EE 230
Lecture 11

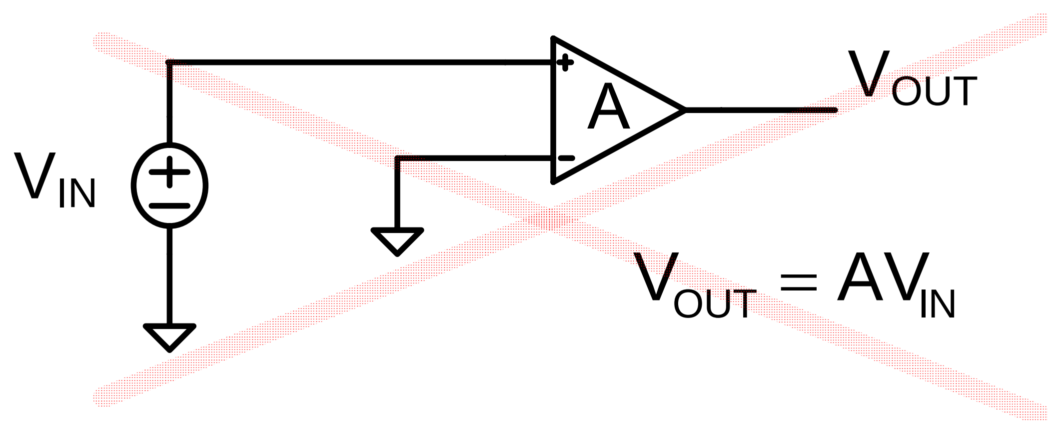
Basic Applications of
Operational Amplifiers

Quiz 8

Although high gain amplifiers are often needed, the operational amplifier, which is a high gain amplifier, is almost never used as an open-loop voltage amplifier.

a) Give two major reasons that the op amp is almost never used as an open-loop voltage amplifier

b) How are large voltage gains practically realized?



And the number is ?

1 3 8

5 4

2 6

9 7

And the number is ?

1 3 8

5 8 4

2 6

9 7

Quiz 8

a) Give two major reasons that the op amp is almost never used as an open-loop voltage amplifier

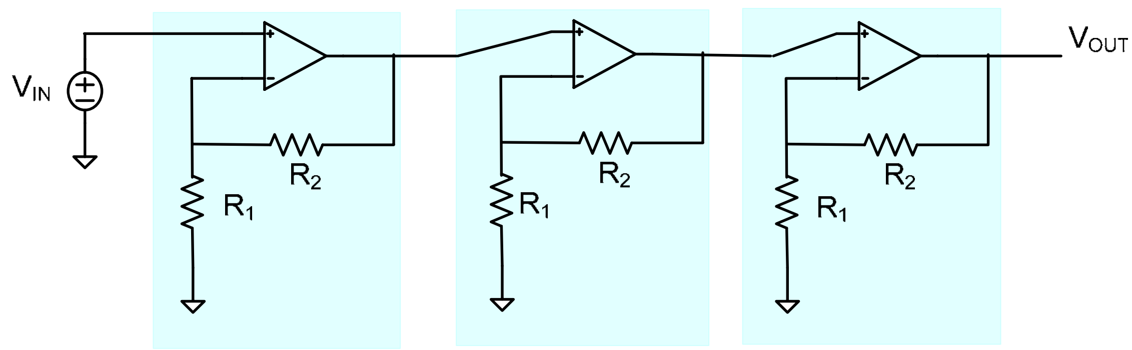
Gain of op amp is nonlinear

Gain of op amp is too variable

Other issues (such as offset voltage) render circuits not usable in most applications

a) How are large voltage gains practically realized?

By a cascade of a larger number of finite gain feedback amplifiers



Review from Last Time

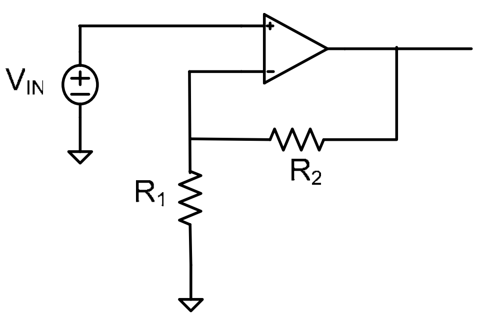
Op Amp input port is termed a “null port”

Virtual short exists between input terminals of op amp when operating as an amplifier

Op Amp is almost never used as an open-loop voltage amplifier

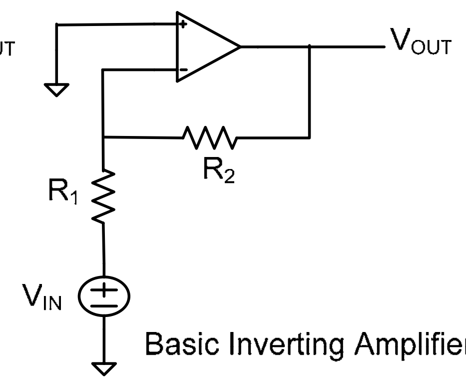
Op Amp is basic high-gain amplifier used to build feedback networks

Although feedback is used in almost all linear applications of op amps, feedback analysis is seldom used to analyze such circuits



