FROM LAST TIME...

Electronic Systems
- Semiconductor materials
- Forward and reverse biasing
- Diode characteristics
- Diode applications
UNIT 2: ELECTRONIC SYSTEMS

PART C: ACTIVE ELECTRONICS (TRANSISTORS)
RECALL THAT A DIODE IS A P-N JUNCTION
A SECOND p- OR n-TYPE REGION
CREATES WHAT TYPE OF DEVICE?
TRANSISTORS PERFORM SIGNAL AMPLIFICATION AND SWITCHING

- **Amplification** – magnify a signal (voltage/current) by transferring energy from an external source
- **Switching** – controlling a relative large current between or voltage across two terminals using a small control current or voltage

TWO MAJOR TYPES OF TRANSISTORS

Bipolar Junction Transistor (BJT)

Field Effect Transistor (FET)

Current controlled

Voltage controlled
BJT CAN BE VIEWED AS A CURRENT-CONTROLLED CURRENT SOURCE

\[ \alpha_{dc} = \frac{i_C}{i_E} \]

\[ \beta_{dc} = \frac{i_C}{i_B} \]

(usually > 0.98) (usually 50 to 300)
BJT CAN BE VIEWED AS A CURRENT-CONTROLLED CURRENT SOURCE

\[ i_E = i_C + i_B \]

\[ \frac{i_E}{i_C} = 1 + \frac{i_B}{i_C} \]

\[ \frac{1}{\alpha_{dc}} = 1 + \frac{1}{\beta_{dc}} \]

\[ \beta_{dc} = \frac{\alpha_{dc}}{1-\alpha_{dc}} \quad \leftrightarrow \quad \alpha_{dc} = \frac{\beta_{dc}}{\beta_{dc}+1} \]
BJT OPERATES IN THREE MODES

- **Cutoff** – Open Switch (no collector current)
  \[ i_C \approx 0, \quad R_{CE} \approx \infty \]

- **Active Linear** – Current Amplification
  \[ i_C = i_B \beta \]

- **Saturation** – Closed Switch \((V_{CE} \rightarrow 0)\)
  \[ i_C \approx i_C(\text{limit}), \quad R_{CE} \approx 0 \]
**IN ACTIVE LINEAR REGION, BJT AMPLIFIES BASE CURRENT**

**Active Linear** – Current Amplification

\[ i_C = i_B \beta; \quad V_{BE} = V_F; \quad V_{CE} > V_F \]

- \( i_C \) proportional to \( i_B \)
- Current amplification factor \( \beta \) (20 ~ 200) often denoted as \( h, h_f \), or \( h_{FE} \) in datasheets.
- Power dissipated: \( P = i_C \cdot V_{CE} \)
IN CUTOFF AND SATURATION REGIONS, BJT ACTS AS A SWITCH

**Cutoff** – Open Switch (no collector current)

\[ i_B = 0; \quad i_C \approx 0; \quad V_{BE} < V_F; \quad V_{CE} \geq 0 \]

- Voltage \( V_{CE} \) can be viewed as an open switch

**Saturation** – Closed Switch (max. collector current)

\[ i_B > \frac{i_C}{\beta}; \quad V_{BE} = V_F; \]

\[ V_{CE} = V_{SAT} \approx 0.2 \, V \]

- \( i_C \) is controlled by the collector circuit
- Voltage \( V_{CE} \) can be viewed as an open switch
**BASE CURRENT CAN TOGGLE BJT SWITCH**

- **Point A** \([i_B \approx 0\text{ or small } V_{IN} (< 0.6 \text{ V})]\)
  - transistor is *cutoff*
  - \(i_C \approx i_E \approx 0 \Rightarrow V_{OUT} \approx V_{CC}\)
  - Switch open!

- **Point B** \([i_B > i_{B(sat)}\text{ or large } V_{IN} (> 0.7 \text{ V})]\)
  - transistor is *saturated*.
  - \(V_{OUT} = V_{CE(sat)} \approx 0.2 \text{ V (very small!)}\)
  - Switch closed!

\[
i_B = \frac{V_{IN} - V_{BE(SAT)}}{R_B}; \quad i_C \approx \frac{V_{CC} - V_{CE(SAT)}}{R_L}
\]
BASE CURRENT CAN TOGGLE BJT SWITCH

Suggested design rule:

Choose circuit values such that, when $V_{in}$ goes high,

$$i_B > \frac{i_C(\text{limit})}{10}$$

Since $\beta_{dc} > 20$ in most cases, this should force the transistor into hard saturation.
BJT SWITCHING IS NOT INSTANTANEOUS

