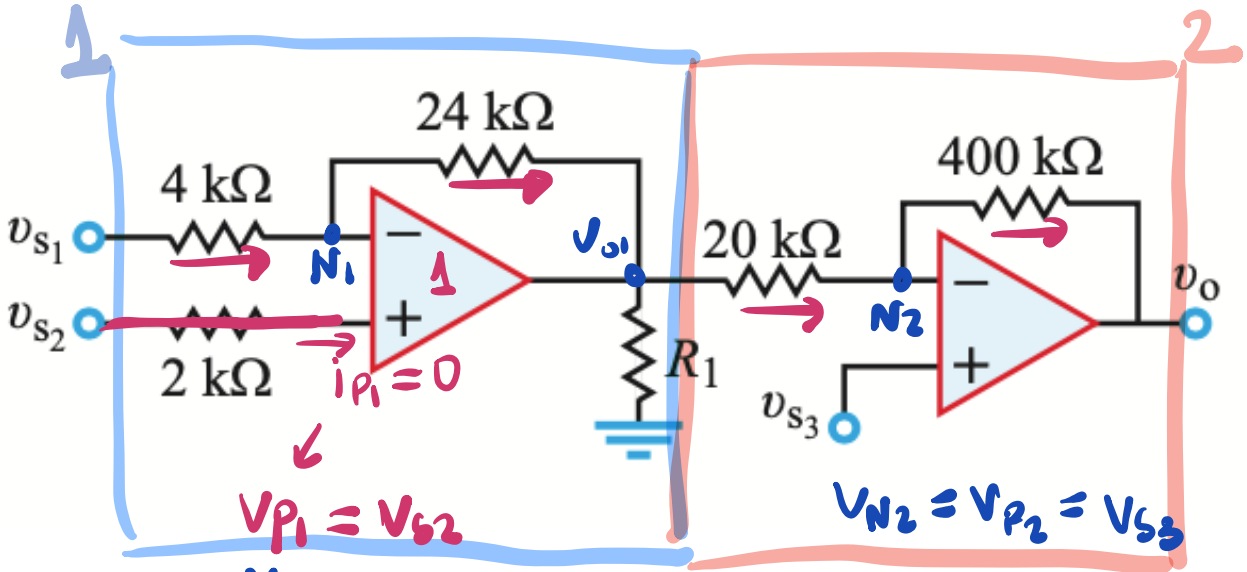
Last Class…



$V_{N1} = V_{P1} = V_{S2}$

KCL @ N_1:

$i_{4K} = i_{24K}$

$$\frac{V_{S1} - V_{S2}}{4K} = \frac{V_{S2} - V_{O1}}{24K}$$

$$6V_{S1} - 6V_{S2} = V_{S2} - V_{O1}$$

$$V_{O1} = 7V_{S2} - 6V_{S1}$$

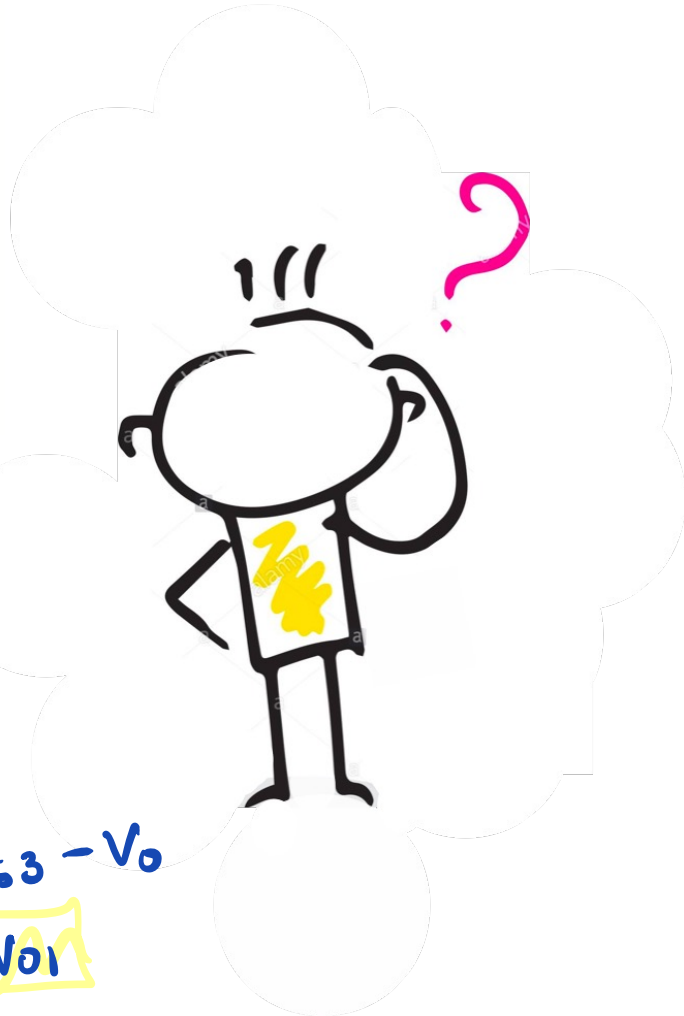
KCL @ N_2:

