Electronic Circuits-1

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Chapter 4: Operational Amplifiers

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Operational Amplifiers

An **operational amplifier**, which is often called an **op-amp**, is a DC-coupled high-gain electronic voltage amplifier with differential inputs and, usually, a single Output. Typically the output of the op-Amp is controlled either by negative feedback, which largely determines the magnitude of its output voltage gain , or by positive feedback, which facilitates regenerative gain and oscillation.

Operational Amplifiers

.High input impedance , at the input terminals (ideally infinite) ; and low output impedance (ideally zero) are important typical characteristics.Op-amps are among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific devices .

Operational Amplifiers

Many standard IC op-amps cost only a few cents in moderate production volume; however some integrated or hybrid operational amplifiers with special performance specifications may cost over $100 US in small quantities. Modern designs are electronically more rugged than earlier implementations and some can sustain direct short circuits on their outputs without damage.

Operational Amplifiers

Features of The Ideal Op.Amp :

(Golden Rules: *logically deduce the operation of any op.amp circuit*)

1-Infinite Voltage Gain ,$A_{VD} = \infty$

2-Input Impedance is ∞ ,$Z_{in}= \infty$

3-Output Impedance is 0 , $Z_o= 0$

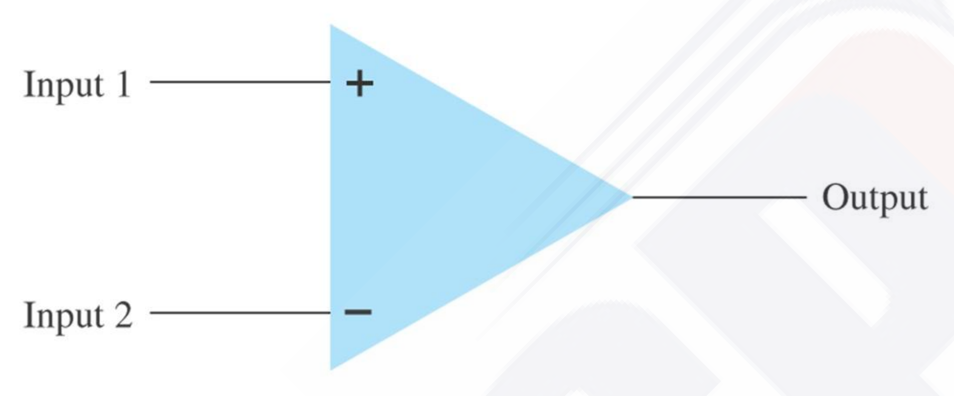
4-Infinite BW = ∞ & GBWP = ∞

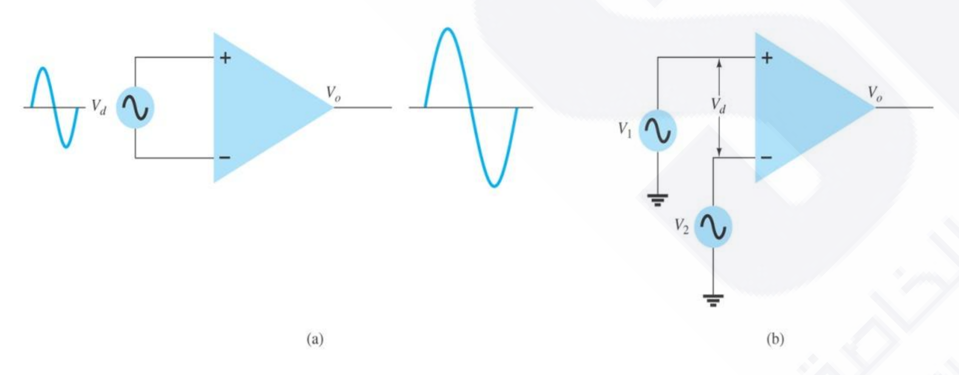
5-Zero input offset voltage(i.e.., exactly zero out if zero in)

An Op.Amp contains several DA stages to achieve a VHVG .Applications: Oscillators/Filters/Instrumentation CCT,….etc.

4.1 Introduction

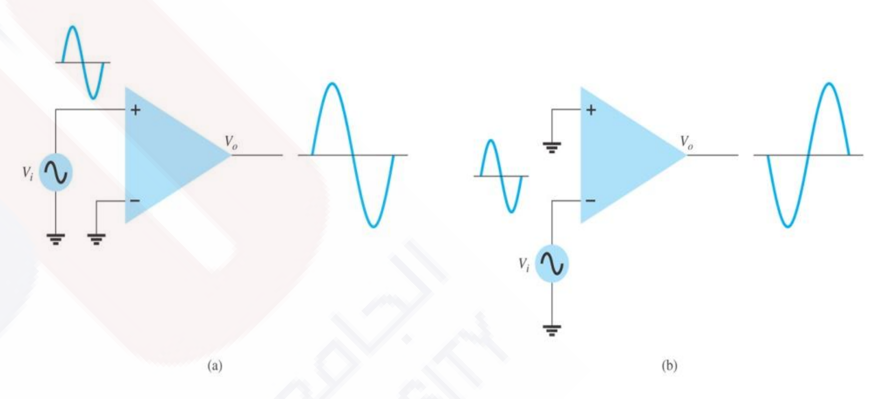
Double-Ended (Differential) Input

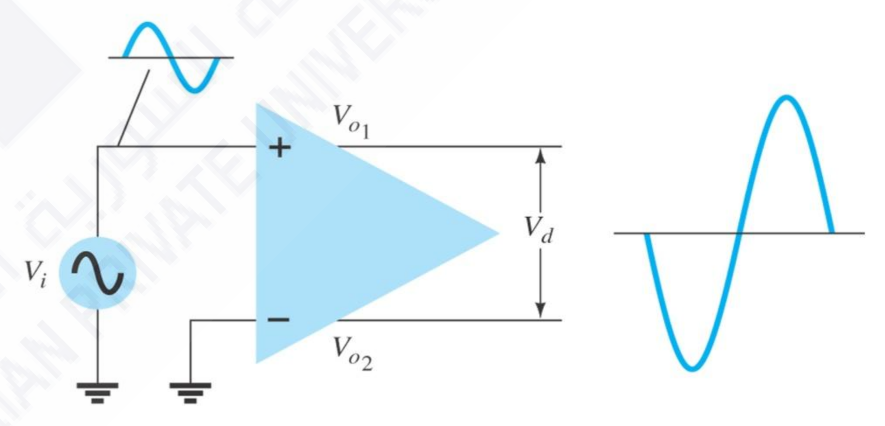




Ideal OP. AMP

Single-Ended Input





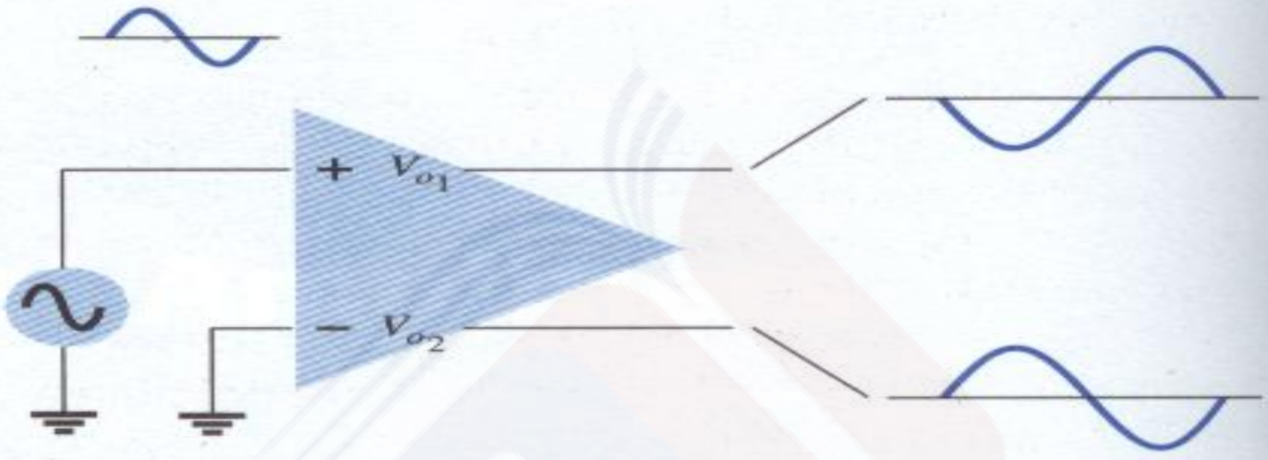


FIG. 10.5

Double-ended output with single-ended input.

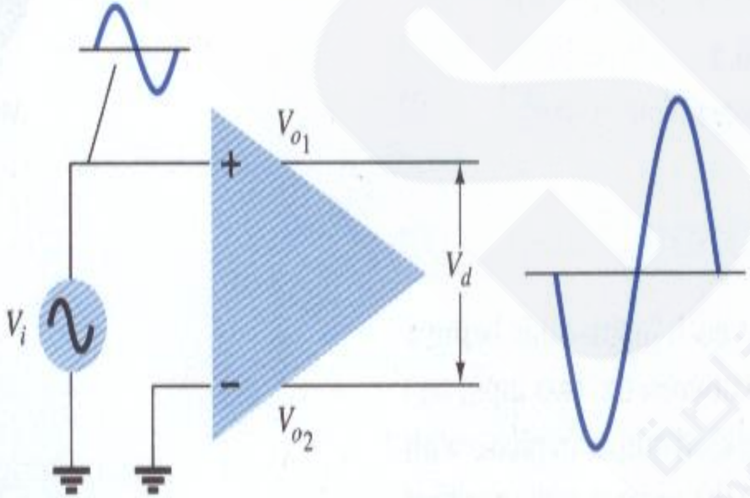


FIG. 10.6

Double-ended output.

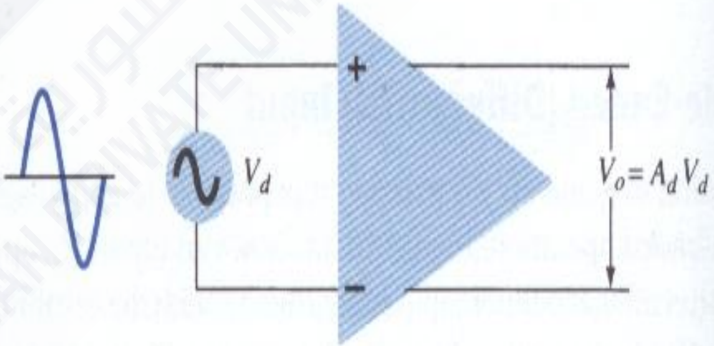
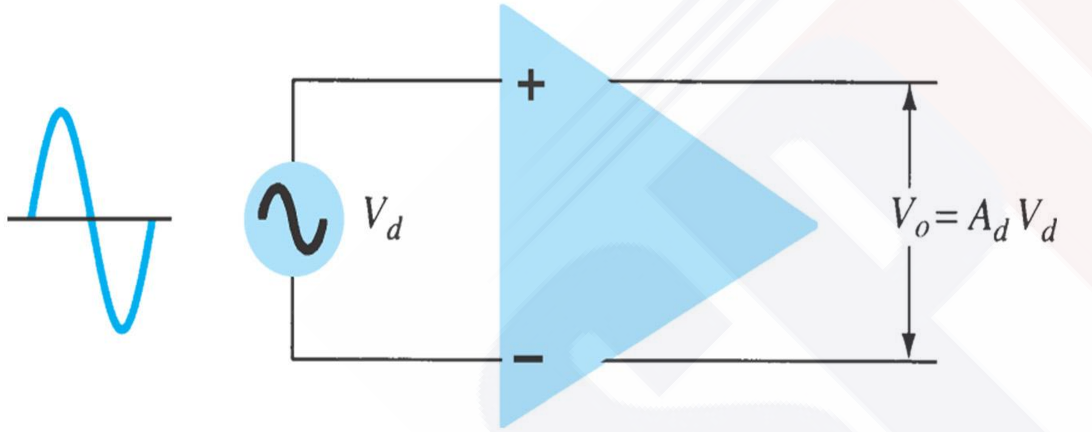


FIG. 10.7

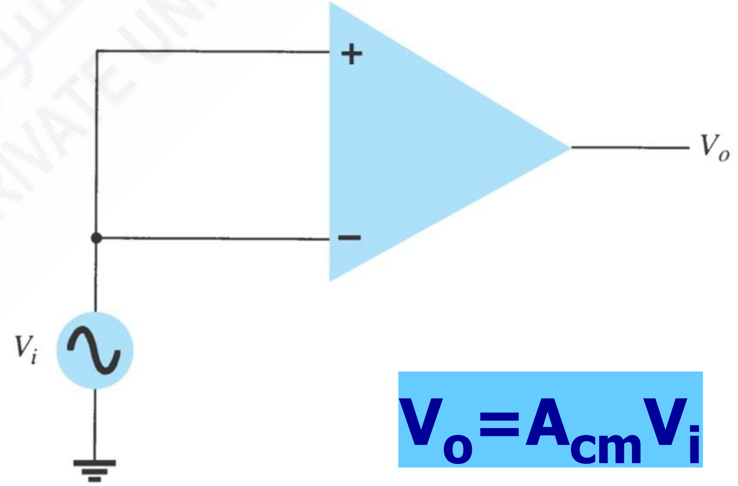
Differential-input, differential-output operation.

Differential Mode & Common Mode



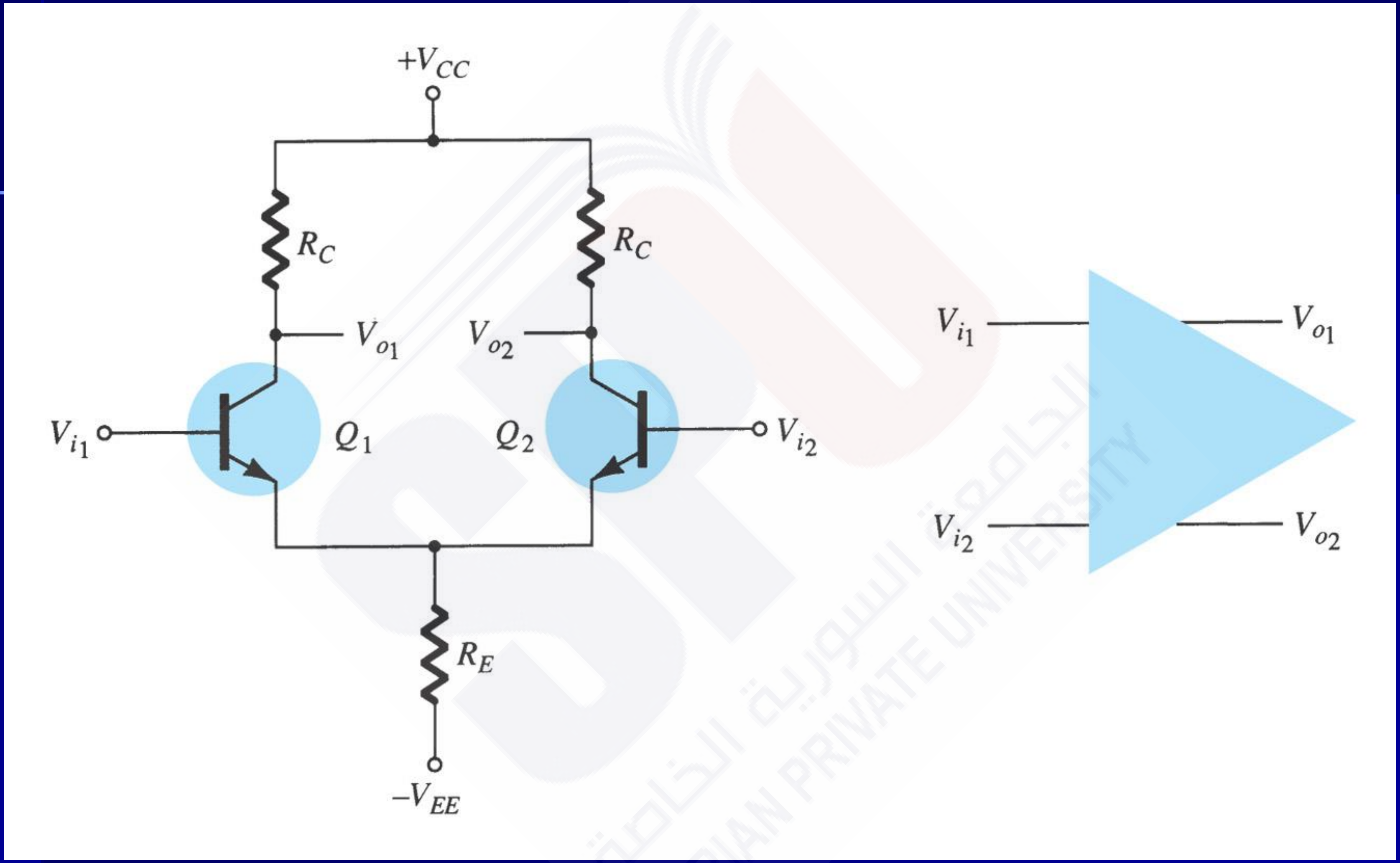
Double-Ended Output

Common-Mode Operation

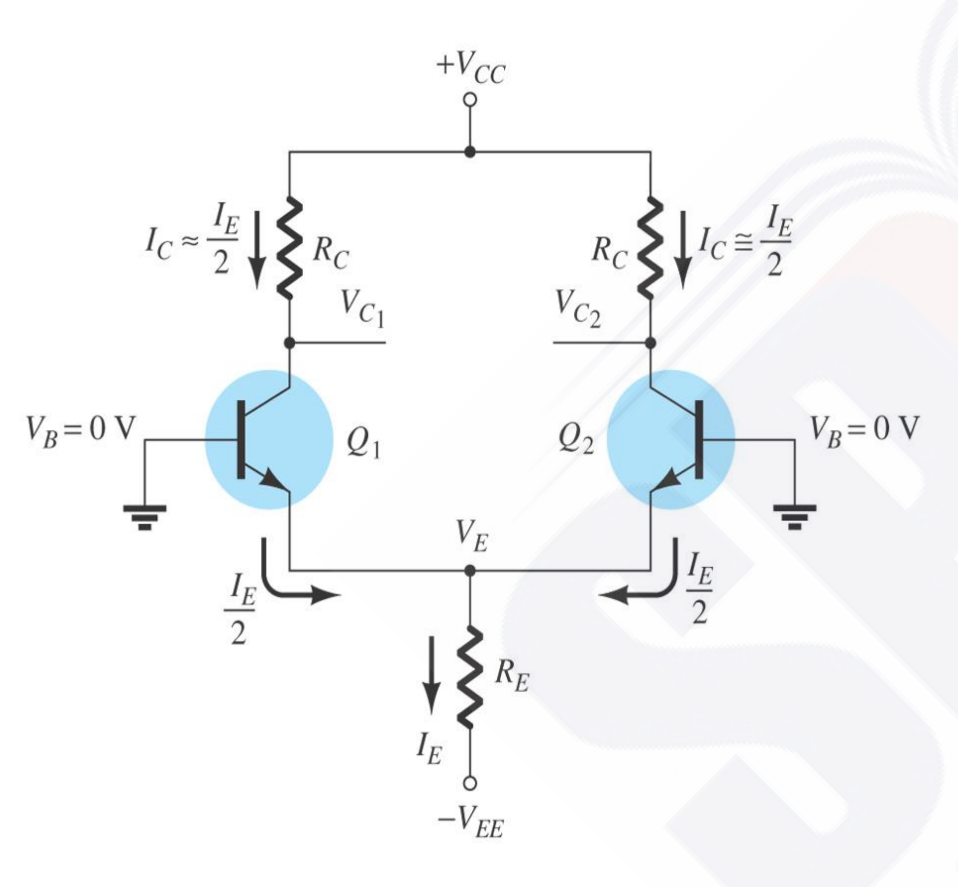


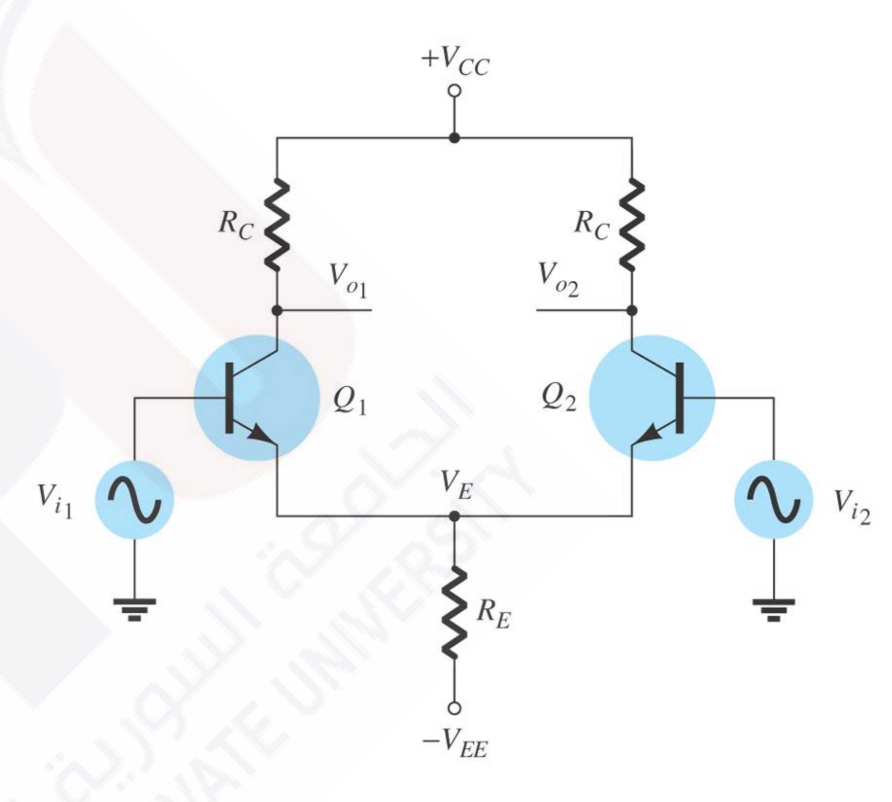
$V_o = A_{cm} V_i$

4.2 Basic Differential Amp Circuit



- DC and AC Operation of Diff. Amp





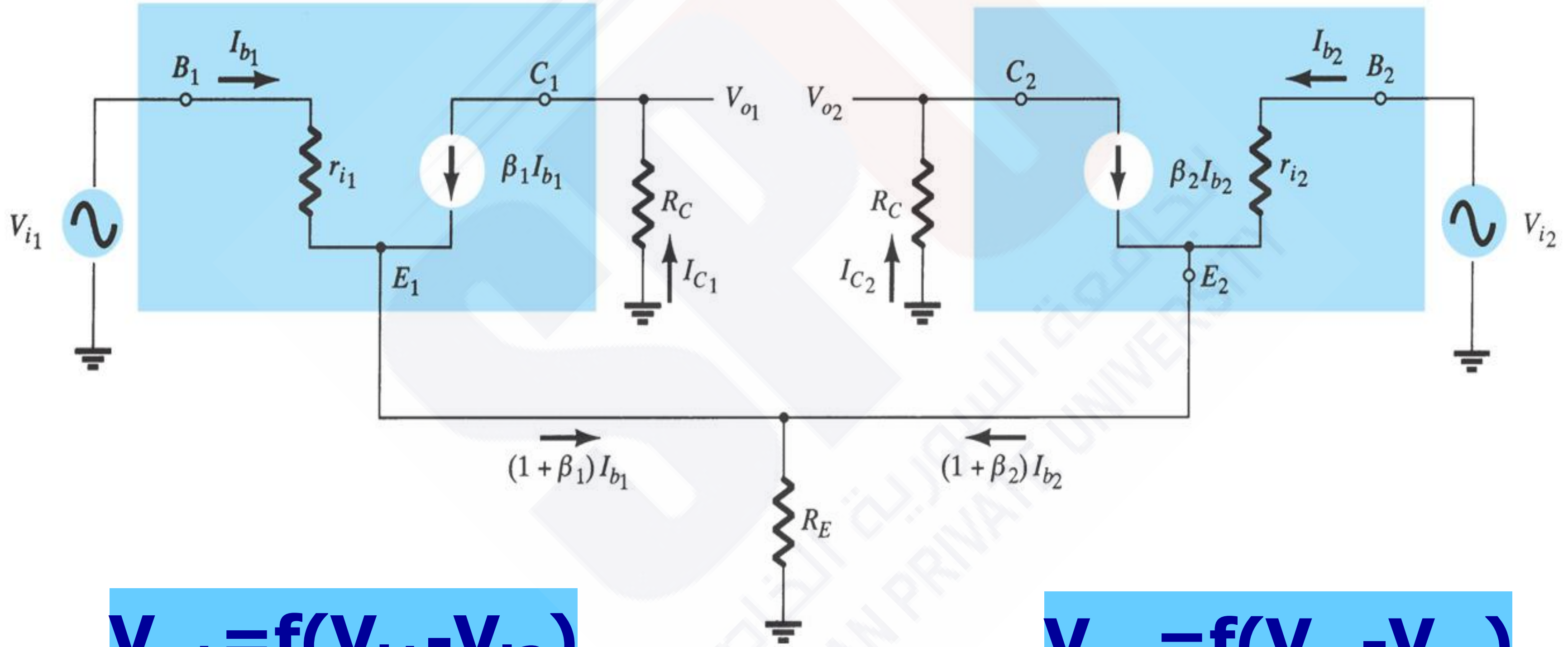
AC connection of differential amplifier.

