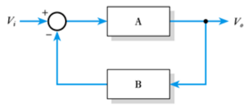
Last time: Feedback and control



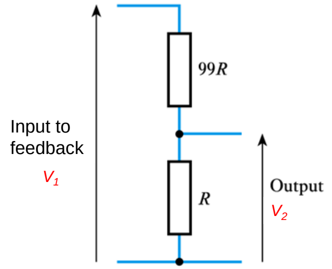
- Have a forward (open loop) gain = *A*
- Have a feedback gain = *B*
- Total system gain (input to output) $G = A/(1+AB)$

- IF $AB>0$ (i.e. positive) we have:
  - Negative feedback and $G < A$
- IF $AB>>1 \Rightarrow A>>1/B$
  - Total system gain $G \approx 1/B$ (Independent of A)

16.1

fortunately, *B* can be based on stable passive components

- Implementing the passive feedback path
  - to get an overall gain of greater than 1 requires a feedback gain *B* of less than 1
  - in our previous example the value of *B* is 0.01
  - this can be achieved using a simple potential divider



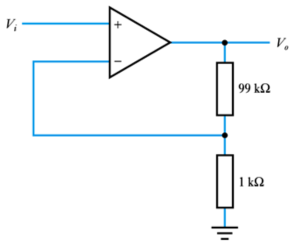
$V_2 = I \cdot R$

$I = \dfrac{V_1}{R+99R}$

$V_2 = \dfrac{V_1}{R+99R} \cdot R = \dfrac{V_1}{100}$

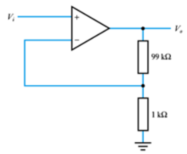
16.2

- Thus, we can implement our feedback arrangement using an active amplifier and a passive feedback network to produce a stable amplifier
- A differential amplifier is effectively an active amplifier combined with a subtractor. A common form is the **operational amplifier** or **op-amp**
- The op-amp arrangement on the right has a gain of 100



16.3

- In this circuit the gain is determined by the passive components and we do not need to know the gain of the op-amp
  - however, earlier we assumed that *AB* >> 1
  - that is, *A* >> 1/*B*
  - that is, **open-loop gain >> closed-loop gain**
  - therefore, the gain of the circuit must be much less than the gain of the op-amp
  - see **Example 15.2** in the course text



16.4

15.6

The effects of negative feedback

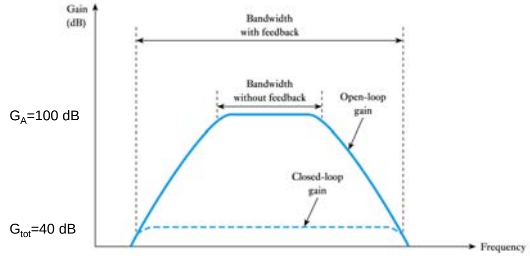
- **Effects on gain**
  - negative feedback produces a gain given by

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

  - there, feedback *reduces* the gain by a factor of $1 + AB$
  - this is the price we pay for the beneficial effects of negative feedback

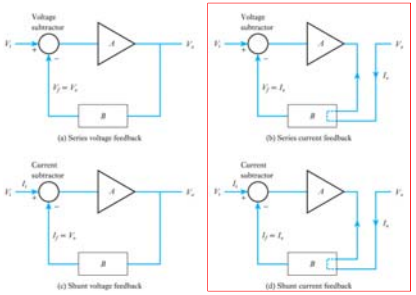
The effects of negative feedback on bandwidth

- amplifiers have limited frequency response and bandwidth
- but bandwidth *increases* as gain is *reduced* with feedback
- in some cases the **gain x bandwidth = constant**



The effects of negative feedback (contd.)

- **Effects on input and output resistance**
  - negative feedback can be used in a number of ways.



