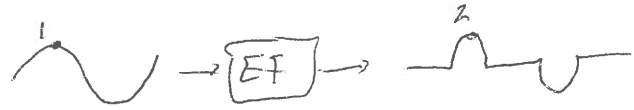
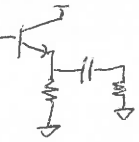
Output Stage & Inedence & Review	Op-amp summary	What is Stability?	ROOT Locus Intro	Gain & Phase Margin
- Clarify emails - why does R loaded EF clip? - Lab test setup & a fair comparison --- backaccb... etc.	- Have diff input & low Zo - Need to gain ↳ Gain stage - Tend to put in feedback, use cure	- No oscillations definition ↳ vs. non-linearity - Passive systems don't oscillate - Accidental vs. purposeful FB & spotting stability	- L(s) setup - True gain & steady-state error - Open-loop vs closed loop gain & poles - want to work w/ L(s)	- Link between Bode & crossing to RHP - Define ϕ margin (covers b) - compensation - max cap load
			6.1.1-4	9.2-3

- Before we start I want to take any Qs you have about output stages and emails
  - ↳ where does power come from if not Vdd
  - ↳ MPTT clear up
    - control L: make S
    - control S: make zero
- we also need to visit impedances in output stages in more detail
  - only one device on in push-pull or class AB
  - looks like weird EF w/ according Rin & Rout, pick V_{BIA} as avg?
  - Measuring Rout



  - ↳ need to compare linear spots where amp is on
  - ↳ eg: $V_2 = (V_1 - 0.7) \cdot \frac{R_L}{R_{out} + R_L}$ & need to correct -0.7 shift
  - Class AB like +ve or -ve EF, comes w/ I_B so can get eg: $g_m|_{I_B}$
- Fair comparisons
  - ↳ compare linearity under same power delivery ← initial plan
  - ↳ compare under constant input ← easier
  - ↳ you don't need to fix non-linearity, just explain it
  - ↳ eg:

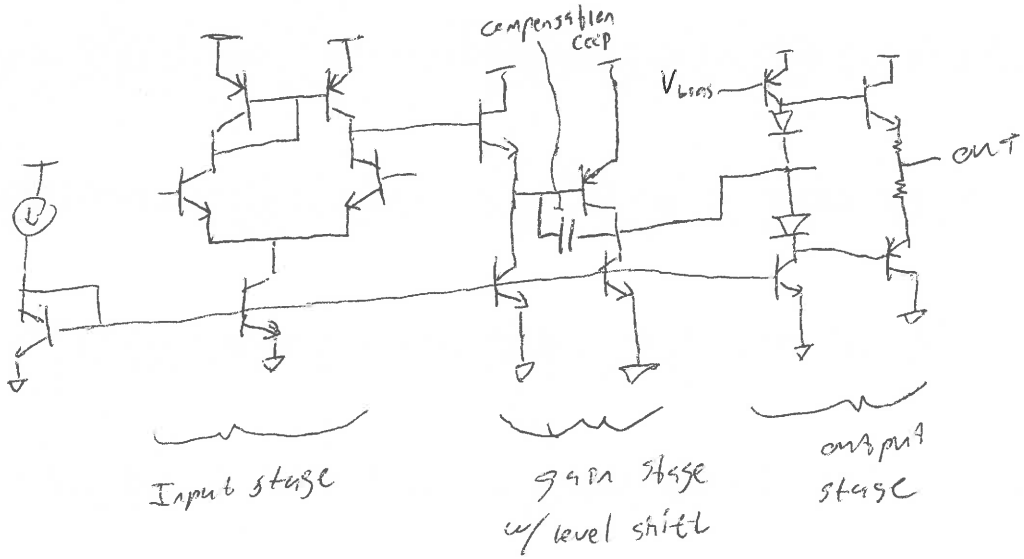


$i_C = i_E + i_L$

$I_S e^{(v_b - v_e)/\phi_T} = \frac{v_E(t)}{R_E} + \frac{V_{cc}/2 - v_E(t)}{R_E}$

- numerical solve → $v_E(v_b)$
- Competing effects @ v_E

Op-amps have 3 things: diff input w/ high Zin ✓
infinite gain ← don't have yet
zero Zout ✓



- DC coupled & uses a level shift
- slew rate
- Compensation cap
  - Big miller feed cap → small BW
  - why there?

- Almost always use op-amps in feedback which has big implications for gain stage
- That's b/c any time you hear "feedback" → think "risk of instability"

What is stability

↳ lots of formal definitions: Lyapunov, Nyquist, BIBO

↳ for us, means: does not latch up & does not oscillate (ok for amplifiers)

↳ can see in f domain: only see energy @ f we put in (+ harmonics if non-linear)