Advantages of Differential Mode

$$I_E = \frac{V_E - (-V_{EE})}{R_E} \approx \frac{V_{EE} - 0.7\ \text{V}}{R_E}$$

$$V_{C_1} = V_{C_2} = V_{CC} - I_C R_C = V_{CC} - \frac{I_E}{2} R_C$$

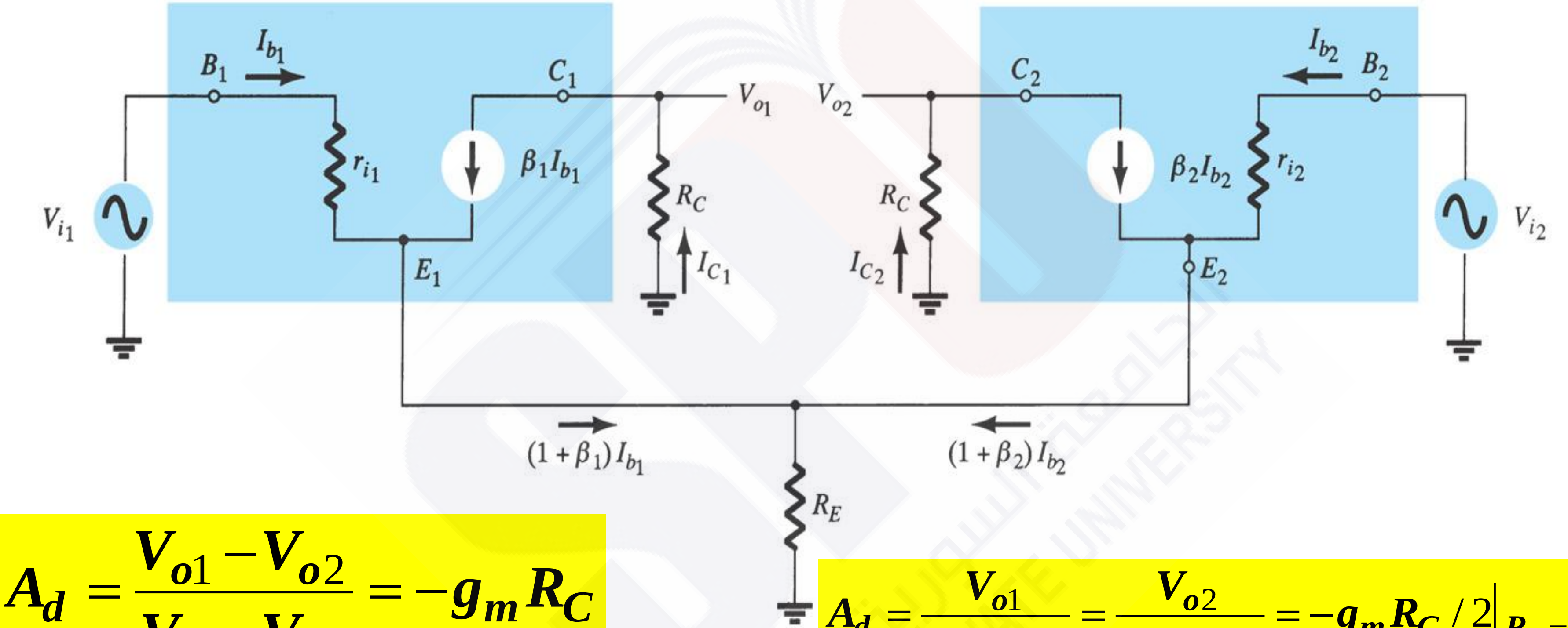
AC equivalent circuit of differential amplifier



$V_{o1}=f(V_{i1}-V_{i2})$

$V_{o2}=f(V_{i1}-V_{i2})$

AC Analysis of Differential Amplifier

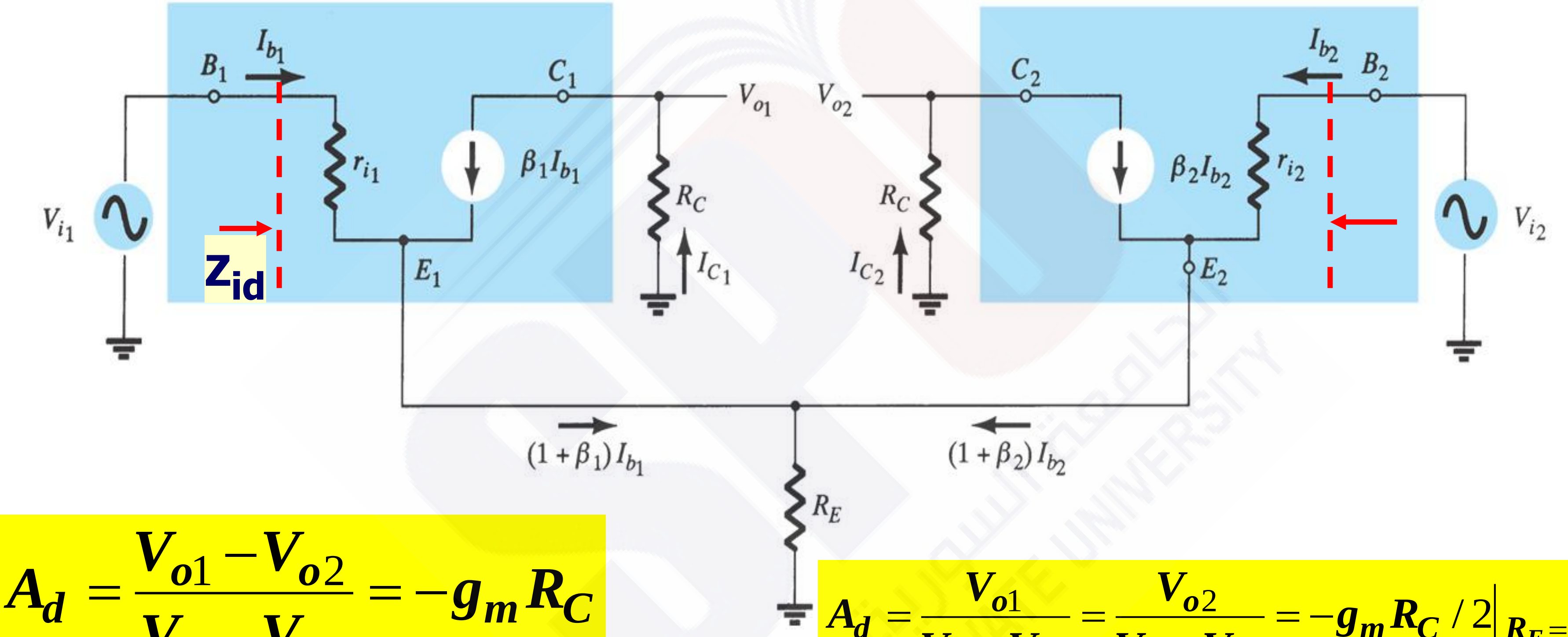


$$A_d = \frac{V_{o1} - V_{o2}}{V_{i1} - V_{i2}} = -g_m R_C$$

$$A_d = \frac{V_{o1}}{V_{i1} - V_{i2}} = \frac{V_{o2}}{V_{i1} - V_{i2}} = -g_m R_C / 2 \Big|_{R_E = \infty}$$

Differential Output **Single Output**

AC Analysis of Differential Amplifier



$$A_d = \frac{V_{o1} - V_{o2}}{V_{i1} - V_{i2}} = -g_m R_C$$

$$A_d = \frac{V_{o1}}{V_{i1} - V_{i2}} = \frac{V_{o2}}{V_{i1} - V_{i2}} = -g_m R_C / 2 \Big|_{R_E = \infty}$$

$Z_{id} = 2\beta r_e$: (between B_1 and B_2)

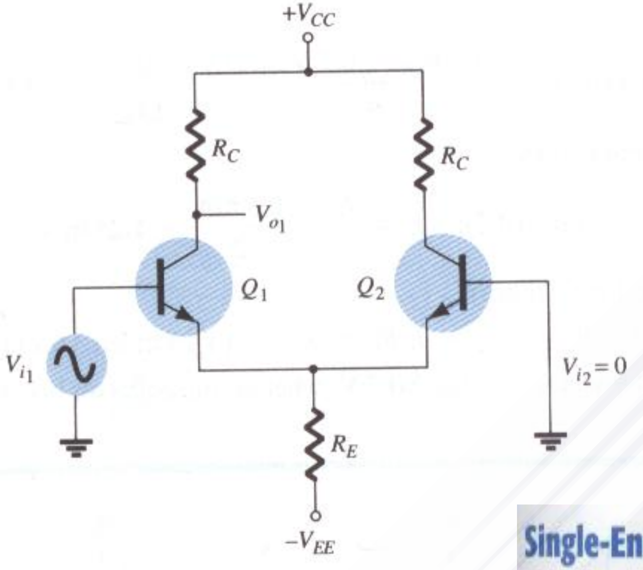


FIG. 10.14
Connection to calculate $A_{V_1} = V_{o_1}/V_{i_1}$.

Single-Ended AC Voltage Gain

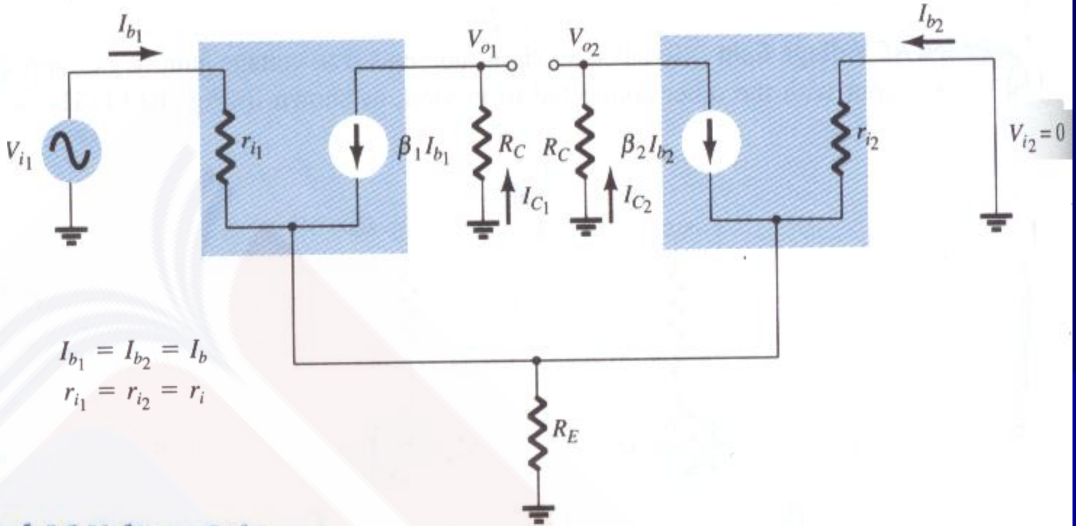


FIG. 10.15
AC equivalent of circuit in Fig. 10.14.

With R_E very large (ideally infinite), the circuit for obtaining the KVL equation simplifies to that of Fig. 10.16, from which we can write

$$V_{i_1} - I_b r_i - I_b r_i = 0$$

so that

$$I_b = \frac{V_{i_1}}{2r_i}$$

If we also assume that

$$\beta_1 = \beta_2 = \beta$$

then

$$I_C = \beta I_b = \beta \frac{V_{i_1}}{2r_i}$$

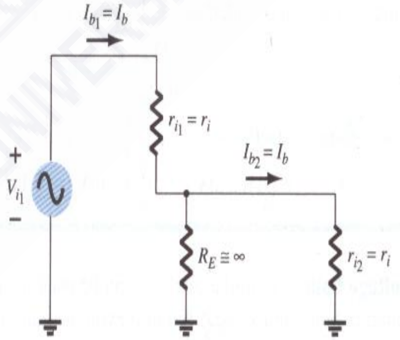


FIG. 10.16
Partial circuit for calculating I_b.

and the output voltage magnitude at either collector is

$$V_o = I_C R_C = \beta \frac{V_{i_1}}{2r_1} R_C = \frac{\beta R_C}{2\beta r_e} V_i$$

$$\boxed{A_v = \frac{V_o}{V_{i_1}} = \frac{R_C}{2r_e}}$$

EXAMPLE 10.2 Calculate the single-ended output voltage V_{o_1} for the circuit of Fig. 10.17.

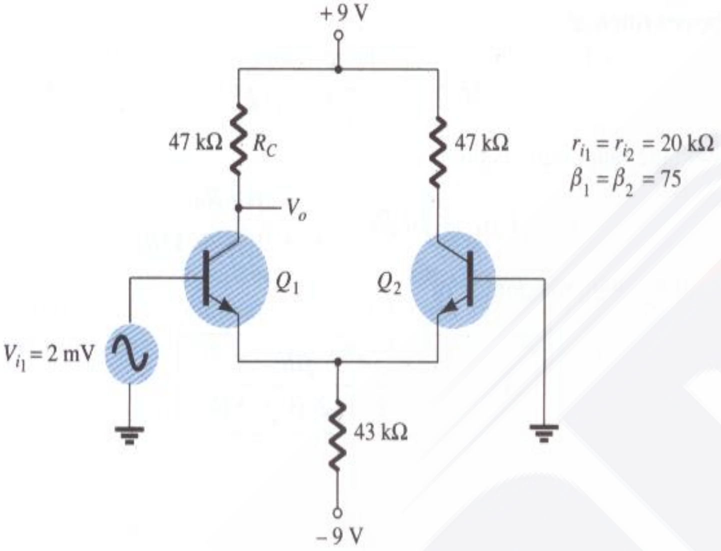


FIG. 10.17
Circuit for Examples 10.2 and 10.3.

Solution: The dc bias calculations provide

$$I_E = \frac{V_{EE} - 0.7\text{ V}}{R_E} = \frac{9\text{ V} - 0.7\text{ V}}{43\text{ k}\Omega} = 193\ \mu\text{A}$$

The collector dc current is then

$$I_C = \frac{I_E}{2} = 96.5\ \mu\text{A}$$

so that $V_C = V_{CC} - I_C R_C = 9\text{ V} - (96.5\ \mu\text{A})(47\text{ k}\Omega) = 4.5\text{ V}$

The value of r_e is

$$r_e = \frac{26}{0.0965} \cong 269\ \Omega$$

The ac voltage gain magnitude can be calculated using Eq. (10.31):

$$A_v = \frac{R_C}{2r_e} = \frac{(47\text{ k}\Omega)}{2(269\ \Omega)} = 87.4$$

providing an output ac voltage of magnitude

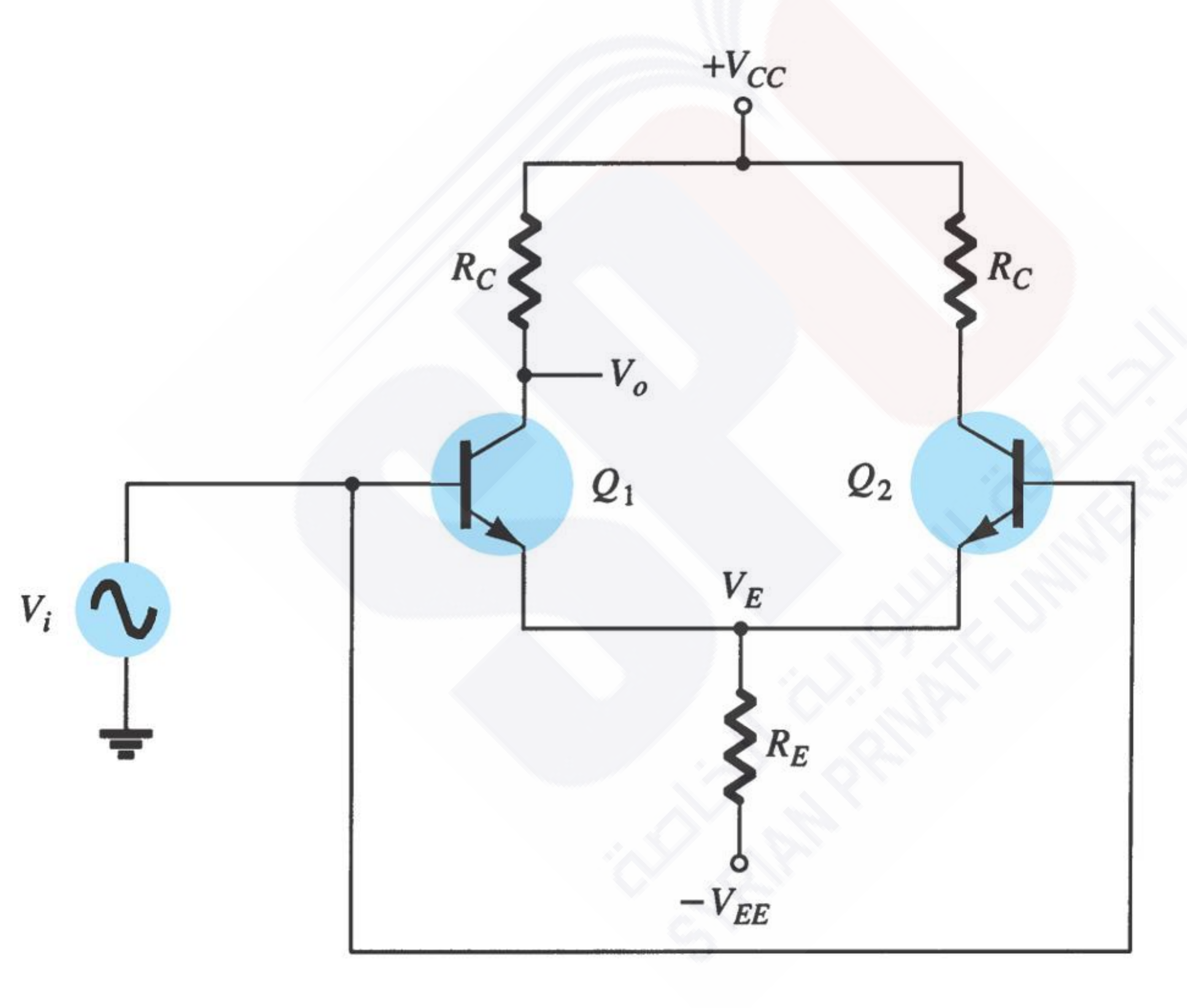
$$V_o = A_v V_i = (87.4)(2\text{ mV}) = 174.8\text{ mV} = \mathbf{0.175\ V}$$

Double-Ended AC Voltage Gain A similar analysis can be used to show that for the condition of signals applied to both inputs, the differential voltage gain magnitude is

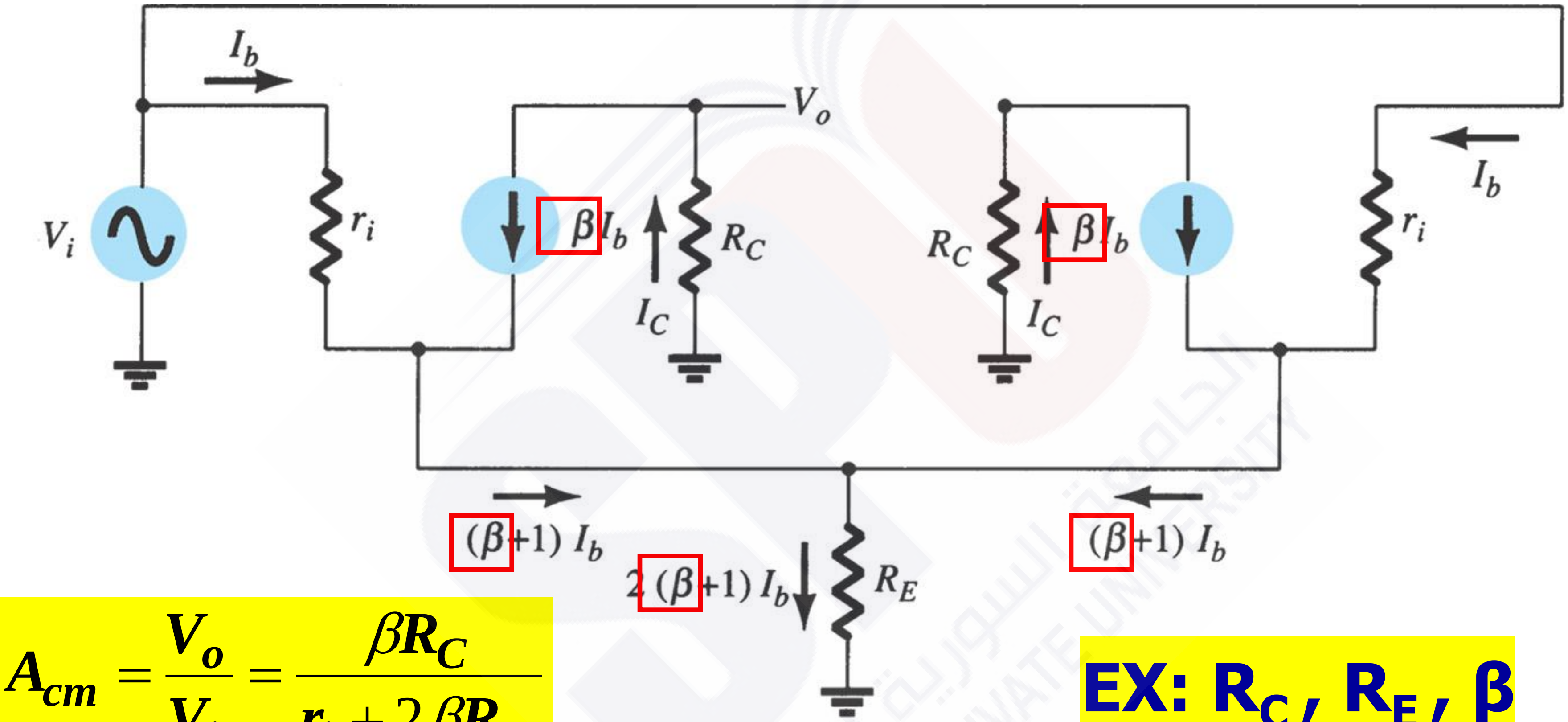
$$\boxed{A_d = \frac{V_o}{V_d} = \frac{\beta R_C}{2r_i}}$$

where $V_d = V_{i_1} - V_{i_2}$.

Common-mode connection.



AC circuit in common-mode connection



$$A_{cm} = \frac{V_o}{V_i} = \frac{\beta R_C}{r_i + 2\beta R_E}$$

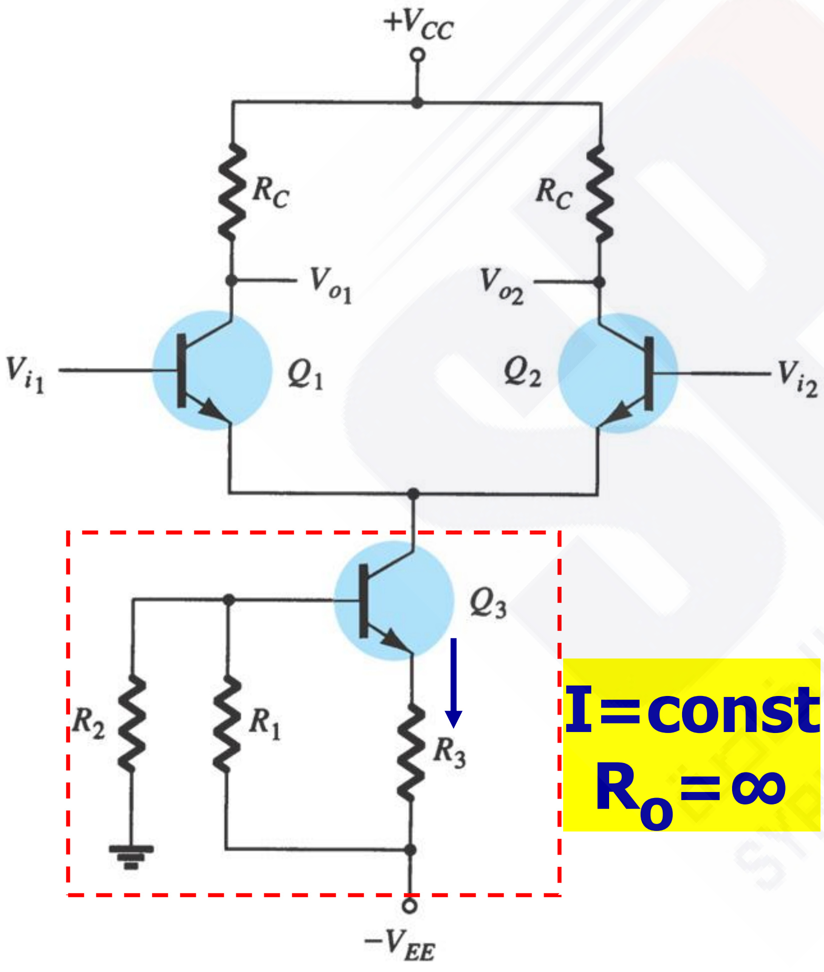
EX: R_C , R_E , β

$$I_b = \frac{V_i - 2(\beta + 1)I_b R_E}{r_i}$$

$$I_b = \frac{V_i}{r_i + 2(\beta + 1)R_E}$$

$$V_o = I_C R_C = \beta I_b R_C = \frac{\beta V_i R_C}{r_i + 2(\beta + 1)R_E}$$

Diff Amp with constant-current source



I=const

$R_o=\infty$

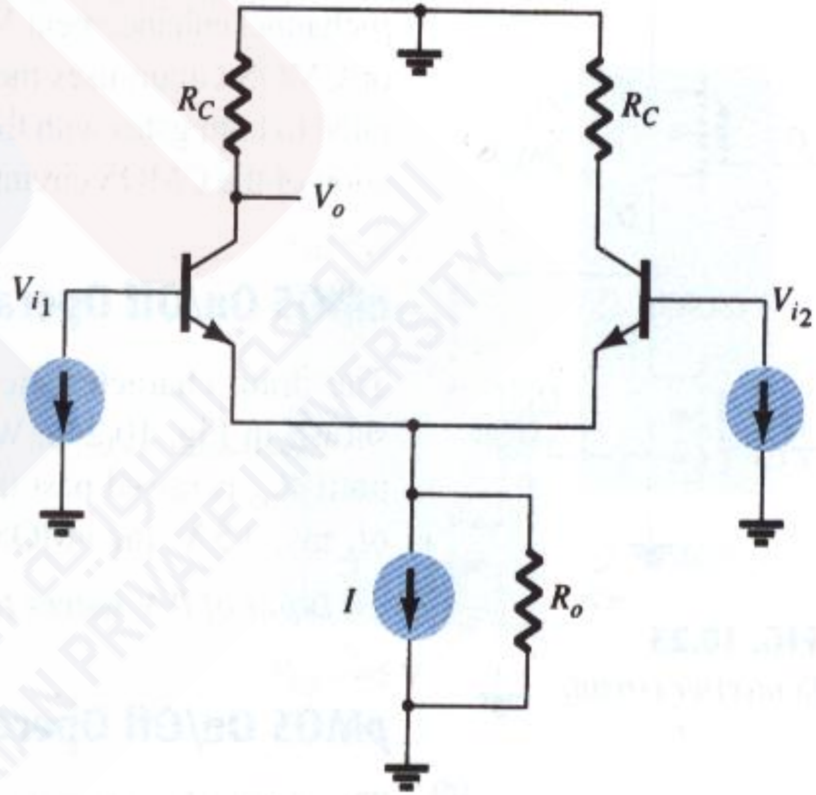
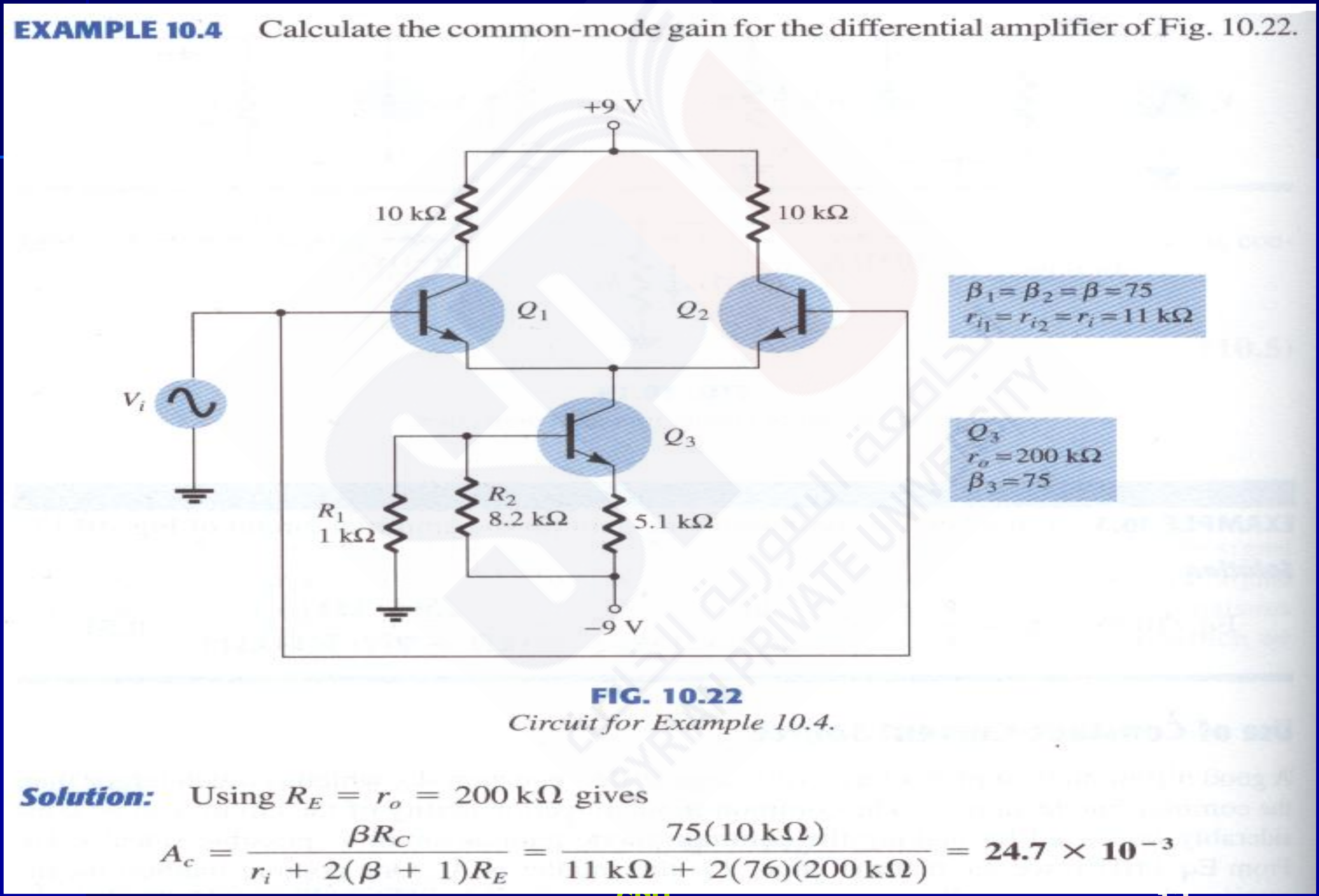


FIG. 10.21

AC equivalent of the circuit of Fig. 10.20.

Diff Amp with constant-current source



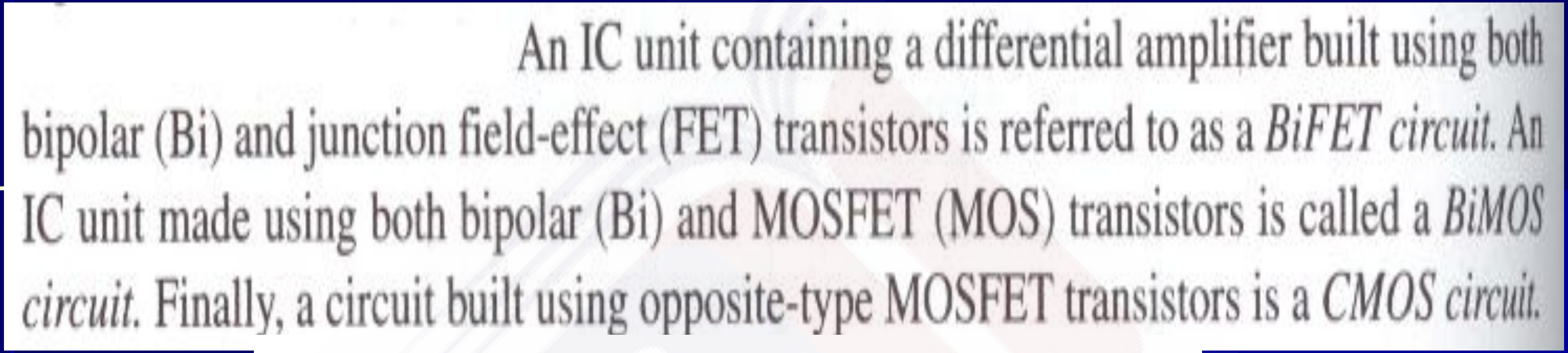
EXAMPLE 10.4 Calculate the common-mode gain for the differential amplifier of Fig. 10.22.

FIG. 10.22
Circuit for Example 10.4.

