2. OPERATIONAL AMPLIFIERS

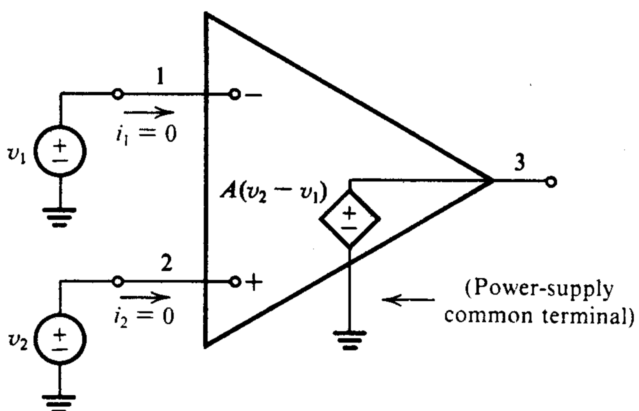
2.1 Basic Configurations

- The op amp is the easiest implementation method for most low power analog applications under 1MHz or so.

  but there are op amps to 40 MHz, and to 50W! $$.

- A typical op amp has a couple of dozen transistors inside — but you don't have to know how it's built to build bigger things from it.

- Always used with feedback and other components, and they are what determine the function



- Idealized model of an op amp.

  We also have two power supply connections, usually +15V, −15V though some use other values. Also possible (uncommon) to use one sided supply.

- Ideal model gives good first approximation to function.
  - infinite input resistances
  - zero output resistance
  - responds only to difference $v_2 - v_1$
  - huge voltage gain (infinite, ideally)

2.2

This is the most basic feedback configuration:

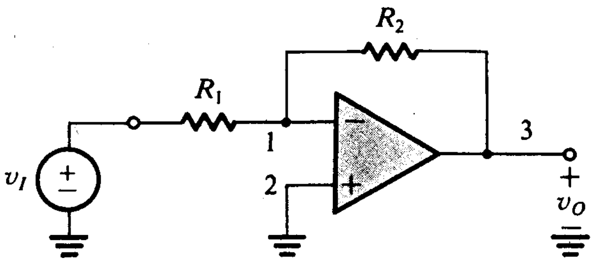
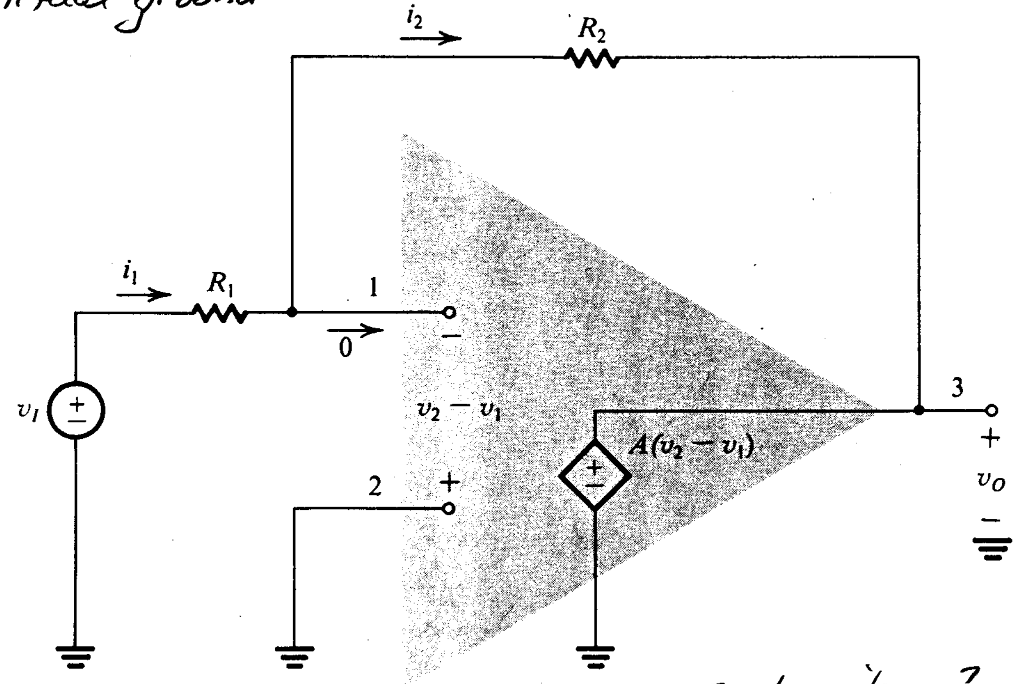


