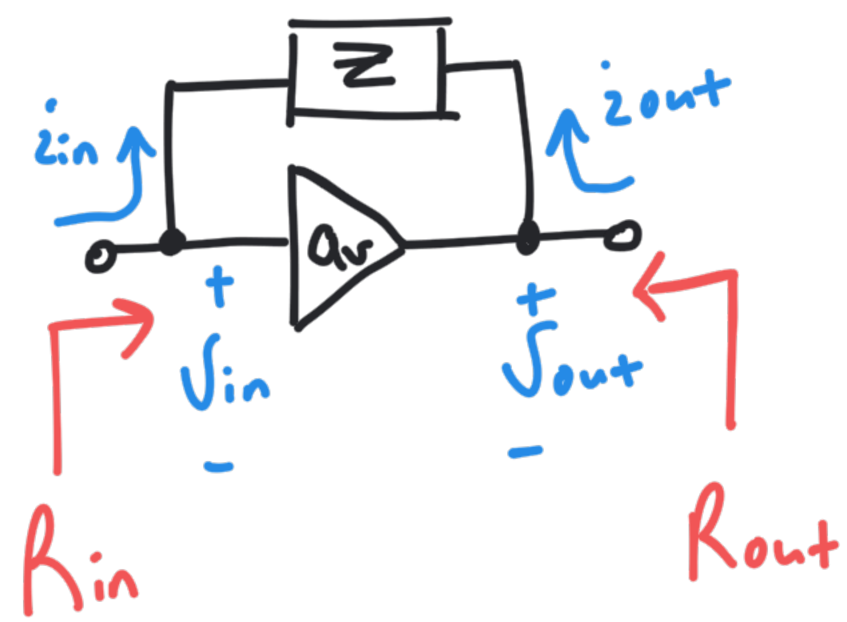
Quick review: Miller Time!



$$Z_{in} = \frac{v_{in}}{i_{in}} = \frac{v_{in}}{\frac{v_{in} - v_{out}}{Z}} = \frac{Z v_{in}}{v_{in} - v_{out}}$$

Input Impedance

$$\boxed{Z_{in} = \frac{Z}{1 - a_v}}$$

for negative feedback: $a_v = -|a_v|$

$$Z_{in} = \frac{Z}{1 + |a_v|}$$

we see that Z_{in} can drastically be reduced.

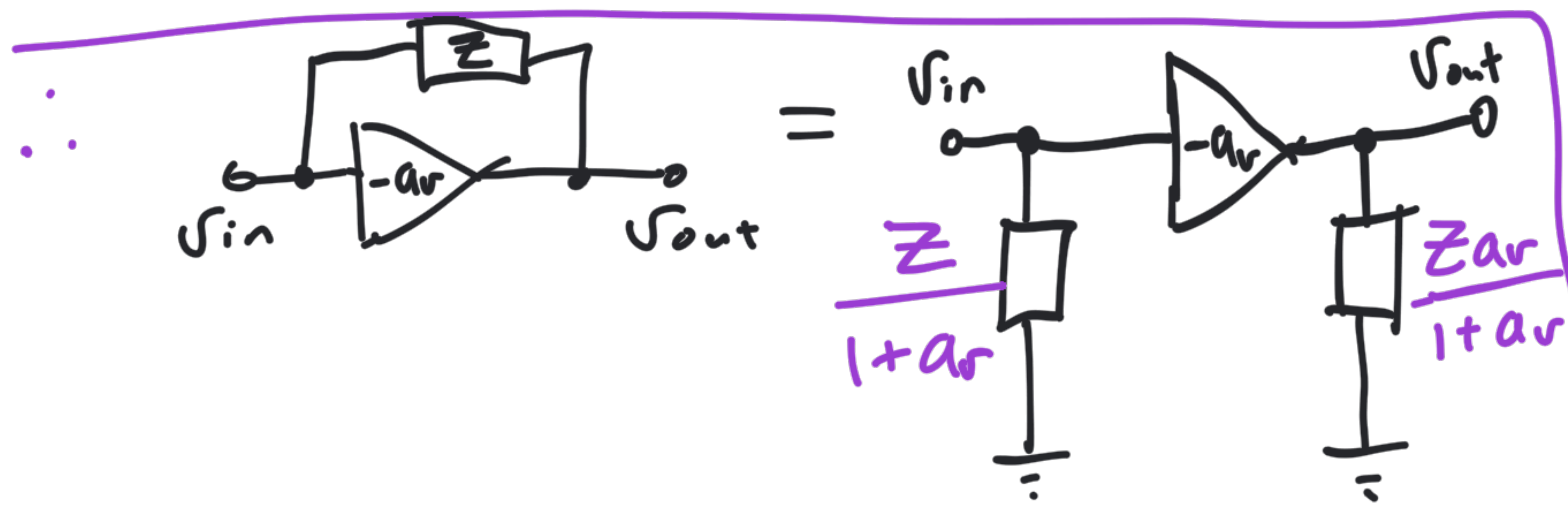
Output Impedance

$$R_{out} = \frac{v_{out}}{i_{out}} = \frac{v_{out}}{\frac{v_{out} - v_{in}}{Z}} = \frac{Z a_v}{a_v - 1}$$

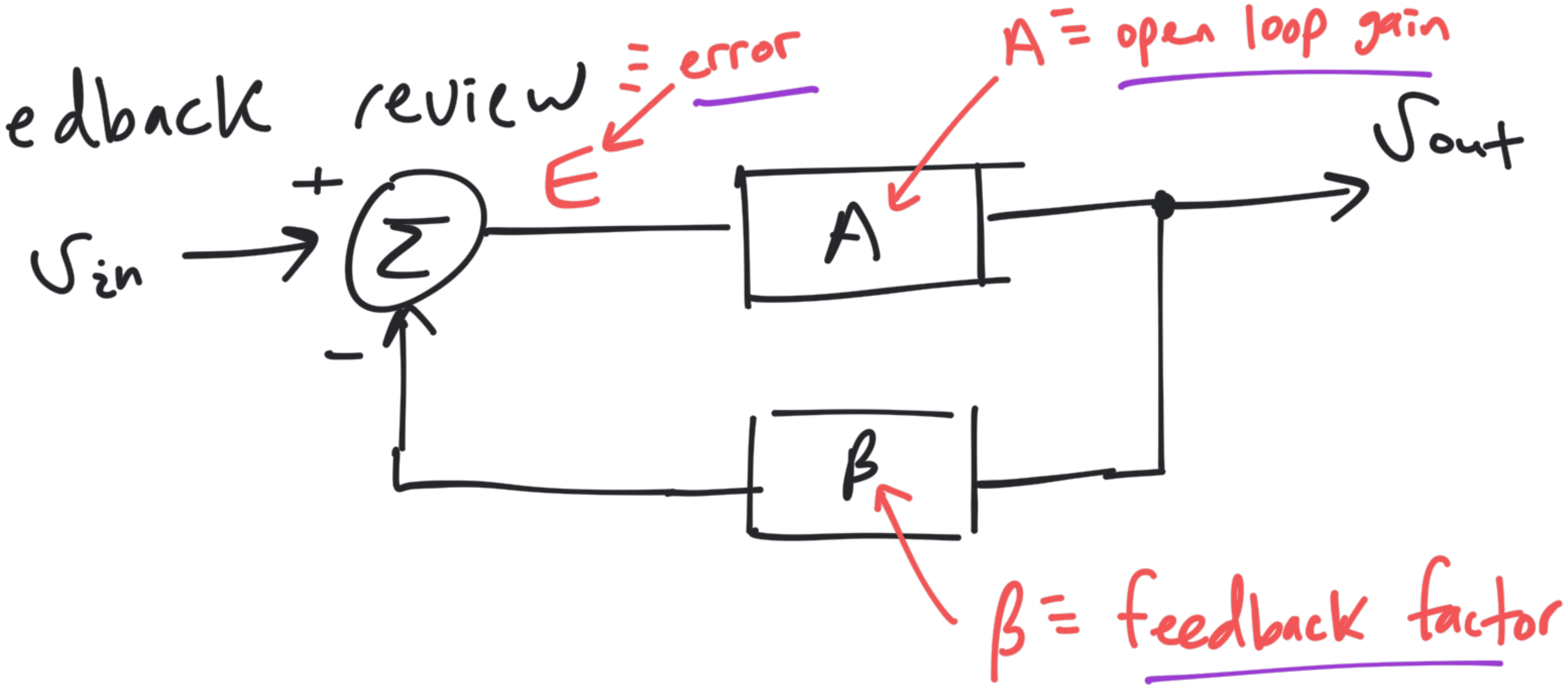
← so, $\boxed{Z_{out} = \frac{Z a_v}{a_v - 1}}$

for negative feedback: $a_v = -|a_v|$

$$Z_{out} = \frac{Z |a_v|}{|a_v| + 1}$$



feedback review



Derivation

$E = V_{in} - V_{out}\beta$

$E = V_{out}/A$

$\therefore \dfrac{V_{out}}{A} = V_{in} - V_{out}\beta$

$V_{out} = AV_{in} - V_{out}A\beta$

$V_{out}(1 - A\beta) = AV_{in}$

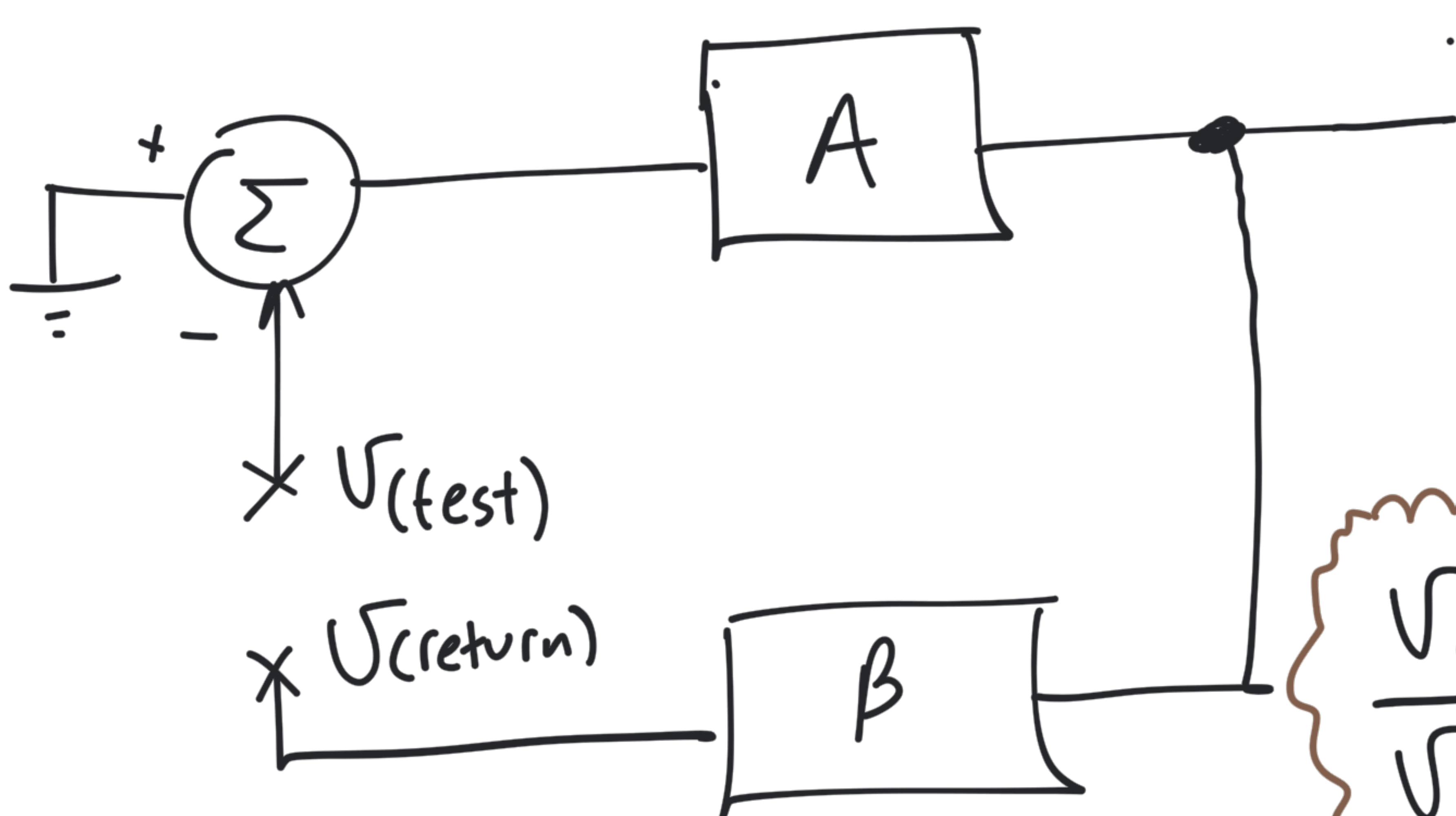
$$\therefore \frac{V_{out}}{V_{in}} = \frac{A}{1 - A\beta}$$

$\dfrac{V_{out}}{V_{in}} \equiv$ closed loop gain

sometimes called "signal gain"

$A\beta \equiv$ loop gain

Break feedback loop to measure/calculate loop gain:



$$\frac{V_{(return)}}{V_{(test)}} = -A\beta$$

Bode Stability criterion (see "A note on stability analysis using Bode Plots" by Hahn et al.)

A closed loop system is stable if the open-loop system is stable and frequency response of $A\beta$ has amplitude $|A\beta| < 1$ at all frequencies corresponding to: $\phi = \pm(180° + n360°)$

$\phi = \angle A\beta$

Technically, this is a sufficient condition for stability, but not a necessary condition. It is possible for a system to have multiple phase crossover frequencies (some w/ amplitudes larger than unity) and still be stable...

I think this is because $A\beta$ is monotonically decreasing at crossover point.

However, for op amp circuits most texts I see say:

instability occurs when $|A\beta| \geq 1$ for $\angle A\beta = \phi = 180°$.

So, to design an oscillator you want $A\beta = 1$ (Barkhausen criterion)

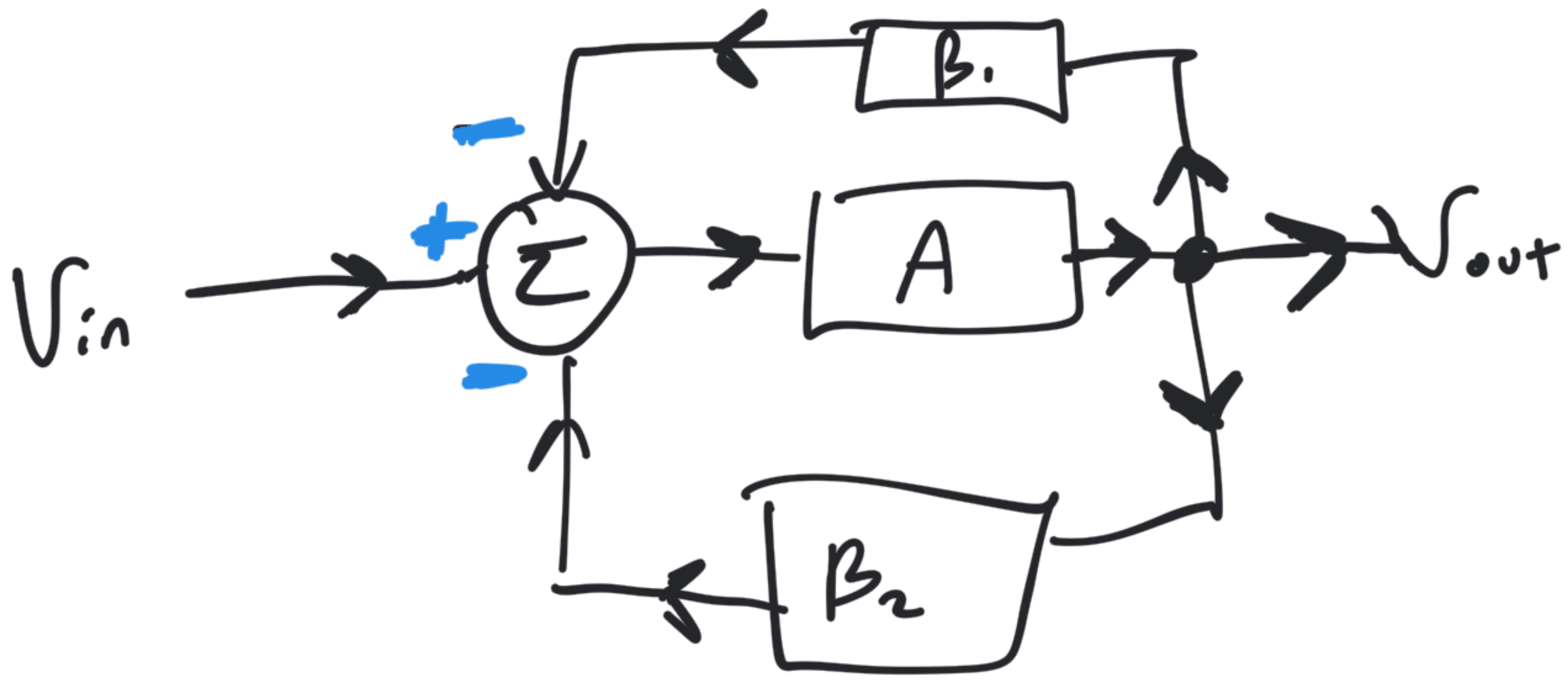
So, loop gain $A\beta$ determines stability.

What happens when $|A\beta| \to 1$ and $\angle A\beta \to 180°$?

- V_{out} starts going to ∞ !
- When V_{out} approaches power supply rail, active devices in amplifier change gain ... This causes A to change and forces $|A\beta| < 1$ or (I guess) $\angle A\beta \neq 180°$ at $|A\beta| = 1$.
- Thus the trajectory of infinite voltage eventually stops!

At this stage one of three things can occur:

1. Nonlinearity in saturation or cutoff causes system to become stable and lockup at current power rail.
2. System saturates (or cuts offs) for a long time before it becomes linear and heads for opposite power rail. This results in highly distorted oscillations (usually quasi-square waves). These oscillators are called <u>relaxation oscillators</u>.
3. System stays linear and reverses direction, heading for opposite power rail. This produces a sin-wave oscillator.



two feed back paths

$$\frac{V_{out}}{V_{in}} = \frac{A}{1 - A(\beta_1 + \beta_2)}$$

system oscillates if $A(\beta_1 + \beta_2) = 1$

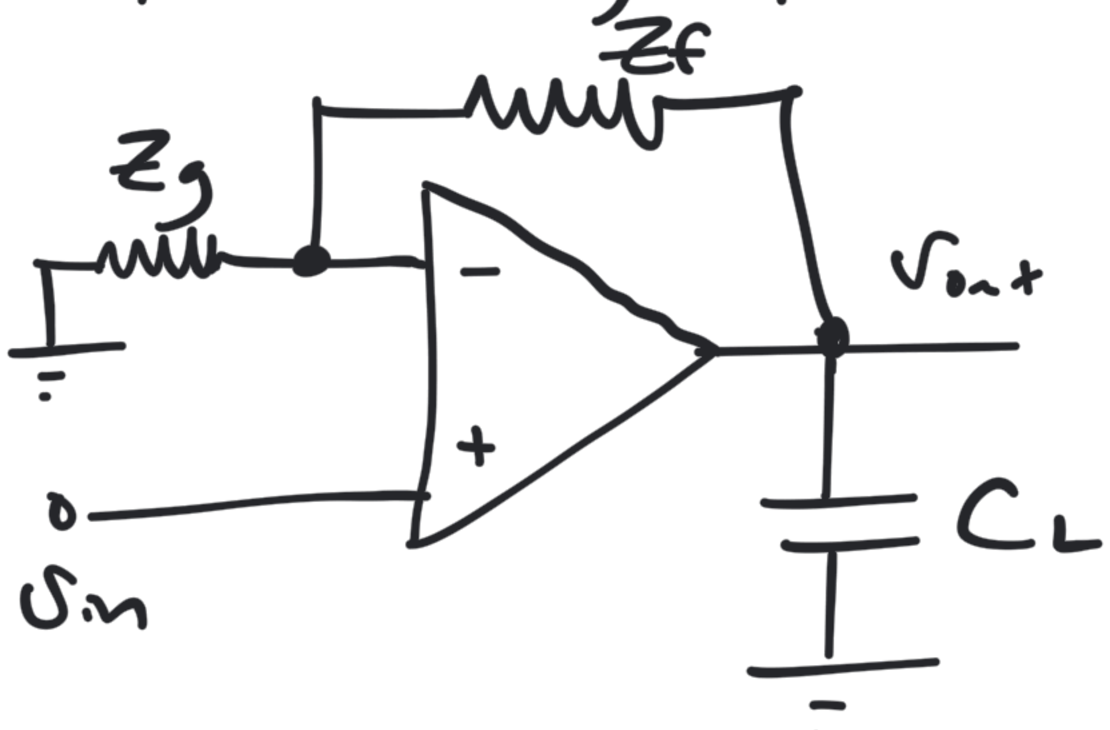
$$\beta_1 + \beta_2 = \frac{1}{A}$$

$$\beta_1 + \beta_2 = 0 \quad (\text{Assume } A >> 1)$$

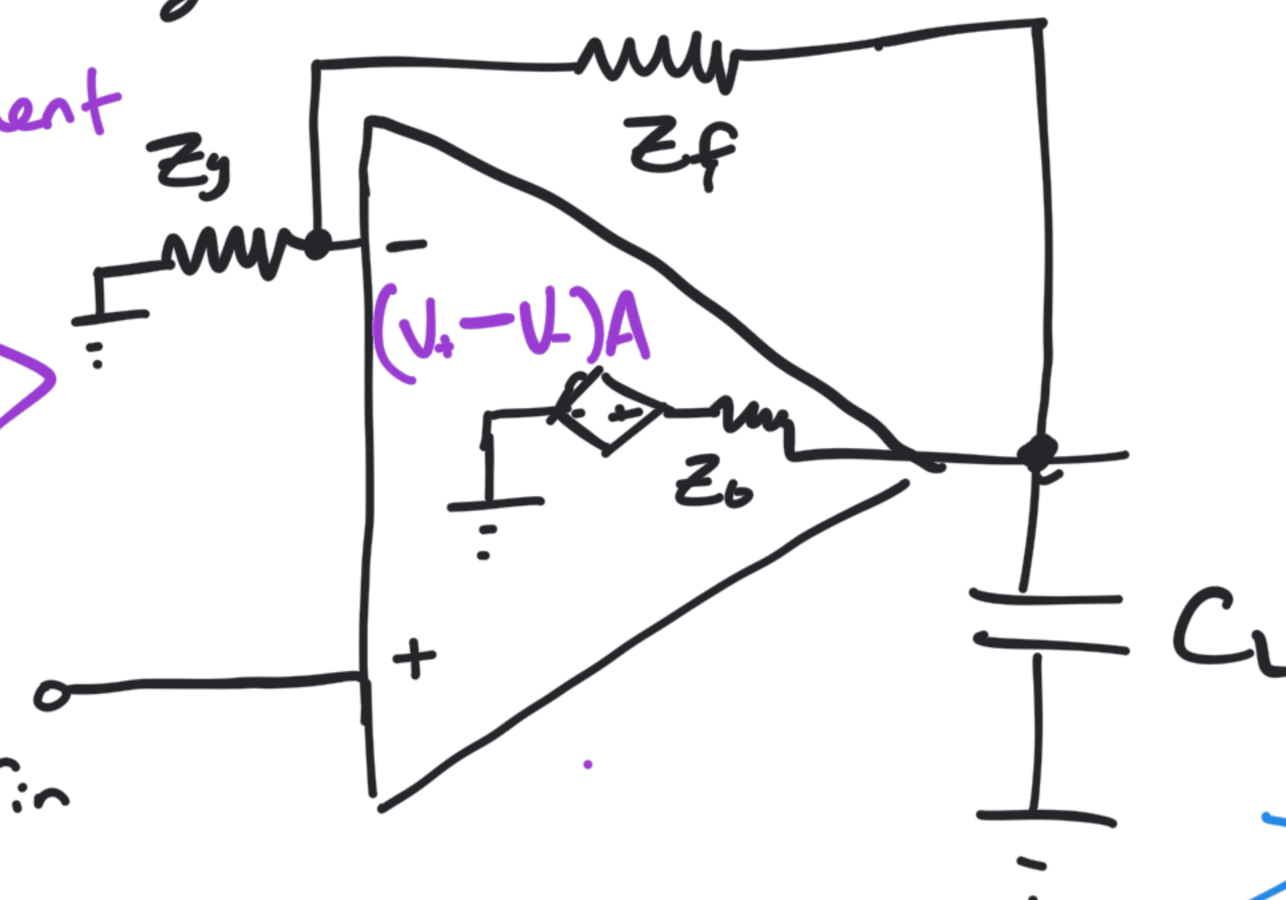
$$\boxed{\beta_1 = -\beta_2}$$

positive and negative feedback sort of (cancel out?

