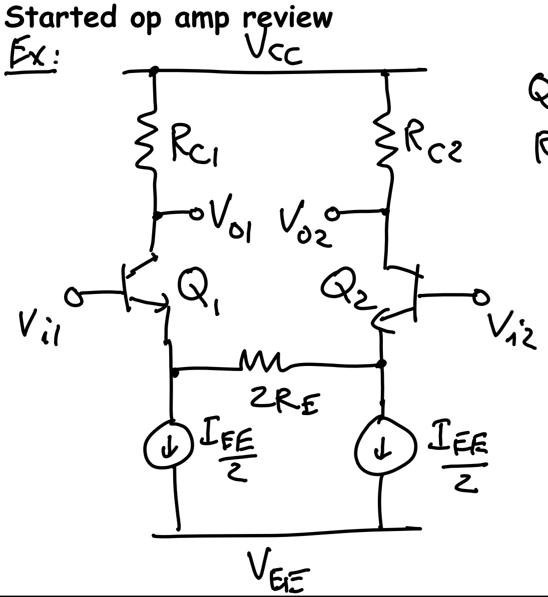
Lecture 13: Op Amps & ECP

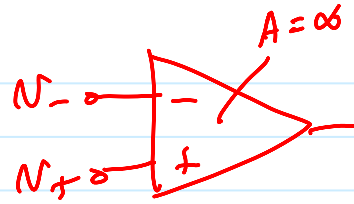
- Announcements:
  - SPICE 3f3 manual online
  - This is the original manual for Berkeley SPICE
  - It might be the only version we can post without violating any licenses
  - ~~Problem 5 on HW#5 will be moved to HW#6~~ actually, we'll just cancel problems, since there are already many problems on HW#6
  - HW#6 will be online tonight
  - I will miss next week's Thursday lecture
  - Will inform you how we will make it up; perhaps by special software that records directly off my computer
- Lecture Topics:
  - Op Amp Review
  - Emitter Coupled Pair (ECP)
- --
- Last Time:
- Started op amp review

Ex:



$Q_1 = Q_2$

$R_{C1} = R_{C2} = R_C$



$N_o = A(N_+ - N_-) = \text{finite}$

$\uparrow \infty$ $\quad \uparrow 0! \rightarrow N_+ = N_-$

Properties of Ideal Op Amps:

① $R_{in} = \infty$ $\xrightarrow{\text{leads to}}$ ④ $i_+ = i_- = 0$

② $R_o = 0$

③ $A = \infty$ $\xrightarrow{\text{leads to}}$ ⑤ $N_+ = N_-$, assuming N_o = finite

↳ Why? Because for $\infty(N_+ - N_-) = N_o$ = finite

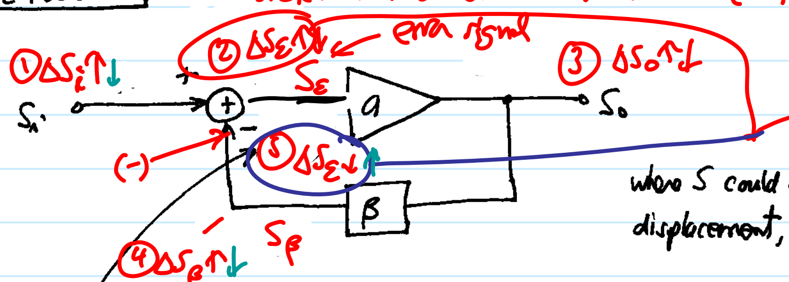
$\therefore \underbrace{N_+ - N_-}_{= \frac{N_o}{\infty}} = 0 \rightarrow N_+ = N_-$

⇒ virtual short ckt. (virtual ground)

Big assumption! (N_o = finite)

How can we assume this? ⟹ only when there is an appropriate negative feedback path!

Negative Feedback → to determine whether or not there's (−) FB, do a perturbation analysis:



oppose ∴ (−) FB

where S could be a current, voltage, displacement, etc., ...