$i_{20K} = i_{400K}$

$$\frac{V_{O1} - V_{S3}}{20K} = \frac{V_{S3} - V_O}{400K}$$

$$20V_{O1} - 20V_{S3} = V_{S3} - V_O$$

$$V_O = 21V_{S3} - 20V_{O1}$$



$$V_O = 21V_{S3} - 20(7V_{S2} - 6V_{S1}) = 21V_{S3} - 140V_{S2} + 120V_{S1}$$

THE OHIO STATE UNIVERSITY

COLLEGE OF ENGINEERING

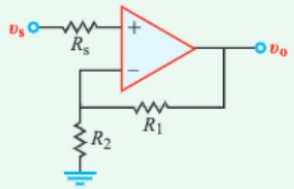
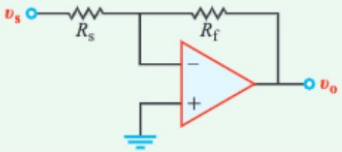
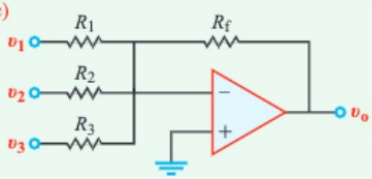
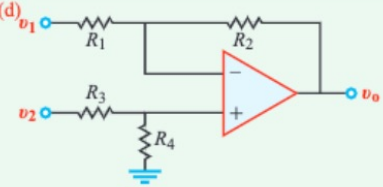
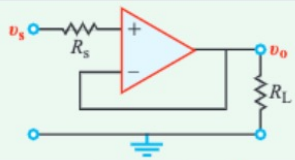
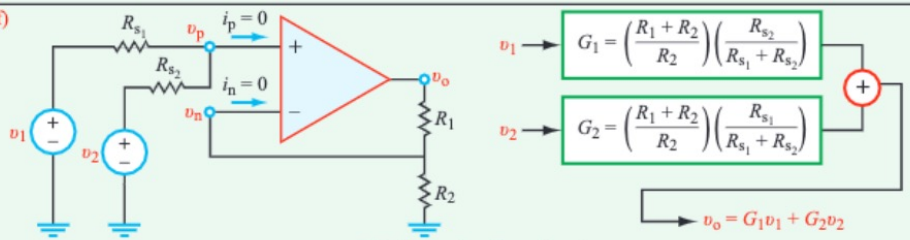
Op-amp models

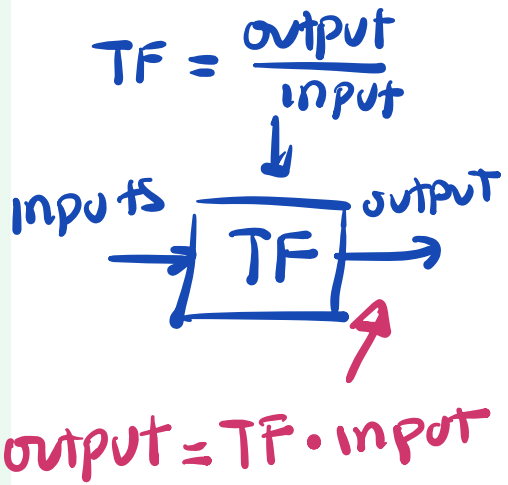
Active Filters

This Lecture…

- Learning Objectives:
  - Combine multiple op-amp circuits together to perform signal processing operations.
  - Analyze and design simple active filters.

Table 4-3: Summary of op-amp circuits.

