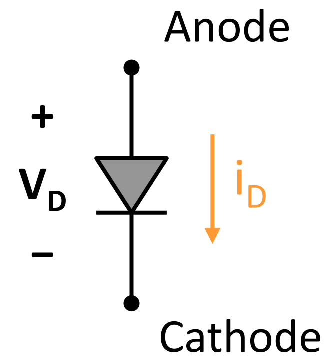
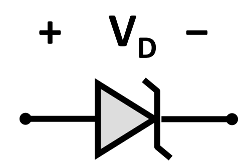
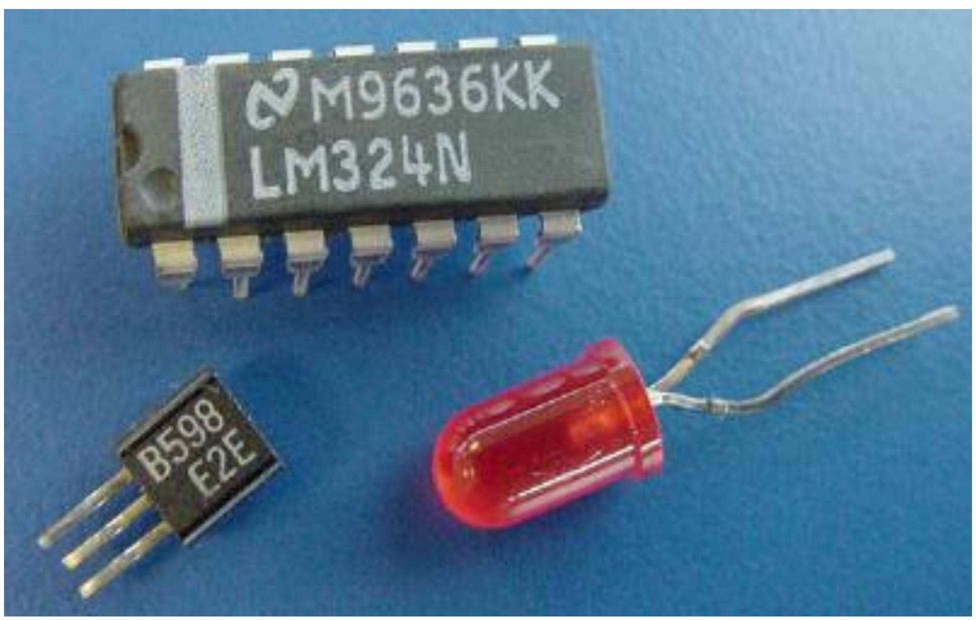
FROM LAST TIME…

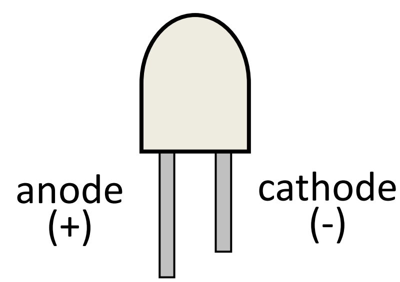
Electronic Systems

- Semiconductor materials
- Forward and reverse biasing
- Diode characteristics
- Diode applications





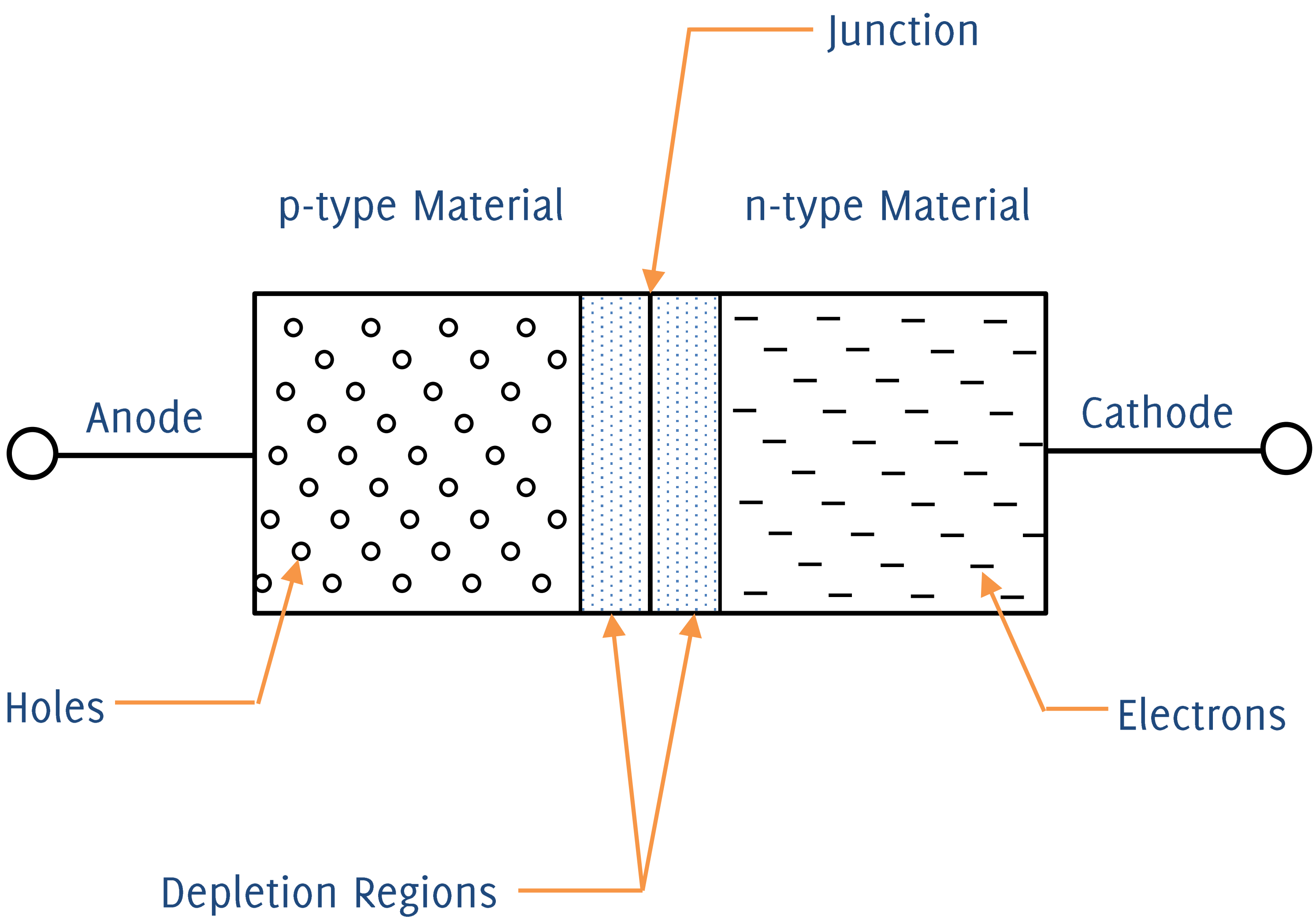




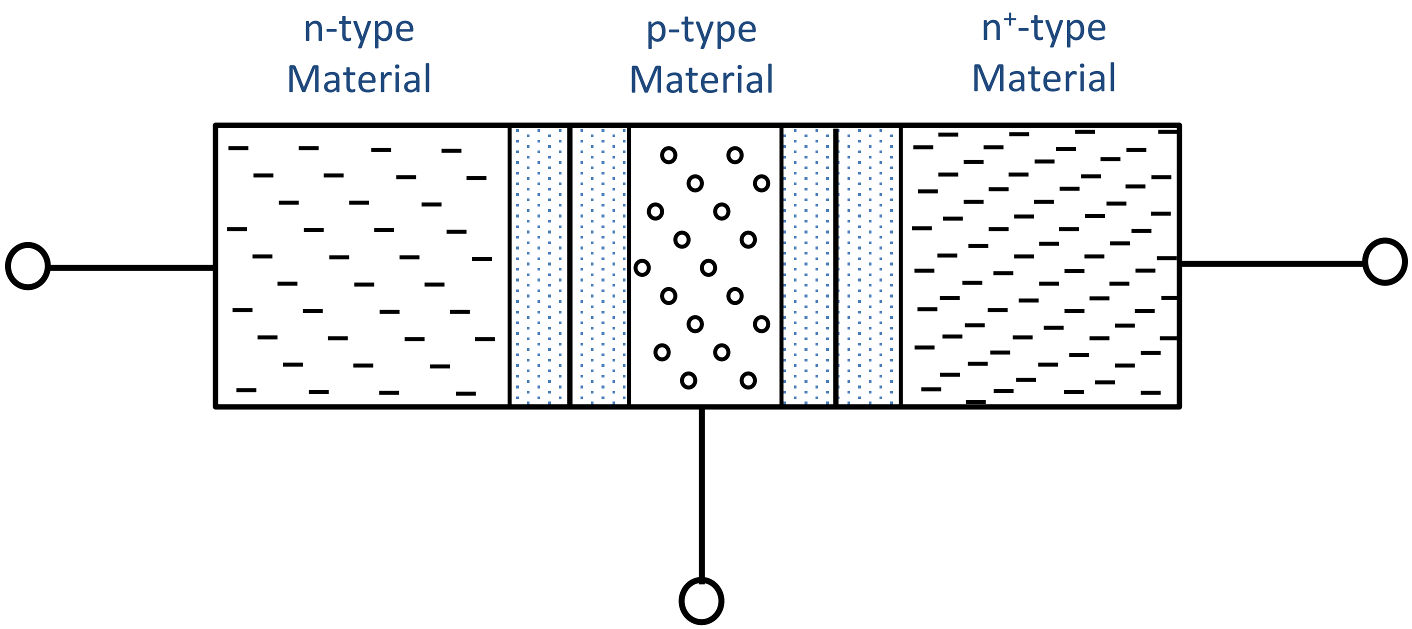
UNIT 2:
ELECTRONIC SYSTEMS

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?