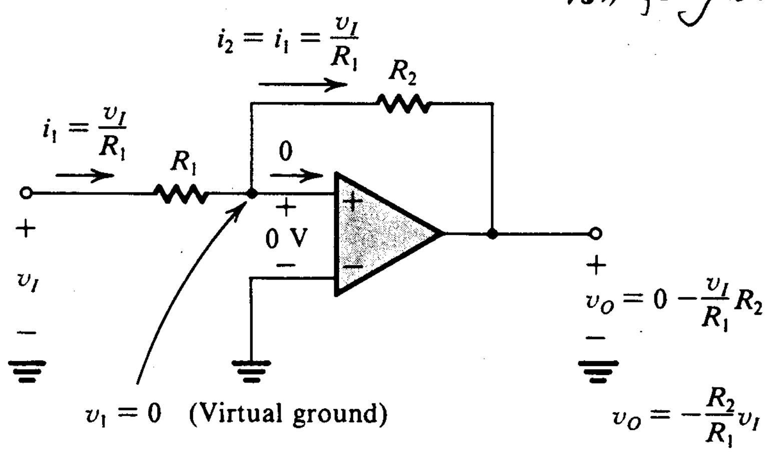
Fig. 2.4

Equivalent circuit:
- negative feedback keeps v_1 close to v_2 (i.e. zero), same polarity as v_I
"virtual ground"



(a)

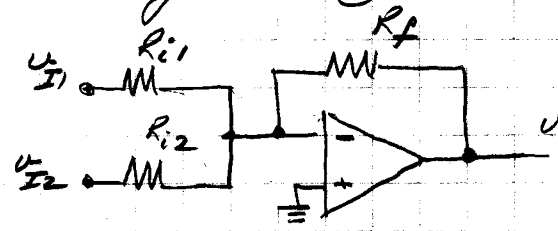
Input resistance?
Output resistance?
Voltage gain ?



(b)

Fig. 2.5

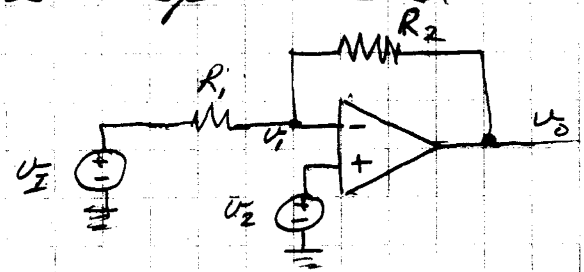
- Because of virtual ground, we can make a summing amp



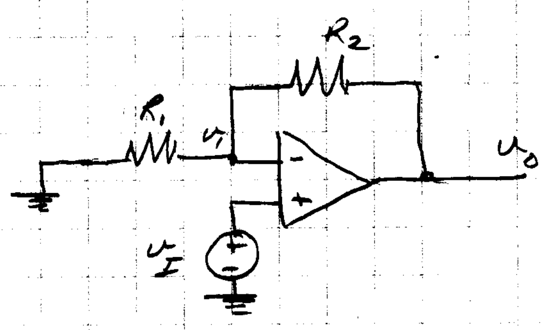
$$v_O = -\left(\frac{R_f}{R_{i1}} v_{I1} + \frac{R_f}{R_{i2}} v_{I2} + \cdots\right)$$

selection of resistors gives different weights per branch

- More generally, if $v_2 \neq 0$, the same argument shows that negative feedback keeps $v_1 \approx v_2$, so that "virtual ground" is just a special case



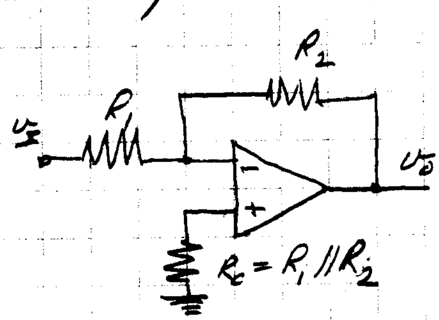
which leads directly to the noninverting configuration