Negative feedback acts to oppose or subtract from input.

$$\left.\begin{aligned} S_o &= a S_\varepsilon \\ S_\varepsilon &= S_i - \beta S_o \end{aligned}\right\} \Longrightarrow \begin{aligned} S_o &= a(S_i - \beta S_o) \\ S_o(1 + a\beta) &= a S_i \end{aligned} \rightarrow \boxed{\frac{S_o}{S_i} = \frac{a}{1 + a\beta}}$$

overall transfer function

$a\beta$ = loop gain

$\beta \triangleq$ feedback factor

$$[a \to \infty] \Longrightarrow \frac{S_o}{S_i} \approx \frac{a}{a\beta} = \frac{1}{\beta} = \text{finite!}$$

$$\therefore S_o = \frac{1}{\beta} S_i = \text{finite} \checkmark$$

(when there is neg. FB around the amplifier)

In Summary:

① Neg. FB can insure S_o = finite even with $a = \infty$.

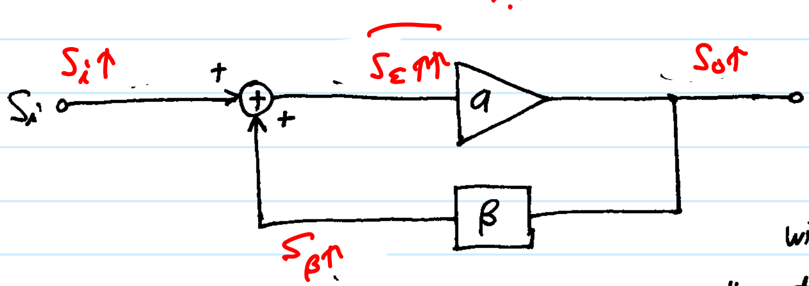
② Overall Gain dependent (or overall T.F.) dependent only on external components. (e.g., β)

③ Overall (closed-loop) gain $\frac{S_o}{S_i}$ is independent of amplifier gain a.

↖ very important! ⟹ as you'll see, when designing amplifiers using transistors, it's easy to get large gain, but it's hard to get an exact gain.
i.e., if you're shooting for $a = 50{,}000$, you might get 47,000 or 60,000 instead.

Contrast w/ Positive Feedback

(+) FB !!!



⇒ output blow up! (for $a\beta > 1$)

↑ will be the case for $a = \infty$

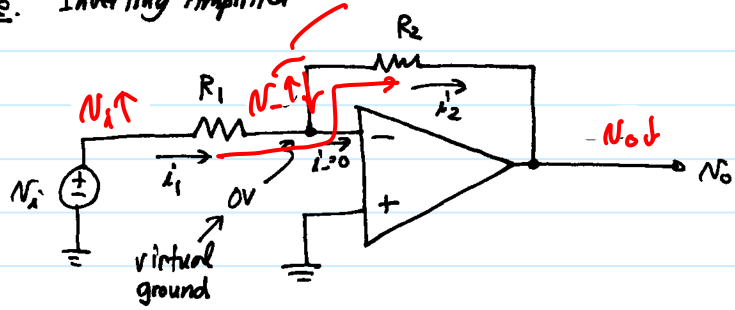
⇒ usually get oscillation!

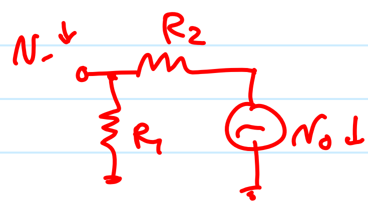
Thus, for a bounded, controllable function, need negative FB around an op amp.

Op Amp Ckts.

Example. Inverting Amplifier

neg. FB ✓





→ ① Verify that there is negative FB. ✓

② ∴ v_o = finite → $v_+ = v_-$ → node attached to (-) terminal is virtual ground

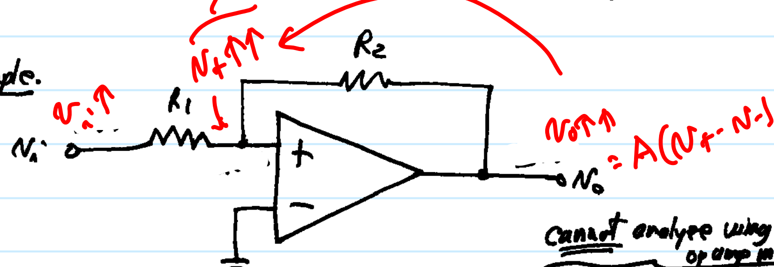
③ $i_- = 0$ ∴ $i_1 = i_2$ ← virtual gnd

$$\left.\begin{aligned} i_1 &= \frac{v_i - 0}{R_1} = \frac{v_i}{R_1} = i_2 \\ v_o &= 0 - i_2 R_2 = -i_2 R_2 \end{aligned}\right\} \Rightarrow v_o = -\left(\frac{v_i}{R_1}\right) R_2 = -\frac{R_2}{R_1} v_i \quad \therefore \boxed{\frac{v_o}{v_i} = -\frac{R_2}{R_1}}$$

Note: Gain dependent only on R_1 & R_2 (external components), not on the op amp gain.

