Electronic Circuits

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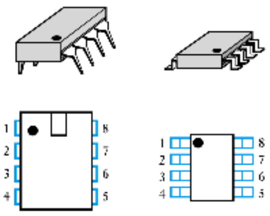
Operational amplifiers

- Introduction
- An ideal operational amplifier
- Basic operational amplifier circuits
- Other useful circuits
- Real operational amplifiers
- Selecting component values
- Effects of feedback on op-amp circuits

Introduction

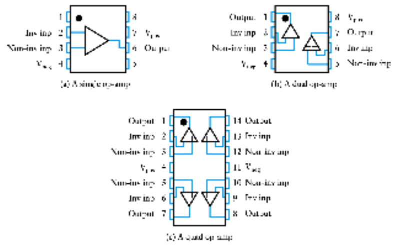
- **Operational amplifiers** (**op-amps**) are among th most widely used building blocks in electronics
  - they are integrated circuits (ICs)
    - often DIL or SMT



(a) A DIL package (b) An SMT package

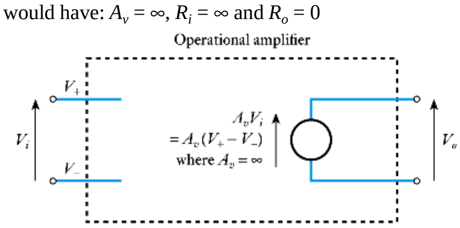
Introduction (contd.)

- A single package will often contain several op-amps



An ideal operational amplifier

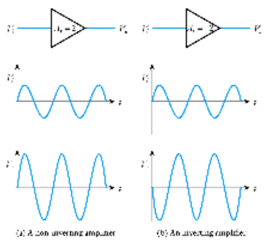
- An *ideal* op-amp would be an ideal voltage amplifier and would have: $A_v = \infty$, $R_i = \infty$ and $R_o = 0$



Equivalent circuit of an ideal op-amp

Basic operational amplifier circuits

- Inverting and non-inverting amplifiers

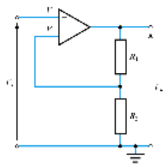


Basic operational amplifier circuits (contd.)

- When looking at feedback we derived the circuit of an amplifier from ‘first principles’
- Normally we use standard ‘**cookbook**’ circuits and select component values to suit our needs
- In analysing these we normally assume the use of ideal op-amps
  - in demanding applications we may need to investigate the appropriateness of this assumption
  - the use of ideal components makes the analysis of these circuits very straightforward

Basic operational amplifier circuits (contd.)

- **A non-inverting amplifier**



Analysis

Since the gain is assumed infinite, if V_o is finite then the input voltage must be zero. Hence

$$V_- = V_+ = V_i$$

Since the input resistance of the op-amp is ∞

$$V_- = V_o \frac{R_2}{R_1 + R_2}$$

and hence, since $V_- = V_+ = V_i$

$$V_i = V_o \frac{R_2}{R_1 + R_2}$$

and

$$G = \frac{V_o}{V_i} = \frac{R_1 + R_2}{R_2}$$

Basic operational amplifier circuits (contd.)

- **Example**

Design a non-inverting amplifier with a gain of 25

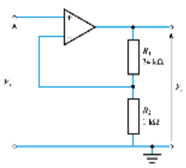
From above $G = \frac{V_o}{V_i} = \frac{R_1 + R_2}{R_2}$

If G = 25 then

$$\frac{R_1 + R_2}{R_2} = 25$$

$$R_1 + R_2 = 25R_2$$

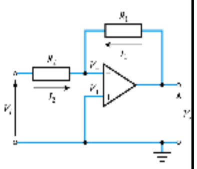
$$R_1 = 24R_2$$



Therefore choose R_2 = 1 kΩ and R_1 = 24 kΩ
(choice of values will be discussed later)

Basic operational amplifier circuits (contd.)

- **An inverting amplifier**



Analysis

Since the gain is assumed infinite, if V_o is finite the input voltage must be zero. Hence

$$V_- = V_+ = 0$$

Since the input resistance of the op-amp is ∞ its input current must be zero, and hence

$$I_1 = -I_2$$

Now $I_1 = \frac{V_o - V_-}{R_1} = \frac{V_o - 0}{R_1} = \frac{V_o}{R_1}$ $\quad I_2 = \frac{V_i - V_-}{R_2} = \frac{V_i - 0}{R_2} = \frac{V_i}{R_2}$

Basic operational amplifier circuits (contd.)

