EE 254

Electronic Instrumentation

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Lecture Note #02

Content (Brief)

1. Operational Amplifiers

- Ideal Op-Amps
  - Open-loop gain
  - Input resistance
  - Output resistance

- Characteristics of Real Op-Amps
  - Open-loop transfer function
  - Voltage gains
  - Bandwidth
  - Slew rate
  - Power bandwidth
  - Clipping
  - Offset voltages and currents
  - Rejection ratios

Characteristics of Real Op-Amps

- Open loop transfer function
- Voltage gains
- Bandwidth
- Slew rate
- Power bandwidth
- Clipping
- Offset voltages and currents
- Rejection ratios

Electrical Characteristics

(V_{CC} = 15V, V_{EE} = - 15V. T_A = 25 °C, unless otherwise specified)

Parameter		Symbol	Conditions		KA741/KA741I Min.	Typ.	Max.	Unit
Input Offset Voltage		V_{IO}	$R_S \le 10K\Omega$		-	2.0	6.0	mV
			$R_S \le 50\Omega$		-	-	-	mV
Input Offset Voltage Adjustment Range		$V_{IO(R)}$	$V_{CC} = \pm 20V$		-	±15	-	mV
Input Offset Current		I_{IO}	-		-	20	200	nA
Input Bias Current		I_{BIAS}	-		-	80	500	nA
Input Resistance (Note1)		R_I	$V_{CC} = \pm 20V$		0.3	2.0	-	MΩ
Input Voltage Range		$V_{I(R)}$	-		±12	±13	-	V
Large Signal Voltage Gain		G_V	$R_L \ge 2K\Omega$	$V_{CC} = \pm 20V$, $V_{O(P-P)} = \pm 15V$	-	-	-	V/mV
				$V_{CC} = \pm 15V$, $V_{O(P-P)} = \pm 10V$	20	200	-	V/mV
Output Short Circuit Current		I_{SC}	-		-	25	-	mA
Output Voltage Swing		$V_{O(P-P)}$	$V_{CC} = \pm 20V$	$R_L \ge 10K\Omega$	-	-	-	V
				$R_L \ge 2K\Omega$	-	-	-	V
			$V_{CC} = \pm 15V$	$R_L \ge 10K\Omega$	±12	±14	-	V
				$R_L \ge 2K\Omega$	±10	±13	-	V
Common Mode Rejection Ratio		CMRR	$R_S \le 10K\Omega$, $V_{CM} = \pm 12V$		70	90	-	dB
			$R_S \le 50\Omega$, $V_{CM} = \pm 12V$		-	-	-	dB
Power Supply Rejection Ratio		PSRR	$V_{CC} = \pm 15V$ to $V_{CC} = \pm 15V$ $R_S \le 50\Omega$		-	-	-	dB
			$V_{CC} = \pm 15V$ to $V_{CC} = \pm 15V$ $R_S \le 10K\Omega$		77	96	-	dB
Transient Response	Rise Time	T_R	Unity Gain		-	0.3	-	µs
	Overshoot	OS	Unity Gain		-	10	-	%
Bandwidth		BW	-		-	-	-	MHz
Slew Rate		SR	Unity Gain		-	0.5	-	V/µs
Supply Current		I_{CC}	$R_L = \infty\Omega$		-	1.5	2.8	mA
Power Consumption		P_C	$V_{CC} = \pm 20V$		-	-	-	mW
			$V_{CC} = \pm 15V$		-	50	85	mW

CMRR (Common Mode Rejection Ratio)