(+) FB ✗

Example.



$= A(v_+ - v_-)$

v_o = L^+ or L^- depending on initial conds.

(+) rail, (-) rail

$v_+ = (+) \longrightarrow L^+$

$v_+ = (-) \longrightarrow L^-$.

Cannot analyze using ideal op amp method!

① Verify that there is neg. FB ✗

∴ $v_o \neq$ finite, $v_+ \neq v_-$

⇒ this ckt. will "rail out"

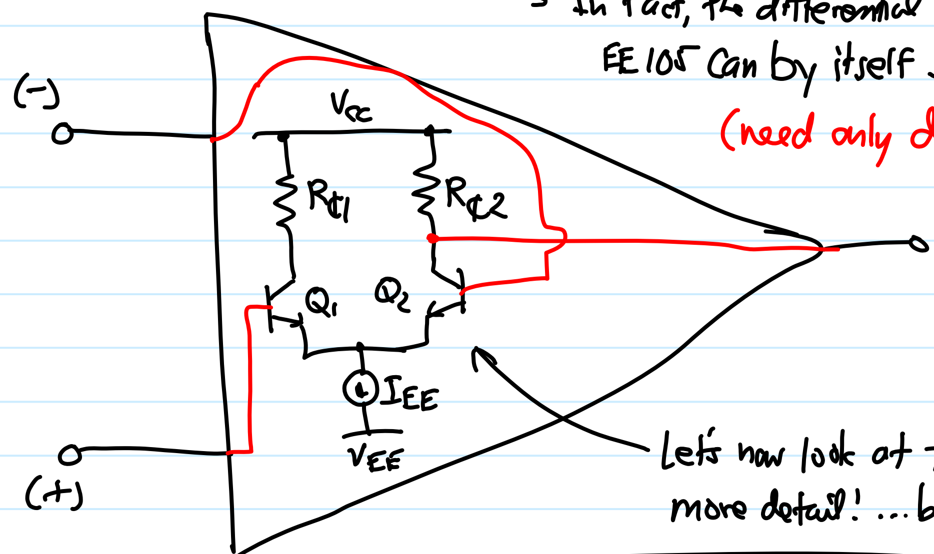
How does one make an op amp? (It turns out, you already know!)

⇒ Basic Needed Attributes:

1. Gain (voltage gain).
2. Two inputs, (+) and (−).
3. One output equal to the difference of the inputs multiplied by some gain.

In fact, the differential pair you studied in EE105 can by itself serve as an op amp!

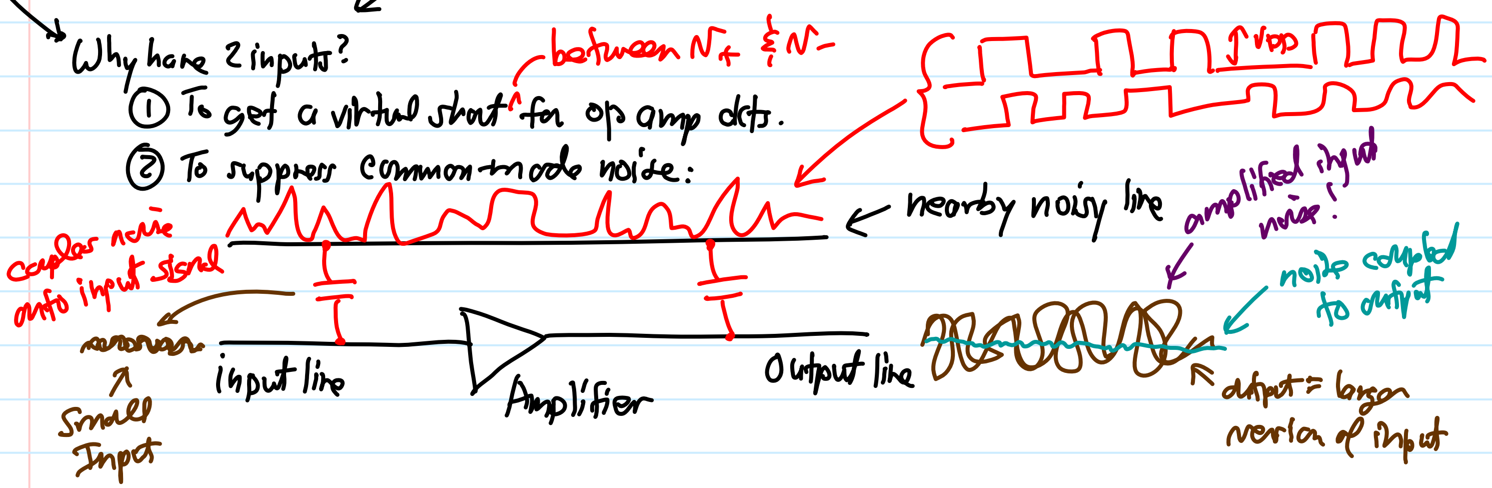
(need only decide which of the inputs is the (+) and (−) terminals)