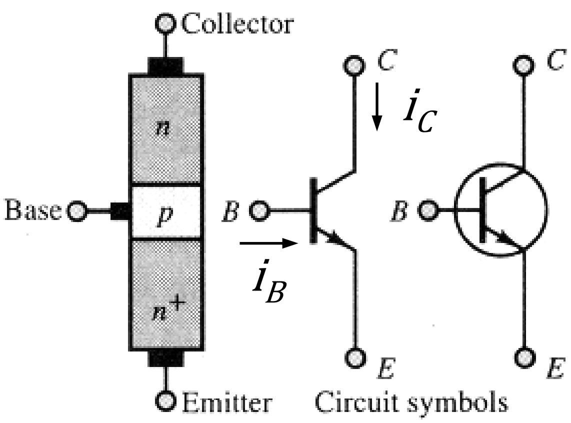
TRANSISTORS PERFORM SIGNAL AMPLIFICATION AND SWITCHING

Image: https://en.wikipedia.org/wiki/File:Transbauformen.jpg

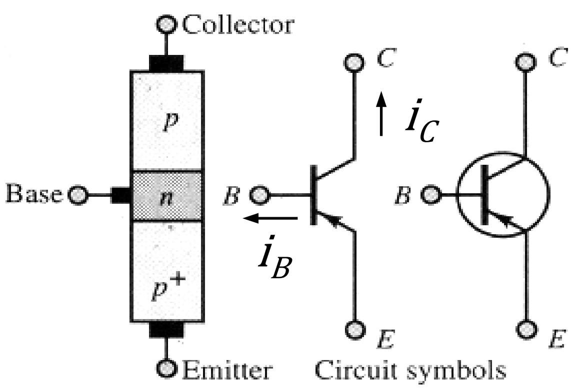
- Amplification – magnify a signal (voltage/current) by transferring energy from an external source
- Switching – controlling a relative large current between or voltage across two terminals using a small control current or voltage

TWO MAJOR TYPES OF TRANSISTORS

Bipolar Junction Transistor (BJT)



npn

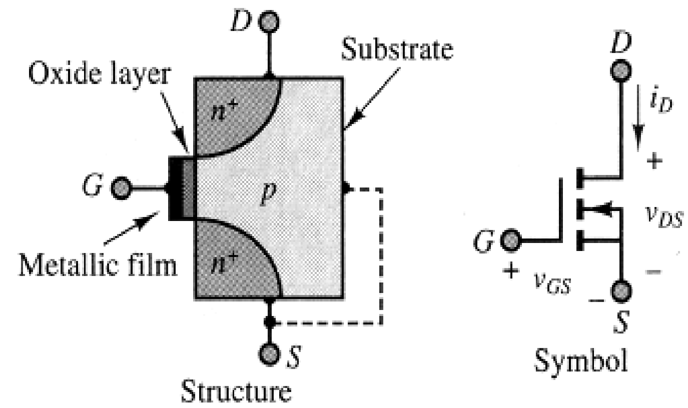


pnp

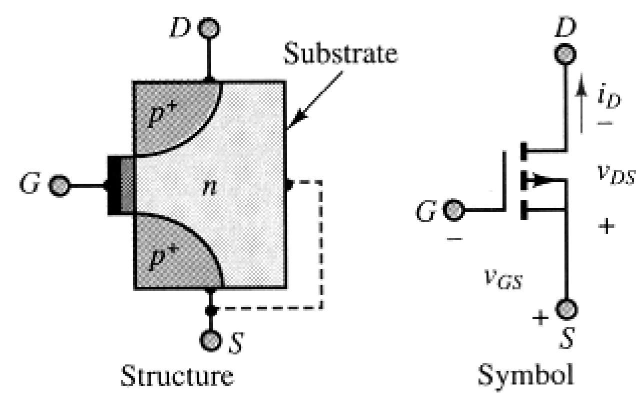
Current controlled

Field Effect Transistor (FET)

MOSFET
n-channel

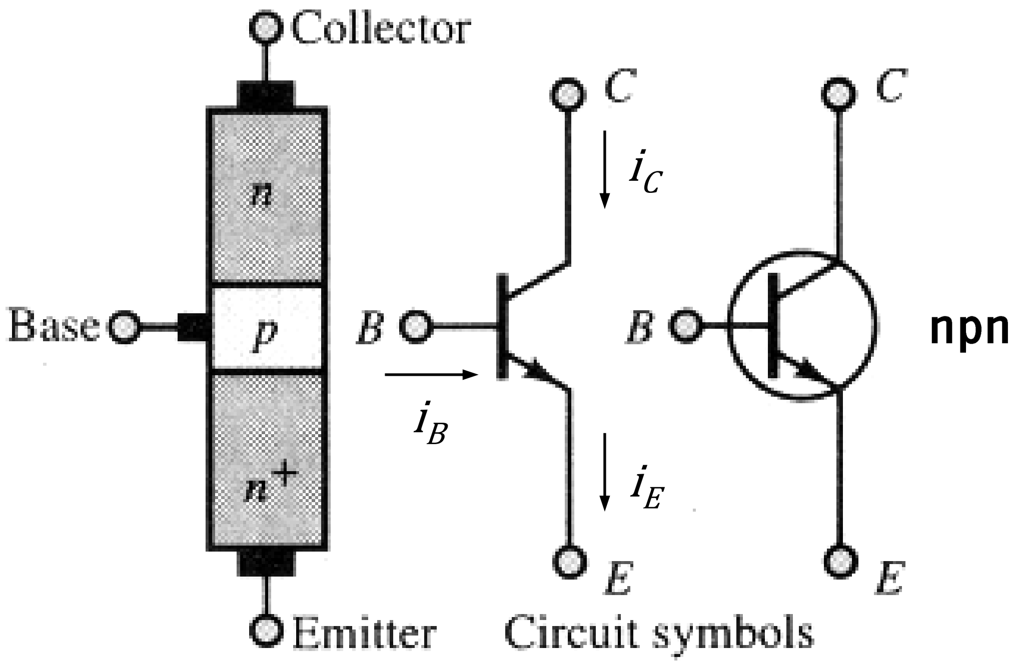


MOSFET
p-channel



Voltage controlled

BJT CAN BE VIEWED AS A CURRENT-CONTROLLED CURRENT SOURCE



$$\alpha_{dc} = \frac{i_C}{i_E}$$ (usually › 0.98)

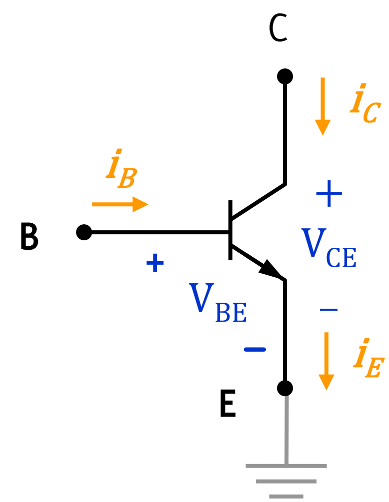
$$\beta_{dc} = \frac{i_C}{i_B}$$ (usually 50 to 300)

BJT CAN BE VIEWED AS A CURRENT-CONTROLLED CURRENT SOURCE

$$i_E = i_C + i_B$$

$$\frac{i_E}{i_C} = 1 + \frac{i_B}{i_C}$$

$$\frac{1}{\alpha_{\text{dc}}} = 1 + \frac{1}{\beta_{\text{dc}}}$$



$$\beta_{\text{dc}} = \frac{\alpha_{\text{dc}}}{1-\alpha_{\text{dc}}} \quad \leftrightarrow \quad \alpha_{\text{dc}} = \frac{\beta_{\text{dc}}}{\beta_{\text{dc}}+1}$$

