7. Electronic Circuits

OP-AMP CIRCUITS

(with op-amp treated as a block)

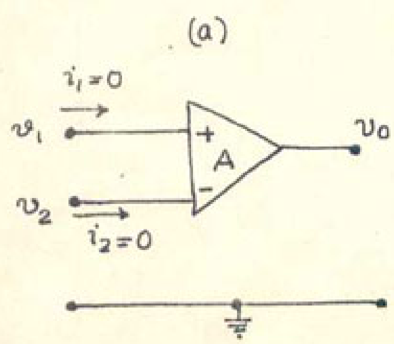
1.0 IC op-amp and its ideal properties:

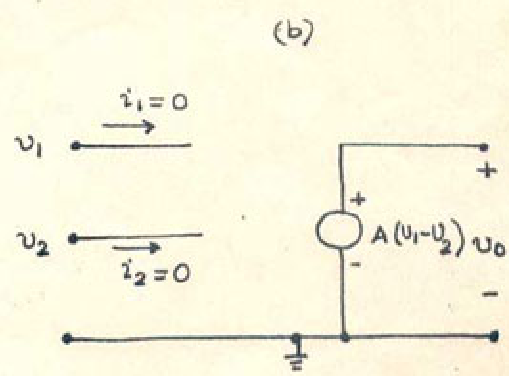
The integrated circuit op-amp is the most prominent and versatile building block of analog circuits. Although initially op-amp was employed to perform various mathematical **operations** like integration, addition, sign changing, function generation etc. (commonly employed for analog computation) from which the generic name ***operational amplifier*** was derived, with the availability of integrated circuit (IC) op-amp as an off-the-shelf item it has now found numerous other applications in many diverse areas of signal processing, instrumentation and measurement, communication etc.

Here, we are mainly concerned with the study of some basic building blocks which can be realised with IC op-amps.

An operational amplifier is basically a very high gain differential amplifier with the following **ideal** properties:

- infinite voltage gain (ie $A \to \infty$)
- Infinite input impedance (ie input terminals draw zero current when connected to source)
- zero output impedance (ie it acts as an ideal voltage source w.r.t output terminal)
- infinite bandwidth (ie gain remains constant from zero frequency to infinity)
- zero offset voltage (ie $V_o = 0$ when $V_1 = 0 = V_2$)
- zero drift (ie parameters not changing with temperature





$i_1 = 0$

$i_2 = 0$

$v_0 = A(v_1 - v_2)$

Fig. 1 (a) ideal op-amp (b) equivalent circuit of an ideal op-amp

An ideal op-amp can be regarded as a differential input VCVS. A large variety of IC op-amps are available out of which the internally compensated types such as μA741, 747, LM 324, LF356 have been the more popular ones. The pin configuration for 741 type op-amp is given in Fig. 2, and its important parameters are given in Table 1.

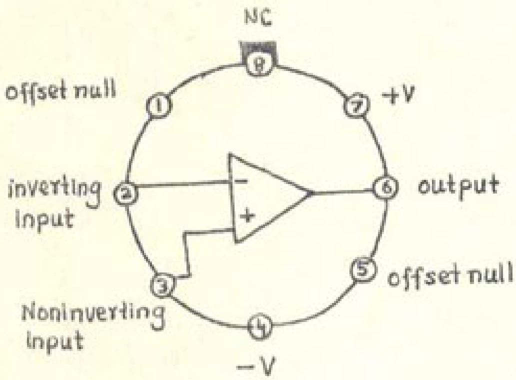


Fig. 2 Pin configuration of 741 type IC op-amp (metal can package)

Table 1 Parameters of 741 op-amp

Parameter	741(c)(typical)
Voltage gain	2×10^5
Input impedance	2 MΩ
output impedance	75 Ω
offset voltage	2 mV
bandwidth (unity gain bandwidth)	1 MHz

2. Basic Analog circuits using op-amps :

In the following we show different controlled sources and other useful circuits can be realised by using IC op-amps. Although in some synthesis techniques the op-amp may be directly used as an infinite-gain VCVS in its own right, it is normally customary to use this device as finite gain VCVS

VCVS circuits: Consider the 3-port VCVS of Fig. 3. Assuming ideal op-amp (ie $Z_{in} = \infty$, $Z_o = 0$, $A \to \infty$) the node equation at node m is

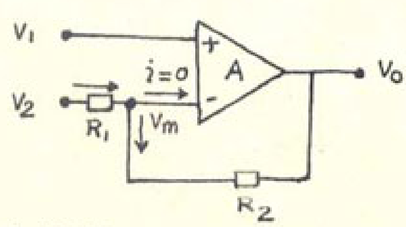


Fig. 3 Three-port VCVS

$$\frac{V_2 - V_m}{R_1} = \frac{V_m - V_o}{R_2} \qquad (1)$$

solving for V_m gives, $v_m = \frac{R_2}{R_1+R_2} V_2 + \frac{R_1}{R_1+R_2} V_o$ (2)

also $(V_1 - V_m)A = V_o$

or $(V_1 - V_m) = \frac{V_o}{A}$ which means $V_1 = V_m$ as $A \to \infty$ (3)

Equation (3) implies a very important property of an ideal op-amp, that due to infinite gain *voltages at the two input terminals of the op-amp are forced to be equal*. Thus, the input terminals of the op-amp exhibit a 'virtual short'. When one of these input terminals is connected to ground the other terminal acts as the 'virtual ground'.

