Lecture 5: Ideal Op Amps

- Announcements:
- HW#2 online and due next Friday via Gradescope, which means you will submit pdf
- General Lab Instruction Manual online in the "Labs" link of the website
- Labs start next week
  - Monday, Sept. 3 is a holiday, so the Monday lab will start one week later
  - The Tuesday lab starts Sept. 4
- Will let in concurrent enrollments soon
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- Lecture Topics:
  - Amplifier Models (2-port networks)
  - Input R_i
  - Output R_o
  - Ideal Voltage Amplifier
  - Ideal Op Amps
  - Negative Feedback
  - Op Amp Circuits
- ------------------------------------
- Last Time:
- Going through amplifier models
- Now, continue with this …

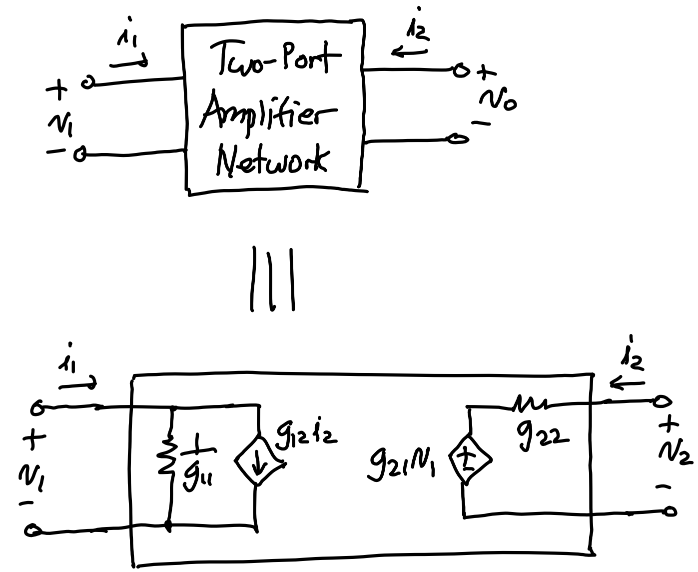
- All of these are equivalent representations, each comprising a gain factor along with an input and output resistance that model the resistance seen looking into the amplifier terminals
- Take for example a voltage amplifier:

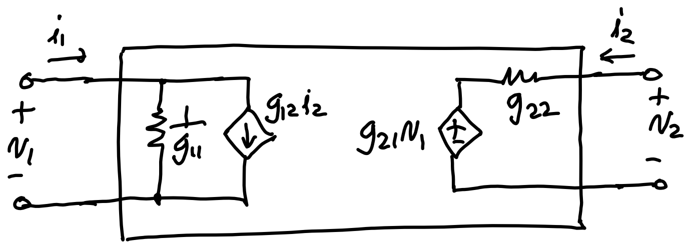
Voltage Amplifier

⇒ most appropriate general model is the g-parameter model → Defining Equations:

Note the matrix form →

$$i_1 = g_{11} v_1 + g_{12} i_2$$
$$v_2 = g_{21} v_1 + g_{22} i_2$$





where:

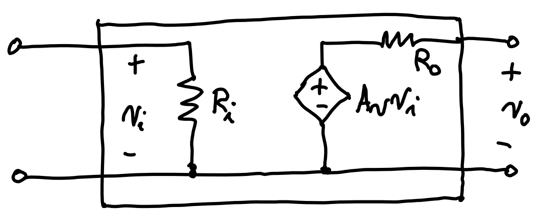
$g_{11} = \left.\frac{i_1}{v_1}\right|_{i_2=0}$ = open-circuit input conductance

$g_{12} = \left.\frac{i_1}{i_2}\right|_{v_1=0}$ = reverse short-circuit current gain

$g_{21} = \left.\frac{v_2}{v_1}\right|_{i_2=0}$ = forward open-circuit voltage gain

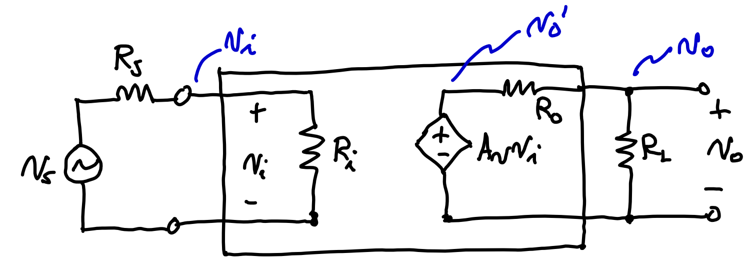
$g_{22} = \left.\frac{v_2}{i_2}\right|_{v_1=0}$ = short-circuit output resistance

Assuming a design to amplify in the forward direction → neglect the current source $g_{12}i_2$ in the g-parameter model → the result:



Voltage Amplifier Model

⇒ R_i & R_o directly influence the total voltage gain via the input & output voltage dividers:



$\frac{v_i}{v_s} = \frac{R_i}{R_i + R_s}$ $\frac{v_o'}{v_i} = A_v$ $\frac{v_o}{v_o'} = \frac{R_L}{R_L + R_o}$