BJT OPERATES IN THREE MODES

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

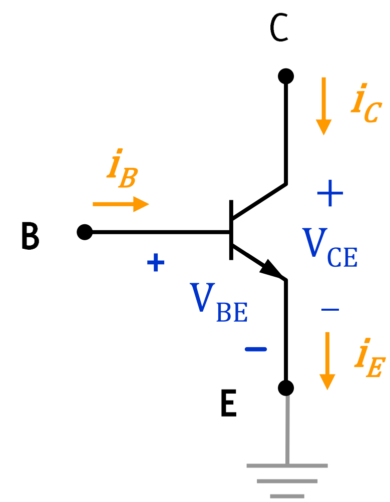
  $i_C \approx 0, \quad R_{CE} \approx \infty$

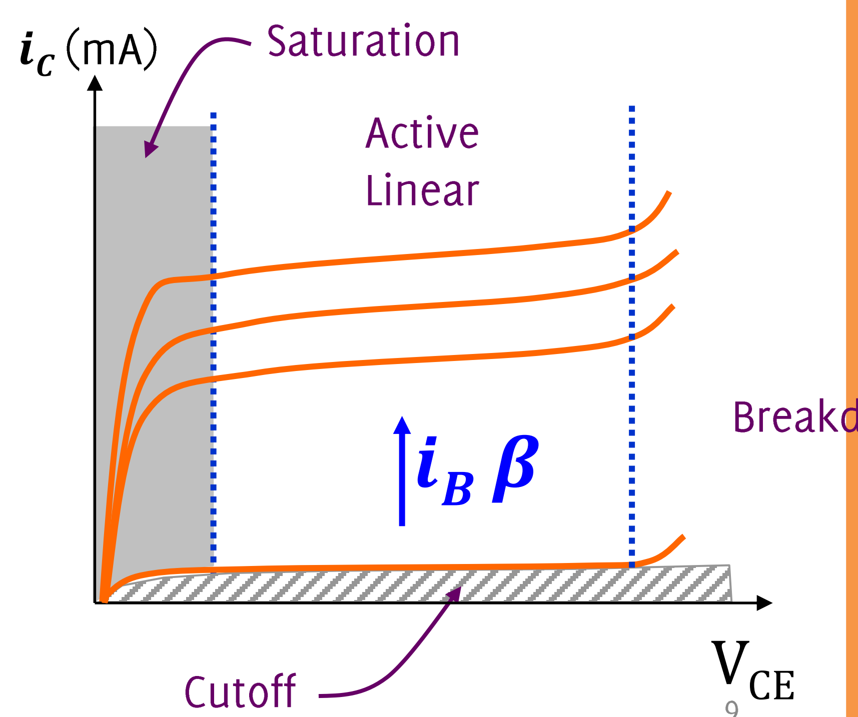
- **Active Linear** – Current Amplification

  $i_C = i_B\,\beta$

- ***Saturation*** – Closed Switch ($V_{CE} \rightarrow 0$)

  $i_C \approx i_{C(\text{limit})}, \quad R_{CE} \approx 0$

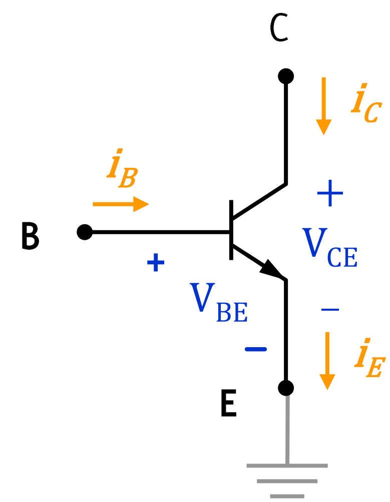




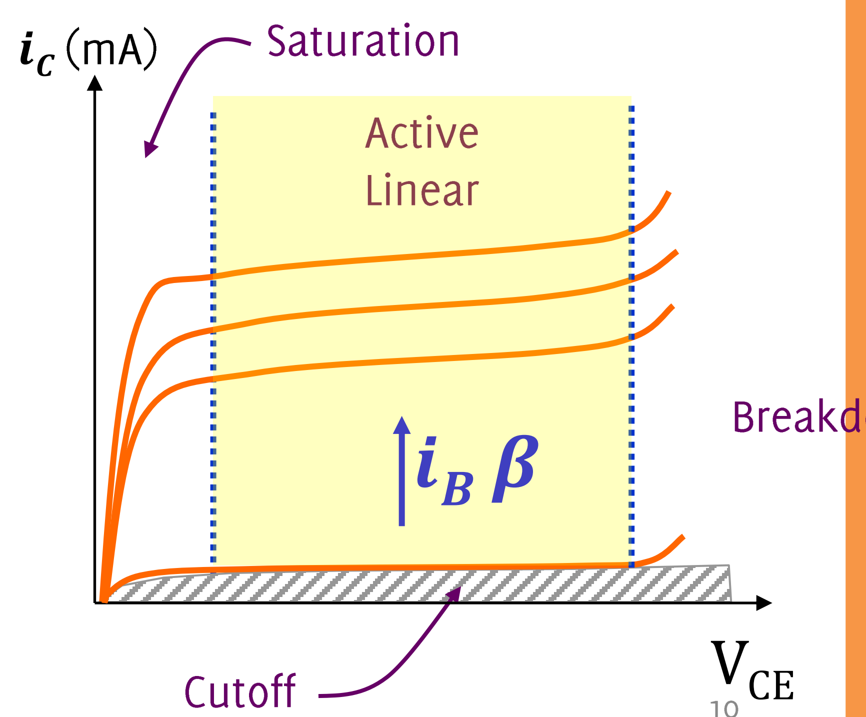
IN ACTIVE LINEAR REGION, BJT AMPLIFIES BASE CURRENT

Active Linear – Current Amplification

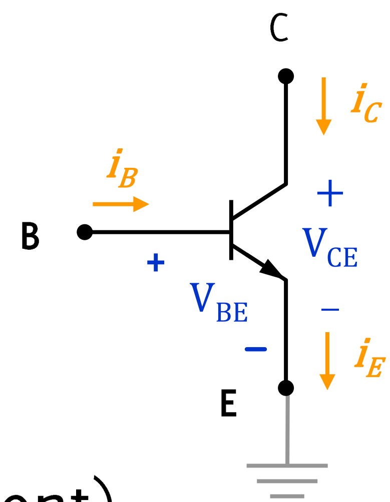
$i_C = i_B\,\beta; \qquad V_{BE} = V_F; \qquad V_{CE} > V_F$



- i_C proportional to i_B
- Current amplification factor β (20 ~ 200) *often* denoted as *h*, *hf*, 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)

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

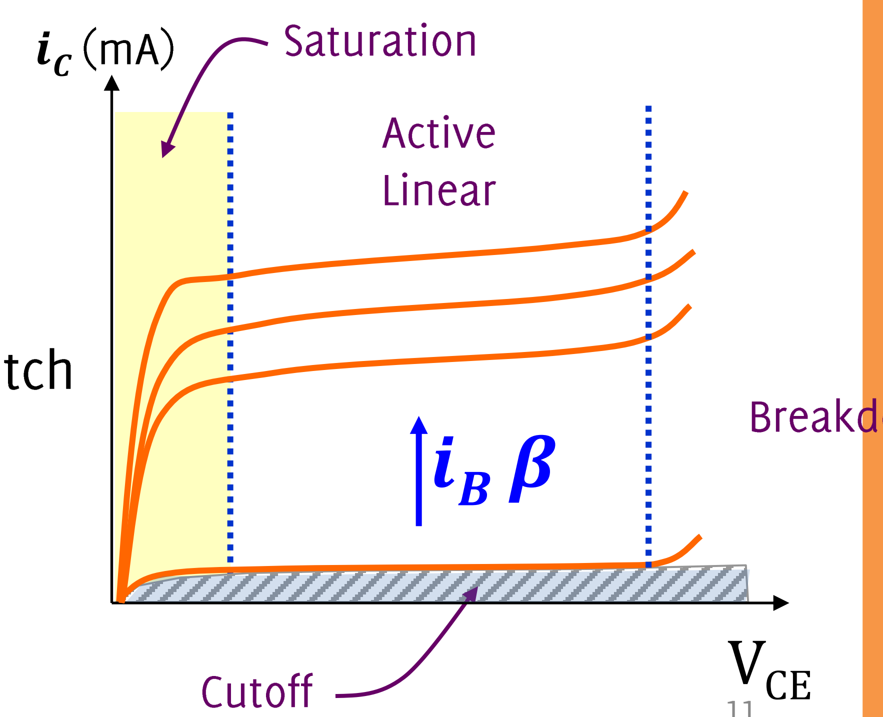
- Voltage V_{CE} can be viewed as an open switch