From (2) and (3)

$$V_o = \left(1+\frac{R_2}{R_1}\right)V_1 - \frac{R_2}{R_1}V_2 \qquad (4)$$

case 1 : $V_1 = 0$ then the circuit assumes the form of Fig. 4 (a) and from (4)

$$V_o = -\frac{R_2}{R_1}V_2 \qquad (6)$$

Thus the circuit acts as an inverting VCVS (or inverting amplifier) of gain $-\frac{R_2}{R_1}$.

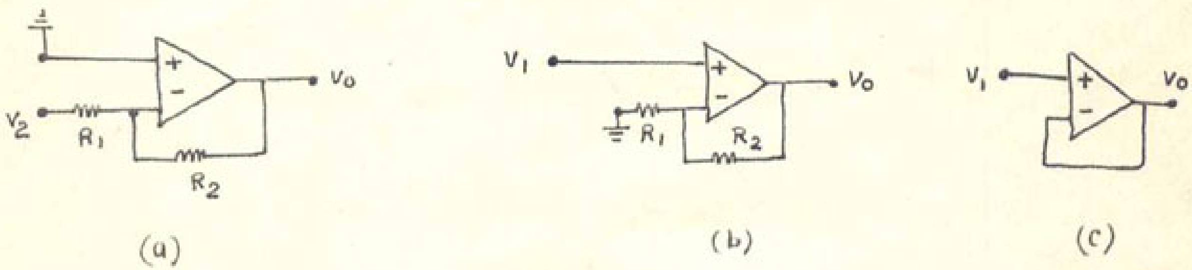


Fig. 4 (a) inverting amplifier gain $= -\frac{R_2}{R_1}$ (b) noninverting amplifier; gain $= (1+\frac{R_2}{R_1})$ (c) voltage follower; gain = 1

case 2 : $V_2 = 0$, then circuit acts as noninverting amplifier with gain $= \left(1+\frac{R_2}{R_1}\right)$ since (4) reduces to

$$V_o = \left(1+\frac{R_2}{R_1}\right)V_1 \qquad (7)$$

with resulting circuit shown in Fig. 4 (b).

case 3 : If R_2 is shorted and R_1 is opened in Fig. 3, the circuit shown in Fig. 4 (c) results for which (from (4))

$$V_o = V_1 \qquad (8)$$

and the circuit acts as a unity gain voltage follower.

Note that all the three VCVS of Fig. 4 have (ideally) zero output impedance; the noninverting VCVS of Fig. 4 (b) and unity gain VCVS of Fig. 4 (c) have (ideally) infinite Z_{in} but Z_{in} for the inverting VCVS is finite and approximately equal to

$$Z_{in} \approx R_1 \qquad (9)$$

Inverting integrator : In Fig. 4 (a) if R_2 is replaced by a capacitor (having transformed impedance $\frac{1}{sC}$) one obtains the circuit of Fig. 5 (a) which is the inverting integrator.

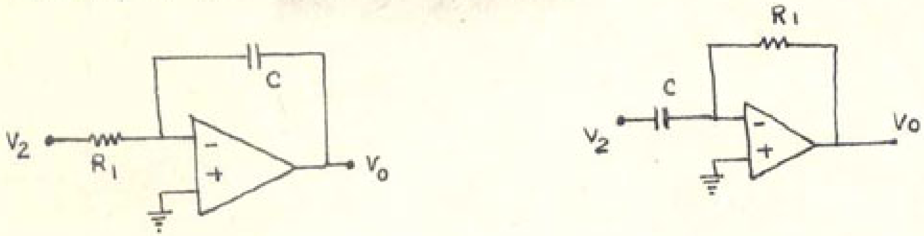


Fig. 5. (a) inverting integrator (b) inverting differentiator (Miller integrator)