Non-inverting op amp : capacitively loaded

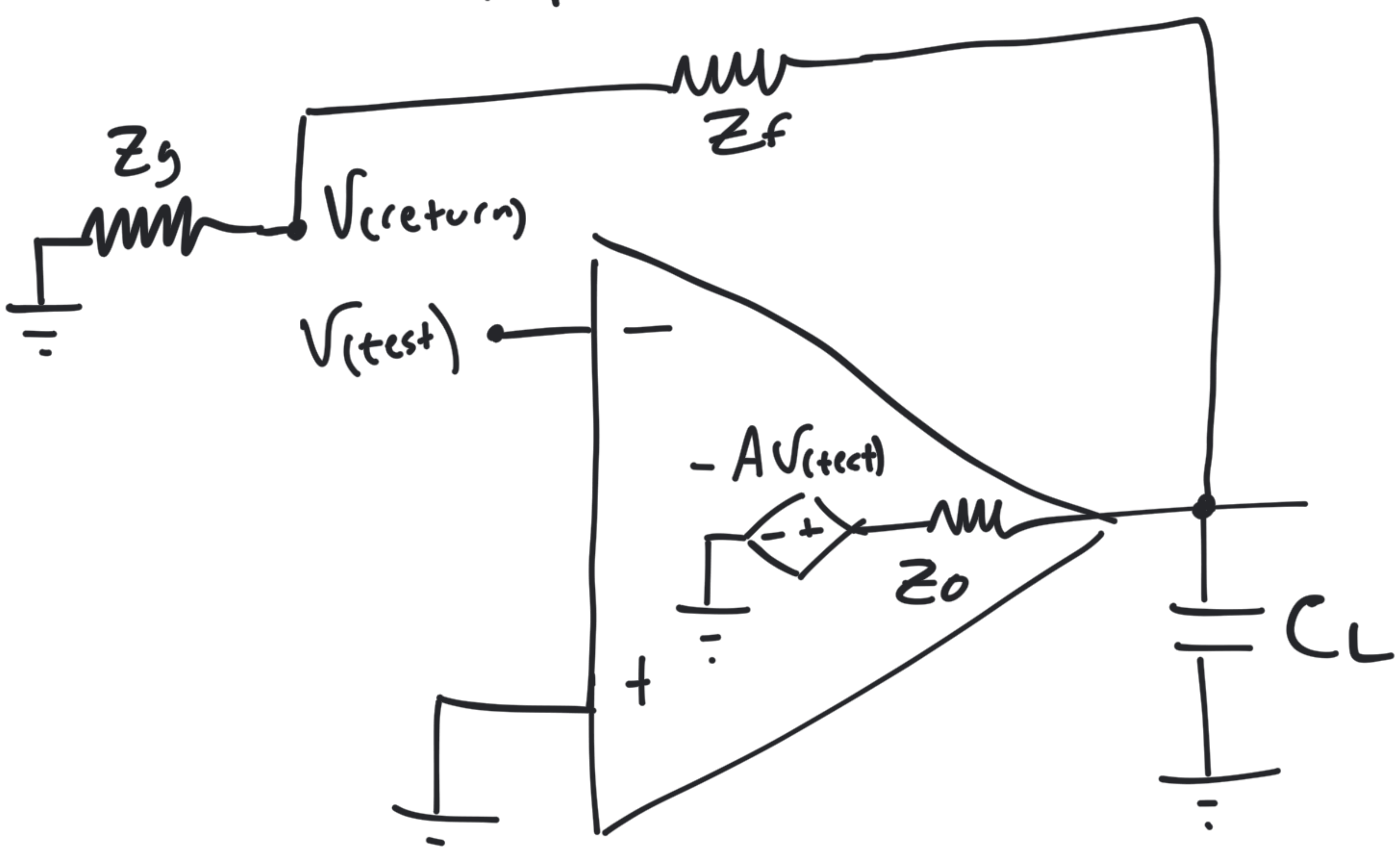


Equivalent Circuit ⟹



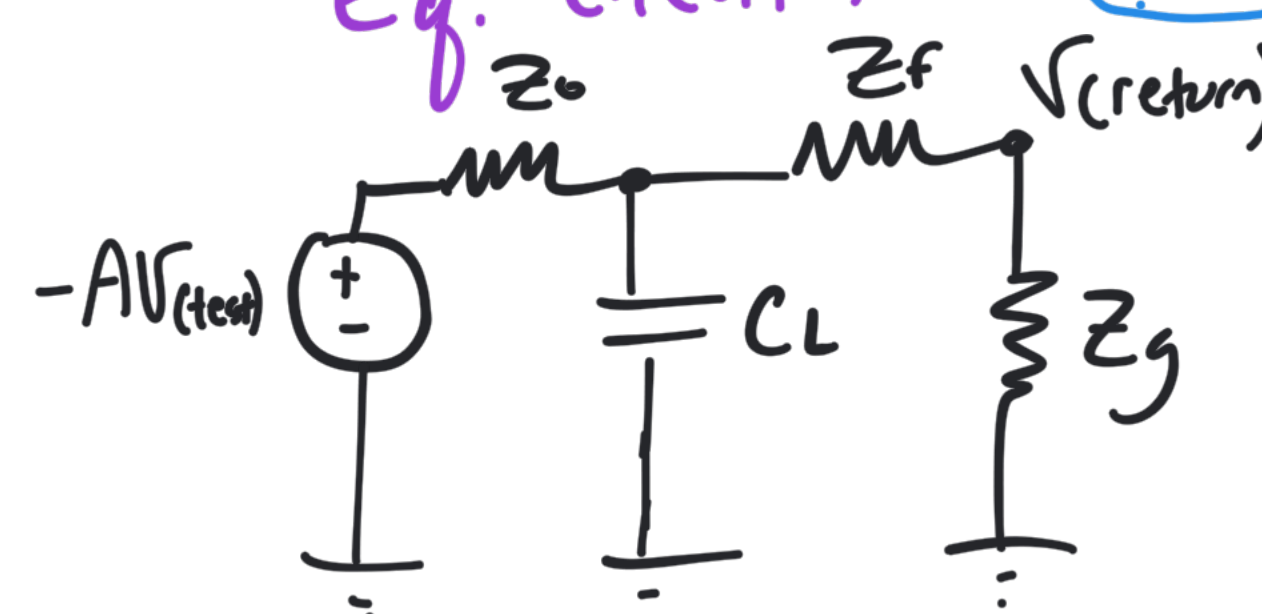
This is all exact same analysis for inverting op amp config!

To find $A\beta$ ... break the connection...

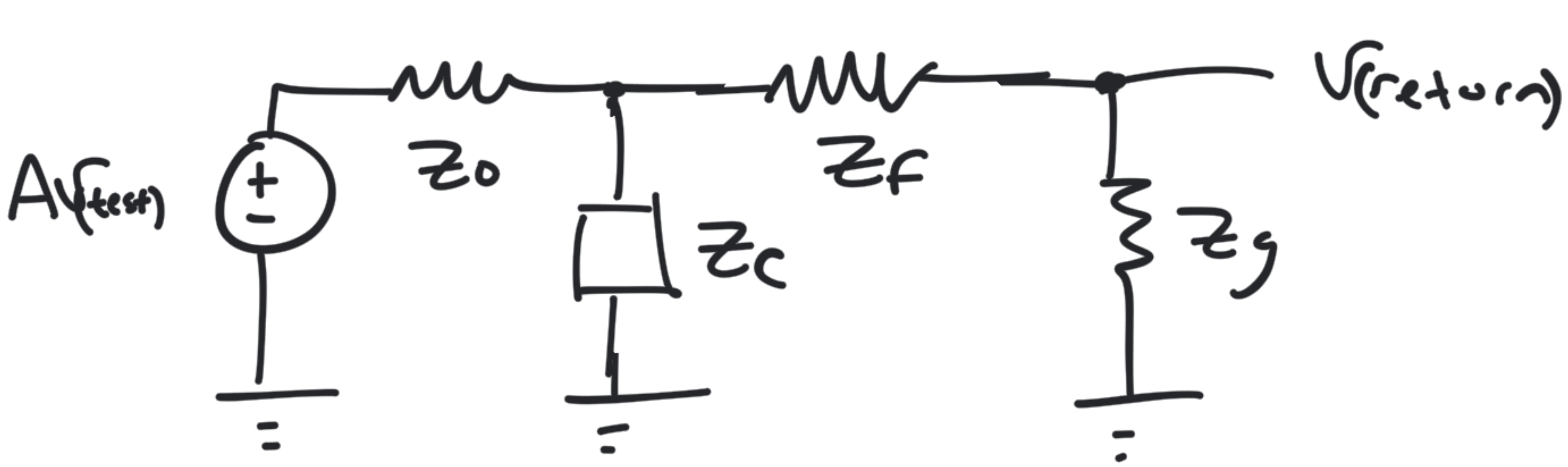


$$A\beta = \frac{V_{(return)}}{V_{(test)}}$$

Eq. circuit:

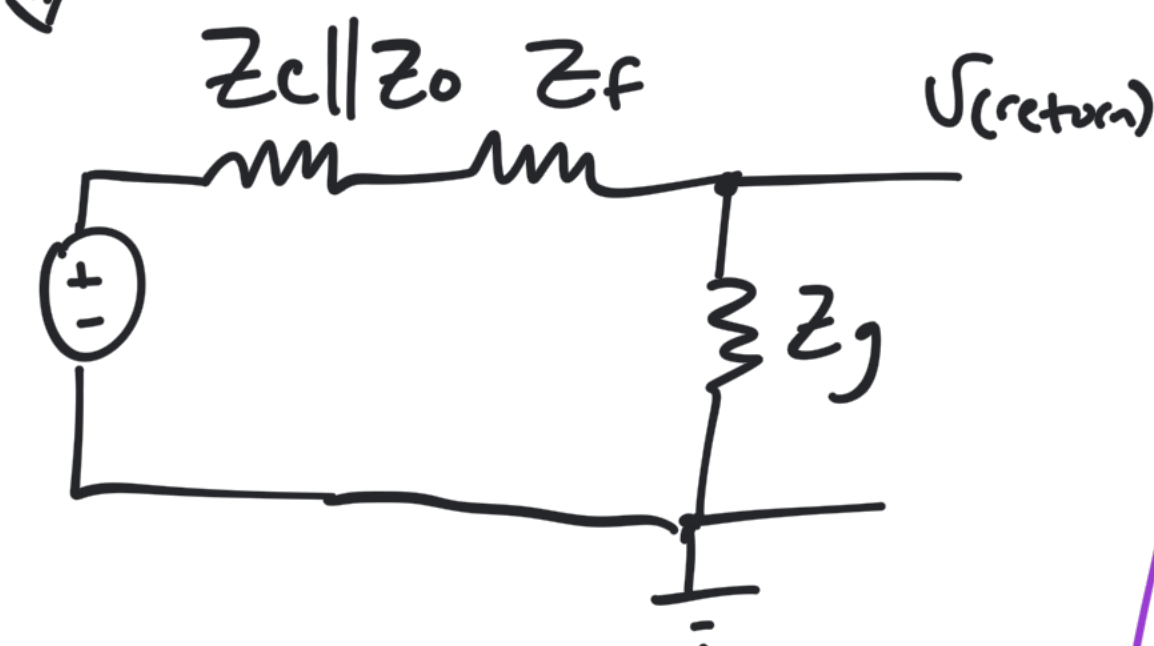


Last circuit



$\Downarrow$

$$\frac{A Z_c}{Z_c + Z_o} V_{(test)}$$



$$\boxed{\frac{V_{(return)}}{V_{(test)}} = A\beta = \frac{A Z_c}{Z_c + Z_o} \; \frac{Z_g}{Z_c \| Z_o + Z_f + Z_g}}$$

Assume $Z_f + Z_g >> Z_c \| Z_o$

$$A\beta = \frac{A Z_c Z_g}{(Z_c + Z_o)(Z_f + Z_g)}$$

$$A\beta = \left(\frac{A Z_g}{Z_f + Z_g}\right)\left(\frac{Z_c}{Z_c + Z_o}\right)$$

$Z_c = \frac{1}{sC_L}$ substitute

$\Downarrow$

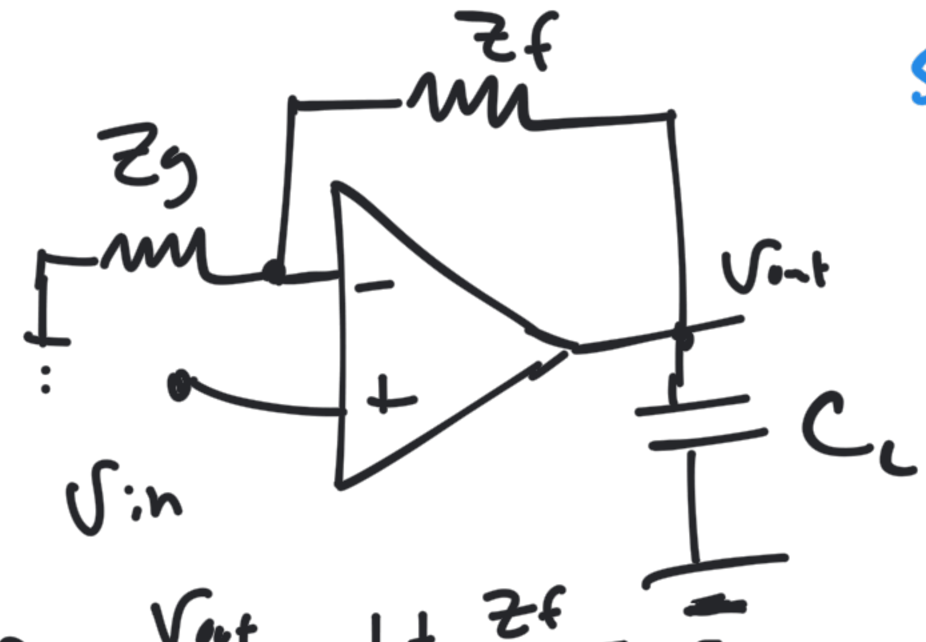
$$A\beta = \left(\frac{A Z_g}{Z_f + Z_g}\right) \frac{1}{1 + sC_L Z_o}$$

real pole at $\frac{1}{C_L Z_o}$

Additional - phase shift!

negative

can cause instabilities!

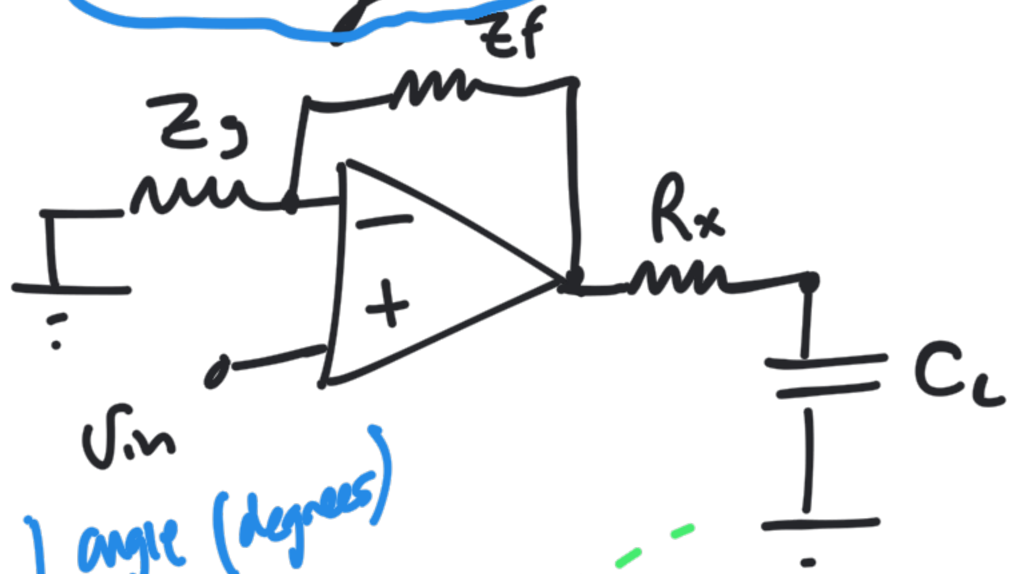


DC (ideal): $\dfrac{V_{out}}{V_{in}} = 1 + \dfrac{Z_f}{Z_g}$

so, C_L (in conjunction w/ non-zero Z_o) <u>slows</u> <u>down</u> output response which adds more <u>phase lag</u> to the loop... Already loop has phase lag due to poles of open-loop gain A... more phase lag means more chance of going unstable...

Remedy 1

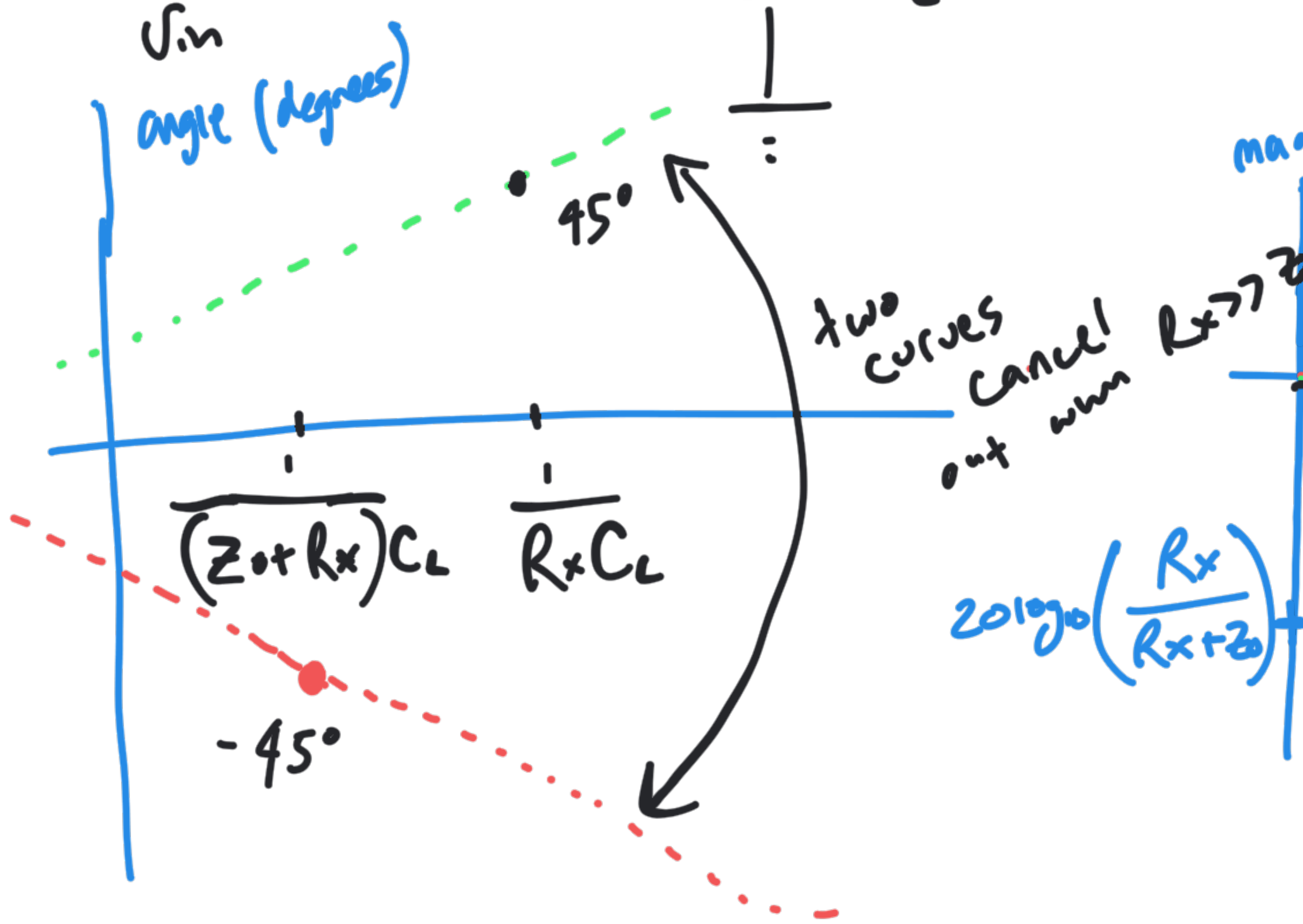
see "Ask the Applications Engineer-25" by Grayson King

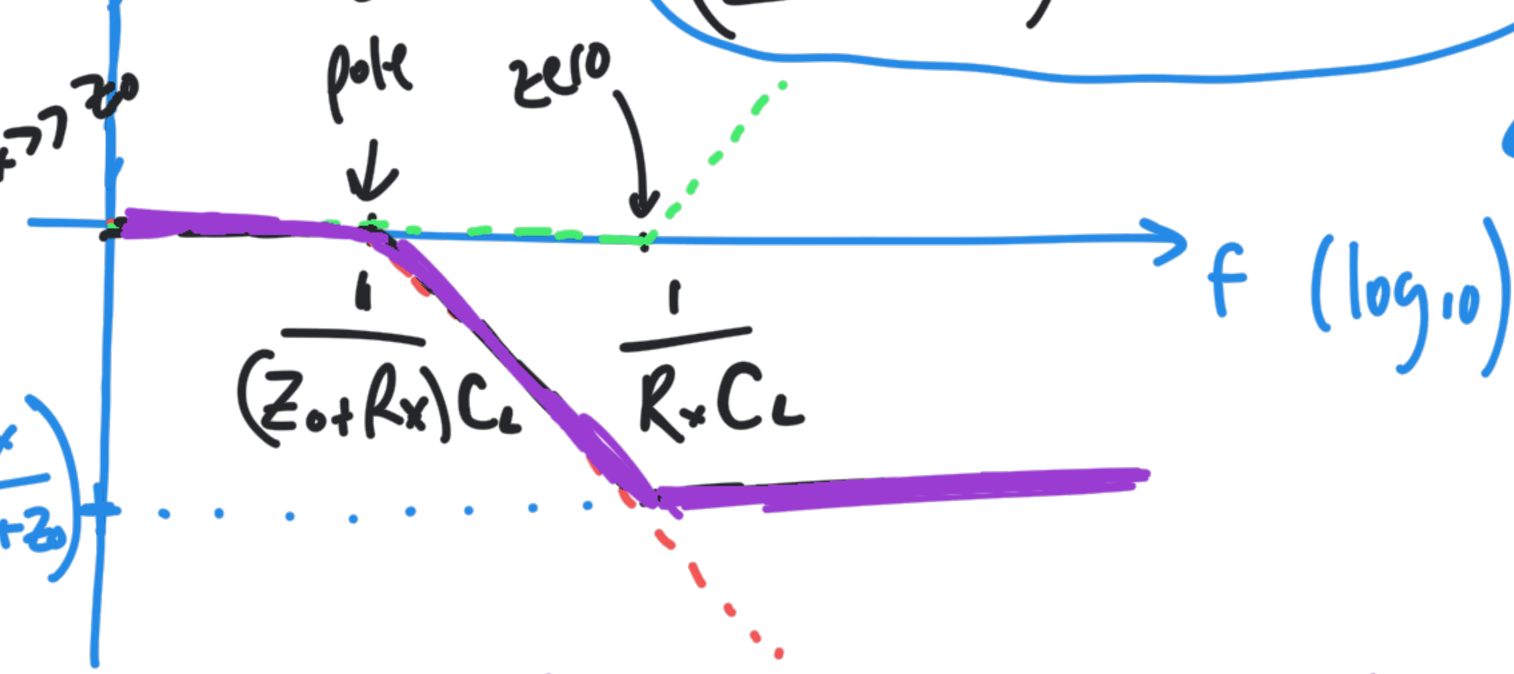


$$A\beta = \left(\frac{A Z_g}{Z_g + Z_f}\right) \frac{R_x + \frac{1}{sC_L}}{R_x + \frac{1}{sC_L} + Z_o}$$

$$= \frac{A Z_g}{Z_g + Z_f} \boxed{\frac{sR_xC_L + 1}{(Z_o + R_x)sC_L + 1}}$$

Bode plot

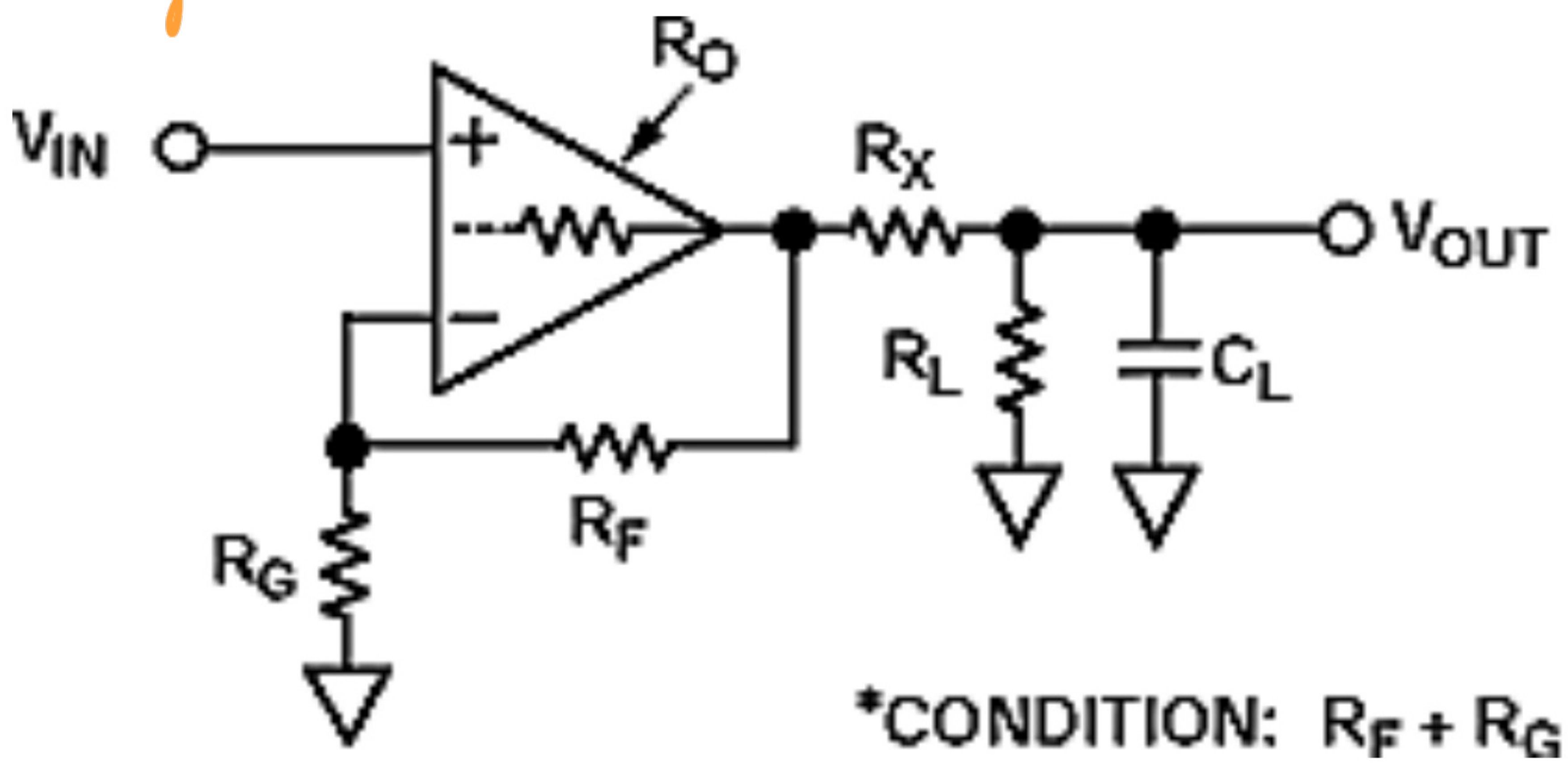




Advantages: one part solution

Disadvantages: output impedance seen by load increases. This can decrease signal gain due to resistor divider action.

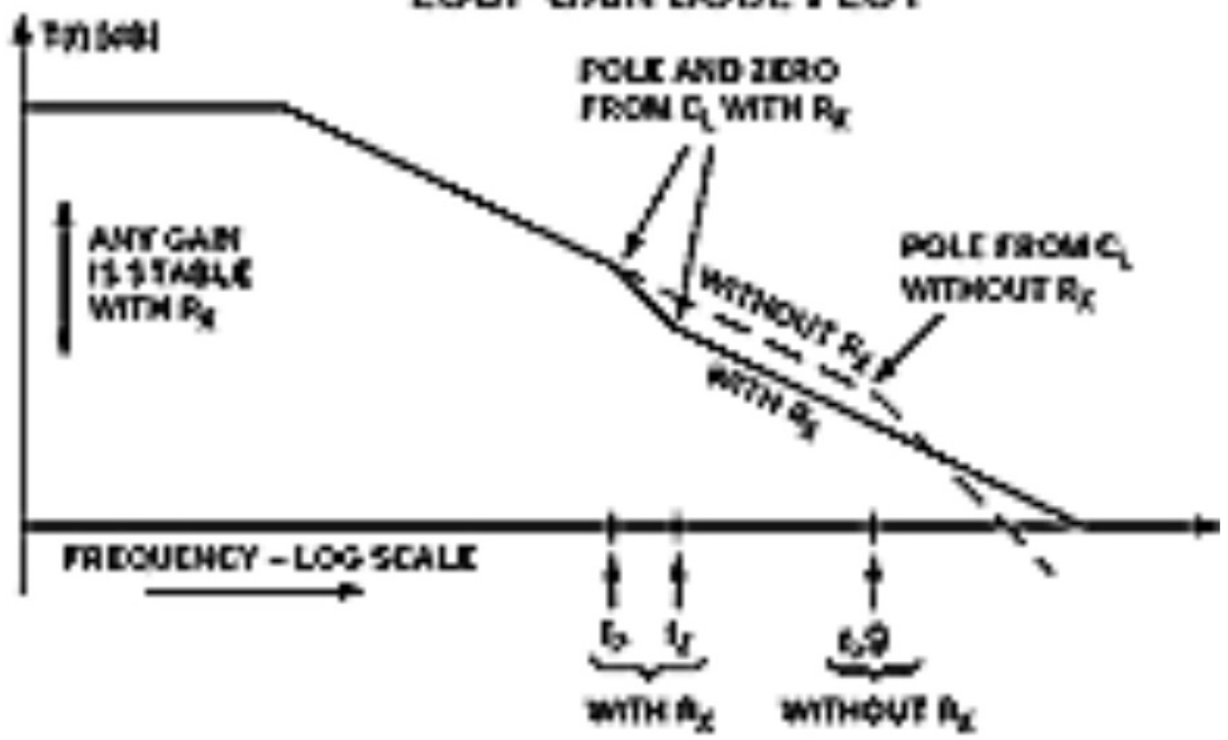
Remedy 1 Cont.