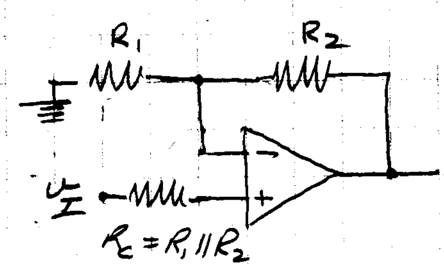


$$v_O = v_I + R_2 \frac{v_I}{R_1}$$
$$= v_I \left(1 + \frac{R_2}{R_1}\right)$$

- Simplified design guidelines:

  — Because of bias currents (Text, 2.12), make resistances seen by +, − terminals equal, using compensating resistor.





- Check to make sure output voltage swing does not exceed supply, less some "backoff".

- Resistances: if too small, then unnecessary loading on source or amp; if too big, then thermal noise, also current into +, − inputs not negligible
  So choose in the range 1kΩ to 100kΩ, and above 10kΩ if possible

- Keep closed loop gains much less than open loop (typically under 100)

- Check max current, max power dissipation in amp.

2.2 Differential Amplifier

• Here's a common problem in instrumentation:

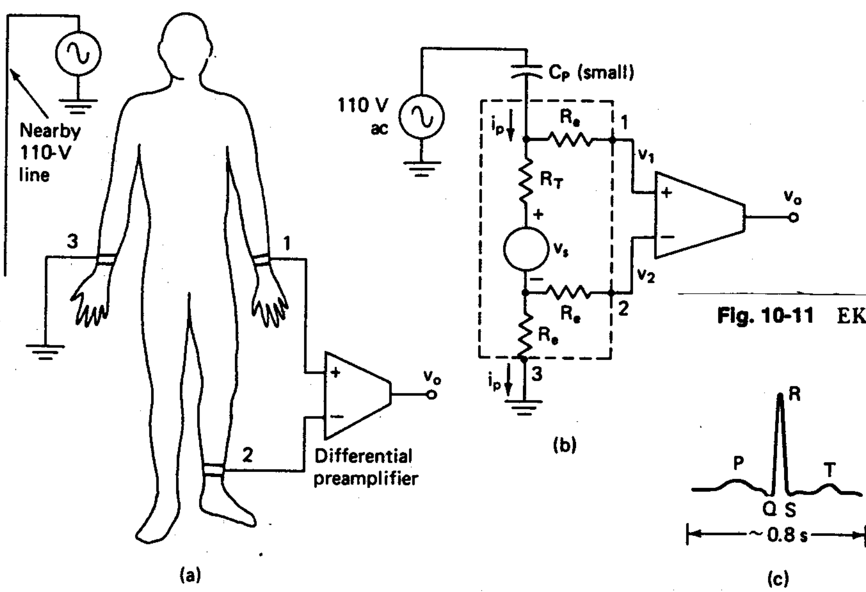


Fig. 10-11 EKG: (*a*) measurement and (*b*) equivalent circuit; (*c*) signal.

from D. Wobschall
Circuit Design for Electronic Instrumentation
McGraw Hill 1979

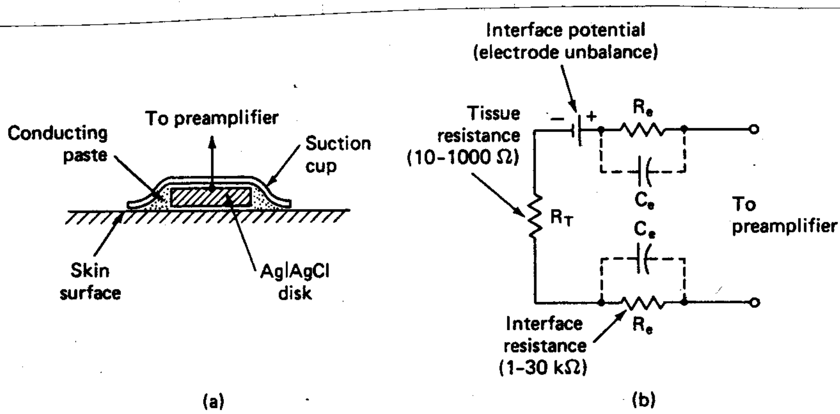


Fig. 10-10 Surface or skin electrodes: (*a*) construction details; (*b*) electrical equivalent circuit for a pair of electrodes.