Replacing R_2 in equation (6) by $\frac{1}{sC}$, the transfer function of the integrator of Fig. 5 (a) is found to be (10)

$$V_0(s) = -\frac{1}{sCR_1} V_2(s)$$

or in time domain

$$V_0(t) = -\frac{1}{CR_1}\int V_2(t)\, dt \qquad (11)$$

Inverting differentiator: Interchanging R_1 and C in Fig. 5 (a) leads to the circuit of Fig. 5 (b) which is inverting differentiator with

$$V_0(s) = -sCR_1 V_2(s) \qquad (12)$$

or in time domain , $$V_0(t) = -CR_1 \frac{dV_2(t)}{dt} \qquad (13)$$

Finite gain differential amplifiers: In the 3-port VCVS of Fig. 3 , if a potential divider is added at the input the circuit of Fig. 6 is obtained for which

$$V_1 = \left(\frac{R_4}{R_3+R_4}\right) e_1 \qquad (14)$$

combining (14) and (4)

$$V_o = \frac{\left(1+\frac{R_2}{R_1}\right)}{\left(1+\frac{R_3}{R_4}\right)} e_1 - \frac{R_2}{R_1} V_2 \qquad (15)$$

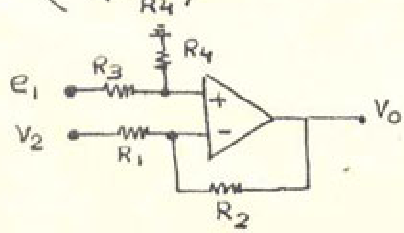


Fig. 6 . K-gain differential amplifier

letting $$\frac{R_2}{R_1} = \frac{\left(1+\frac{R_2}{R_1}\right)}{\left(1+\frac{R_3}{R_4}\right)} = k \qquad (16)$$

the circuit realises a k-gain differential amplifier for which the required resistor values are found to be

$$R_2 = kR_1 \; ; \; R_4 = kR_3 \qquad (17)$$

The above configuration has a limitation that the input impedances at the two input terminals are not infinite as desired. An alternative k-gain differential amplifier circuit which does possess this feature is shown in Fig. 7

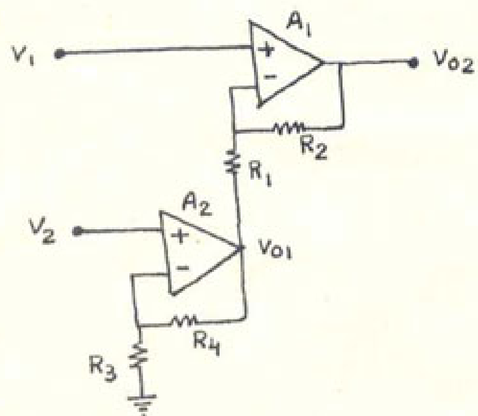


Fig. 7 Finite gain differential amplifier with infinite input impedance

In this circuit A_2 is connected as a noninverting VCVS due to which

$$V_{01} = \left(1+\frac{R_4}{R_3}\right)V_2 \qquad (18)$$

A_1 alongwith R_2 and R_1 realises a 3-port VCVS similar to Fig. 3, hence utilising equation (4) we can write

$$V_{02} = \left(1+\frac{R_2}{R_1}\right)V_1 - \frac{R_2}{R_1}V_{01} \qquad (19)$$

substituting (18) in (19) we obtain

$$V_{02} = \left(1+\frac{R_2}{R_1}\right)V_1 - \frac{R_2}{R_1}\left(1+\frac{R_4}{R_3}\right)V_2 \qquad (20)$$

For obtaining k-gain, $\left(1+\frac{R_2}{R_1}\right) = \frac{R_2}{R_1}\left(1+\frac{R_4}{R_3}\right) = k$ (21)

In other words, resistor values must be chosen according to

$$R_2 = (k-1)R_1 \; ; \; R_3 = (k-1)R_4 \qquad (22)$$

Negative impedance Convertor: The circuit realisation of the NIC is shown in Fig. 8

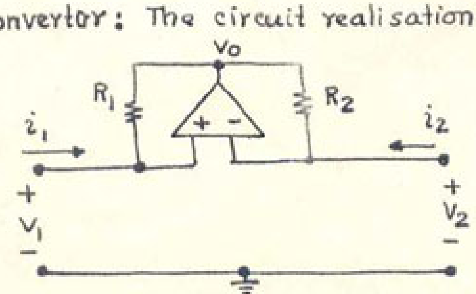


Fig. 8 op-amp realisation of the NIC

Routine analysis gives $$i_1 = \frac{V_1 - V_0}{R_1} \tag{23}$$

$$i_2 = \frac{V_2 - V_0}{R_2} \tag{24}$$

Due to the property of the ideal op-amp

$$V_1 = V_2 \tag{25}$$

From (23)–(24) $$\frac{i_1}{i_2} = \frac{R_2}{R_1} \tag{26}$$

Thus, the transmission matrix of the circuit is given by

$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -\frac{R_2}{R_1} \end{bmatrix} \begin{bmatrix} v_2 \\ -i_2 \end{bmatrix} \tag{27}$$

From the above transmission matrix it is seen that the circuit is a NIC with

$$A = 1 \,, \quad |D| = \left| \frac{R_2}{R_1} \right| \tag{28}$$

so that upon terminating port 2 into Z_L impedance looking at port 1 is given by

$$Z_{in} = -\left(\frac{R_1}{R_2}\right) Z_L \tag{29}$$

Current Controlled Voltage Sources: The circuit is shown in Fig. 9 . Since noninverting input terminal is connected to ground, due to infinite gain, the inverting input terminal is forced to have ground potential (virtual ground) due to which $v_m = 0$.