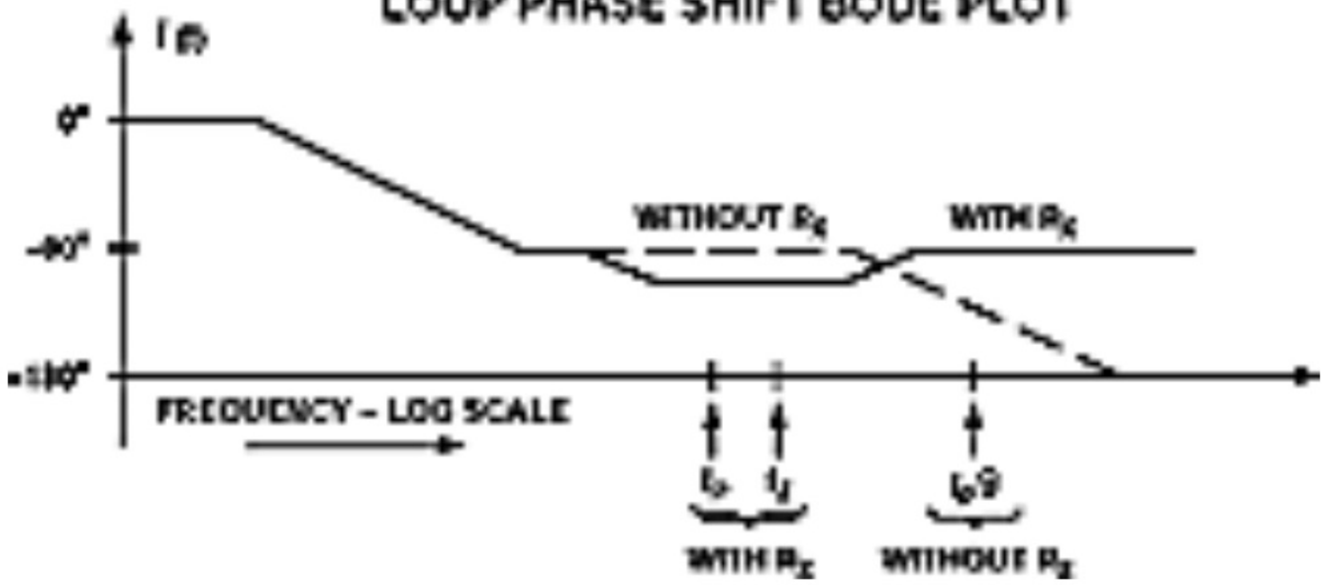


$$^{*}f_z = \frac{1}{2p[(R_O + R_X) \parallel R_L]C_L}$$

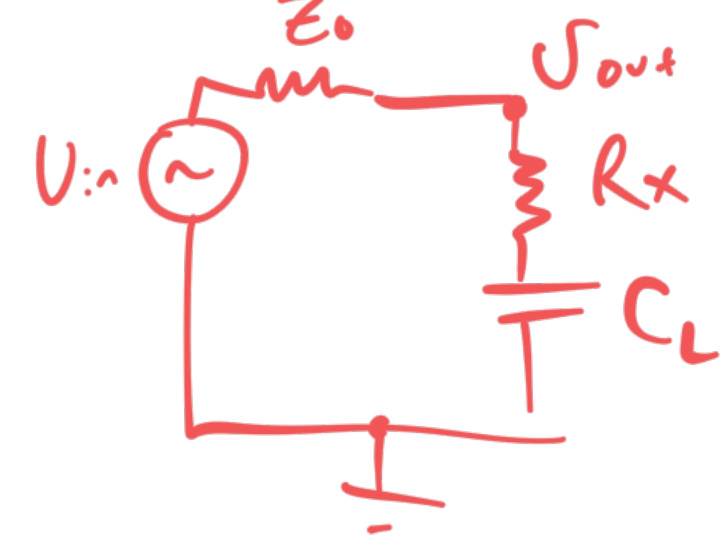
$$= \frac{1}{2p(R_O + R_X)\, C_L} + \frac{1}{2pR_LC_L}$$

*CONDITION: $R_F + R_G >> R_O$





Aside:



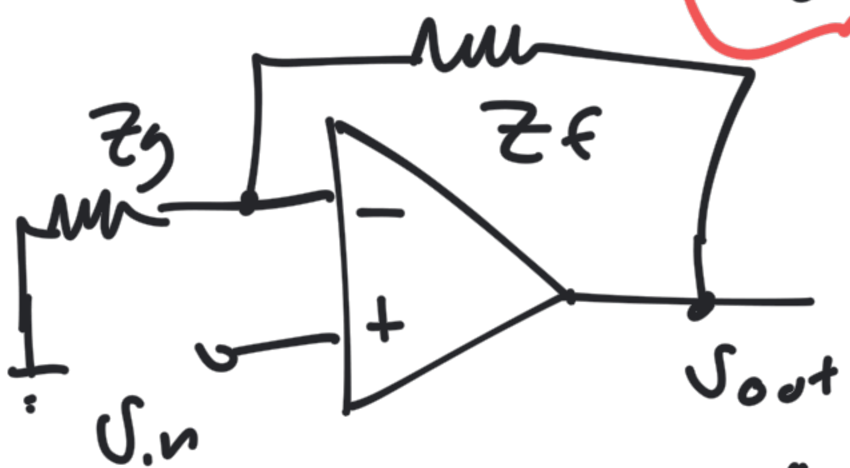
$$V_{out} = V_{in}\left(\frac{R_x + \frac{1}{sC_L}}{R_x + \frac{1}{sC_L} + Z_o}\right)$$

$$\frac{V_{out}}{V_{in}} = \frac{1 + sC_LR_x}{1 + sC_L(R_x + Z_o)}$$

$\boxed{\text{Remedy 2}}$ Increase closed loop gain (i.e. signal gain)

simplest method!

$$A\beta = \underbrace{\frac{A Z_g}{Z_g + Z_f}}_{\text{decrease this factor!}} \frac{1}{1 + sC_L Z_o}$$



$$\frac{1}{\beta} = \frac{Z_g + Z_f}{Z_g}$$

$$\text{signal gain} = \frac{A}{1 + A\beta} \simeq \overbrace{1 + \frac{Z_f}{Z_g}}^{} \quad \text{for large } A\beta >> 1$$

decrease β $\rightarrow$ increase $\frac{1}{\beta}$ $\rightarrow$ increase signal gain $\rightarrow$ decrease loop gain $A\beta$

(stability increases!)

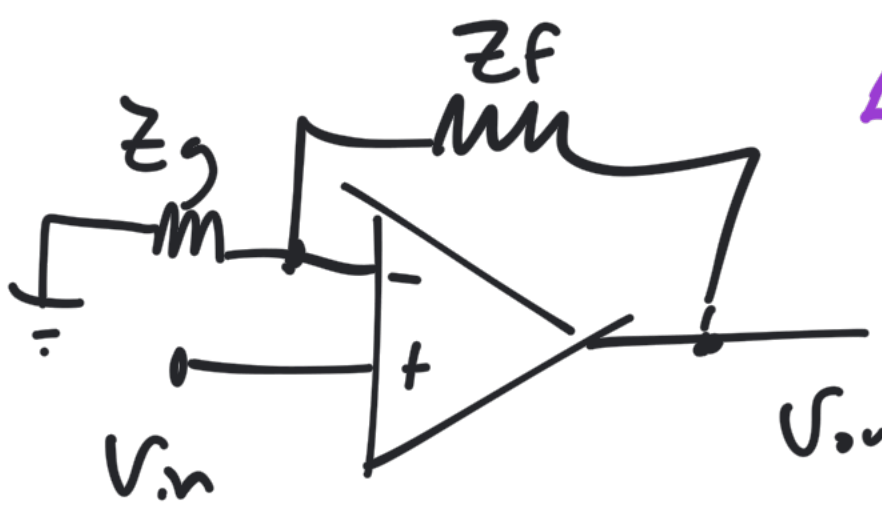
Advantages: very simple

Disadvantages: You may have to deal w/ a bunch of unwanted gain... power waste!

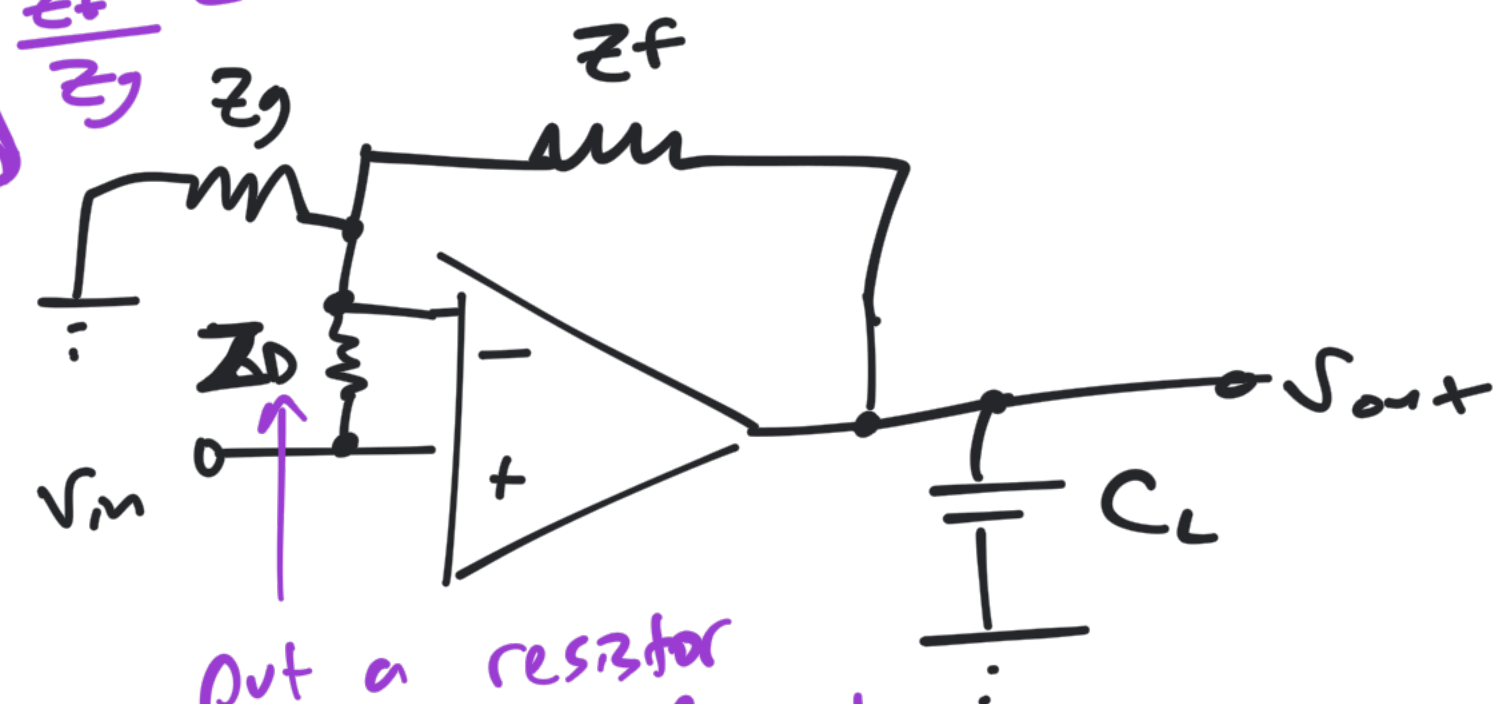
Remedy 3

Noise gain manipulation

original:



same signal gain: $1 + \frac{Z_f}{Z_g}$ ← ideal op amp



put a resistor between op amp inputs!

In this case:

$$A\beta = A \frac{Z_g \| Z_D}{Z_g \| Z_D + Z_f} \frac{1}{1 + sC_L Z_o}$$

Advantages: Does not change signal gain.

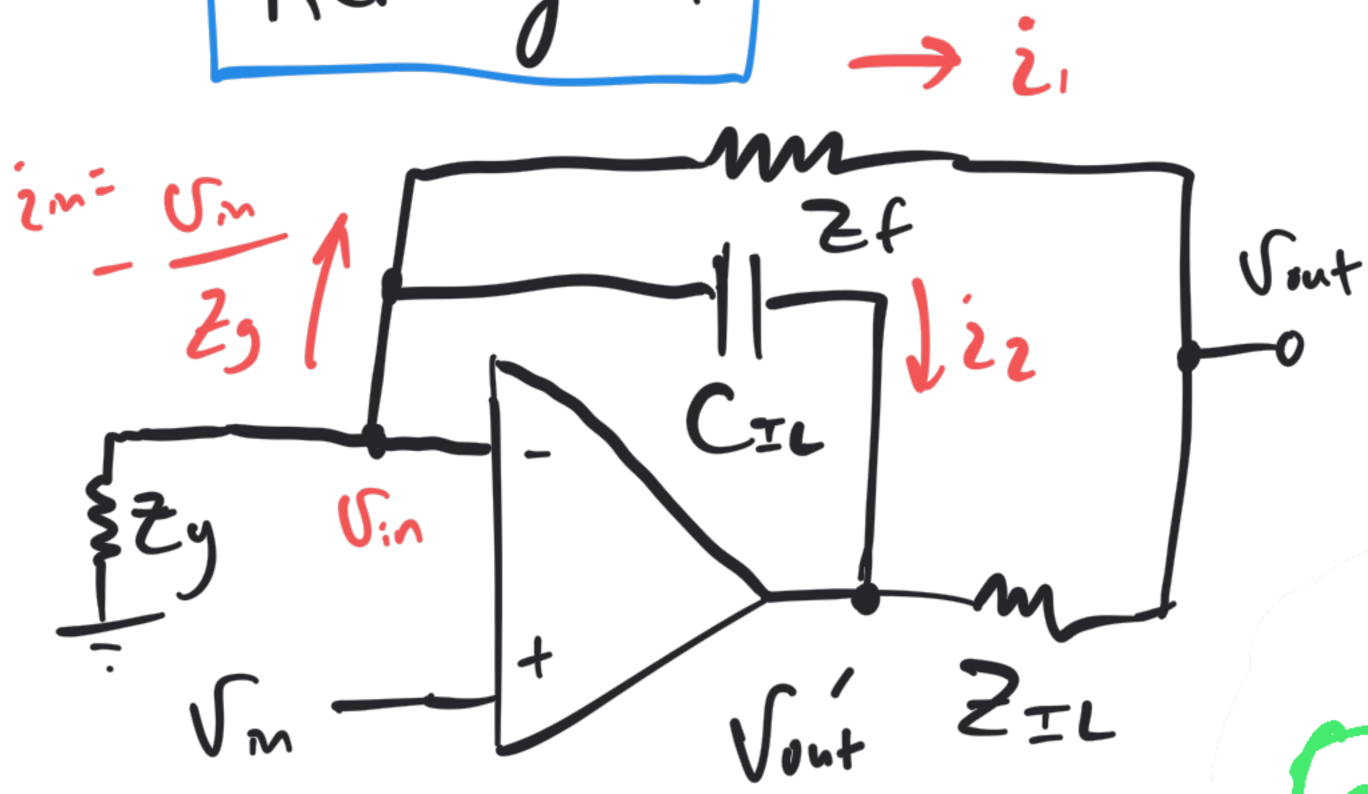
Disadvantages: Increases noise...

I'm guessing this also "messes with" input impedance (i.e. lowers it)

Remedy 4

Split feedback (sometimes called "in-the-loop" compensation method)

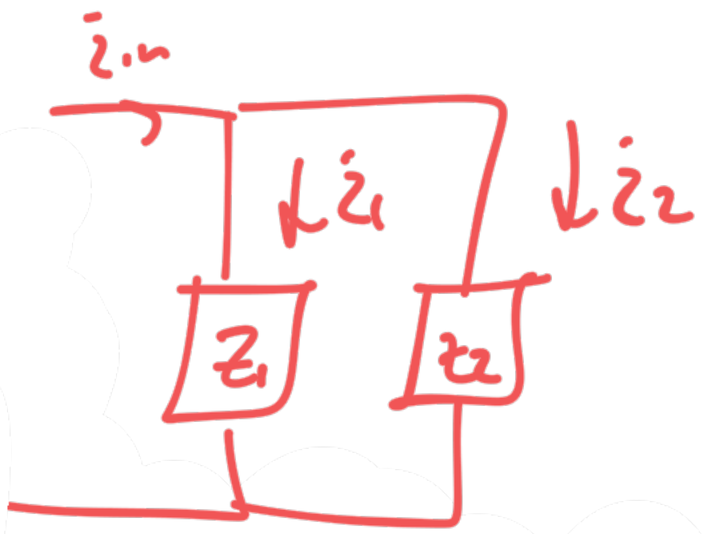
See "Ask the application engineer - 32"



ideal op amp:

① $i_1 = i_{in}\left(\dfrac{\frac{1}{sC_{IL}}}{\frac{1}{sC_{IL}} + Z_f + Z_{IL}}\right)$

recall:



$i_1 = i_{in}\dfrac{Z_2}{Z_1 + Z_2}$

② $i_1 = \dfrac{v_{in} - v_{out}}{Z_f}$

First, find closed loop gain:

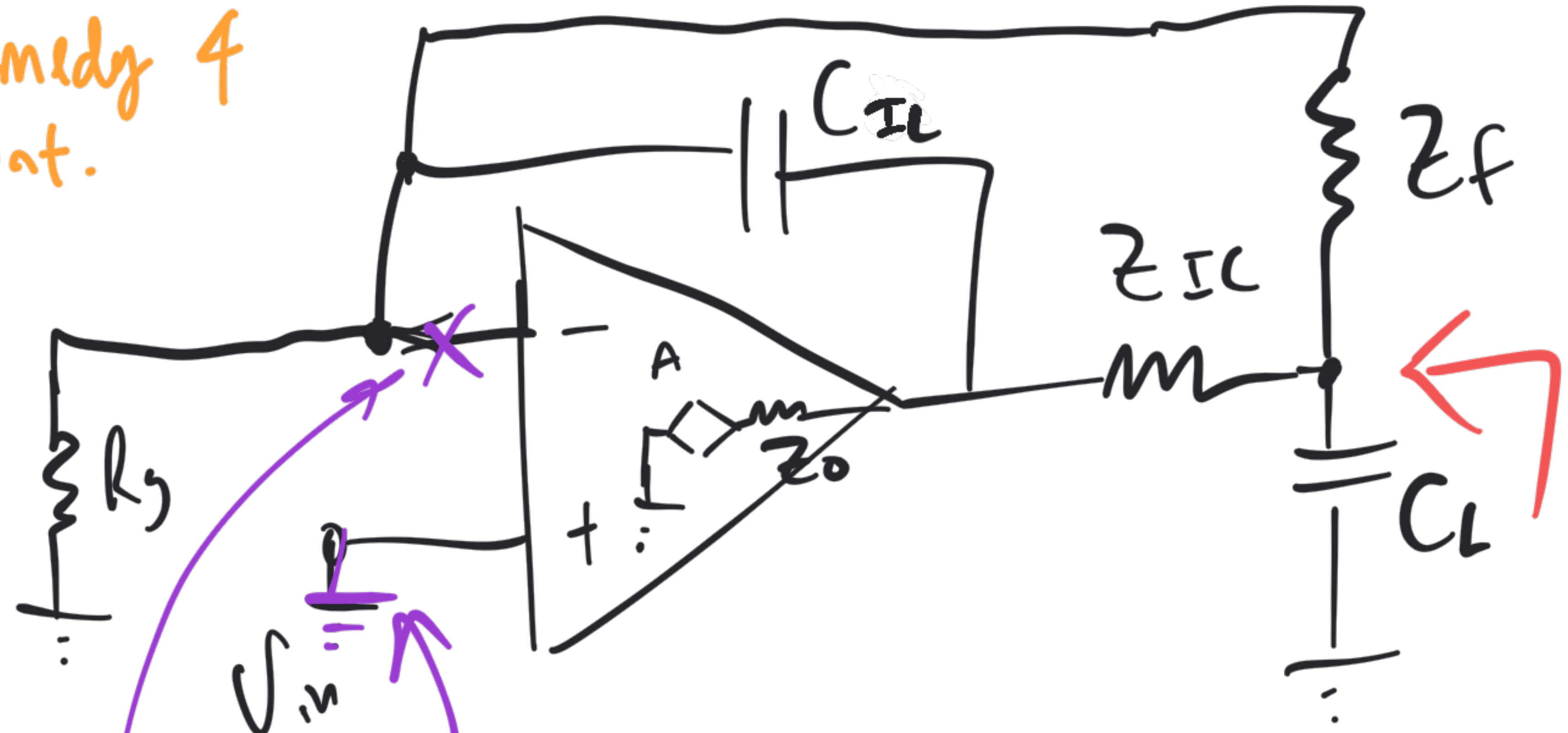
$$\therefore \frac{v_{in} - v_{out}}{Z_f} = -\frac{v_{in}}{Z_g}\left(\frac{1}{1 + sC_{IL}(Z_f + Z_{IL})}\right)$$

$$v_{out} = v_{in} + \frac{Z_f}{Z_g} v_{in}\left(\frac{1}{1 + sC_{IL}(Z_f + Z_{IL})}\right)$$

$$\frac{v_{out}}{v_{in}} = 1 + \frac{Z_f}{Z_g}\left(\frac{1}{1 + sC_{IL}(Z_f + Z_{IL})}\right)$$

if $Z_f \gg Z_{IL}$ then closed loop BW $= \dfrac{1}{2\pi C_f Z_f}$

Remedy 4 cont.



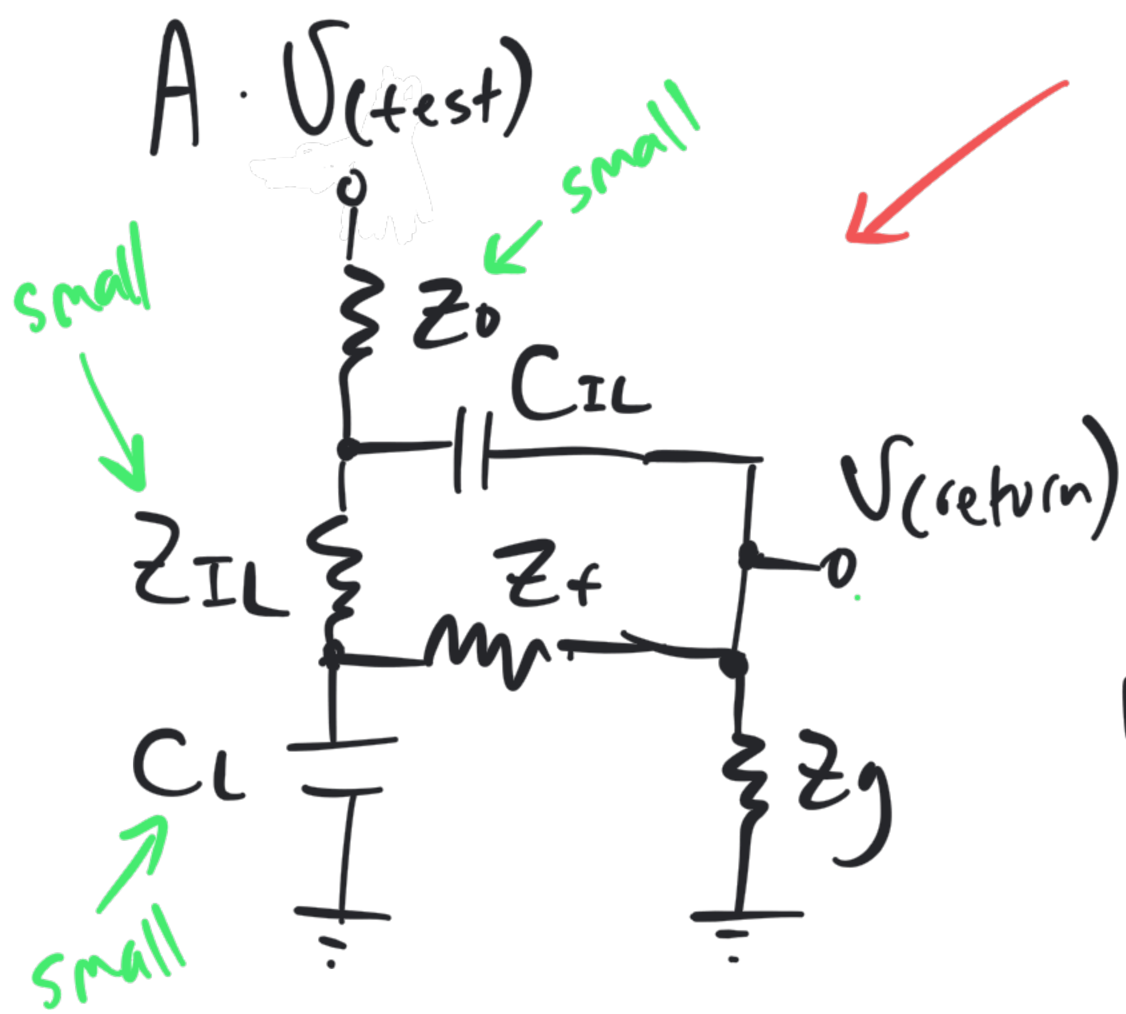
at low frequencies:
$C_{IL} \simeq$ open

$Z_n \simeq 0$
since Z_{IL} is in-the-loop!
(this is desired)...

Calculate $A\beta$:
Break the loop!
and set $V_{in} = 0V$

Two caps separated by resistors (pole-splitting)
means we have two poles!

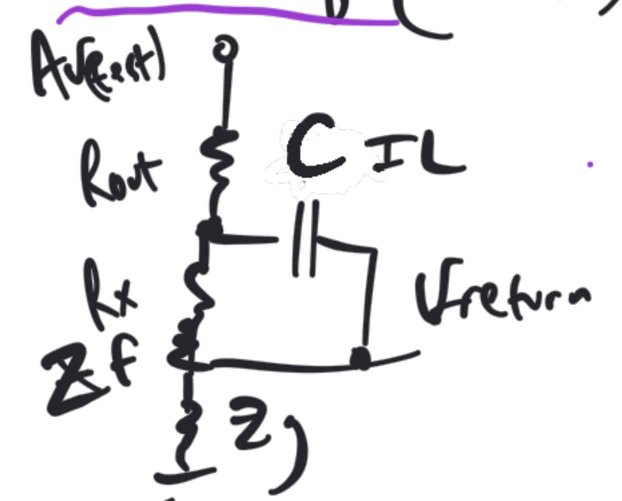
C_L & C_{IL} = open (low f)
short (high f)



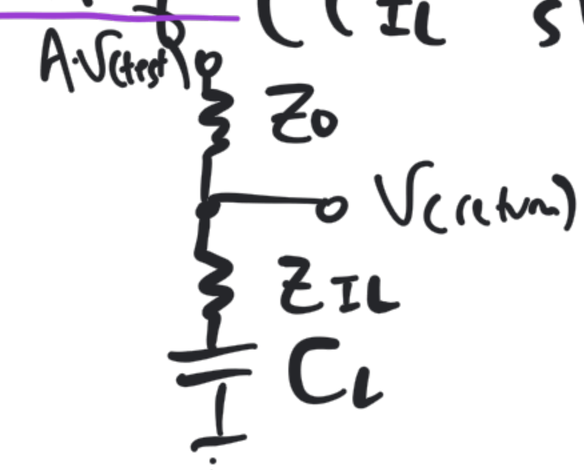
design: $C_{IL} >> C_L$
$Z_{IL} << Z_f$
$Z_o << Z_g$

can find sets of 2 poles and 2 zeros to equate to cancel them out!