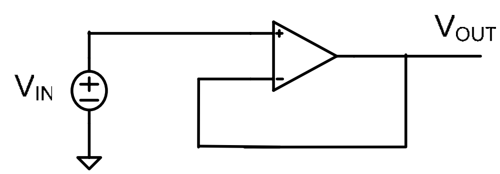
Basic Noninverting Amplifier

$$A_V = \frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_2}{R_1}$$



Basic Inverting Amplifier

$$A_V = \frac{V_{OUT}}{V_{IN}} = -\frac{R_2}{R_1}$$

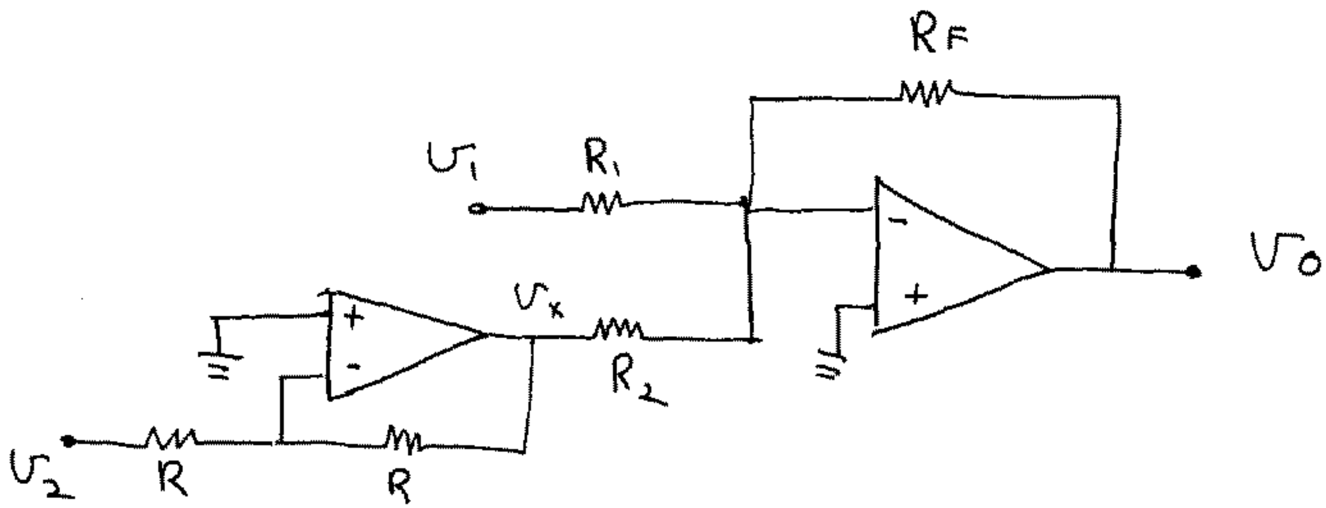


Basic Buffer Amplifier

$$A_V = \frac{V_{OUT}}{V_{IN}} = 1$$

$$v_o = -\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2 - \frac{R_f}{R_3} v_3$$

- All weights are negative

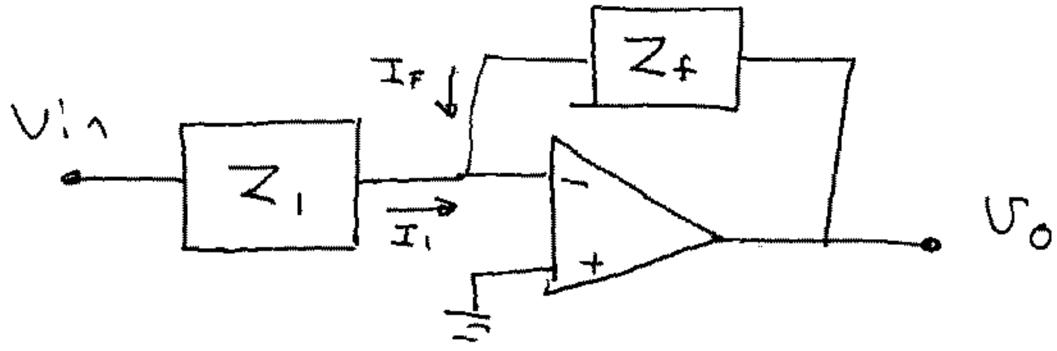


$$\left.\begin{aligned} v_o &= -\frac{R_F}{R_1} v_1 - \frac{R_f}{R_2} v_x \\ v_x &= -v_2 \end{aligned}\right\}$$

$$\therefore \quad v_o = \frac{R_f}{R_2} v_2 - \frac{R_f}{R_1} v_1$$

Any number of inverting and noninverting inputs can be added.

Generalized Inverting Amplifier



s-domain impedances

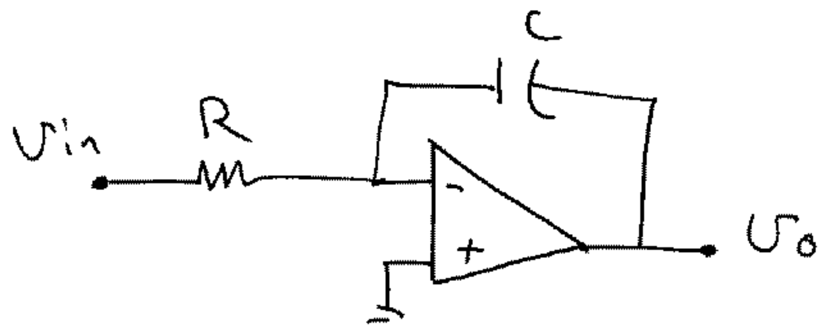
$$I_1 = \frac{v_{in}}{Z_1}$$

$$I_F = \frac{v_o}{Z_f}$$

$$I_1 = -I_F$$

$$\frac{v_o}{v_i} = -\frac{Z_f}{Z_1}$$

what if $Z_f = 1/sC$, $Z_1 = R$



$$\frac{v_o}{v_i} = -\frac{1}{RCs}$$

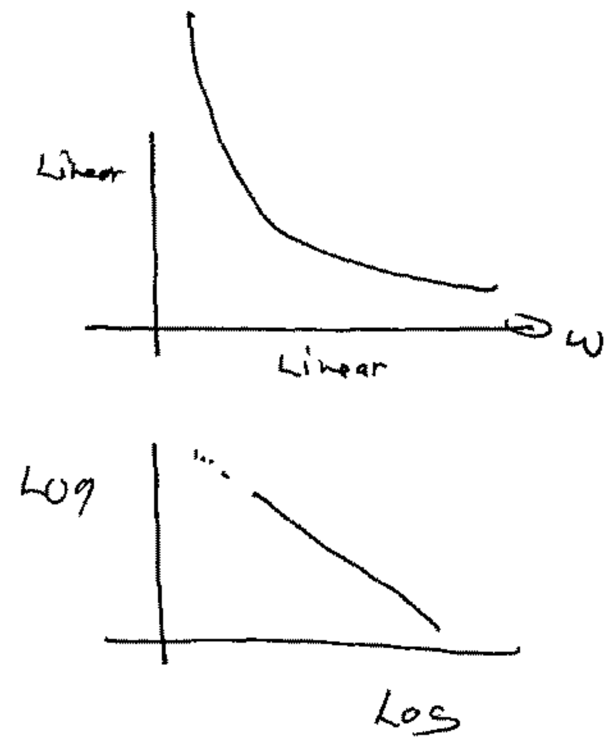
what is this?