Op-Amp Circuit	Block Diagram
(a)  Noninverting Amp (v_o independent of R_s)	$v_s \rightarrow G = \frac{R_1 + R_2}{R_2} \rightarrow v_o = Gv_s$
(b)  Inverting Amp	$v_s \rightarrow G = -\frac{R_f}{R_s} \rightarrow v_o = Gv_s$
(c)  Inverting Summing Amp	$v_1 \rightarrow G_1 = -R_f/R_1$, $v_2 \rightarrow G_2 = -R_f/R_2$, $v_3 \rightarrow G_3 = -R_f/R_3$, $(+) \rightarrow v_o = G_1v_1 + G_2v_2 + G_3v_3$
(d)  Subtracting Amp	$v_1 \rightarrow G_1 = -\frac{R_2}{R_1}$, $v_2 \rightarrow G_2 = \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right)$, $(+) \rightarrow v_o = G_1v_1 + G_2v_2$
(e)  Voltage Follower / Buffer (v_o independent of R_s and R_L)	$v_s \rightarrow G = 1 \rightarrow v_o = v_s$
(f)  Noninverting Summing Amp	$v_1 \rightarrow G_1 = \left(\frac{R_1 + R_2}{R_2}\right)\left(\frac{R_{s_2}}{R_{s_1} + R_{s_2}}\right)$, $v_2 \rightarrow G_2 = \left(\frac{R_1 + R_2}{R_2}\right)\left(\frac{R_{s_1}}{R_{s_1} + R_{s_2}}\right)$, $(+)$, $v_o = G_1v_1 + G_2v_2$

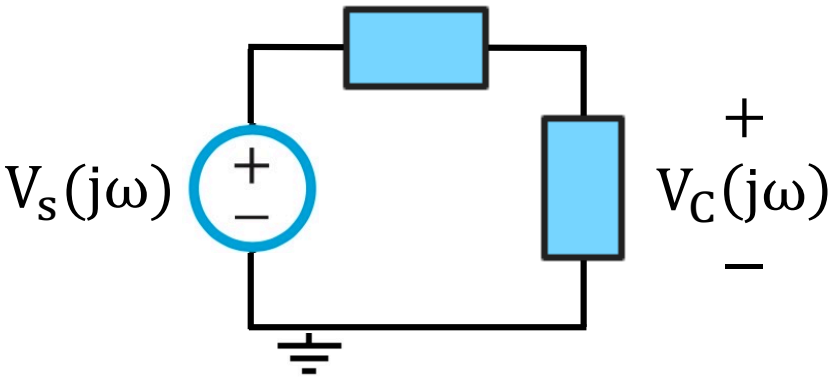


Active Filters

- A filter that contains an active component (op-amps).
- Op-amps can provide amplification (gain) in addition to the filtering effects.

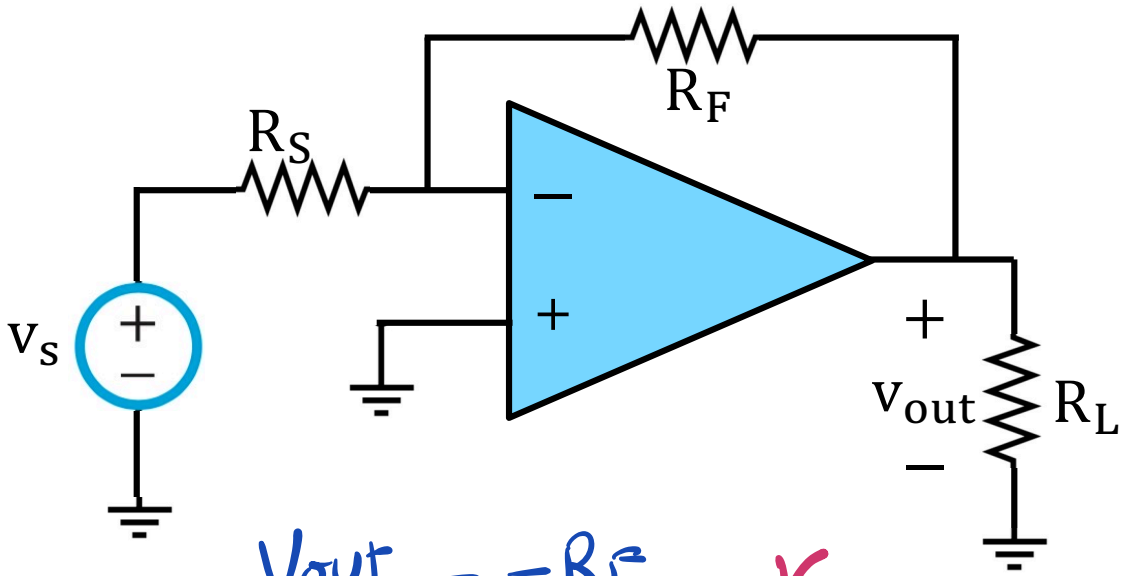
Passive

Review on LPF:

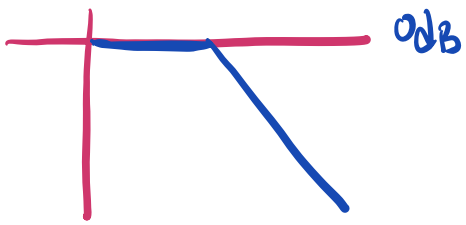


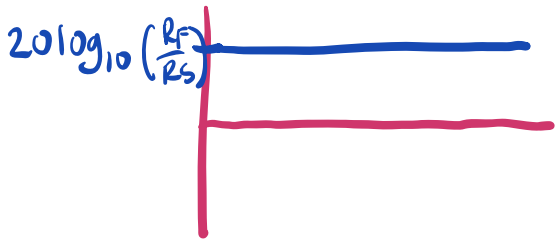
$$\frac{V_C}{V_S} = \frac{1}{1 + jwCR}$$

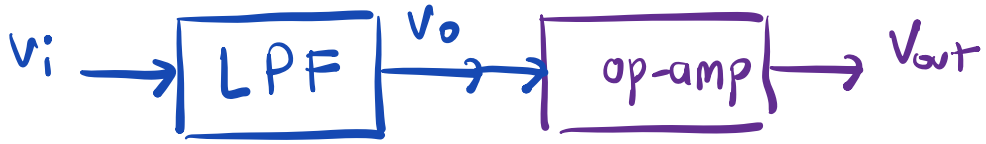
Review on Inverting Amplifier:



$$\frac{V_{out}}{V_S} = \frac{-R_F}{R_S} = K$$







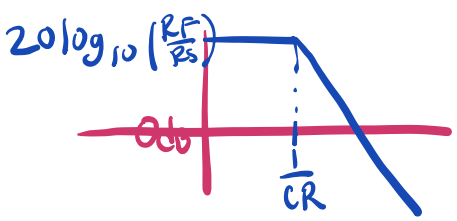
$$V_o = \frac{1}{1+jwCR} \cdot V_i$$

$$V_{out} = G \cdot V_o$$

$$= -\frac{R_F}{R_S} \cdot V_o$$

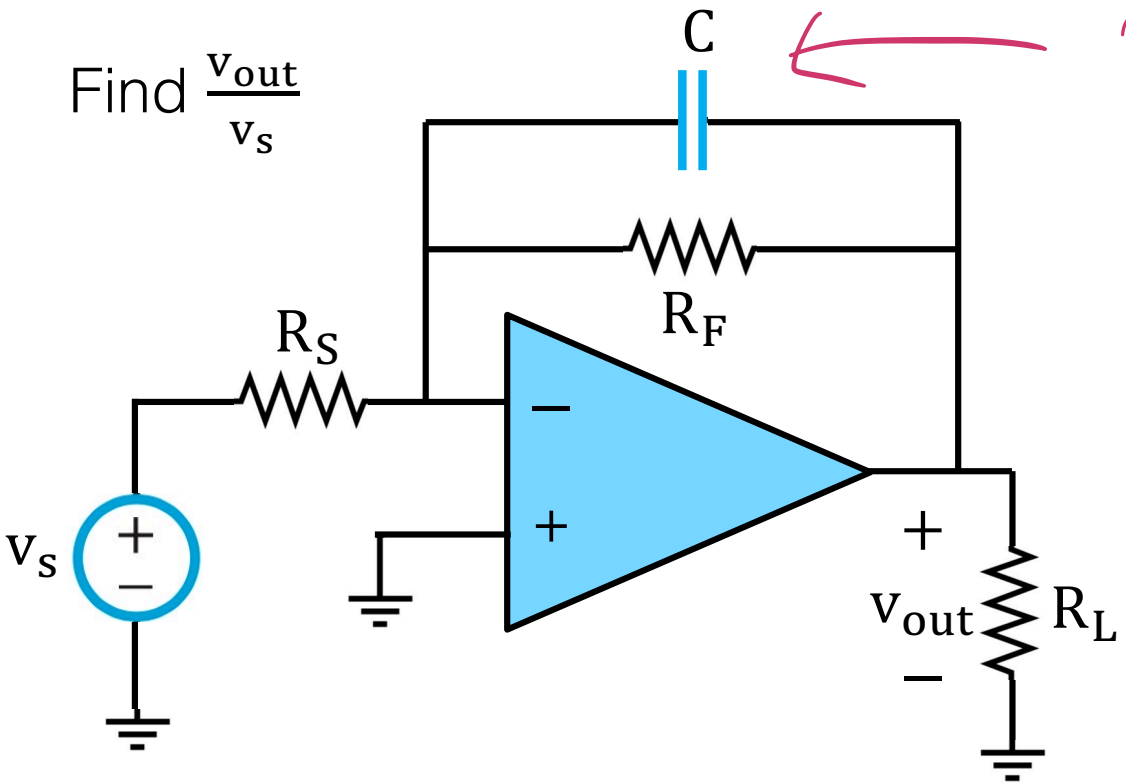
$$V_{out} = -\frac{R_F}{R_S} \cdot \frac{1}{1+jwCR} \cdot V_i$$