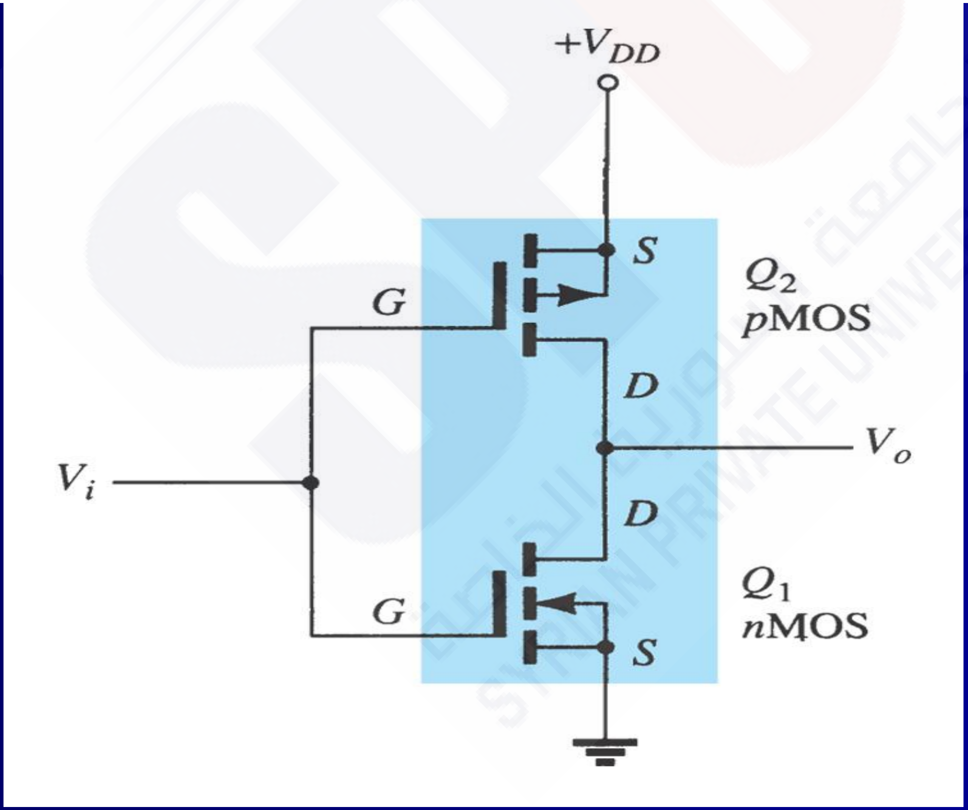
Solution: Using $R_E = r_o = 200\ \text{k}\Omega$ gives

$$A_c = \frac{\beta R_C}{r_i + 2(\beta + 1)R_E} = \frac{75(10\ \text{k}\Omega)}{11\ \text{k}\Omega + 2(76)(200\ \text{k}\Omega)} = \mathbf{24.7 \times 10^{-3}}$$

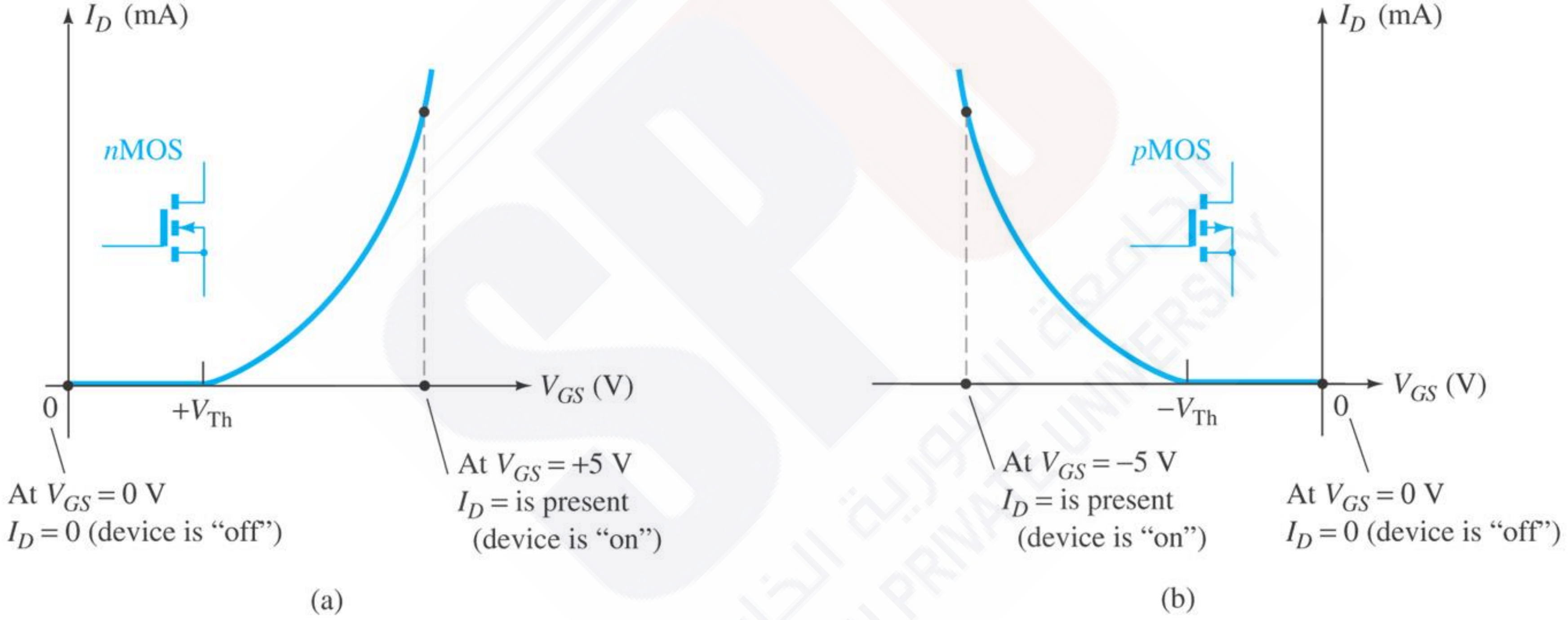
CMOS inverter circuit



An IC unit containing a differential amplifier built using both bipolar (Bi) and junction field-effect (FET) transistors is referred to as a *BiFET circuit*. An IC unit made using both bipolar (Bi) and MOSFET (MOS) transistors is called a *BiMOS circuit*. Finally, a circuit built using opposite-type MOSFET transistors is a *CMOS circuit*.



CMOS Transfer Characteristics



At $V_{GS} = 0$ V
$I_D = 0$ (device is "off")

At $V_{GS} = +5$ V
$I_D =$ is present
(device is "on")

(a)

At $V_{GS} = -5$ V
$I_D =$ is present
(device is "on")

At $V_{GS} = 0$ V
$I_D = 0$ (device is "off")

(b)

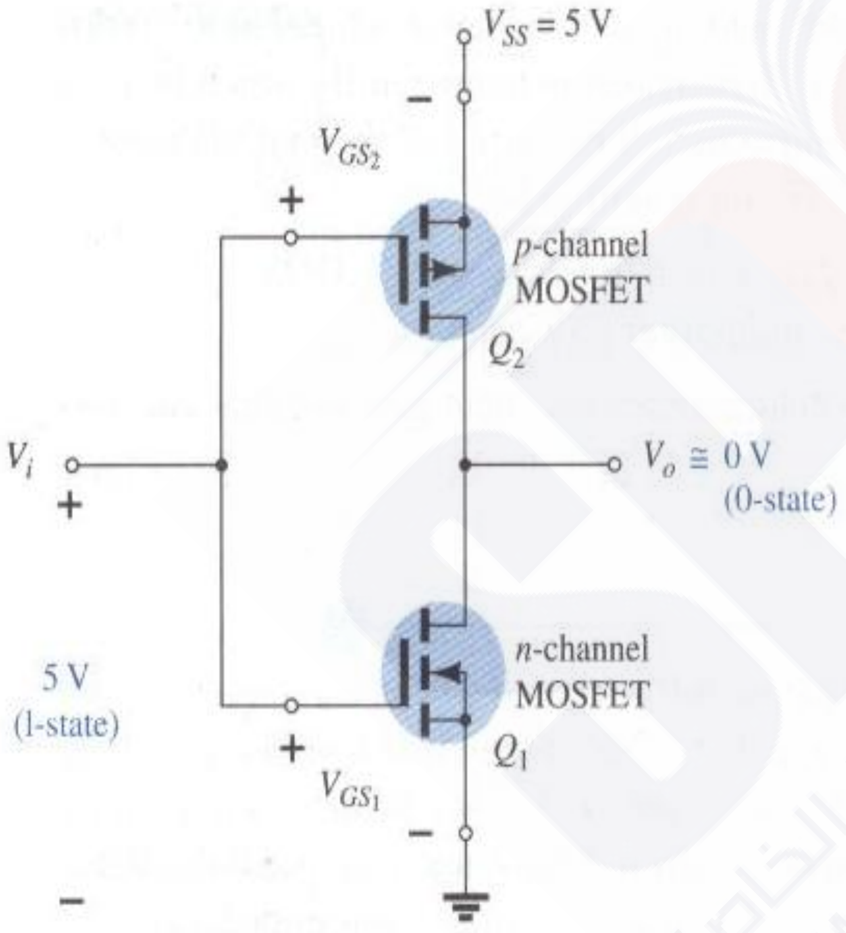


FIG. 6.48
CMOS inverter.

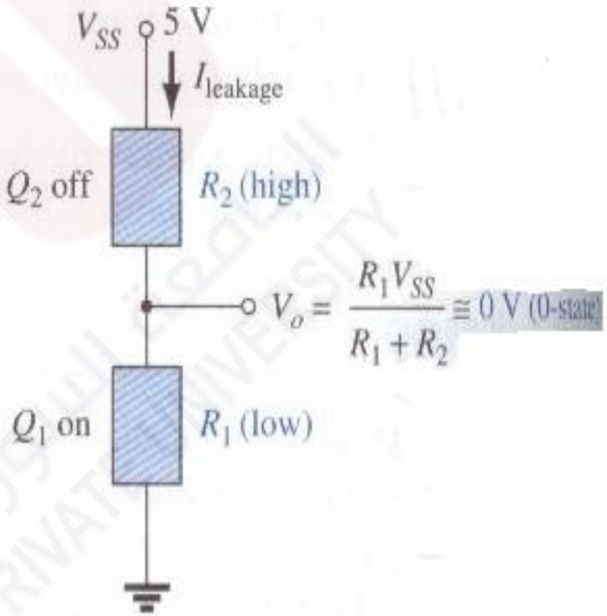
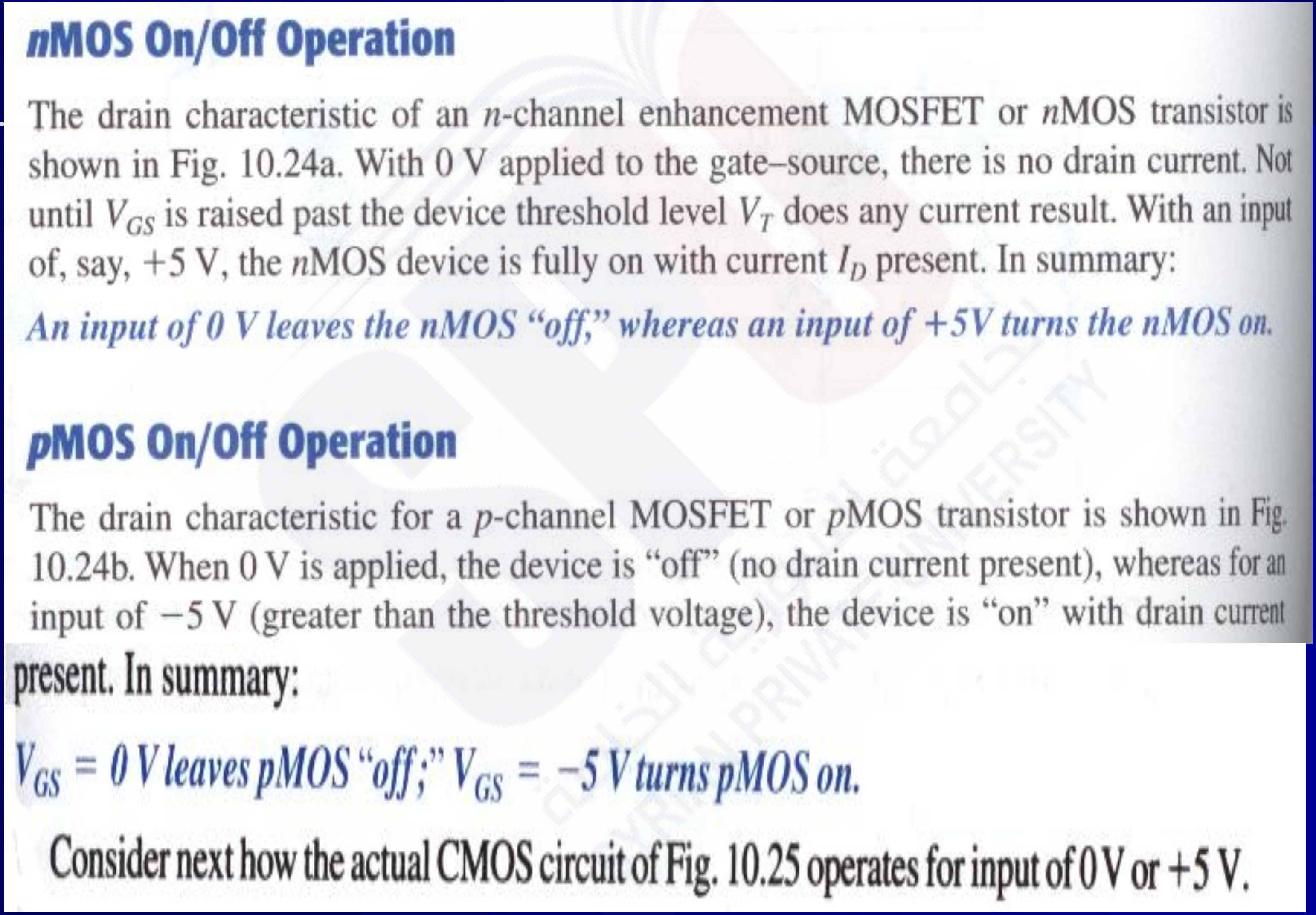


FIG. 6.49
Relative resistance levels for $V_i = 5$ V (1-state).



*n*MOS On/Off Operation

The drain characteristic of an *n*-channel enhancement MOSFET or *n*MOS transistor is shown in Fig. 10.24a. With 0 V applied to the gate–source, there is no drain current. Not until V_{GS} is raised past the device threshold level V_T does any current result. With an input of, say, +5 V, the *n*MOS device is fully on with current I_D present. In summary:

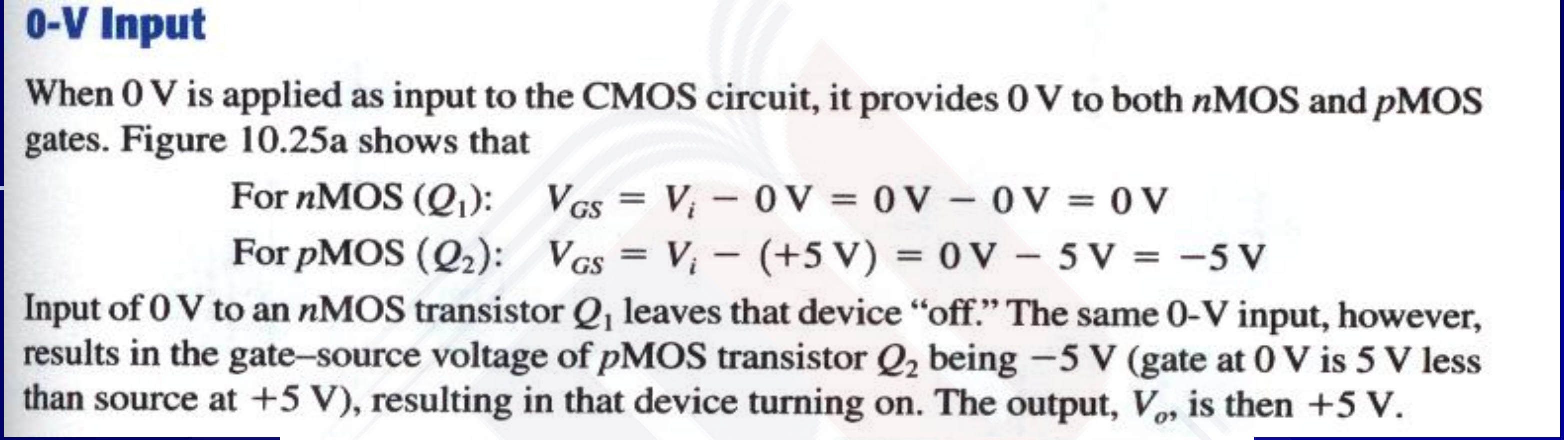
An input of 0 V leaves the nMOS "off," whereas an input of +5V turns the nMOS on.

*p*MOS On/Off Operation

The drain characteristic for a *p*-channel MOSFET or *p*MOS transistor is shown in Fig. 10.24b. When 0 V is applied, the device is "off" (no drain current present), whereas for an input of −5 V (greater than the threshold voltage), the device is "on" with drain current present. In summary:

V_{GS} = 0 V leaves pMOS "off;" V_{GS} = −5 V turns pMOS on.

Consider next how the actual CMOS circuit of Fig. 10.25 operates for input of 0 V or +5 V.



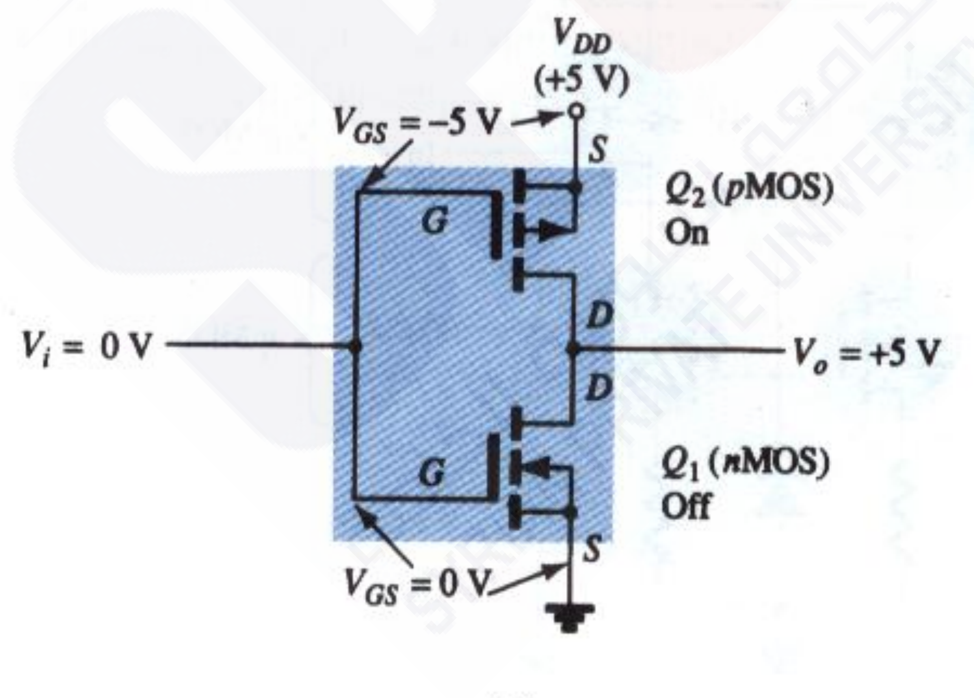
0-V Input

When 0 V is applied as input to the CMOS circuit, it provides 0 V to both *n*MOS and *p*MOS gates. Figure 10.25a shows that

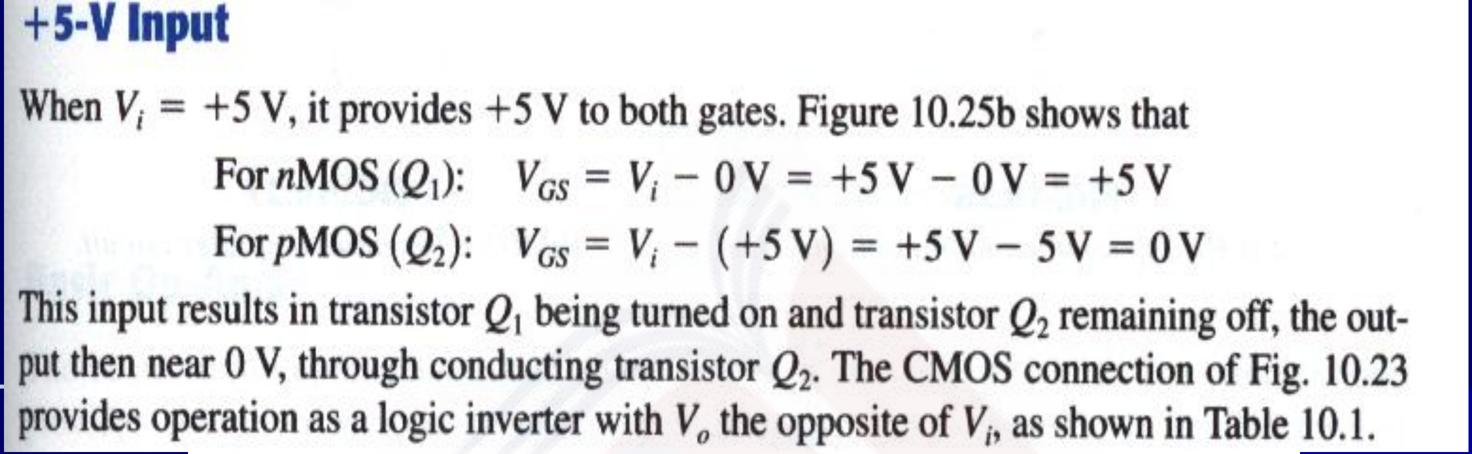
For *n*MOS (Q_1): $V_{GS} = V_i - 0\text{ V} = 0\text{ V} - 0\text{ V} = 0\text{ V}$

For *p*MOS (Q_2): $V_{GS} = V_i - (+5\text{ V}) = 0\text{ V} - 5\text{ V} = -5\text{ V}$

Input of 0 V to an *n*MOS transistor Q_1 leaves that device "off." The same 0-V input, however, results in the gate–source voltage of *p*MOS transistor Q_2 being −5 V (gate at 0 V is 5 V less than source at +5 V), resulting in that device turning on. The output, V_o, is then +5 V.



(a)



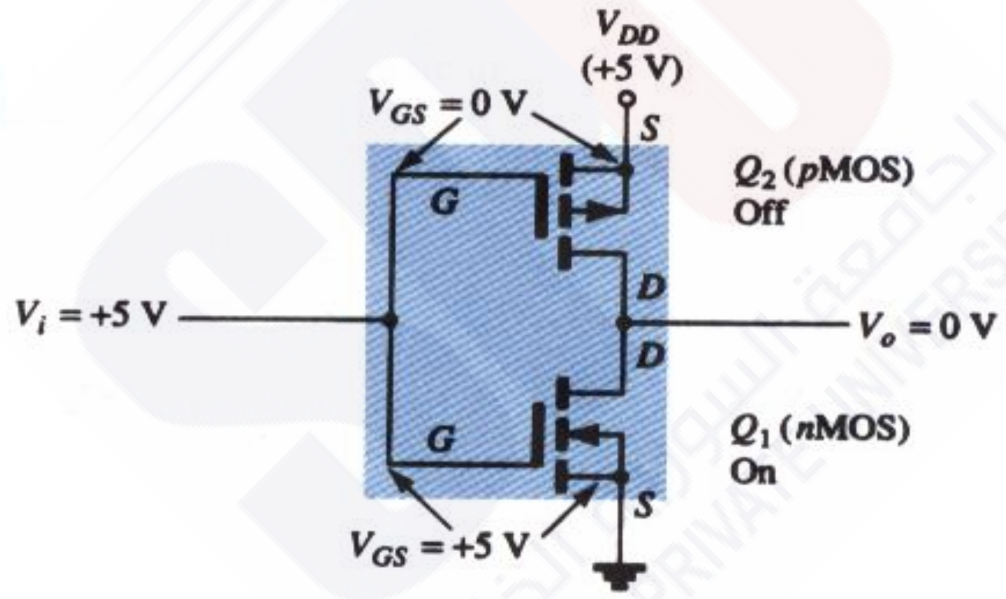
+5-V Input

When V_i = +5 V, it provides +5 V to both gates. Figure 10.25b shows that

For *n*MOS (Q_1): $V_{GS} = V_i - 0\text{ V} = +5\text{ V} - 0\text{ V} = +5\text{ V}$

For *p*MOS (Q_2): $V_{GS} = V_i - (+5\text{ V}) = +5\text{ V} - 5\text{ V} = 0\text{ V}$

This input results in transistor Q_1 being turned on and transistor Q_2 remaining off, the output then near 0 V, through conducting transistor Q_2. The CMOS connection of Fig. 10.23 provides operation as a logic inverter with V_o the opposite of V_i, as shown in Table 10.1.



(b)

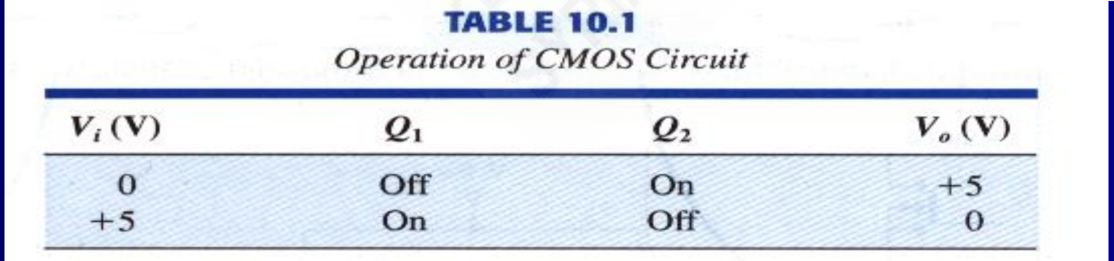


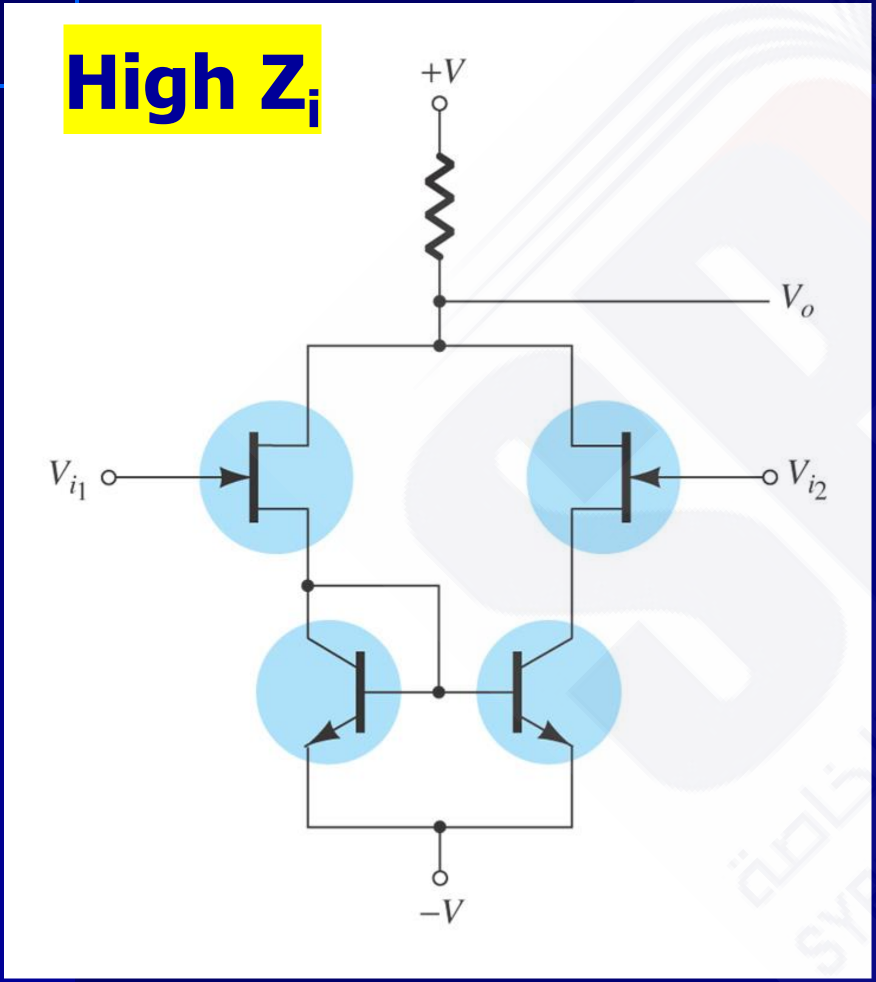
TABLE 10.1

Operation of CMOS Circuit

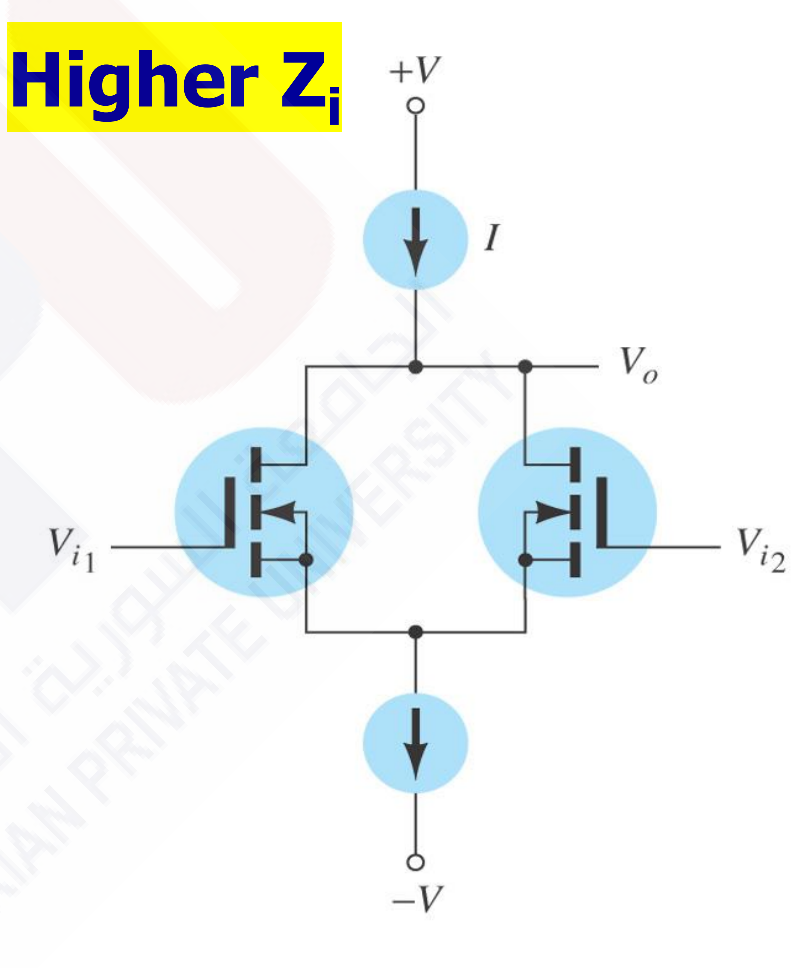
V_i (V)	Q_1	Q_2	V_o (V)
0	Off	On	+5
+5	On	Off	0