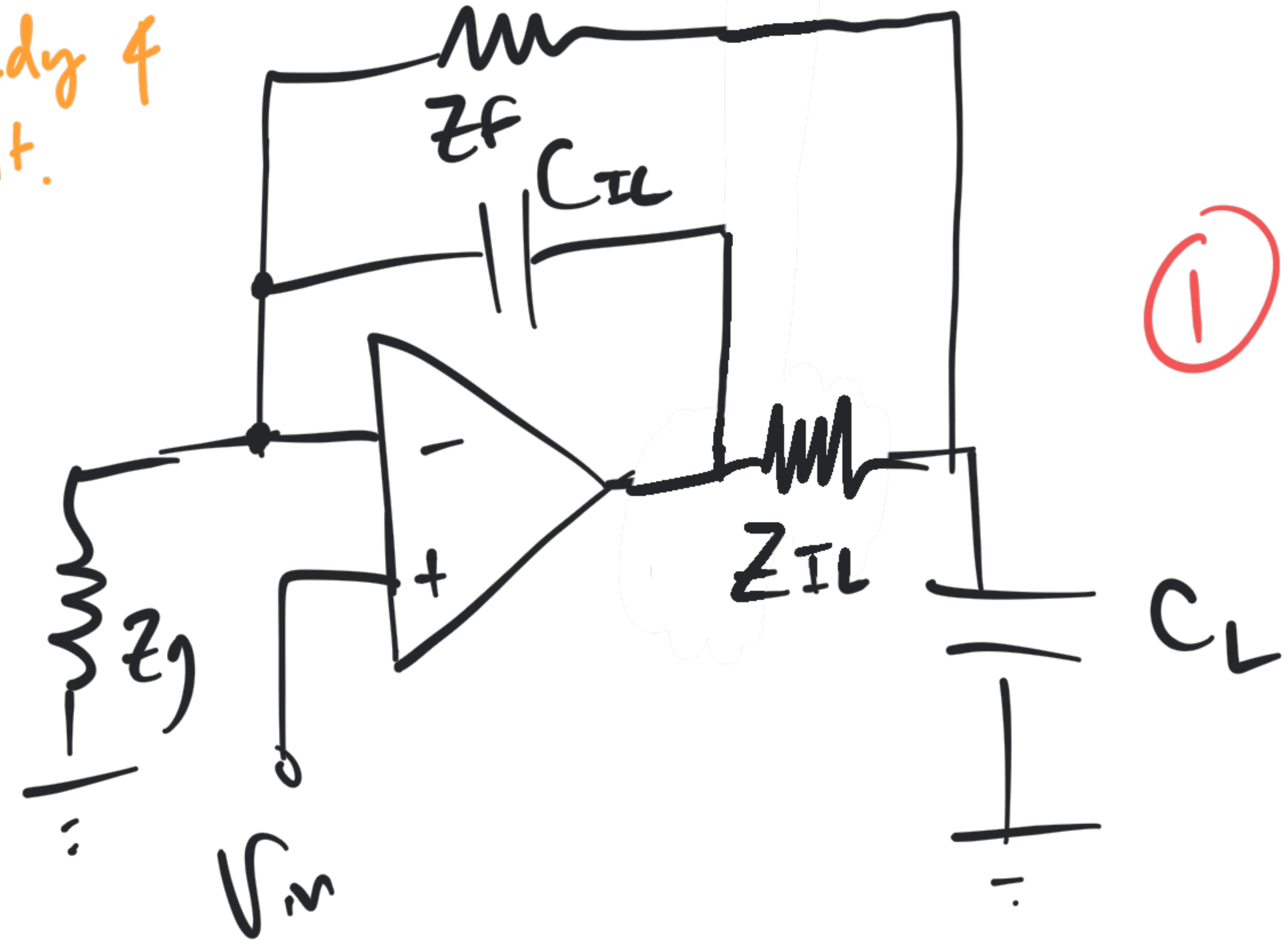
Lowish freq (C_L open)



Highish freq (C_{IL} shorted)



Remedy 4 cont.

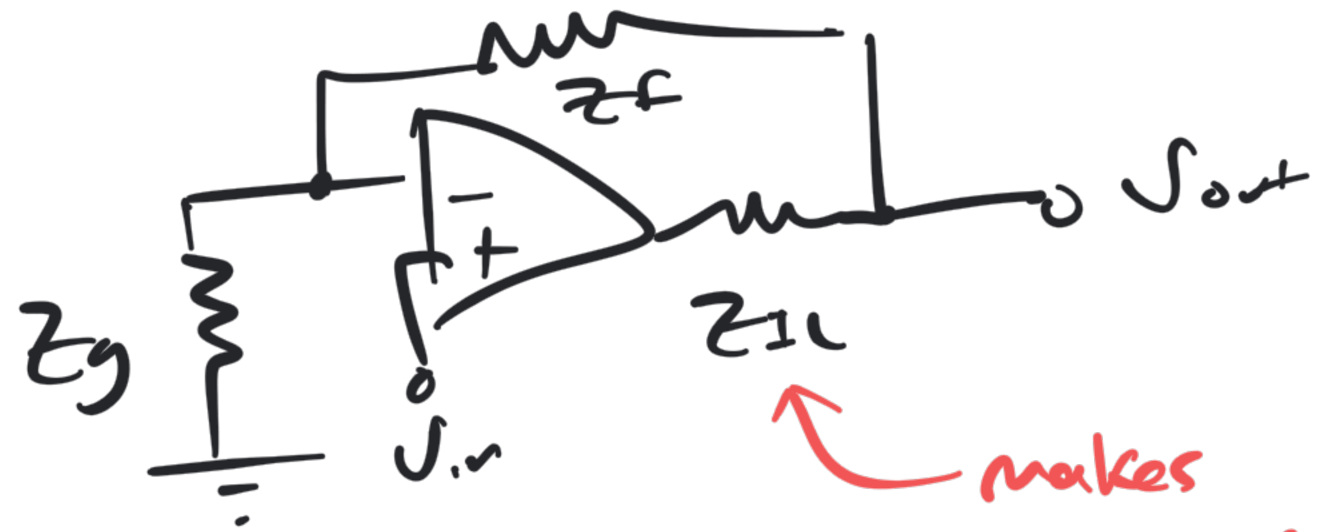


Another way to look @ problem

① At low frequencies:

$C_{IL} \simeq$ open

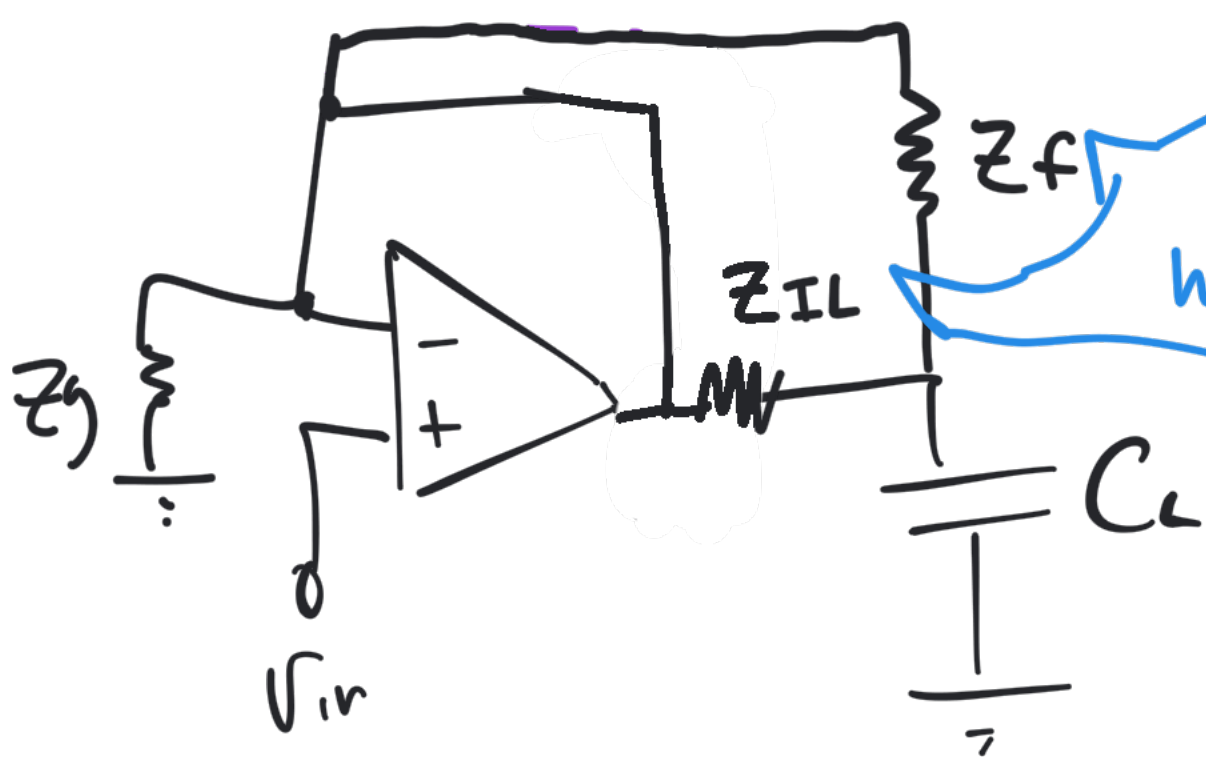
$C_L \simeq$ open ← don't need to worry about (i.e. phase shift due to $(Z_{IL}+Z_o)C_L$ is small)



makes no difference (since it's in the loop!)

② At mid-frequencies: $C_{IL} \simeq$ short

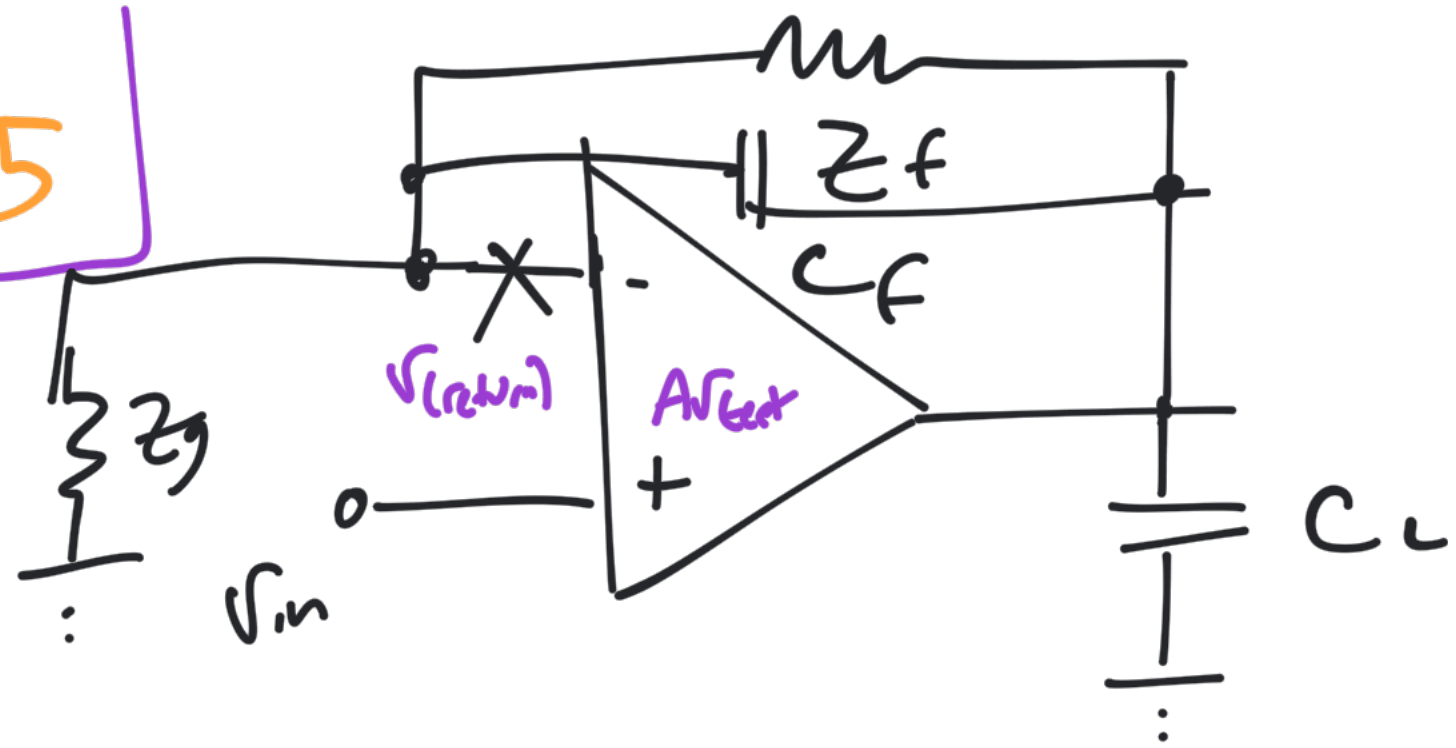
$C_L \simeq$ open-ish ← still not a big deal... i.e. phase shift due to $(Z_{IL}+Z_o)C_L$ is still small



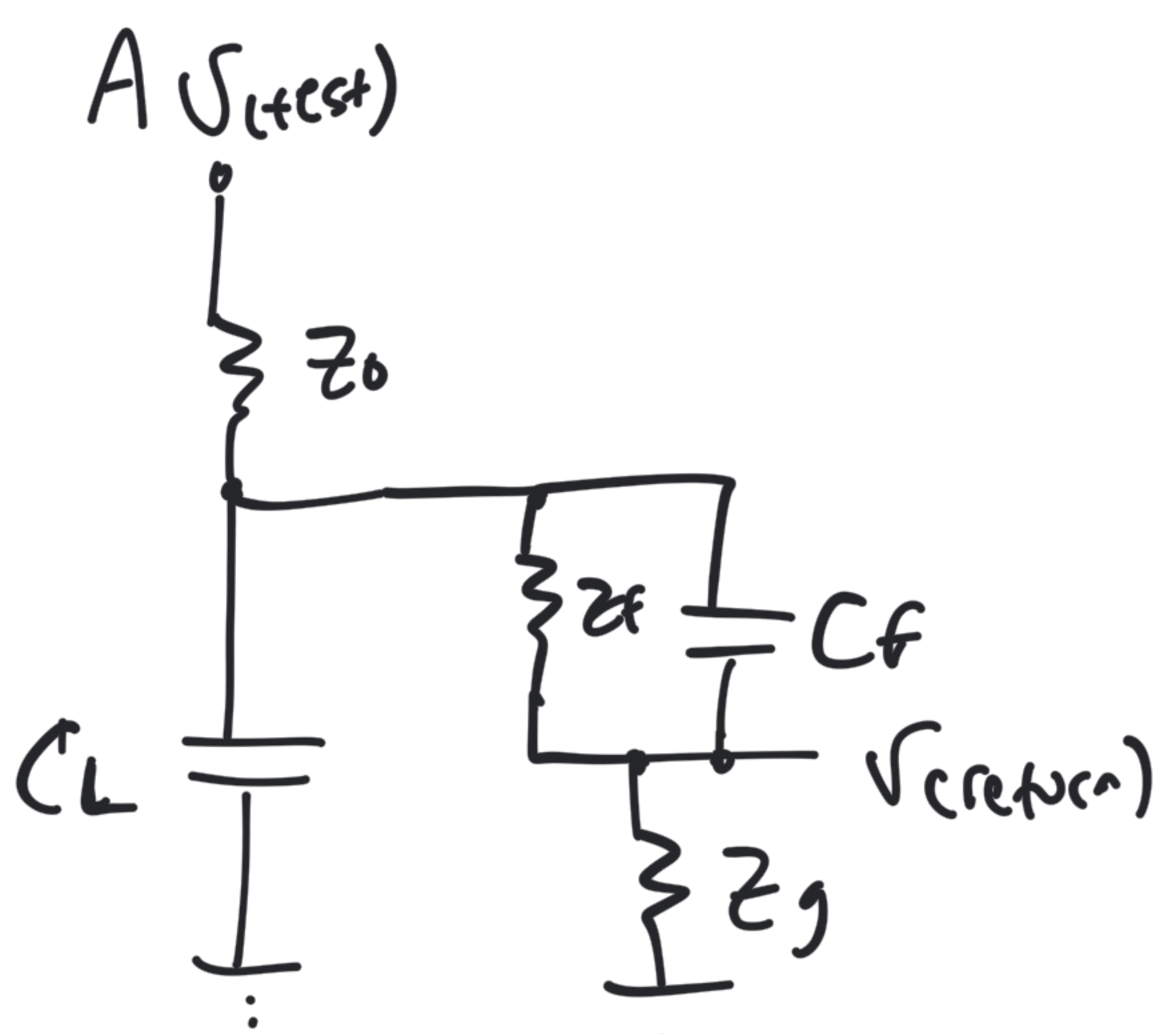
hi, we are here to stop you from creating oscillations!

Ah, shucks!

(possible) Remedy 5



Aβ calculation:



$$V_{(return)} = A V_{(test)} \cdot \frac{C_L \| (C_f \| Z_f + Z_g)}{C_L \| (C_f \| Z_f + Z_g) + Z_o} \cdot \frac{Z_g}{Z_g + Z_f \| C_f}$$

To much algebra for me...
if I use previous approx:

pole: $\frac{1}{2\pi Z_o C_L}$, $\frac{1}{2\pi (Z_f \| Z_g) C_f}$ ← make large

Bad

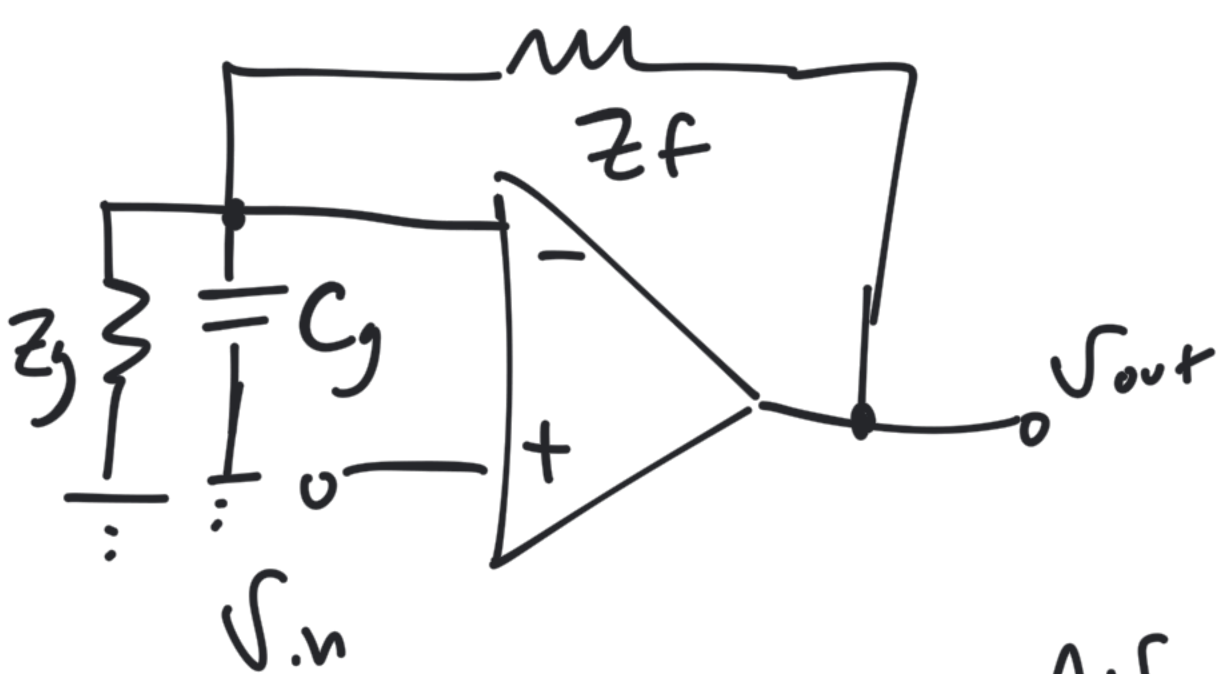
zeros: ∞, $\frac{1}{2\pi Z_f C_f}$

larger freq

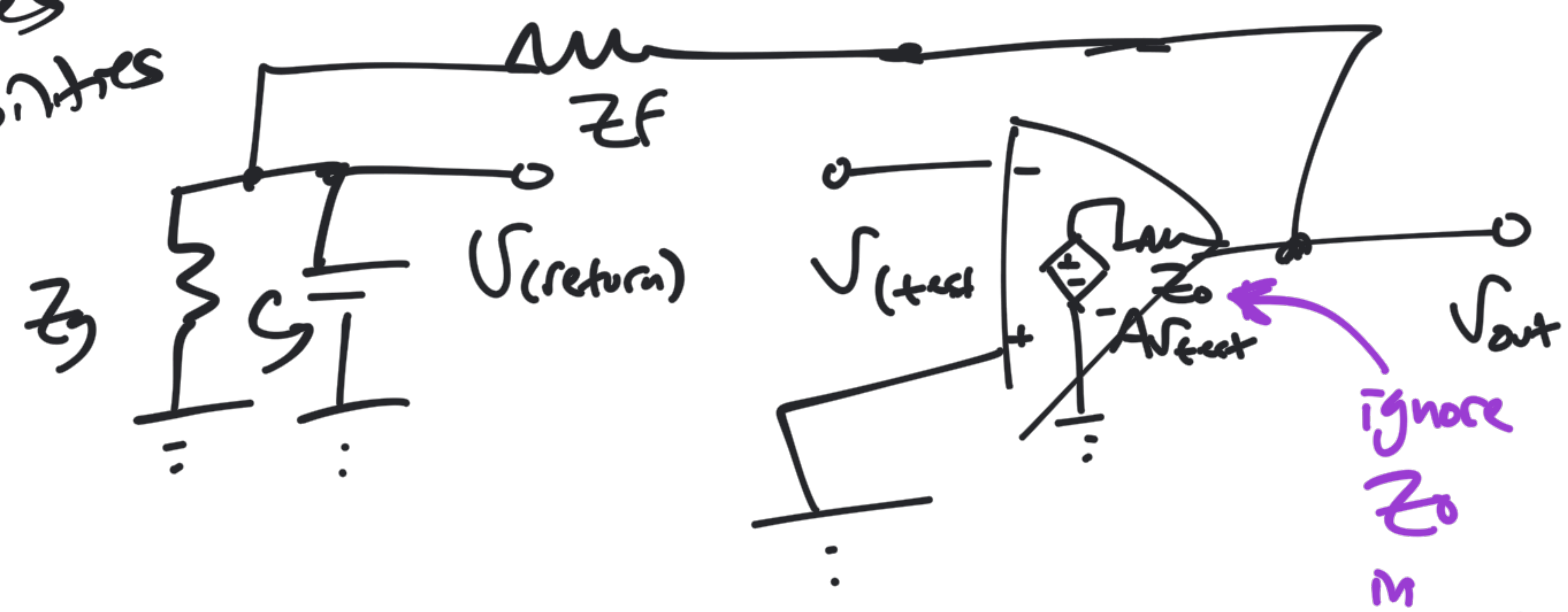
smaller freq

cancel out pole maybe?