Electrical Characteristics

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				$V_{CC} = \pm 15V$, $V_{O(P-P)} = \pm 10V$	20	200	-	
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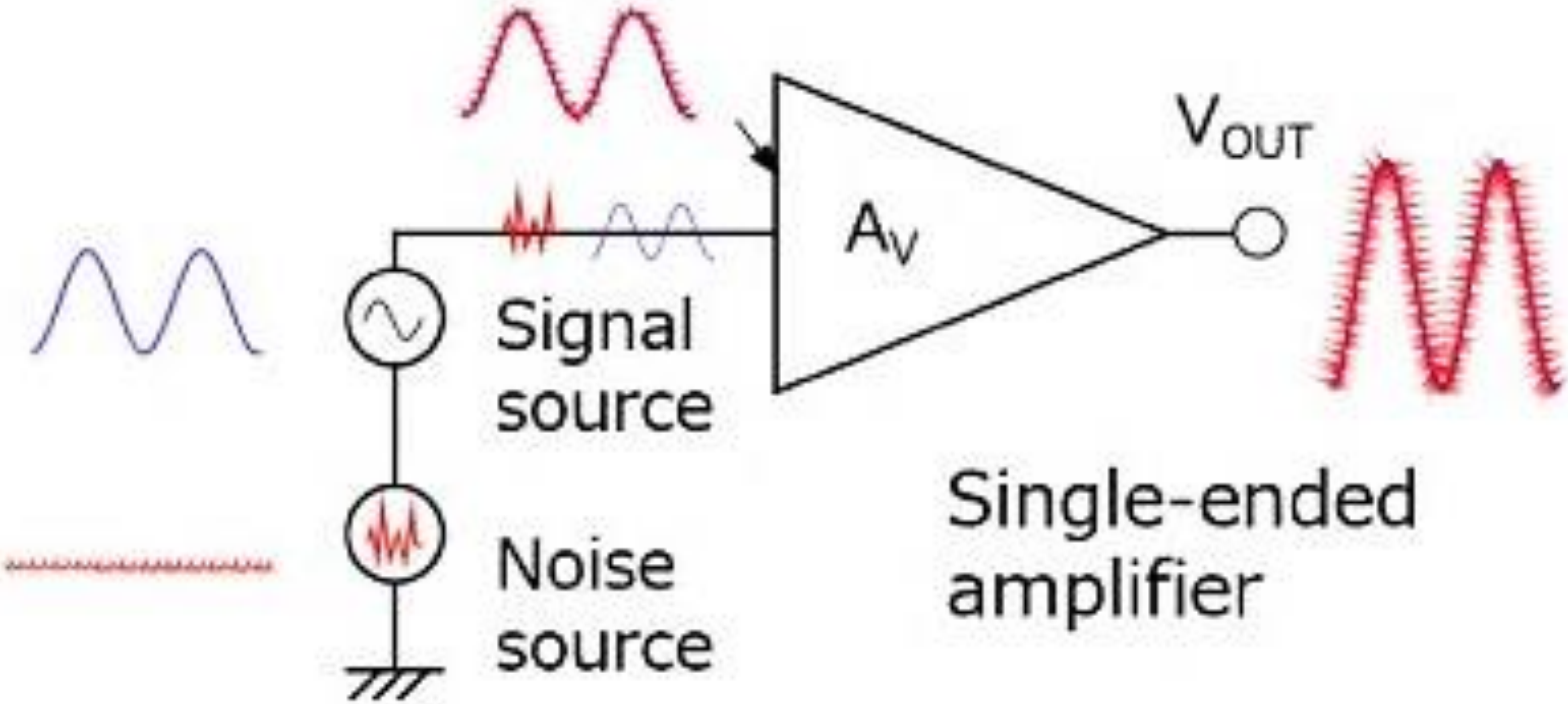
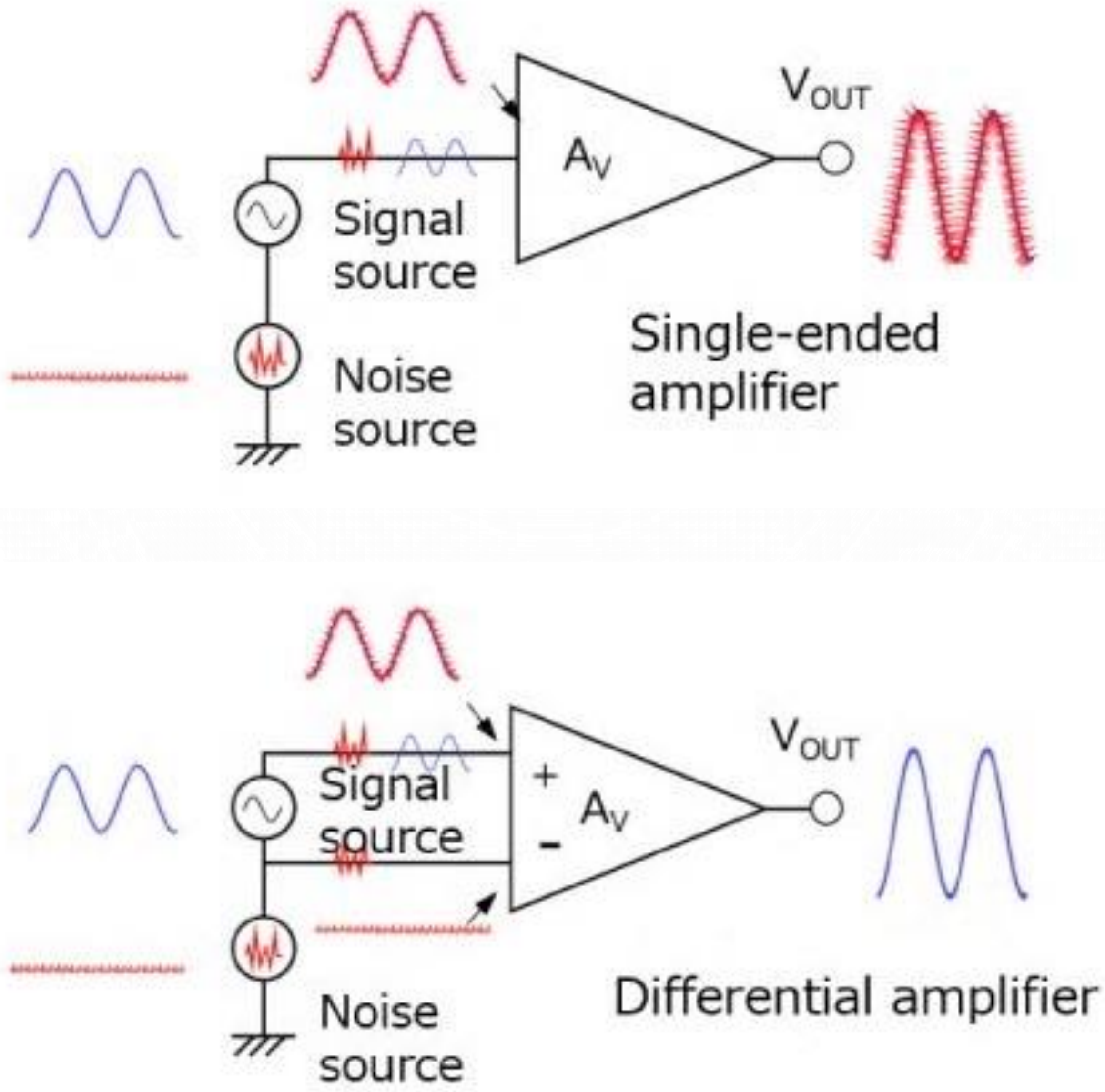
Output Voltage Swing		$V_{O(P-P)}$	$V_{CC} = \pm 20V$	$R_L \geq 10K\Omega$	-	-	-	V
				$R_L \geq 2K\Omega$	-	-	-	
			$V_{CC} = \pm 15V$	$R_L \geq 10K\Omega$	±12	±14	-	
				$R_L \geq 2K\Omega$	±10	±13	-	
Common Mode Rejection Ratio		CMRR	$R_S \leq 10K\Omega$, $V_{CM} = \pm 12V$		70	90	-	dB
			$R_S \leq 50\Omega$, $V_{CM} = \pm 12V$		-	-	-	
Power Supply Rejection Ratio		PSRR	$V_{CC} = \pm 15V$ to $V_{CC} = \pm 15V$ $R_S \leq 50\Omega$		-	-	-	dB
			$V_{CC} = \pm 15V$ to $V_{CC} = \pm 15V$ $R_S \leq 10K\Omega$		77	96	-	
Transient Response	Rise Time	T_R	Unity Gain		-	0.3	-	µs
	Overshoot	OS			-	10	-	%
Bandwidth		BW	-		-	-	-	MHz
Slew Rate		SR	Unity Gain		-	0.5	-	V/µs
Supply Current		I_{CC}	$R_L = \infty\Omega$		-	1.5	2.8	mA
Power Consumption		P_C	$V_{CC} = \pm 20V$		-	-	-	mW
			$V_{CC} = \pm 15V$		-	50	85	