4.3 BiFET & BiMOS differential amplifier circuit

High Z_i

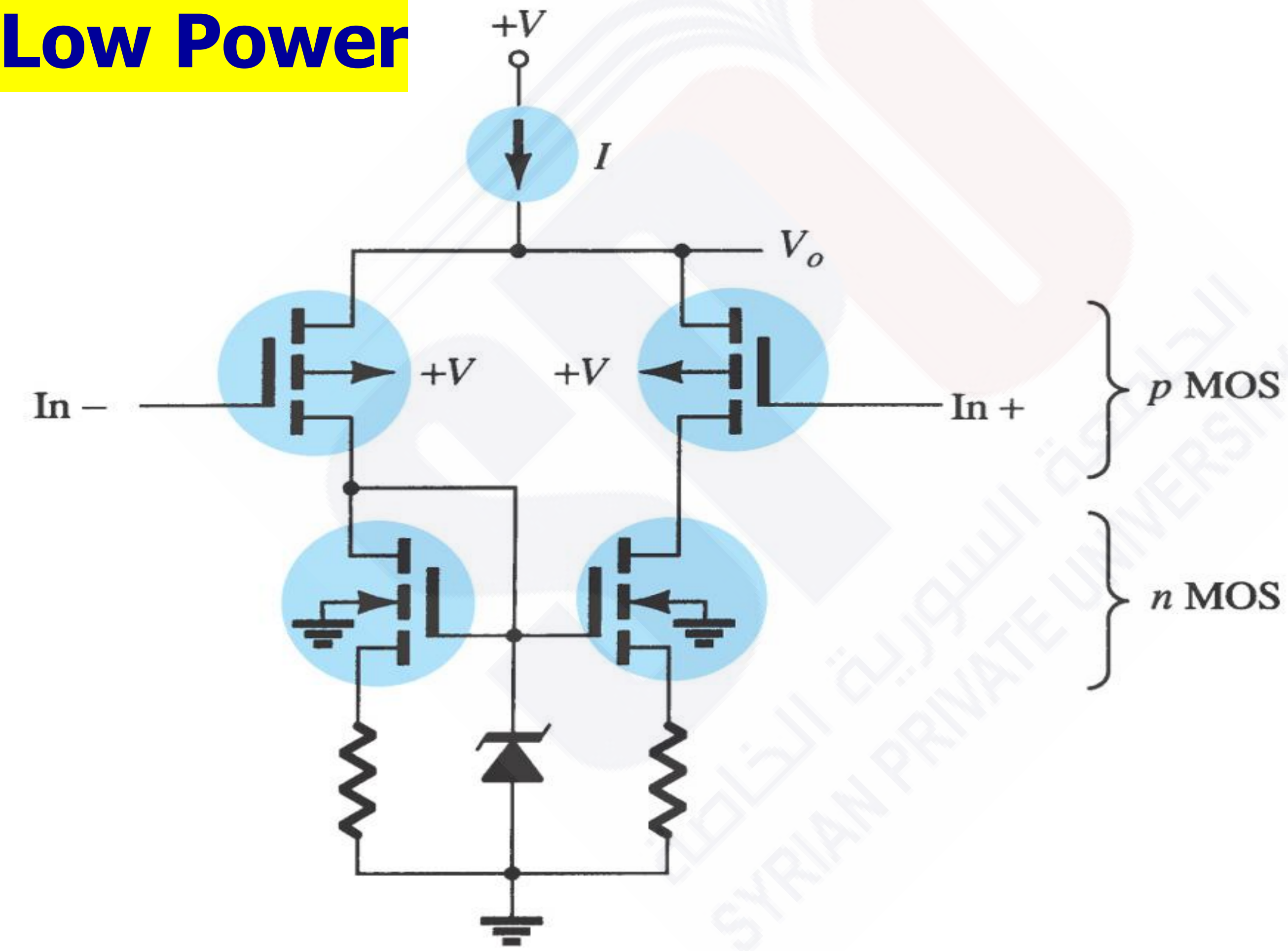


Higher Z_i

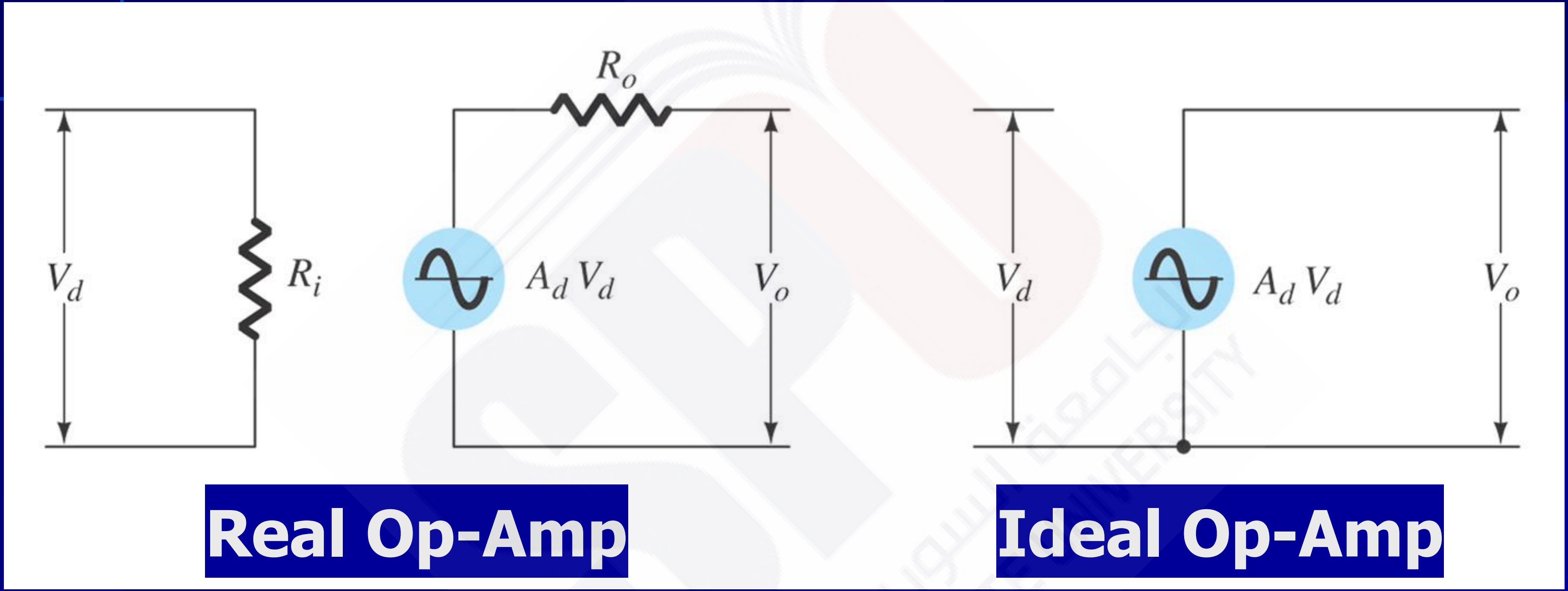


CMOS differential amplifier

Low Power

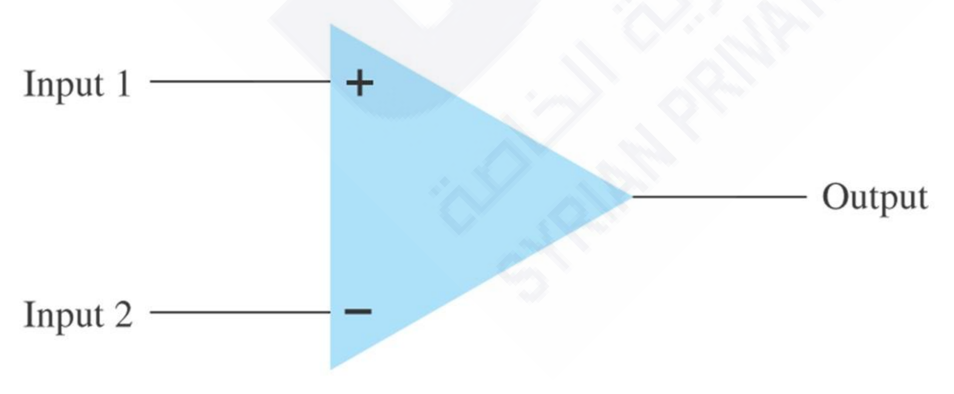


AC equivalent of op-amp circuit

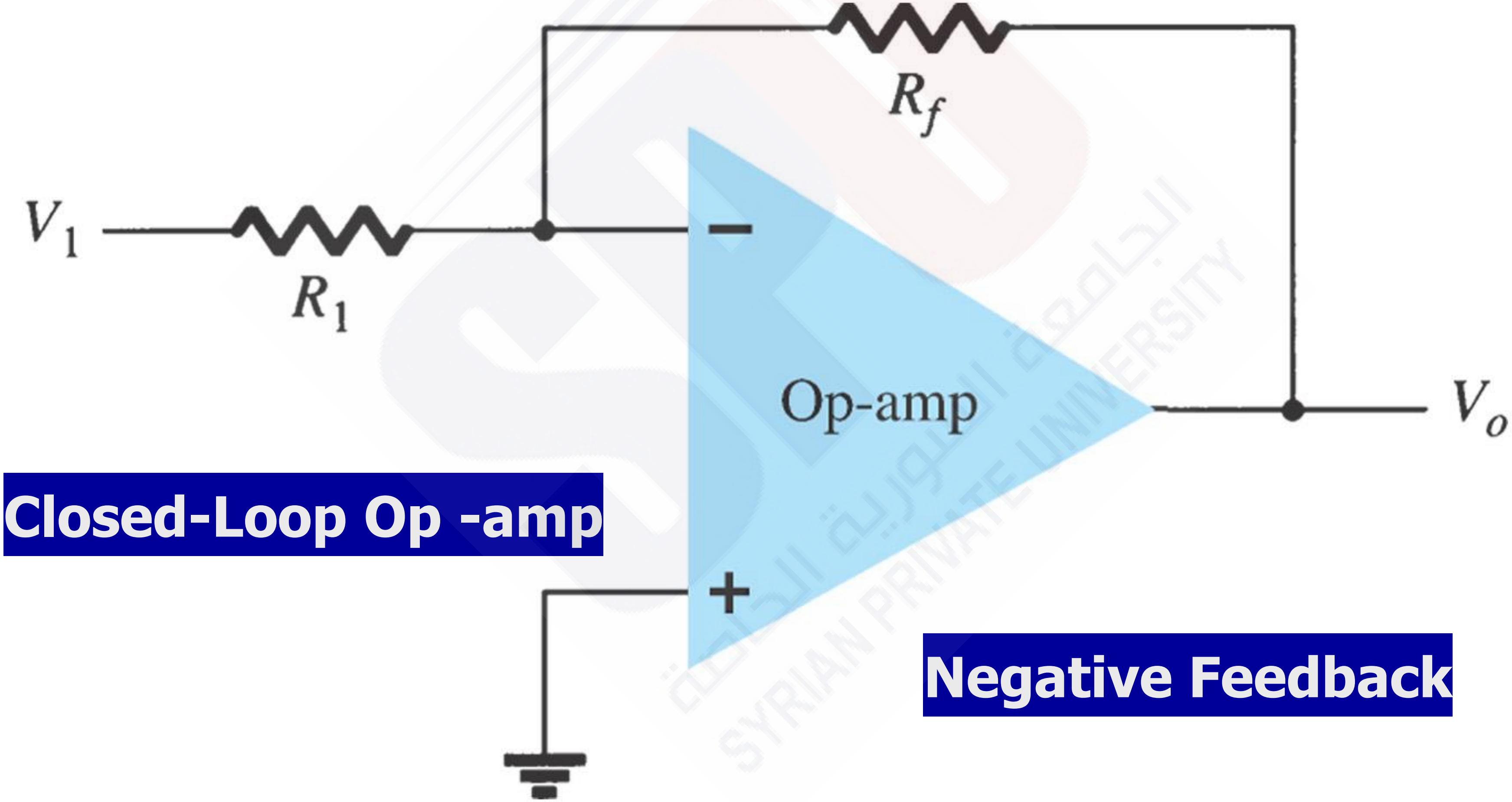


Real Op-Amp

Ideal Op-Amp

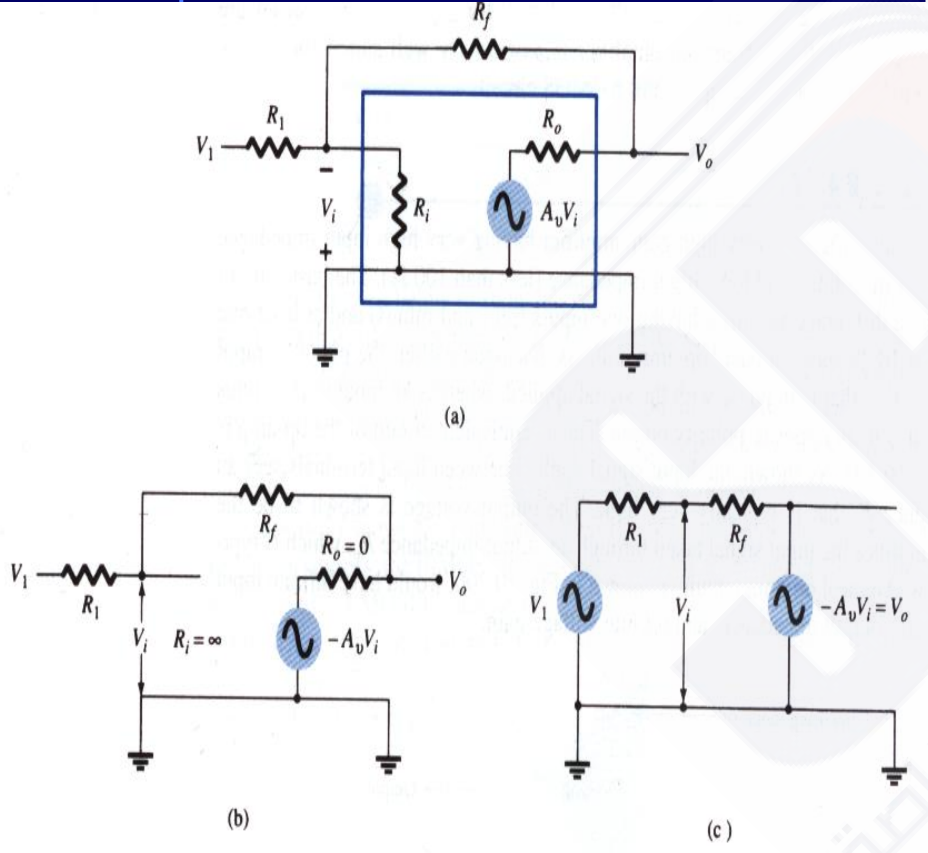


4.4 Basic Op-Amp circuits



Closed-Loop Op -amp

Negative Feedback



Using superposition, we can solve for the voltage V_1 in terms of the components due to each of the sources. For source V_1 only ($-A_vV_i$ set to zero),

$$V_{i_1} = \frac{R_f}{R_1 + R_f} V_1$$

For source $-A_vV_i$ only (V_1 set to zero),

$$V_{i_2} = \frac{R_1}{R_1 + R_f}(-A_vV_i)$$

The total voltage V_i is then

$$V_i = V_{i_1} + V_{i_2} = \frac{R_f}{R_1 + R_f} V_1 + \frac{R_1}{R_1 + R_f}(-A_vV_i)$$

which can be solved for V_i as

$$V_i = \frac{R_f}{R_f + (1 + A_v)R_1} V_1$$

If $A_v \gg 1$ and $A_vR_1 \gg R_f$, as is usually true, then

$$V_i = \frac{R_f}{A_vR_1} V_1$$

Solving for V_o/V_i, we get

$$\frac{V_o}{V_i} = \frac{-A_vV_i}{V_i} = \frac{-A_v}{V_i}\frac{R_fV_1}{A_vR_1} = -\frac{R_f}{R_1}\frac{V_1}{V_i}$$

so that

$$\boxed{\frac{V_o}{V_1} = -\frac{R_f}{R_1}}$$

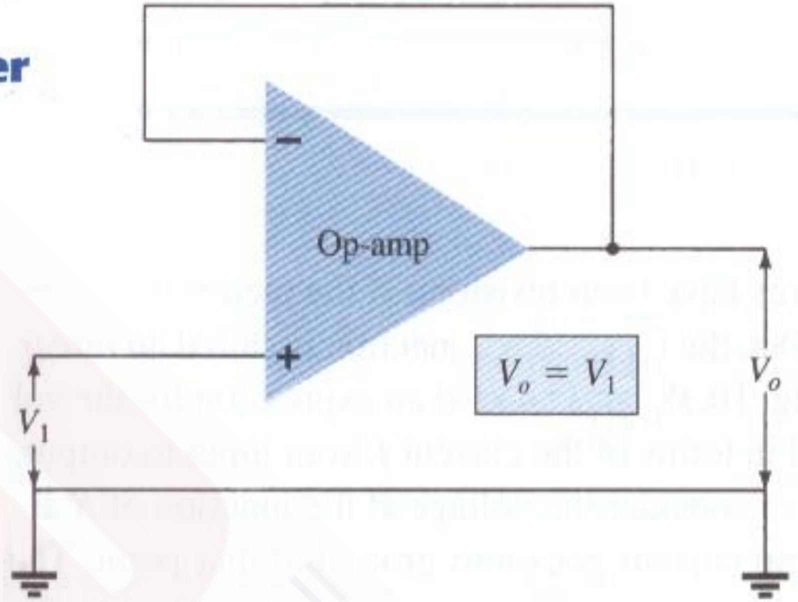
Unity Gain

If $R_f = R_1$, the gain is

$$\text{Voltage gain} = -\frac{R_f}{R_1} = -1$$

so that the circuit provides a unity voltage gain with 180° phase inversion. If R_f is exactly R_1, the voltage gain is exactly 1.

Unity Follower



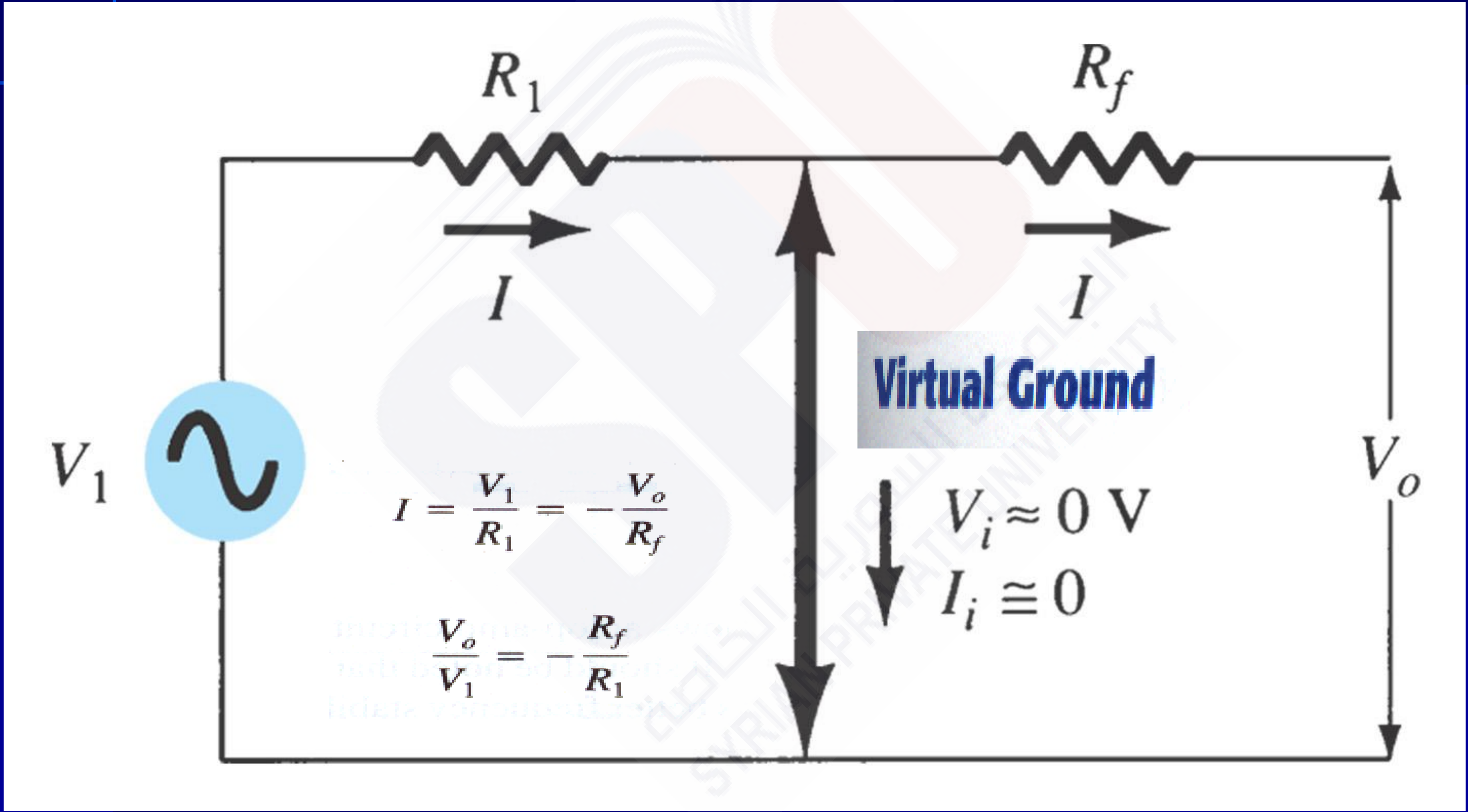
Constant-Magnitude Gain

If R_f is some multiple of R_1, the overall amplifier gain is a constant. For example, if $R_f = 10R_1$, then

$$\text{Voltage gain} = -\frac{R_f}{R_1} = -10$$

and the circuit provides a voltage gain of exactly 10 along with an 180° phase inversion from the input signal. If we select precise resistor values for R_f and R_1, we can obtain a wide range of gains, the gain being as accurate as the resistors used and is only slightly affected by temperature and other circuit factors.

Virtual ground in an op-amp.



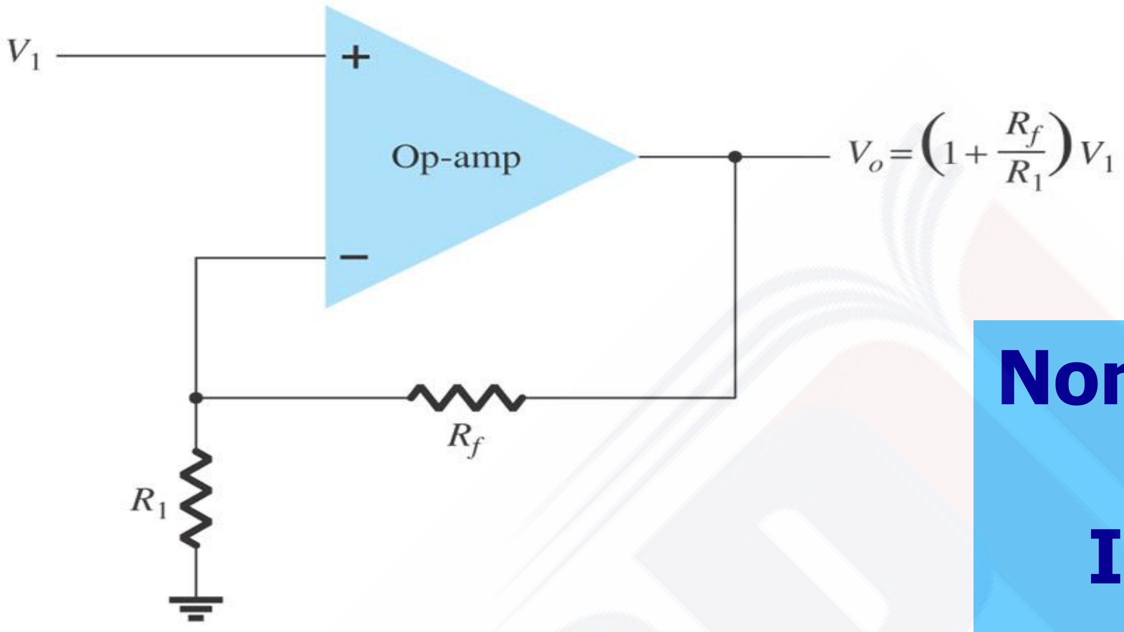
$$I = \frac{V_1}{R_1} = -\frac{V_o}{R_f}$$

$$\frac{V_o}{V_1} = -\frac{R_f}{R_1}$$

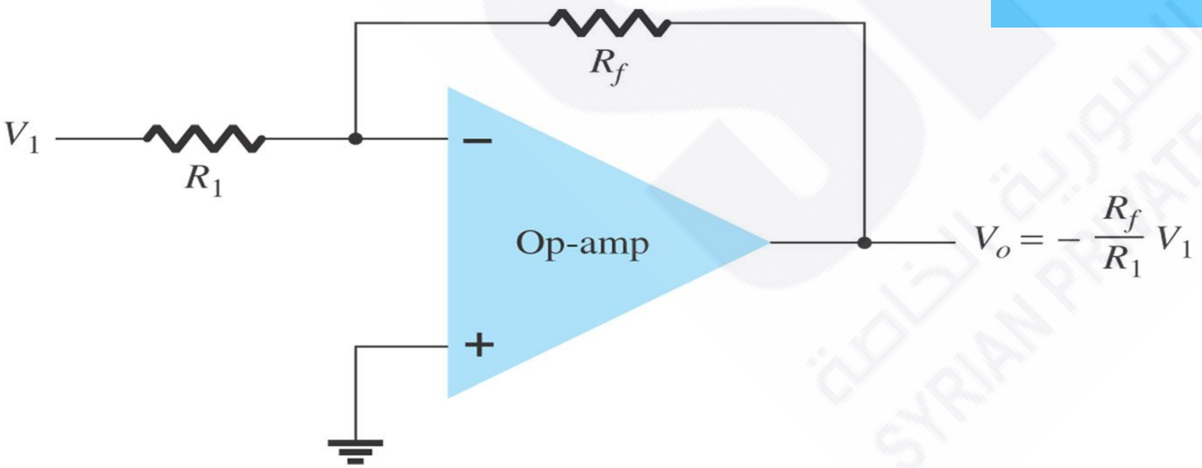
$V_i \approx 0$ V

$I_i \cong 0$

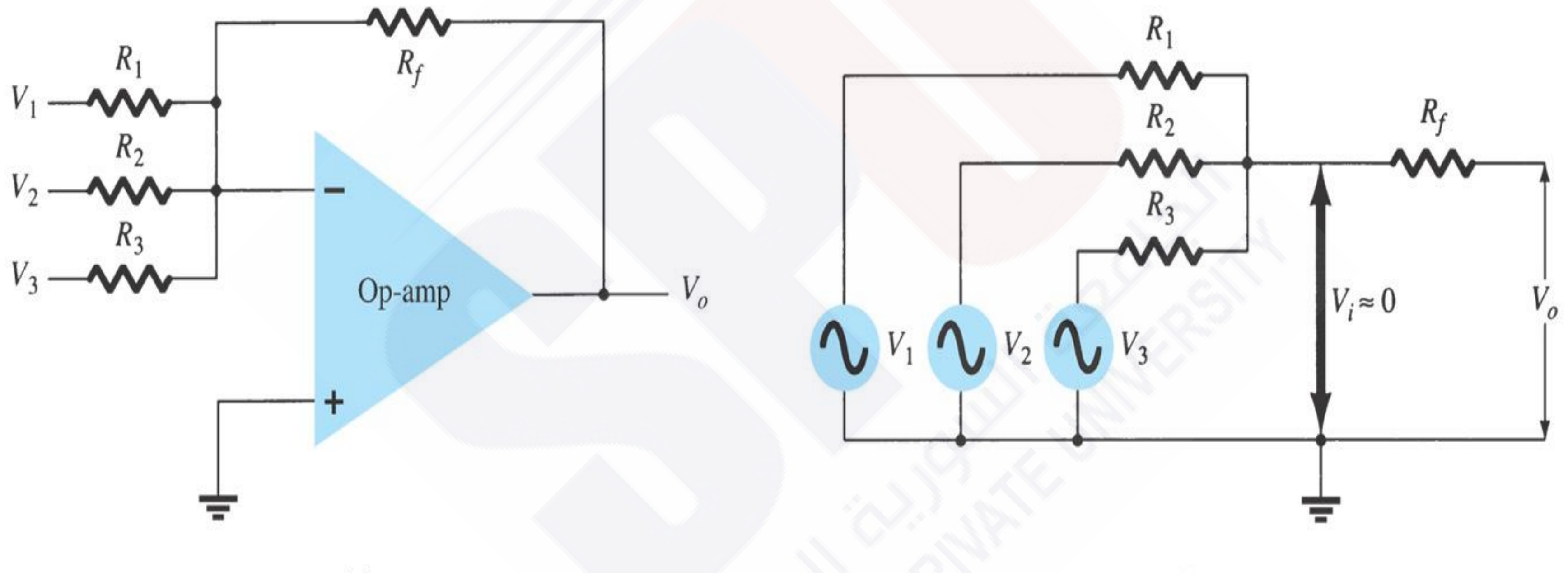
Non-Inverting Amp
&
Inverting Amp



(a)