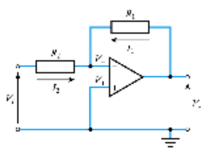
- **Analysis (continued)**

Therefore, since $I_1 = -I_2$

$$\frac{V_o}{R_1} = -\frac{V_i}{R_2}$$

or, rearranging

$$G = \frac{V_o}{V_i} = -\frac{R_1}{R_2}$$



- Here V_- is held at zero volts by the operation of the circuit, hence the circuit is known as a **virtual earth circuit**

Basic operational amplifier circuits (contd.)

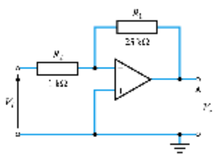
- **Example**

Design an inverting amplifier with a gain of –25

From above $G = \frac{V_o}{V_i} = -\frac{R_1}{R_2}$

If G = –25 then $-\frac{R_1}{R_2} = -25$

$$R_1 = 25R_2$$



Therefore choose R_2 = 1 kΩ and R_1 = 25 kΩ
(we will consider the choice of values later)

Other useful circuits

- In addition to simple amplifiers, op-amps can also be used in a range of other circuit
- The next few slides show a few examples of op-amp circuits for a range of purposes
- The analysis of these circuits is similar to that of the non-inverting and inverting amplifiers but (in most cases) this is *not* included here
- For more details of these circuits see the relevant section of the course text (as shown on the slides)

Other useful circuits (contd.)

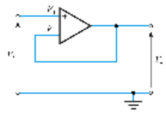
- **A unity gain buffer amplifier**

Analysis

This is a special case of the non-inverting amplifier with $R_1 = 0$ and $R_2 = \infty$

Hence

$$G = \frac{R_1 + R_2}{R_2} = \frac{R_1}{R_2} + 1 = \frac{0}{\infty} + 1 = 1$$

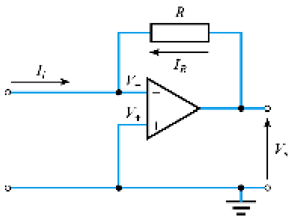


Thus the circuit has a gain of unity

- At first sight this might not seem like a very useful circuit, however, it has a high input resistance and a low output resistance and is therefore useful as a **buffer amplifier**

Other useful circuits (contd.)

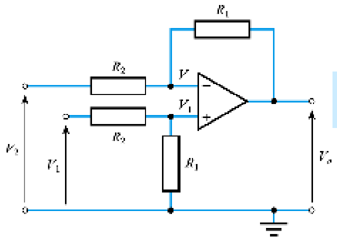
- **A current to voltage converter**



$$V_o = -I_i R$$

Other useful circuits (contd.)

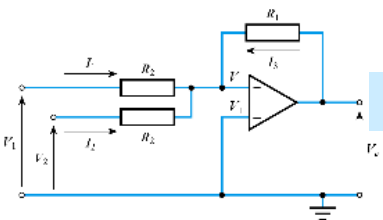
- **A differential amplifier (or subtractor)**



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

Other useful circuits (contd.)

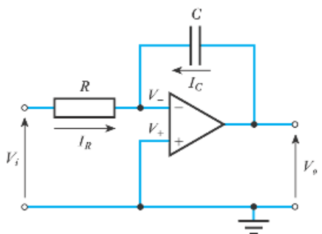
- **An inverting summing amplifier**



$$V_o = -(V_1 + V_2)\frac{R_1}{R_2}$$

Other useful circuits (contd.)

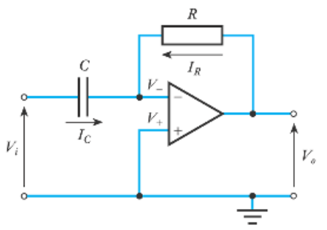
- **An integrator**



$$V_o = -\frac{1}{RC}\int_0^t V_i \, dt$$

Other useful circuits (contd.)

- **A differentiator**



$$V_o = -RC\frac{dV_i}{dt}$$

Real operational amplifiers

- So far we have assumed the use of **ideal op-amps**
  - these have $A_v = \infty$, $R_i = \infty$ and $R_o = 0$
- Real components do not have these ideal characteristics (though in many cases they approximate to them)
- In this section we will look at the characteristics of typical devices
  - perhaps the most widely used general purpose op-amp is the 741

Real operational amplifiers (contd.)