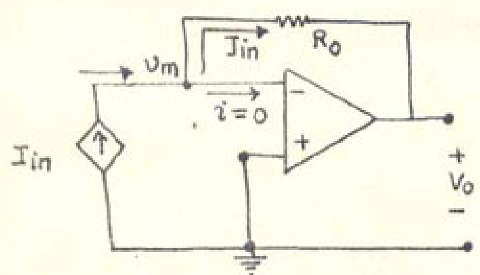


Fig. 9 CCVS

Also, due to infinite z_{in}, no current is drawn by the op-amp input terminal.

Hence, $$I_{in} = \frac{0 - V_0}{R_0}$$

$$\text{or} \quad V_0 = -R_0 I_{in} \tag{30}$$

and the circuit acts as an inverting CCVS.

Noninverting CCVS can be obtained in two different ways as shown in Fig. 10 :(i) by

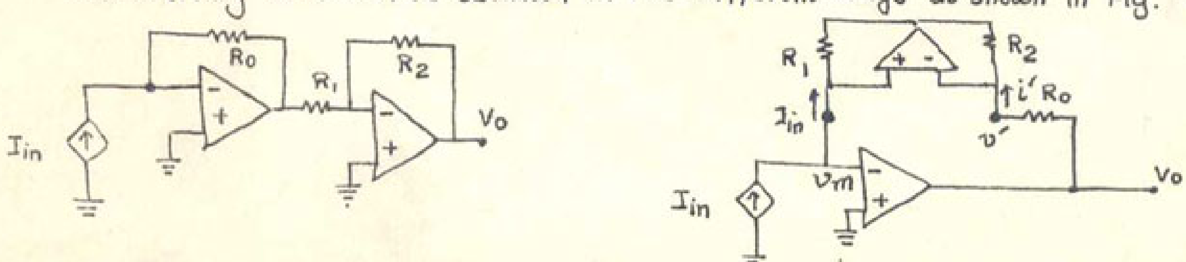


Fig. 10 Noninverting CCVS structures

cascading an inverting VCVS so that

$$V_0 = -(R_0 I_{in})\left(-\frac{R_2}{R_1}\right) = +\left(\frac{R_0 R_2}{R_1}\right) I_{in} \qquad (31)$$

(ii) by putting a NIC with $A = 1$, $D = -\frac{R_2}{R_1}$ in the feed back path. Analysis gives

$$V_0 = i' R_0 + v' = i' R_0 = \left(\frac{R_1}{R_2}\right) I_{in} R_0 = +\left(\frac{R_1 R_0}{R_2}\right) I_{in} \qquad (32)$$

(since $v' = v_m = 0$ and $i' = -\frac{R_1}{R_2} I_{in}$)

Voltage-Controlled-Current-sources : Consider the circuit shown in Fig. 11 (a). By judicious redrawing it can be rearranged as in Fig. 11 (b) where it is easy to recognise an NIC terminated into R realising a $-R$ at input port of NIC. Consequently, we obtain the equivalent circuit of Fig. 11 (c). Analysis of this equivalent circuit gives

$$I_{out} = \frac{V_L}{-R} + \frac{V_L - V_{in}}{R} = -\frac{V_{in}}{R} \qquad (33)$$

Hence, the circuit of Fig. 11 (a) is an inverting VCCS.

