Electronic Circuits

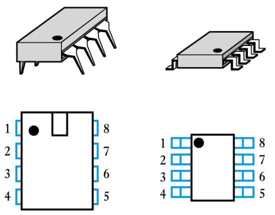
Prof. Dr. Nizamettin AYDIN
naydin@yildiz.edu.tr
http://www.yildiz.edu.tr/~naydin

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…

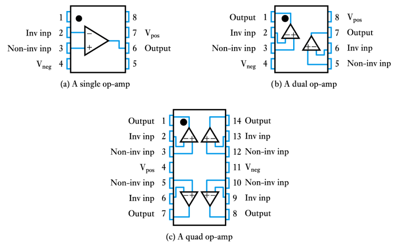
- Operational amplifiers (op-amps) are among the most widely used building blocks in electronics
  - they are integrated circuits (ICs)
    - often DIL or SMT



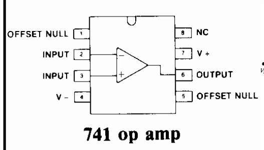
(a) A DIL package (b) An SMT package

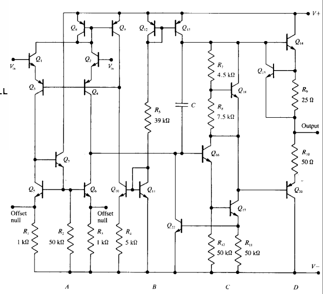
…Introduction

- A single package will often contain several op-amps



Inside the Op-Amp (IC-chip)



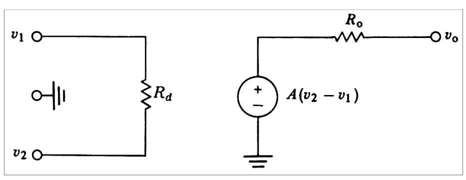


20 transistors
11 resistors
1 capacitor

Ideal Op-Amp

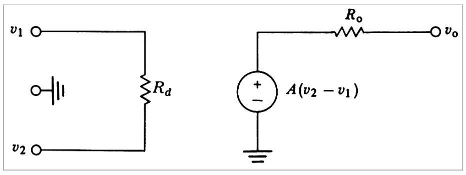
- Most bioelectric signals are small and require amplifications

Op-amp equivalent circuit:



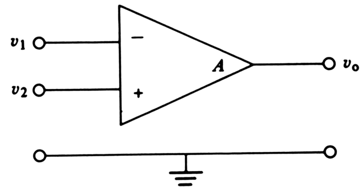
The two inputs are v_1 and v_2. A differential voltage between them causes current flow through the differential resistance R_d. The differential voltage is multiplied by A, the gain of the op amp, to generate the output-voltage source. Any current flowing to the output terminal v_o must pass through the output resistance R_o.

Ideal Characteristics



- $A = \infty$ (gain is infinity)
- $V_o = 0$, when $v_1 = v_2$ (no offset voltage)
- $R_d = \infty$ (input impedance is infinity)
- $R_o = 0$ (output impedance is zero)
- Bandwidth = ∞ (no frequency response limitations) and no phase shift

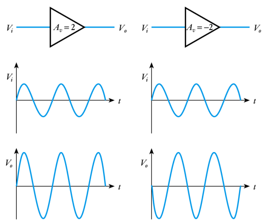
Two Basic Rules



- **Rule 1**
  - When the op-amp output is in its linear range, the two input terminals are at the same voltage.
- **Rule 2**
  - No current flows into or out of either input terminal of the op amp.

Basic operational amplifier circuits…

- Inverting and non-inverting amplifiers



(a) A non-inverting amplifier (b) An inverting amplifier

…Basic operational amplifier circuits…

- 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…

- A non-inverting amplifier

Analysis

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

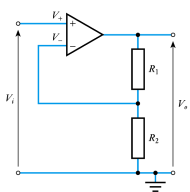
$$V_- = V_+ = V_i$$

Since the input resistance of the op-amp is ∞

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

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

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



…Basic operational amplifier circuits…

- Example

Design a non-inverting amplifier with a gain of 25

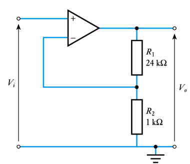
From above $G = \frac{V_o}{V_i} = \frac{R_1 + R_2}{R_2}$

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

$$R_1 + R_2 = 25R_2$$

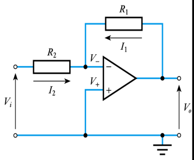
$$R_1 = 24R_2$$

Therefore choose $R_2 = 1\ \text{k}\Omega$ and $R_1 = 24\ \text{k}\Omega$
(choice of values will be discussed later)



…Basic operational amplifier circuits…

- An inverting amplifier



Analysis...

