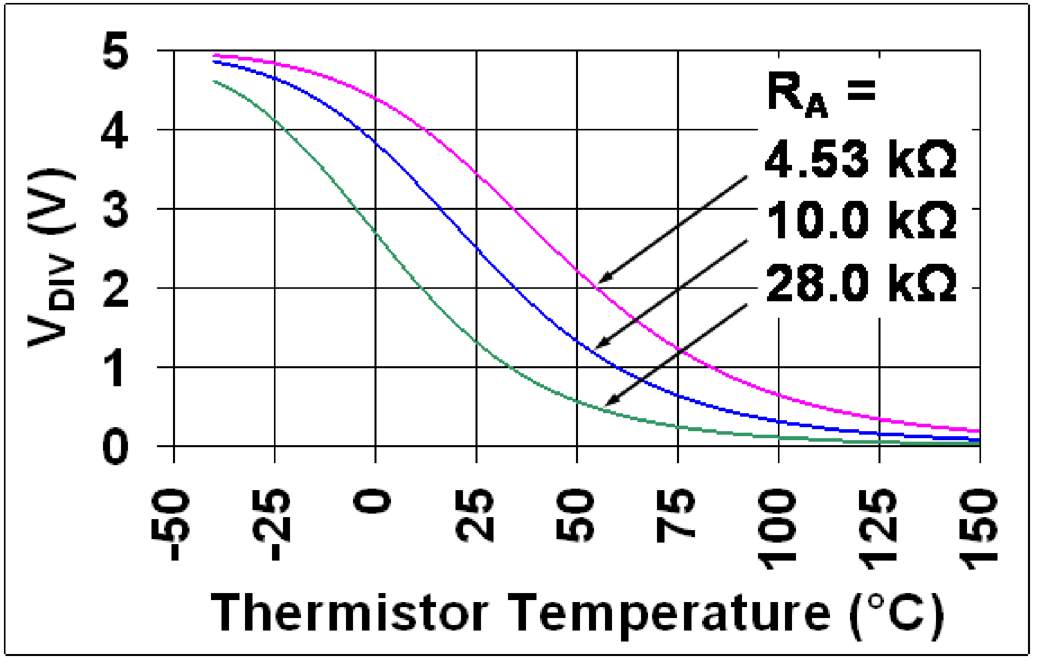
- **Resistance to Voltage Conversion**
  - **Requires current excitation**
    - Voltage Reference and Resistor
    - Current Reference
  - **R_{THERM} vs. temperature**
    - Is very non-linear
    - Is approximately exponential
  - **Voltage divider**
    - Ratiometric (V_{DD} = ADC's VREF)