We won't discuss systems where: feedback ∝ I_{out}

- negative feedback can either *increase* or *decrease* the input or output resistance depending on how it is used.
  - if the output voltage is fed back this tends to make the output voltage more stable by *decreasing* the output resistance
  - Not covered: if the output current is fed back this tends to make the output current more stable by *increasing* the output resistance
  - if a voltage related to the output is subtracted from the input voltage this *increases* the input resistance
  - if a current related to the output is subtracted from the input current this *decreases* the input resistance
  - the factor by which the resistance changes is $(1 + AB)$
  - we will apply this to op-amps in a later lecture

- **Effects on distortion and noise**
  - many forms of **distortion** are caused by a non-linear amplitude response
    - that is, the gain varies with the amplitude of the signal
  - since feedback tends to stabilise the gain it also tends to reduce distortion – often by a factor of (1 + *AB*)
  - **noise** produced *within* an amplifier is also reduced by negative feedback – again by a factor of (1 + *AB*)
    - note that noise already corrupting the input signal is *not* reduced in this way – this is amplified along with the signal

- **Effects on stability**
  - from earlier we know that

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

  - so far we have assumed that *A* and *B* are positive real numbers
  - real amplifiers produce phase shifts as gain falls with frequency
  - a phase shift of 180° represents an inversion of the gain
  - this will turn *negative* feedback into *positive* feedback
  - therefore, feedback has implication for **stability**
  - we will return to look at stability in later lectures

Negative feedback – a summary

15.7

- All negative feedback systems share some properties
  1. They tend to maintain their output independent of variations in the forward path or in the environment
  2. They require a forward path gain that is greater than that which would be necessary to achieve the required output in the absence of feedback
  3. The overall behaviour of the system is determined by the nature of the feedback path
- Unfortunately, negative feedback does have implications for the **stability** of circuits – discussed in later lectures

Further Study

Video 15C

Further Study

- The Further Study section at the end of Chapter 15 sites an air conditioning system as an example of an arrangement that can be either open- or closed-loop in operation.
- Identify a range of other control systems and decide whether these are open- or closed-loop arrangements and then watch the video.

Storey: Electronics: A Systems Approach 4th Ed.

Key points Feedback and control

- Feedback is used in almost all automatic control systems
- Feedback can be either negative or positive
- If the gain of the forward path is A, the gain of the feedback path is B and the feedback is subtracted from the input then

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

- If AB is positive and much greater than 1, then $G \approx 1/B$
- Negative feedback can be used to overcome problems of variability within active amplifiers
- Negative feedback can be used to increase bandwidth, and to improve other circuit characteristics

Today: Operational amplifiers

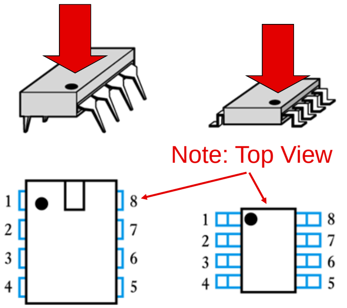
Chapter 16

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

Introduction

5.1

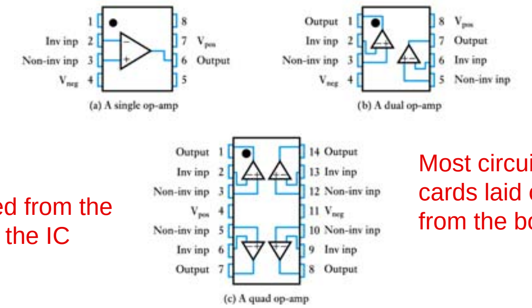
- **Operational amplifiers** (**op-amps**) are among the most widely used ***building blocks*** in electronics
  - they are integrated circuits (ICs)
    - often DIL (dual in-line) or SMT (surface mount technology)



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

Introduction (contd.)

- A single package will often contain several op-amps



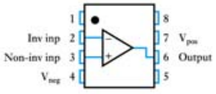
Note:

Viewed from the top of the IC

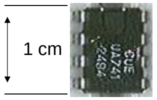
Most circuit cards laid out from the bottom!!

Introduction (contd.)