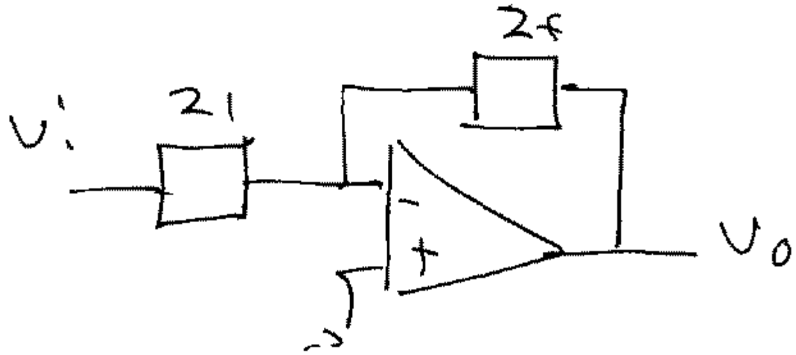
$$T(s) = -\frac{1}{RCs}$$

$$T(j\omega) = -\frac{1}{j\omega RC}$$

$$|T(j\omega)| = \frac{1}{\omega RC}$$

Integrator Gain





$$\frac{V_o}{V_i} = -\frac{Z_f}{Z_1}$$

Let $Z_1 = \frac{1}{sC}$

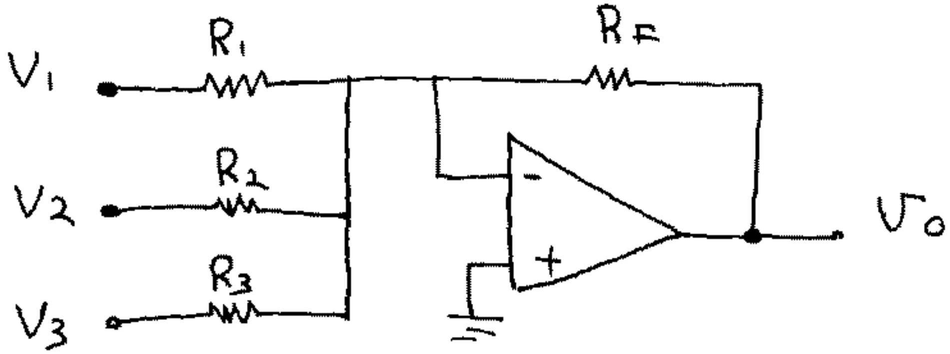
$Z_f = R$

$$\therefore \frac{V_o}{V_i} = -\frac{sCR}{\cancel{R}}$$

Differentiator (Inverting)

- Not widely used
- Noise relentlessly amplified
- stability problems with implementation

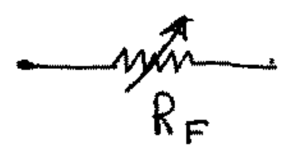
Summing Amplifier



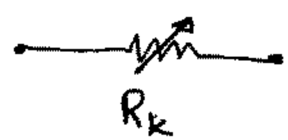
$$\frac{v_o}{R_F} + \frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} = 0$$

$$\therefore \quad v_o = -\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2 - \frac{R_f}{R_3} v_3$$

- Termed a "mixer" in the audio communit,
- Any number of inputs can be used
- R_f can adjust all gains together

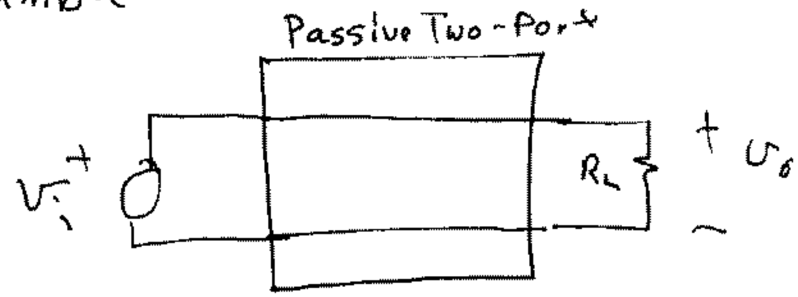


- Individual gains can be independently adjusted



The following pages were in response to questions from students.

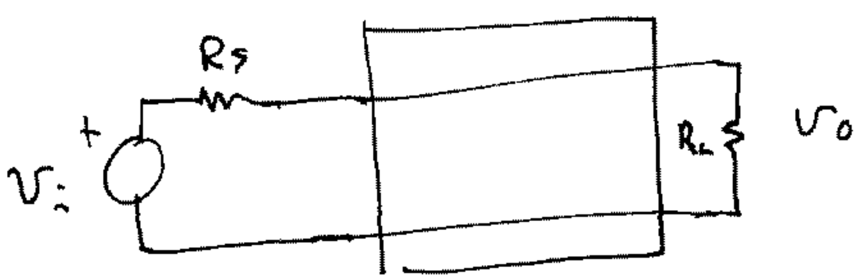
Example:



$$\frac{v_o}{v_i} = 1$$

Why will this not serve as a buffer since $A_v = 1$?