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

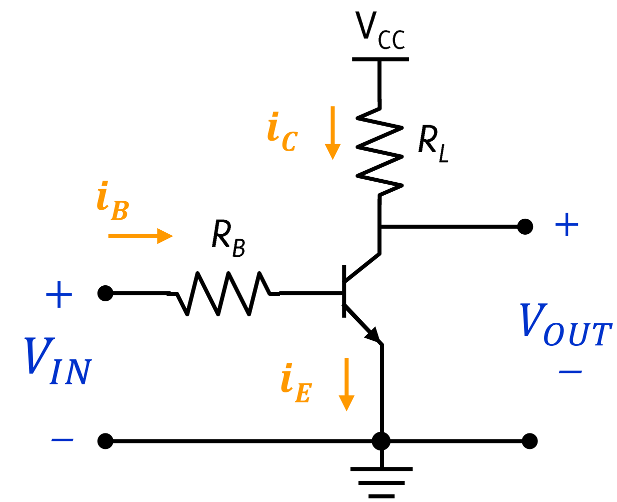


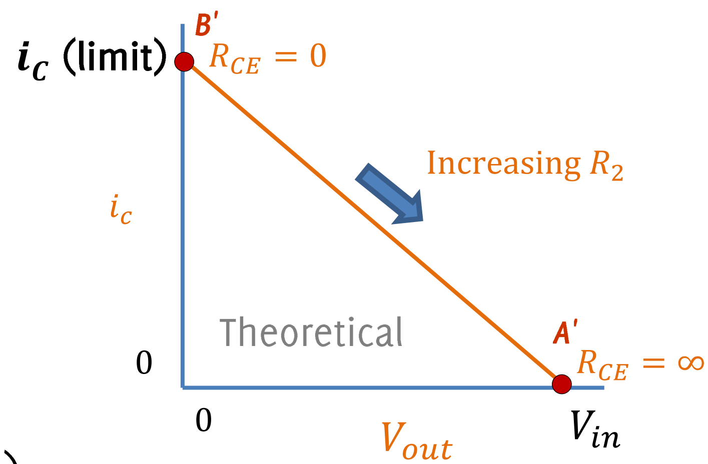
BASE CURRENT CAN TOGGLE BJT SWITCH

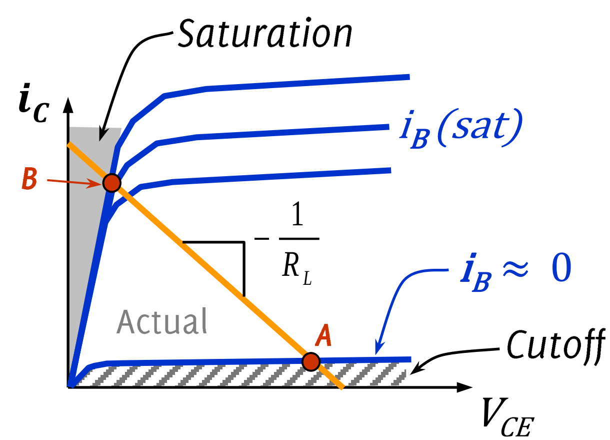
- ***Point A*** [$i_B \approx 0$ or *small* V_{IN} (< 0.6 V)]
  - transistor is ***cutoff***
  - $i_C \approx i_E \approx 0 \Rightarrow V_{OUT} \approx V_{CC}$
  - Switch open!

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

$$i_B = \frac{V_{IN} - V_{BE(SAT)}}{R_B}; \quad i_C \approx \frac{V_{CC} - V_{CE(SAT)}}{R_L}$$







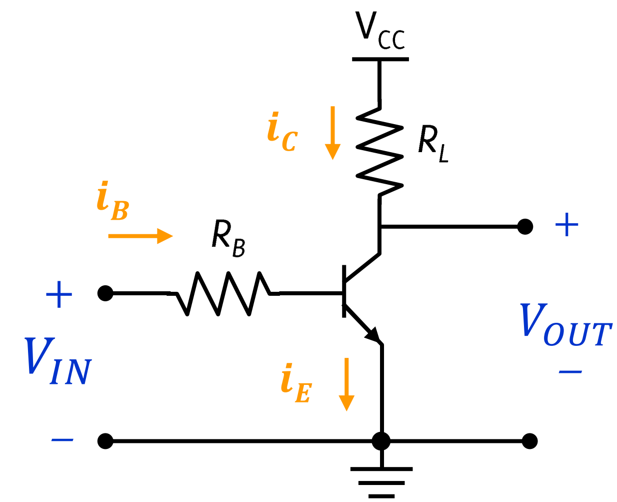
BASE CURRENT CAN TOGGLE BJT SWITCH

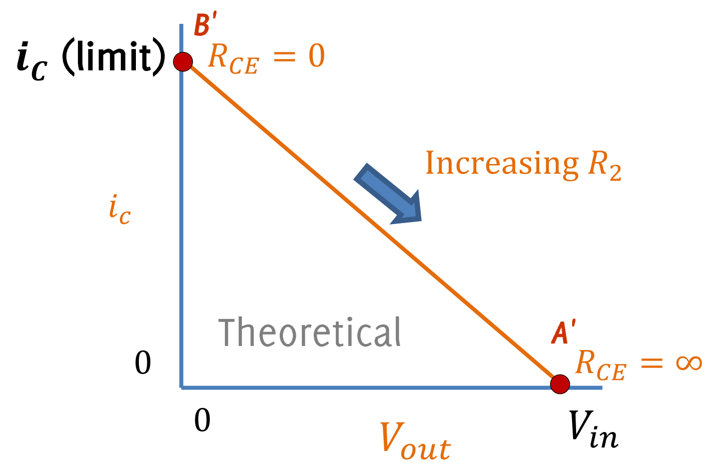
Suggested design rule:

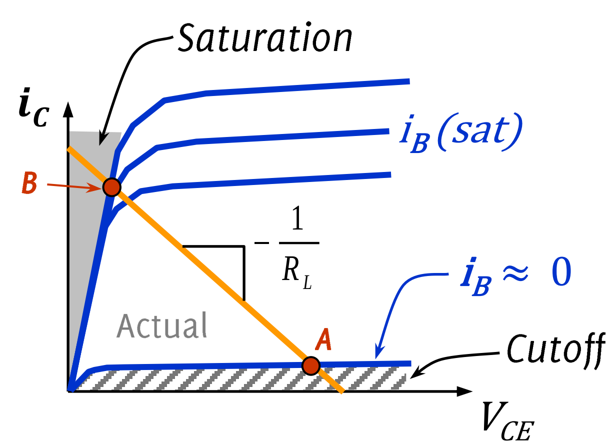
Choose circuit values such that, when V_{in} goes high,

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

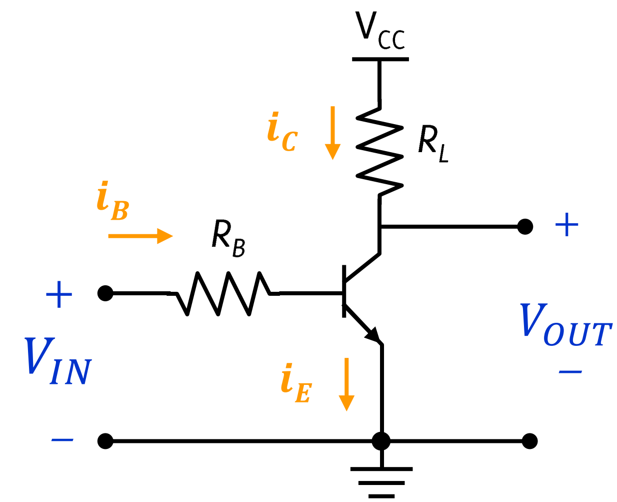
Since $\beta_{\text{dc}} > 20$ in most cases, this should force the transistor into hard saturation.