$$\frac{V_{out}}{V_i} = \underbrace{-\frac{R_F}{R_S}}_{\text{gain}} \cdot \underbrace{\frac{1}{1+jwCR}}_{\text{LPF}}$$



Example 1

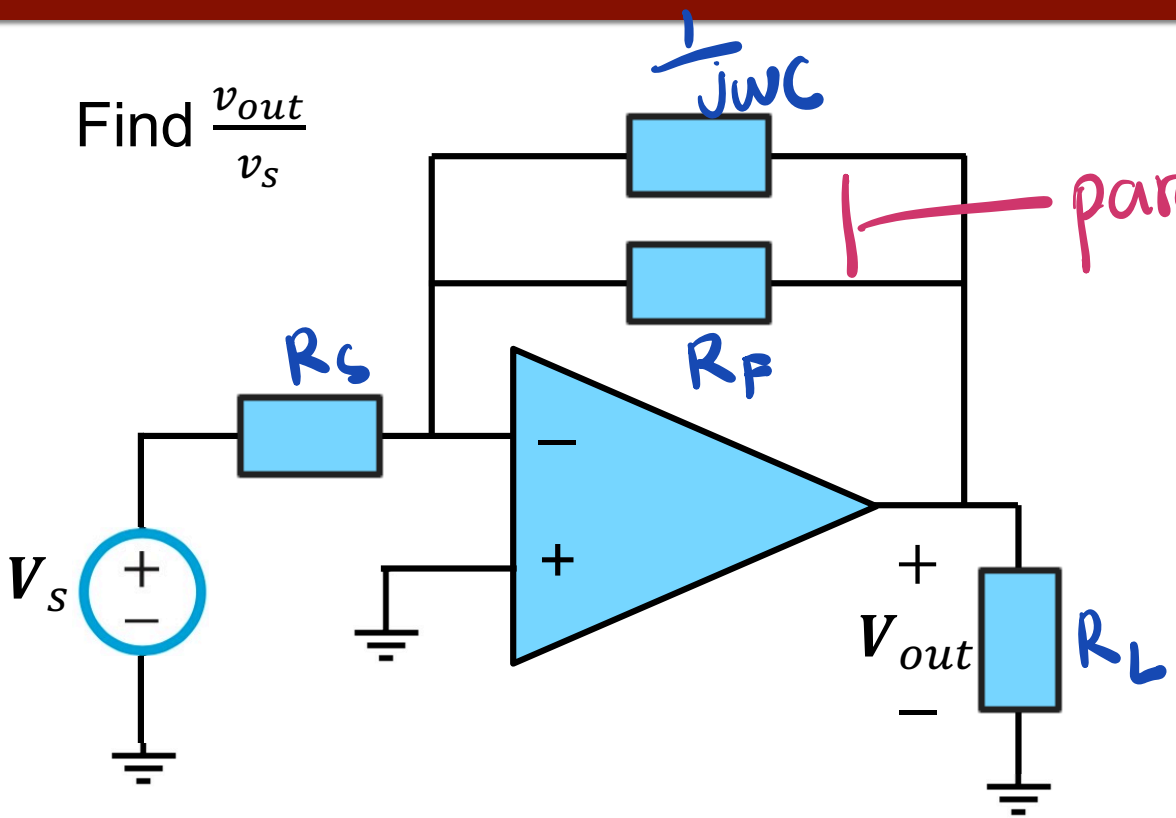
Find $\frac{v_{out}}{v_s}$



phasor domain

$$z_C = \frac{1}{j\omega C}$$

Find $\frac{v_{out}}{v_s}$