Ground Noise Problem???

- How to overcome this issue?



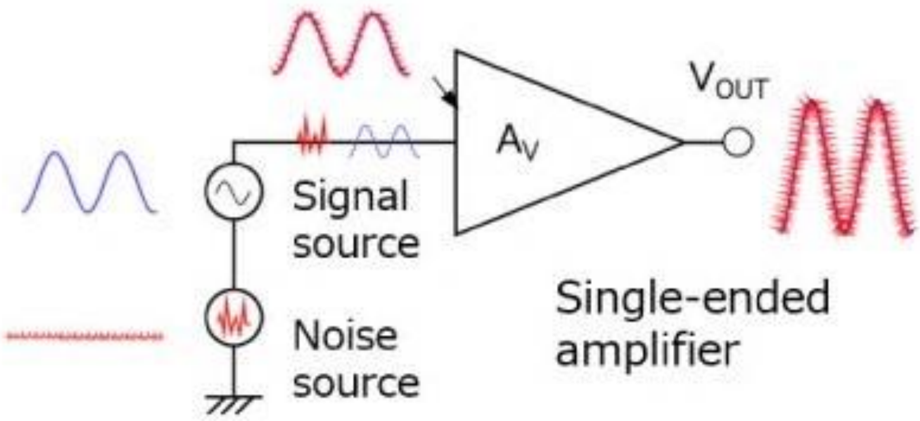
Ground Noise Problem???

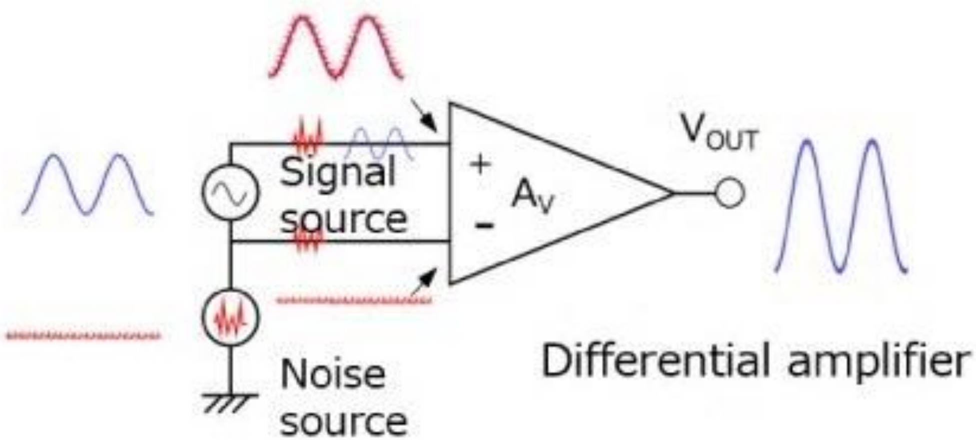


CMRR (Common Mode Rejection Ratio)