Resistive Sensors – Thermistor
Divider Output Voltage

- Increasing R_A:
  - Lowers “Linear” Temperature Range
  - Reduces Self-Heating

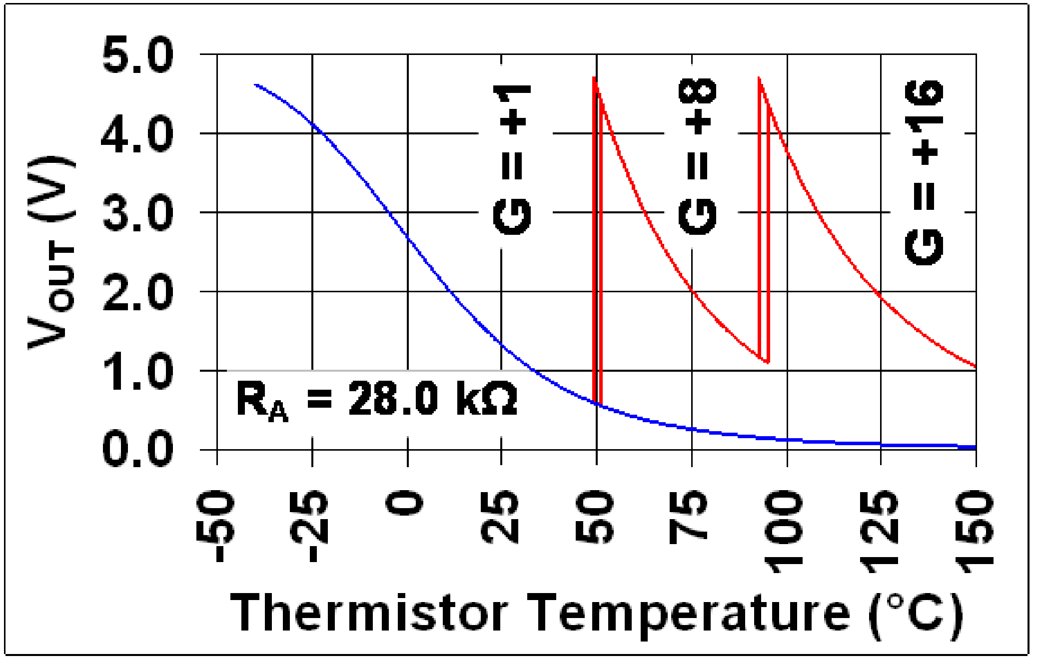




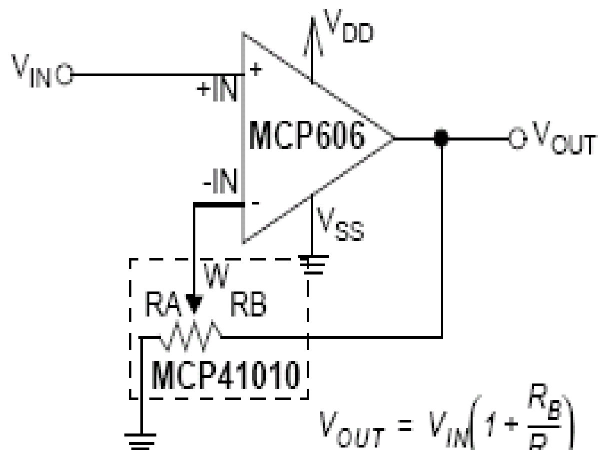
Resistive Sensors – Thermistor
With PGA and Filter

- PGA Gain = 1 only
  - Limited Temperature Range
    - Poor linearity
    - Poor sensitivity
  - Easier Design

- PGA Gain = 1, 8, 16
  - Full Temperature Range
    - Good Linearity
    - Good Sensitivity
  - Much Better Accuracy



Digital Potential Meter MCP41XXX



$$V_{OUT} = V_{IN}\left(1 + \frac{R_B}{R_A}\right)$$

Where:

$$R_A = \frac{R_{AB}(256 - D_n)}{256} \qquad R_B = \frac{R_{AB}D_n}{256}$$

R_{AB} = *Total Resistance of pot*

D_n = *Wiper setting for* D_n = *0 to 255*

FIGURE 4-5: Single-supply, programmable, non-inverting gain amplifier.

Features

- 256 taps for each potentiometer
- Potentiometer values for 10 kΩ, 50 kΩ and 100 kΩ
- Single and dual versions
- SPI™ serial interface (mode 0,0 and 1,1)
- ±1 LSB max INL & DNL
- Low power CMOS technology
- 1 µA maximum supply current in static operation
- Multiple devices can be daisy-chained together (MCP42XXX only)
- Shutdown feature open circuits of all resistors for maximum power savings
- Hardware shutdown pin available on MCP42XXX only
- Single supply operation (2.7V - 5.5V)
- Industrial temperature range: -40°C to +85°C
- Extended temperature range: -40°C to +125°C

Digital Potentiometers

- **6-bit**
  - Non- Volatile
    - U/D
      - MCP4021 Pot, 8MSOP
      - MCP4022 Rheo, 6SOT23
      - MCP4023 Pot, 6SOT23
      - MCP4024 Rheo, 5SOT23
  - Volatile
    - U/D
      - MCP4011 Pot, 8MSOP
      - MCP4012 Rheo, 6SOT23
      - MCP4013 Pot, 6SOT23
      - MCP4014 Rheo, 5SOT23
- **7-bit**
  - Non- Volatile
    - SPI
      - MCP4141/2 Single
      - MCP4241/2 Dual
      - MCP4341/2 Quad
    - I^2C
      - MCP4541/2 Single
      - MCP4641/2 Dual
      - MCP4441/2 Quad
  - Volatile
    - SPI
      - MCP4131/2 Single
      - MCP4231/2 Dual
      - MCP4331/2 Quad
    - I^2C
      - MCP4531/2 Single
      - MCP4631/2 Dual
      - MCP4431/2 Quad
      - MCP40(D)17/8/9
- **8-bit**
  - Non- Volatile
    - SPI
      - MCP4161/2 Single
      - MCP4261/2 Dual
      - MCP4361/2 Quad
    - I^2C
      - MCP4561/2 Single
      - MCP4661/2 Dual
      - MCP4461/2 Quad
  - Volatile
    - SPI
      - MCP41/2XXX
      - MCP4151/2 Single
      - MCP4251/2 Dual
      - MCP4351/2 Quad
    - I^2C
      - MCP4551/2 Single
      - MCP4651/2 Dual
      - MCP4451/2 Quad

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Mixed Signal
Demo & Eval Boards

New Release Information

- **Documentation links**
  - **Product Datasheets**
    - MCP651, “50 MHz, 6 mA Op Amps with mCal”
    - MCP621, “20 MHz, 2.5 mA Op Amps with mCal”
  - **Application Notes**
    - AN1177, “Op Amp Precision Design: DC Errors”
    - AN1258, “Op Amp Precision Design: PCB Layout Techniques”
    - AN1353, “Op Amp Rectifiers, Peak Detectors and Clamps”

Op Amp Application Circuits

Other Applications

- Audio and video pre-amplifiers and buffers
- Voltage and current regulators
- Analog-to-digital converter driver
- Digital-to-analog converter buffer
- Oscillators and waveform generators
- Analog computer(Integrator, Differentiator, etc..)