- **Voltage gain**
  - typical gain of an operational amplifier might be 100 – 140 dB (voltage gain of $10^5 - 10^6$)
  - 741 has a *typical* gain of 106 dB (2×10^5)
  - high gain devices might have a gain of 160 dB (10^8)
  - while not infinite, the gain of most op-amps is ‘high-enough’
  - however, gain varies between devices and with temperature

Real operational amplifiers (contd.)

- **Input resistance**
  - typical input resistance of a 741 is 2 MΩ
  - very variable, for a 741 it can be as low as 300 kΩ

  - the above value is typical for devices based on **bipolar transistors**
  - op-amps based on **field-effect transistors** generally have a much higher input resistance – perhaps 10^{12} Ω

  - we will discuss bipolar and field-effect transistors later

Real operational amplifiers (contd.)

- **Output resistance**
  - typical output resistance of a 741 is 75 Ω
  - again very variable

  - often of more importance, is the maximum output current
  - the 741 will supply 20 mA

  - high-power devices may supply an amp or more

Real operational amplifiers (contd.)

- **Supply voltage range**
  - a typical arrangement would use supply voltages of +15 V and – 15 V, but a wide range of supply voltages is usually possible
  - the 741 can use voltages in the range ±5 to ±18 V
  - some devices allow voltages up to ±30 V or more
  - others, designed for low voltages, may use ±1.5 V

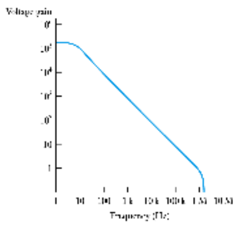
  - many op-amps permit single voltage supply operation, typically in the range 4 to 30 V

Real operational amplifiers (contd.)

- **Common-mode rejection ratio**
  - an ideal op-amp would not respond to common-mode signals.
  - real amplifiers do respond to some extent
  - the common-mode rejection ratio (CMRR) is the ratio of the response produced by a differential-mode signal to that produced by a common-mode signal
  - typical values for CMRR might be in the range 80 to 120 dB
    - 741 has a CMRR of about 90 dB

Real operational amplifiers (contd.)

- **Frequency response**
  - typical 741 frequency response is shown here
  - upper cut-off frequency is a few hertz
  - frequency range generally described by the **unity-gain bandwidth**
  - high-speed devices may operate up to several gigahertz



Selecting component values

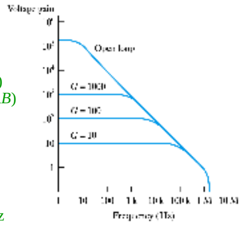
- Our analysis assumed the use of an ideal op-amp
- When using real components we need to ensure that our assumptions are valid
- In general this will be true if we:
  - limit the gain of our circuit to *much less* than the open-loop gain of our op-amp
  - choose external resistors that are *small* compared with the input resistance of the op-amp
  - choose external resistors that are *large* compared with the output resistance of the op-amp.
- Generally we use resistors in the range 1 to 100 kΩ

Effects of feedback on op-amp circuits

- **Effects of feedback on the Gain**
  - negative feedback *reduces* gain from A to $A/(1 + AB)$
  - in return for this loss of gain we get consistency, provided that the open-loop gain is much greater than the closed-loop gain (that is, $A >> 1/B$)
  - using negative feedback, standard cookbook circuits can be used – greatly simplifying the design
  - these can be analysed without a detailed knowledge of the op-amp itself

Effects of feedback on op-amp circuits (contd.)

- **Effects of feedback on frequency response**
  - as the gain is *reduced* the bandwidth is *increased*
  - gain × bandwidth ≈ constant
    - since gain is *reduced* by $(1 + AB)$ bandwidth is *increased* by $(1 + AB)$
  - for a 741, gain × bandwidth ≈ 10^6
    - if gain = 1000 BW ≈ 1000 Hz
    - if gain = 100 BW ≈ 10,000 Hz



Effects of feedback on op-amp circuits (contd.)

- **Effects of feedback on input and output resistance**
  - input/output resistance can be increased or decreased depending on how feedback is used.
    - we looked at this in an earlier lecture
    - in each case the resistance is changed by a factor of $(1 + AB)$

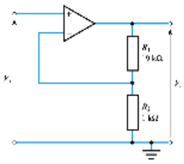
Example

- if an op-amp with a gain of 2×10^5 is used to produce an amplifier with a gain of 100 then:

$$A = 2 \times 10^5$$
$$B = 1/G = 0.01$$
$$(1 + AB) = (1 + 2000) \approx 2000$$

Effects of feedback on op-amp circuits (contd.)

