Electronics Switches & Controls

- Conventional controls
  - Potentiometer
  - switches
- Transistor as switches and controls
  - FET-based
  - BJT-based
Variable potentiometers

- Variable resistance sometime needed (see Labs)

- Potentiometer provides such a variable resistance.

- Make sure the circuit works for any transistor from this batch.

\[ V_L = \frac{R_2 R_L}{R_1 R_L + R_2 R_L + R_1 R_2} \cdot V_s \]
Electronics Switches

-Switches are elements with two states « Open » and « Close »

-Simplest switches are mechanical switches
Refresher on transistors

- Transistors can be used as switches, to control resistance, etc…

**BJT**

\[ I_E = I_B + I_C \]

**FET**

\[ I_G = I_S + I_D \]

**JFET P-channel**

**JFET N-channel**
### Operating mode of a NPN BJT

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Equation Descriptions</th>
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</table>
| **Active mode** | $V_{BE} \approx 0.7V$  
$\sim 0.3V < V_{CE} < V_{CC}$  
$I_c \approx \beta I_B$                     |
| **Open mode**   | $I_B \approx 0$  
$V_{CE} \approx V_{CC}$  
$I_C \approx 0$                                         |
| **Sat. mode**   | $V_{BE} \approx 0.8V$  
$V_{CE} \approx 0.2V$  
$I_c \neq \beta I_B$                     |

- **Active mode**: $I_C = \beta I_B$, $V_{CE} < V_{CC}$
- **Open mode**: $I_C = 0$, $V_{CE} = V_{CC}$
- **Sat. mode**: $V_{BE} = 0.8V$, $V_{CE} = 0.2V$, $I_c \neq \beta I_B$

$V_{CC} = \text{external voltage source supply to } C \text{ and } E$. $V_{CE}$ cannot be larger than $V_{CC}$!

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Operating mode a NPN BJT

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Condition</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active mode</td>
<td>$V_{BE} \approx -0.7V$</td>
<td>$-0.3V &lt; V_{CE} &lt; V_{CC}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$I_c \approx \beta I_B$</td>
</tr>
<tr>
<td>Open mode</td>
<td>$I_B \approx 0$</td>
<td>$V_{CE} \approx V_{CC}$</td>
</tr>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

Active mode: $\sim 0.7V$

Open mode: $\sim 0.8V$

Saturated mode: $\sim 0.2V$

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BJT as a switch

$t<0: \quad V_{BE} < 0.7V \rightarrow \text{Open mode}$

$I_{RC} = 0$

$t>0: \quad V_{BE} > \sim 0.8V, \text{so that } R_c I_c \sim V_{CC} \rightarrow V_{CE} \sim \text{few } 100mV$

$V_{CC} \sim \sim 0.2V << V_{CC}$

$I_{RC} = \frac{V_{CC} - 0.2}{R_c} \approx \frac{V_{CC}}{R_c}$

“Closed switch”

“Open switch”

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BJT as a switch

Closed switch

Open switch

\[ I_C \approx \frac{V_{cc}}{R_c} \]

IBmin (Closed switch) \[ \approx \frac{V_{cc}}{R_c \beta} \approx \frac{V_{BE_{min}} - 0.8}{R_B} \]
BJT as a switch: turning on/off a light

- BJT with 5 V voltage source,

- Design a system to switch a 20 mA, 5V lamp on and off,

- The gain factor for a given batch of transistor varies between $100 < \beta < 500$,

- Make sure the circuit works for any transistor from this batch.

\[
i_B = \frac{1}{\beta} i_c \Rightarrow \max(i_B) = \frac{1}{\min(\beta)} i_c \Rightarrow \max(i_B) = 0.2 mA
\]

\[
V_{IN} = V_{BE} + R_B i_B \Rightarrow R_B = \frac{V_{IN} - V_{BE}}{i_B} = \frac{5 - 0.6}{0.2} \times 10^3 = 22 k\Omega
\]
**BJT as an amplifier**

**assumptions:**

- Transistor operates in **active mode** when $v_B = 0$
- **Amplitude** of $v_B$ signal **small** enough to have active mode operation
- In 1st approximation: $V_B \equiv V_{BB} + v_b$
  
  $$\rightarrow I_E \approx \frac{V_B - V_{BE}}{R_E} \approx I_C = I_C^\prime + i_c \quad (I_B < \ll I_C)$$

Neglecting variation of $V_{BE}$:

$$\rightarrow i_c \approx \frac{v_B}{R_E}$$

Finally: $V_{out} = V_{cc} - R_c I_c = V_S + v_s$

with $V_S = V_{cc} - R \cdot I_C$

and

$$v_s = -R_c i_c = -\frac{R_c}{R_E} v_b$$

Signal $v_B$ is amplified by a factor

$$A_v = -\frac{R_c}{R_E}$$

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BJT as an amplifier: light detection