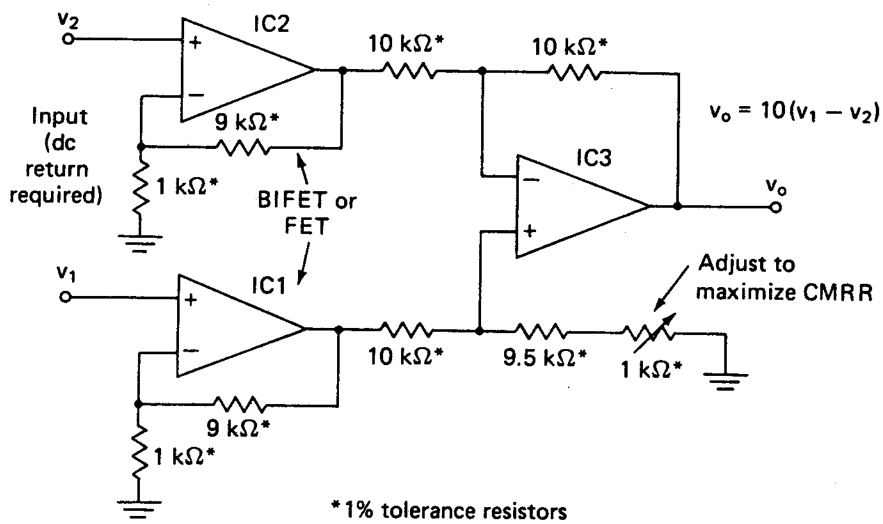


Fig. 10-12 Differential-input preamplifier, standard dc version.

solution:

two buffer amps with gain (how much?) followed by a differential amp

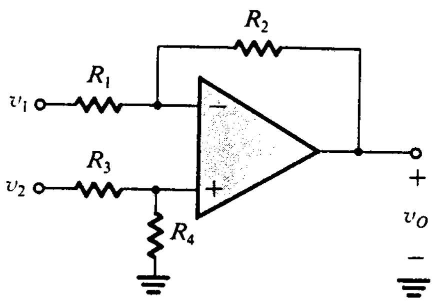


Fig. 2.19 A difference amplifier.

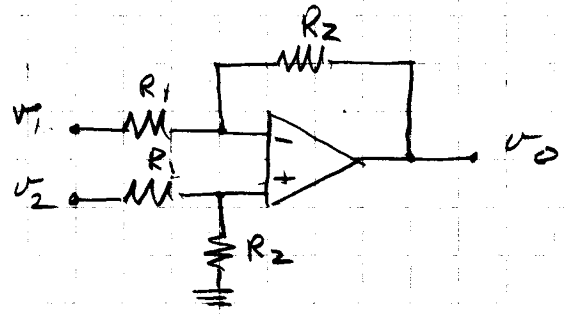
Since $v_- = v_+$

$$\frac{1}{R_1}\left(v_1 - \frac{R_4}{R_3+R_4}v_2\right) = \frac{1}{R_2}\left(\frac{R_4}{R_3+R_4}v_2 - v_o\right)$$