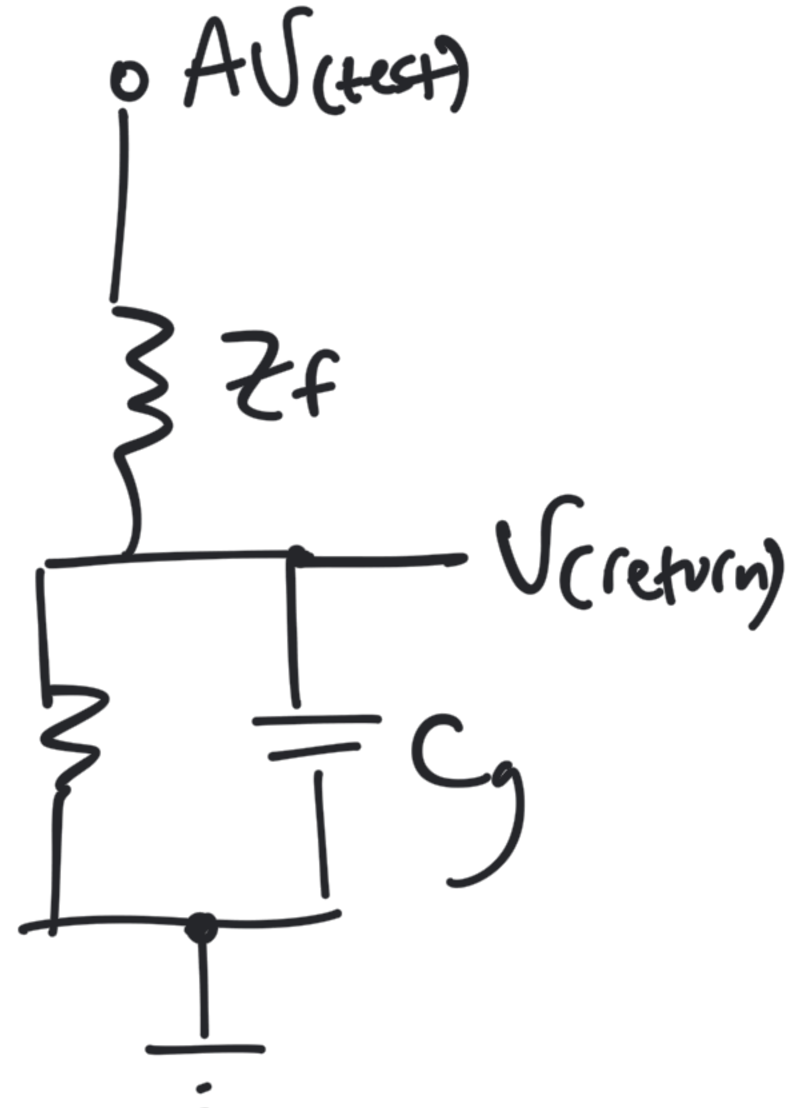
$\boxed{\text{input capacitance:}}$ ← also causes instabilities



find $A\beta$:



ignore Z_o in calculation (assume $Z_f \gg Z_o$)



$$Z_g = R_g \| C_g = \frac{\frac{R_g}{sC_g}}{R_g + \frac{1}{sC_g}} = \frac{R_g}{1 + sC_gR_g}$$

$$\frac{V_{(return)}}{V_{(test)}} = A\frac{Z_g}{Z_g + Z_f}$$

$$= A\frac{R_g}{R_g + Z_f(1 + sC_gR_g)}$$

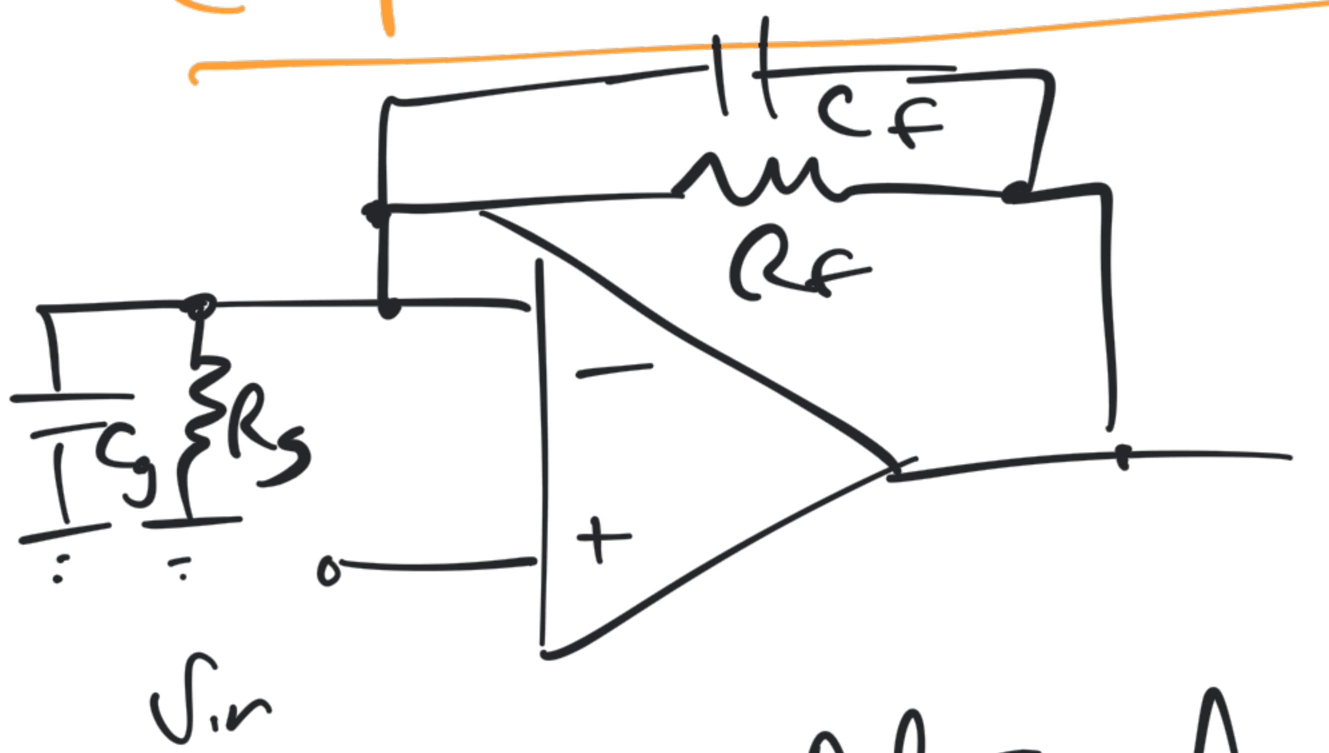
can add instability!

$$= A\frac{R_g}{(R_g + Z_f) + sC_gR_gZ_f}$$

pole @ $\frac{1}{(R_g \| R_f)C_f}$

$$= A\frac{R_g}{R_g + Z_f} \cdot \left(\frac{1}{1 + (R_g \| R_f)sC_f}\right)$$

Compensation method for input capacitance



$$Z_f = \frac{\frac{R_f}{sC_fR_f}}{R_f + \frac{1}{sC_fR_f}} = \frac{R_f}{sC_fR_f + 1}$$

$$Z_g = \frac{R_g}{sC_gR_g + 1}$$

From previous figure

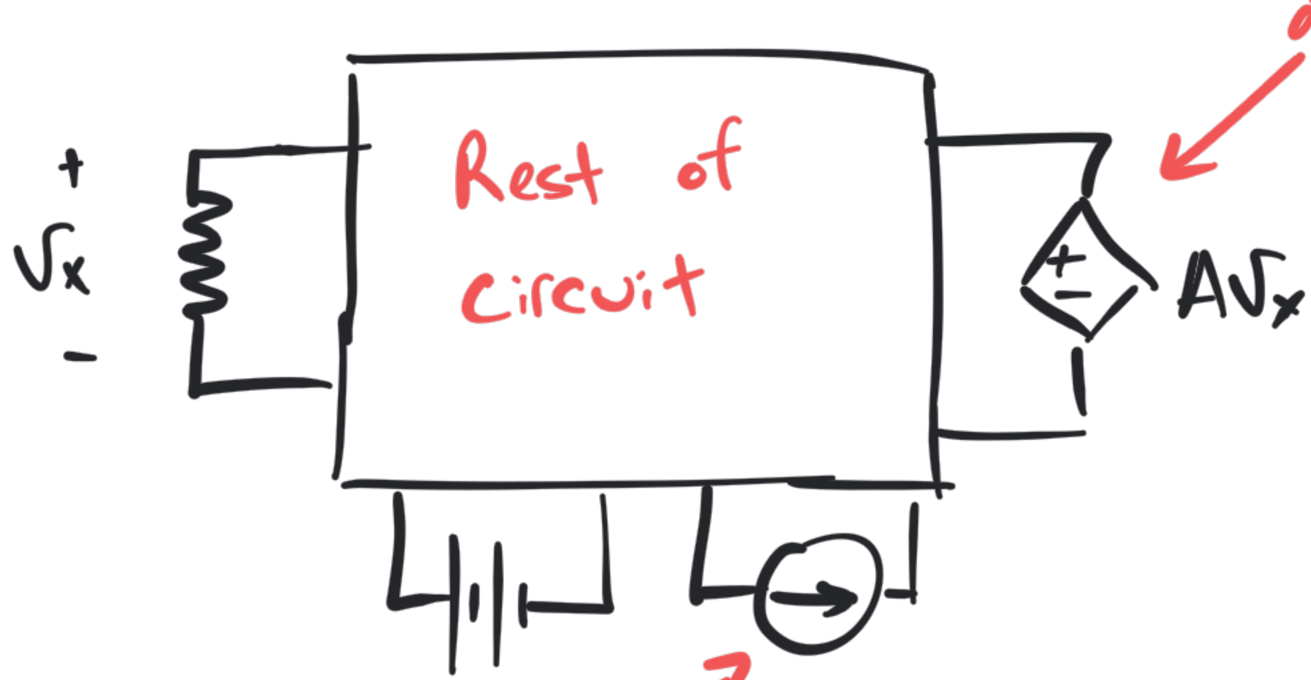
$$A\beta = A\frac{Z_g}{Z_f + Z_g}$$

$$= A\left(\frac{\frac{R_g}{sC_gR_g+1}}{\frac{R_g}{sC_gR_g+1} + \frac{R_f}{sC_fR_f+1}}\right)$$

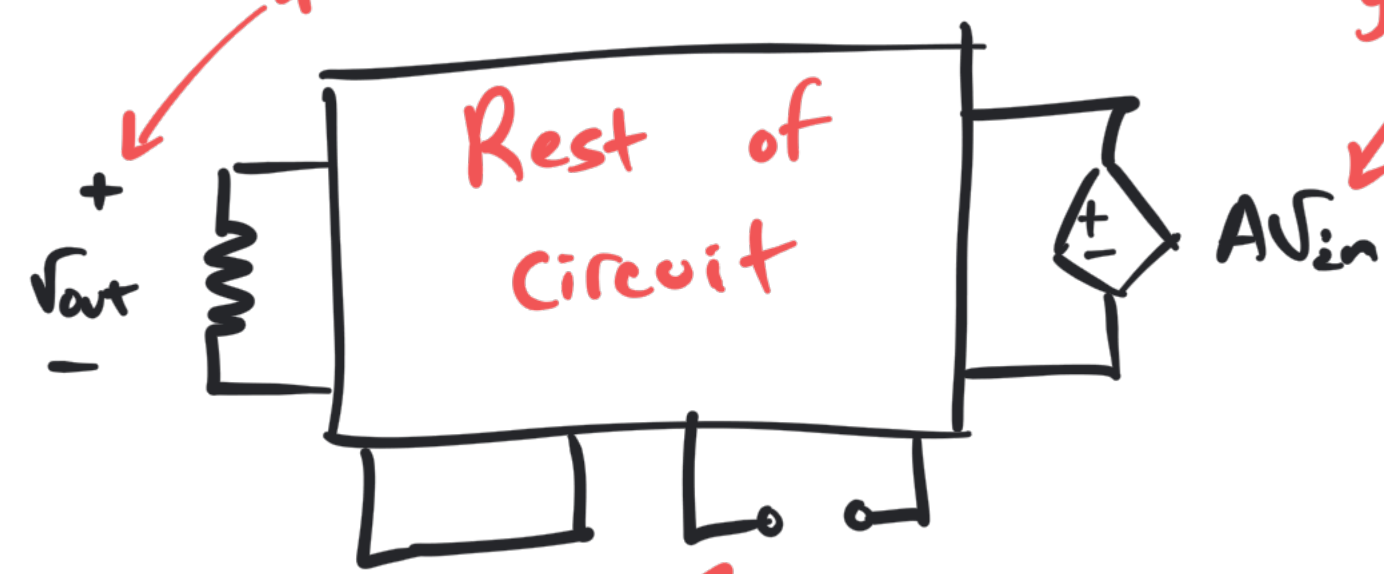
Let $R_gC_g = R_fC_f$: $A\beta = A\dfrac{R_g}{R_g + R_f}$

Cool!

Return ratio: another (related) way to determine stability... works great for sources w/ one dependent source...



Stable?



$$\mathcal{R} = \text{Return ratio} = -\frac{v_{out}}{v_{in}}$$

circuit unstable if: $|\mathcal{R}| \geq 1$

when

$$\angle \mathcal{R} = 180° + n\,360°$$

The general idea

Makes sense:

here $|\mathcal{R}| \geq 1$ when $\angle \mathcal{R} = 180°$

... positive feedback... uncontrolled regeneration!

1 small → 2 Bigger

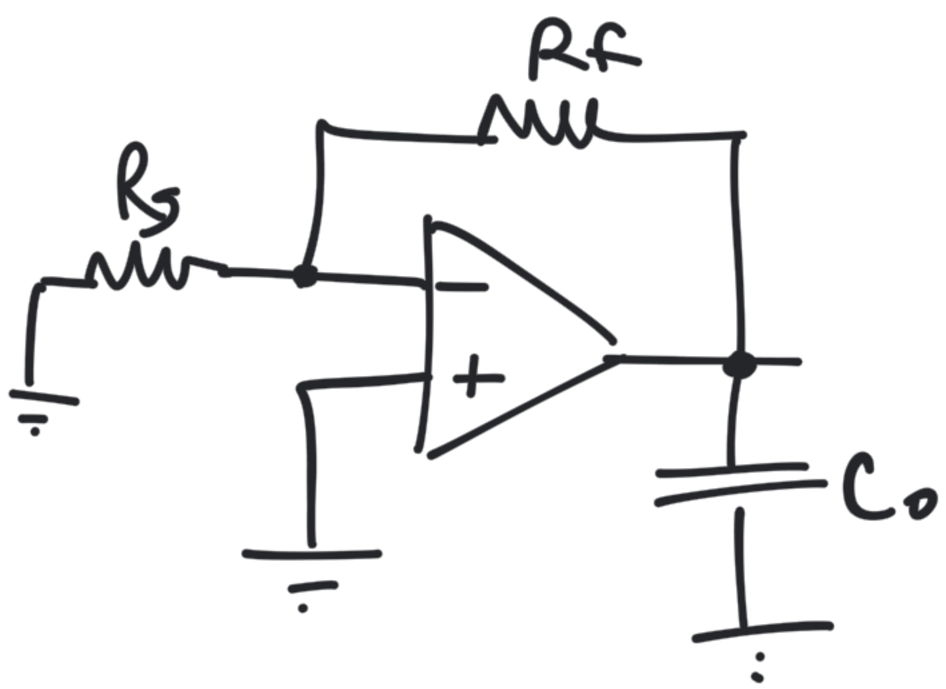
3 Bigger ← 4 Bigger

5 Bigger! ← 6 BIGGER

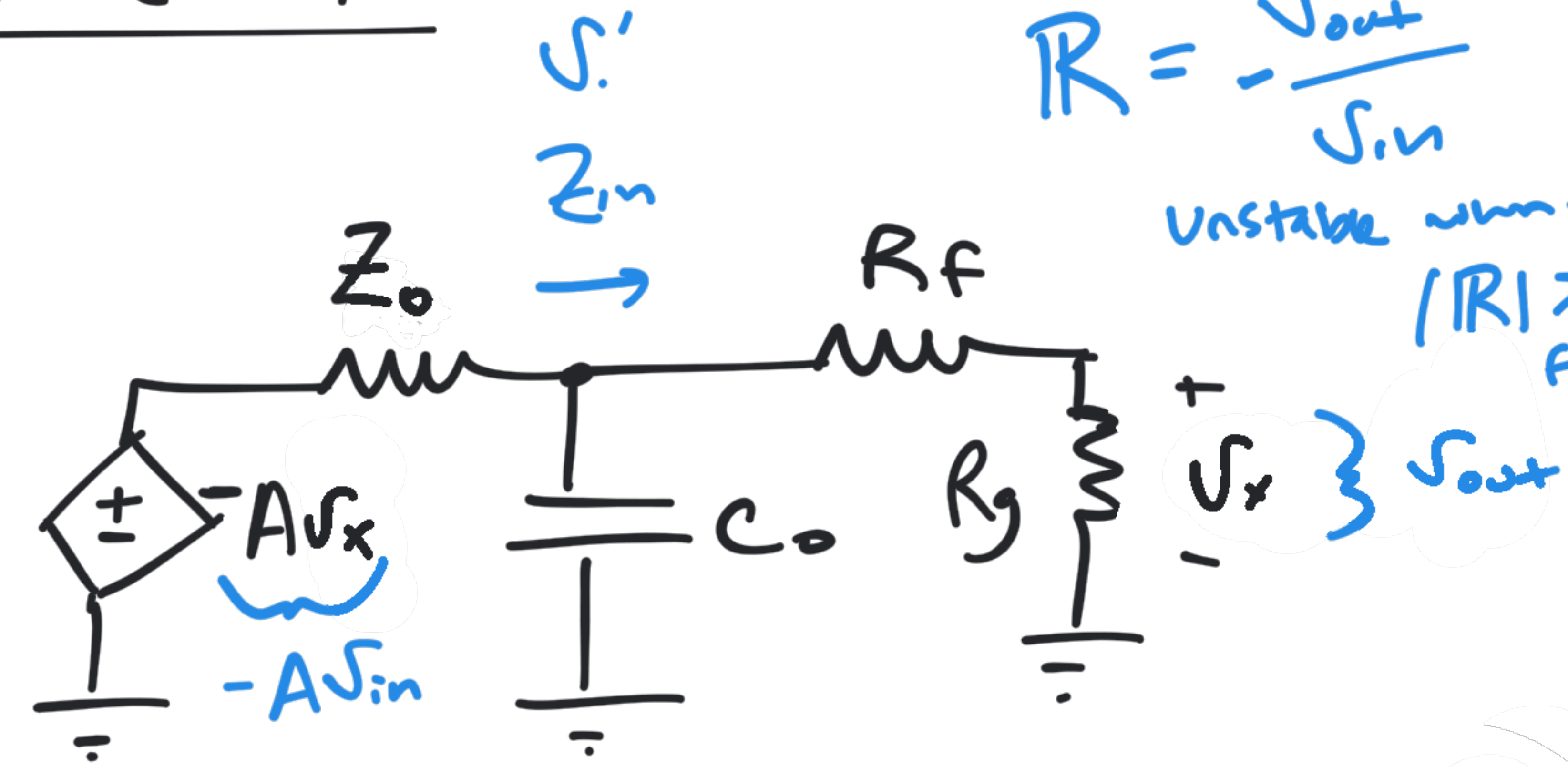
NOTE: in general $\mathcal{R} \neq \beta A$

Good paper: Demystifying Bilateral Feedback analysis by Yun Chiu

Example



Equiv circuit



$$\mathbb{R} = -\frac{v_{out}}{v_{in}}$$

unstable when:
$|\mathbb{R}| > 1$
for $\angle \mathbb{R} = 180° + n360°$

$$Z_{in} = \frac{1}{sC_o} \,\|\, (R_f + R_g) = \frac{R_f + R_g}{1 + sC_o(R_f + R_g)}$$

$$v' = \frac{Z_{in}}{Z_{in} + Z_o}(-Av_{in})$$

$$= \frac{(R_f + R_g)}{(R_f + R_g) + Z_o + sC_oZ_o(R_f + R_g)}(-Av_{in})$$

$$\simeq \frac{1}{1 + sC_oZ_o}$$

$$\frac{v_{out}}{v_{in}} = \frac{v'\left(\frac{R_g}{R_f + R_g}\right)}{v_{in}} = \frac{R_g}{R_f + R_g}\,\frac{-A}{1 + sC_oZ_o}$$

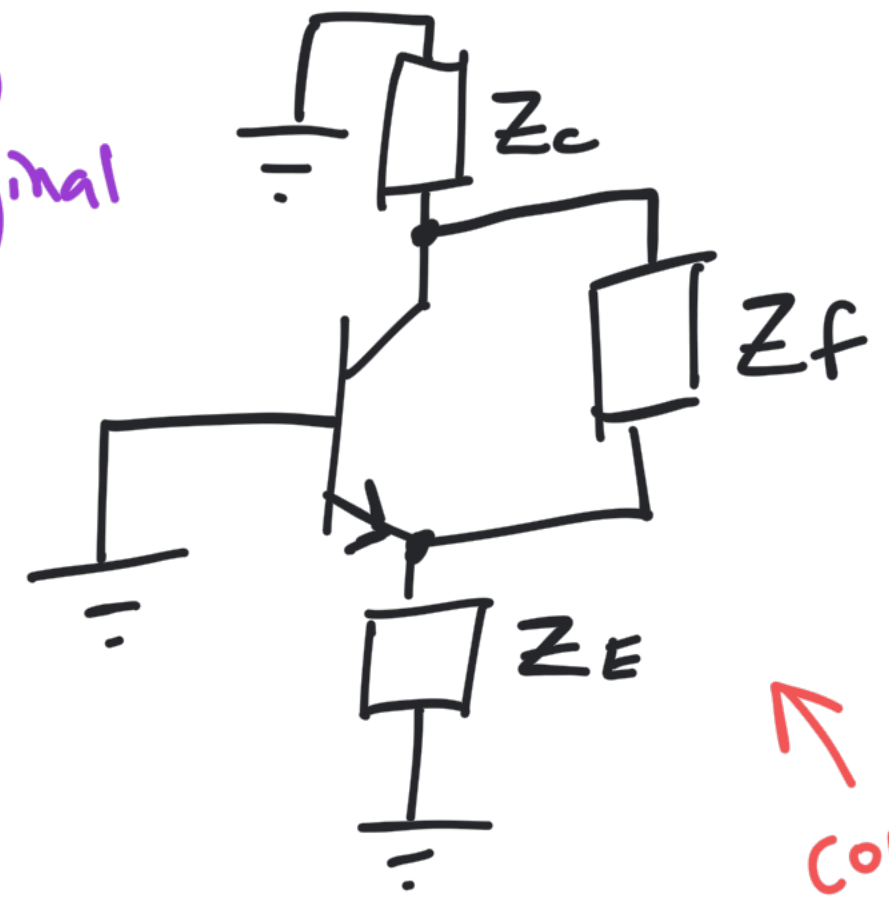
return ratio

$$\mathbb{R} = A\frac{R_g}{R_g + R_f}\,\frac{1}{1 + sC_oZ_o}$$

$$\mathbb{R} = -\frac{v_{out}}{v_{in}}$$

Stability analysis BJT transistor amplifier

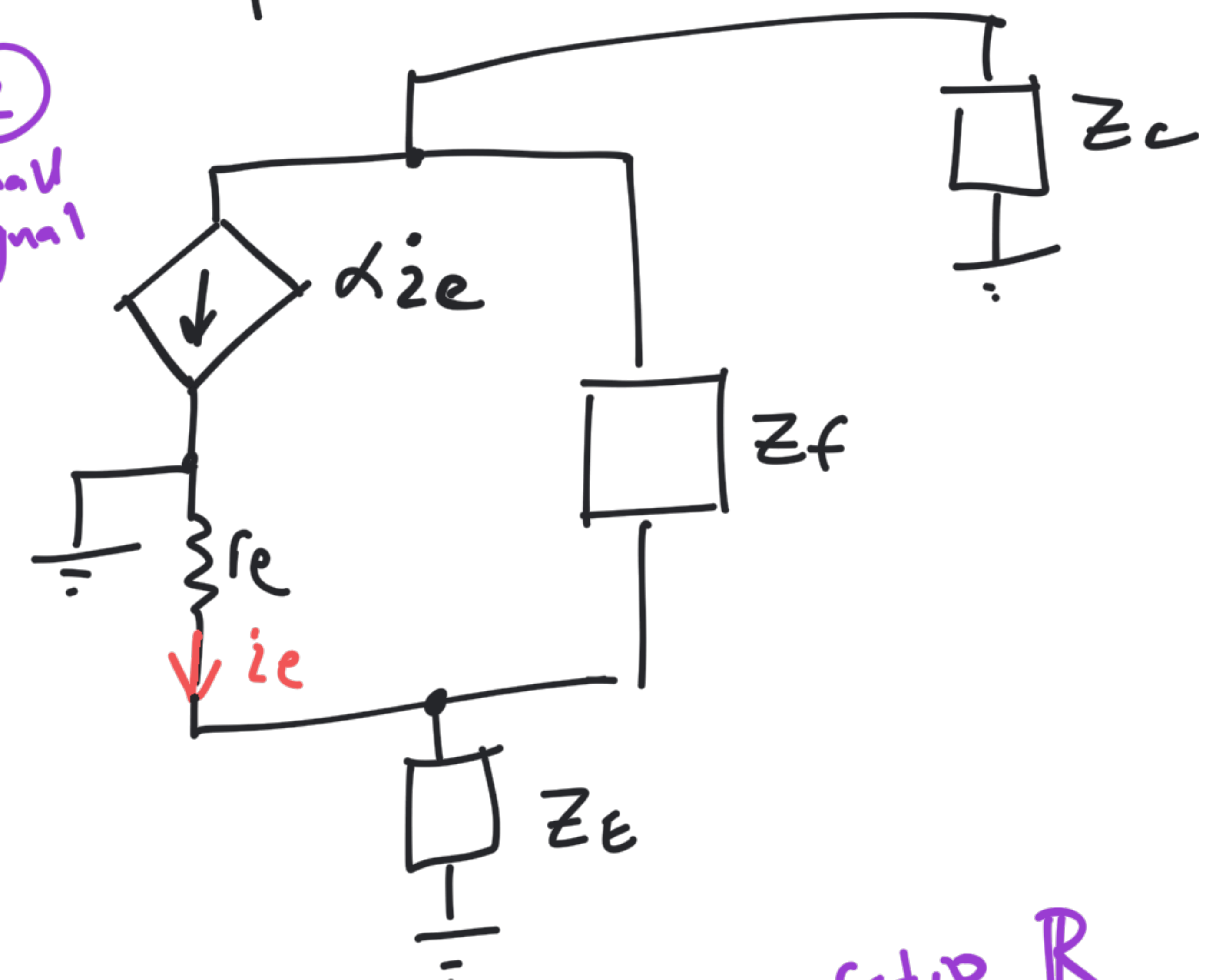
① original



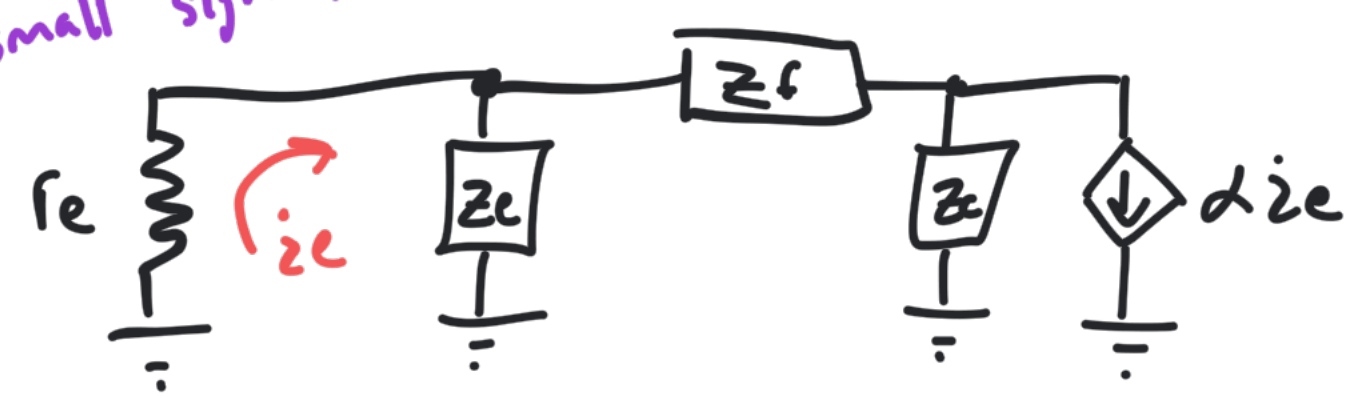
small signal model ⇒

common base configuration

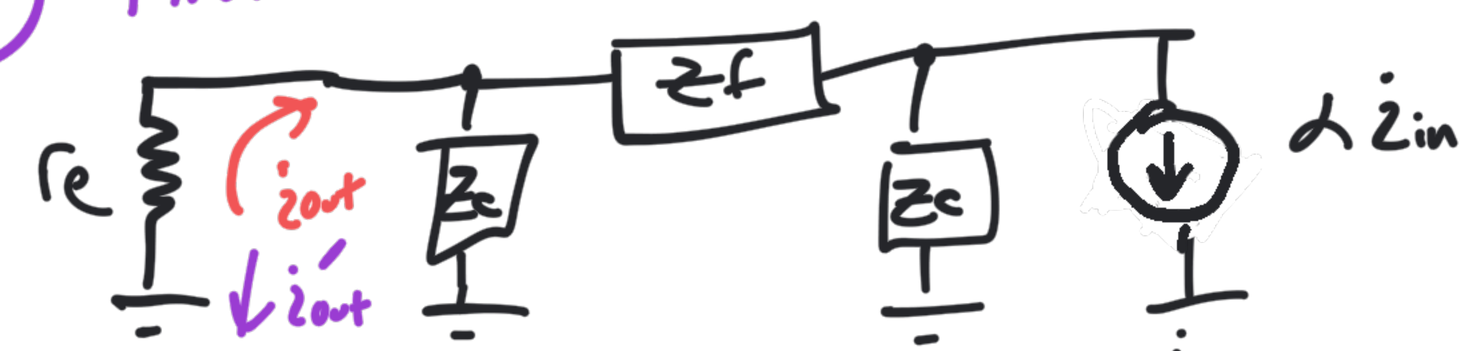
② small signal



③ re-draw small signal



④ Find Return ratio $\mathbb{R}$

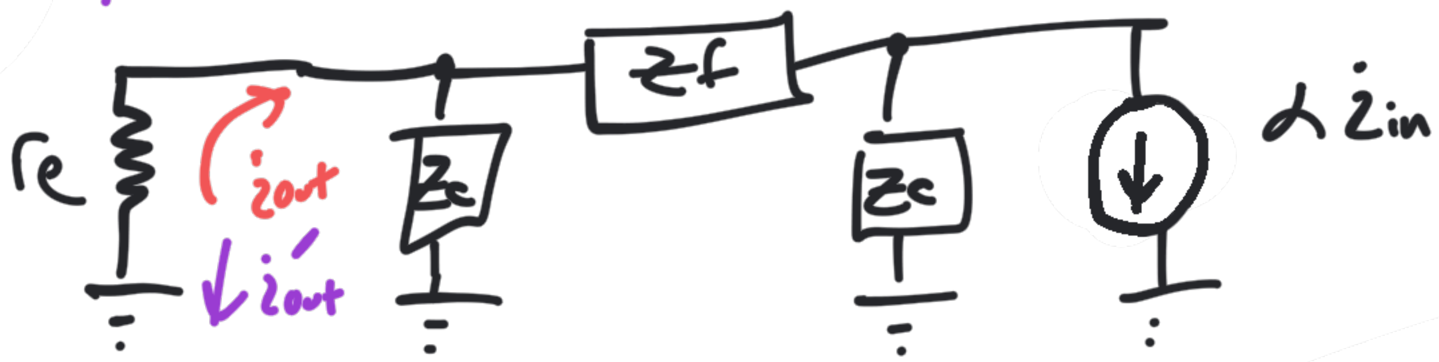


$$\mathbb{R} = -\frac{i_{out}}{i_{in}} = \frac{i_{out}'}{i_{in}}$$

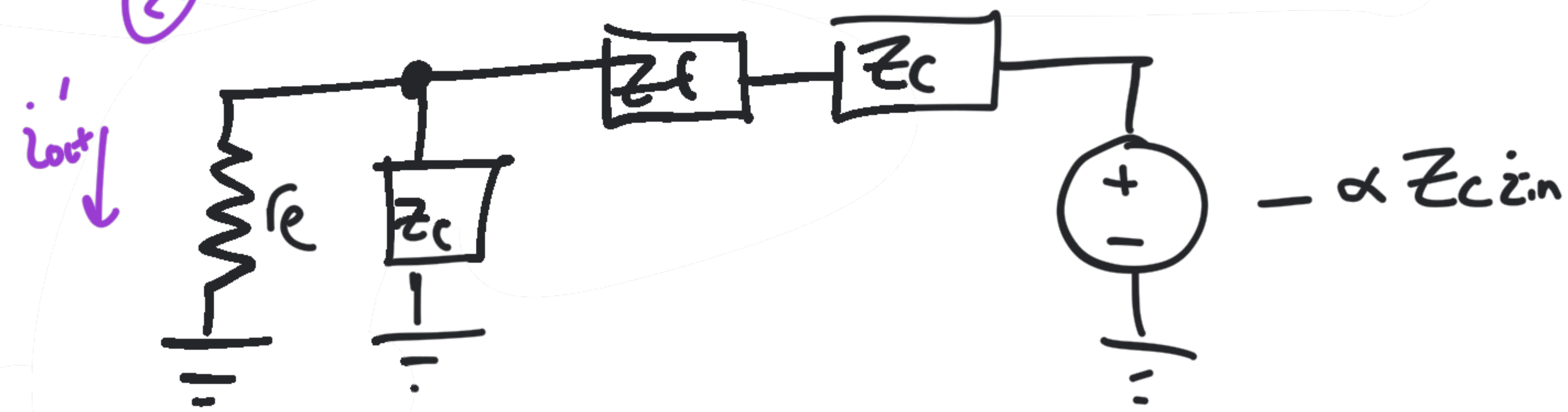
circuit unstable if $|\mathbb{R}| > 1$ when $\angle \mathbb{R} = 180^\circ + n360^\circ$