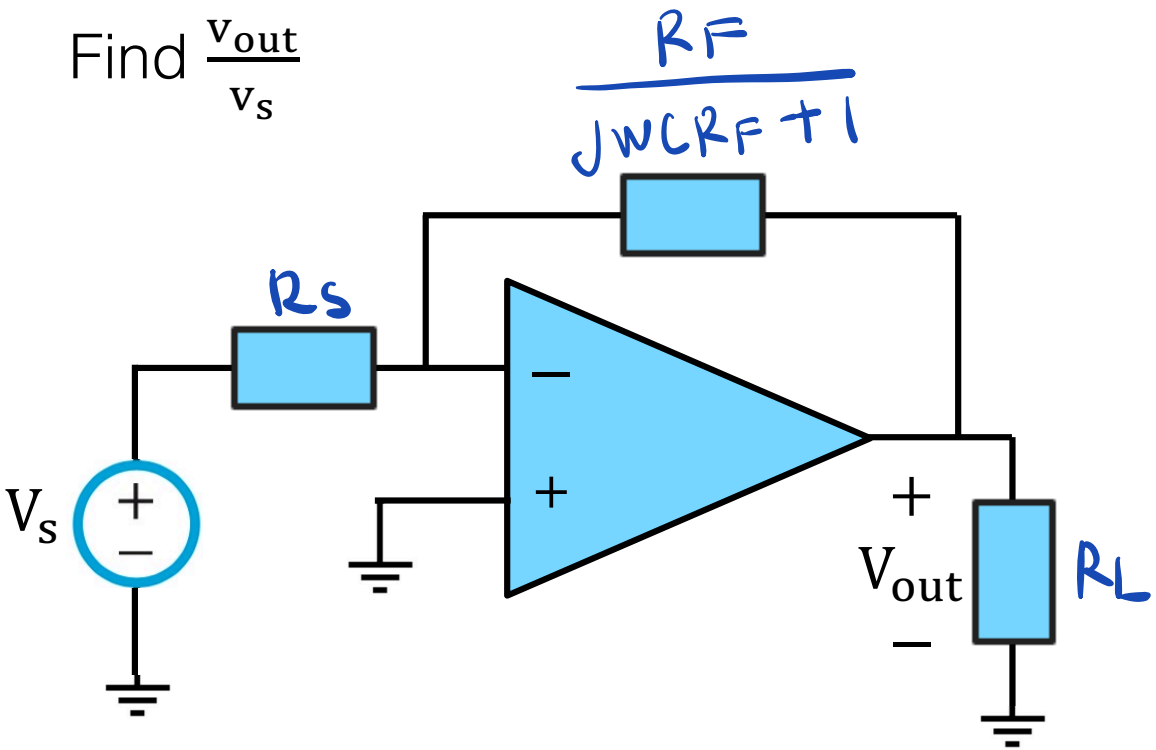
parallel

$$Z_F = \frac{\frac{R_F}{j\omega C}}{R_F + \frac{1}{j\omega C}} \times \frac{j\omega C}{j\omega C}$$

$$= \frac{R_F}{j\omega C R_F + 1}$$

Active Low-Pass Filter

Find $\frac{V_{out}}{V_s}$

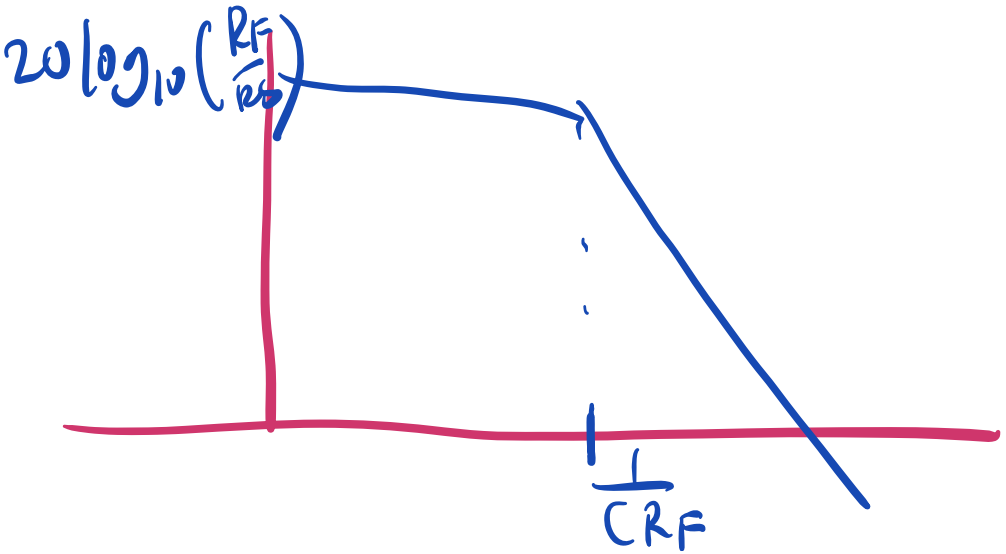


inverting op-amp.

