Subject to **Negative Feedback** ...

\[ v^+ \approx v^- \]

\[ v^+ - v^- = \frac{v_{out}}{A_{vd}} \quad A_{vd} \to \infty \]
\[ \approx 0 \]

\[ i^+ \sim 0 \quad i^- \sim 0 \]

**Supply Voltages Bound** \( v_{out} \)

\[ V^- \leq v_{out} \leq V^+ \]
Determine Node Voltages $v_x$ and $v_y$
Exercise 1

Build Me

$$V_{out} = ?$$
\[ v^+ \text{ (outside)} = 0 \quad \rightarrow \quad v^+ \text{ (inside)} = v_{os} \]
Offset Source and Adjustment

Symmetry?
Put Ice on Me

LM741

$V_{os}$ Variation?

Exercise 2

Variation?
Digital to Analog Conversion

Why?
- Analog World
- Music, Video, Actuators, ...

Given Bits \( b_1, b_2, b_3, \ldots \)

Voltage Reference

Most Significant Bit

\[ v_{out} = V_{ref} \left( b_1 2^{-1} + b_2 2^{-2} + b_3 2^{-3} + \ldots \right) \]
3-Bit String DAC

\[ b_x = \begin{cases} 
  1 & \text{switch closed} \\
  0 & \text{switch open} 
\end{cases} \]

Example: 101

\[ \frac{5V_{ref}}{8} \]

**N Bits:**

- **2**\(^N\) Resistors
- **2 x (2**\(^N\) - 1\) Switches

High Speed!
4-Bit Current-Mode DAC

\[ \begin{align*}
    &b_x = \begin{cases} 
    1 & \text{switch closed} \\
    0 & \text{switch open} 
    \end{cases} \\
    &v_{out} = \frac{V_{ref}}{R} \left( 2^{-1}b_1 + 2^{-2}b_2 + 2^{-3}b_3 + 2^{-4}b_4 \right)
\end{align*} \]

\[ i' = b_1i_1 + b_2i_2 + b_3i_3 + b_4i_4 \]

\[ v_{out} = i'R_f \]
Integrated-Circuit Resistors

R Specified in Ohms/Square $\Omega/\square$

Large-Value IC Resistors Are Physically Large (Long)
4-Bit R-2R Current-Mode DAC

\[ i_{\text{ref}} = \frac{0 - (-V_{\text{ref}})}{R} \]

\[ i_1 = \frac{V_{\text{ref}}}{2R} = i_{x1} \]

\[ i_2 = \frac{V_{\text{ref}}}{4R} = i_{x2} \]

\[ \text{etc.} \]

N Bits:
2N + 1 Resistors
N Switches
4-Bit R-2R Current-Mode DAC

\[ v_{out} = \frac{V_{ref}}{R} \left( 2^{-1}b_1 + 2^{-2}b_2 + 2^{-3}b_3 + 2^{-4}b_4 \right)R_f \]

\[ i' = b_1i_1 + b_2i_2 + b_3i_3 + b_4i_4 \]

\[ b_x = \begin{cases} 
1 & \rightarrow \text{virtual ground} \\
0 & \rightarrow \text{ground} 
\end{cases} \]
4-Bit R-2R Voltage-Mode DAC

To Op-Amp Amplifier and Output

Example: 0100

\[ v_y = V_{ref} \left( \frac{3R \parallel 2R}{3R \parallel 2R + 2R} \right) = \frac{3V_{ref}}{8} \]

\[ v_x = v_y \left( \frac{2R}{R + 2R} \right) = \frac{V_{ref}}{4} \]

\[ b_x = \begin{cases} 
1 & \rightarrow V_{ref} \\
0 & \rightarrow \text{ground}
\end{cases} \]
Offset Error and Gain Error

Both Easily Adjusted to Zero

Offset Error

Gain Error

Digital Input (v_{LSB})

Analog Output (v_{LSB})

offset error

gain error
Non-Adjustable - Critical Specifications

Integral Non-Linearity

Differential Non-Linearity

INL and DNL

Digital Input

Analog Output ($v_{\text{LSB}}$)

INL error
At 100

1 LSB

DNL error
at 011
MX7245 Parallel-Input DAC (12 Bits)
MAX5231 Serial-Input DAC (12 Bits)

Offset Adjusts
### Table 1. Serial Data Format

<table>
<thead>
<tr>
<th>MSB &lt; 16-bits of serial data &gt; LSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Control Bits</td>
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<tr>
<td>C2..C0</td>
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</tbody>
</table>

### Table 2. Serial-Interface Programming Commands

<table>
<thead>
<tr>
<th>16-BIT SERIAL WORD</th>
<th>FUNCTION</th>
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<tbody>
<tr>
<td>C2</td>
<td>C1</td>
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<tr>
<td>0</td>
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X = Don't care.

* S0 must be zero for proper operation.
MAX5231 INL and DNL Data