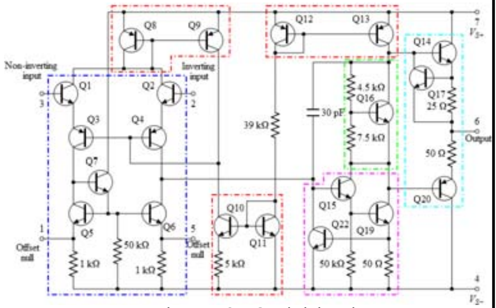
- What's in the box?



(a) A single op-amp



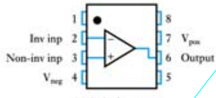
LM741
In production since 1968



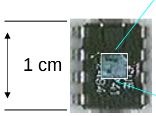
Price: 5.78 NOK (DigiKey)

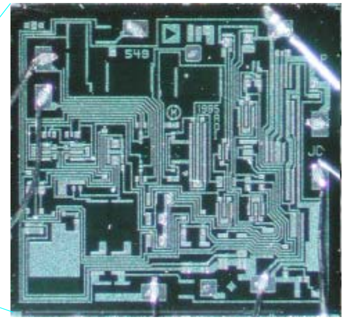
Introduction (contd.)

- What's in the box?



(a) A single op-amp

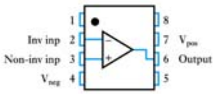




LM741
In production since 1968

Amplifiers

- We have seen that we can use operational amplifiers to create single input, differential and subtractor amplifiers
- But ***right out of the box*** operational amplifiers will ***NOT*** do this:



(a) A single op-amp

Can not just connect two signals to pin 1 and 2, and output an amplified version of their difference

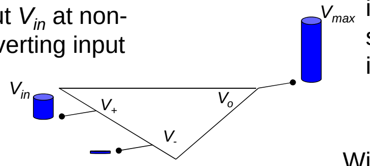
Need external feedback circuitry to accomplish this

Amplifiers (contd.)

- The amplifier has zero output when there is no voltage difference between the V_+ and V_- inputs.
- But, ANY difference in voltage between V_+ and V_- will force the output to swing AS FAR AS IT CAN in an attempt to cancel the voltage difference (by trying to adjust inverting input)
- Require Feedback to control how far the output swings

Amplifiers without feedback

Put V_{in} at non-inverting input



Put *0 V* at inverting input

Output tries to bring inverting input up to the same voltage as the non-inverting input

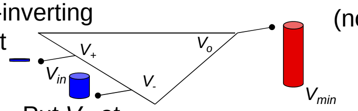
Without feedback, output will go to maximum

(It has no way to get voltage to V_-)

Slew rates ≈ a few volts/μs

Amplifiers without feedback (contd.)

Put *0 V* at non-inverting input



Put V_{in} at inverting input

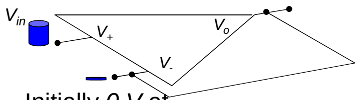
Without feedback, output will go to *minimum*

(no way to get voltage to V_-)

Output tries to bring inverting input *down* to the same voltage as the non-inverting input

Amplifiers with (negative) feedback

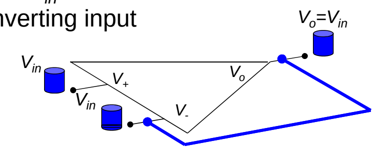
Put V_{in} at non-inverting input



Initially *0 V* at inverting input

Amplifiers with (negative) feedback

Put V_{in} at non-inverting input



Voltage at the non-inverting input rises with V_o

Output tries to bring inverting input up to the same voltage as the non-inverting input

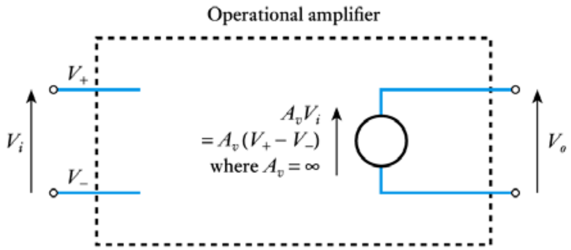
Since there is no voltage drop in the loop, the output stops rising when $V_{out}=V_{in}$