$$v_o = -\frac{R_2}{R_1}v_1 + \frac{1+R_2/R_1}{1+R_3/R_4}v_2$$

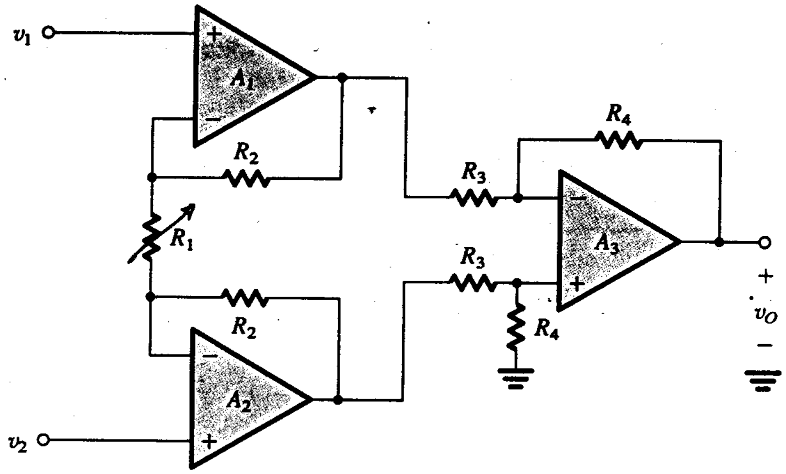
choose $R_2/R_1 = R_4/R_3$, and

$$v_o = \frac{R_2}{R_1}(v_2 - v_1)$$



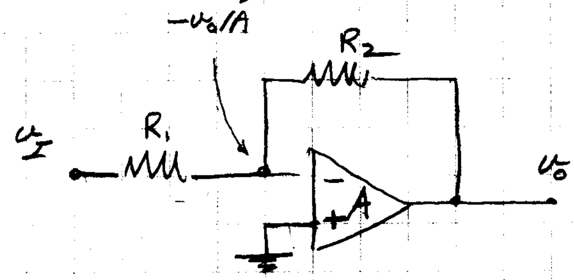
input resistance, common mode
$\frac{1}{2}(R_1+R_2)$

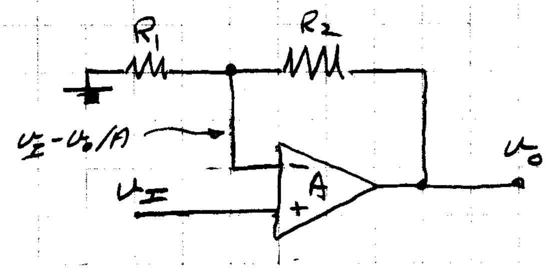
input resistance, differential mode
$2R_1$



a better circuit.
- high input impedance
- single gain adjustment

2.2 Finite and Frequency Dependent Open Loop Gain





Open loop gain is finite, though usually large.

$$\frac{v_I + v_o/A}{R_1} = \frac{-v_o/A - v_o}{R_2} \qquad\qquad \frac{v_I - v_o/A}{R_1} = \frac{v_o - v_I + v_o/A}{R_2}$$

$$\frac{v_o}{v_I} = G = \frac{-R_2/R_1}{1 + (1+\frac{R_2}{R_1})/A} \qquad\qquad \frac{v_o}{v_I} = G = \frac{1 + R_2/R_1}{1 + (1+\frac{R_2}{R_1})/A}$$

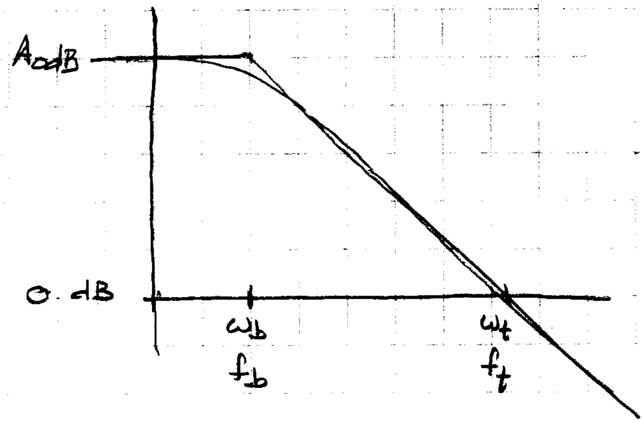
$$= -\frac{R_2}{R_1}\,\frac{\beta A}{1+\beta A} \qquad\qquad = \left(1+\frac{R_2}{R_1}\right)\frac{\beta A}{1+\beta A}$$

$$= (1-\beta^{-1})\,\frac{\beta A}{1+\beta A} \qquad \beta = \frac{R_1}{R_1+R_2} \qquad = \frac{1}{\beta}\,\frac{\beta A}{1+\beta A}$$

If $\beta A \gg 1$, then G (closed loop gain) not sensitive to the actual value, and $v_+ \approx v_-$.