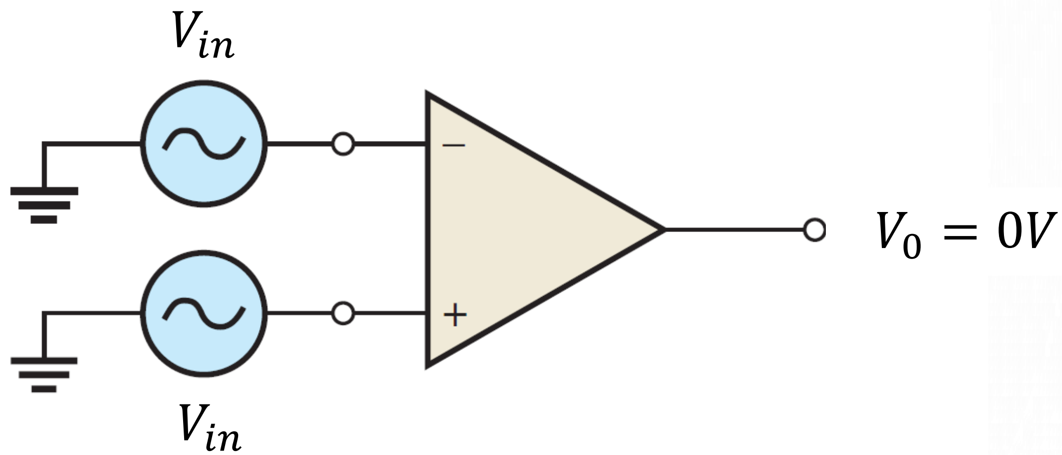
- **There are two main causes of common-mode noise:**

1. Noise is generated in the wires and cables, due to electromagnetic induction, etc., and it causes a difference in potential (i.e., noise) between the signal source ground and the circuit ground.
2. Current flowing into the ground of a circuit from another circuit causes a ground potential rise (noise).



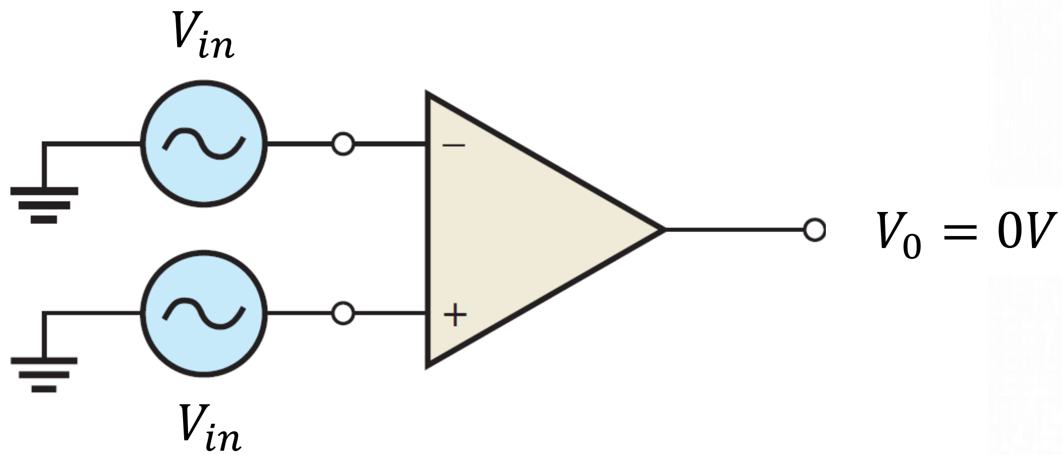


CMRR



- One of the most important specification and Op-Amp parameter.
- Unwanted signals (noise) appearing with the same polarity on both input lines are essentially cancelled by the op-amp and do not appear on the output.
- i.e. two input signals will cancel and resulting a zero output voltage.
- This action is called ***common-mode rejection***. The parameter is called as CMRR (common-mode rejection ratio).

CMRR



- **Ideally**, an op-amp provides a very high gain for differential-mode signals and zero gain for common-mode signals.
- If unwanted signals appears commonly on both op-amp inputs, output will not be zero.
- Common-mode signals (noise) are generally the result of the radiated energy on the input lines, from adjacent lines, the 50Hz power line or other sources.

CMRR

- **Practical op-amps** have a very small common-mode gain (usually much less than 1), while providing a high open-loop differential voltage gain (usually several thousand).
- The higher the open-loop gain (compared to the common-mode gain), the better the performance of the op-amp in terms of rejection of common-mode signals.
- This suggests that a good measure of the op-amp's performance in rejecting unwanted common-mode signals is the ratio of the **open-loop differential voltage gain, $\boldsymbol{A_{ol}}$, to the common-mode gain, $\boldsymbol{A_{cm}}$.**
- The common-mode rejection ratio, CMRR can be calculated as:

$$\mathrm{CMRR} = \frac{A_{ol}}{A_{cm}}$$

CMRR

- The higher the CMRR, the better.
- A very high value of CMRR means that the open-loop gain, A_{ol}, is high and the common-mode gain, A_{cm}, is low.
- The CMRR is often expressed in decibels (dB) as

$$\mathrm{CMRR} = \frac{A_{ol}}{A_{cm}} \qquad\qquad \mathrm{CMRR} = 20\log_{10}\left(\frac{A_{ol}}{A_{cm}}\right)$$

- The **open-loop voltage gain**, *Aol*, of an op-amp is the internal voltage gain of the device and represents the ratio of output voltage to input voltage when there are no external components.
- The open-loop voltage gain is set entirely by the internal design. Open-loop
- voltage gain can range up to 200,000 (106 dB) and is not a well-controlled parameter. Datasheets often refer to the open-loop voltage gain as the *large-signal voltage gain*.