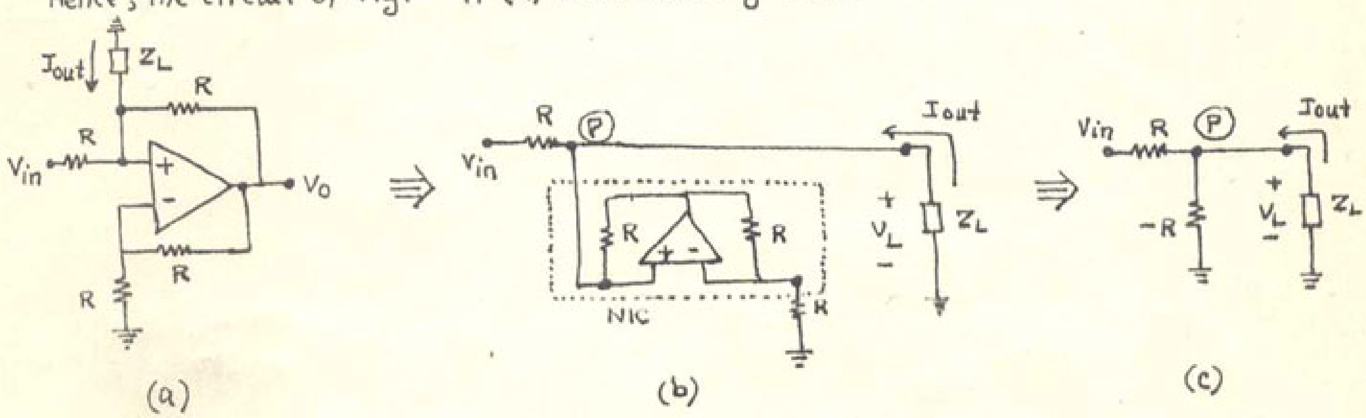


Fig. 11 Inverting VCCS

A slightly different arrangement giving a noninverting VCCS is shown in Fig. 12 (a)

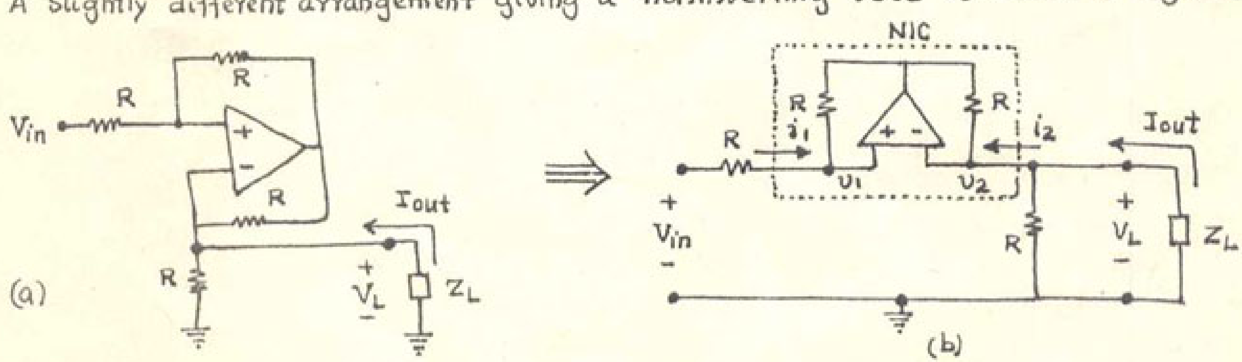


Fig. 12 Noninverting VCCS

With some arrangement the circuit can be redrawn as in Fig. 12 (b) where once again we can identify an NIC. For the NIC

$$v_1 = v_2 = v_L \qquad (34)$$

also as the two resistors of NIC are identical, $i_1 = i_2$ $\qquad (35)$

but $i_1 = \frac{V_{in} - V_1}{R}$; $i_2 = i_{out} - \frac{V_2}{R} = i_{out} - \frac{V_1}{R}$ (using (34)), (36)

substituting (35) into (36) we get

$$\frac{V_{in} - V_1}{R} = i_{out} - \frac{V_1}{R}$$

$$\text{ie} \quad i_{out} = + \frac{V_{in}}{R} \qquad (37)$$

Current Controlled current Sources : op-amp realisation of CCCS can be obtained by cascading CCVS and VCCS as shown in Fig. 13 .

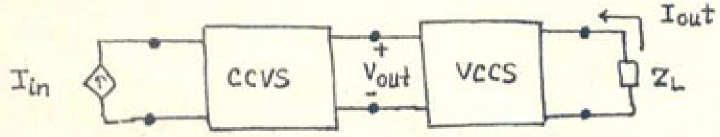
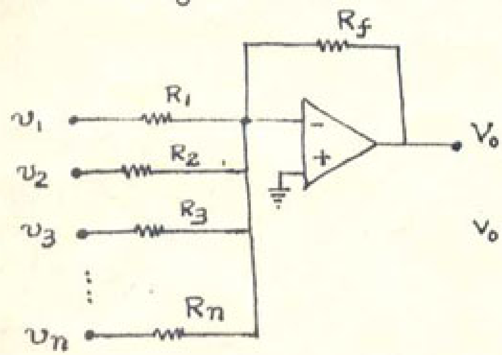


Fig. 13 Realisation of CCCS

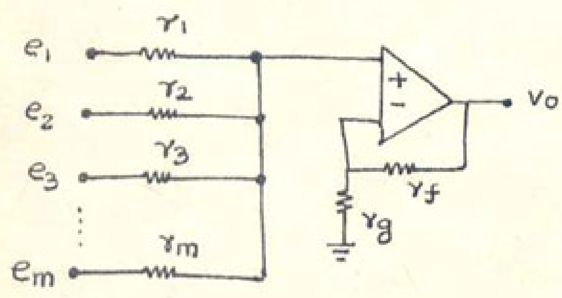
Weighted Summers : Active synthesis invariably requires circuits capable of performing summation of analog voltages . Realisations of inverting , noninverting and generalised summers are shown in Fig. 14 (a)-(c).