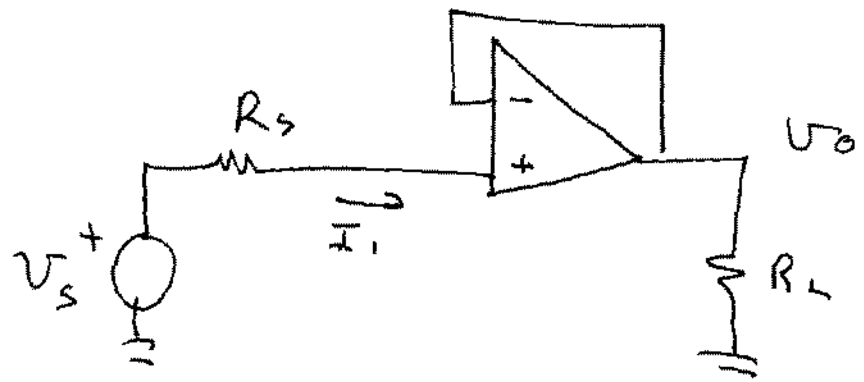
- No power gain



$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_S}$$

- Gain dependent upon R_S

Power Gain of Buffer



$I_1 = 0 \quad \therefore \quad P_s = (v_s)(I_1) = 0$

$$P_L = \frac{v_o^2}{R_L} = \frac{v_s^2}{R_L}$$

$\therefore$ Power gain is infinite

When is input impedance not a problem?

a) If $R_s = 0$

b) If R_s is a known constant

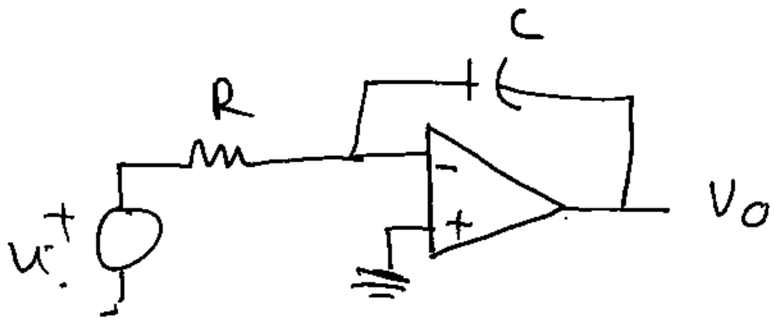
(Not versatile)

c) When accuracy not a problem

1) $R_s << R_1$

2) Audio to end user

Inverting Integrator



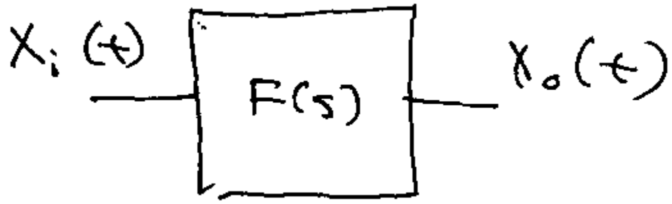
$$\frac{V_o}{V_i} = -\frac{1}{RCS}$$

Inverting because gain is negative

$$R_o = 0$$

$$R_{in} = R$$

- Seldom used in open-loop application
- widely used in feedback application



If $x_i(t)$ has <u>any</u> dc component

$$F(s) = 1/s$$

$$x_o(t) = \int_0^\infty x_i(t) = \int_0^\infty \left(A_0 + A_1 \sin(\omega t + \theta_1) + \cdots \right)$$

$$= \underbrace{\int_0^\infty A_0 \, dt}_{\lim_{t\to\infty} A_0(t) \;\to\; \text{diverge to } \infty} + A_1 \int_0^\infty \sin(\omega t + \theta_1) + A_2 \int_0^\infty \sin(2\omega t + \theta_2) + \cdots$$

- Integrator function is ill-conditoned for open loop applications

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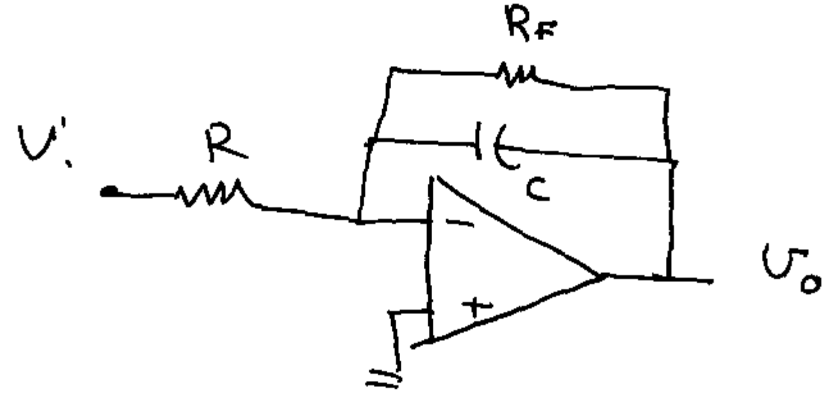
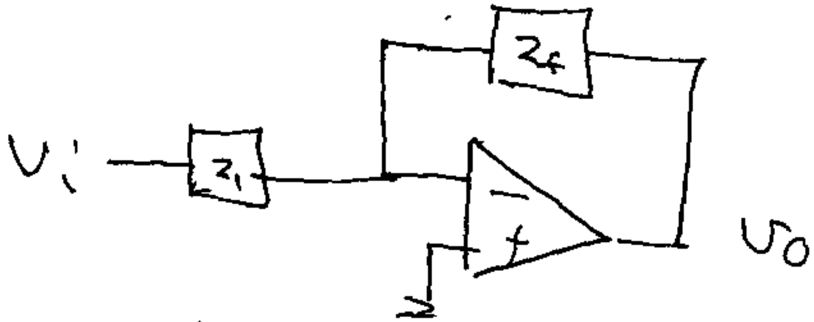
Method for approx. open loop integration