CMRR

- If CMRR is100,000, what does it mean?

- A CMRR of 100,000, for example, means that the desired input signal (differential) is amplified 100,000 times more than the unwanted noise (common-mode).
- If the amplitudes of the differential input signal and the common-mode noise are equal, the desired signal will appear on the output 100,000 times greater in amplitude than the noise.
- Thus, the noise or interference has been essentially eliminated.

Output Voltage Swing ($V_{O(P-P)}$)

- With no input signal, the output of an op-amp is ideally 0 V.
- This is called the **quiescent output voltage**.
- When an input signal is applied, the ideal limits of the peak-to-peak output signal are $\pm V_{cc}$
- In practice, however, this ideal can be approached but never reached.
- $V_{O(P-P)}$ varies with the load connected to the op-amp and increases directly with load resistance.
- For example, from the KA741 datasheet

Parameter	Symbol	Conditions		KA741/KA741I			Unit
				Min.	Typ.	Max.	
Output Voltage Swing	$V_{O(P-P)}$	$V_{CC} = \pm 20V$	$R_L \geq 10K\Omega$	-	-	-	V
			$R_L \geq 2K\Omega$	-	-	-	
		$V_{CC} = \pm 15V$	$R_L \geq 10K\Omega$	±12	±14	-	
			$R_L \geq 2K\Omega$	±10	±13	-	

Output Voltage Swing ($V_{O(P-P)}$)

- Some op-amps do not use both positive and negative supply voltages.
- One example is when a single dc voltage source is used to power an op-amp that drives an analog-to-digital converter.
- In this case, the op-amp output is designed to operate between ground and a full scale output that is near (or at) the positive supply voltage.
- Op-amps that operate on a single supply use the terminology V_{OH} and V_{OL} to specify the maximum and minimum output voltage. (Note that these are not the same as the digital definitions of V_{OL} and V_{OH}.)

Input Offset Voltage

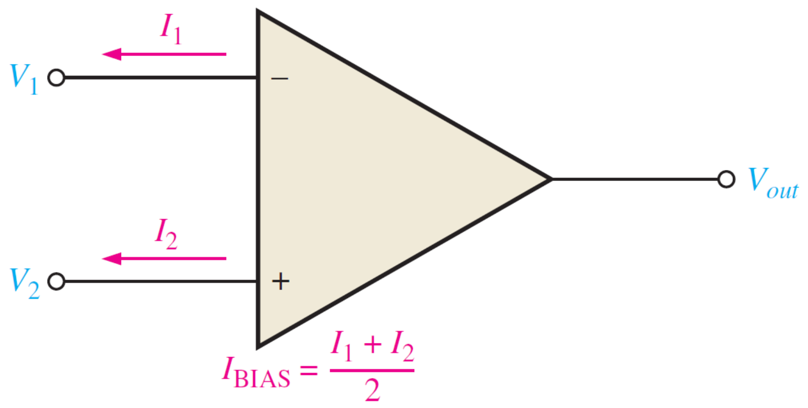
- The ideal op-amp produces zero volts out for zero volts in.
- In a practical op-amp, however, a small dc voltage, VOUT(error), appears at the output when no differential input voltage is applied. Its primary cause is a slight mismatch of the base-emitter voltages of the differential amplifier input stage of an op-amp.
- As specified on an op-amp datasheet, the input offset voltage, VOS, is the differential dc voltage required between the inputs to force the output to zero volts.
- Typical values of input offset voltage are in the range of 2 mV or less. In the ideal case, it is 0 V.

Parameter	Symbol	Conditions	KA741/KA741I			Unit
			Min.	Typ.	Max.	
Input Offset Voltage	V_{IO}	$R_S \leq 10K\Omega$	-	2.0	6.0	mV
		$R_S \leq 50\Omega$	-	-	-	

Input Bias Current

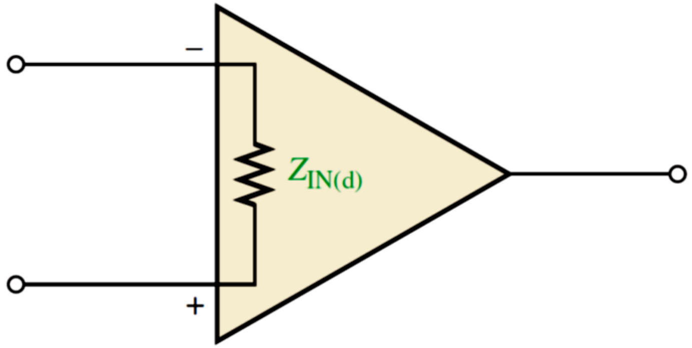
- You have seen that the input terminals of a bipolar differential amplifier are the transistor bases and, therefore, the input currents are the base currents.
- The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage.
- By definition, the input bias current is the average of both input currents and is calculated as follows:

$$I_{BIAS} = \frac{I_1 + I_2}{2}$$

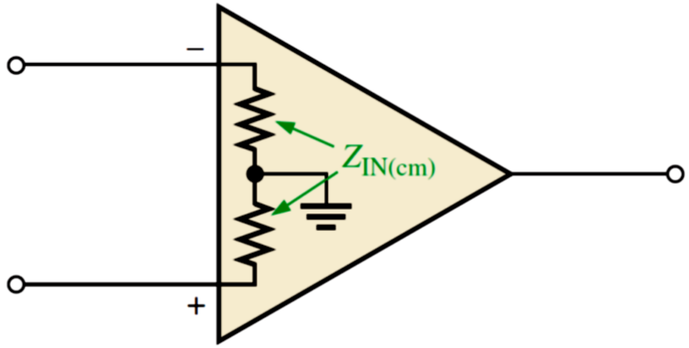


Input Impedance

- Two basic ways of specifying the input impedance of an op-amp are the differential and the common mode.
- The differential input impedance is the total resistance between the inverting and the noninverting inputs (a).
- Differential impedance is measured by determining the change in bias current for a given change in differential input voltage.
- The common-mode input impedance is the resistance between each input and ground and is measured by determining the change in bias current for a given change in common-mode input voltage (b).



(a) Differential input impedance



(b) Common-mode input impedance

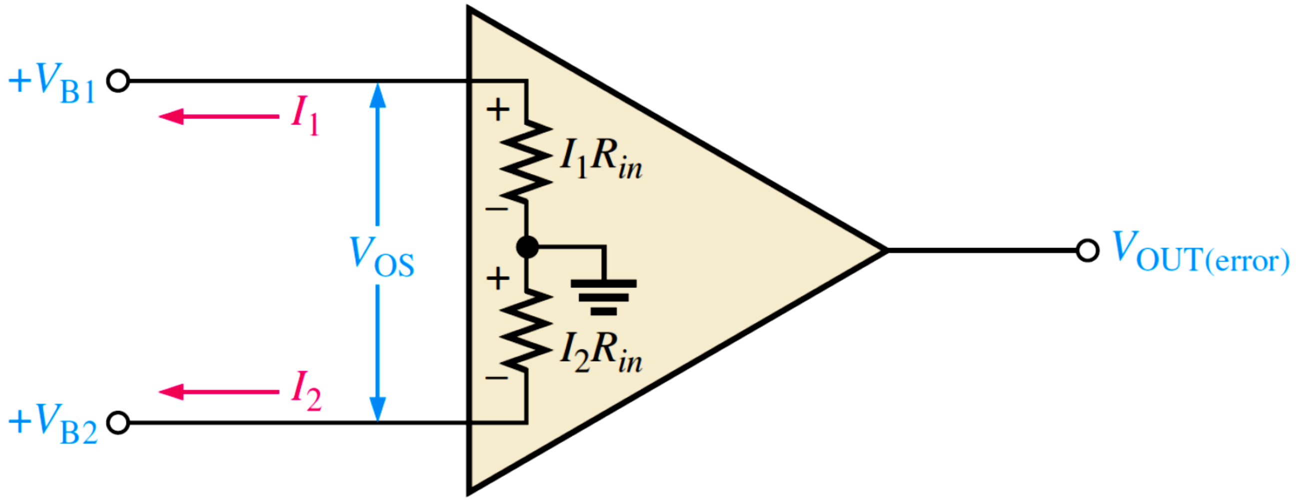
Input Offset Current

- Ideally, the two input bias currents are equal, and thus their difference is zero.
- In a practical op-amp, however, the bias currents are not exactly equal.
- The input offset current, I_{OS}, is the difference of the input bias currents, expressed as an absolute value.

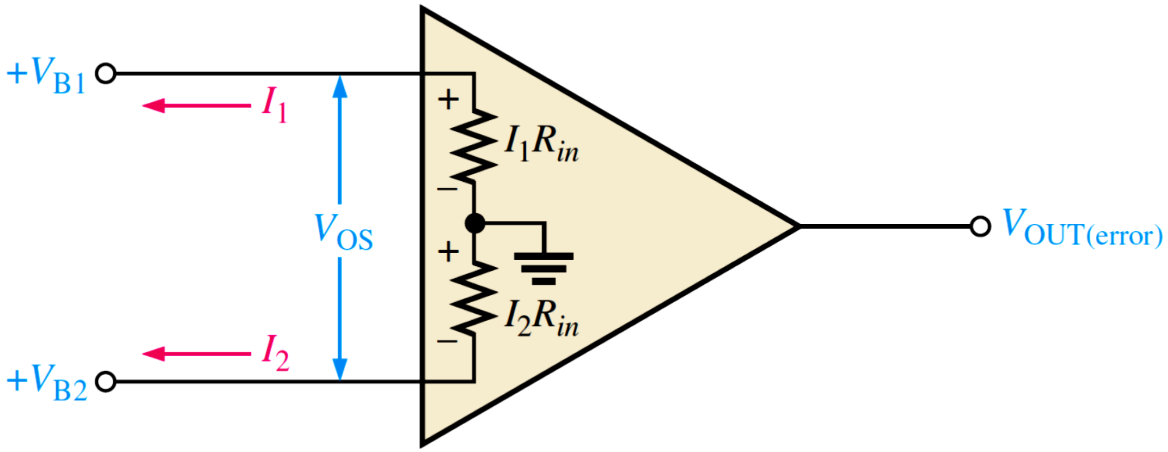
$$I_{OS} = |I_1 - I_2|$$

Input Offset Current

- Actual magnitudes of offset current are usually at least an order of magnitude (ten times) less than the bias current.
- In many applications, the offset current can be neglected.
- However, high-gain, high-input impedance amplifiers should have as little I_{OS} as possible because the difference in currents through large input resistances develops a substantial offset voltage, as shown in Figure