From previous slide:

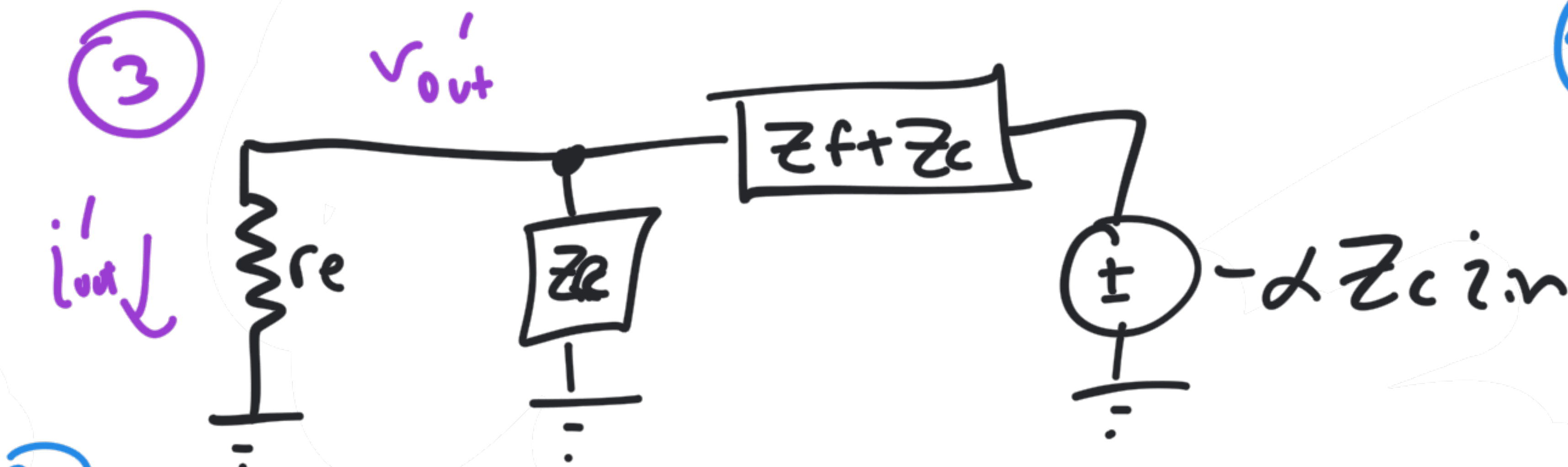
① Find Return ratio R



②



③



④ voltage divider rule:

$$v'_{out} = \frac{r_e \| Z_e}{r_e \| Z_e + Z_f + Z_c}\left(-\alpha Z_c i_{in}\right)$$

⑤

$$i'_{out} = \frac{v'_{out}}{r_e} = \frac{r_e \| Z_e}{r_e \| Z_e + Z_f + Z_c}\left(\frac{-\alpha Z_c i_{in}}{r_e}\right)$$

⑥

$$\boxed{R = \frac{i'_{out}}{i_{in}} = \frac{r_e \| Z_e}{r_e \| Z_e + Z_f + Z_c}\left(\frac{-\alpha Z_c}{r_e}\right)}$$

From previous slide

$$\boxed{\mathbb{R} = \frac{r_e \| Z_e}{r_e \| Z_e + Z_f + Z_c}\left(\frac{-\alpha Z_c}{r_e}\right)}$$

$$\hookrightarrow \mathbb{R} = \left(\frac{\cancel{r_e} Z_e}{r_e + Z_e}\right)\left(\frac{-\alpha Z_c}{\cancel{r_e}}\right)\left(\frac{1}{\frac{r_e Z_e}{r_e + Z_e} + Z_f + Z_c}\right)$$

$$\mathbb{R} = \frac{-\alpha Z_c Z_e}{r_e Z_e + (Z_f + Z_c)(r_e + Z_e)}$$

General Equation →

$$\boxed{\mathbb{R} = \frac{-\alpha Z_c Z_e}{r_e Z_e + Z_f r_e + Z_f Z_e + Z_c r_e + Z_c Z_e}}$$

common base Colpitt's oscillator:

Let $Z_c = j\omega L_c$

$Z_e = \frac{1}{j\omega C_e}$

$Z_f = \frac{1}{j\omega C_f}$

$$\rightarrow \mathbb{R} = \frac{-\alpha \frac{L_c}{C_e}}{\underbrace{r_e\left(\frac{1}{j\omega C_e} + \frac{1}{j\omega C_f} + j\omega L_c\right)}_{\text{imaginary term}} + \left(-\frac{1}{\omega^2 C_e C_f} + \frac{L_c}{C_e}\right)}$$

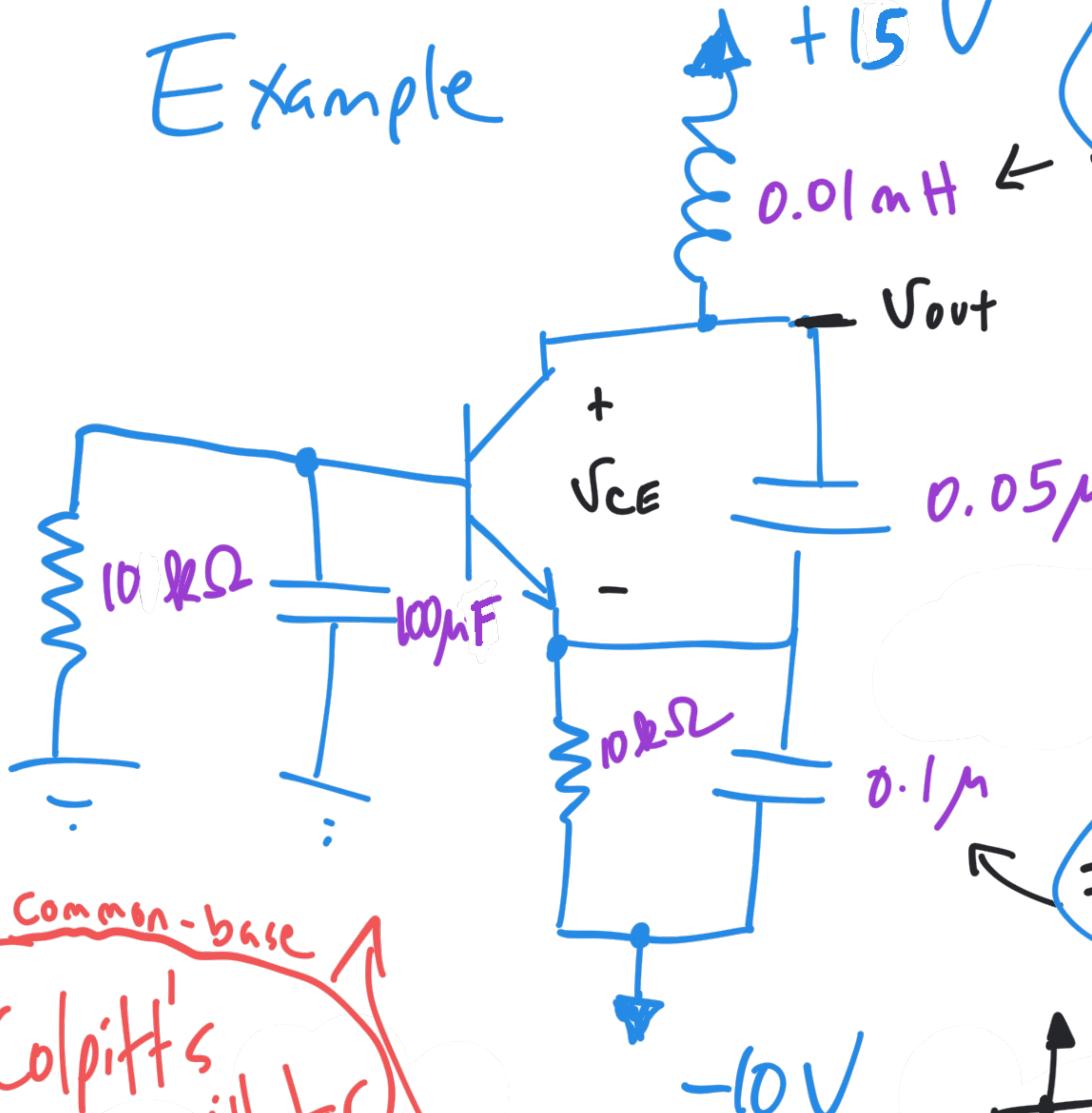
resonance when imaginary term = 0

$$\rightarrow \omega_0 = \frac{1}{\sqrt{L_c \cdot \frac{C_e C_f}{C_e + C_f}}}$$

@ $\omega_0 \rightarrow \mathbb{R} < -1$ for oscillation

$$\rightarrow \frac{C_e}{C_e + C_f} \geq 1 - \alpha$$

Example



$Z_L = j\omega_0 L = j17.32\,\Omega$

$Z_f = -j11.546\,\Omega$

$Z_e = -j5.77\,\Omega$

Bias current:

$$I_E = \frac{10 - 0.7}{10\,k\Omega} = 0.93\,mA$$

$$f_0 \cong 275\ kHz$$

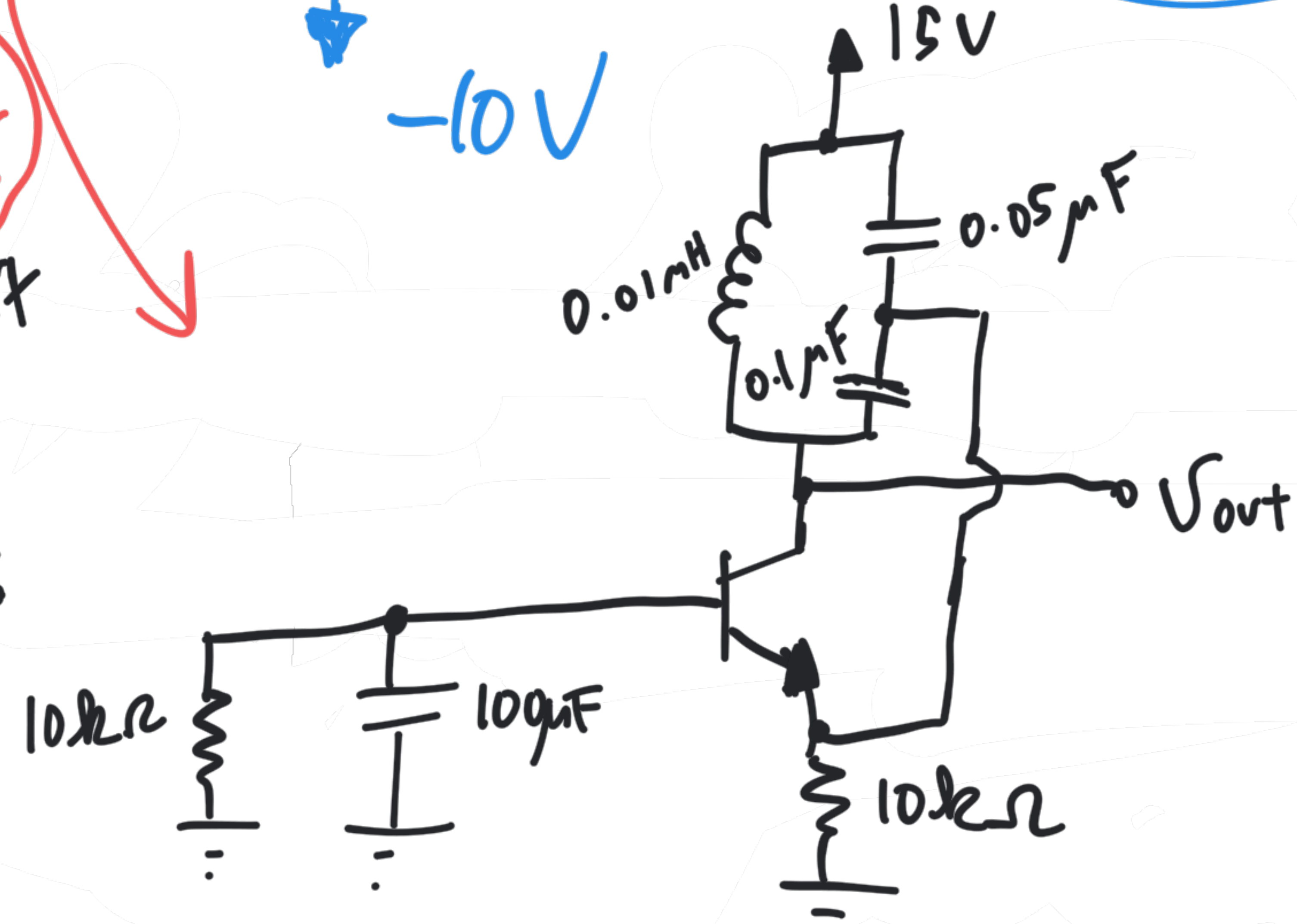
Check:

$$\frac{C_e}{C_e + C_f} = 0.667 \geq \underbrace{1-\alpha}_{=0.1} \quad (\alpha \approx 0.9)$$ ✓

Common-base Colpitt's oscillator

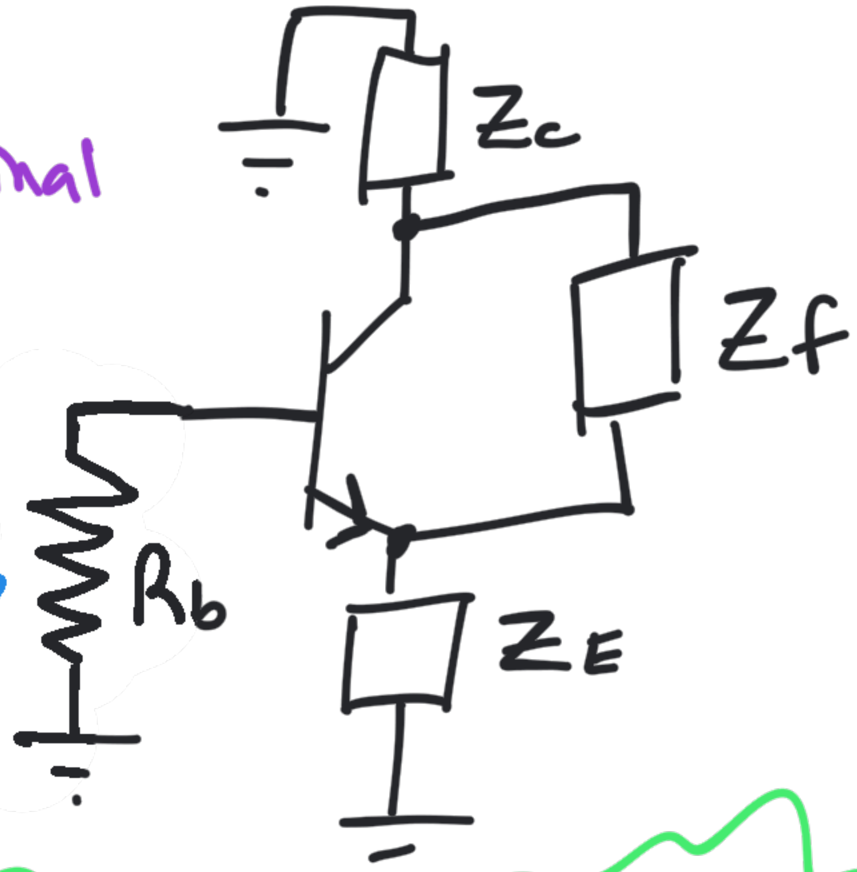
This was checked w/ LTspice

Another circuit w/ small signal equivalent:



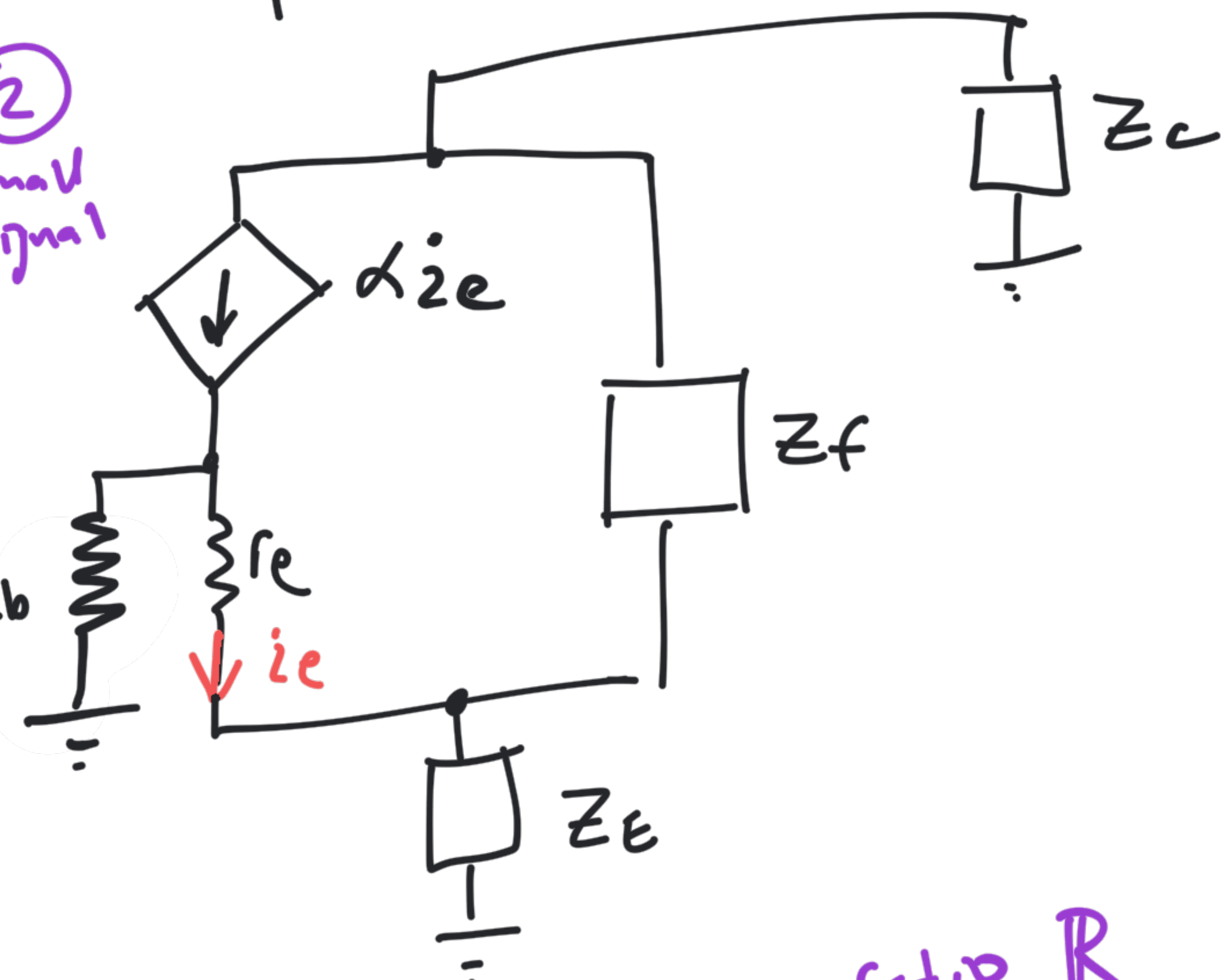
Stability analysis BJT transistor amplifies

① original



small signal model ⟹

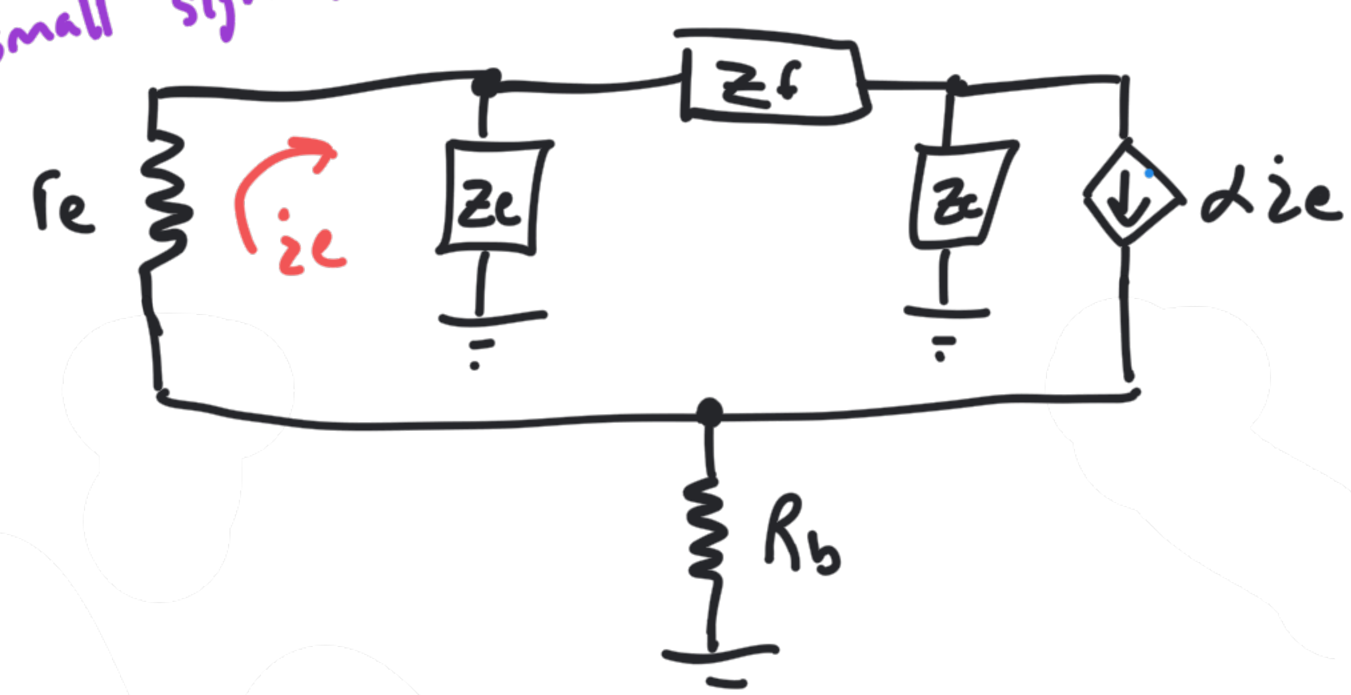
② small signal



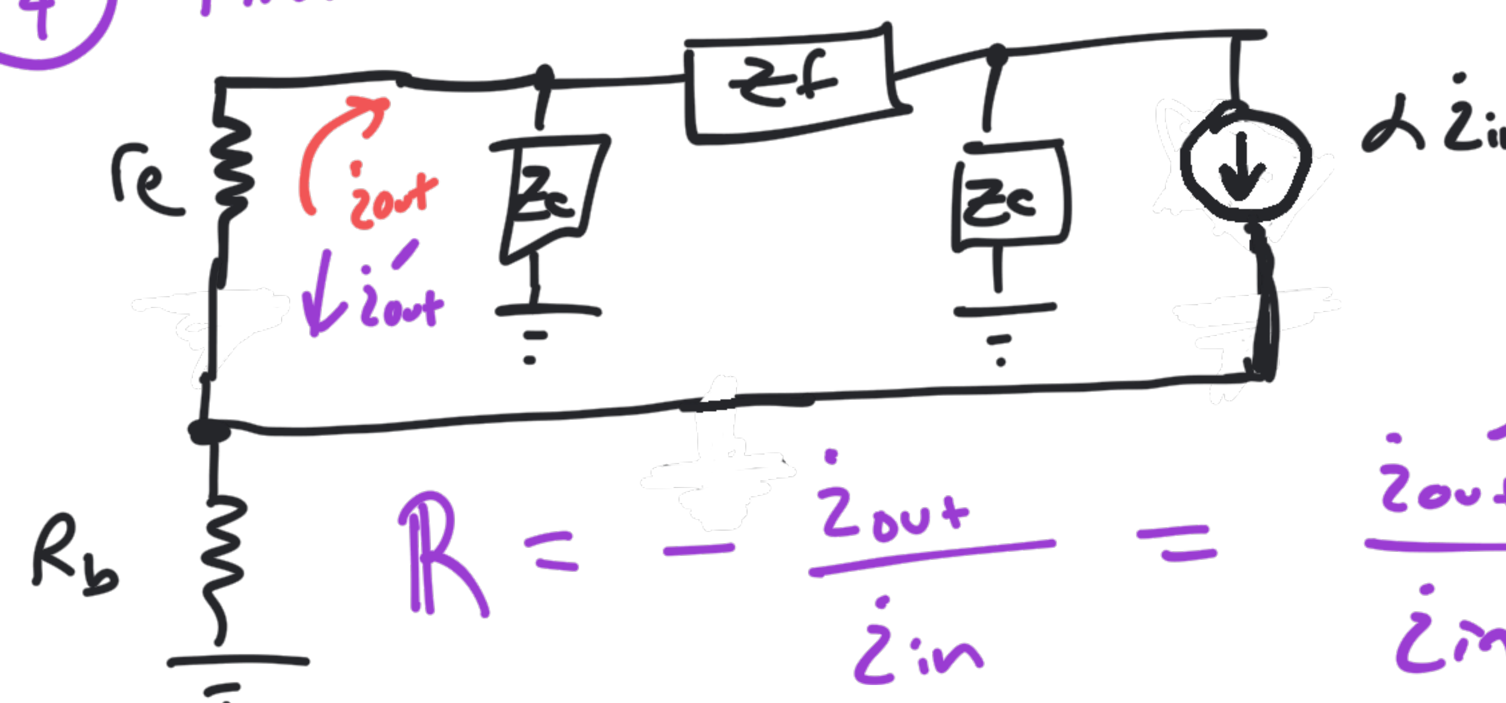
what does Rb do?