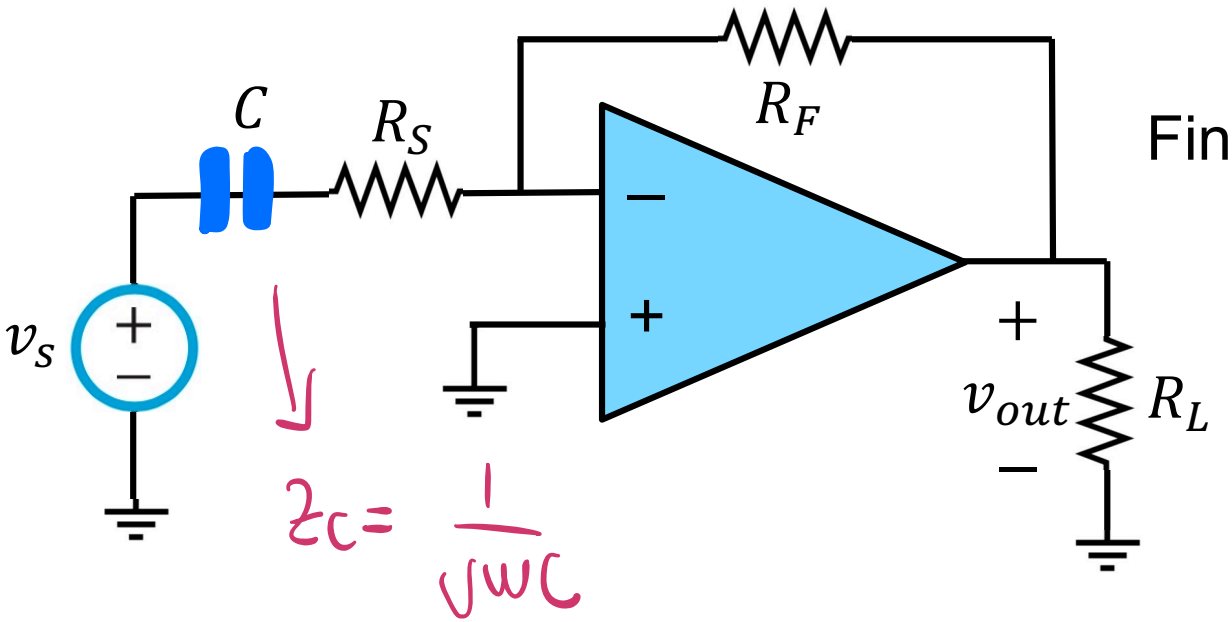
$$\frac{V_{out}}{V_s} = -\frac{Z_F}{R_S}$$