(a)



$$V_0 = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \cdots + \frac{R_f}{R_n} v_n \right)$$

(b)



(c)

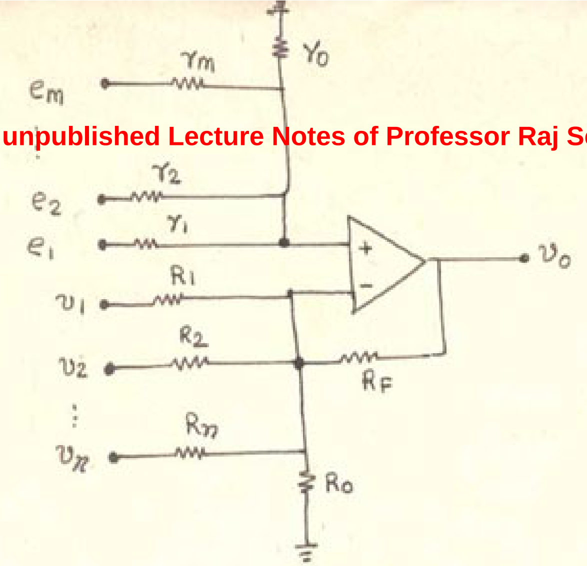


Fig. 14 Realisation of various summers (a) inverting summer (b) noninverting summer (c) generalised weighted summer.

3. Miscellaneous Circuits and Techniques :

In the following some interesting circuits and techniques are presented which can be understood and analysed on the basis of understanding of the building blocks discussed in the previous section.

3.1 *capacitance multiplier* :

The given circuit has

$$Z_{in} = \frac{v_1}{i_1} = \frac{1}{sC\left(1+\frac{R_2}{R_1}\right)}$$

thus, behaving as an equivalent capacitance $C_{eq} = C\left(1+\frac{R_2}{R_1}\right)$

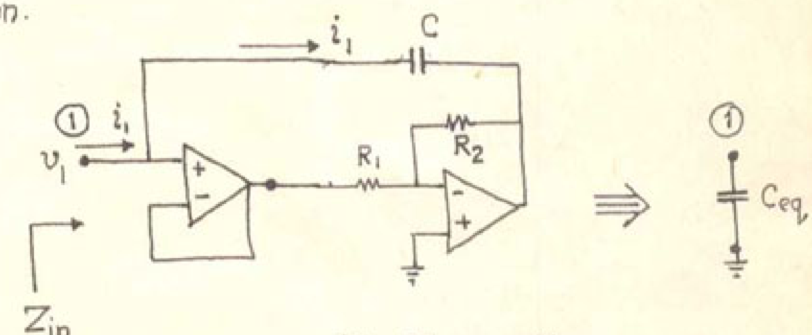


Fig. 15 capacitance multiplier

This circuit is useful in creating *artificially* large values of capacitances while using low-valued C which is normally available.

3.2 *Inductance Simulator* :

The circuit has

$$Z_{in} = R_1 + sCR_1R_2$$

thus, representing an inductance

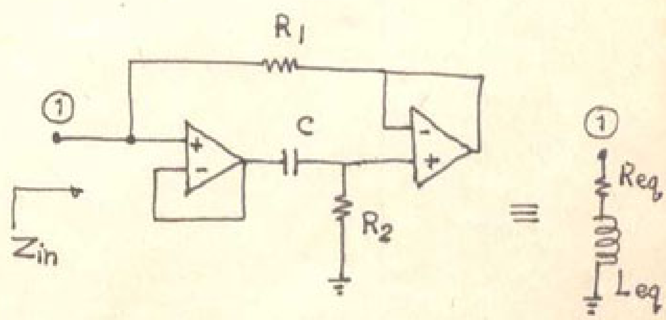


Fig. 16

$L_{eq} = CR_1R_2$ Henries with quality factor equal to $Q_{eq} = \frac{\omega L_{eq}}{R_{eq}} = \omega C R_2$

3.3 *Non inverting Integrator :*

Although inverting integrator followed by an inverting amplifier gives noninverting integrator, this approach needs two op-amps. A circuit which does this job with just one op-amp is Deboó's integrator shown here. Analysis gives