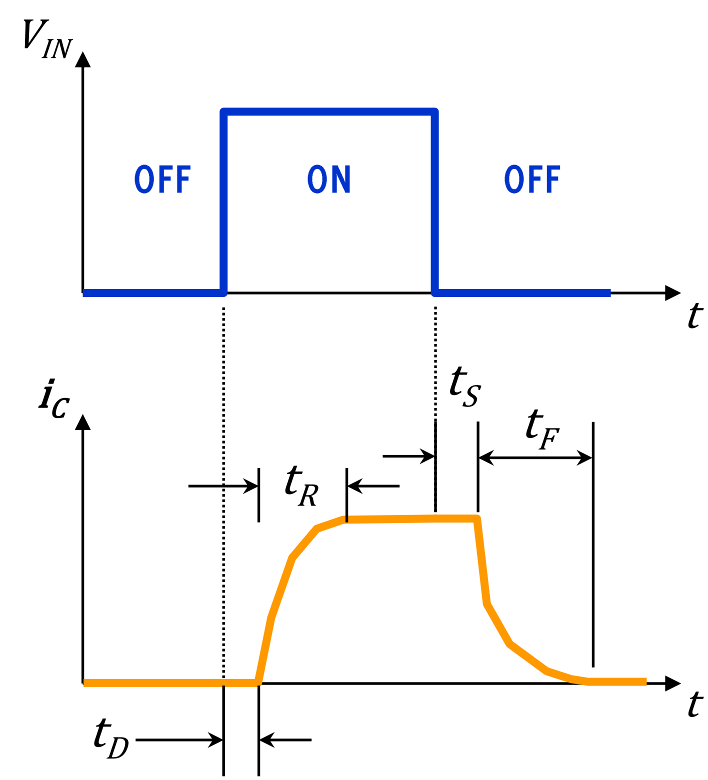




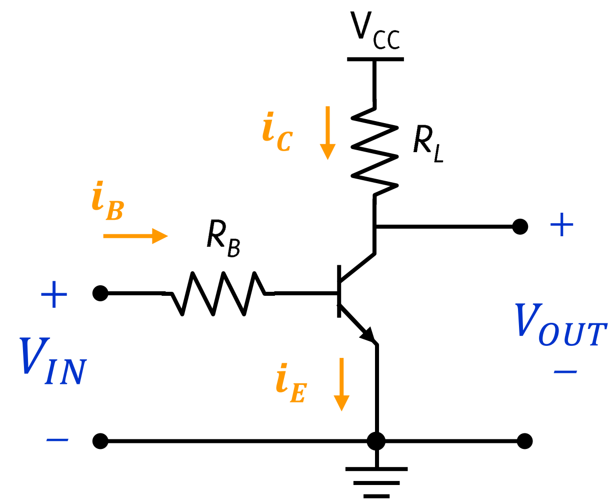
BJT SWITCHING IS NOT INSTANTANEOUS



- 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



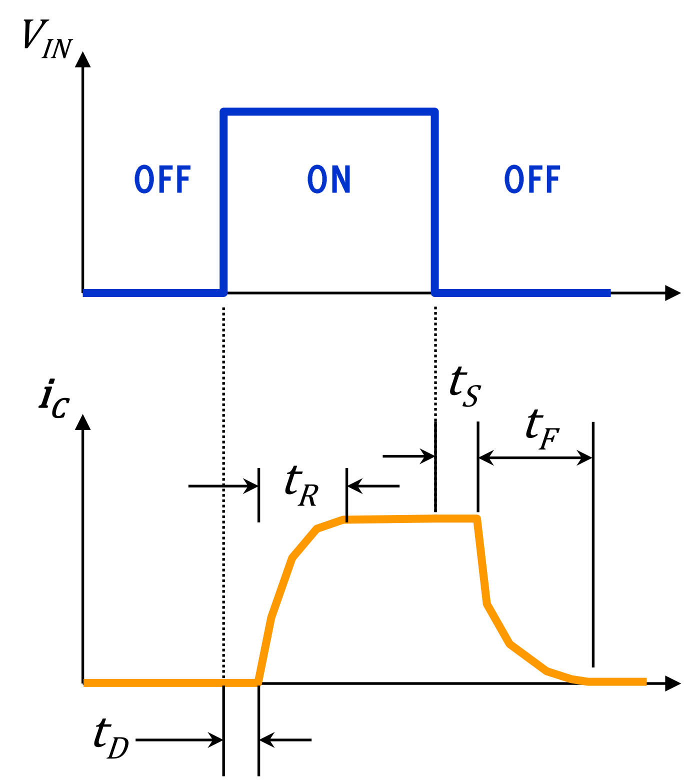
Turn-ON and Turn-OFF Time

- turn-ON time $t_{ON} = t_D + t_R$
- turn-OFF time $t_{OFF} = t_S + t_F$

Typical values for 2N3904 transistor:

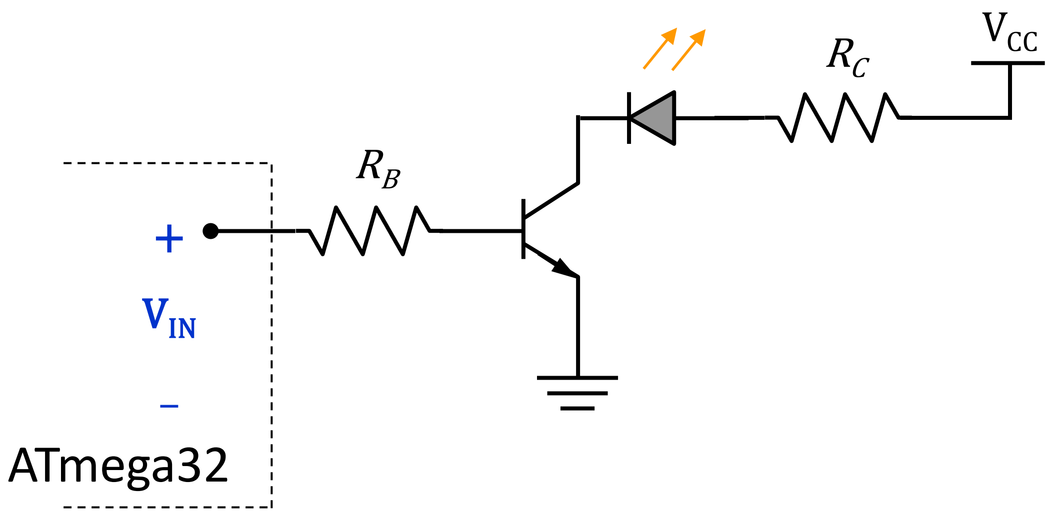
- t_d = 35 nsec
- t_r = 35 nsec
- t_s = 200 nsec
- t_f = 50 nsec

turn-ON time = 70 nsec
turn-OFF time = 250 nsec



EXAMPLE: BJT AS ON/OFF SWITCH

LED Driver

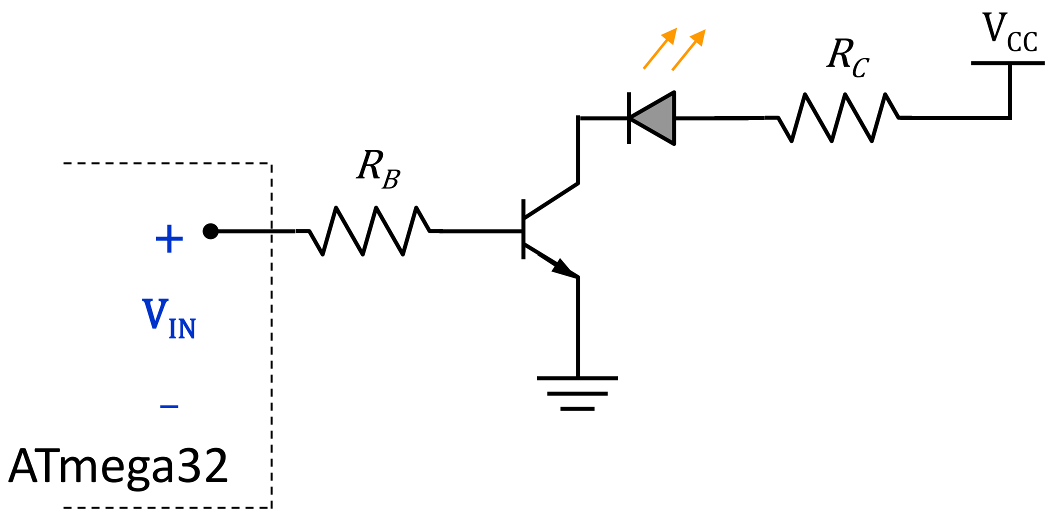


Select R_B to protect logic control circuit

- 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

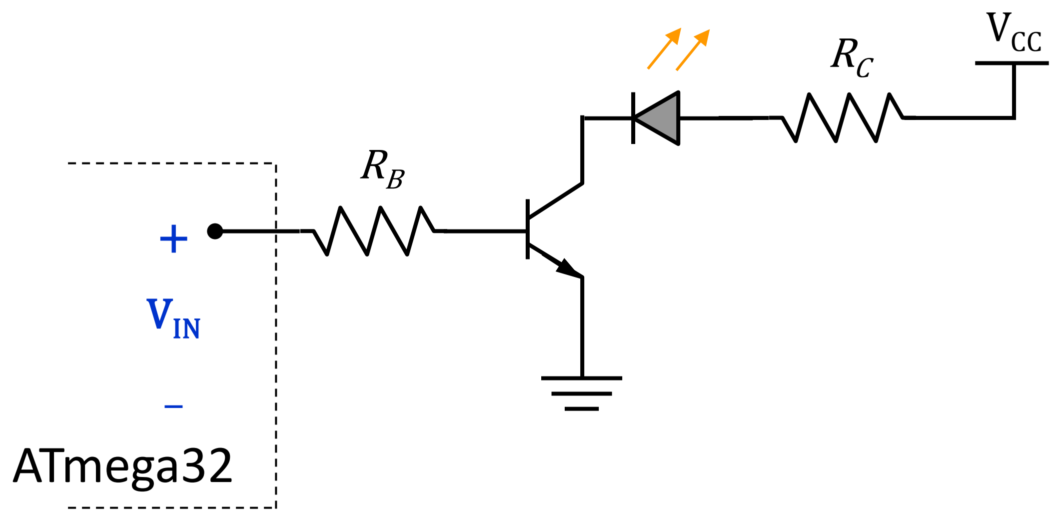


$$R_B > \frac{V_{IN} - V_F}{I_{DO,max}} = \frac{4.3\text{ V}}{40\text{ mA}} = 107.5\ \Omega \approx 110\ \Omega$$

To avoid overloading digital output, might actually double or quadruple R_B!