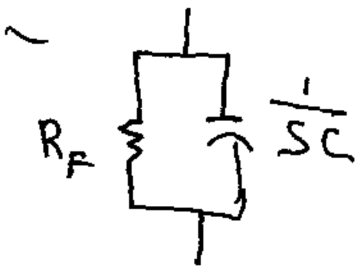
- R_F very large

$$v_o \simeq -\frac{1}{RC}\int_0^t V_i(t)\,dt + V_i(0)$$



Lossy Integrator

$Z_f \sim$



$Z_1 \sim$

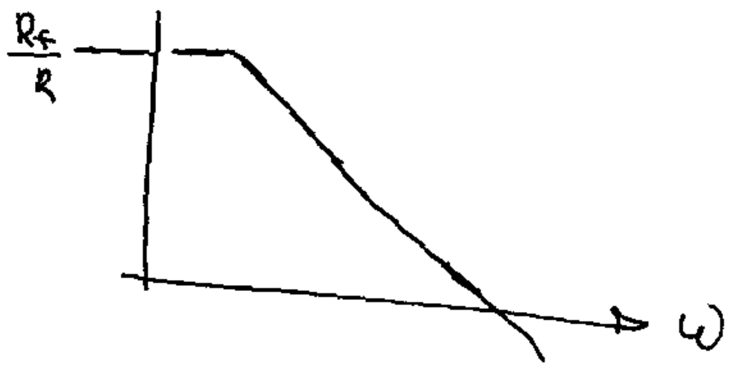
$$Z_f = \frac{(R_f)\,{}^1\!/_{SC}}{R_f + {}^1\!/_{SC}} = \frac{R_f}{1 + R_f C S}$$

$$\frac{V_o}{V_i} = -\frac{Z_f}{Z_1} = -\frac{R_f}{(1 + R_f C S)\,R}$$

Ideally $R_f = \infty$

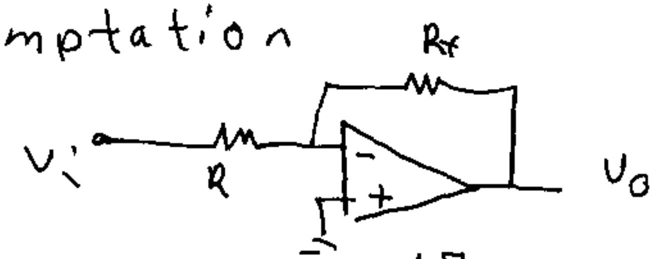
$$\frac{V_o}{V_i} = -\frac{1}{RCS}$$

$$\left|\frac{V_o}{V_i}\right| = \frac{R_f/R}{\sqrt{1 + (R_f C \omega)^2}}$$

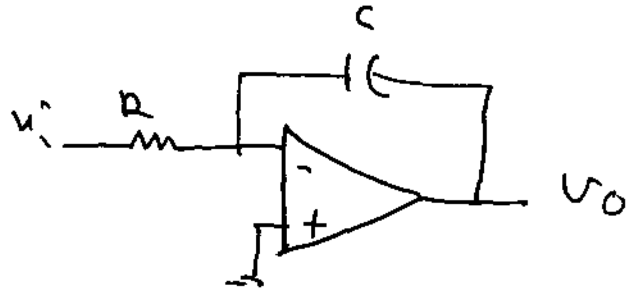


Noninverting Integrator.