With feedback, output will Always go to the point where $\Delta V_{inputs} = 0$

An ideal operational amplifier

16.2

- 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

Real vs. Ideal Op-Amps

Parameter	Ideal Op Amp	Typical Op Amp
Differential voltage gain A	∞	$10^5 - 10^9$
Common mode voltage gain	0	10^{-5}
Gain bandwidth product f	∞	1-20 MHz
Input resistance R	∞	$10^6\,\Omega$ (bipolar) $10^9 - 10^{12}\,\Omega$ (FET)
Output resistance R	0	100-1000 Ω

Simpson, Robert E., Introductory Electronics for Scientists and Engineers, 2nd Ed., Allyn and Bacon, 1987

Close enough to ideal that we can analyse circuits assuming ideal op-amps

Basic operational amplifier circuits

Video 16A 16.3

- 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
- Open-loop gain so big, assume system gain =1/B
- 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
  - But the use of ideal components makes the analysis of these circuits very straightforward

Basic operational amplifier circuits (contd.)

- Two Basic Rules

  1)An Op-Amp will do whatever is necessary with its output to adjust the voltage at its inverting input so that it is equal to the voltage at its non-inverting input. I.e. make the voltage difference between its inputs equal to zero.

  2)Op-Amp inputs draw virtually no current (0.2nA to fA). (*For an ideal op-amp $I_{in} = 0$*)

Horowitz, Paul and Hill, Winfred,The Art of Electronics, Cambridge University Press, 1980

Basic operational amplifier circuits (contd.)

- **A non-inverting amplifier**

Analysis: Where does the current flow?

Since the gain is assumed infinite, if V_o is finite there is no difference in input voltages (Rule1).

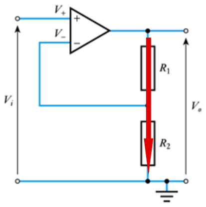
Hence: $V_- = V_+ = V_i$

Since the input resistance of the op-amp is ∞ and no current flows into it (Rule 2)

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

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 (contd.)

- **Example** (see **Example 16.1** in the course text)

Design a non-inverting amplifier with a gain of 25

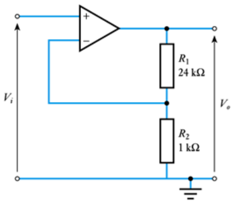
From above $G = \frac{V_o}{V_i} = \frac{R_1 + R_2}{R_2}$

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.)

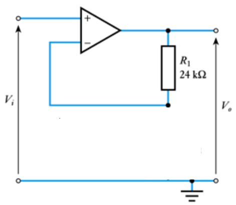
- **What happens if R_2 goes away?**

Well, how much current, I_f, will flow from output to input through R_1?

•Answer: None (Rule 2-no current flows into the inputs!)

•Means that no voltage is dropped across R_1

•Means that voltage at inverting input = V_o



ΔV at inputs =0 when $V_o = V_i$

Basic operational amplifier circuits (contd.)

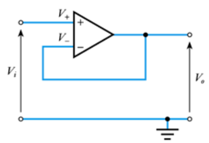
- **A unity gain buffer amplifier**

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**

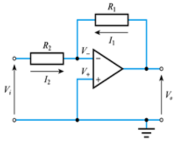
16.3.2

- **An inverting amplifier**

Analysis

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

$$V_- = V_+ = 0 \quad (Rule\ 1)$$



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

$$I_1 + I_2 - I_{in-} = 0 \qquad But\ as\ I_{in-} = 0 \ \ (Rule\ 2) \quad I_1 = -I_2$$

Now

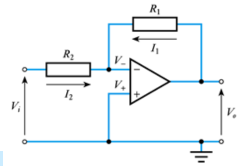
$$I_1 = \frac{V_o - V_-}{R_1} = \frac{V_o - 0}{R_1} = \frac{V_o}{R_1} \qquad I_2 = \frac{V_i - V_-}{R_2} = \frac{V_i - 0}{R_2} = \frac{V_i}{R_2}$$