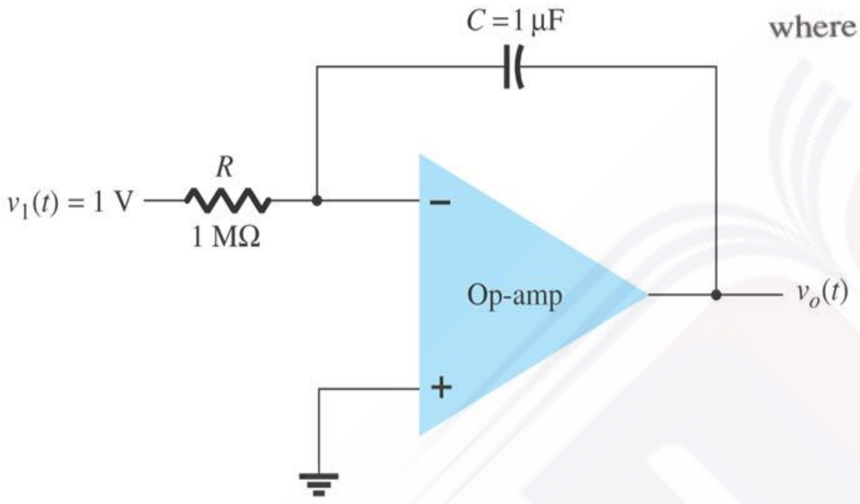
Adder Circuit



(a) (b)

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

Integrator Circuit

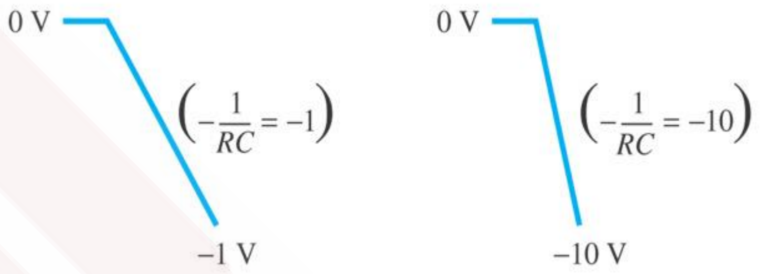


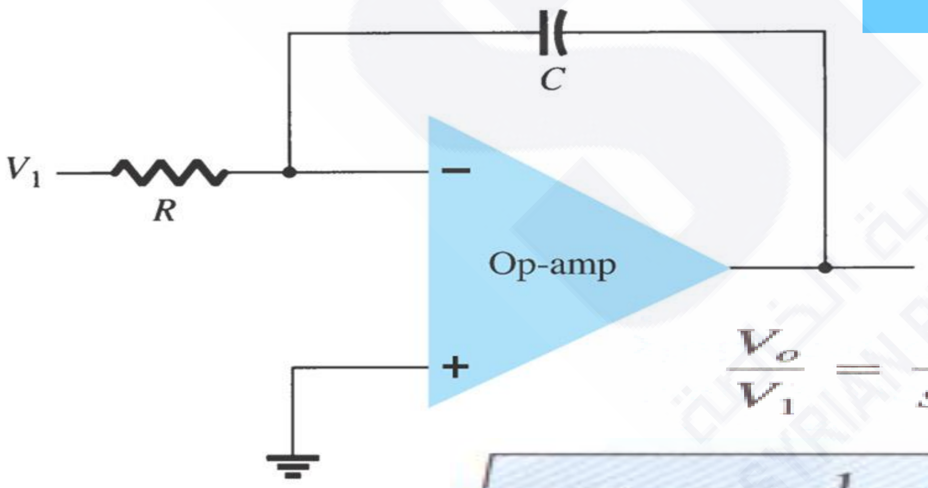
(a)

$$X_C = \frac{1}{j\omega C} = \frac{1}{sC}$$

where $s = j\omega$ is in the Laplace notation.* Solving for V_o/V_1 yields

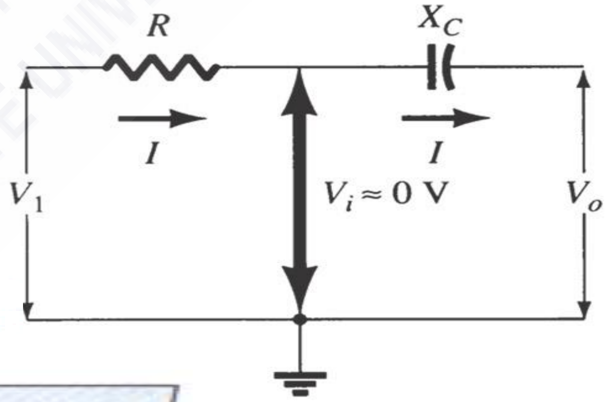
$$I = \frac{V_1}{R} = -\frac{V_o}{X_C} = \frac{-V_o}{1/sC} = -sCV_o$$



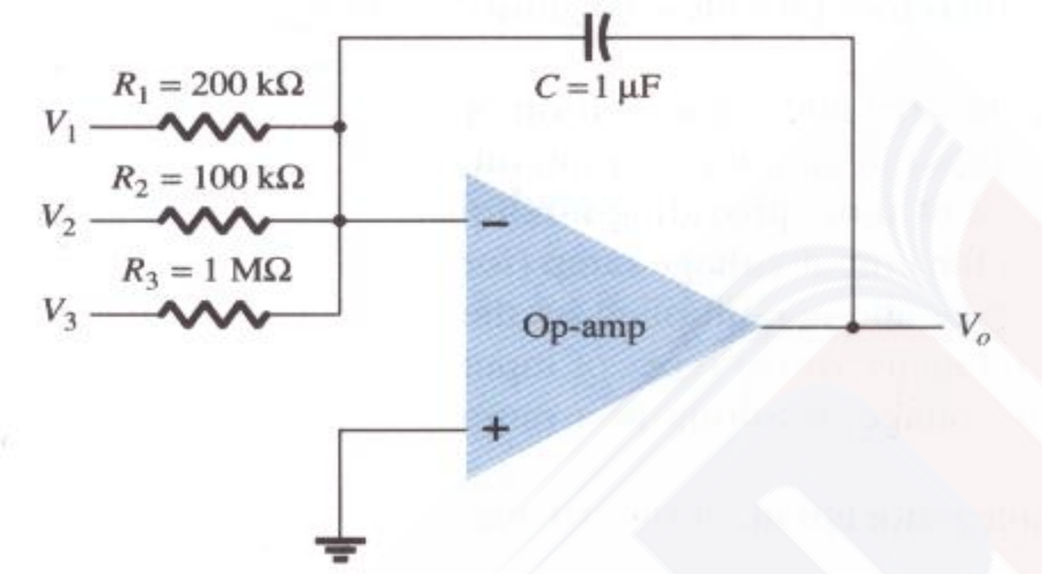


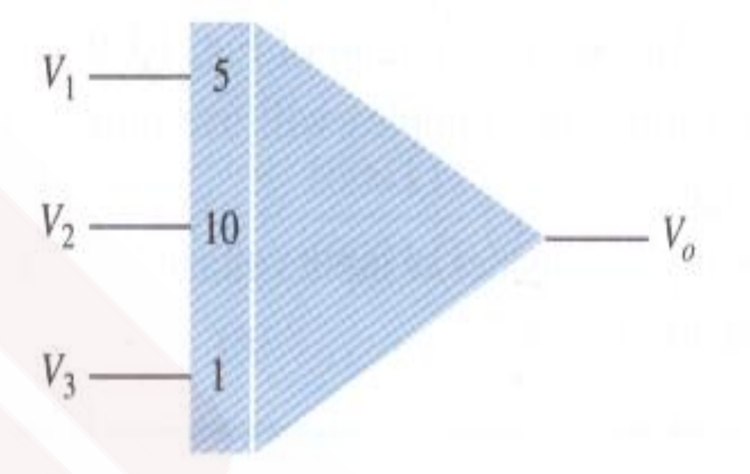
$$\frac{V_o}{V_1} = \frac{-1}{sCR}$$

$$\boxed{v_o(t) = -\frac{1}{RC}\int v_1(t)\,dt}$$



(b)





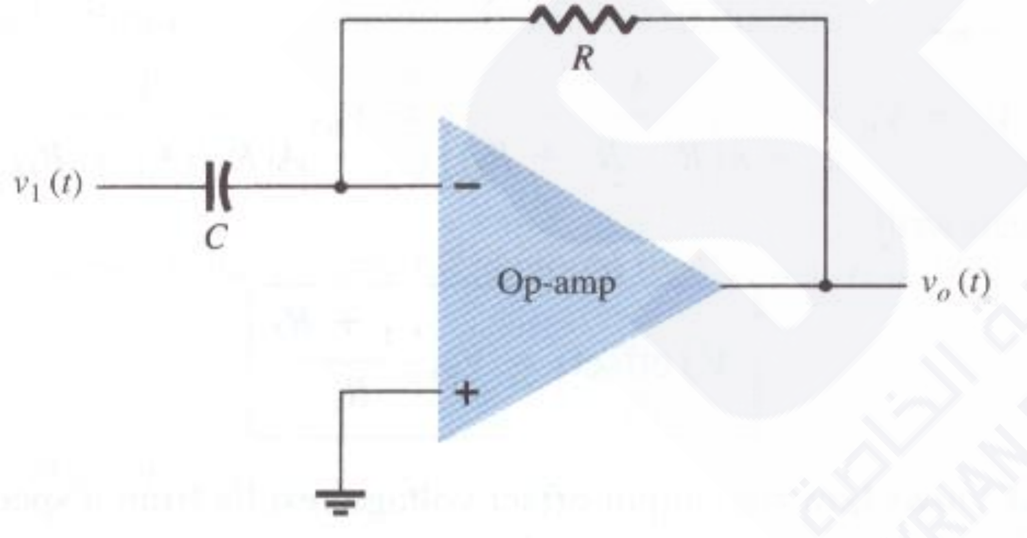
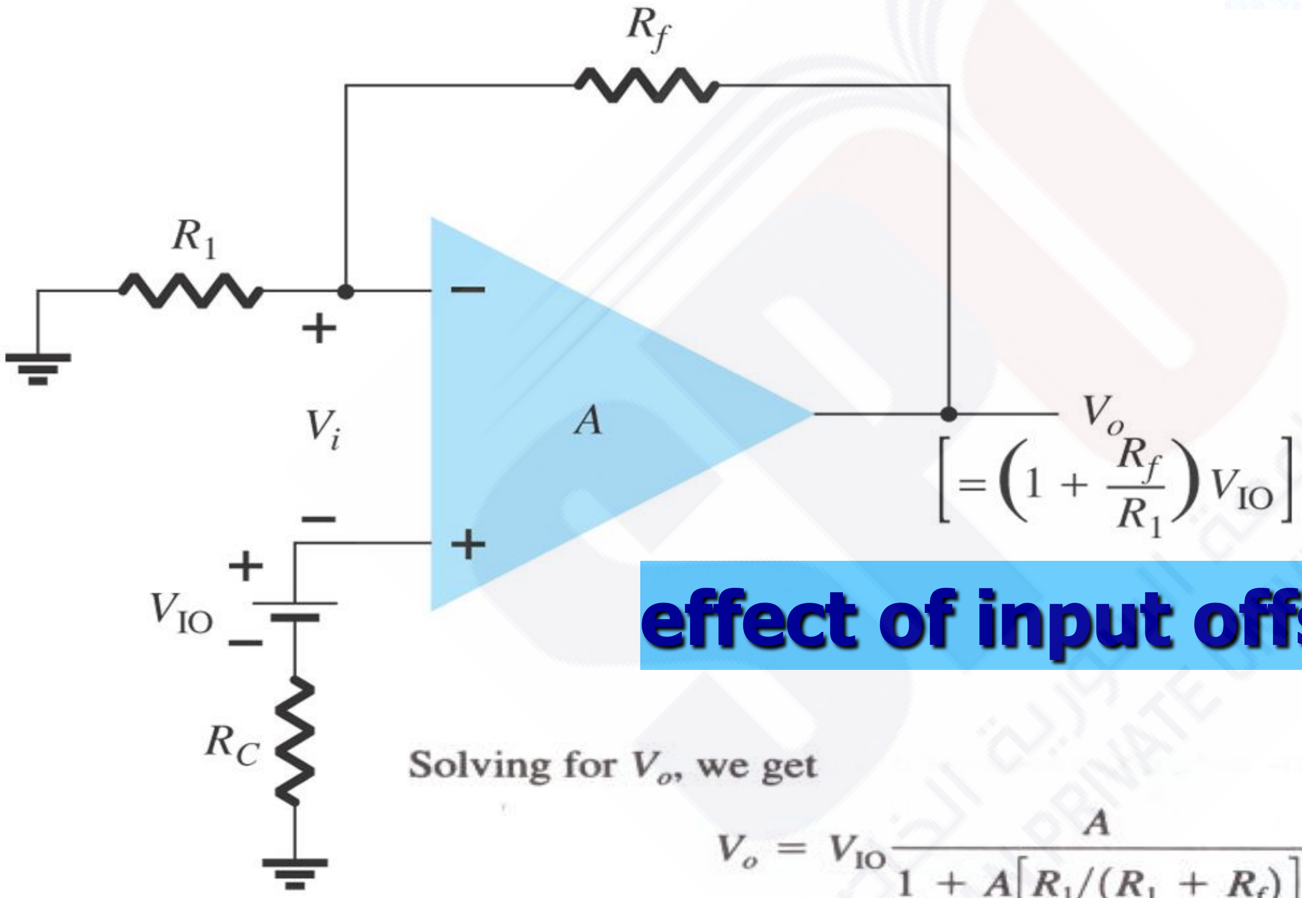


FIG. 10.41
Differentiator circuit.

$$\boxed{v_o(t) = -RC\frac{dv_1(t)}{dt}}$$

4.5 OP-Amp Specifications

$$V_o = AV_i = A\left(V_{IO} - V_o\frac{R_1}{R_1 + R_f}\right)$$



effect of input offset voltage V_{IO}

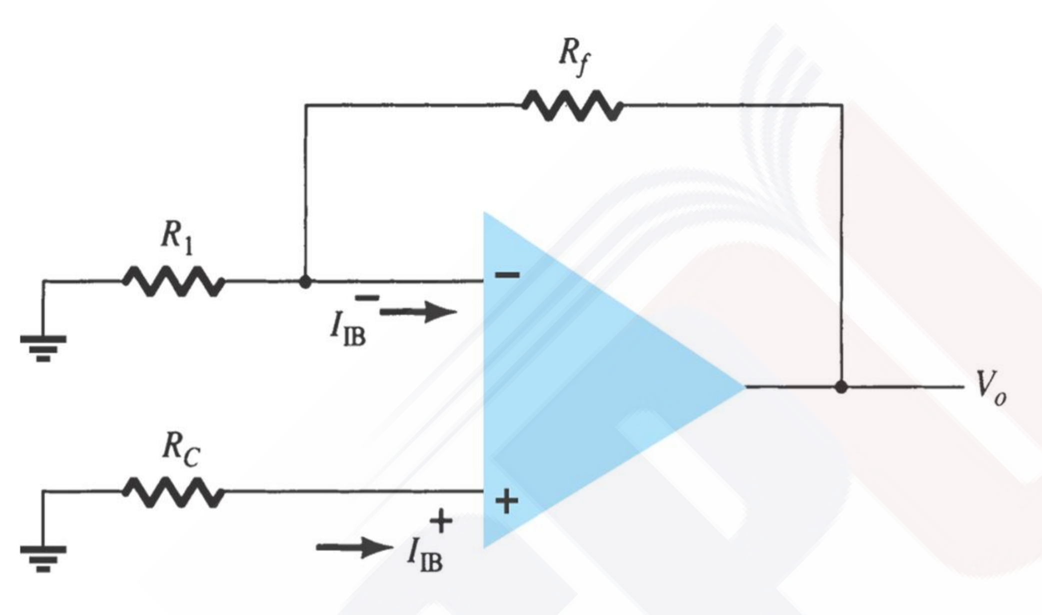
Solving for V_o, we get

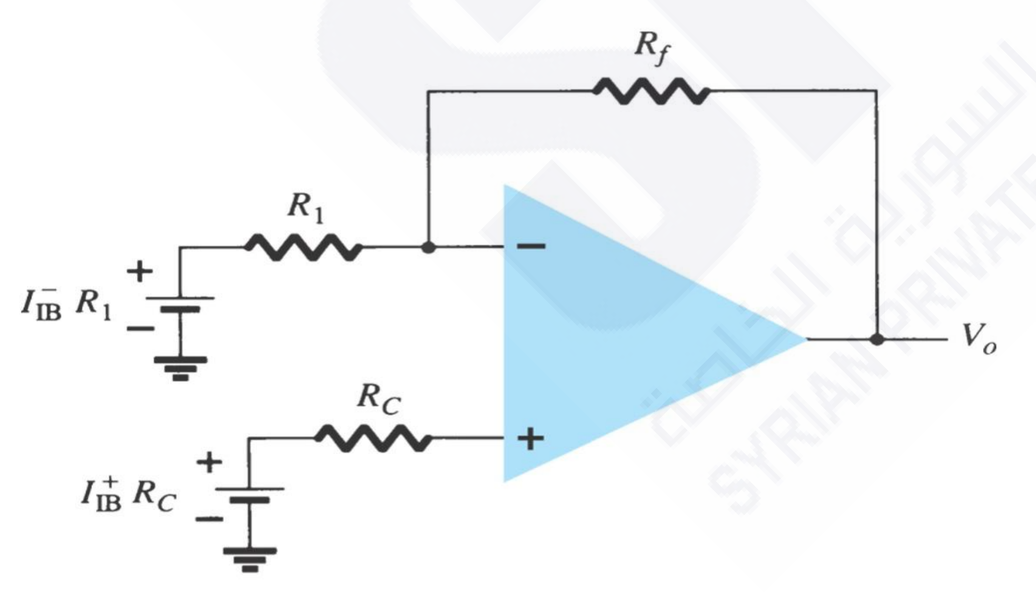
$$V_o = V_{IO}\frac{A}{1 + A[R_1/(R_1 + R_f)]} \approx V_{IO}\frac{A}{A[R_1/(R_1 + R_f)]}$$

from which we can write

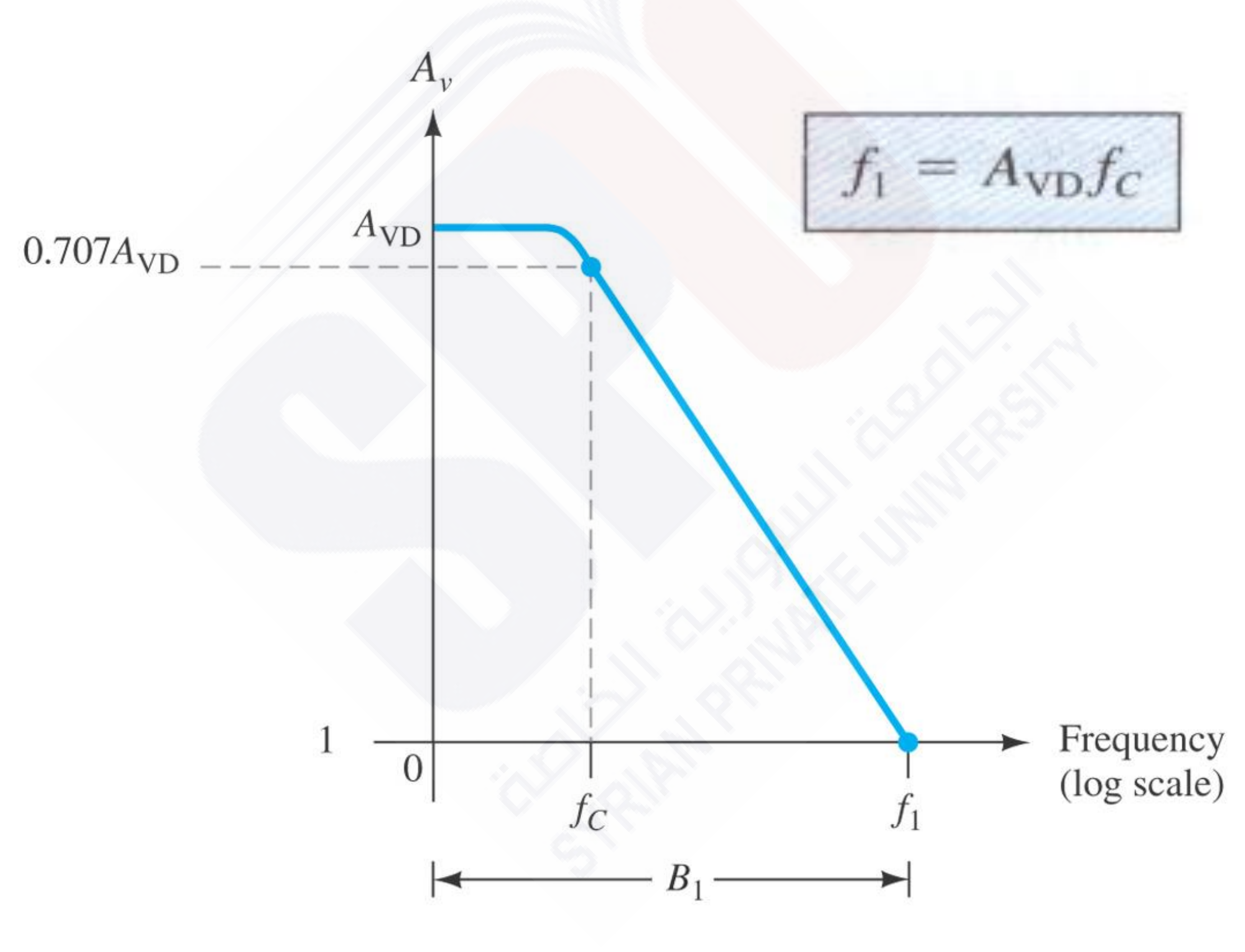
$$\boxed{V_o(\text{offset}) = V_{IO}\frac{R_1 + R_f}{R_1}}$$

input bias currents





Gain versus frequency plot



$f_1 = A_{VD} f_C$

Slew Rate

$SR=\Delta V_o/\Delta t\ [V/\mu S]=A_{CL}\ (\Delta V_i/\ \Delta t)$

A Parameter to Specify the Maximum Rate of Change of the Output Signal

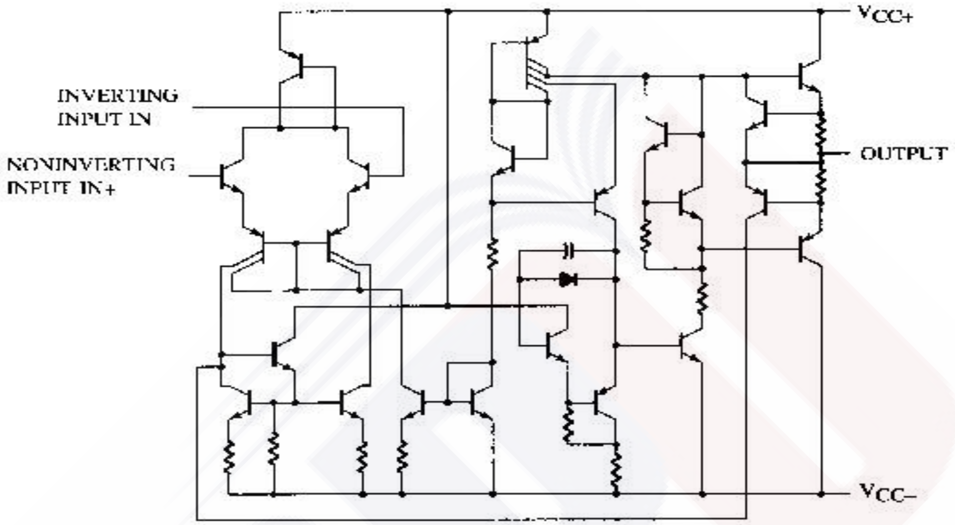
Ex: $V_o=K\sin\omega t$; Differentiating ,yields :- $\Delta V_o/\Delta t=K\omega\cos\omega t$,then $SR=K\omega$,if $\omega t=0$,then:

$$f_{\max} \le \frac{SR}{2\pi K}\ \ [\mathrm{Hz}]$$

Slew Rate

Maximum Signal frequency at which an op.amp may operate depends on both the bandwidth (BW) and slew rate(SR) parameters of op.amp. $f \leq SR/2\pi k$

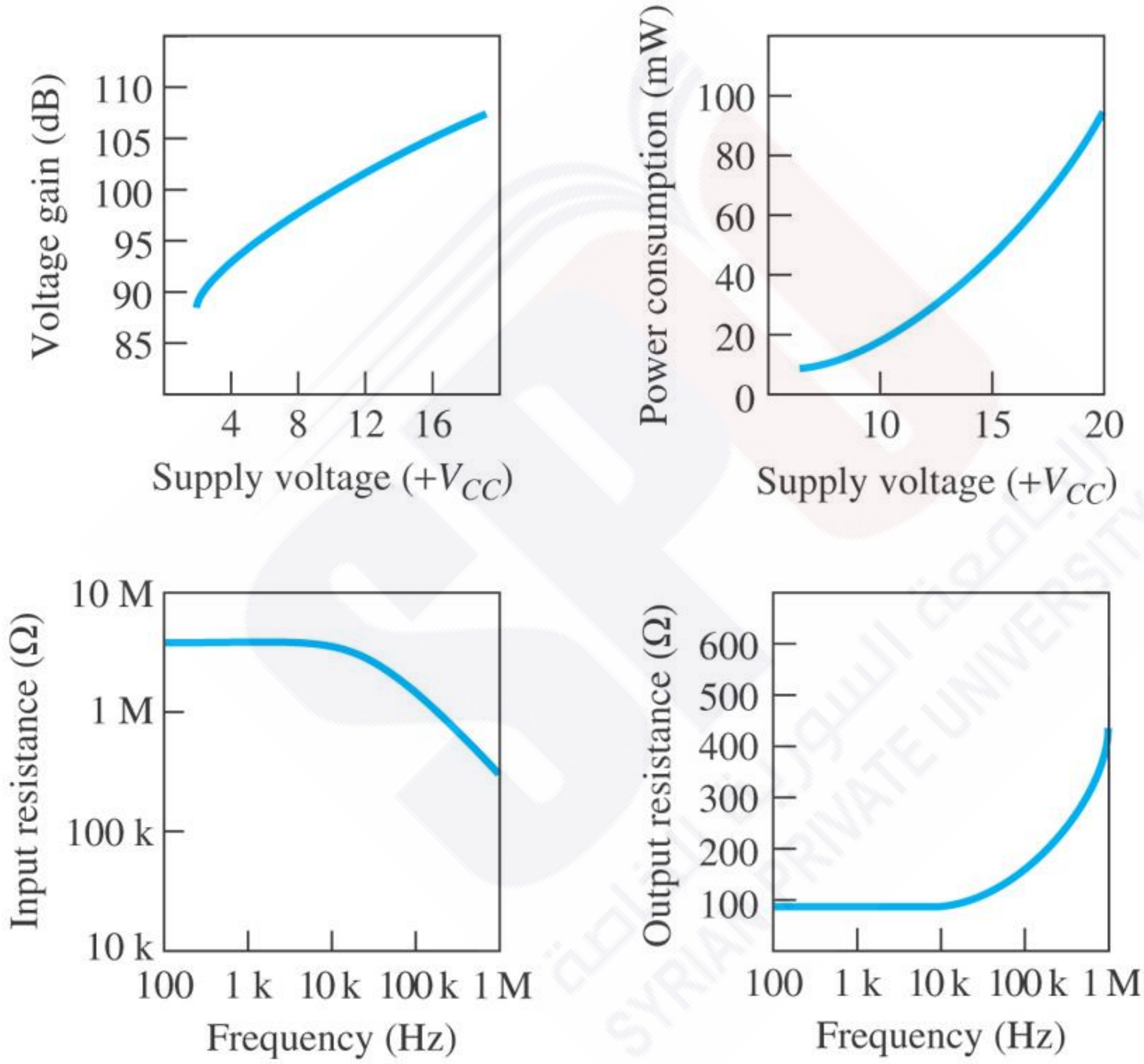
Or $\omega \leq SR/k$



absolute maximum ratings over operating free-air temperature range (unless otherwise noted)