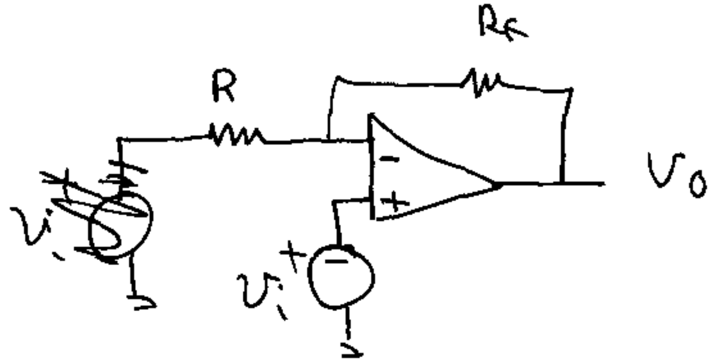
Temptation

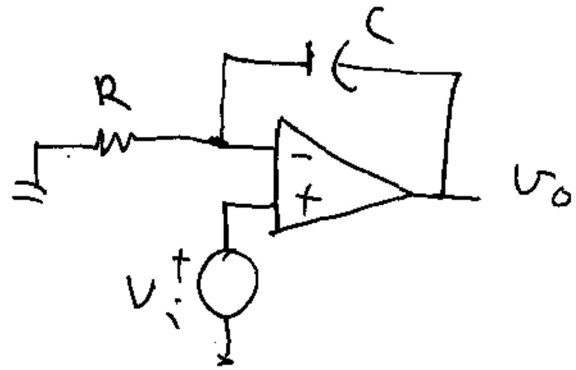


$$\frac{v_o}{v_i} = -\frac{R_f}{R}$$



$$\frac{v_o}{v_i} = -\frac{1}{RCs}$$





$$v_i = v_o\left(\frac{R}{R+1/sC}\right)$$

$$v_i = v_o\,\frac{RCs}{1+RCs}$$

$$\therefore\ \frac{v_o}{v_i} = \frac{1+RCs}{RCs}$$

This is not a noninverting integrator

Noninverting Integrator

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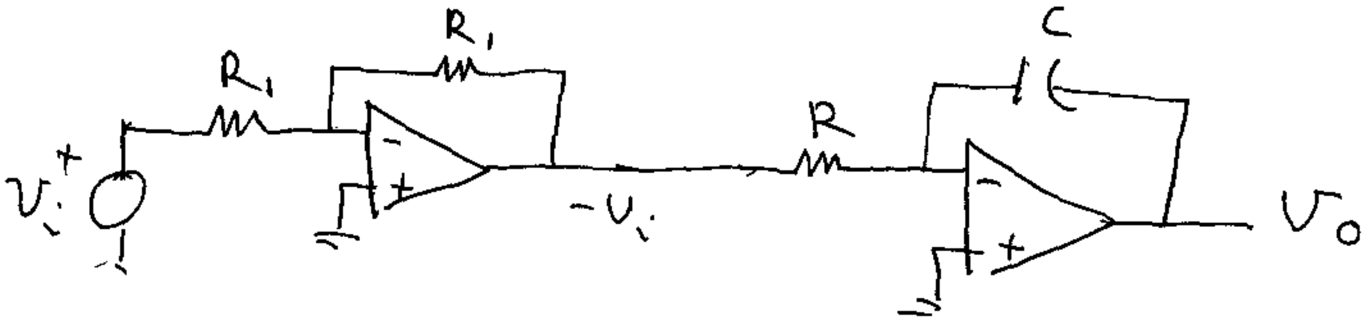
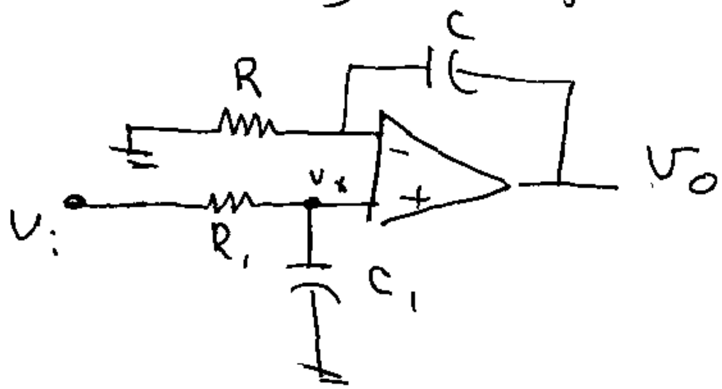


$$v_o = \frac{1}{RCs} v_i$$

— follow inverting integrator with inverter instead

- Most popular noninverting integrator structure

Noninverting Integrator



$$V_x = \frac{\frac{1}{sC_1}}{R_1 + 1/sC_1} V_i = \frac{1}{1+R_1C_1S} V_i$$

$$V_x = \frac{R}{R + 1/sC} V_o = \frac{RCS}{1+RCS} V_o$$

$$\frac{V_o}{V_i} = \left(\frac{1}{1+R_1C_1S}\right)\left(\frac{1+RCS}{RCS}\right)$$

If $R_1C_1 = RC$ (pole/zero cancellation)

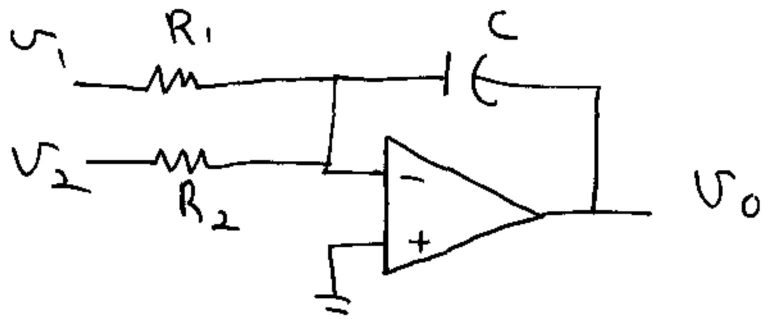
$$\frac{V_o}{V_i} = \frac{1}{RCS}$$

Advantage: eliminated one opamp

Disadvantage: - two capacitors

- precise relationships between $R_1C_1 = RC$

Summing Inverting Integrator.



$$v_0 = -\frac{1}{R_1 C s} v_1 - \frac{1}{R_2 C s} v_2$$

Applications to solving differential equations.

Example:

$$\underline{V_o = K_1 \int V_o + K_2 \iint V_o + K_3 V_i}$$

standard integral form

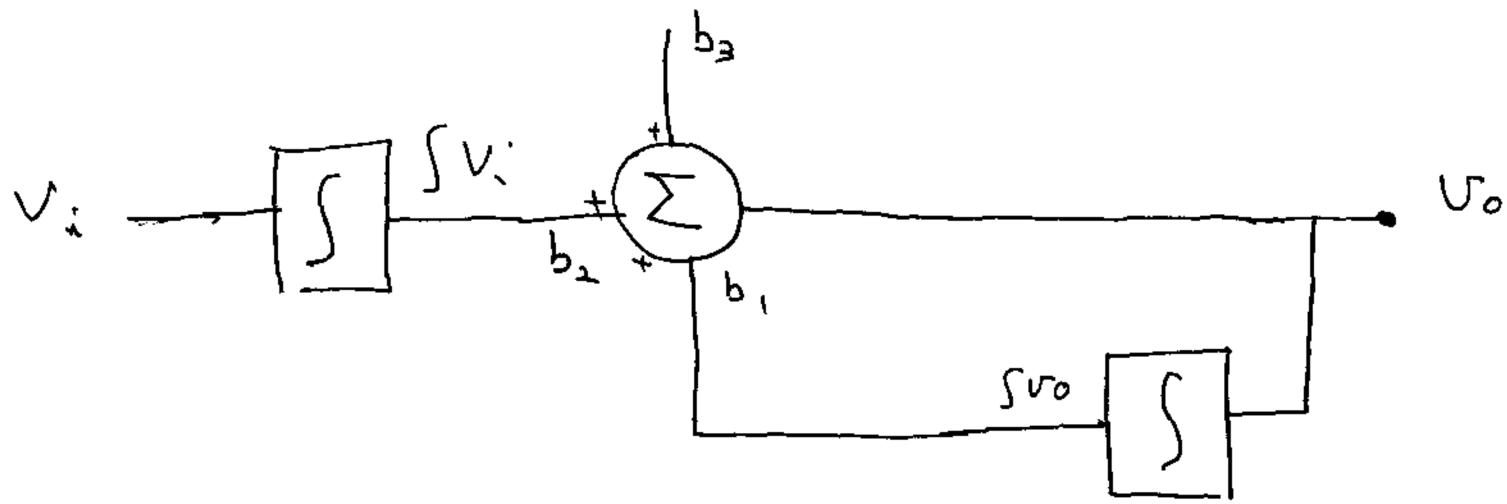
$$V_o' = K_1 V_o + K_2 \int V_o + K_3 V_i'$$