This is the new thing here!

③ re-draw small signal



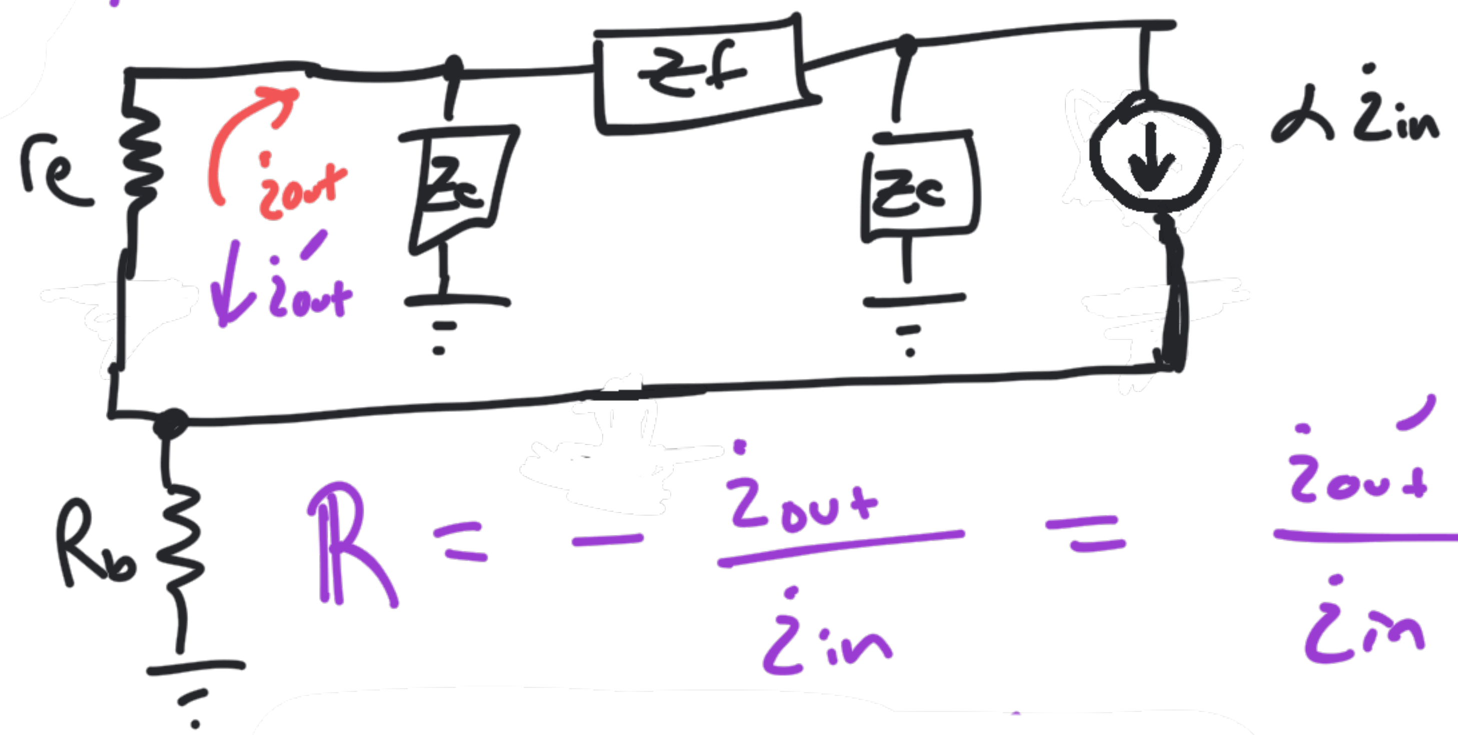
④ Find Return ratio $\mathbb{R}$



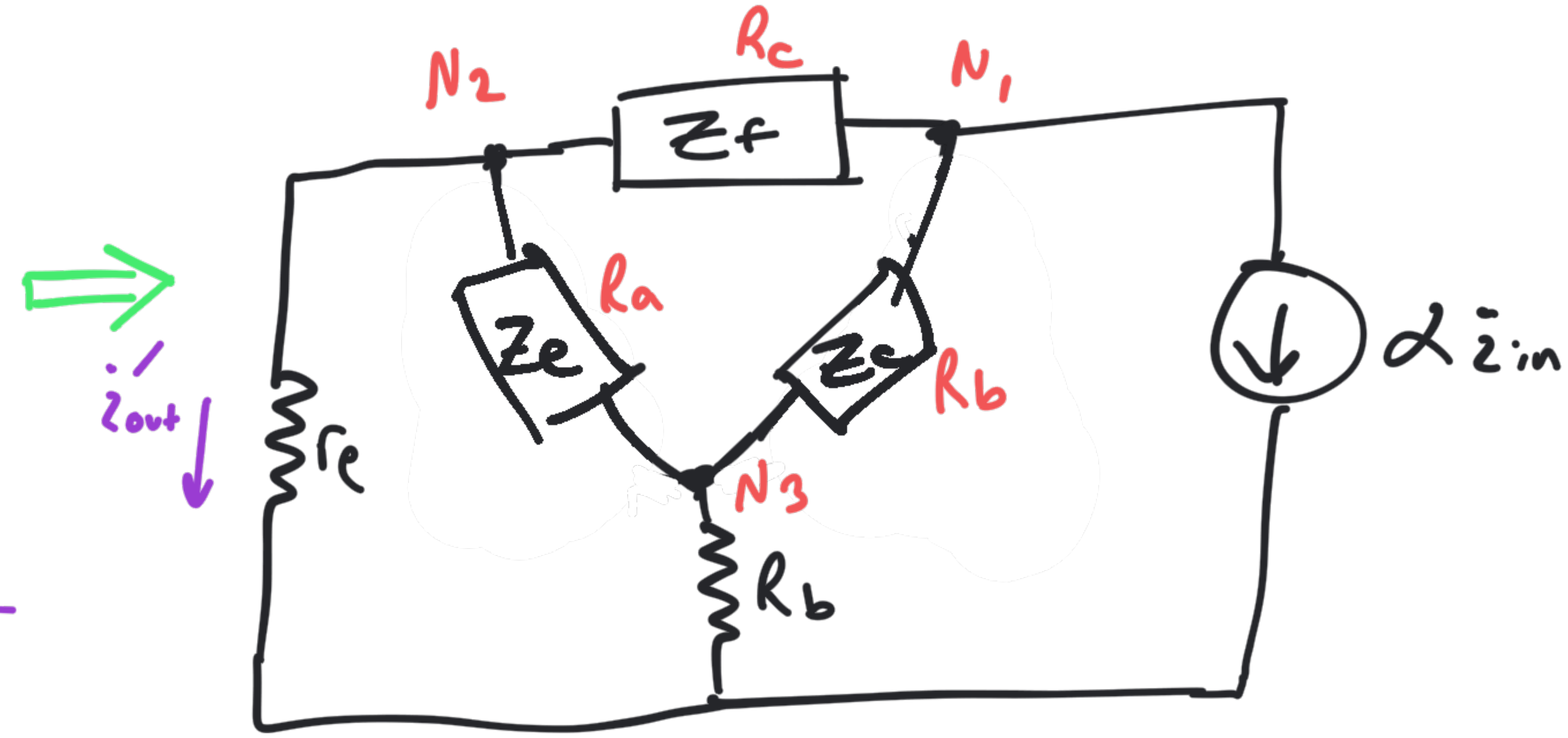
$$\mathbb{R} = -\frac{i_{out}}{i_{in}} = \frac{i_{out}'}{i_{in}}$$

circuit unstable if $|\mathbb{R}| > 1$ when $\angle\mathbb{R} = 180° + n360°$

Find Return ratio $\mathbb{R}$

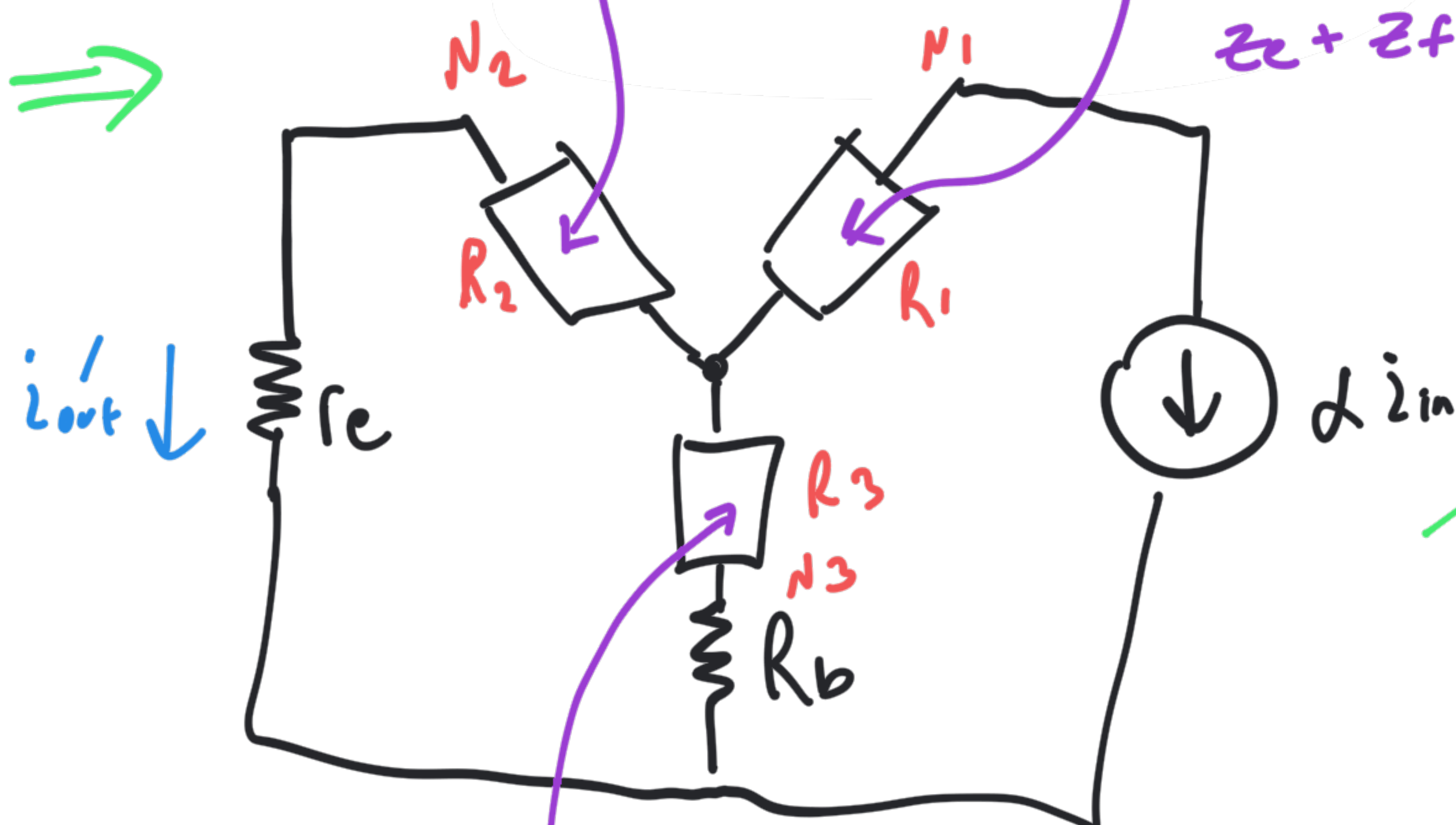


$$\mathbb{R} = -\frac{i_{out}}{i_{in}} = \frac{i_{out}'}{i_{in}}$$

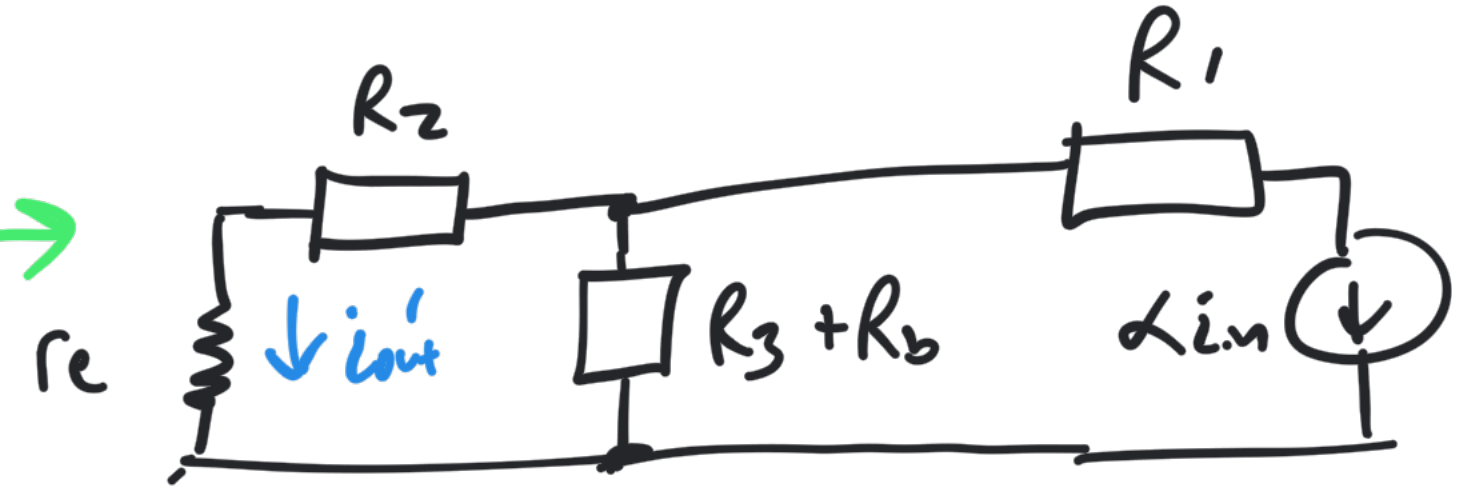


$$R_2 = \frac{R_a R_c}{R_a + R_b + R_c} = \frac{Z_e Z_f}{Z_e + Z_f + Z_c}$$

$$R_1 = \frac{Z_c Z_f}{Z_c + Z_f + Z_e}$$



$$R_3 = \frac{Z_e Z_c}{Z_e + Z_f + Z_c}$$



$$i_{out}' = -\alpha\, i_{in} \left(\frac{R_3 + R_b}{R_2 + r_e + R_3 + R_b} \right)$$

$$\frac{i_{out}'}{i_{in}} = -\alpha \left(\frac{R_3 + R_b}{R_2 + r_e + R_3 + R_b} \right)$$

$$\mathbb{R} = -\alpha \left(\frac{Z_e Z_c + R_b (Z_e + Z_f + Z_c)}{Z_e Z_f + Z_e Z_c + (R_b + r_e)(Z_e + Z_f + Z_c)} \right)$$

$$\mathbb{R} = -\alpha\left(\frac{Z_e Z_c + R_b(Z_e + Z_f + Z_c)}{Z_e Z_f + Z_e Z_c + (R_b + r_e)(Z_e + Z_f + Z_c)}\right)$$

Let $Z_e \to 0$ (short) : $\mathbb{R} = \dfrac{-\alpha R_b}{R_b + r_e}$ (not going to oscillate even if $R_b \to Z_b$)

complex impedance

Let $Z_f \to \infty$ (open) : $\mathbb{R} = \dfrac{-\alpha R_b}{Z_e + R_b + r_e}$ (Does not seem like this can oscillate... even if $R_b \to Z_b$)

complex impedance

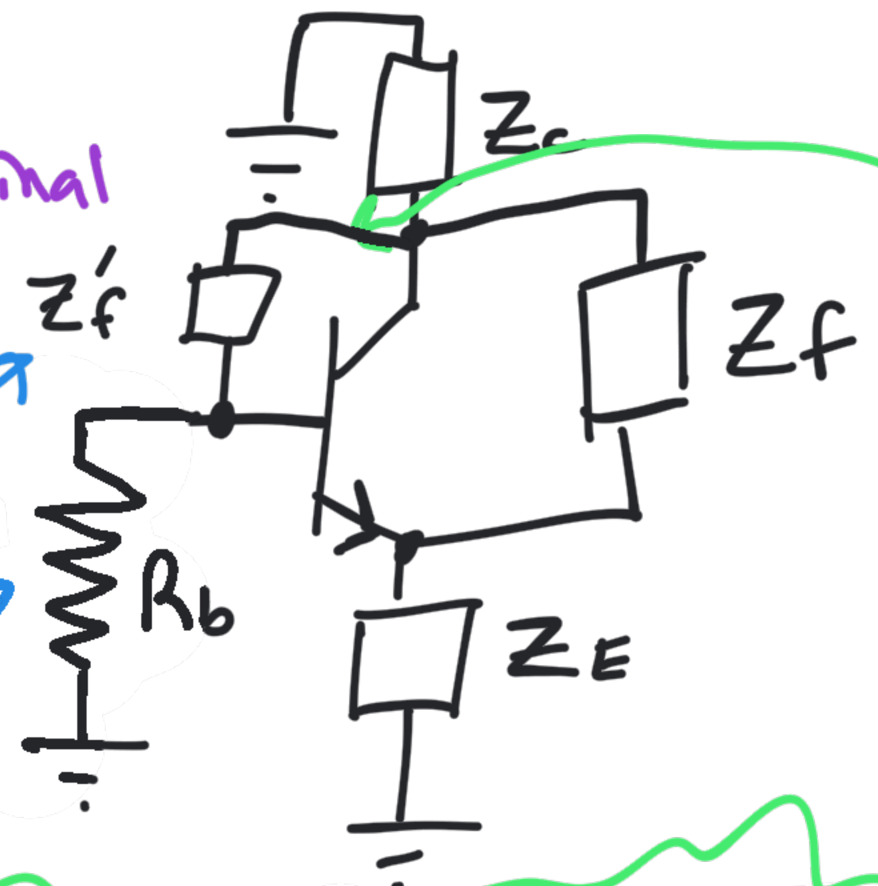
Let $Z_c \to 0$ (short) : $\mathbb{R} = \dfrac{-\alpha R_b (Z_e + Z_f)}{Z_e Z_f + (R_b + r_e)(Z_e + Z_f)}$

no obvious way to oscillate either...

So, all in all it does't look like R_b does much to stability!

Stability analysis BJT transistor amplifier

① original

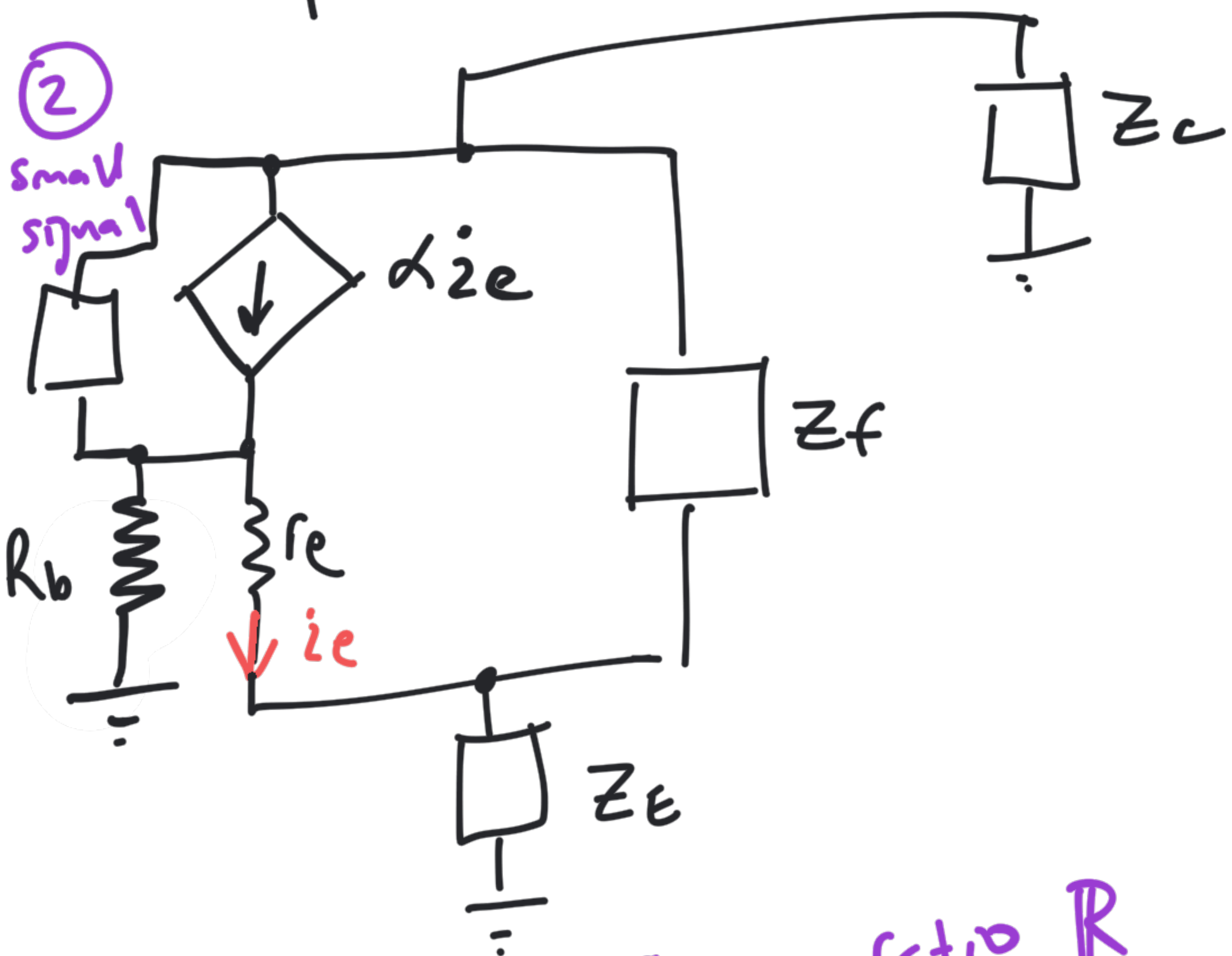


What does R_b do?

What does Z_f' do?

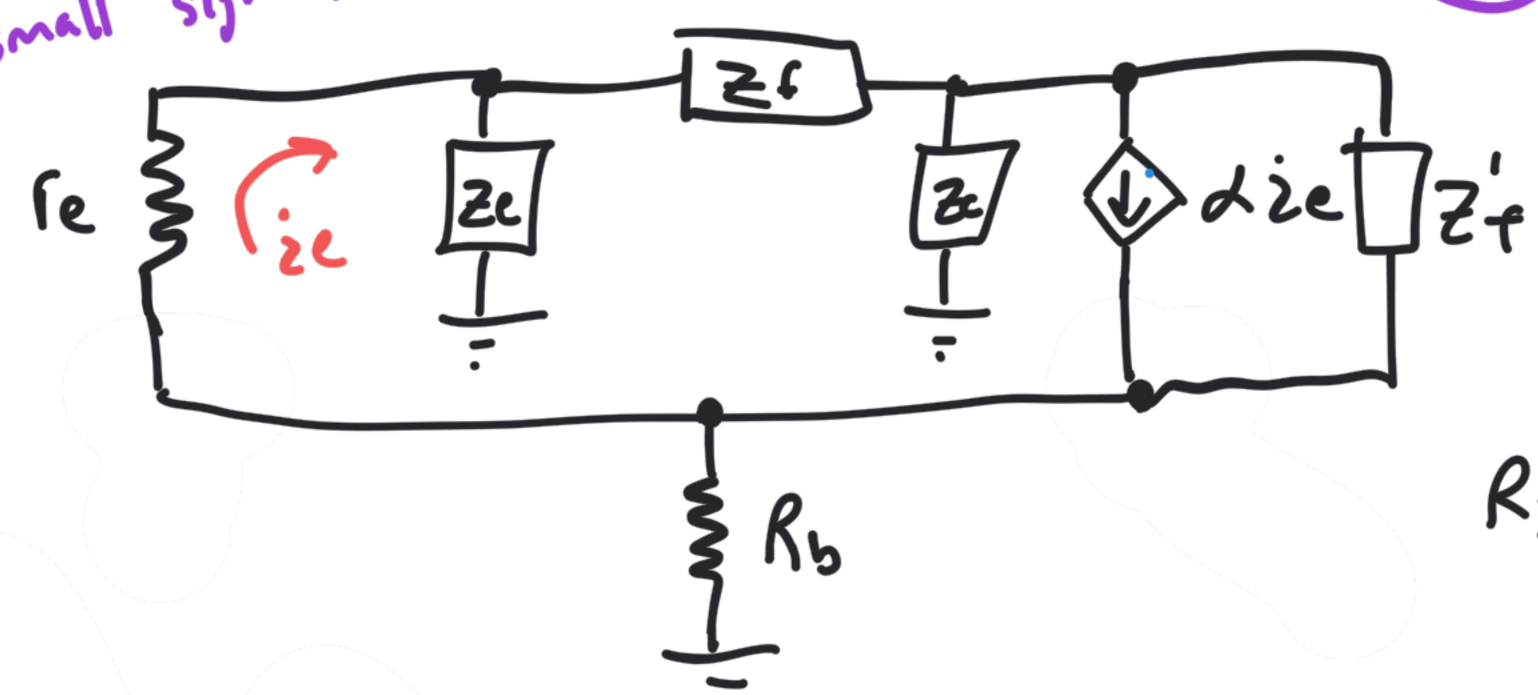
small signal model $\Longrightarrow$

② small signal

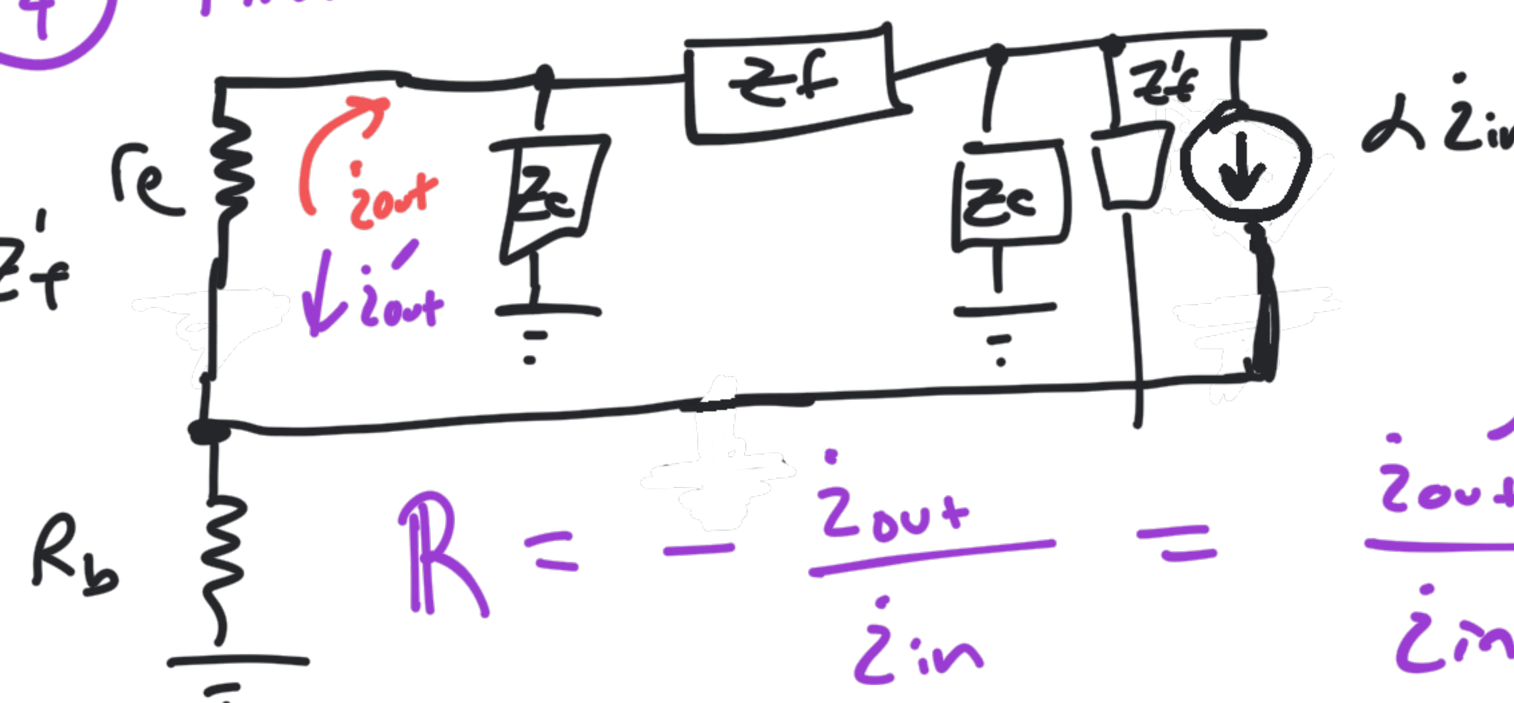


These are the new things here!