EXAMPLE: BJT AS ON/OFF SWITCH

LED Driver

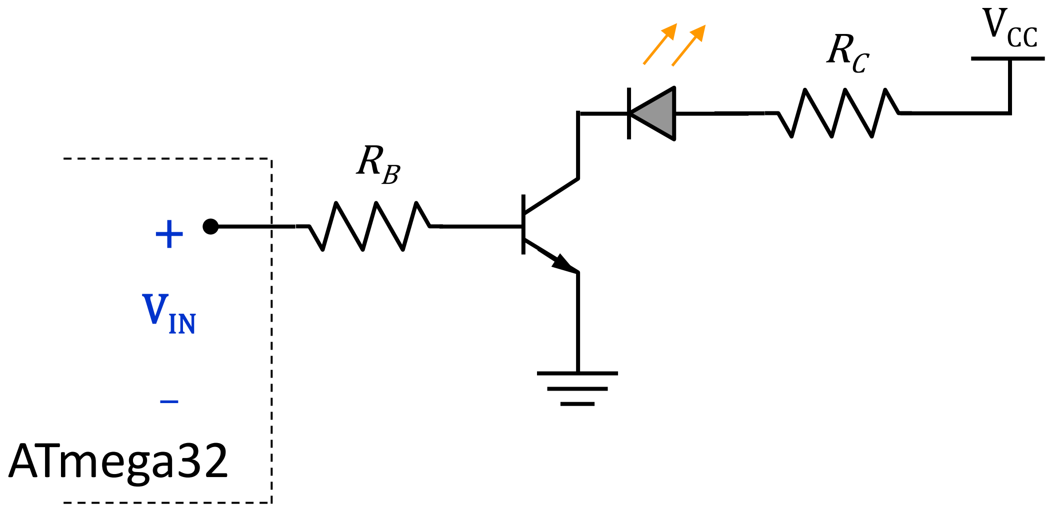


Select R_C to protect LED

- 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



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

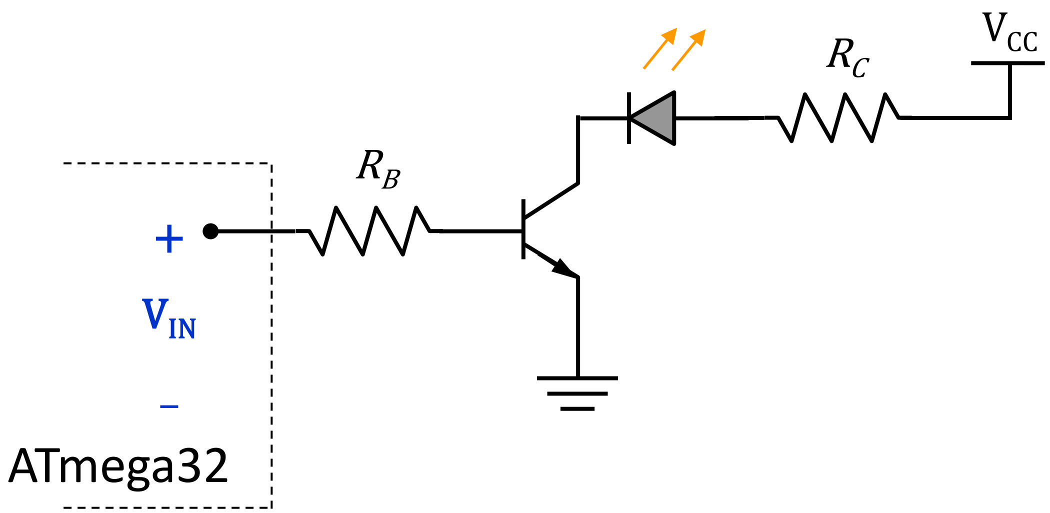
$$R_C > \frac{V_{CC} - V_{LED} - V_{CE(sat)}}{i_{C(\max)}} = \frac{(5-2-0.2)\text{V}}{40\ \text{mA}} = 70\ \Omega$$

To maintain hard saturation,

$$i_B > 4\ \text{mA} \Longrightarrow R_B < 1075\ \Omega$$

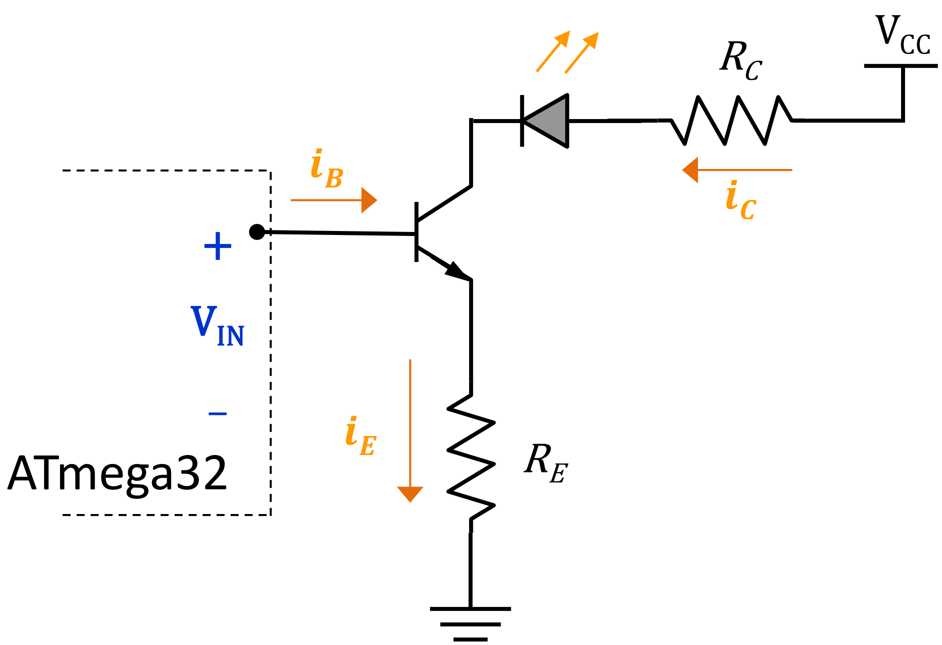
EXAMPLE: BJT AS ON/OFF SWITCH

LED Driver



Shortcoming: Switch circuit works well as long as V_{CC} is sufficiently high. But variations in LED voltage drop or β could affect brightness when supply voltage is small.

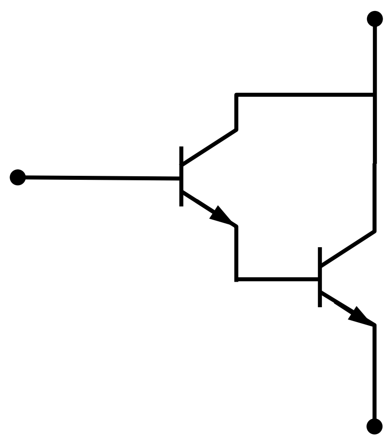
BJT AS CURRENT SOURCE



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

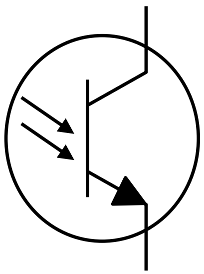
- Composite current gain is the product of the two stages
- β can sometime exceeds 10,000
- Most often found in power electronics that are designed to drive large current load
- Smaller than two individual transistors because the collector is shared