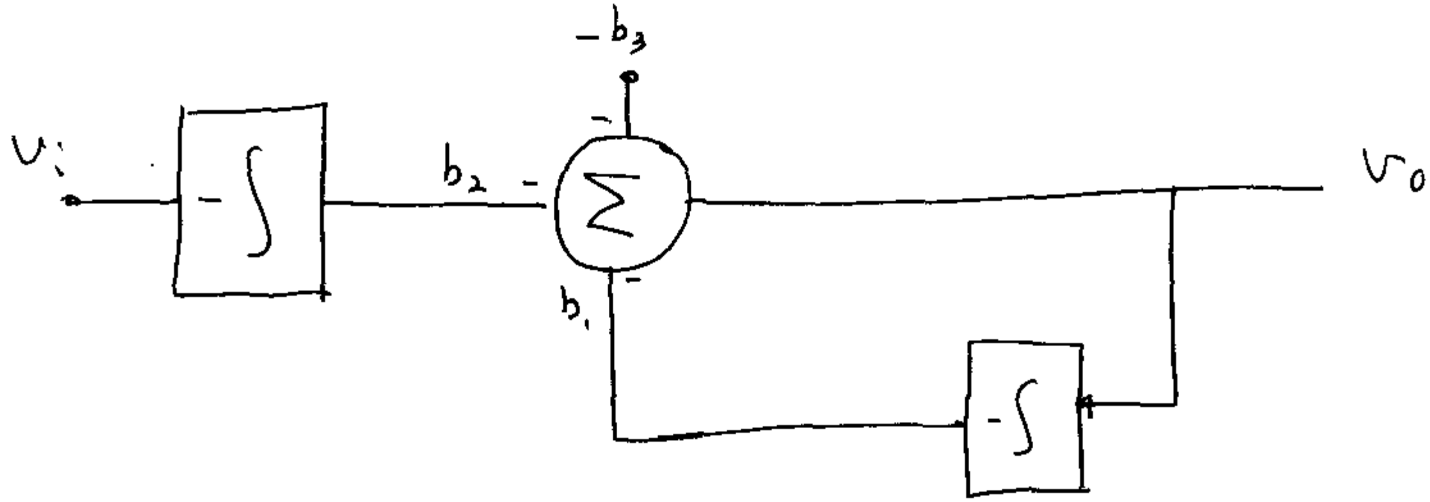
$$V_o'' = K_1 V_o' + K_2 V_o + K_3 V_i''$$

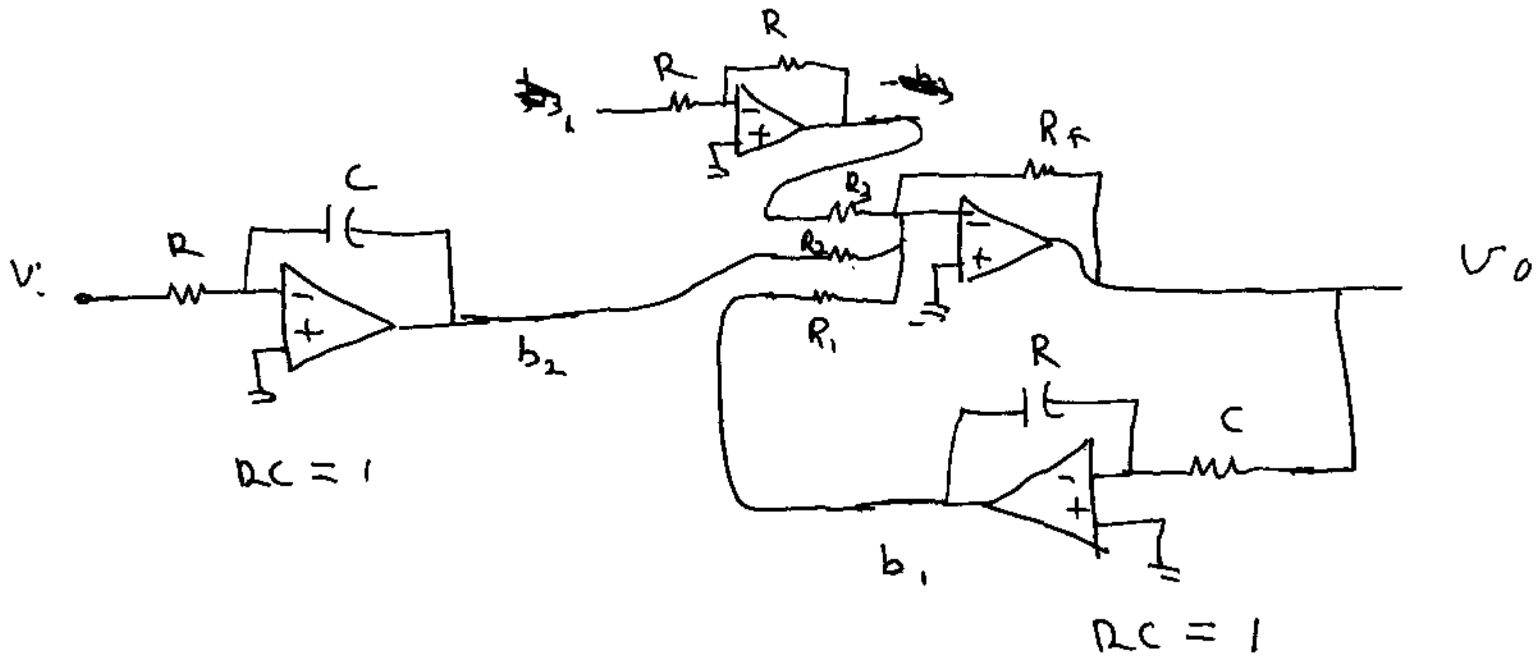
$$\underline{V_o = a_1 V_o' + a_2 V_o'' + a_3 V_i''}$$