- The open loop gain depends on frequency like a STC lowpass

$$A = \frac{A_o}{1 + j\,\omega/\omega_b}$$



unity gain bandwidth

$$\omega_t = A_o\,\omega_b \qquad f_t = A_o f_b$$

We don't much care what the gain is around ω_b or less (why?). At higher frequencies,

$$A \approx \frac{A_o \omega_b}{j\omega} = \frac{\omega_t}{j\omega} = \frac{f_t}{jf} = \frac{f_t}{f}\angle -90^\circ$$

- Effect on closed loop

$$\frac{\beta A}{1+\beta A} = \frac{1}{1 + \frac{1}{\beta A}} = \frac{1}{1 + j\,\omega/\beta\omega_t}$$

The 3 dB bandwidth is now $\omega_{3dB} = \beta\omega_t < \omega_t$

Note that $\beta = \frac{1}{G}$ for noninverting, so if you want more gain, you sacrifice bandwidth ω_{3dB}. In fact,

$$G\,\omega_{3dB} = \omega_t = \text{constant} \qquad \text{(non inverting)}$$

$$G\,f_{3dB} = f_t$$

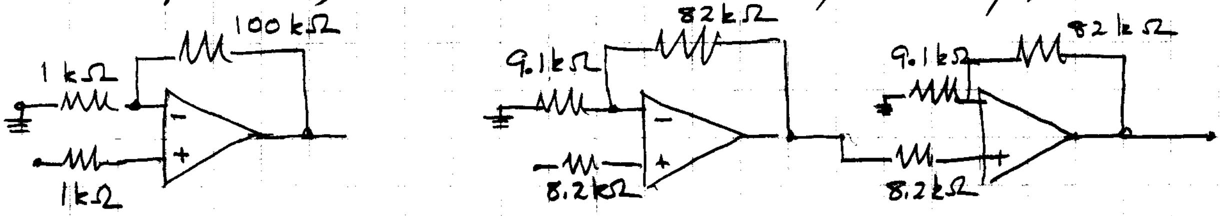
and

$$(1+G)\,f_{3dB} = f_t \qquad \text{(inverting)}$$

- The constant gain bandwidth product is very important when you deal with wideband signals. For example, suppose the signal has 20 kHz bandwidth and the op amp has 1 MHz unity gain bandwidth. If we need 40 dB of amplification, is there a problem?

  - We need an amplitude gain $A_v = 100$. This makes $f_{3dB} = 1\,\text{MHz}/100 = 10\,\text{kHz}$. The signal will be grossly distorted.

  - But if we did it in two stages of 20 dB ($A_v = 10$), then each stage has $f_{3dB} = 100\,\text{kHz}$, and the cascade is down 6 dB at 100 kHz and only 0.34 dB (4% in amplitude) at 20 kHz. That's probably fine.



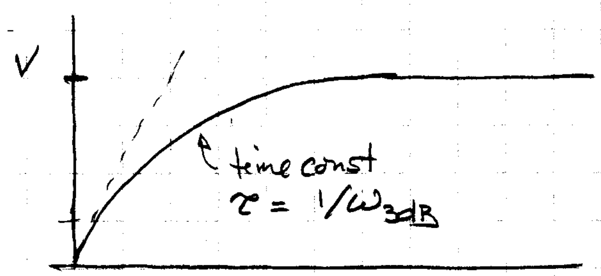
2.3 Slew Rate

- Op amps have another limitation on rate of change of the output voltage. The derivative is limited to the slew rate

$$\left|\frac{dv_o}{dt}\right| \le \text{slew rate} \qquad (0.5\ \text{V}/\mu\text{s for 741})$$

This shows up for signals with large amplitude and/or high frequency.

Example — step response.

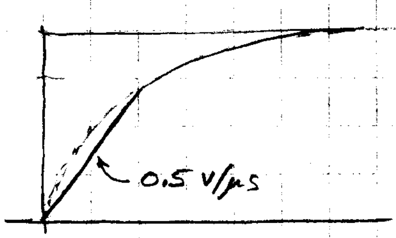


$$V(1 - e^{-\omega_{3dB} t})$$

initial slope $V\omega_{3dB} = 2\pi V f_{3dB}$

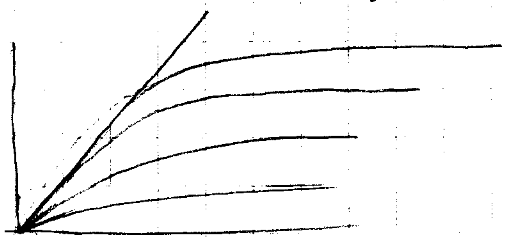
If $2\pi V f_{3dB} <$ slew rate, no problem, amplifier behaves as predicted by STC model.