16.33

- **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**
- Real amp V_- and V_+ are at the ~same potential, $R_{in} \approx R_2$
- As $V_- \rightarrow V_+$ then $R_{in} \rightarrow R_2$ (perfect amplifier)

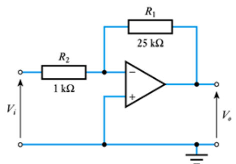
16.34

- **Example** (see **Example 16.2** in the course text)

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

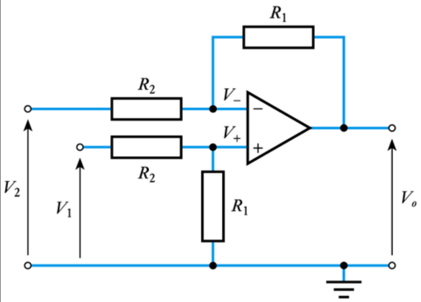
$$R_1 = 25R_2$$

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

16.35

16.4.3

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

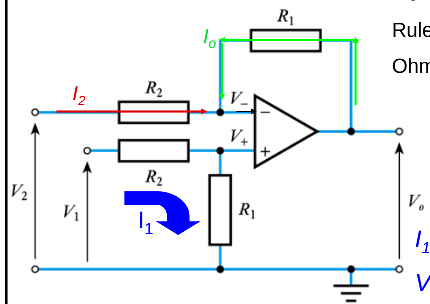


$$V_o = (V_1 - V_2)\frac{R_1}{R_2}$$

16.36

Analysis of differential amplifier

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



KCL → $I_2 + I_o + I_{in-} = 0$

Rule 2 → $I_{in-} = 0$

Ohms law → $(V_2 - V_-)/R_2 + (V_o - V_-)/R_1 = 0$

$V_- = V_+$

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

$I_1 = V_1 / (R_1 + R_2)$

$V_+ = V_1 R_1 / (R_1 + R_2)$

Some other useful circuits

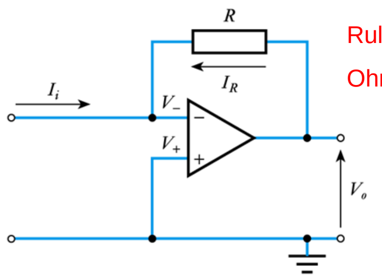
Video 16B

16.4

- 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 (clues to analysis are)
- For more details of these circuits see the relevant section of the course text (as shown on the slides)

16.4.2

- **A current to voltage converter**



KCL → $I_i + I_R - I_{in-} = 0$

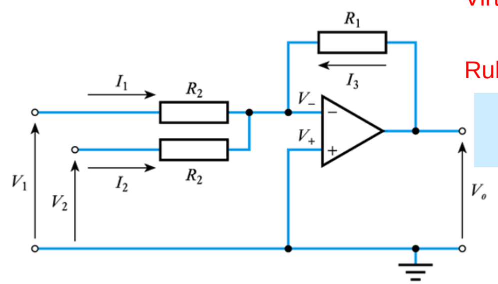
Rule 2 → $I_{in-} = 0$

Ohms law → $I_R = V_o / R$

$$V_o = -I_i R$$

16.4.4

- **An inverting summing amplifier**



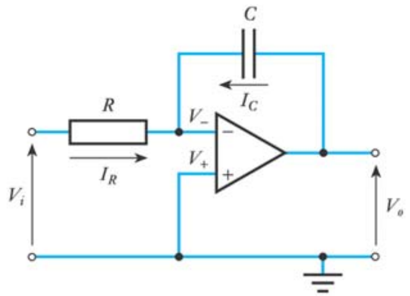
Virtual Ground, KCL: $I_1 + I_2 + I_3 - I_{in-} = 0$