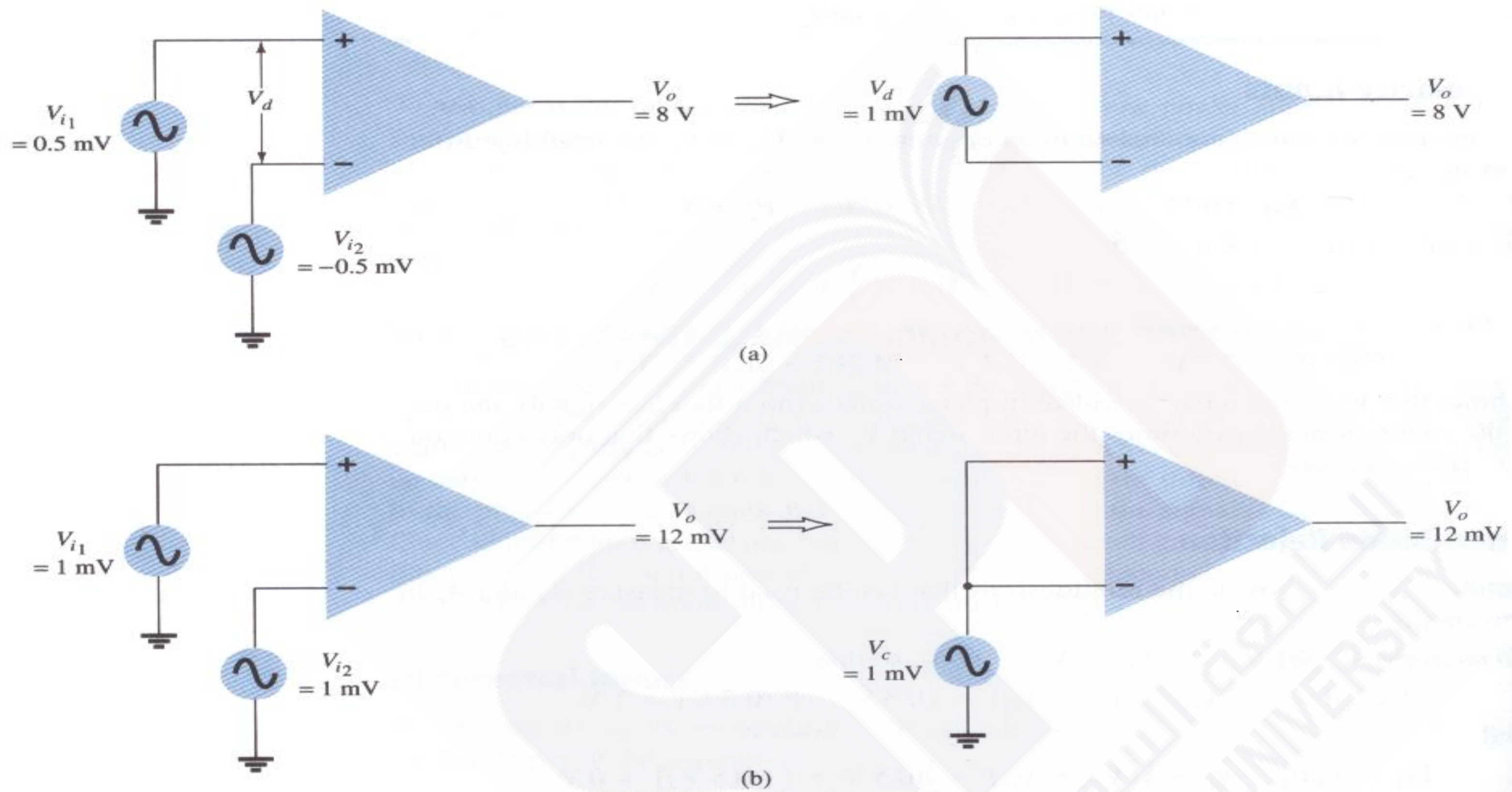
		uA741M	uA741C	UNIT
Supply voltage V_{CC+} (see Note 1)		22	18	V
Supply voltage V_{CC-} (see Note 1)		−22	−18	V
Differential input voltage (see Note 2)		± 30	± 30	V
Input voltage any input (see Notes 1 and 3)		± 15	± 15	V
Voltage between either offset null terminal (N1/N2) and V_{CC-}		± 0.5	± 0.5	V
Duration of output short-circuit (see Note 4)		unlimited	unlimited	
Continuous total power dissipation at (or below) 25°C free-air temperature (see Note 5)		500	500	mW
Operating free-air temperature range		−55 to 125	0 to 70	°C
Storage temperature range		−65 to 150	−65 to 150	°C
Lead temperature 1,6 mm (1/16 inch) from case for 60 seconds	FH, FK, J, JG, or U package	300	300	°C
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds	D, N, or P package		260	°C

NOTES:
1. All voltage values, unless otherwise noted, are with respect to the midpoint between V_{CC+} and V_{CC-}.
2. Differential voltages are at the noninverting input terminal with respect to the inverting input terminal.
3. The magnitude of the input voltage must never exceed the magnitude of the supply voltage or 15 volts, whichever is less.
4. The output may be shorted to ground or either power supply. For the uA741M only, the unlimited duration of the short-circuit applies at (or below) 125°C case temperature or 75°C free-air temperature.
5. For operation above 25°C free-air temperature, refer to Dissipation Derating Curves, Section 2. In the J and JG packages, uA741M chips are alloy mounted; uA741C chips are glass mounted.



Voltage gain (dB)
110
105
100
95
90
85
4
8
12
16
Supply voltage (+V_{CC})
Power consumption (mW)
100
80
60
40
20
0
10
15
20
Supply voltage (+V_{CC})
Input resistance (Ω)
10 M
1 M
100 k
10 k
100
1 k
10 k
100 k
1 M
Frequency (Hz)
Output resistance (Ω)
600
500
400
300
200
100
100
1 k
10 k
100 k
1 M
Frequency (Hz)

EXAMPLE 10.21 Calculate the CMRR for the circuit measurements shown in Fig. 10.52.



Solution: From the measurement shown in Fig. 10.52a, using the procedure in step 1 above, we obtain

$$A_d = \frac{V_o}{V_d} = \frac{8\text{ V}}{1\text{ mV}} = 8000$$

The measurement shown in Fig. 10.52b, using the procedure in step 2 above, gives us

$$A_c = \frac{V_o}{V_c} = \frac{12\text{ mV}}{1\text{ mV}} = 12$$

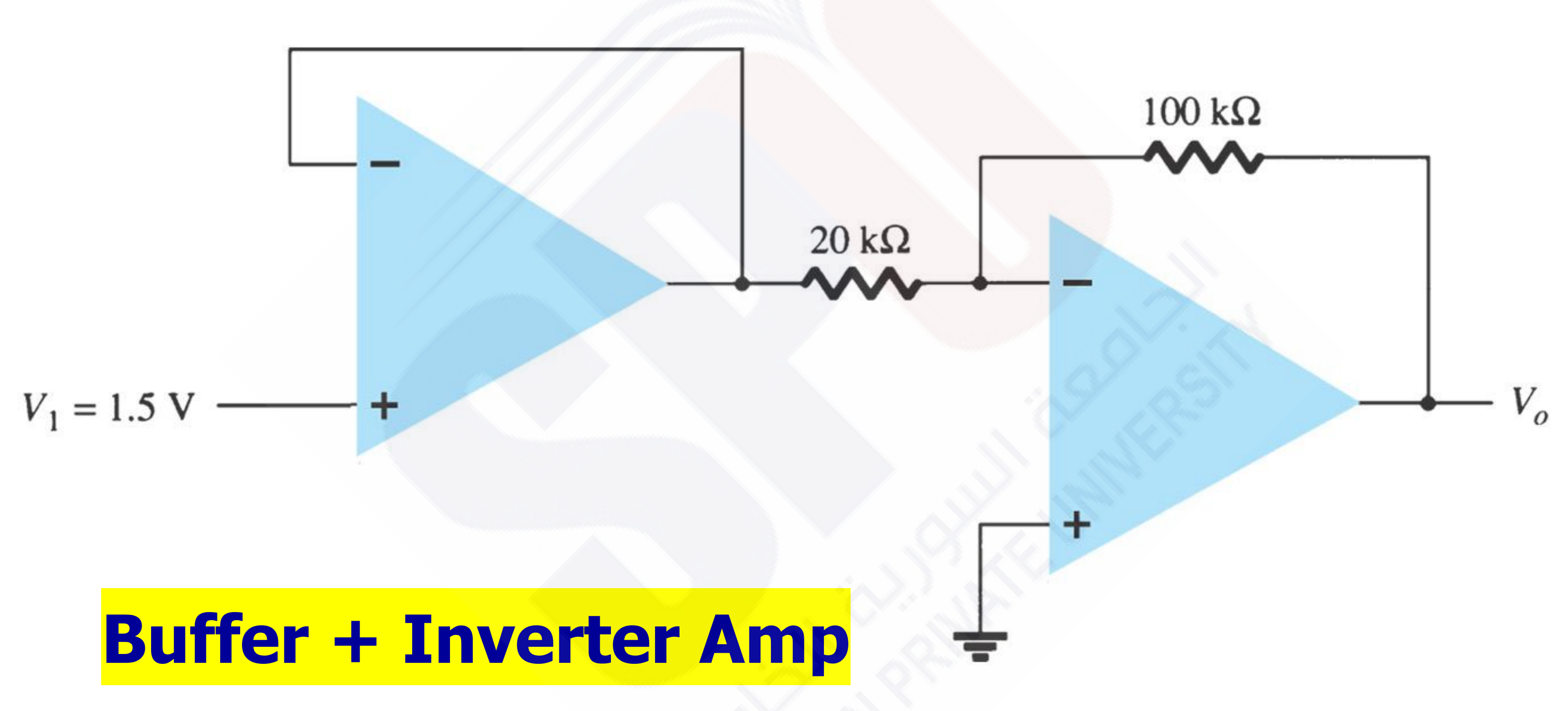
Using Eq. (10.28), we obtain the value of CMRR,

$$\text{CMRR} = \frac{A_d}{A_c} = \frac{8000}{12} = \mathbf{666.7}$$

which can also be expressed as

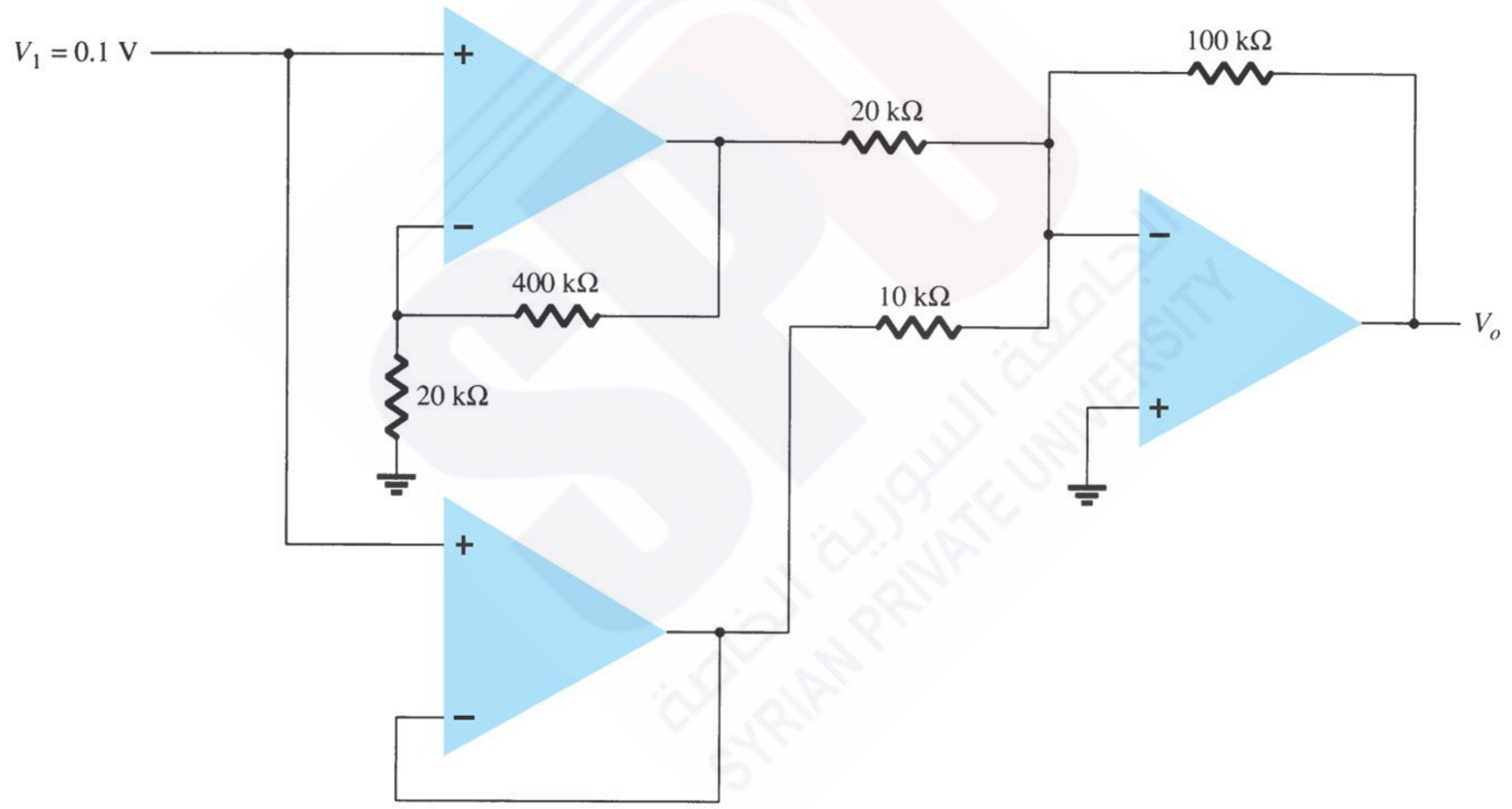
$$\text{CMRR} = 20\log_{10}\frac{A_d}{A_c} = 20\log_{10}666.7 = \mathbf{56.48\ dB}$$

4.6 Op-Amp Applications

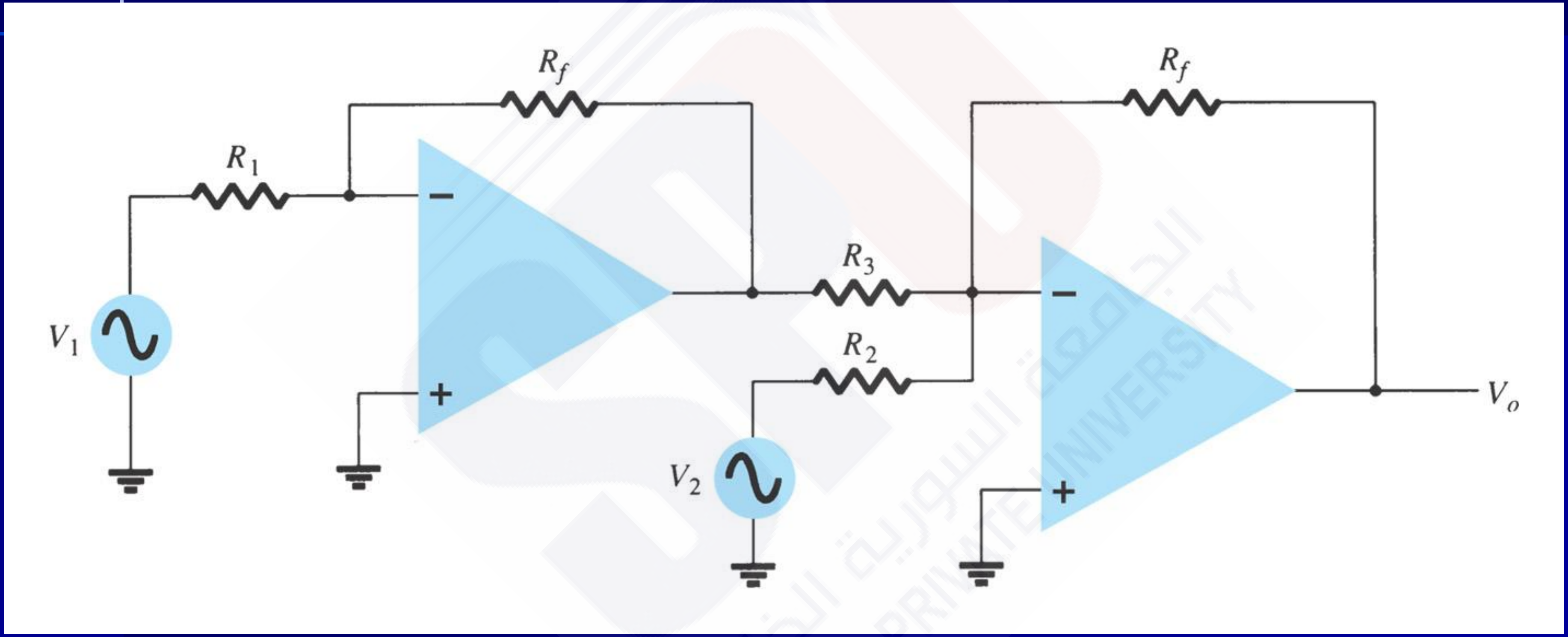


Buffer + Inverter Amp

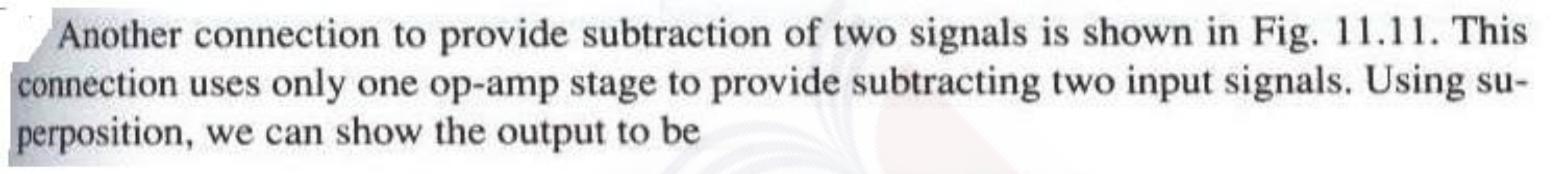
Applications Of Op-Amp



Circuit for subtracting two signals

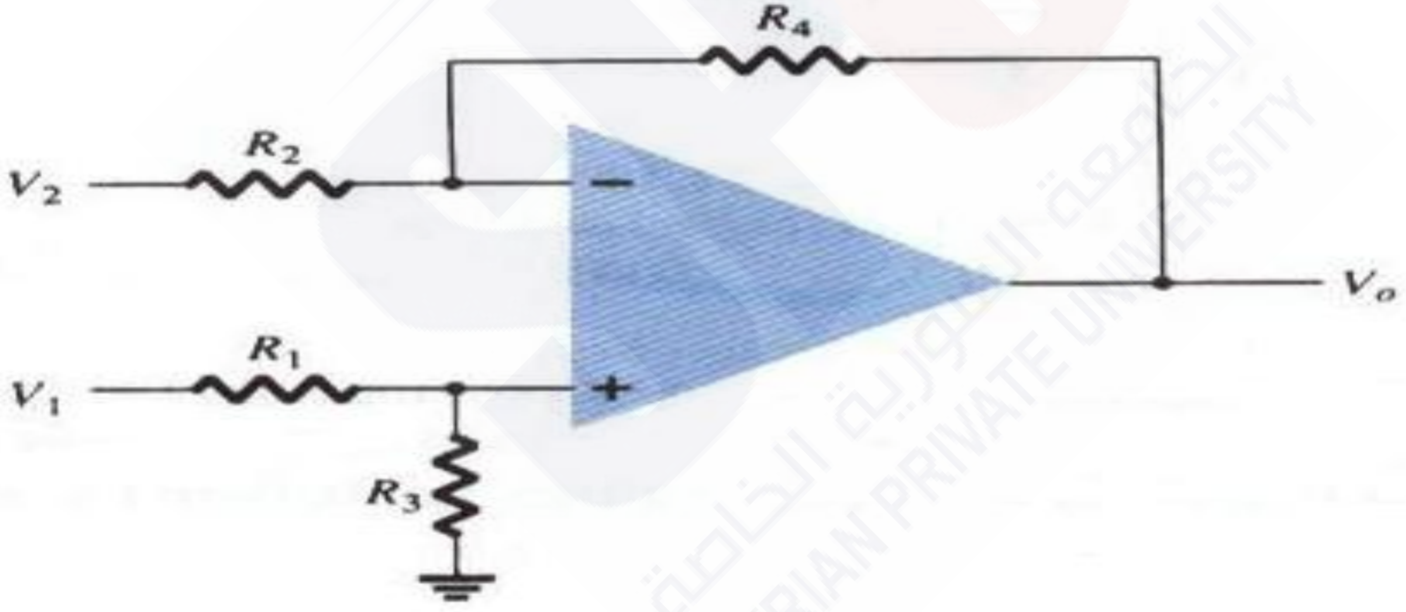


Circuit for subtracting two signals



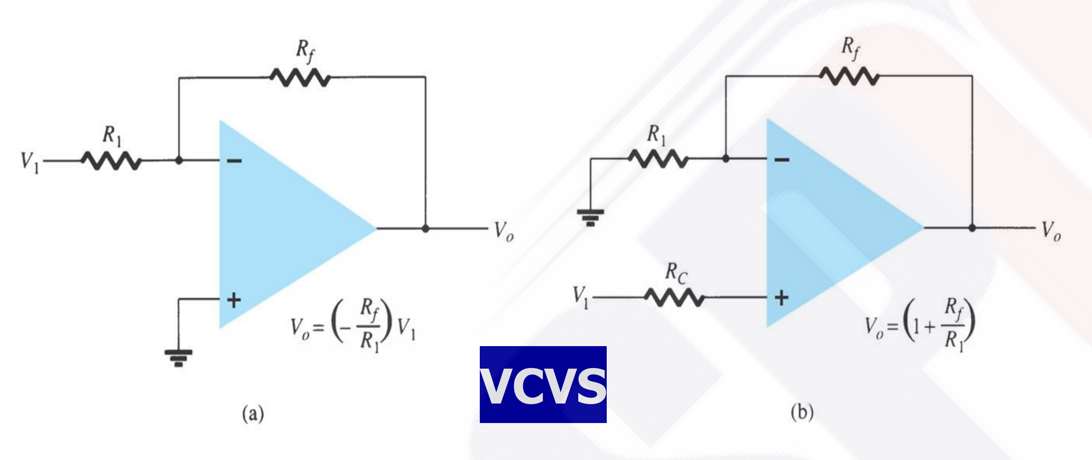
Another connection to provide subtraction of two signals is shown in Fig. 11.11. This connection uses only one op-amp stage to provide subtracting two input signals. Using superposition, we can show the output to be

$$V_o = \frac{R_3}{R_1 + R_3} \frac{R_2 + R_4}{R_2} V_1 - \frac{R_4}{R_2} V_2$$

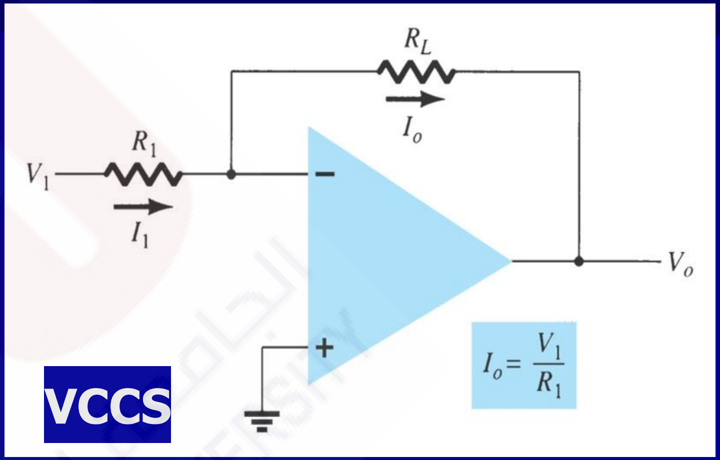


Subtraction circuit.

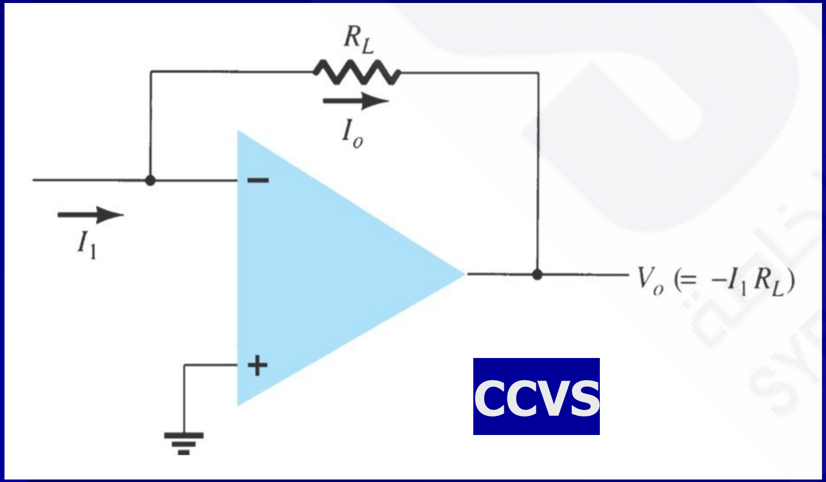
Practical V/C Controlled Sources



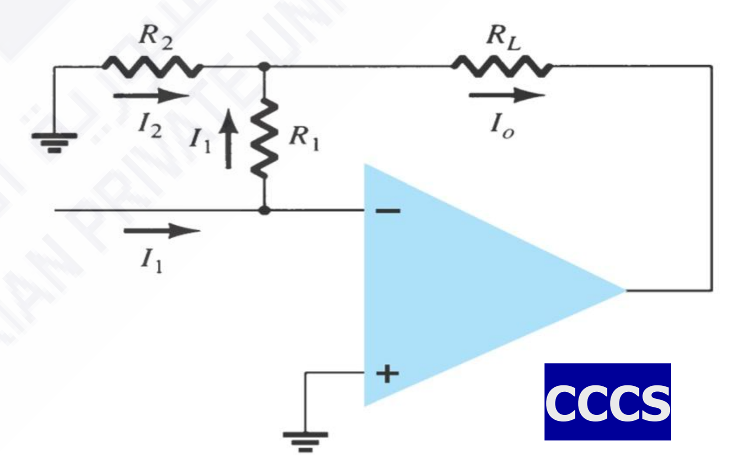
VCVS



VCCS



CCVS



CCCS

Practical Voltage-Controlled Voltage Source

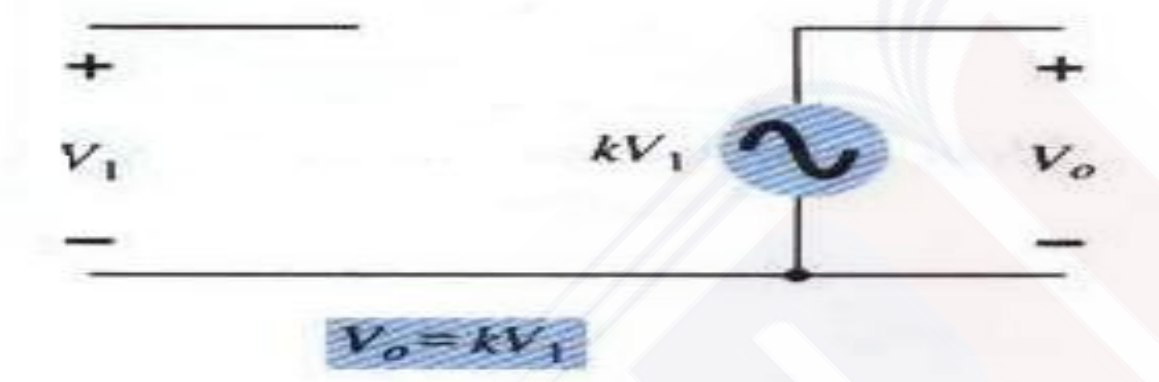
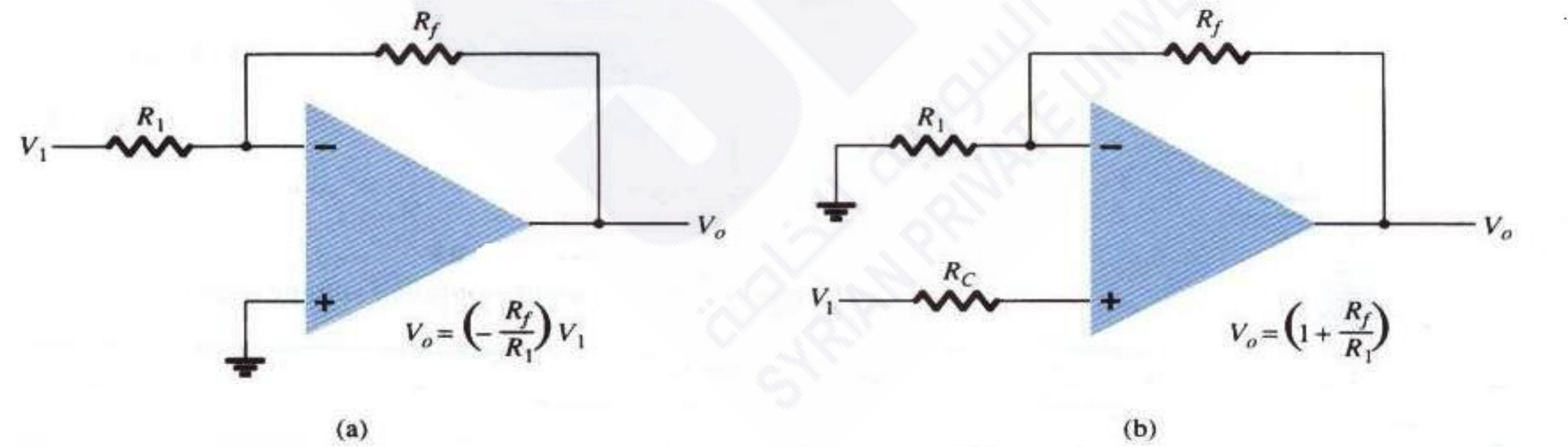


FIG. 11.16
Ideal voltage-controlled voltage source.

$$\boxed{V_o = -\frac{R_f}{R_1} V_1 = kV_1}$$

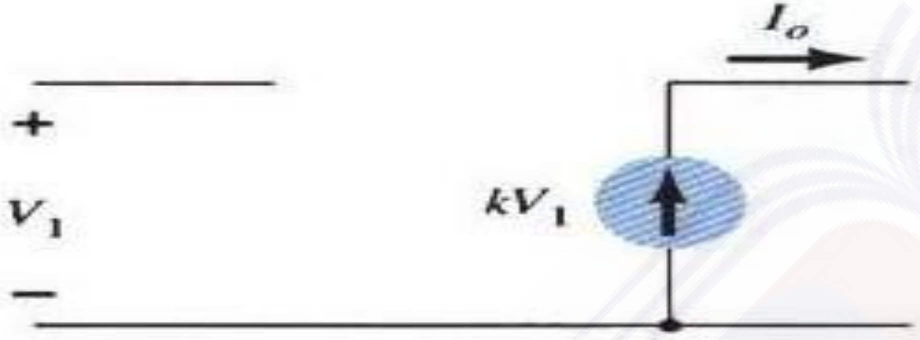


(a)

(b)

FIG. 11.17
Practical voltage-controlled voltage source circuits.