But suppose $f_{3dB} = 20$ kHz, $V = 10$ V and it's a 741?

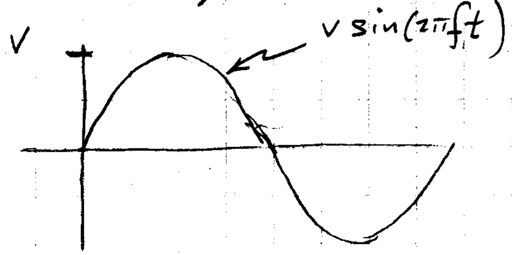


$2\pi V f_{3dB} = 1.25$ volts/μs
initial slope

Note that if $V = 4$ V, then $2\pi f_{3dB} V \cong 0.5$ V/μs



For sinusoidal input

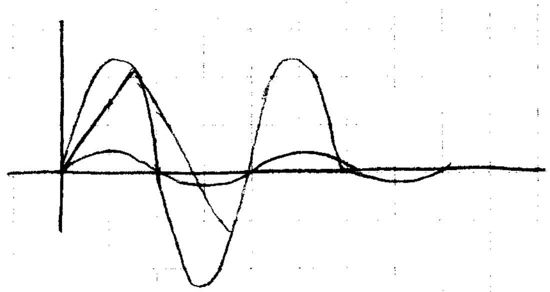


max slope $2\pi f V$

We could design a 100 kHz bandwidth, and feel safe with a 50 kHz sine wave. But if the amplitude V is

$$V > \frac{\text{slewrate}}{2\pi f} = \frac{0.5 \text{ volt/μs}}{2\pi\ 50/\text{ms}} = 1.6 \text{ volt}$$

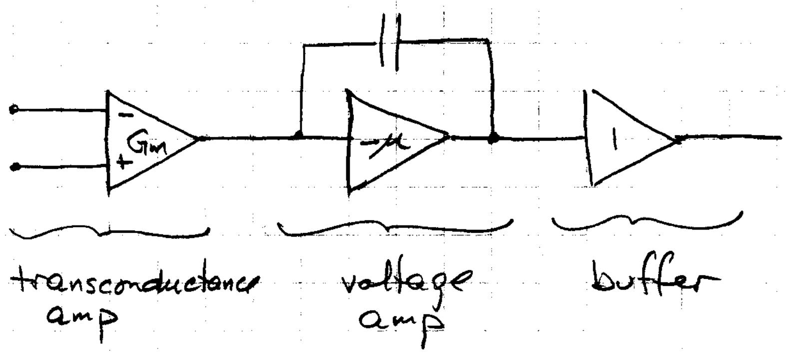
then distortion...



So the safe feeling was deceptive!

2.4 Inside The Op Amp

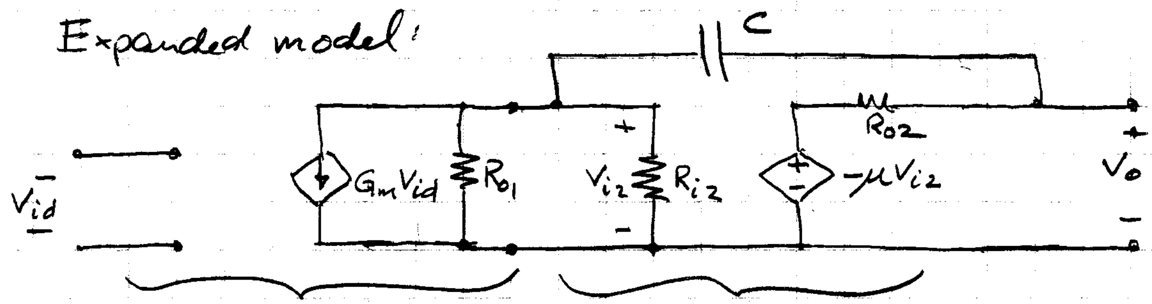
- Both the bandwidth limitation (ω_t) and the slew rate limitation have their origin in an internal capacitor