Input Offset Current



- The offset voltage developed by the input offset current is

$$V_{OS} = I_1R_{in} - I_2R_{in} = (I_1 - I_2)R_{in}$$

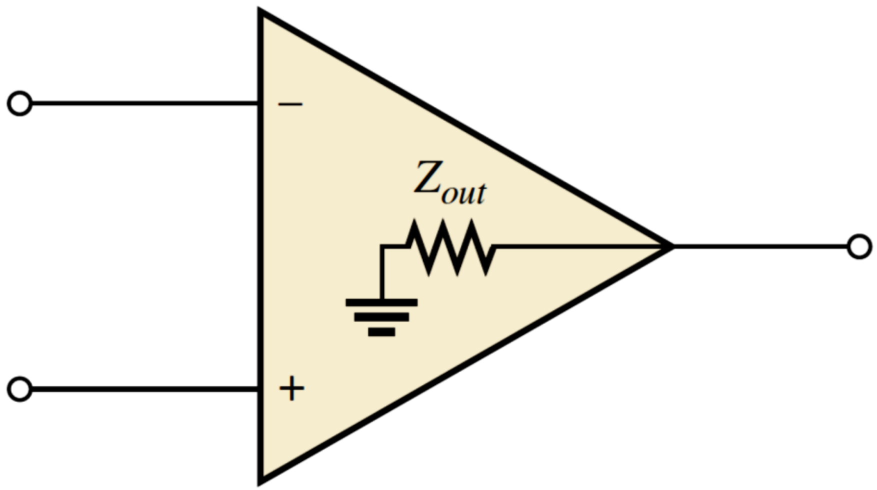
$$\boldsymbol{V_{OS} = I_{OS}R_{in}}$$

- The error created by I_{OS} is amplified by the gain A_v of the op-amp and appears in the output as

$$V_{OUT(error)} = A_v I_{OS} R_{in}$$

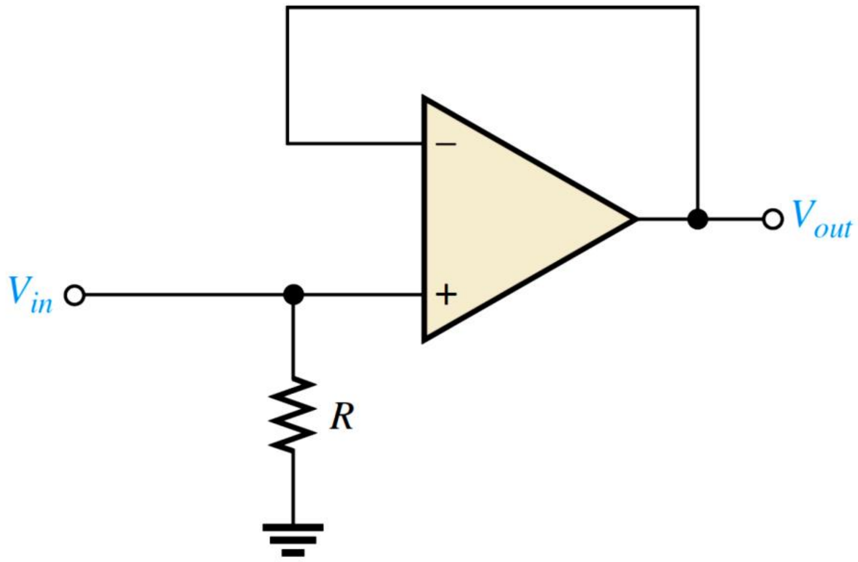
Output Impedance

- The *output impedance* is the resistance viewed from the output terminal of the op-amp.



Slew Rate

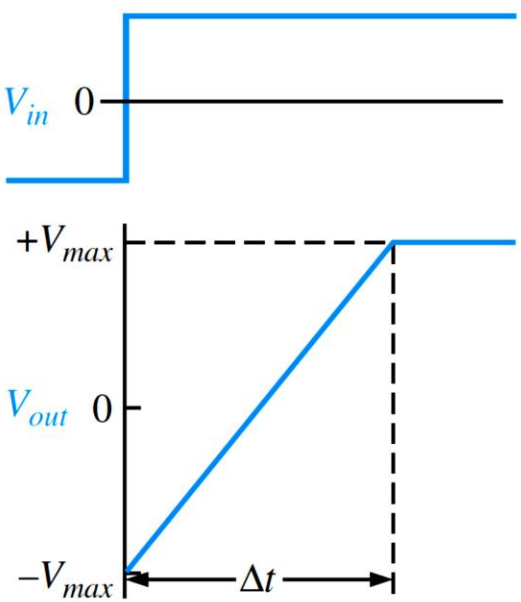
- The maximum rate of change of the output voltage in response to a step input voltage is the slew rate of an op-amp.
- The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp.
- Slew rate is measured with an op-amp connected as shown in Figure.