- $t_D$ (Delay time)
  Time transistor remains off after input current is applied

- $t_R$ (Rise time)
  Time required for $i_C$ to reach 90% of its final value

- $t_S$ (Storage time)
  Time $i_C$ remains close to the maximum value after input current is removed

- $t_F$ (Fall time)
  Time required for $i_C$ to fall to below 10% of its final value
BJT SWITCHING IS NOT INSTANTANEOUS

Turn-ON and Turn-OFF Time

- turn-ON time \( t_{ON} = t_D + t_R \)
- turn-OFF time \( t_{OFF} = t_S + t_F \)

Typical values for 2N3904 transistor:

- \( t_d = 35 \text{ nsec} \)
- \( t_r = 35 \text{ nsec} \)
- \( t_s = 200 \text{ nsec} \)
- \( t_f = 50 \text{ nsec} \)

\( t_{ON} = 70 \text{ nsec} \)
\( t_{OFF} = 250 \text{ nsec} \)
EXAMPLE: BJT AS ON/OFF SWITCH

LED Driver

Select $R_B$ to protect logic control circuit

- Assume TTL signal at $V_{IN}$
  - 5 V = HIGH
  - 0 V = LOW
- Digital output can supply 40 mA when $V_{IN}$ is HIGH
EXAMPLE: BJT AS ON/OFF SWITCH

LED Driver

\[ R_B > \frac{V_{IN} - V_F}{I_{DO,max}} = \frac{4.3 \text{ V}}{40 \text{ mA}} = 107.5 \text{ } \Omega \approx 110 \text{ } \Omega \]

To avoid overloading digital output, might actually double or quadruple \( R_B \)!
EXAMPLE: BJT AS ON/OFF SWITCH

LED Driver

Select $R_C$ to protect LED

- Assume $V_{CC} = 5V$
- Assume LED has forward bias of 2V and maximum power dissipation of 80 mW
EXAMPLE: BJT AS ON/OFF SWITCH

LED Driver

\[ i_{C\text{(max)}} = \frac{P_{\text{max}}}{V_{\text{LED}}} = \frac{80 \text{ mW}}{2 \text{ V}} = 40 \text{ mA} \]

\[
R_C > \frac{V_{\text{CC}} - V_{\text{LED}} - V_{\text{CE(sat)}}}{i_{C\text{(max)}}} = \frac{(5 - 2 - 0.2)\text{V}}{40 \text{ mA}} = 70 \text{ Ω}
\]

To maintain hard saturation, 
\[ i_B > 4 \text{ mA} \Rightarrow R_B < 1075 \text{ Ω} \]
EXAMPLE: BJT AS ON/OFF SWITCH

LED Driver

Shortcoming: Switch circuit works well as long as $V_{CC}$ is sufficiently high. But variations in LED voltage drop or $\beta$ could affect brightness when supply voltage is small.
BJT AS CURRENT SOURCE

Maintain LED brightness by regulating collector current. Eliminate resistor $R_B$ from BJT switch circuit, then add resistor $R_E$. Enforce desired current flow by intelligent choice of $R_E$. Transistor operation is in the active region.
A DARLINGTON PAIR JOINS TWO BJT TRANSISTORS

- Composite current gain is the product of the two stages
- $\beta$ can sometime exceeds 10,000
- Most often found in power electronics that are designed to drive large current load
- Smaller than two individual transistors because the collector is shared

\[ npn \text{ Darlington} \]
INCOMING LIGHT CAUSES A PHOTOTRANSISTOR TO SWITCH

- Special class of transistor whose junction between the base and emitter allows it to act as a photodiode.
- Slower than a photodiode, but with the gain of a transistor.
A PHOTO-INTERRUPTER ACTS AS AN OPTICAL SWITCH

- LED + phototransistor pair can be used to detect the presence of an object that may partially or completely interrupt the light between the LED and phototransistor.
AN OPTO-ISOLATOR PROVIDES CIRCUIT SEPARATION

- LED + Phototransistor pair.
ELECTRO-MECHANICAL RELAY SWITCHES

Images:
http://www.automationdirect.com/adc/Overview/Catalog/Relays-_z-_Timers/Electro-Mechanical_Relays
http://slab.concordia.ca/2009/arduino/relays/
http://paramountindt.tradeindia.com/electromechanical-relay-542067.html
ELECTRO-MECHANICAL RELAYS CAN ISOLATE ELECTRICAL CIRCUITS
ELECTRO-MECHANICAL RELAY SWITCH