Rule 2: $I_{in-} = 0$

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

16.4.5

- **An integrator**



Since $I_c + I_R = 0$ (Rule 2)
$I_c = -V_i / R$

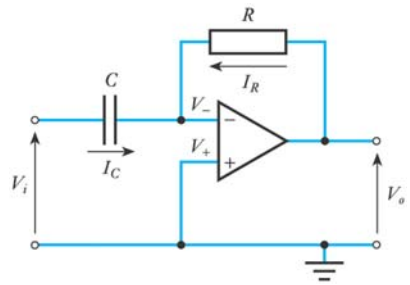
Since $V_- = V_+ = 0$ (Rule 1)
$V_o = V_c$

$$v_c(t) = \frac{1}{C}\int_0^t i_c(t')dt'$$

$$V_o = -\frac{1}{RC}\int_0^t V_i \mathrm{d}t$$

16.4.6

- **A differentiator**



Since $I_c + I_R = 0$ (Rule 2)
$I_c = -V_o / R$

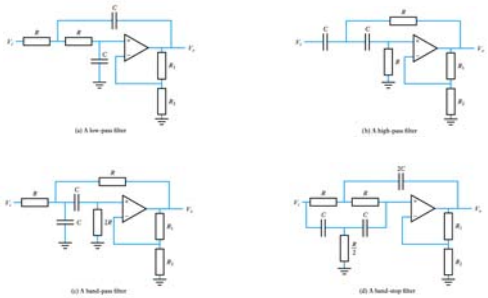
Since $V_- = V_+ = 0$ (Rule 1)
$V_i = V_c$

$$i_c(t) = C\frac{dv_c(t)}{dt}$$

$$V_o = -RC\frac{\mathrm{d}V_i}{\mathrm{d}t}$$

16.4.7

- **Active filters**



Real operational amplifiers

16.5

- 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

- **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

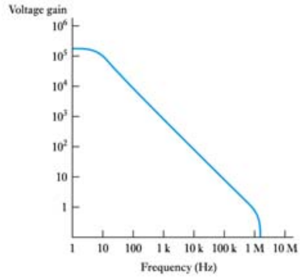
- **Input resistance**
  - typical input resistance of a 741 is 2 MΩ
  - very variable, for a 741 it can be as low as 300 kΩ
  - the above value is typical for devices based on **bipolar transistors**
  - op-amps based on **field-effect transistors** generally have a much higher input resistance – perhaps 10^{12} Ω
  - we will discuss bipolar and field-effect transistors later

- **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

- **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

- **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

- **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

16.6

- 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

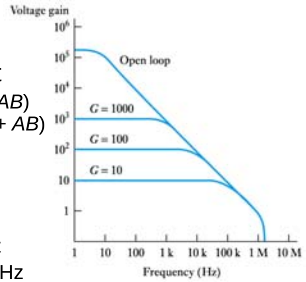
Effects of feedback on op-amp circuits

16.7

- **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

Video 16C

- **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



Video 16D

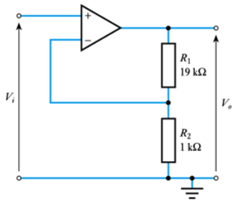
- **Effects of feedback on input and output resistance**
  - input/output resistance can be increased or decreased depending on how feedback is used
    - we looked at this in an earlier lecture
    - in each case the resistance is changed by a factor of (1 + *AB*)

Example

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

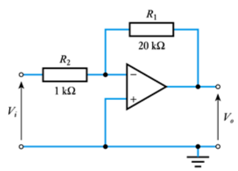
$$A = 2 \times 10^5$$
$$B = 1/G = 0.01$$
$$(1 + AB) = (1 + 2000) \approx 2000$$

- **Example** (see **Example 16.5** in the course text)
  - 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 × 10^5 × 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

- **Example** (see **Example 16.6** in the course text)
  - 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 × 10^5 × 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

Further Study

Video 16E

Further Study

- The Further Study section at the end of Chapter 16 looks at the identification of op-amp circuits.
- Normally our task is to design a circuit to perform a given task. However, it is also useful to be able to look at a circuit and see what it does!
- Look at the circuits given in the text and see if you can work out their function. Then look at the video to see if you are correct.

16.57

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

16.58