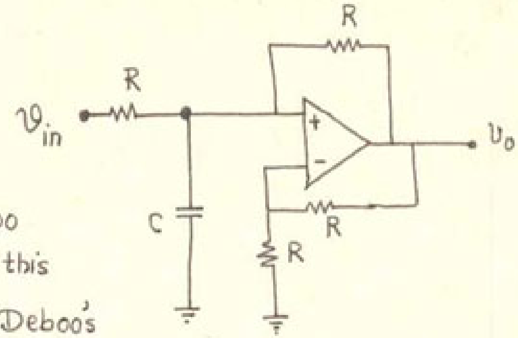


Fig. 17 Deboó's integrator

$$v_0(t) = +\frac{2}{CR}\int V_{in}(t)\,dt \quad \text{or} \quad \frac{V_0(s)}{V_1(s)} = +\frac{2}{sCR}$$

3.4 *Noninverting Differentiator :*

The accompanying circuit by proposed by Horrocks. Analysis shows

$$V_0(t) = \frac{CR}{2}\,\frac{dV_{in}(t)}{dt}$$

or equivalently

$$\frac{V_0(s)}{V_1(s)} = +\frac{sCR}{2}$$

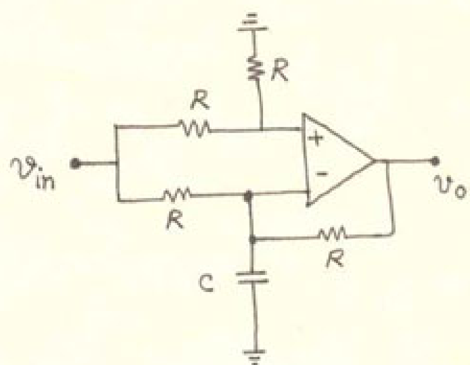


Fig. 18 Horrock's differentiator

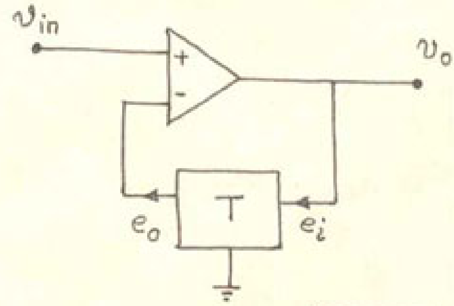
3.5 *Inverse function Generation :*

Fig. 19 (a) and (b) show an interesting concept according to which if a network having

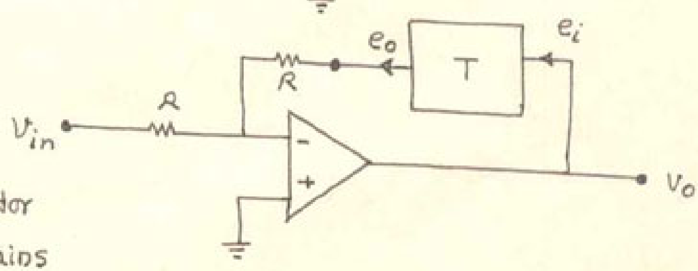
$$e_0 = T\,e_i$$

is put in the feedback path of an op-amp the over all circuit generates

$$v_0 = T^{-1}\,v_{in}$$

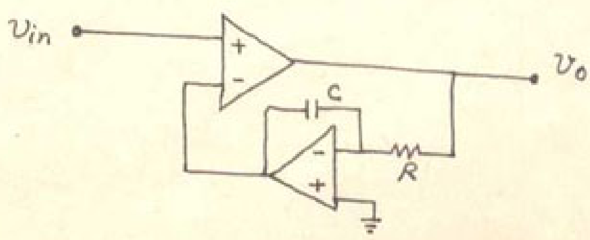


(a)



(b)

As an example in Fig 19 (c) we show by putting an integrator in the feedback path, one obtains a differentiator.



(c)

