Midterm 1: \( n=37 \), \( G=11 \)

Midterm 2: probably paper

Op-amps
- What operations?
- Structure
- LM324
- Cases 2 stage.

Mathematical operation amplifier

1940s anti-aircraft artillery M-9 gun director

Parkinson

1952 KZ-LW
- \( A_0 = 20,000 \)
- \( W_n = 2 \text{Mhz} \)

Philbrick
- \( \pm 50 \text{V swing into 50k\Omega} \)
- 150V plate-to-cathode
- \( I_p = 300 \mu A \), \( I_s = 10nA \)
- \( V_{os} = -1.5 \text{ to } 0.75 \text{V} \)
- \( V_{sup} = \pm 300 \text{V} \)

Apollo
- Nike
- EC128 before 1980

How do you simulate a differential element?

Building block: summing amp.

Input

Virtual ground

\[ V_i = \text{inputs could be from other mathematical operations} \]
\[ i_n = C \frac{dv_i}{dt} \]
\[ v_o = -R_f C \frac{dv_i}{dt} \]
\[ i_n = \frac{v_i}{R} \]
\[ v_o = -\int_0^t \frac{i_n}{C} dt = -\int_0^t \frac{v_i}{RC} dt \]

At \( t=0 \), when voltage was reset, the system is an "integrator wind-up".

With a log table, even addressing can multiply:

\[ A \cdot B = \exp\left(\ln A + \ln B\right) \]

4 operations
4 op-amps

Initially tubes, then NPN, then integrated NPN
NPN, NPN
integrated PMOS, NMOS, CMOS

Can solve any linear ODE
EE128 Lab
Apollo (countless weapons systems)
Non-linear

\[ i_n = I_3 e^{-\frac{V_i}{V_{TH}}} \]
\[ v_o = -R_f I_3 e^{-\frac{V_o}{V_{TH}}} \]
\[ v_o = v_{+2} \ln\left(\frac{V_i}{V_3}\right) \]

Bias network

Big differential gain
Low common mode gain

More gain
Output

Compensation (Miller)
Low impedance high swing
Simplest (terrible)

- Low gain
- Low impedance

Better

- ...more text...

1936

\[ \frac{V_{TH}}{I_C} \parallel \frac{V_C}{I_C} = \frac{V_{TH}}{I_C} \]

Better

- Increase input resistance
- Darlington

\[ \frac{I_{C4D}}{I_{B4}} = \frac{I_{CE}}{\beta_4} \]
\[ \frac{V_{T4D}}{I_{C4D}} = \frac{\beta_4 \cdot V_{TH}}{I_{C4D}} \]

\[ \beta_4 \beta_3 \cdot V_{TH} \]

But now \[ V_{IL} = V_{CC} - V_{BE4} - V_{BE4D} \]

\[ V = \text{same} \]
Vb too low

Sense input and substitute!

Input impedance:

Add parallelism (50)

Find:

Diff gain (common mode)

Complementary

Output swing

Slow rate

Power supply rejection ratio

Noise

Gain stage 4.5

550pF parallel 1kR

2kR

1kR

Complementary

Vc = upside down LM324

Add an NPN VBE to swing Vc back up

Comes 2 steps

R1 and V1 = 1kR

V1 = 1kV

R2 = 2.5k
Current mirrors

Q: if \( \frac{W}{L} \) (W, L) same
- \( V_a \), \( m_{OX} \) same
- \( V_s \), \( V_c \) same

and \( g = 0 \), how different can \( I_D \), \( R \) be?
- Assume both \( V_D \) in saturation

\[
I_D = \frac{m_{OX} \cdot \frac{W}{L}}{2} \cdot \left( 1 + \frac{V_D}{V_a} \right) \]

\[
\frac{I_D}{I_0} = \frac{m_{OX} \cdot \frac{W}{L} \cdot V_a}{2} \cdot \left( 1 + \frac{V_D}{V_a} \right)
\]

\[
\frac{\Delta I_D}{I_D} = \frac{m_{OX} \cdot \frac{W}{L} \cdot V_a}{2} \cdot \left( 1 + \frac{V_D}{V_a} \right)
\]

E.g. \( g = 10 \), \( V_D = 1 \)

\[
\frac{\Delta I_D}{I_D} = \frac{10 \cdot \frac{W}{L} \cdot V_a}{2} \cdot \left( 1 + \frac{1}{V_a} \right)
\]

= \( \frac{\Delta V_D}{V_D} = \frac{\Delta V_D}{V_a} \)

- 10% \( I_D \)

To set sources and sinks, mirror to top

To vary \( \frac{W}{L} \)

Make integer ratios (copies of same base transfer)

Can still have rational fractions

\[
\left( \frac{m}{L} \right)_0 = N \left( \frac{m}{L} \right)_0 \quad \left( \frac{m}{L} \right)_3 = M \left( \frac{m}{L} \right)_0
\]

\[
\frac{I_D}{I_{DS}} = \frac{M}{N}
\]

Longer channels a good idea