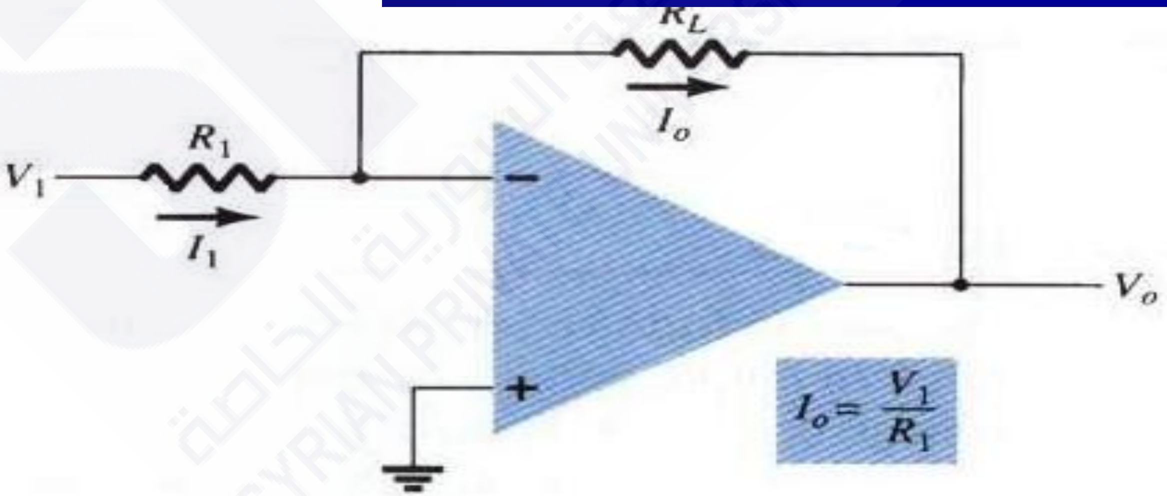
Practical Voltage–Controlled Current Source



$I_o = kV_1$

FIG. 11.18
Ideal voltage-controlled current source.

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



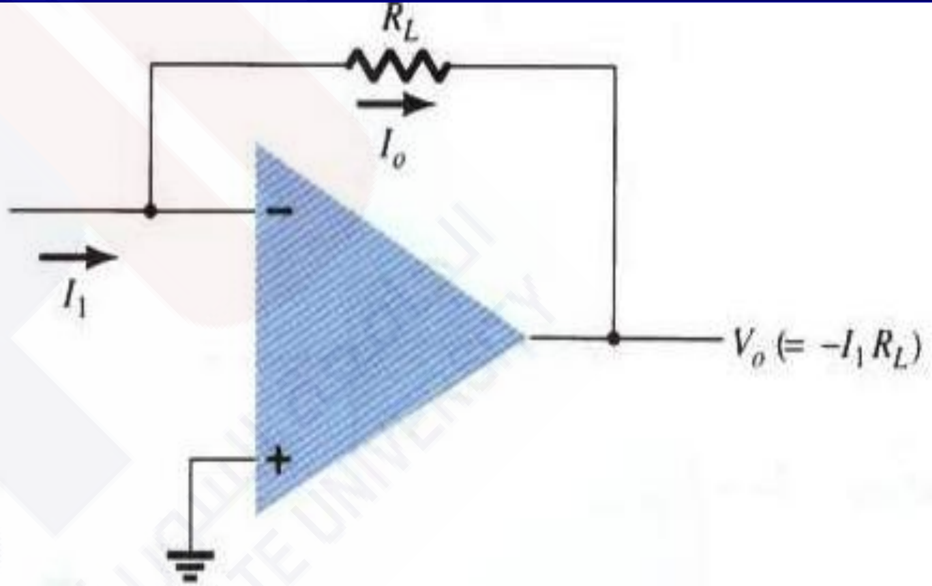
$I_o = \frac{V_1}{R_1}$

FIG. 11.19
Practical voltage-controlled current source.

Practical Current – Controlled Voltage Source

$V_o = kI_1$

FIG. 11.20
Ideal current-controlled voltage source.



$$\boxed{V_o = -I_1 R_L = kI_1}$$

Practical Current - Controlled Current Source

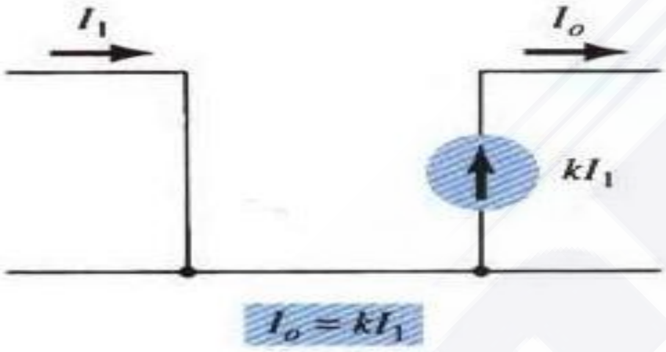


FIG. 11.22
Ideal current-controlled current source.

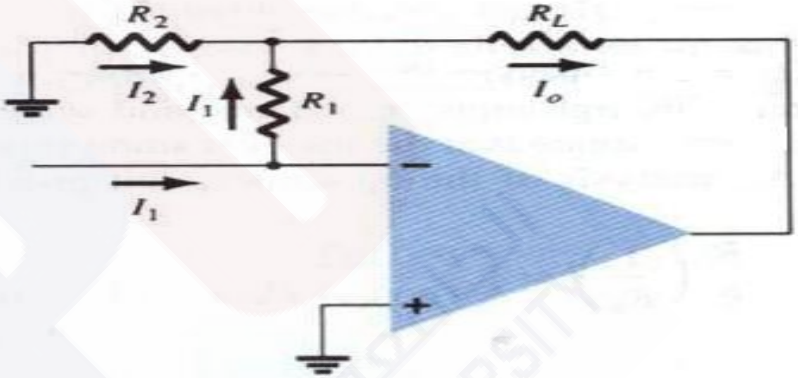
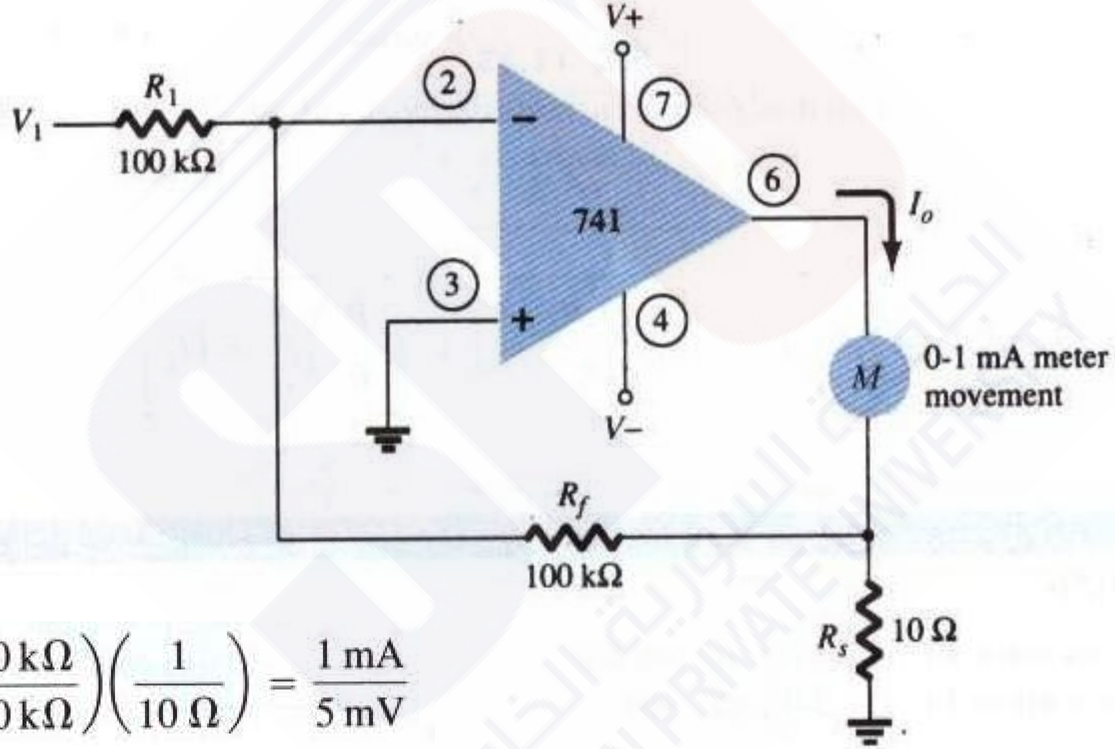


FIG. 11.23
Practical form of current-controlled current source.

$$I_o = I_1 + I_2 = I_1 + \frac{I_1R_1}{R_2} = \left(1 + \frac{R_1}{R_2}\right)I_1 = kI_1$$

$$\left|\frac{I_o}{V_1}\right| = \frac{R_f}{R_1}\left(\frac{1}{R_S}\right) = \left(\frac{100\,\text{k}\Omega}{100\,\text{k}\Omega}\right)\left(\frac{1}{10\,\Omega}\right) = \frac{1\,\text{mA}}{10\,\text{mV}}$$

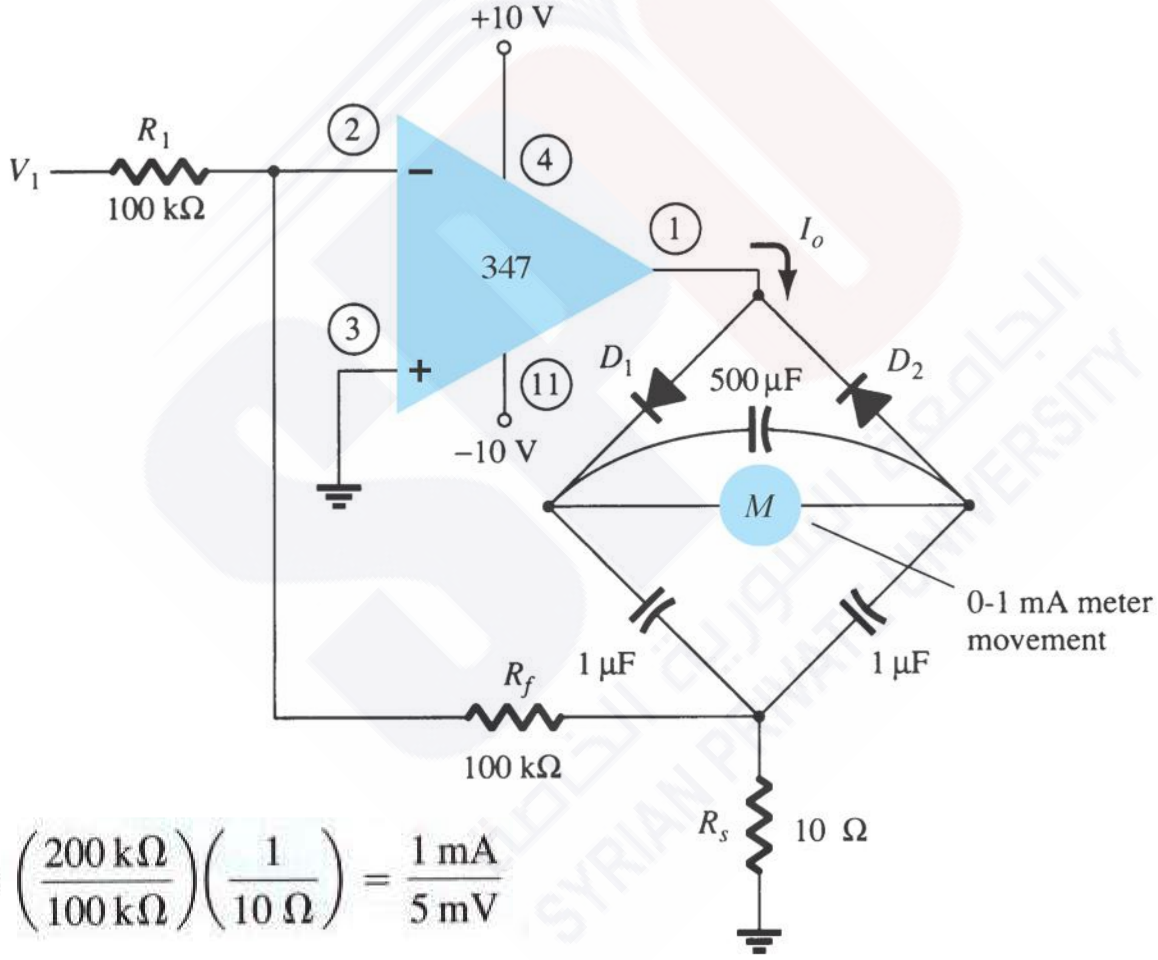


$$\left|\frac{I_o}{V_1}\right| = \left(\frac{200\,\text{k}\Omega}{100\,\text{k}\Omega}\right)\left(\frac{1}{10\,\Omega}\right) = \frac{1\,\text{mA}}{5\,\text{mV}}$$

FIG. 11.25

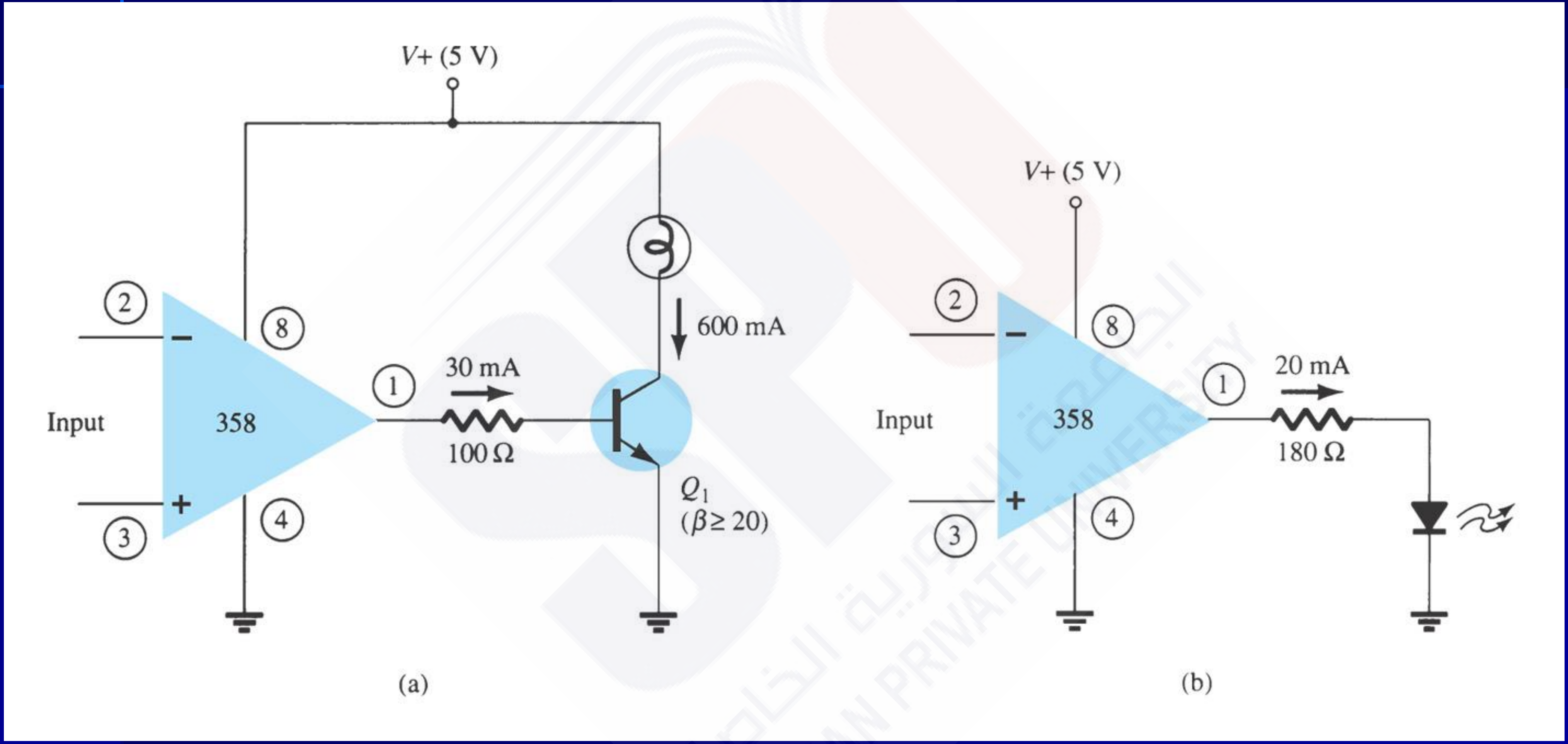
Op-amp dc millivoltmeter.

AC millivoltmeter using op-amp.

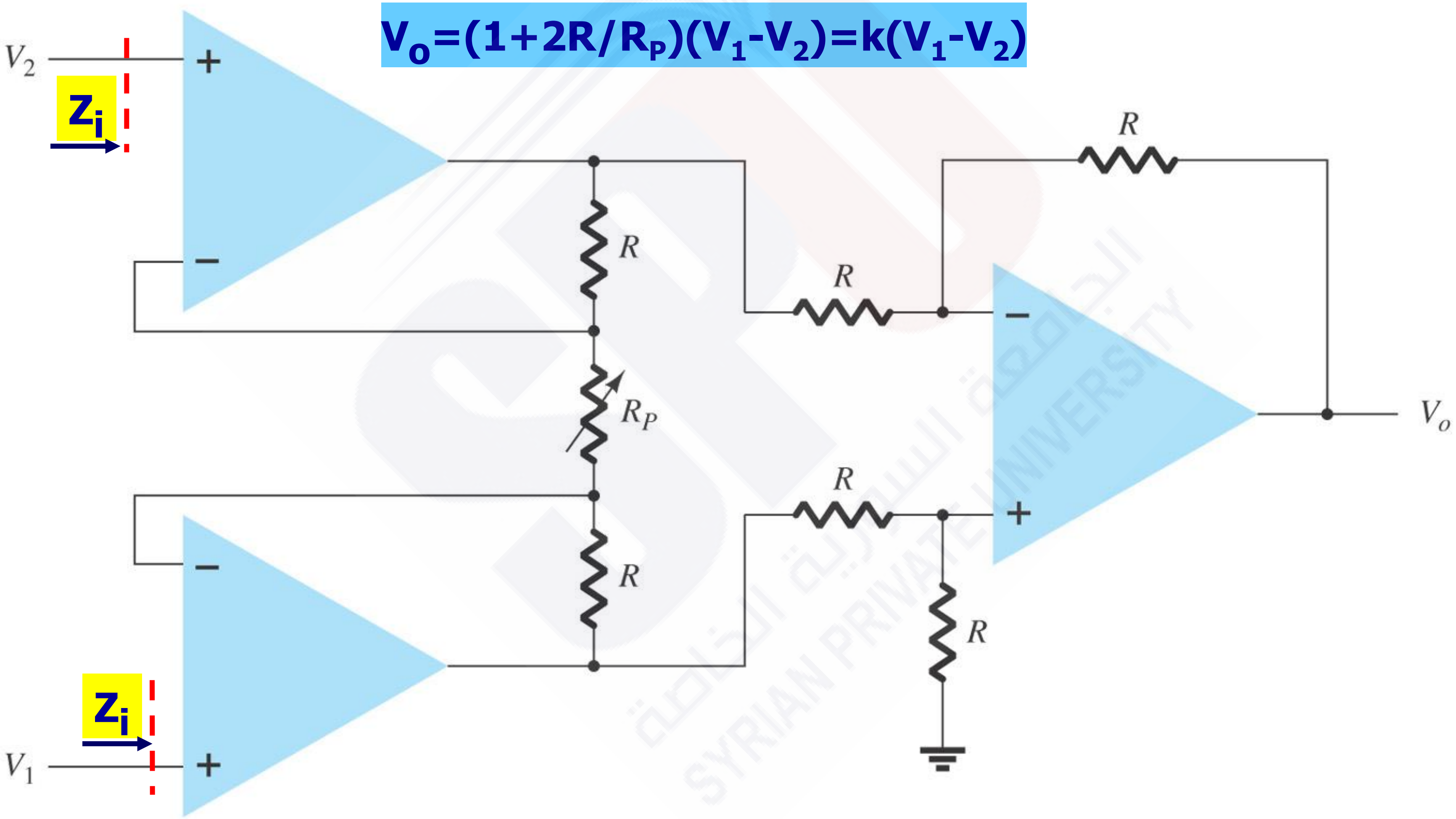


$$\left|\frac{I_o}{V_1}\right| = \left(\frac{200\,\text{k}\Omega}{100\,\text{k}\Omega}\right)\left(\frac{1}{10\,\Omega}\right) = \frac{1\,\text{mA}}{5\,\text{mV}}$$

Display driver circuits: (a) lamp driver; (b) LED driver

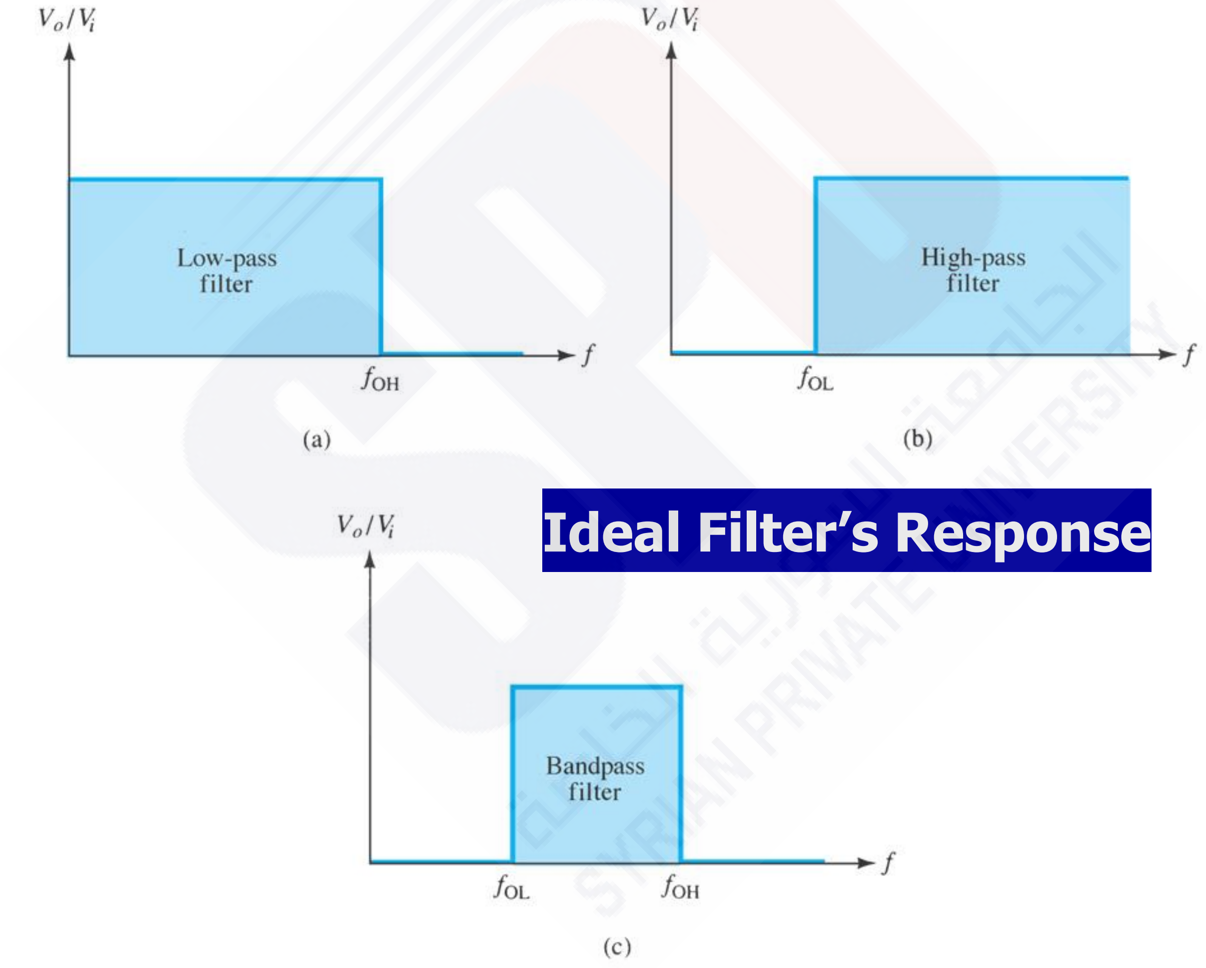


Instrumentation amplifier



$$V_o=(1+2R/R_P)(V_1-V_2)=k(V_1-V_2)$$

4.7 Active Filters



Ideal Filter’s Response

Filters Types

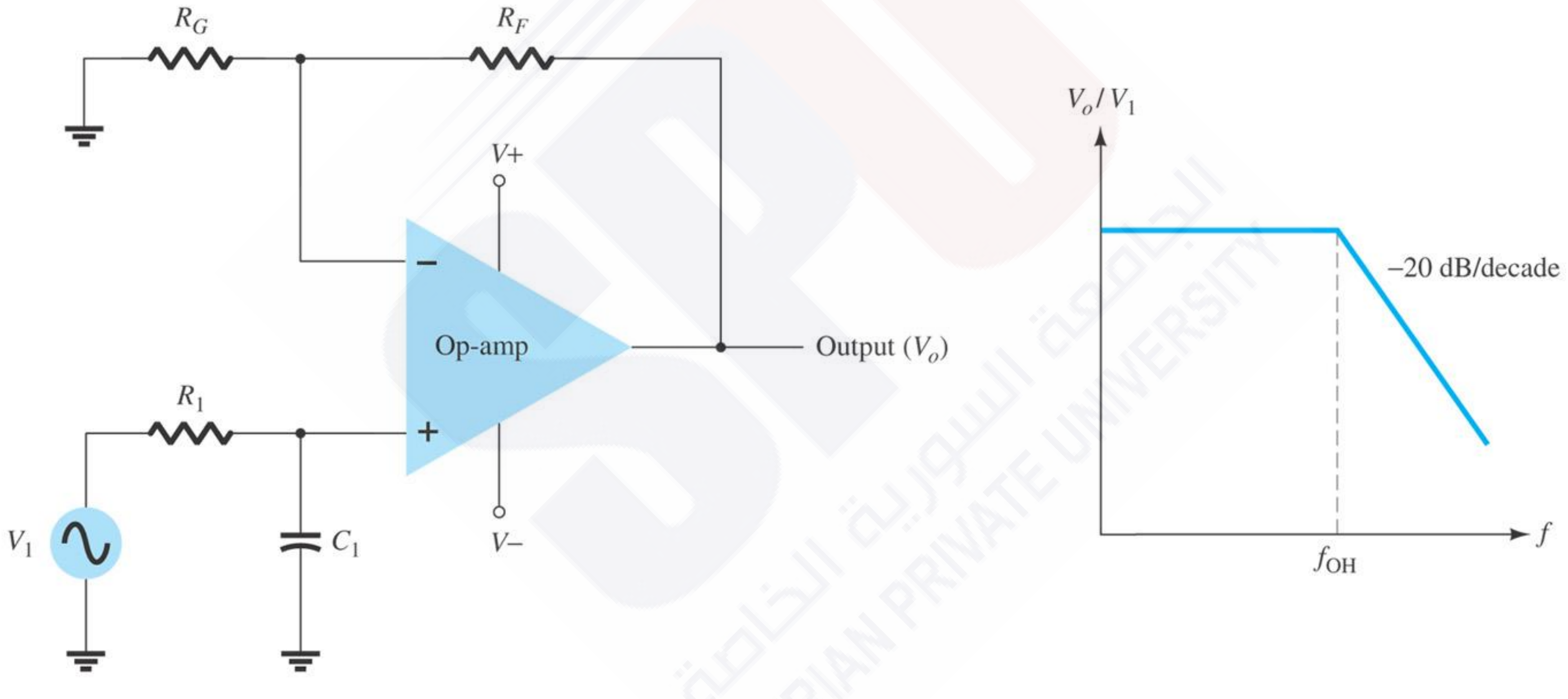
1. Passive Filters: (R,L,C)