Fig. 19 (a) $v_0 = T^{-1}\,v_{in}$

(b) $v_0 = -T^{-1}\,v_{in}$

(c) $v_0 = -sCR\,v_{in}$

The following fig. shows how this idea can be implemented on a given single

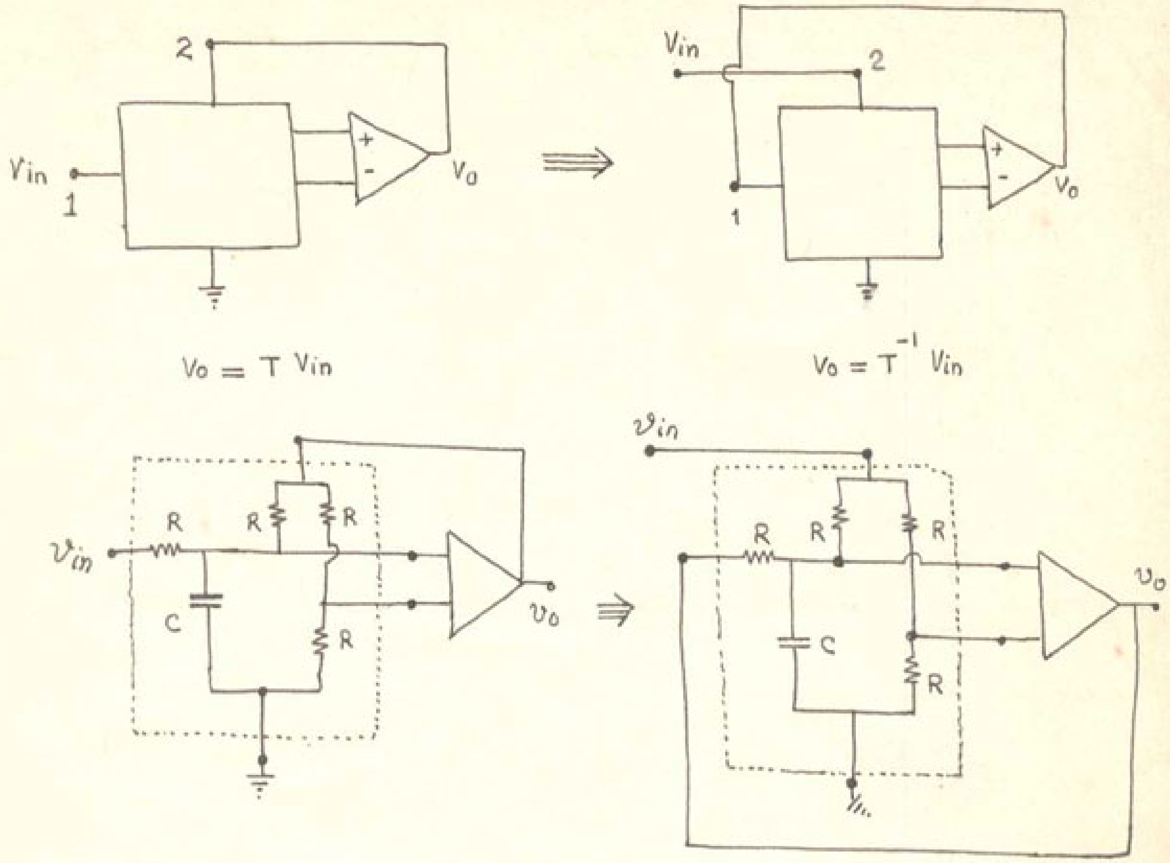
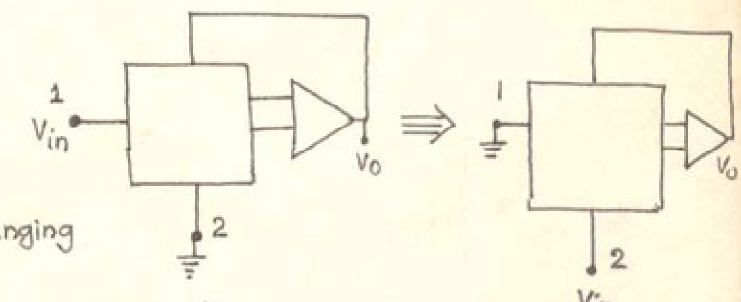


Fig. 20

op-amp circuit without requiring any additional op-amp. As an example, Deboo's integrator and Horrocks differentiator are shown to be derivable from each other.

3.6 Complementary function generation:

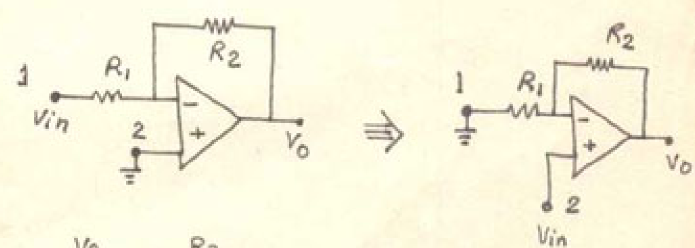
In some cases one requires to generate a complementary function $(1-T)$ starting from a given function T (relating V_o and V_{in}). This can be accomplished by simply interchanging input and ground terminals as shown in Fig. 21



$V_o = T\, V_{in}$

$V_o = (1-T)\, V_{in}$

Note that inverting amplifier and non inverting amplifier can be seen to be related to each other by this transformation.



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

$$\frac{V_o}{V_{in}} = 1 - \left(-\frac{R_2}{R_1}\right) = 1 + \frac{R_2}{R_1}$$

An important application of this transformation is in deriving a notch filter circuit starting from a bandpass circuit and vice versa.

Fig. 21 The complementary transformation (Hilberman's Theorem)