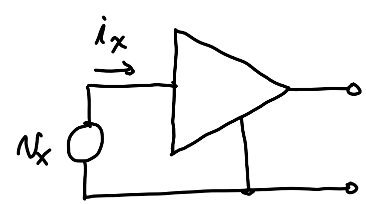
$\therefore \frac{v_o}{v_s} = \frac{R_i}{R_i + R_s} A_v \frac{R_L}{R_L + R_o}$ = total voltage gain $\neq A_v$ ← ideal

$\frac{v_o}{v_s} = \frac{v_i}{v_s} \cdot \frac{v_o'}{v_i} \cdot \frac{v_o}{v_o'}$

these terms attenuate the intended gain!

get when $R_i = \infty$ & $R_o = 0$ ← These values define an ideal voltage amplifier!

To Determine R_i:

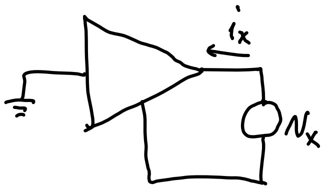


① Apply test voltage source, v_x.

② Measure resulting current, i_x.

③ $R_i = \frac{v_x}{i_x}$ ← same as $\frac{1}{g_{11}} = \left.\frac{v_1}{i_1}\right|_{i_2=0}$ from the g-parameter model

To Determine R_o (for a voltage amplifier)



① Ground input. (Zero out all independent sources.)

② Apply test voltage source, v_x.

③ Measure resulting current, i_x.

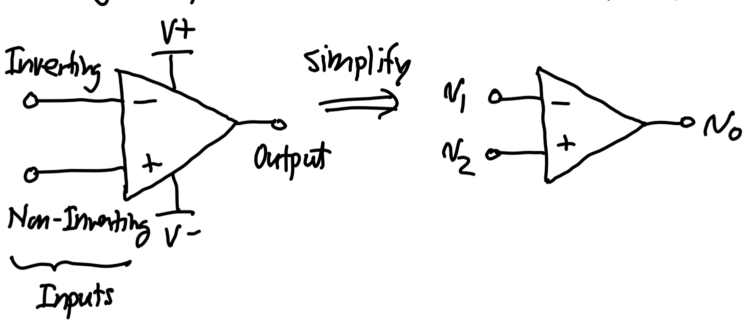
④ $R_o = \frac{v_x}{i_x}$ ← Same as $g_{22} = \frac{v_2}{i_2}\Big|_{v_1=0}$ from the g-parameter model

Ideal Operational Amplifier (op amps)

⇒ the work horse of analog electronics

⇒ Combinations of op amps w/ feedback components allow realization of analog computers, sampled-data systems, A/D converters, DAC's, instrumentation amplifiers, ...

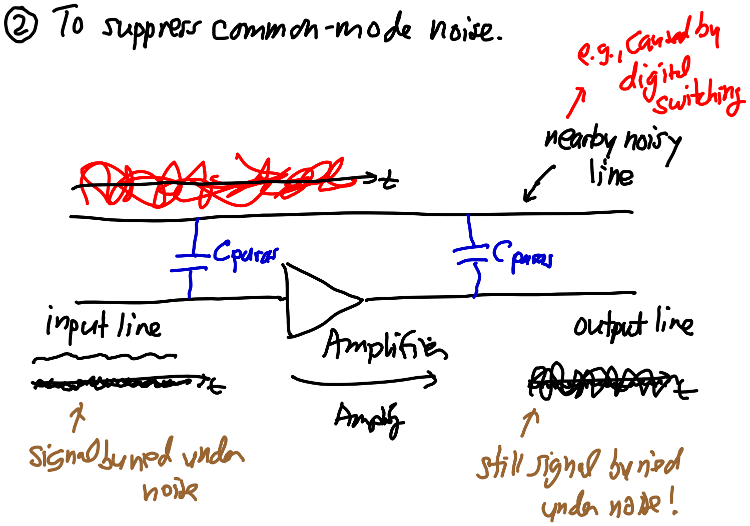
⇒ in general, have a minimum of 5 terminals:



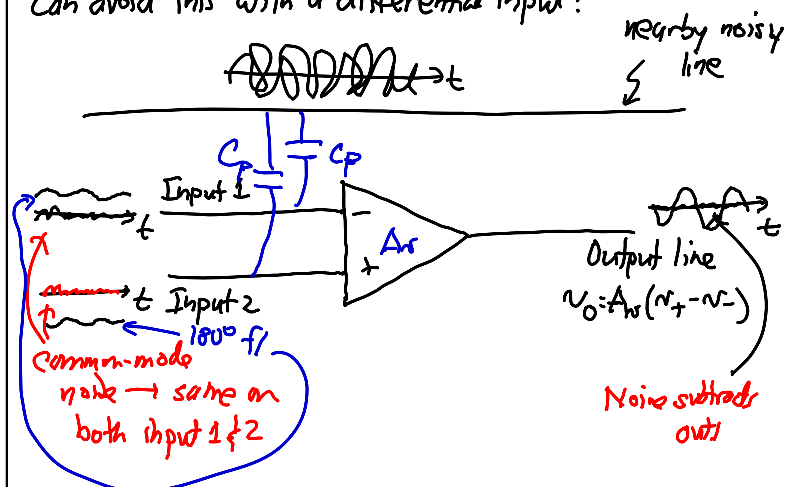
Why have 2 inputs?