Application Notes

- AN1151 - PIC18F2520 MCP3909 3-Phase Energy Meter Reference Design
- AN1291 - Low Cost Shunt Power Meter using MCP3909 and PIC18F25K20
- AN994 - IEC Compliant Active-Energy Meter Design Using the MCP3905A/6A
- AN1327A - Avoiding MOSFET Driver Overstress
- AN1256 - Microchip's Power MOSFET Driver Simulation Models
- AN763 - Latch-Up Protection for MOSFET Drivers
- AN786 - Considerations for Driving Power MOSFETs in High-Current, Switch Mode Regulators
- AN799 - Matching MOSFET Drivers to MOSFETs
- AN1258 - Op Amp Precision Design: PCB Layout Techniques
- AN1297 - Microchip's Op Amp SPICE Macro Models
- AN1306 - Thermocouple Circuit Using MCP6V01 and PIC18F2550
- AN1316 - Using Digital Potentiometers for Programmable Amplifier Gain
- AN679 - Temperature Sensing Technologies

More…. → Please visit www.microchip.com/analog

Summary

We Have Met Our Objectives

- Learned the basic op amp concepts and terminology.
- Understood the typical DC and AC specifications found in our op amp datasheet.
- Worked on the op amp application circuits.
- Learned Microchip Analog and Interface Products Offerings (Treelink for Analog and Interface Product Selection and Reference Demo Boards)

Quiz Answer

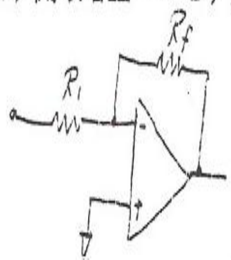
(B) 1. 理想運算放大器之定義不包含

A）輸入阻抗＝∞　B）輸出阻抗＝∞　C）開環增益＝∞　D）頻率響應＝∞

"0"

(C) 2. 右側電路之輸入阻抗爲

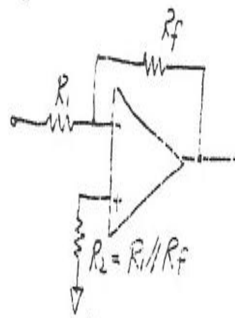
A）∞　B）0　C）R1　D）Rf



(C) 3. 右側電路之 R2 作用爲何

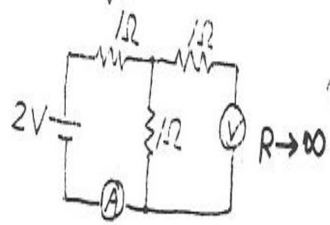
A）增加輸出阻抗　B）減少消耗電流

C）平衡 Ibias 所造成的 Vos　D）增加頻寬



(C) 4. 右圖之電流錶讀值爲

A）2A　B）2/1.5 A　C）1A　D）0A



(A) 5. 上題之電壓錶讀值爲

A）1V　B）2V　C）1/1.5 V　D）0V

R→0

(A) 6. 若一 OP-AMP 之 GBWP 爲 10MHz，若在小信號放大時，增益爲 10 倍則頻寬爲

A）1 MHz　B）10 MHz　C）100 KHz　D）需考慮扭轉率（Slew Rate）

(D) 7. 若一 OP-AMP 接單電源且使用 2 個電阻，則以下何者爲真

A）反相或非反相輸入端可爲負電壓　B）可以構成反相放大器　C）可構成 Audio 信號放大　D）若 Vin>0，可以構成非反相放大器

(C) 8 若一 OP- AMP 之 Vos＝2mV，作小信號放大 Gain＝100 倍，當 Vin＝0，則 V_o ＝

A）2 mV　B）100mV　C）200mV　D）0mV

(B) 9. 對於 OP 作爲隨耦級，以下敘述何者爲非

A）增加輸入阻抗　B）增加輸出阻抗　C）增加輸出驅動能力　D）電壓增益＝1

"減少"

(E) 10. 以 CMOS 構成的 OP-AMP 有些特點，以下何者爲非

A）低 Supply current　B）低 Ibias　C）容易做到 rail-to-rail Input/Output　D）低雜訊　E）高速放大

(Bandwidth Limitation)

References

- [1] MCP601/2/3/4, MCP6021/2/3/4, MCP6041/2/3/4 Datasheets
- **[2] Applications Note An722 "Operational Amplifier DC Specifications and Applications", Baker, Bonnie C, Microchip Technology Inc., 2000**
- **[3] Applications Note An723 "Operational Amplifier AC Specifications and Applications", Baker, Bonnie C, Microchip Technology Inc., 2000**
- [4] "Analog Integrated Circuit Design", Wiley 1997 by Martin, Johns.
- [5] "Design of Analog CMOS Integrated Circuits" International Edition 2001 by Razavi,Behzad.
- **[6] "Microelectronic Circuits" Fourth Edition 1998 by Sedra, Adel S. and Smith, Kenneth C.**
- [7] Paul Horowitz and Winfield Hill, "The Art of Electronics 2nd Ed. " Cambridge University Press, Cambridge, 1989
- [8] Black, H., Stabilized Feedback Amplifiers, Bell System Technical Journal 13, 1/35
- [9] Graeme, J.G., Feedback Models Reduce Op Amp Circuits to Voltage Dividers, EDN, June 20, 1991

Thank You
for attending the class!

www.microchip.com/analog