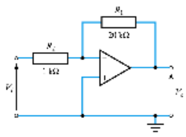
- **Example**
  - determine the input and output resistance of the following circuit assuming op-amp is a 741



Open-loop gain (A) of a 741 is 2×10^5
Closed-loop gain ($1/B$) is 20, $B = 1/20 = 0.05$
$(1 + AB) = (1 + 2 \times 10^5 \times 0.05) = 10^4$
Feedback senses output *voltage* therefore it *reduces* output resistance of op-amp (75 Ω) by 10^4 to give 7.5 mΩ
Feedback subtracts a *voltage* from the input, therefore it *increases* the input resistance of the op-amp (2 MΩ) by 10^4 to give 20 GΩ

Effects of feedback on op-amp circuits (contd.)

- **Example**
  - determine the input and output resistance of the following circuit assuming op-amp is a 741



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Feedback senses output *voltage* therefore, it *reduces* output resistance of op-amp (75 Ω) by 10^4 to give 7.5 mΩ
Feedback subtracts a *current* from the input, therefore it *decreases* the input resistance. In this case the input sees R_2 to a virtual earth, therefore the input resistance is 1 kΩ

Key points

- Operational amplifiers are among the most widely used building blocks in electronic circuits
- An *ideal* operational amplifier would have infinite voltage gain, infinite input resistance and zero output resistance
- Designers often make use of cookbook circuits
- Real op-amps have several non-ideal characteristics However, if we choose components appropriately this
  should not affect the operation of our circuits
- Feedback allows us to increase bandwidth by trading gain against bandwidth
- Feedback also allows us to alter other circuit characteristics

Op-Amp Applications

Constant-gain multiplier
Voltage summing
Voltage buffer
Controlled sources
Instrumentation circuits
Active filters

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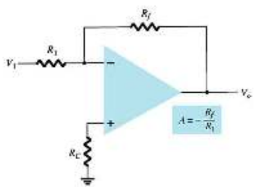
Constant-Gain Amplifier

Inverting Version



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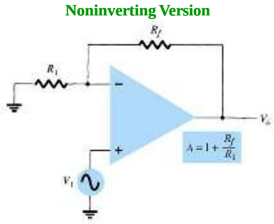
Constant-Gain Amplifier

Noninverting Version



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Multiple-Stage Gains

The total gain (3-stages) is given by:

$$A = A_1 A_2 A_3$$

or

$$A = \left(1+\frac{R_f}{R_1}\right)\left(-\frac{R_f}{R2}\right)\left(-\frac{R_f}{R3}\right)$$

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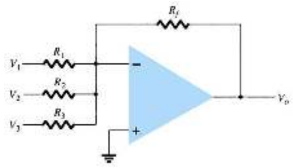
Voltage Summing

The output is the sum of individual signals times the gain:

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$



[Formula 14.3]

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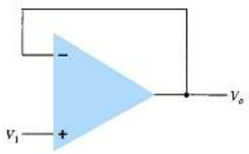
Voltage Buffer

Any amplifier with no gain or loss is called a **unity gain amplifier**.

The advantages of using a unity gain amplifier:

- Very high input impedance
- Very low output impedance

Realistically these circuits are designed using equal resistors ($R_1 = R_f$) to avoid problems with offset voltages.



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Controlled Sources

Voltage-controlled voltage source
Voltage-controlled current source
Current-controlled voltage source
Current-controlled current source

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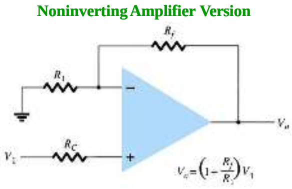
Voltage-Controlled Voltage Source

The output voltage is the gain times the input voltage. What makes an op-amp different from other amplifiers is its impedance characteristics and gain calculations that depend solely on external resistors.

Noninverting Amplifier Version



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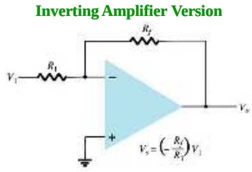
Voltage-Controlled Voltage Source

The output voltage is the gain times the input voltage. What makes an op-amp different from other amplifiers is its impedance characteristics and gain calculations that depend solely on external resistors.