$$= -\frac{\frac{R_F}{JWCR_F+1}}{R_S}$$

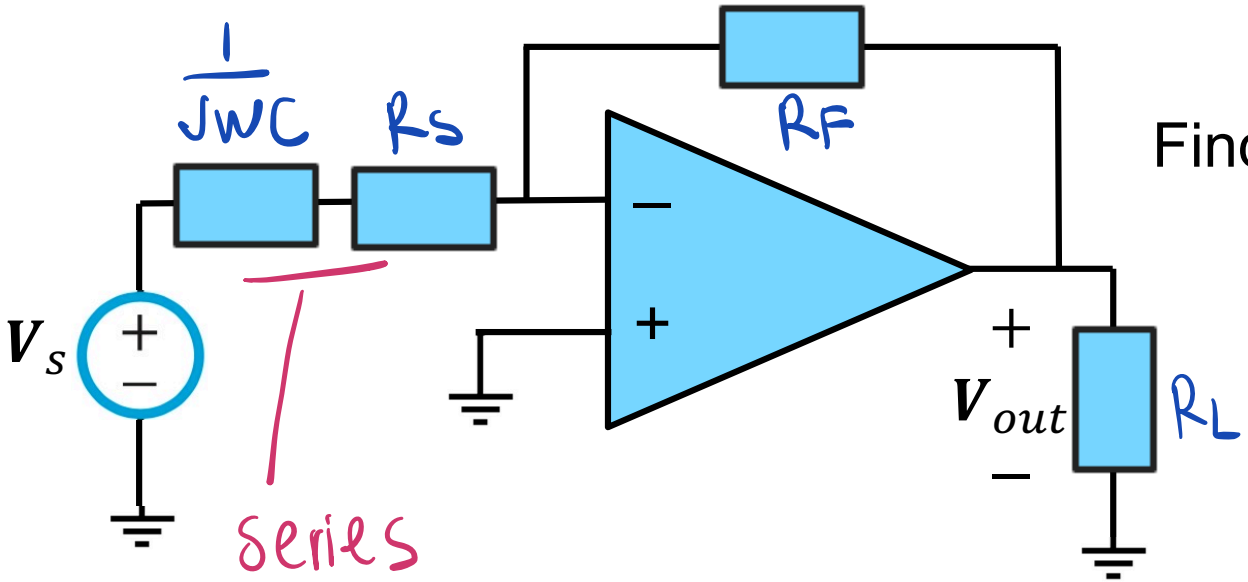
$$= \underbrace{-\frac{R_F}{R_S}}_{\text{gain}} \cdot \underbrace{\frac{1}{1+jwCR_F}}_{LPF}$$



Example



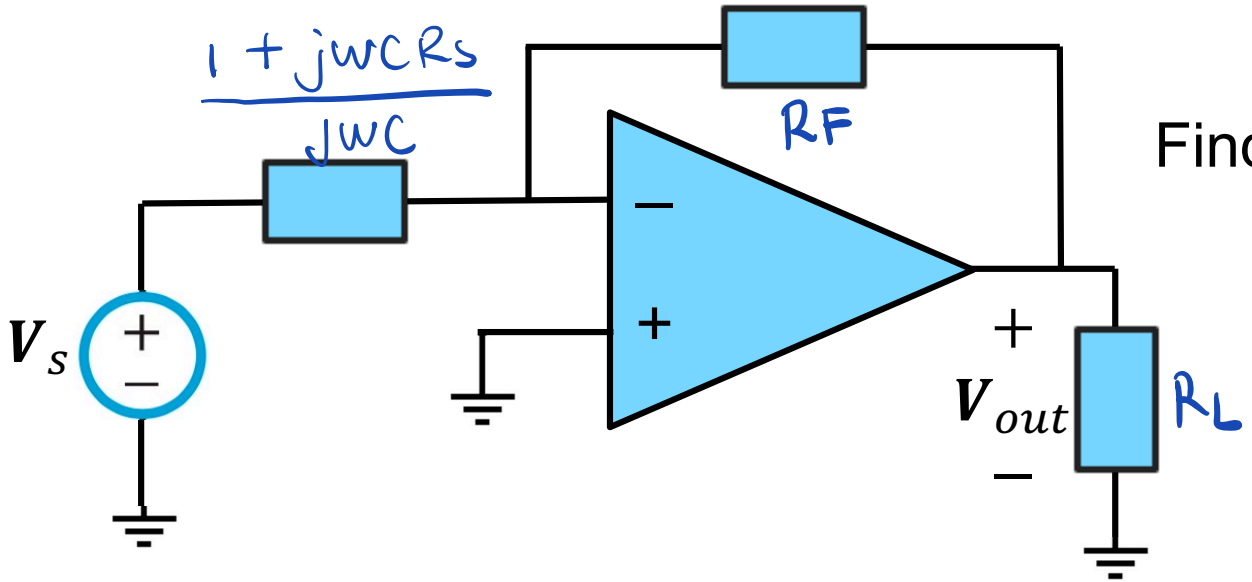
Find $\frac{v_{out}}{v_s}$



Find $\frac{v_{out}}{v_s}$

$$\frac{1}{jwC} + Rs = \frac{1 + jwCRs}{jwC}$$

Active High-Pass Filter



inverting op-amp

Find $\frac{v_{out}}{v_s} = -\frac{R_F}{Z_s}$

$$= \frac{-R_F/1}{\frac{1 + j\omega CR_s}{j\omega C}}$$

$$= -\frac{j\omega CR_F}{1 + j\omega CR_s}$$

$$= \frac{-R_F}{R_s} \cdot \frac{j\omega CR_s}{1 + j\omega CR_s}$$

gain HPF