***npn* 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.



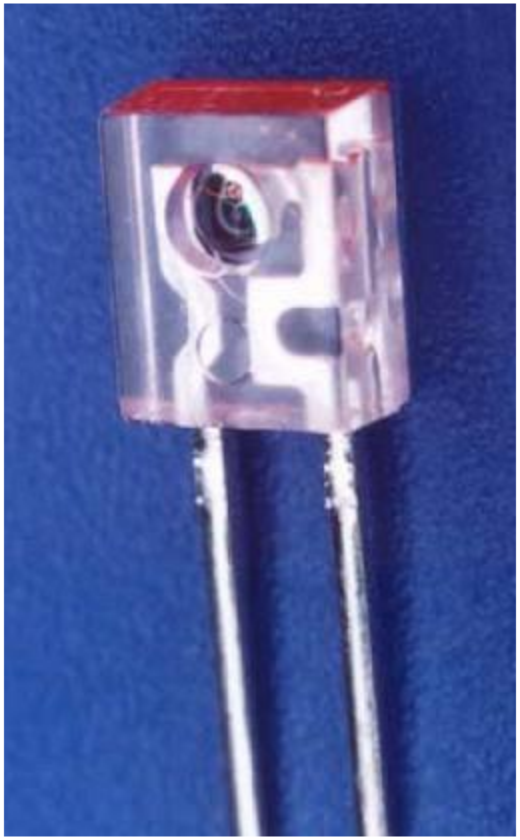


Image: http://hades.mech.northwestern.edu/images/d/d6/Phototransistor.jpg

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

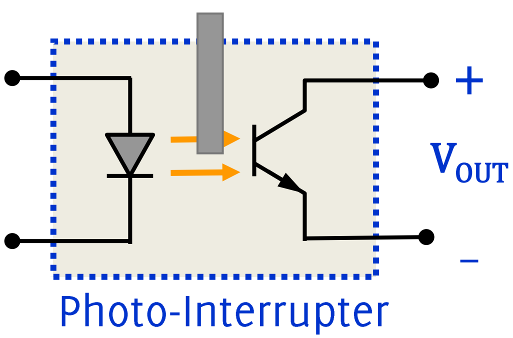
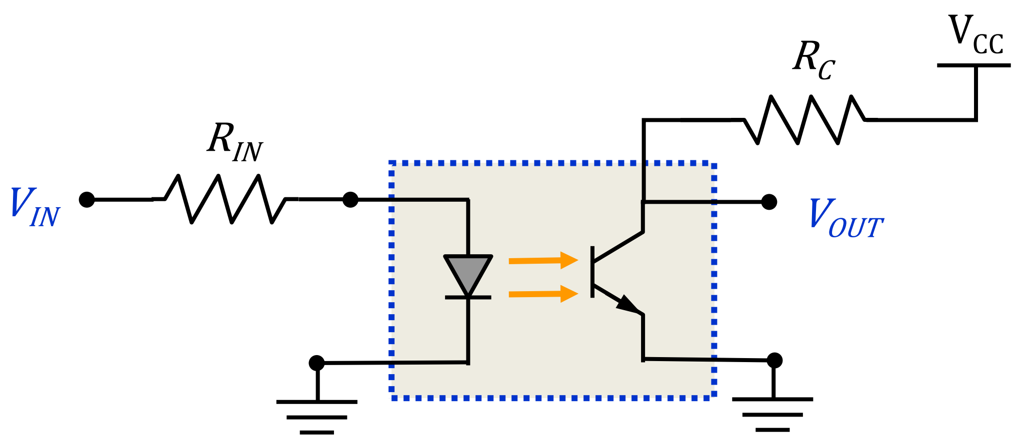


Image: https://www.sparkfun.com/products/9299

AN OPTO-ISOLATOR PROVIDES CIRCUIT SEPARATION

- LED + Phototransistor pair.



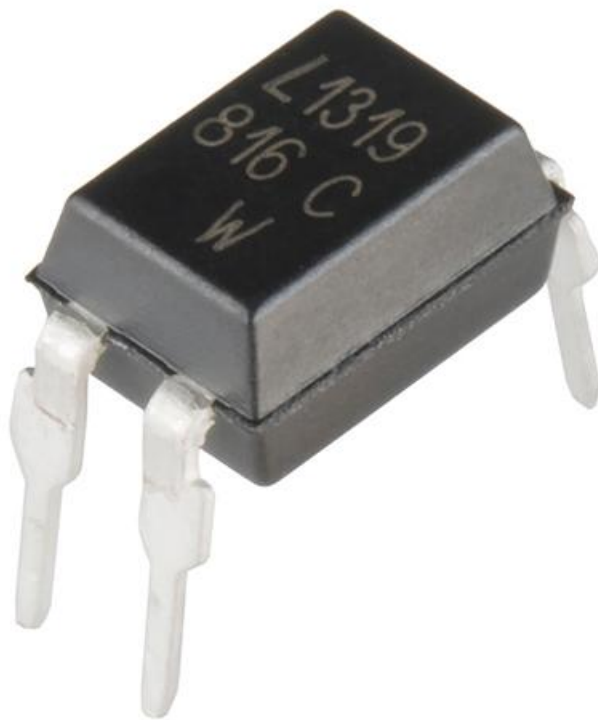
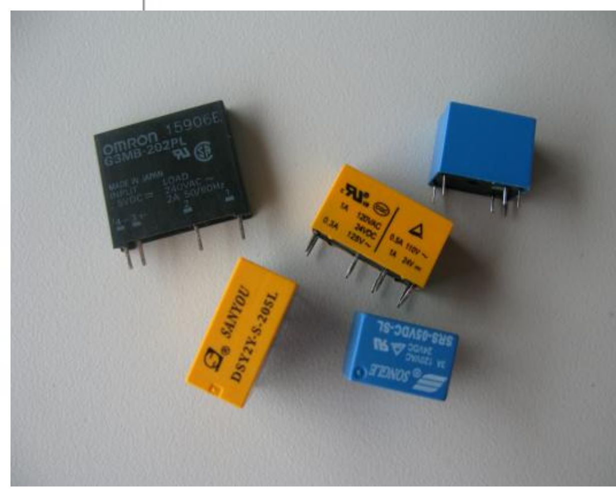