③ re-draw small signal



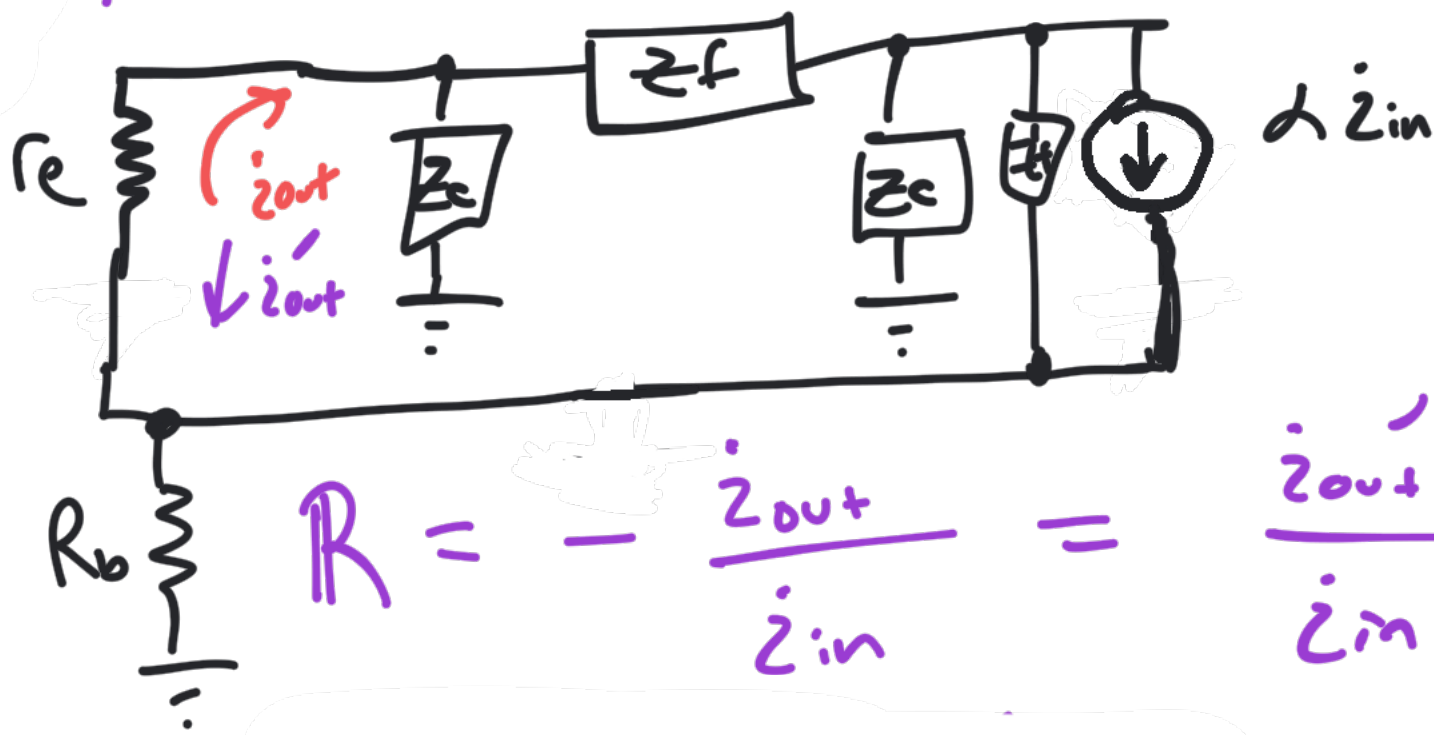
④ Find Return ratio R



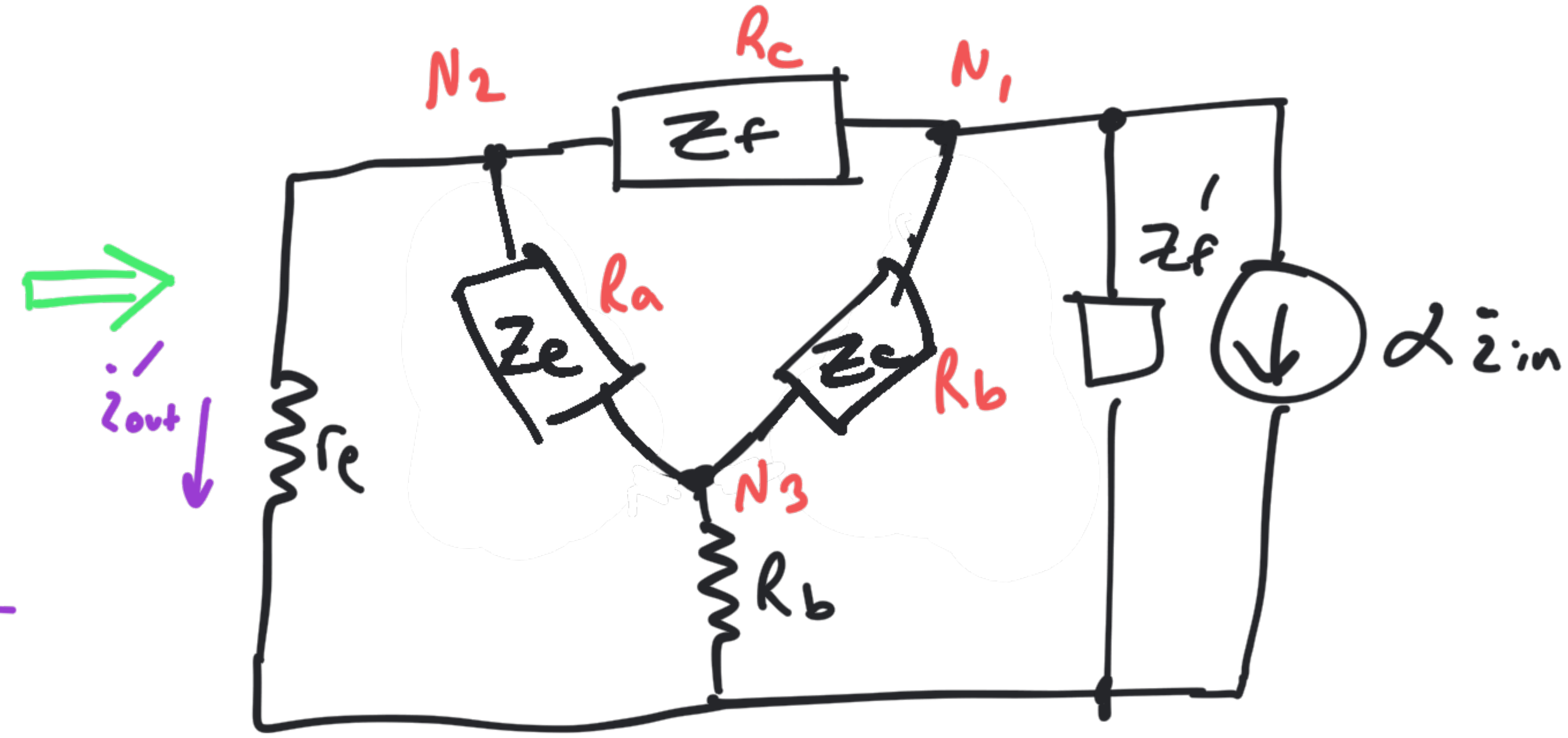
$$R = -\frac{i_{out}}{i_{in}} = \frac{i_{out}'}{i_{in}}$$

circuit unstable if $|R| > 1$ when $\angle R = 180° + n360°$

Find Return ratio $\mathbb{R}$

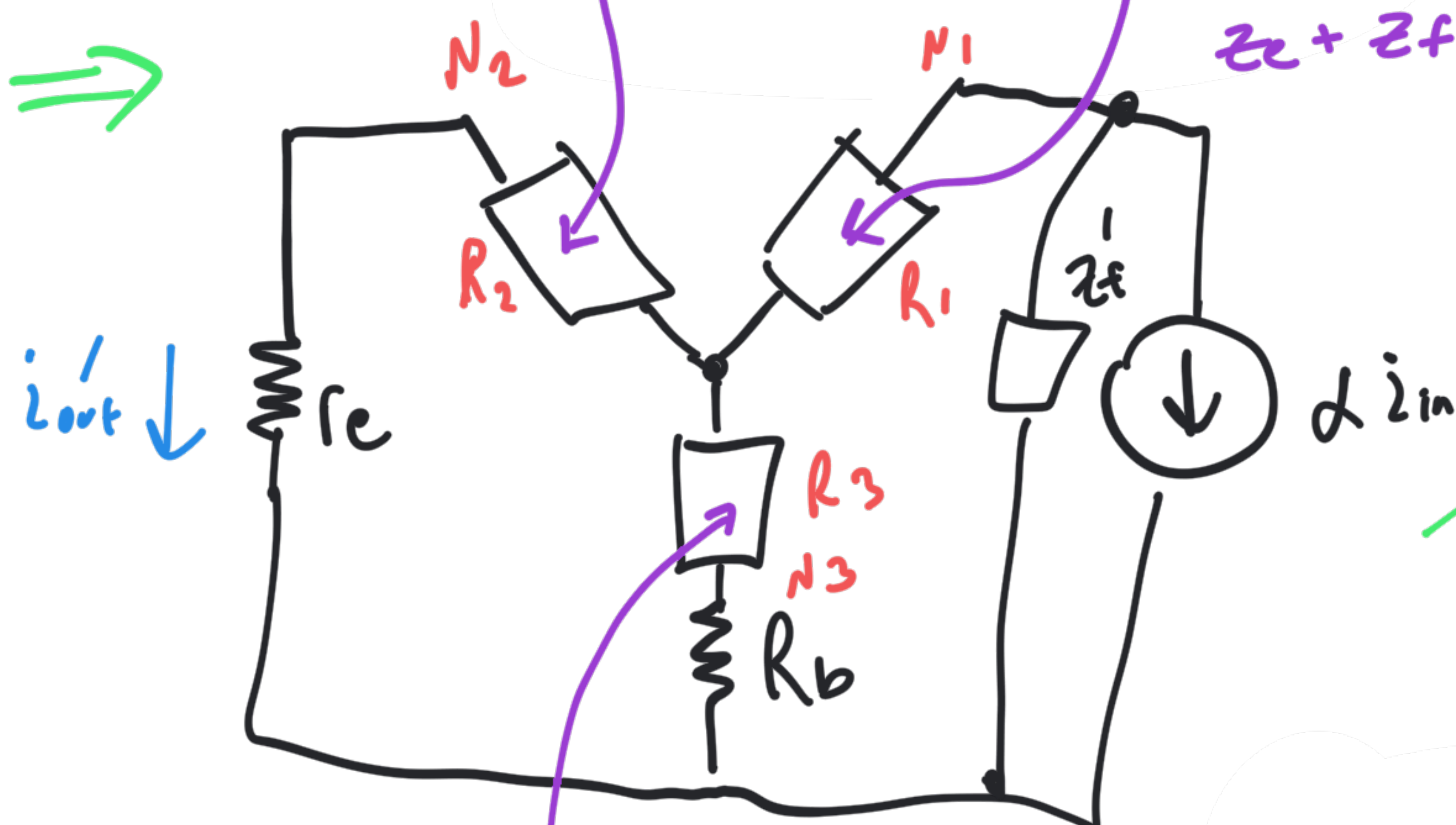


$$\mathbb{R} = -\frac{i_{out}}{i_{in}} = \frac{i_{out}'}{i_{in}}$$

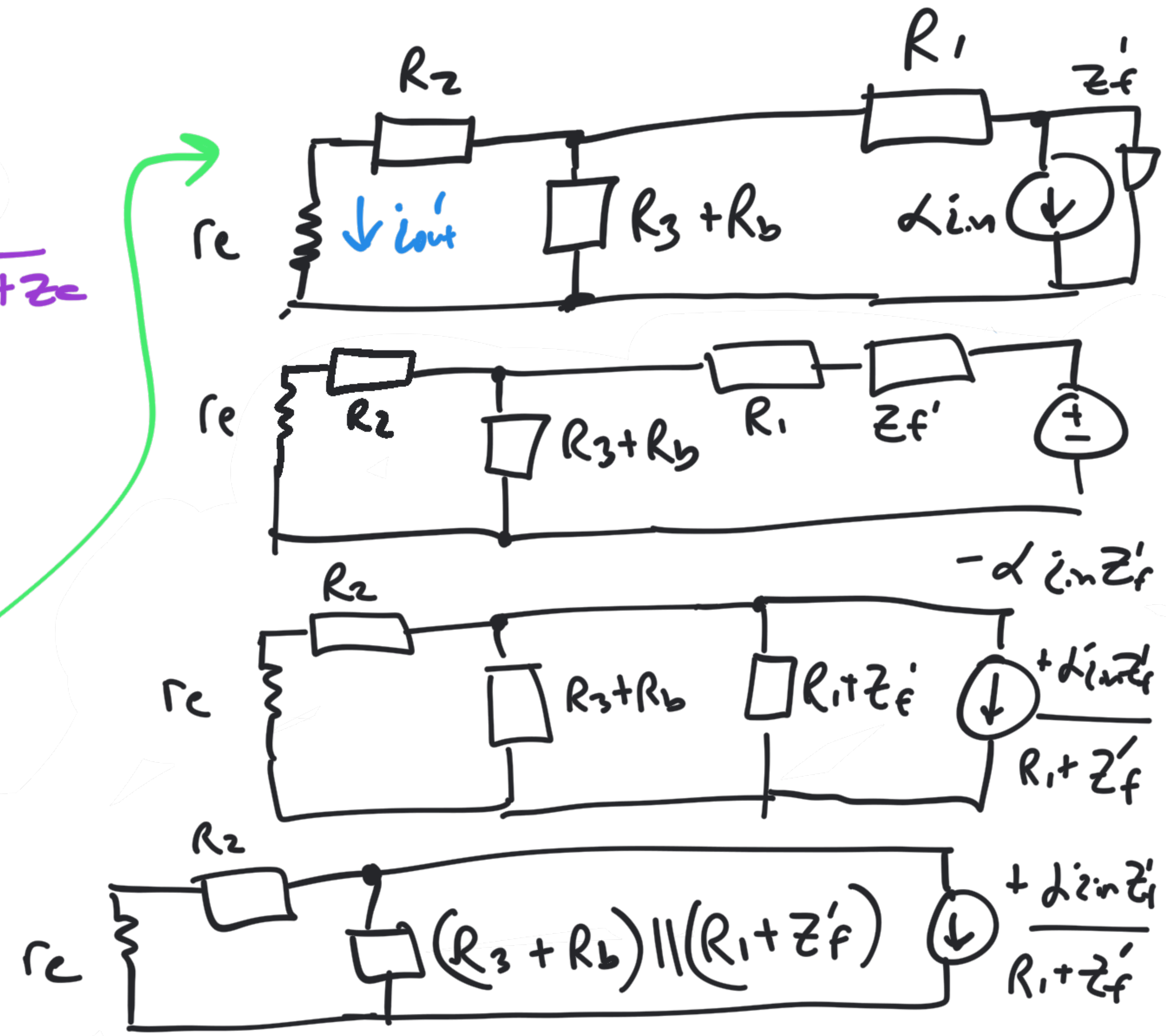


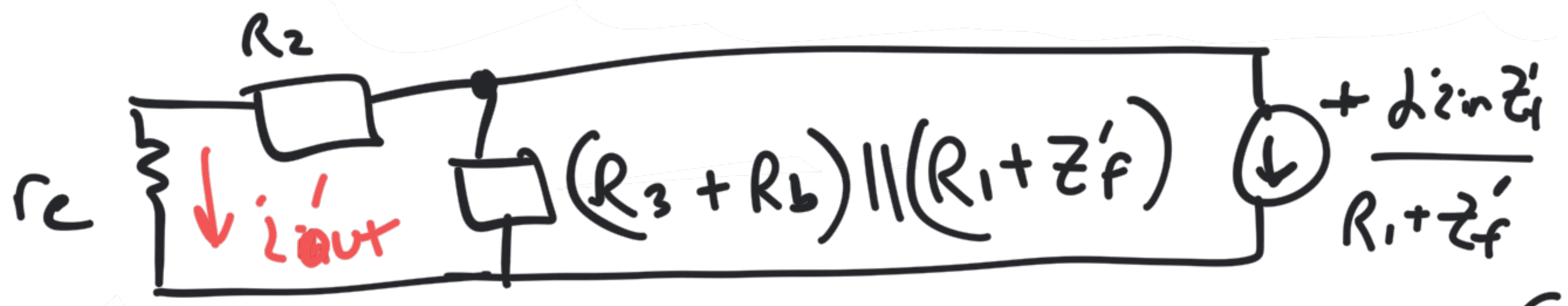
$$R_2 = \frac{R_a R_c}{R_a + R_b + R_c} = \frac{Z_e Z_f}{Z_e + Z_f + Z_c}$$

$$R_1 = \frac{Z_c Z_f}{Z_c + Z_f + Z_e}$$



$$R_3 = \frac{Z_e Z_c}{Z_e + Z_f + Z_c}$$





$$R = \frac{i'_{out}}{i_{in}} = -\alpha \frac{Z_f'}{R_1+Z_f'} \frac{(R_3+R_b)\|(R_1+Z_f')}{r_e+R_2+(R_3+R_b)\|(R_1+Z_f')}$$

$$R = = -\alpha \frac{Z_f'}{\cancel{R_1+Z_f'}} \frac{(R_3+R_b)\cancel{(R_1+Z_f')}}{(r_e+R_2)(R_3+R_b+R_1+Z_f')+(R_3+R_b)(R_1+Z_f')}$$

$$= -\alpha Z_f' \frac{(R_3+R_b)}{(R_3+R_b)(r_e+R_2+R_1+Z_f')+(r_e+R_2)(R_1+Z_f')}$$

$$\Sigma = Z_e + Z_c + Z_f$$

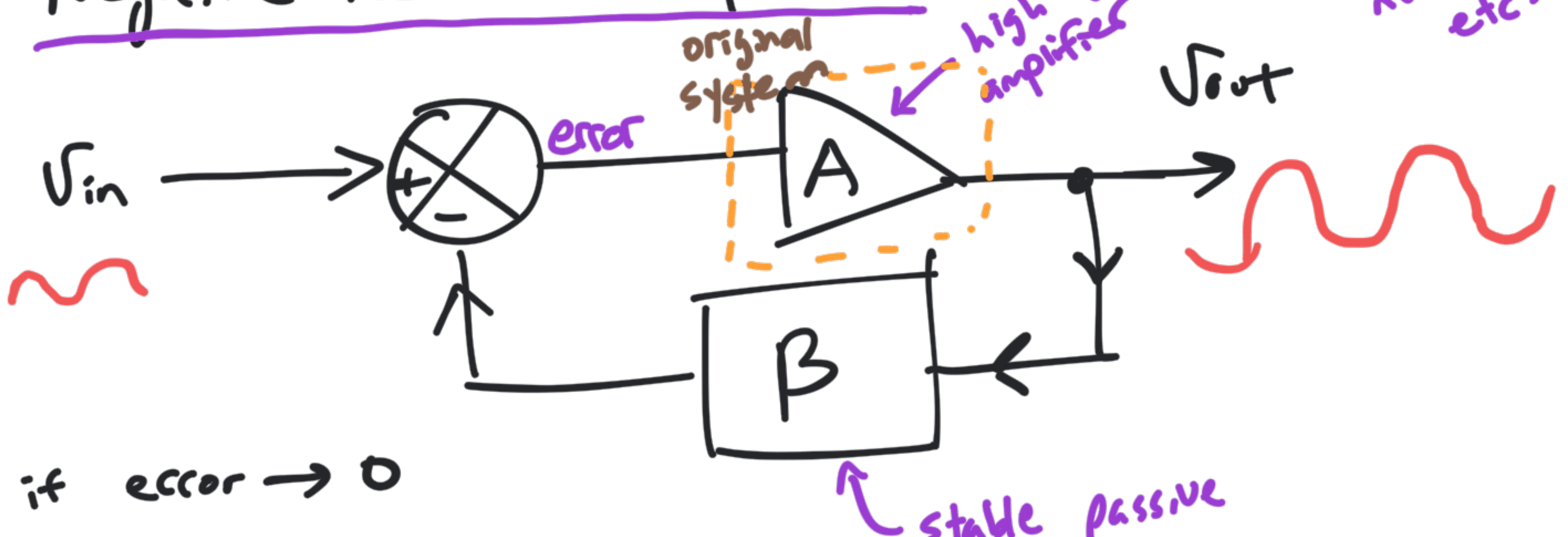
$$= -\alpha Z_f' \frac{(Z_eZ_c)\Sigma + R_b\Sigma^2}{(Z_eZ_c\Sigma + R_b\Sigma^2)\left(r_e + \frac{Z_eZ_f+Z_cZ_f}{\Sigma} + Z_f'\right) + (r_e\Sigma^2 + R_2\Sigma^2)\left(\frac{Z_cZ_f}{\Sigma}+Z_f'\right)}$$

Not sure where to go from here

Negative feedback comparison

bottom line: Trade amplifier gain for linearity, less sensitivity to temp etc, better freq response (flatter over BW of amplifier) impedance improvement, etc.

Negative feedback amplifier



$$\frac{V_{out}}{V_{in}} = \frac{A}{1+A\beta}$$

loop gain

$$\simeq \frac{1}{\beta} \quad \text{for } A\beta \gg 1$$

advantages of neg. feedback: linearity, const. freq response (input/output impedance improvements... not shown)

if error → 0

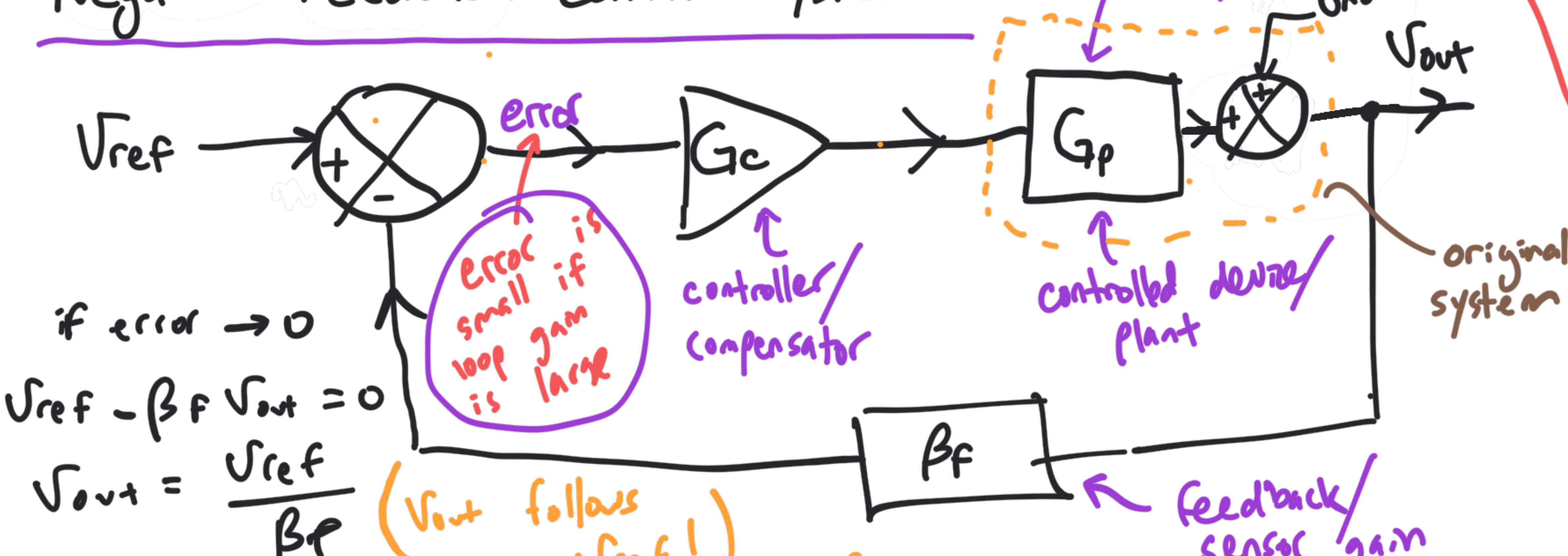
$V_{in} - \beta V_{out} = 0$

→ $V_{out} = \frac{1}{\beta} V_{in}$ (stable gain! independent of A!)

advantages of neg. feedback: noise/disturbance reduction, output follows input

bottom line: make G_c big so error is small and V_{out} tracks V_{ref}

Negative feedback control system



if error → 0

$V_{ref} - \beta_f V_{out} = 0$

$V_{out} = \frac{V_{ref}}{\beta_f}$ (V_{out} follows V_{ref}! independent of G_p!)

$$\frac{V_{out}}{V_{ref}} = \frac{G_c G_p}{1 + G_c G_p \beta_f}$$

loop gain

$$\simeq \frac{1}{\beta_f} \quad \text{for } G_c G_p \beta_f \gg 1$$

$$\frac{V_{out}}{V_{noise}} = \frac{1}{1 + G_c G_p \beta_f}$$

$$\simeq 0 \quad \text{for } G_c G_p \beta_f \gg 1$$