Inverting Amplifier Version



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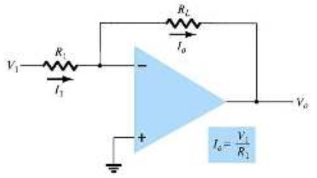
Voltage-Controlled Current Source

The output current is:

$$I_o = \frac{V_1}{R_1} = kV_1$$



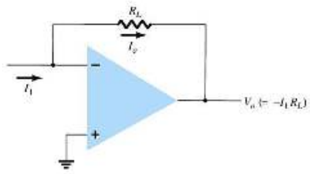
Current-Controlled Voltage Source

This is simply another way of applying the op-amp operation. Whether the input is a current determined by V_{in}/R_1 or as I_1:

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

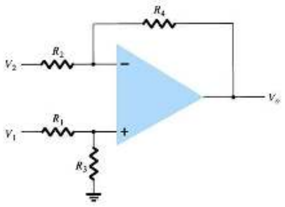
or

$$V_{out} = -I_1 R_L$$



Current-Controlled Current Source

This circuit may appear more complicated than the others but it is really the same thing.



$$V_{out} = -\left(\frac{R_f}{R_{in}}\right) V_{in} \qquad I_o = -\frac{V_{in}}{R_1 \parallel R_2}$$

$$\frac{V_{out}}{R_f} = -\frac{V_{in}}{R_1 \parallel R_2} \qquad I_o = -V_{in}\left(\frac{R_1 + R_2}{R_1 \times R_2}\right)$$

$$\frac{V_{out}}{R_f} = -\frac{V_{in}}{R_{in}} \qquad I_o = -\frac{V_{in}}{R_1}\left(\frac{R_1 + R_2}{R_2}\right)$$

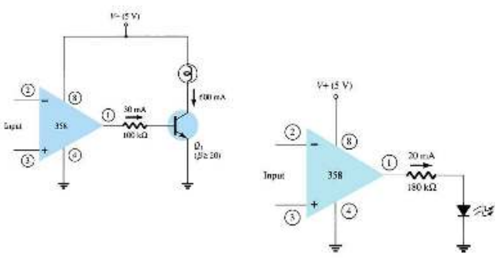
$$I_o = -I\left(1 + \frac{R_1}{R_2}\right) = kI$$

Instrumentation Circuits

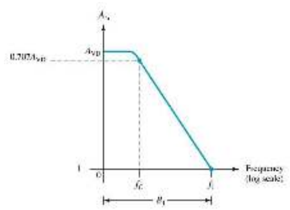
Some examples of instrumentation circuits using op-amps:

- Display driver
- Instrumentation amplifier

Display Driver



Instrumentation Amplifier



For all Rs at the same value (except R_p):

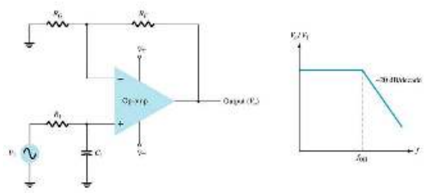
$$V_o = \left(1 + \frac{2R}{R_P}\right)(V_1 - V_2) = k(V_1 - V_2)$$

Active Filters

Adding capacitors to op-amp circuits provides external control of the cutoff frequencies. The op-amp active filter provides controllable cutoff frequencies and controllable gain.

- Low-pass filter
- High-pass filter
- Bandpass filter

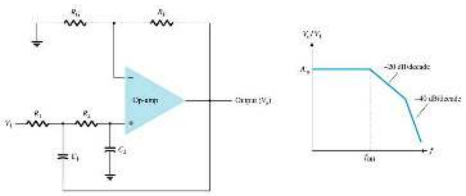
Low-Pass Filter—First-Order



The upper cutoff frequency and voltage gain are given by:

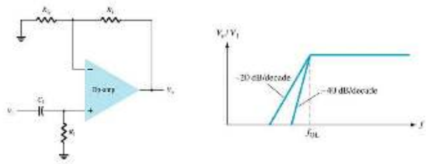
$$f_{OH} = \frac{1}{2\pi R_1 C_1} \qquad A_v = 1 + \frac{R_f}{R_1}$$

Low-Pass Filter—Second-Order



The roll-off can be made steeper by adding more RC networks.

High-Pass Filter



The cutoff frequency is determined by:

$$f_{OL} = \frac{1}{2\pi R_1 C_1}$$

Bandpass Filter

There are two cutoff frequencies: upper and lower. They can be calculated using the same low-pass cutoff and high-pass cutoff frequency formulas in the appropriate sections.