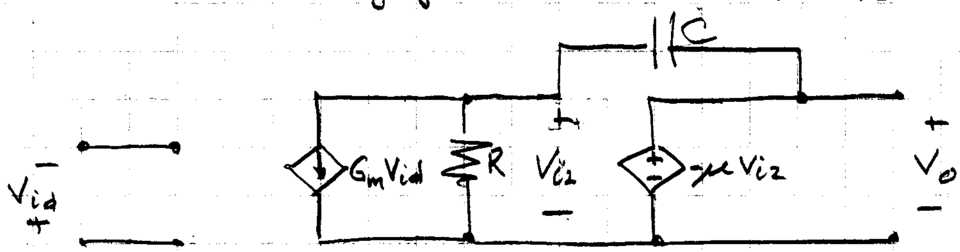
simplified model of op amp

The capacitor is deliberate — it prevents oscillation at very high frequencies.

- Expanded model:

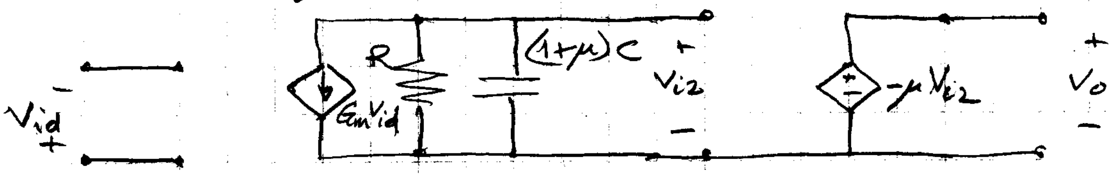


- R_{o2} is negligible. Combine $R_{o1} \parallel R_{i2} = R$



- Solve by circuit analysis, or just oberve that the voltage difference across C is $(1+\mu) V_{i2}$, so $1+\mu$ times as much current as through C to ground; equivalently $(1+\mu)C$ to ground.

very simple equivalent



dc gain $= -\mu G_m R$, time constant $= RC(1+\mu) = \frac{1}{\omega_b}$

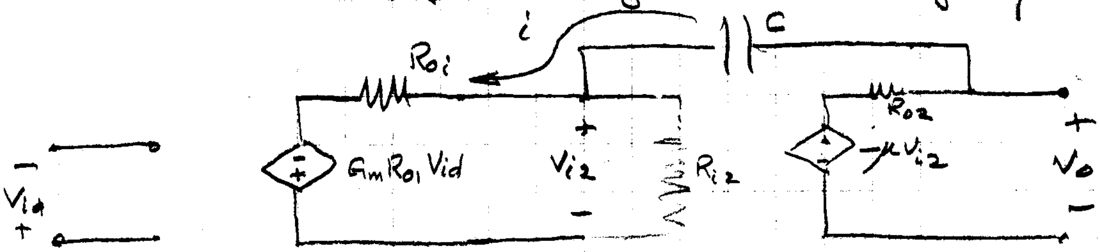
transfer function $\frac{-\mu G_m R}{1 + sRC(1+\mu)}$

unity gain frequency

$$\frac{\mu G_m R}{\omega_t RC(1+\mu)} = 1 \implies \omega_t \cong \frac{G_m}{C}$$

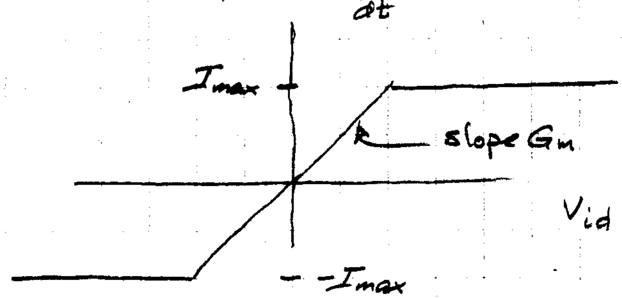
so the larger the compensating capacitor, the lower the unity gain frequency.

- slew rate; rearrange the original model slightly



- ignore R_{i2} (very large), so all current flows through C
- virtual ground at V_{i2} (negative feedback, large μ)
- $\frac{dV_o}{dt} = \frac{1}{C} i = \frac{G_m}{C} V_{id}$

but voltage $G_m R_{o1} V_{id}$ is limited, so current $G_m V_{id}$ is limited, so $\frac{dV_o}{dt}$ is limited



A limitation on dV_o/dt value, as well as on V_o value.