- Previous circuit can be used to amplify low intensity signal, e.g. such as produced in photodiode (typically 1 µA/1µW of incident light)

- Circuit is modified as follows:

  Output voltage is given by:

  \[ V_{OUT} = V_{CC} - R_C I_C \]

  From ground-E-B-ground loop:

  \[ I_C = \frac{V_B - V_{BE}}{R_E} \approx \frac{R_D I_D - V_{BE}}{R_E} \approx \frac{R_D I_D - 0.7}{R_E} \]

  Finally output voltage is:

  \[ V_{OUT} = V_{CC} - (R_D I_D - 0.7) \frac{R_C}{R_E} \]

  \[ = V_{CC} + 0.7 \frac{R_C}{R_E} - \frac{R_D R_C}{R_E} I_D \]

  \[ = \overline{V}_{OUT} - \frac{R_D R_C}{R_E} I_D \]

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Two-states electronics

- When $V_{in} = 0$ transistor is open, $V_{out} = 20$ V

- As $V_{in}$ increases the transistor turns on (active mode) and current begin to flow $\rightarrow V_{out}$ is lowered toward ground.

- Eventually $V_{BE} \approx 0.8$ V (saturated mode), and when $V_{in} \approx 1$ V $\rightarrow I_c = \beta I_b \approx 20$ mA so $V_{OUT}$ is close to 0

- This circuit has only two output states (with exception of $0.8 \ V < V_{in} < 1$ V)

- Two-states electronics important components of digital electronics
FET as control

Pinch-off regime for $V_{DS} > V_{DS_{sat}}$:

$$I_D \approx I_{DSS} \left(1 - \frac{V_{GS}}{V_{GS_{off}}} \right)^2 = k \left(V_{GS} - V_{GS_{off}} \right)^2 \quad k = \frac{I_{DSS}}{V_{GS_{off}}^2}$$

Linear (Ohmic) regime for $V_{DS} < V_{DS_{sat}}$:

$$I_D \approx 2k \left[ \left( V_{GS} - V_{GS_{off}} \right) - \frac{V_{DS}}{2} \right] \cdot V_{DS}$$
When \( V_{GS} \leq V_{GS_{off}} \), the channel is depleted \( \Rightarrow \) transistor is **blocked**

When \( V_{GS_{off}} < V_{GS} < 0 \), and \( V_{DS} > V_{GS} + V_P \), (with \( V_P \sim |V_{GS_{off}}| \)), \( \Rightarrow \) \( ID \) saturate and its value is quadratically dependent upon \( V_{GS} \).

\( V_P \) is the value of \( V_{DS} \) for which \( ID \) saturates and \( V_{GS} \) is zero.

The pinch-off regime occurs for \( V_{DS} = V_{GS} + V_P \) (\( V_{GS} \) is non zero)

For \( 0 < V_{DS} \ll V_{GS} + V_P \), \( ID \) is proportional to \( V_{DS} \) (linear regime) and the slope is smaller as \( V_{GS} \) tends toward \( V_{GS_{off}} \).
FET as resistance control

For $V_{GS} > V_{GSoff}$ and $V_{DS} < V_{GS} + V_P$:

$$R_{DS} \approx \frac{1}{k \cdot \left[ (V_{GS} + V_P) - \frac{V_{DS}}{2} \right]}$$

example:

$$\rightarrow v_{out} = \frac{R_{DS}}{R_{DS} + R} v_{in}$$

= variable attenuation controlled by $V_{con}$

Choosing $R \gg R_{DS_{on}}$, $v_{out}$ varies between $\sim 0$ et $v_{in}$

Problem:
$R_{DS}$ depends on $V_{DS}$ → nonlinear response

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FET as resistance control: a better solution

\[ R_{DS} \approx \frac{1}{k \cdot \left( (V_{GS} + V_P) - \frac{V_{DS}}{2} \right)} \]

\[ V_{GS} = \frac{V_{DS}}{2} + \frac{V_{com}}{2} \quad (I_G \approx 0) \]

\[ R_{DS} \approx \frac{1}{k(V_{com} + V_P)} \]

Better linearity than circuit in previous slide
FET as resistance control: variable frequency filter

- Variably controlled resistance in an low (or high) pass filter
- Dynamical adjustment of cut off frequency

\[ R_{DS} \approx \frac{1}{k(V_{com} + V_P)} \]

\[ \omega \approx \frac{1}{R_{DS} C} \]
FET switch based on MOFSET

Based on a voltage divider

\[ v_{OUT} = \frac{47k\Omega}{R_{DS} + 47k\Omega} v_{in} \]

- When gate at ground

\[ R_{DS} > 10^{10} \Omega \Rightarrow v_{OUT} \approx 0 \]

- When gate at +15 V

\[ R_{DS} \approx 100 \Omega \Rightarrow v_{OUT} \approx v_{in} \]

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FET switch based on MOFSET: example of application

Selection of cut-off frequency

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