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

$$V_- = V_+ = 0$$

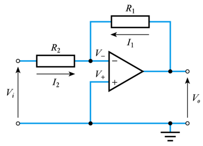
Since the input resistance of the op-amp is ∞ its input current must be zero, and hence

$$I_1 = -I_2$$

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…

...Analysis



Therefore, since $I_1 = -I_2$

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

or, rearranging

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

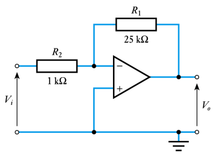
- Here V_- is held at zero volts by the operation of the circuit, hence the circuit is known as a virtual earth circuit

…Basic operational amplifier circuits

- Example

Design an inverting amplifier with a gain of –25

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



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

$$R_1 = 25R_2$$

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…

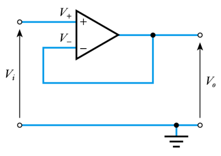
- A unity gain buffer amplifier

Analysis

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

Hence

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

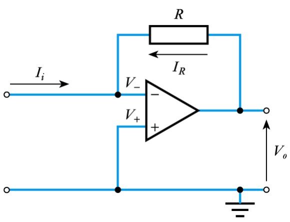


Thus the circuit has a gain of unity

- 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…

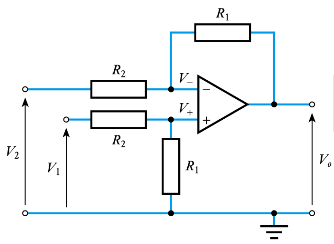
- A current to voltage converter



$$V_o = -I_i R$$

…Other useful circuits…

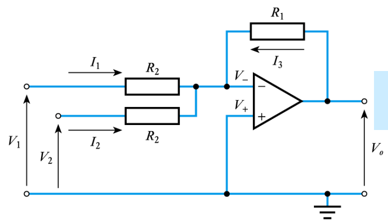
- A differential amplifier (or subtractor)



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

…Other useful circuits…

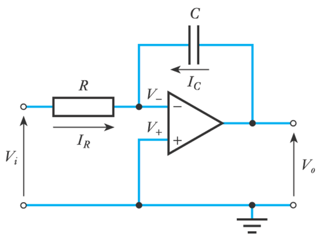
- An inverting summing amplifier



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

…Other useful circuits…

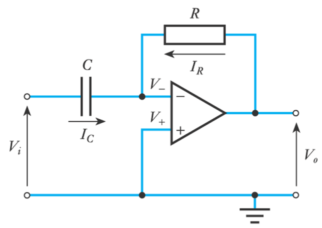
- An integrator



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

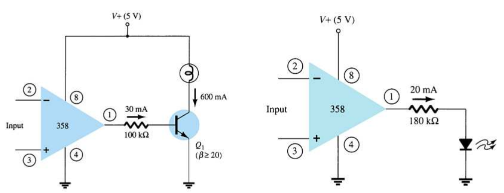
…Other useful circuits

- A differentiator



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

Display Driver

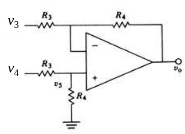


Differential Amplifiers

- **Differential Gain G_d**

$$G_d = \frac{v_o}{v_4 - v_3} = \frac{R_4}{R_3}$$

- **Common Mode Gain G_c**
  - For ideal op amp if the inputs are equal then the output = 0, and the $G_c = 0$.
  - No differential amplifier perfectly rejects the common-mode voltage.
- **Common-mode rejection ratio *CMMR***
  - Typical values range from 100 to 10,000

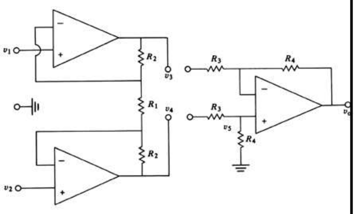


$$v_o = \frac{R_4}{R_3}(v_4 - v_3)$$

$$CMRR = \frac{G_d}{G_c}$$

- Disadvantage of one-op-amp differential amplifier is its low input resistance

Instrumentation Amplifiers



Differential Mode Gain

$$v_3 - v_4 = i(R_2 + R_1 + R_2)$$

$$v_1 - v_2 = iR_1$$

$$G_d = \frac{v_3 - v_4}{v_1 - v_2} = \frac{2R_2 + R_1}{R_1}$$

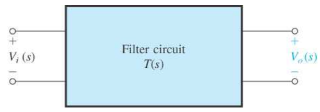
Advantages: High input impedance, High CMRR, Variable gain

25

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.

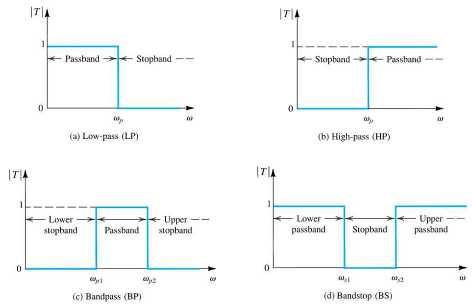
- Low-pass filter
- High-pass filter
- Bandpass filter
- Bandstop filter



The filter transfer function $T(s) \equiv V_o(s)/V_i(s)$.