Pros:
- Inexpensive
- Large selection
- When properly sized, can handle high currents and voltages
- Resistant to electrical surges

Cons:
- Bulky
- Prone to "sticking" or mechanical fatigue
- Slow (5 to 15 msec) switching time
- Limited cycle rate
- Substantial current needed to pull in relay
SOLID-STATE RELAYS ALSO PROVIDE SWITCHING CAPABILITIES

- May switch AC or DC
- May use optical coupling
FIELD-EFFECT TRANSISTORS (FET) ARE USUALLY EITHER JFET OR MOSFET

- JFET = Junction FET

- MOSFET = Metal-Oxide-Semiconductor FET
A JFET USES A p-n JUNCTION AS THE GATE CONNECTION

- *Reverse* biasing the gate voltage reduces the drain current
- Positive gate voltage is never applied (as it would initiate gate current)
FETS HAVE TWO MODES OF OPERATION

- Depletion Mode: current flow is restricted by narrowing the channel available for current flow.
- Enhancement Mode: current channel is widened to increase current flow.
A MOSFET IS A GOOD POWER DEVICE, AS GATE CURRENT IS LOW

- Devices available that can operate in either *enhancement mode* (gate-source voltage forward biased) or *depletion mode* (gate-source voltage reverse-biased)
- Very high input impedance at the gate – good for digital applications

Enhancement mode
*n*-channel MOSFET
Threshold voltage \( (V_T) \) is the voltage between gate and substrate when n-channel begins to form.

- Allows drain-to-source conduction.
- Threshold voltage may also be denoted as \( V_{GS(on)} \) and is typically between 1 and 5 V.
MOSFETS (ENHANCEMENT-MODE) HAVE FOUR OPERATING REGIONS

- Cutoff state – Transistor is turned OFF
  \[ V_{GS} < V_T \Rightarrow i_D \approx 0; \quad V_{DS} \approx V_{DD} \]

- Ohmic state – Linear (or triode) region
  \[ (V_{GS} > V_T \& V_{DS} < V_{GS} - V_T \ll V_{DD}) \Rightarrow i_D \approx V_{DD}/R_D; \]
  - \( i_D \) controlled by drain circuit
  - Connection from D to S acts as a small voltage-controlled resistor

- Constant current – Active region
  \[ (V_{GS} > V_T \& V_{DS} > V_{GS} - V_T) \Rightarrow i_D \propto (V_{GS} - V_T)^2 \]
  - \( i_D \) controlled by gate-source voltage
  - Power dissipated: \( P = i_D \cdot V_{DS} \)

- Breakdown – Transistor will get VERY HOT!
**GATE VOLTAGE CAN TOGGLE MOSFET SWITCH**

- **Point A** ($V_{IN} < V_T$)
  - transistor is cutoff
  - $i_D \approx i_S \approx 0 \implies V_{OUT} \approx V_{DD}$
  - Switch open!

- **Point B** ($V_{IN} > V_T$)
  - transistor is in Ohmic region
  - $V_{OUT} = V_{DD} - V_{DS} = V_{DD} - i_D(V_{G1}) \cdot R_D$
  - Switch closed!

The MOSFET transistor can be viewed as a gate voltage controlled switch or it can also be viewed as an inverter!
EXAMPLE: CMOS INVERTER

Complementary Metal-Oxide Semiconductor (CMOS)

Jeff Shelton – 22 January 2015
BJT VS. MOSFET (SWITCHING)

Both can be used as current amplifiers:

- BJT: collector current \( i_C \) proportional (linear) to base current \( i_B \).
- MOSFET: drain current \( i_D \) proportional to square of gate voltage \( V_G \).

Both can be used as three terminal switches or voltage inverters:

- BJT switches gave rise to TTL logic.
- MOSFET switches gave rise to CMOS logic.
BJT VS. MOSFET (SWITCHING)

- BJT's usually have larger current capacity than similar sized MOSFETs.
- BJT's have slower switching rates.
- BJT's less susceptible to static voltage spikes.
- MOSFETs have much higher input impedance and are normally off, which translates to less operating power drain.
- MOSFETs more easily fabricated into integrated circuit form.
- MOSFETs less prone to thermal runaway.
COMING UP...

Electronic Systems
  ▪ Interfacing electronic systems
  ▪ Operational amplifiers (op-amps)

Computer Systems
  ▪ Why do Computer Systems matter?
  ▪ Combinational logic
  ▪ Sequential logic
  ▪ Finite state machines