standard differential form

$$v_o = b_1 \int v_o + b_2 \int v_i + b_3$$



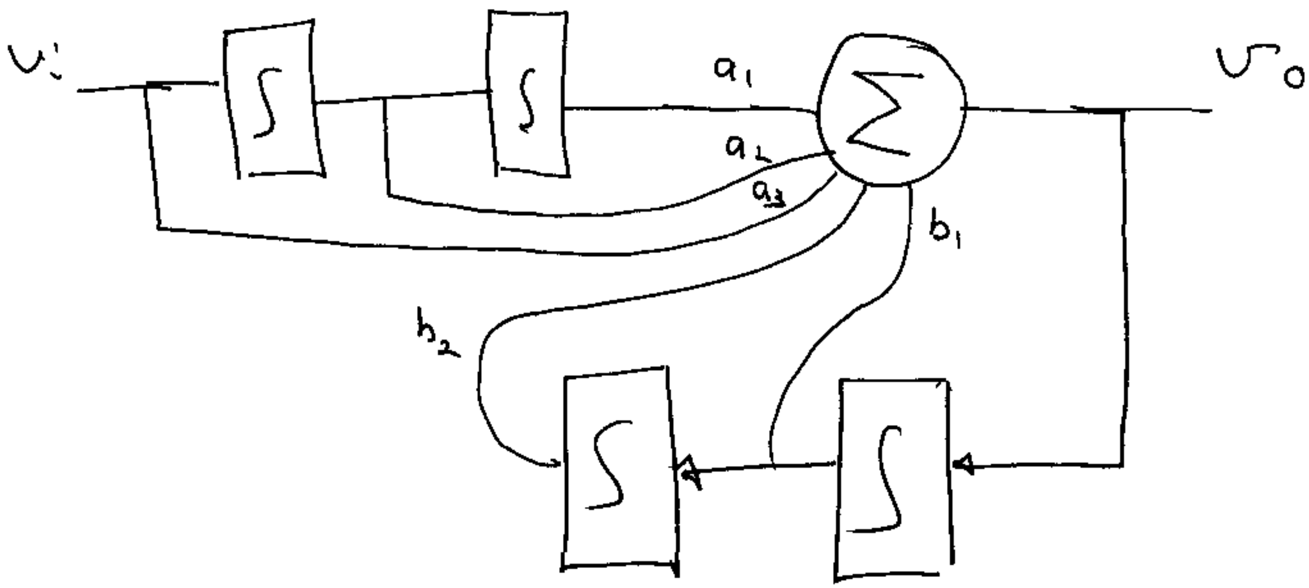




$$\frac{R_f}{R_1} = b_1 \qquad \frac{R_f}{R_2} = b_2 \qquad \frac{R_f}{R_3} = b_3$$

- Straightforward to solve an arbitrary differential equation with inverting integrators, summing amplifiers and inverters

- Analog Computer solves differential equations



$$v_o = \frac{a_1 v_i}{s} + \frac{a_2 v_i}{s^2} + a_3 v_i + \frac{b_1 v_o}{s} + \frac{b_2 v_o}{s^2}$$

$$\frac{v_o}{v_i} = \frac{a_3 s^2 + a_2 s + a_1}{s^2 - b_1 s - b_2}$$

any coeff can be positive or negative or zero

Arbitrary transfer function synthesis is easy to achieve.

$$v_o = \frac{1}{b_2} v_o'' - \frac{b_1}{b_2} v_o' - \frac{a_1}{b_2} v_i - \frac{a_2}{b_2} v_i' - \frac{a_3}{b_2} v_i''$$

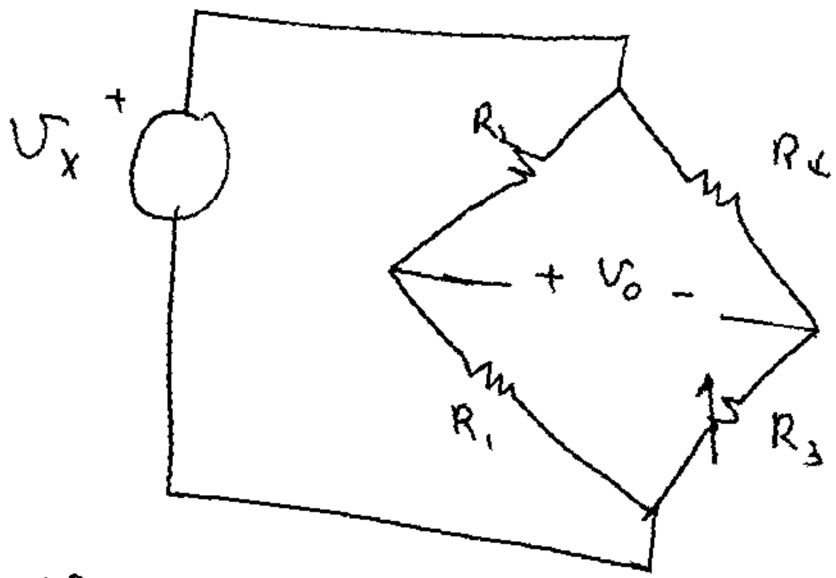
$$v_o = \alpha_2 v_o'' + \alpha_1 v_o' + \beta_0 v_i + \beta_1 v_i' + \beta_2 v_i''$$

standard differential form

Differential Amplifiers.

$$U_o = K(U_2 - U_1)$$

Information is carried in difference of two voltages.



U_x might be large ($V_x = 10 \sin \omega t$)

$V_o \sim (10E-6) \sin \omega t$