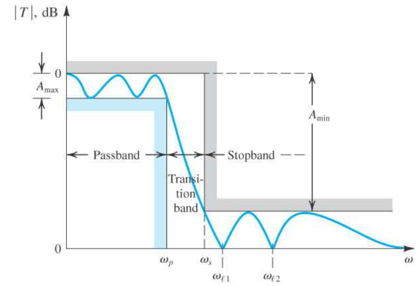
26

Ideal transmission characteristics



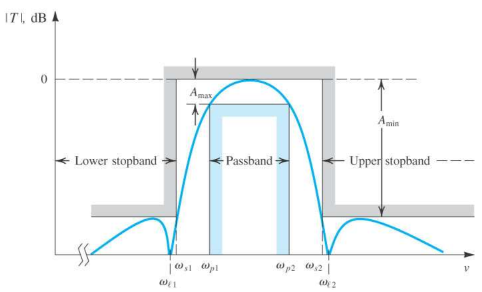
27

Specification of the transmission characteristics of a low-pass filter



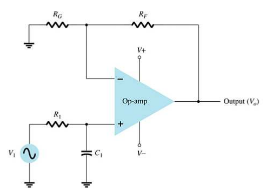
28

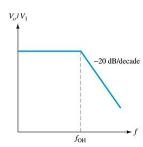
Specification of the transmission characteristics of a bandpass filter



29

Low-Pass Filter—First-Order



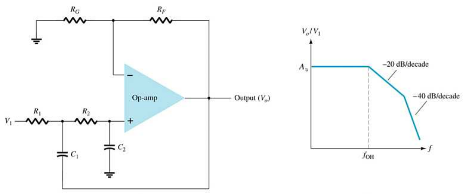


The upper cutoff frequency and voltage gain are given by:

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

30

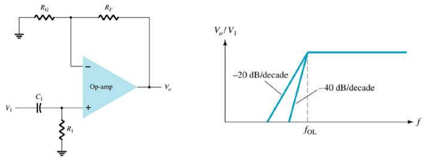
Low-Pass Filter—Second-Order



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

31

High-Pass Filter



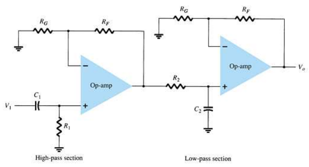
The cutoff frequency is determined by:

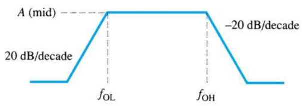
$$\mathbf{f_{OL} = \frac{1}{2\pi R_1 C_1}}$$

32

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.





33

Multiple-Stage Gains…

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

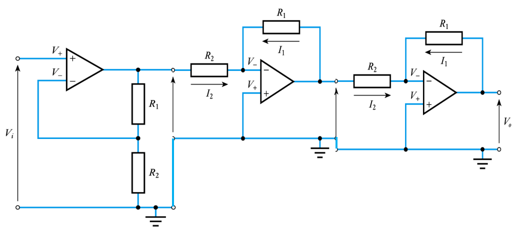
$$\mathbf{A = A_1 A_2 A_3}$$

or

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

34

…Multiple-Stage Gains



$$A_1 = \frac{V_o}{V_i} = \frac{R_1 + R_2}{R_2} \qquad A_2 = \frac{V_o}{V_i} = -\frac{R_1}{R_2} \qquad A_3 = \frac{V_o}{V_i} = -\frac{R_1}{R_2}$$

$$A = A_1 \times A_2 \times A_3 = \frac{R_1 + R_2}{R_2} \times \left(-\frac{R_1}{R_2}\right) \times \left(-\frac{R_1}{R_2}\right) = \frac{R_1^3 + R_1^2 \times R_2}{R_2^3}$$

35

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

36

…Real operational amplifiers…

- 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…

- 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…

- 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 1 amper or more

…Real operational amplifiers…

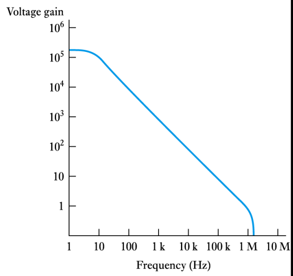
- Supply voltage range
  - a typical arrangement would use supply voltages of +15 V and – 15 V, but a wide range of supply voltages is usually possible
  - the 741 can use voltages in the range ±5 to ±18 V
  - some devices allow voltages up to ±30 V or more
  - others, designed for low voltages, may use ±1.5 V
  - many op-amps permit single voltage supply operation, typically in the range 4 to 30 V

…Real operational amplifiers…

- 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

- 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

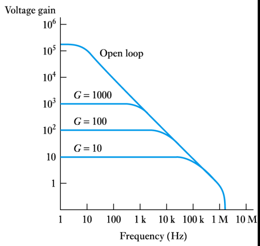
- Our analysis assumed the use of an ideal op-amp
- When using real components we need to ensure that our assumptions are valid
- In general this will be true if we:
  - limit the gain of our circuit to *much less* than the open-loop gain of our op-amp
  - choose external resistors that are *small* compared 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…

- 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



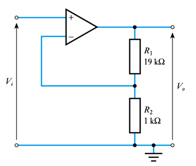
…Effects of feedback on op-amp circuits…

- 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…

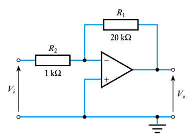
- Example
  - determine the input and output resistance of the following circuit assuming op-amp is a 741



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

- 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 *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