(a) Test circuit

Slew Rate

- It gives a worst-case (slowest) slew rate. Recall that the high frequency components of a voltage step are contained in the rising edge and that the upper critical frequency of an amplifier limits its response to a step input.
- For a step input, the slope on the output is inversely proportional to the upper critical frequency.
- Slope increases as upper critical frequency decreases.
- A pulse is applied to the input and the resulting ideal output voltage is indicated in Figure



(b) Step input voltage and the resulting output voltage

Slew Rate

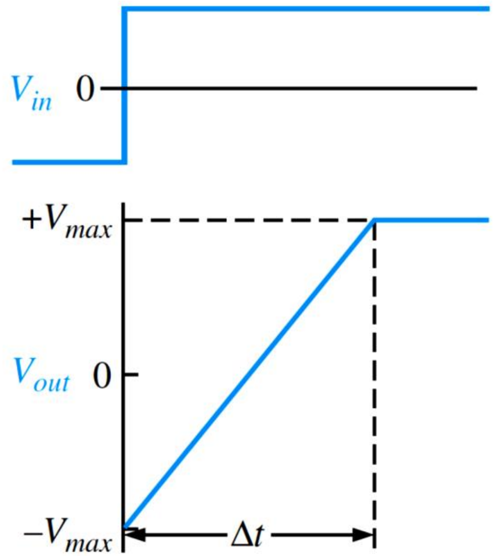
- The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit.
- A certain time interval Δt, is required for the output voltage to go from its lower limit $-V_{max}$ to its upper limit $+V_{max}$ once the input step is applied.
- The slew rate is expressed as

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

- Where;

$$\Delta V_{out} = +V_{max} - \ (-V_{max})$$

- The unit of slew rate is volts per microsecond ($V/\mu s$).



(b) Step input voltage and the resulting output voltage

Comparison of Op-Amp Parameters

- As you can see from the table, there is a wide difference in certain specifications.
- All designs involve certain compromises, so in order for designers to optimize one parameter, they must often sacrifice another parameter.
- Choosing an op-amp for a particular application depends on which parameters are important to optimize.
- Parameters depend on the conditions for which they are measured.
- For details on any of these specifications, consult the datasheet.

Comparison of Op-Amp Parameters

OP-AMP	CMRR (dB) (TYP)	OPEN-LOOP GAIN (dB) (TYP)	GAIN-BANDWIDTH PRODUCT (MHz) (TYP)	INPUT OFFSET VOLTAGE (mV) (MAX)	INPUT BIAS CURRENT (nA) (MAX)	SLEW RATE (V/µs) (TYP)	COMMENT
AD8009	50	N/A	320[1]	5	150	5500	Extremely fast, low distortion, uses current feedback
AD8055	82	71		5	1200	1400	Low noise, fast, wide bandwidth, gain flatness 0.1 dB, video driver
ADA4891	68	90[2]		2500	0.002	170	CMOS-extremely low bias current, very fast, useful as video amplifier
ADA4092	85	118	1.3	0.2	50	0.4	Single supply (2.7 V to 36 V) or two supply operation, low power
FAN4931	73	102	4	6	0.005	3	Low cost CMOS, low power, output swings to within 10 mV of rail, extremely high input resistance
FHP3130	95	100	60	1	1800	110	High current output (to 100 mA)
FHP3350	90	55	190	1	50	800	High speed; useful as video amp
LM741C	70	106	1	6	500	0.5	General-purpose, overload protection, industry standard
LM7171	110	90	100	1.5	1000	3600	Very fast, high CMRR, useful as an instrumentation amplifier
LMH6629	87	79	800[3]	0.15	23000	530	Fast, ultra low noise, low voltage
OP177	130	142		0.01	1.5	0.3	Ultra-precision; very high CMRR and stability
OPA369	114	134	0.012	0.25	0.010	0.005	Extremely low power, low voltage, rail-to-rail.
OPA378	100	110	0.9	0.02	0.15	0.4	Precision, very low drift, low noise
OPA847	110	98	3900	0.1	42,000	950	Ultra low-noise, wide bandwidth amplifier, voltage feedback

[1] Depends on gain; gain = 10 is shown
[2] Depends on gain; gain = 2 is shown
[3] Small signal

Comparison of Op-Amp Parameters

- There is a wide difference in certain specifications, in the table.
- All designs involve certain compromises, so in order for designers to optimize one parameter, they must often sacrifice another parameter.
- Choosing an op-amp for a particular application depends on which parameters are important to optimize.
- Parameters depend on the conditions for which they are measured.
- For details on any of these specifications, consult the datasheet.
- Most available op-amps have three important features: short-circuit protection, no latch-up, and input offset nulling.
- Short-circuit protection keeps the circuit from being damaged if the output becomes shorted, and the no latch-up feature prevents the op-amp from hanging up in one output state (high or low voltage level) under certain input conditions.
- Input offset nulling is achieved by an external potentiometer that sets the output voltage at precisely zero with zero input.