Oscillations come from poles on imaginary axis

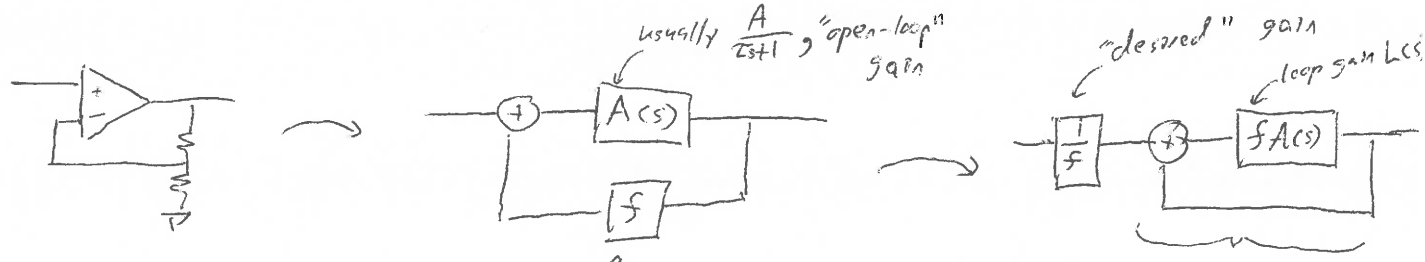
↳ poles might swing to RHP & back to LHP ~ describing functions

↳ but our amps have LHP poles (exact analysis)

↳ feedback <u>moves poles</u> (example in a second)

↳ we have parasitic feedback ~ load rings & make Vin big ~ have tiny high f excitation @ all times
~ supply moves

Tiny intro to root locus techniques



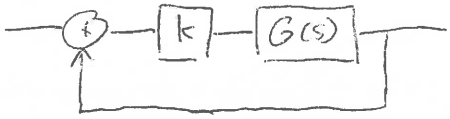
$$A_{CL} = \frac{V_o}{V_i} = \frac{1}{f} \cdot \frac{L(s)}{1+L(s)}$$

"closed loop" gain

$$\text{error} = \frac{1}{1+L(s)} \approx \frac{1}{L(s)}$$

↳ approx as L(0) if slow

- root-locus techniques designed for P control system



Let $G(s) = \frac{G}{\tau s+1}$, note $L(s) = k\,G(s)$

$$\frac{v_o}{v_i} = \frac{\frac{kG}{\tau s+1}}{1+\frac{kG}{\tau s+1}} = \frac{kG}{\tau s+1+kG} = \underbrace{\frac{k}{1+k}}_{\text{error from here}} \cdot G \cdot \underbrace{\frac{1}{\frac{\tau}{k+1}s+1}}_{\text{pole has moved!}}$$

— can draw pictures showing how pole moves called root-locus diagrams

— Good @ drawing diagrams lets us reason about L(s) (usually well known) w/o thinking about $A_{cl}(s)$ (usually pain in butt)

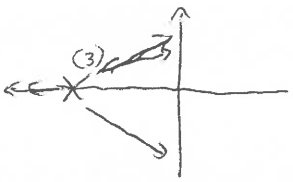
— Aside: in op-amp example $A_{cl} \approx \frac{1}{f}$ & pole location $\propto \tau/Af$ $(k = Af)$

↳ smaller f increases τ & increases gain

↳ leads to constant gain-bandwidth product ← result of 1st order roll-off in op-amps

↳ $\tau = \frac{1}{\omega_c}$ so $\omega_c = \frac{Af}{\tau}$. $\omega_c \cdot A_{cl} = \frac{Af}{\tau} \cdot \frac{1}{f} = \frac{A}{\tau}$ ← constant! prod BW is setting A_{cl} closed-loop

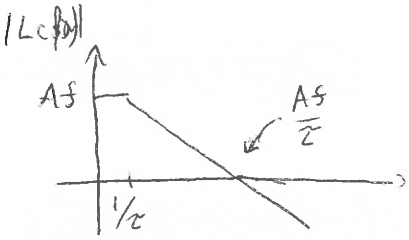
- we don't have full root-locus training, want fast way to get from $L(s)$ to stability
- circuit design done w/ awesome hack called phase margin



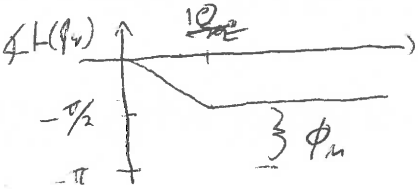
- care where closed loop poles are on $j\omega$ axis or RHP
- Definitely unstable if $L(s) = -1$ b/c $A_{CL} \to \infty$
- If becoming unstable, poles crossing imaginary axis
- Can find $L(j\omega) = -1$ to get instability, comes from Bode.

Can easily find $L(j\omega) = -1 \to |L(j\omega)| = 1$ & $\measuredangle L(j\omega) = -\pi$

- Look for $|L(j\omega)| = 1$ on Bode plot ... called crossover



- (crossover corresponds to non-unity gain in feedback loop comprised of $L(s)$ → rolloff in A_{cl})



- Distance from 180° of phase @ crossover is your phase margin
- How far are you from crossing imaginary axis?
  - ~ v. dicey in conditionally stable systems

→ positive ϕ_m usually means stable ←

You try ~ system w/ 2 widely spaced poles, 2nd pole @ crossover

- can relate ϕ_m to peak overshoot
- 45° very modest → $Q = 3$ or $\zeta = 0.12$

$\phi_m = 45°$ ← classy point

Coming up
- Feedback applications → oscillators!
- why do op-amps look like 1 pole?
  ie: what is the virtue of compensation cap?