2. Active Filters: (RC,Op-Amp)

3. Digital Filters: (DSP,A/D & D/A)

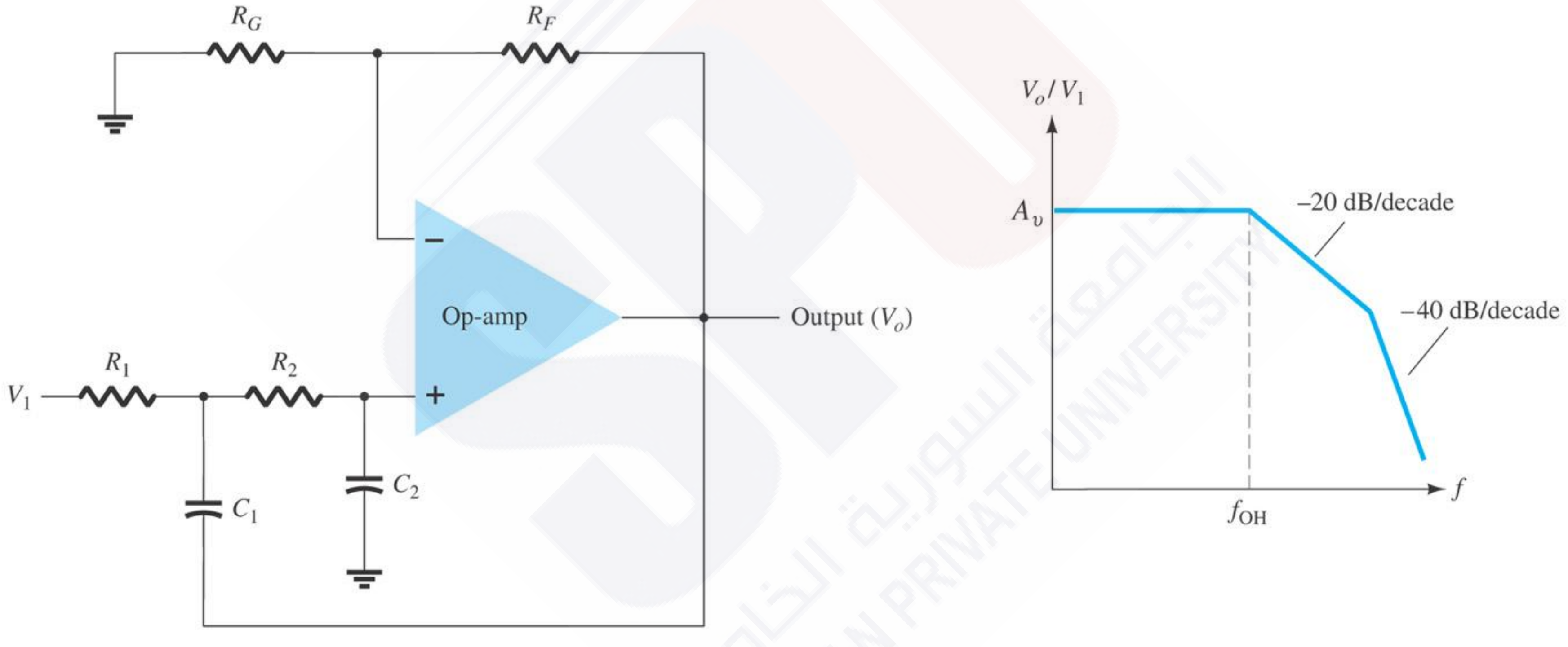
All of them to have: LPF, HPF, BPF, BRF

First-order low-pass active filter



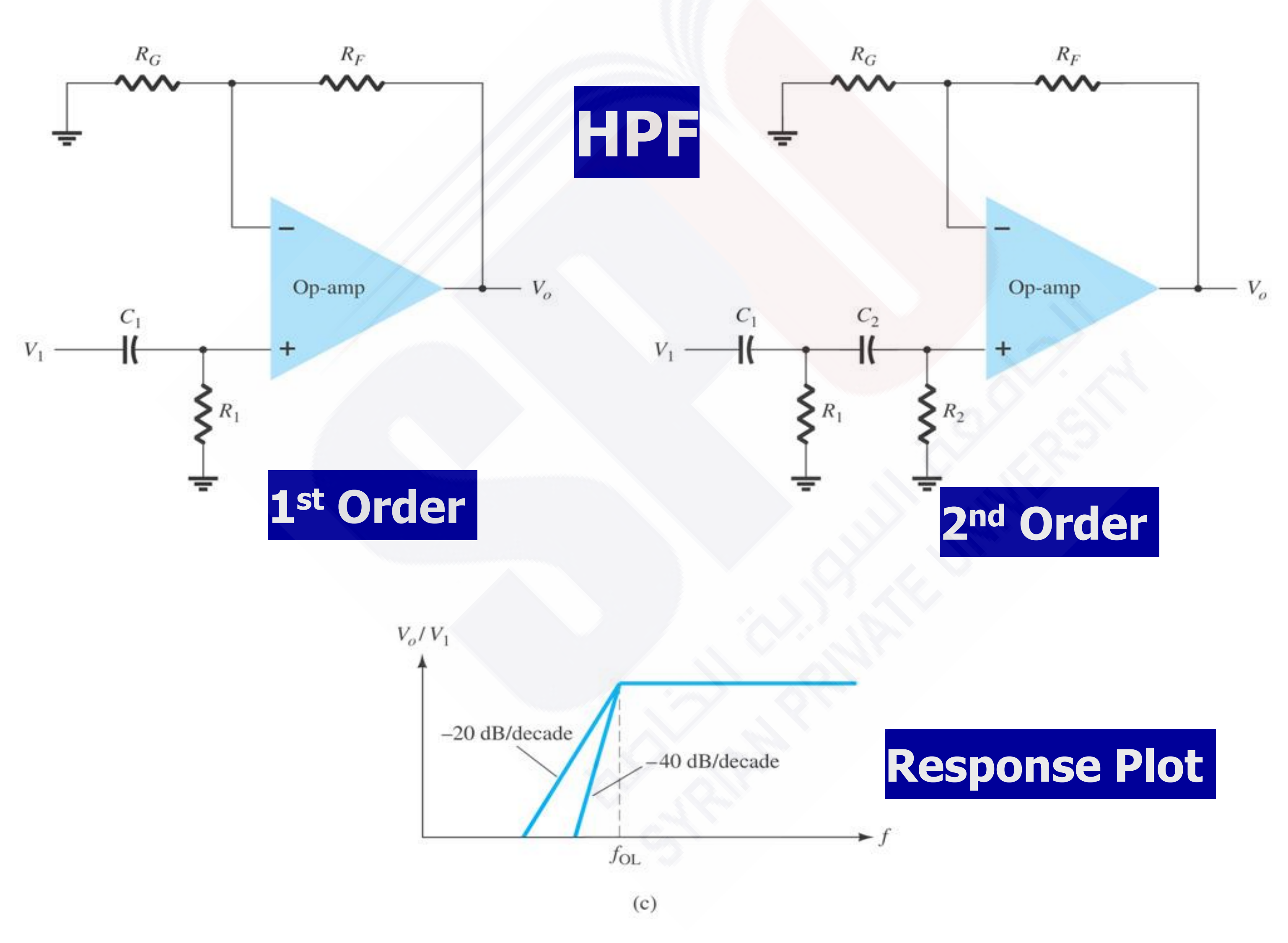
(a) (b)

Second-order low-pass active filter



(a) (b)

Different Orders Of Active Filters



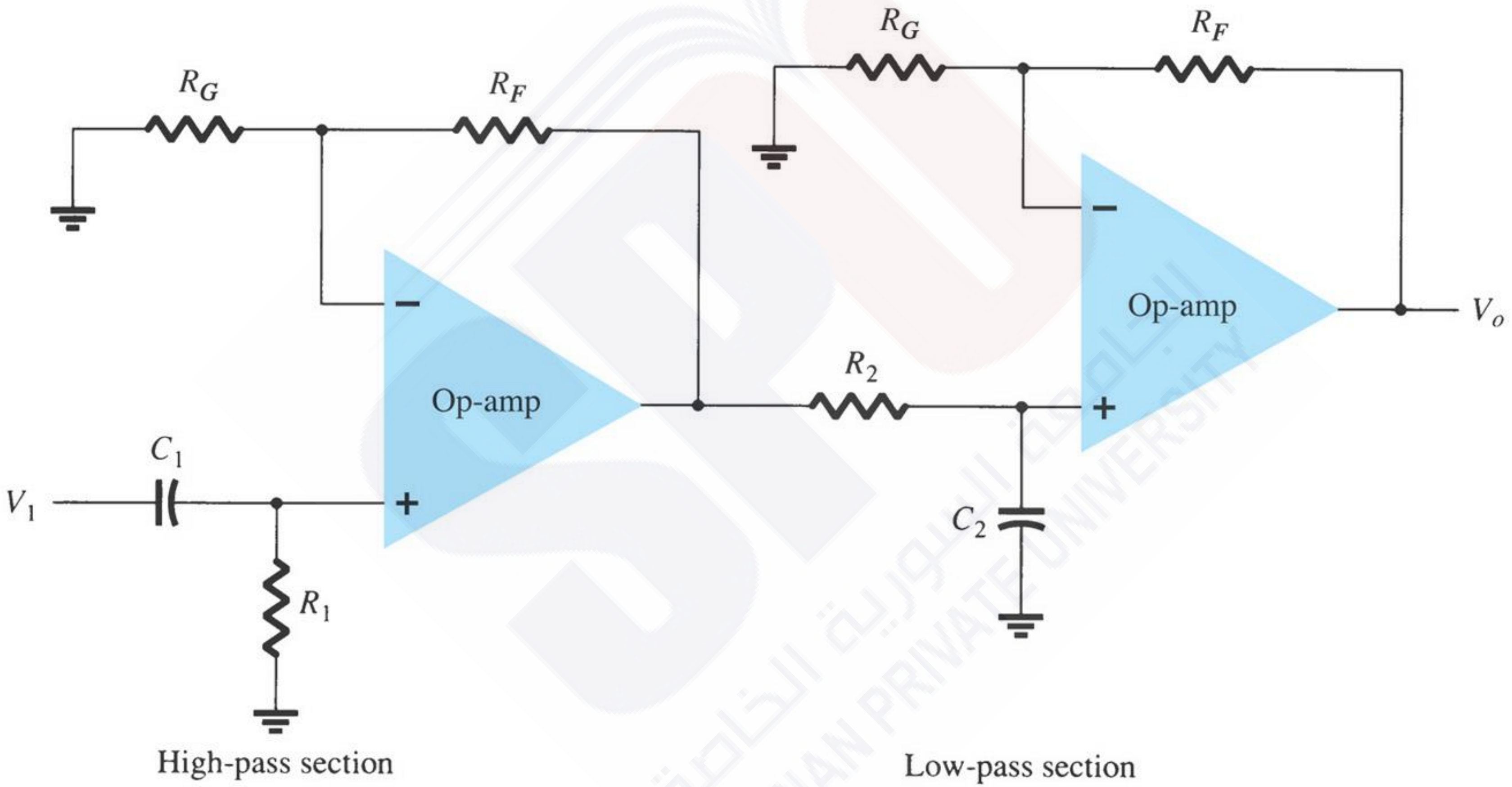
HPF

1st Order

2nd Order

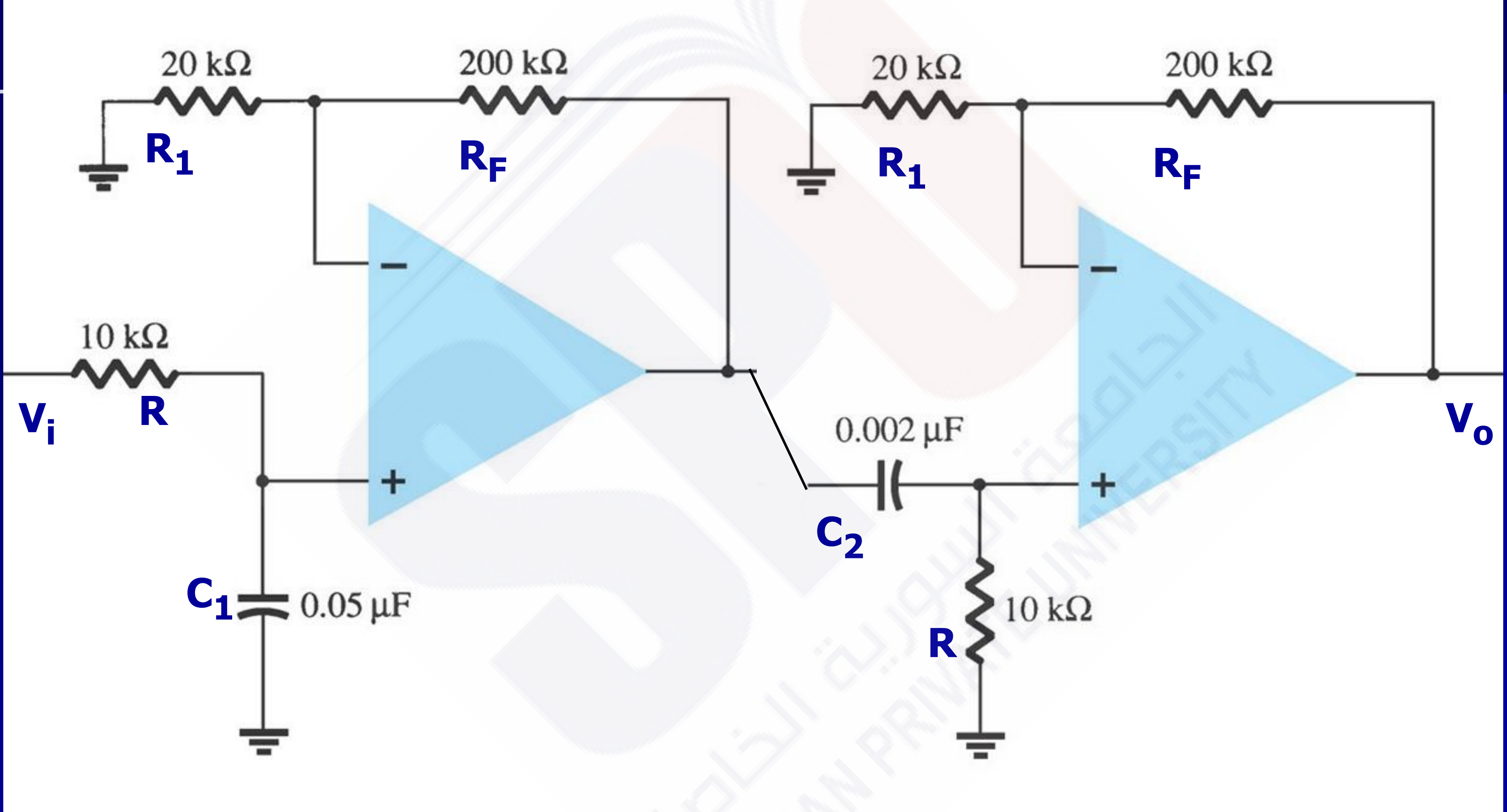
Response Plot

Band-pass active filter

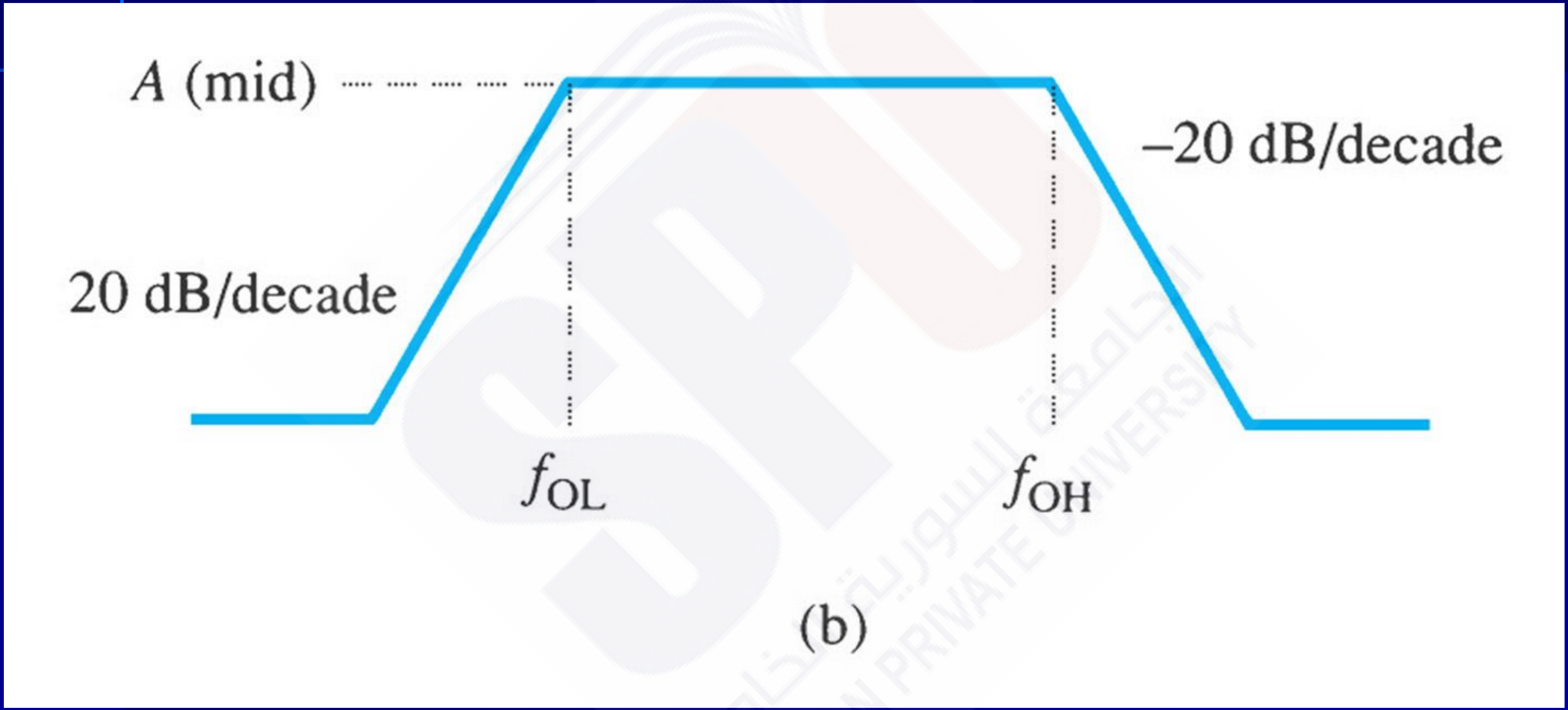


(a)

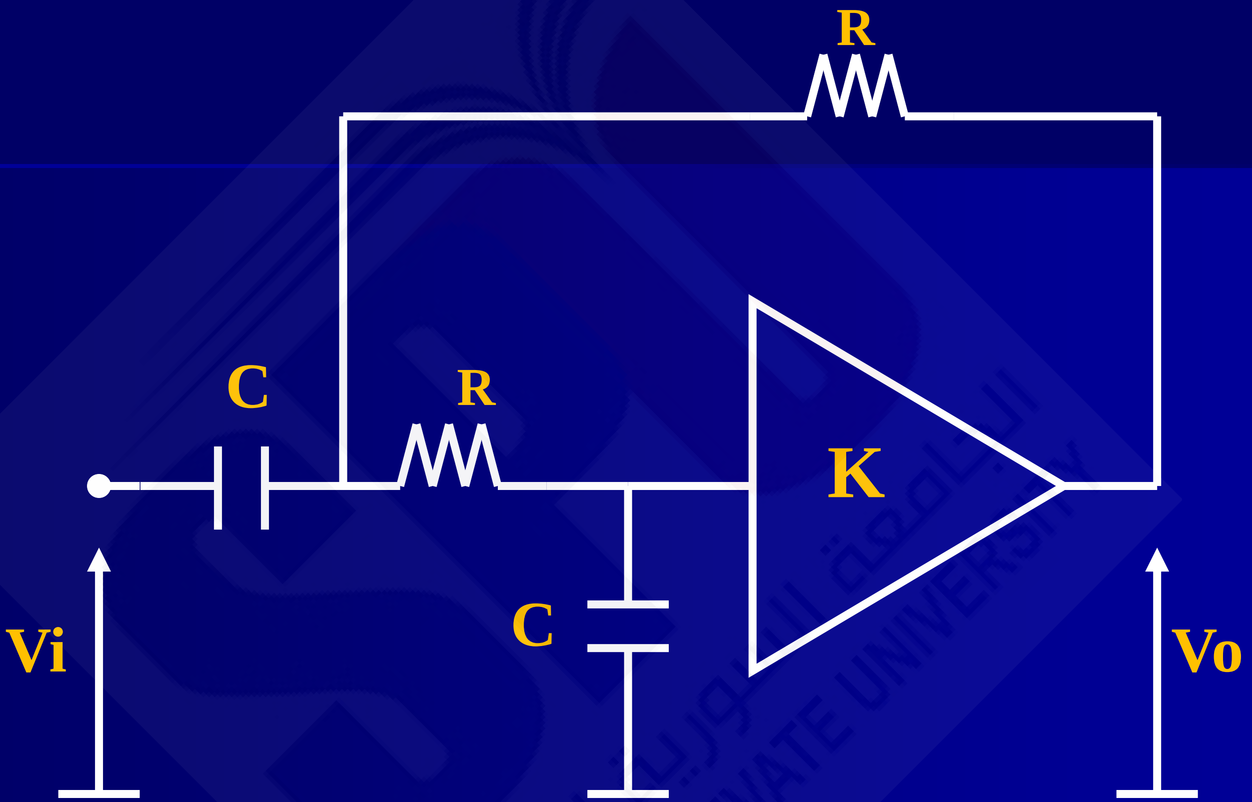
Filter = ?

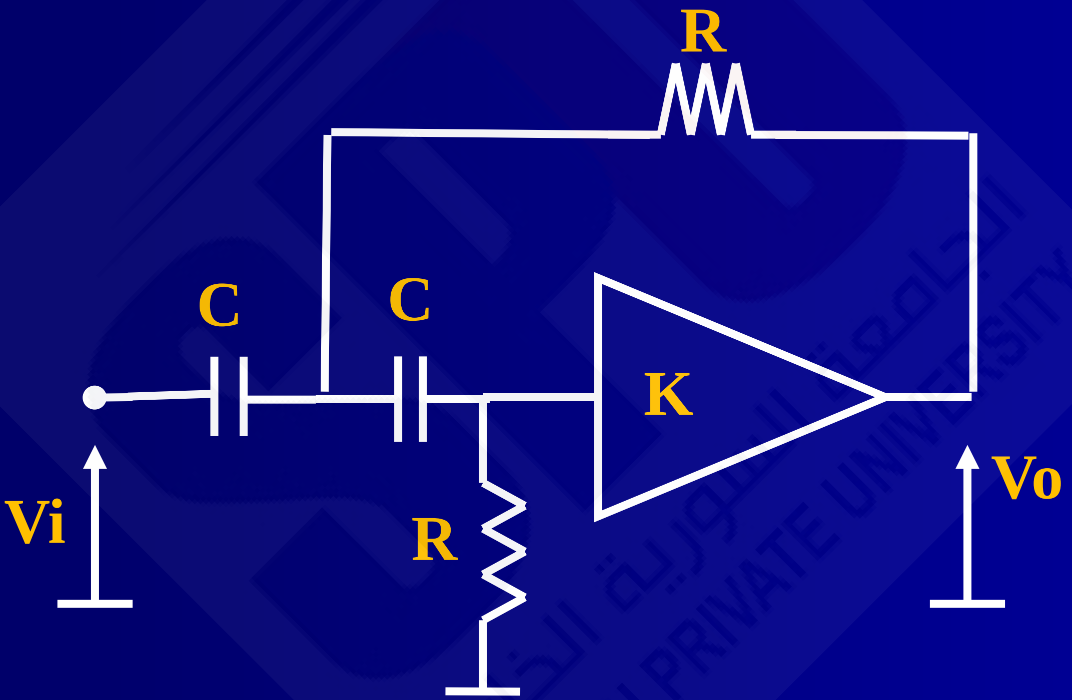

20 kΩ
R_1
200 kΩ
R_F
20 kΩ
R_1
200 kΩ
R_F
10 kΩ
V_i
R
0.002 μF
C_2
V_o
C_1
0.05 μF
10 kΩ
R

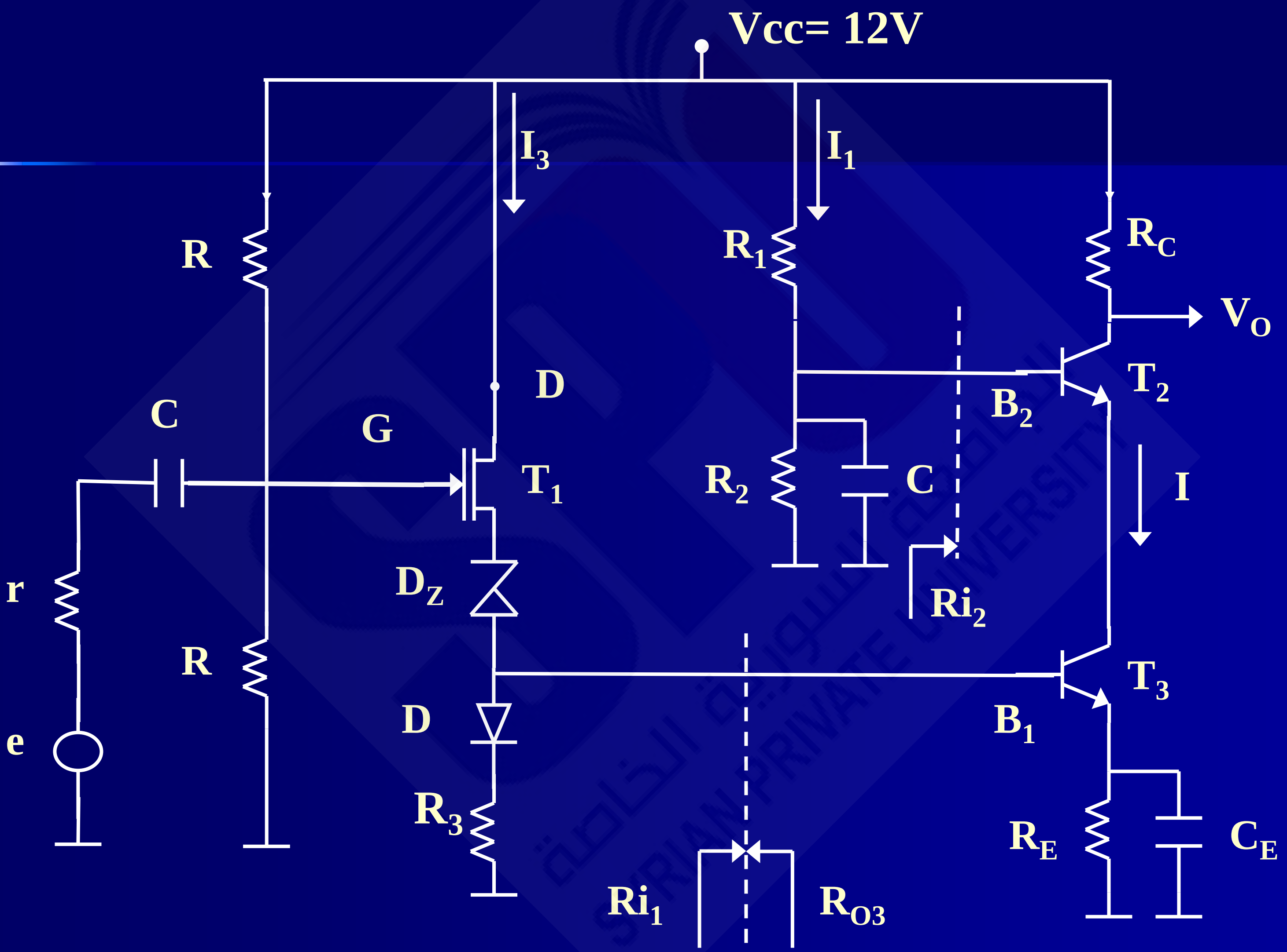
Band-pass active filter



(b)


R
C
R
K
C
Vi
Vo


R
C
C
K
Vi
R
Vo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I_3
I_1
R
R_1
R_C
V_O
D
T_2
B_2
C
G
T_1
R_2
C
I
r
D_Z
Ri_2
R
T_3
B_1
e
D
R_3
R_E
C_E
Ri_1
R_{O3}