① To get a virtual ground for op amp ckts.

② To suppress common-mode noise.

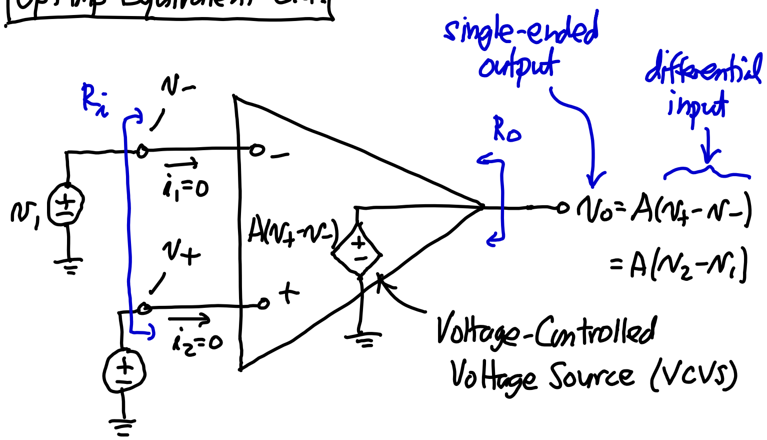


Can avoid this with a differential input:



Perhaps the best way to define an op amp is via its equivalent ckt:

Op Amp Equivalent Ckt.



Properties of Ideal Op Amps:

① $R_i=\infty$ ⟶ ④ $i_+=i_-=0$

② $R_o=0$

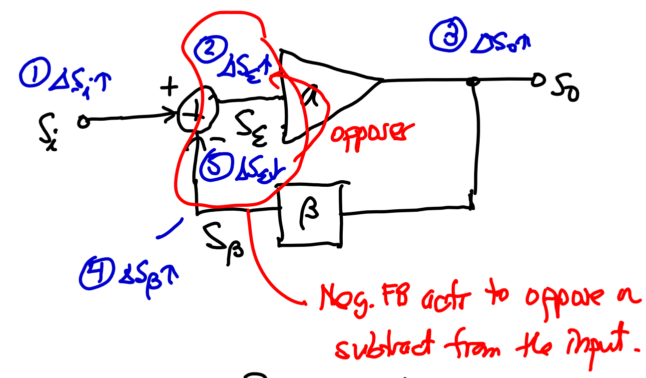
③ $A=\infty$ ⟶ ⑤ $v_+=v_-$, assuming $v_o=$ finite

Why? $\infty(v_+-v_-)=v_o=$ finite

$\therefore v_+-v_-=0 \rightarrow v_+=v_-$ ← Source of "virtual ground"

Big Assumption!
↳ only holds when we have negative feedback!

Negative Feedback

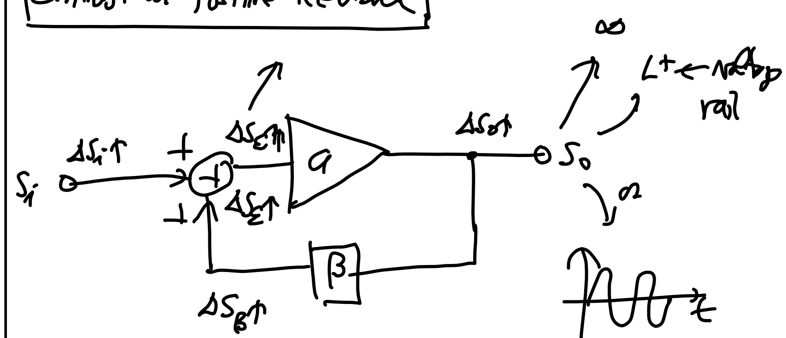


$$\left.\begin{aligned} S_o &= aS_\varepsilon \\ S_\varepsilon &= S_i-\beta S_o \end{aligned}\right\} \quad S_o=a(S_i-\beta S_o)$$

$$S_o(1+a\beta)=aS_i \rightarrow \boxed{\frac{S_o}{S_i}=\frac{a}{1+a\beta}}$$

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

Contrast w/ Positive Feedback



- **Remarks**: (on neg. FB)
- Neg. FB can insure v_o = finite even with a=infinity
- Overall closed-loop gain (or transfer function) is dependent only on external components (e.g., β)
- Overall closed-loop gain S_o/S_i is independent of amplifier gain a
- This is very important, since it's easy to get large amplifier gain, but it's hard to get an exact value
  - If you're shooting for a=50,000, you might get 47,000 or 60,000 instead
  - But it won't matter much in the feedback ckt.

Op Amp Ckts.

Example. Inverting Amplifier