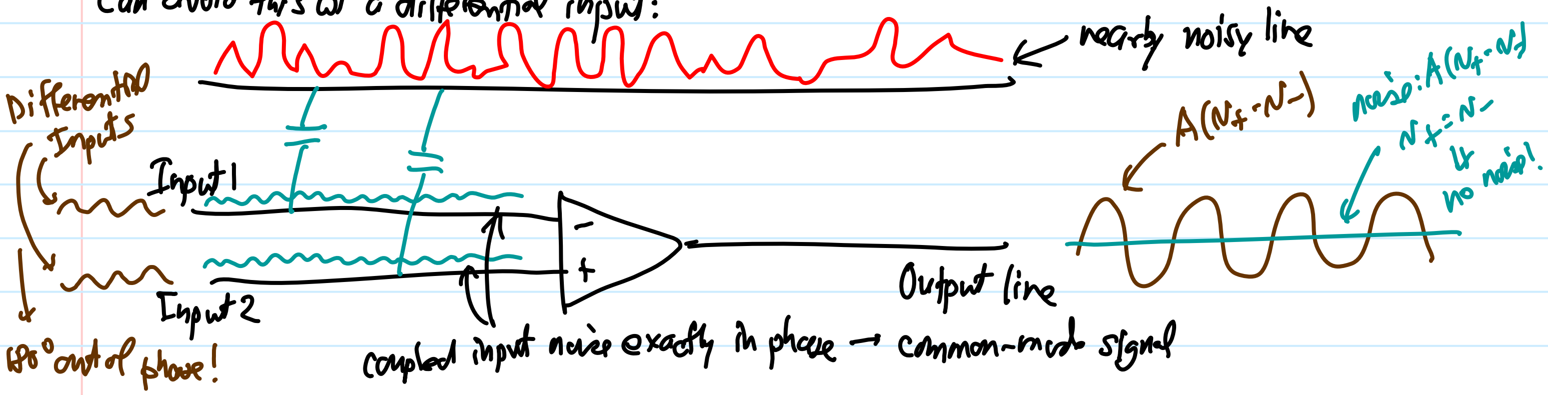
Let's now look at the diff. pair in more detail! ... but first

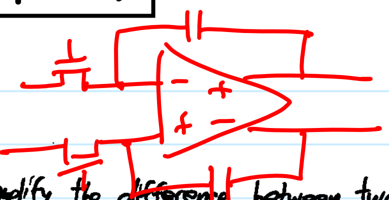
Why have 2 inputs?

1. To get a virtual short between v_+ & v_- for op amp ckts.
2. To suppress common-mode noise:

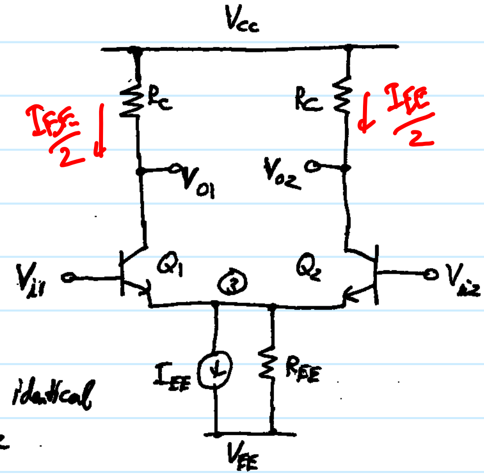


Can avoid this w/ a differential input:





$\boxed{\text{Differential Pair}}$ (Emitter Coupled Pair)



Assume:
Q_1 & Q_2 identical
$R_{c1} = R_{c2}$

Purpose: Amplify the difference between two signals regardless of their common-mode DC values (or their common-mode values in general)

Definitions: $V_{id} = V_{i1} - V_{i2}$ (differential input)

$V_{icm} = \frac{V_{i1} + V_{i2}}{2}$ (common-mode input)

$$\Rightarrow \begin{cases} V_{i1} = V_{icm} + \frac{V_{id}}{2} \\ V_{i2} = V_{icm} - \frac{V_{id}}{2} \end{cases}$$

Differential Gain $= A_d = \frac{V_{o1} - V_{o2}}{V_{id}} = \frac{V_{od}}{V_{id}}$ (want this to be large for this differential amplifier)

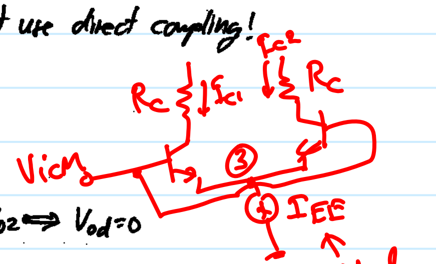
Common-Mode Gain $= A_{cm} = \frac{V_{o1}}{V_{cm}}$ or $\frac{V_{o2}}{V_{cm}}$ (want this to be small so that the amp rejects common-mode signals)

Common-Mode Rejection Ratio $=$ CMRR $= \frac{A_{dm}}{A_{cm}}$ (should be very high to favor the differential-mode and reject the common-mode)

⇒ we also want a high Common-Mode Input Range to reject DC input offsets

⇒ Note: No need for bypass capacitors (large) to the inputs or outputs → can just use direct coupling!

$\boxed{\text{Biasing \& Large Signal Common-Mode Behavior}}$



Case: $R_{EE} = \infty$ → ideal current source biasing → $I_{E1} = I_{E2} = \frac{I_{EE}}{2}$ → $V_{o1} = V_{o2}$ ⇒ $V_{od} = 0$

↑ Ideal: If V_{cm}↑ → $V_③$↑, but current draw from I_{EE} stays constant ∴ I_{c1} & I_{c2} stay constant → bias pt. doesn't change

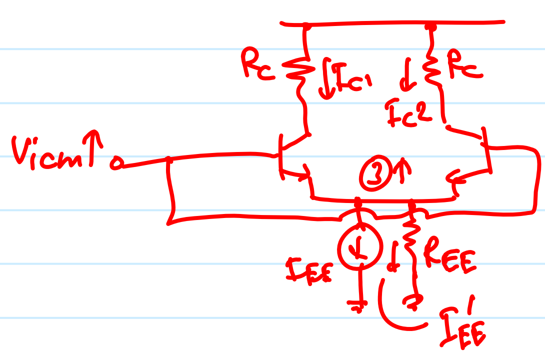
$g_{m1} = \frac{1}{2}\frac{I_{EE}}{V_T}$

Case: R_{EE} = finite

$V_③ = V_{i1} - V_{BE(on)}$

↑ Actual: If V_{icm}↑ → $V_③$↑ → $I_{E1} = I_{E2}$↑ (current draw $= I_{EE} + \frac{V_③}{R_{EE}}$)

⇒ in general, R_{EE} will be large, so this component won't be large, and the bias pt. won't Δ much



If V_{icm}↑ → I_{EE}'↑ → $I_{E1} = I_{E2}$↑ → $I_{c1} = I_{c2}$↑ → V_{ocm}↓

Small-Signal Analysis of Diff. Pair

Consider v_{i2} & short v_{i1}:

$v_{o1} = -\frac{1}{2} g_m v_{i1} R_C$; $+\frac{1}{2} g_m v_{i2} R_C$

$v_{o2} = -\frac{1}{2} g_m v_{i2} R_C$; $+\frac{1}{2} g_m v_{i1} R_C$

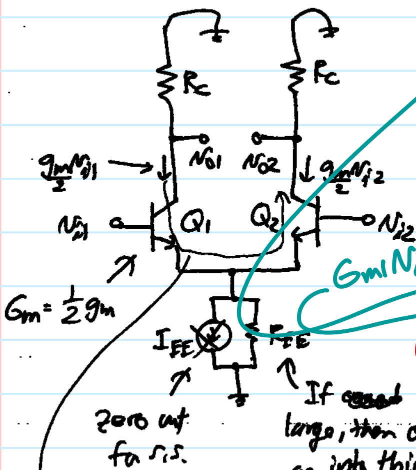
v_{o1} & v_{o2}

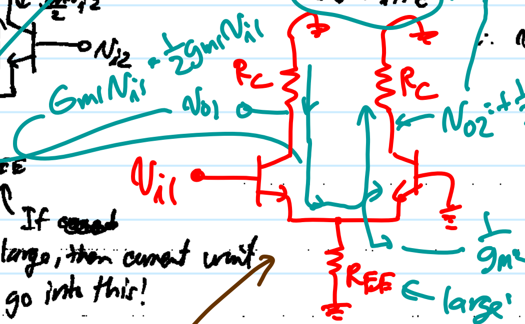
$v_{o1} = -\frac{1}{2} g_m R_C (v_{i1} - v_{i2})$

$v_{o2} = +\frac{1}{2} g_m R_C (v_{i1} - v_{i2})$

$\therefore\ v_{od} = v_{o1} - v_{o2} = -g_m R_C (v_{i1} - v_{i2})$

$\therefore\ \boxed{\frac{v_{od}}{v_{id}} = A_{dm} = -g_m R_C}$

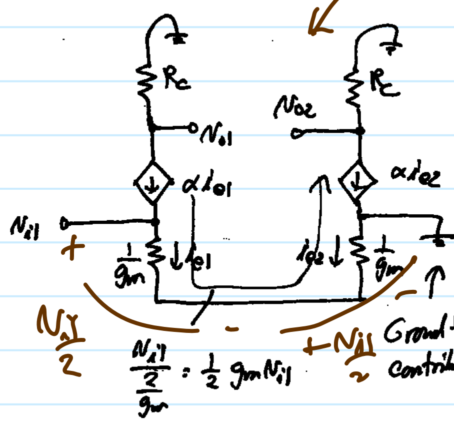




$G_{m1} = \frac{g_{m1}}{2}$

⇒ Easiest to see this happening using the T-model: (for those who must see the model ckt.)

↳ This time also get the $\frac{v_{o1} - v_{o2}}{v_{i1}}$ gain!



$v_{o1} = -\frac{1}{2} g_m R_C v_{i1}$

$v_{o2} = +\frac{1}{2} g_m R_C v_{i1}$

$v_{o1} - v_{o2} = -g_m R_C v_{i1}$

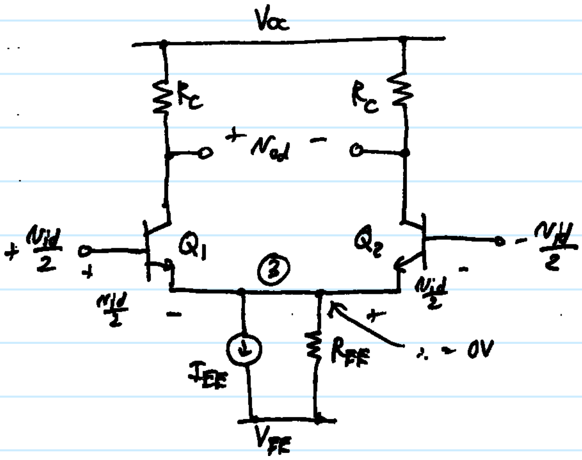
$\therefore\ \boxed{\frac{v_{od}}{v_{i1}} = -g_m R_C}$

$\boxed{\frac{v_{o2}}{v_{i1}} = \frac{1}{2} g_m R_C}$

$\boxed{\frac{v_{o1}}{v_{i1}} = -\frac{1}{2} g_m R_C}$

Diff. Mode Analysis

Assume a ckt. w/ only diff. input:



Total current thru I_{EE} = const.

⟶ V_E = const. as input changes

⟶ ③ acts as an incremental ground! ⟶ $v_③ = 0V$ (always!)

∴ we can ground ③, and thus, have a $\boxed{\text{Differential Half Ckt.}}$

↓

Note: Can really only make this for a purely symmetrical ckt.!