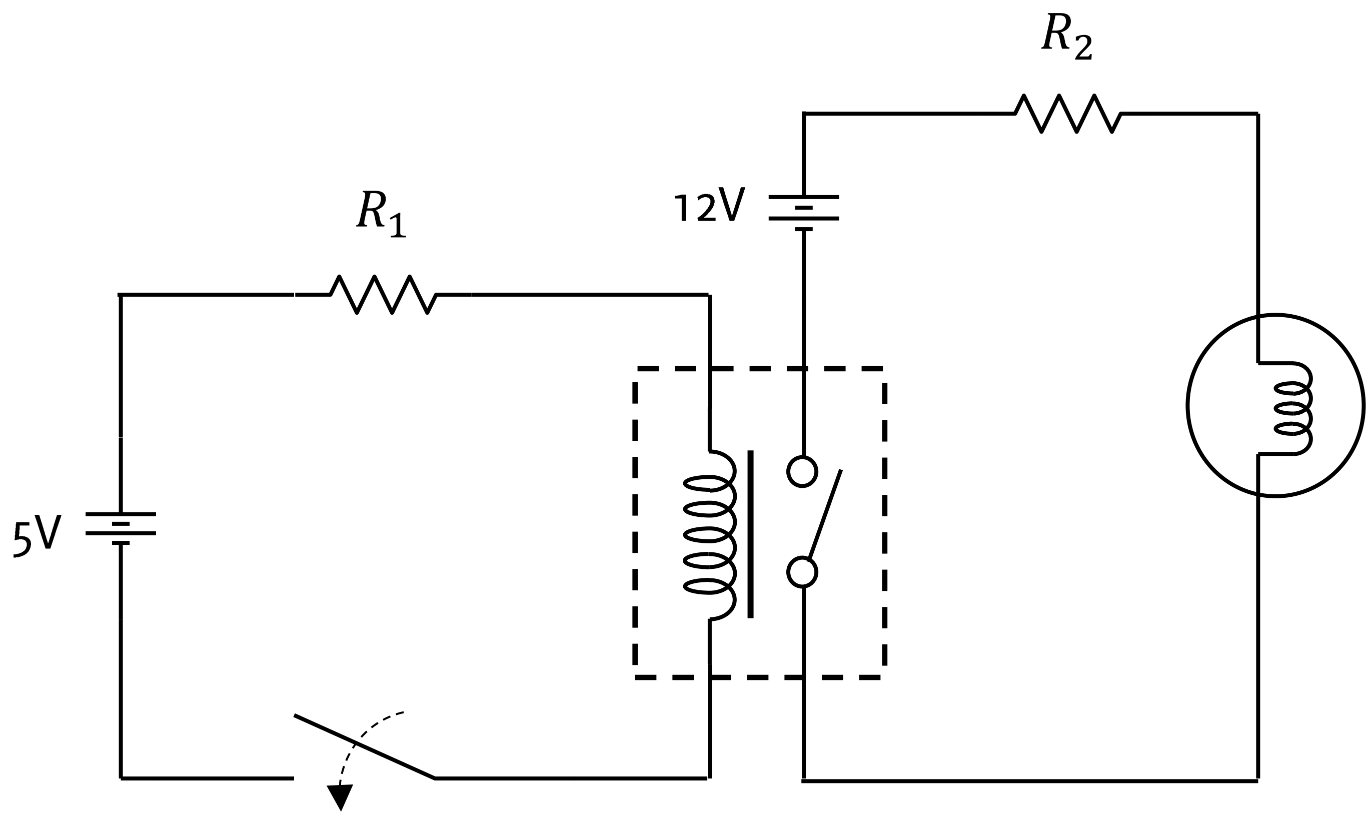
Image: www.sparkfun.com/products/314

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



SPST

ELECTRO-MECHANICAL RELAY SWITCH

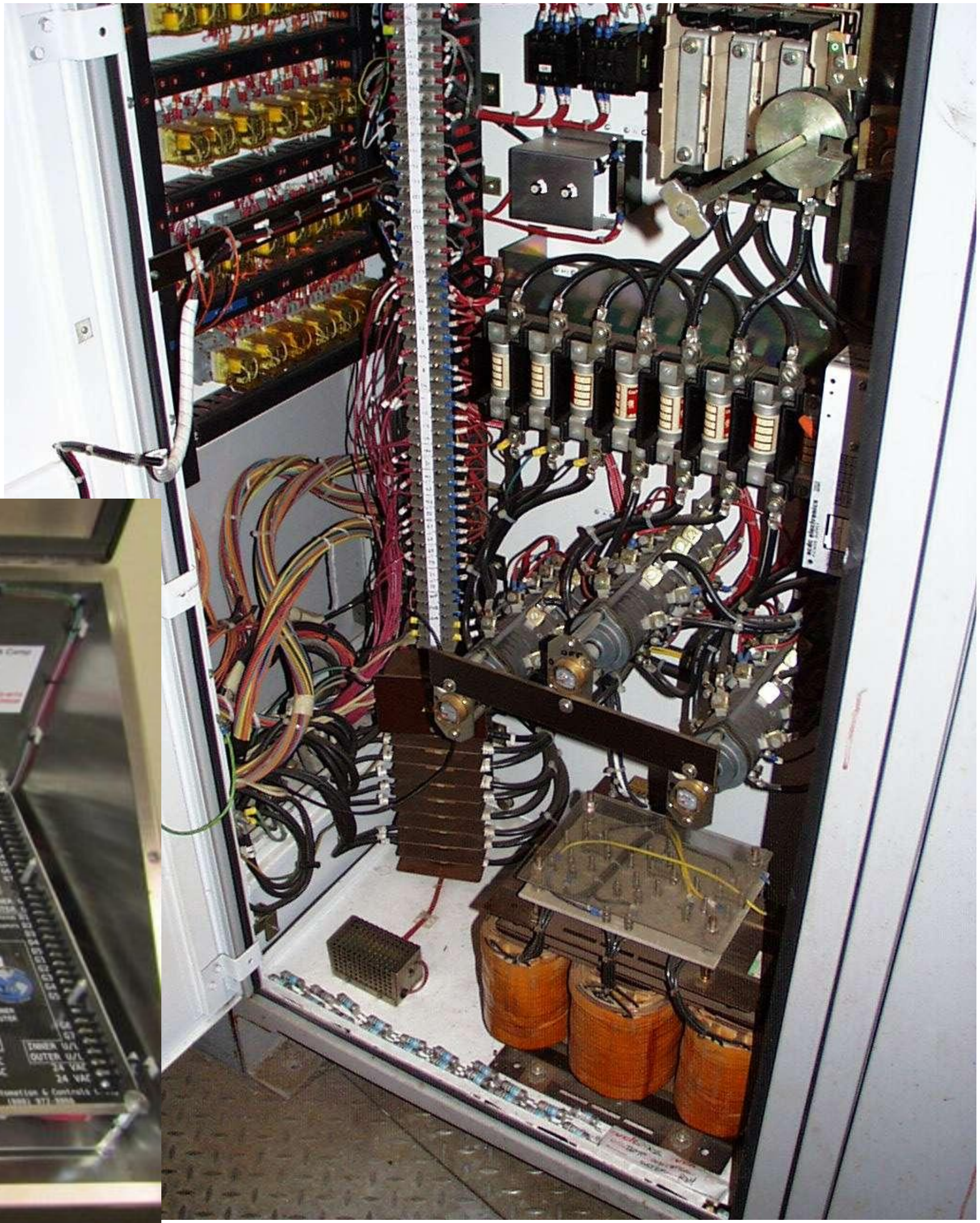
Pros:

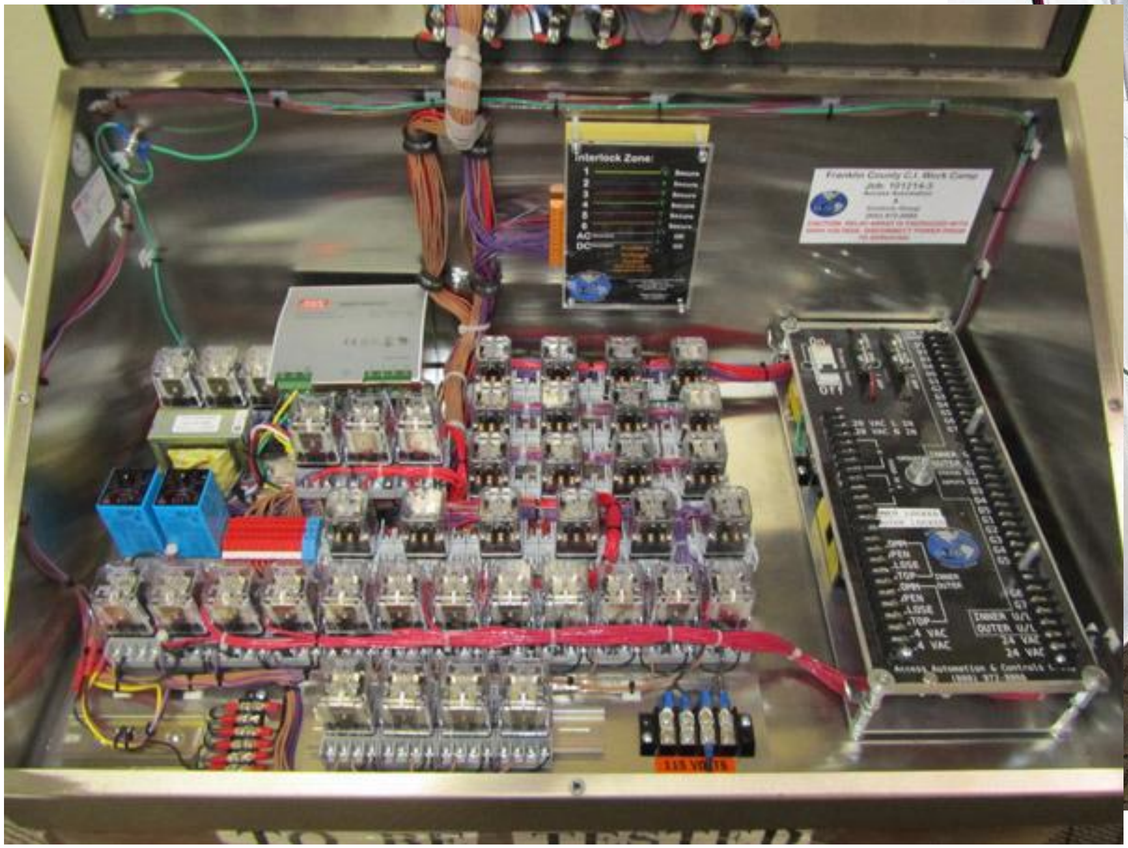
- Inexpensive
- Large selection
- When properly sized, can handle high currents and voltages
- Resistant to electrical surges

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

RELAY LOGIC

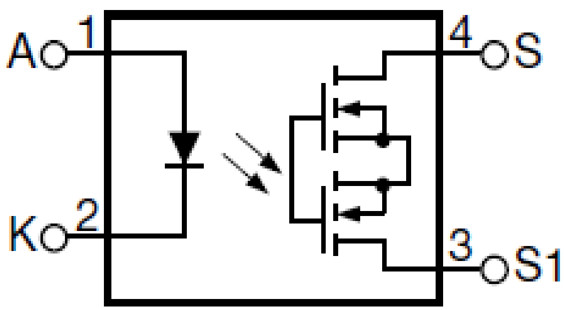


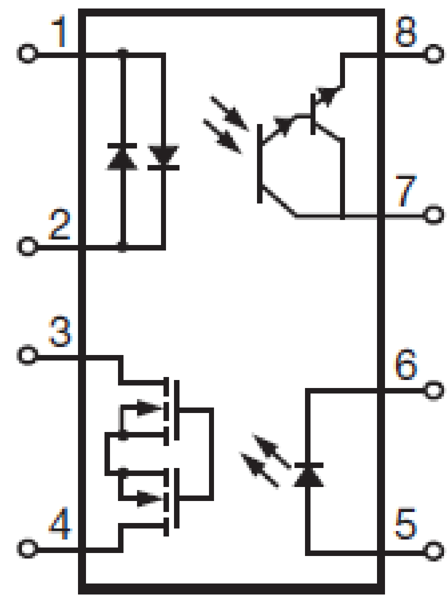


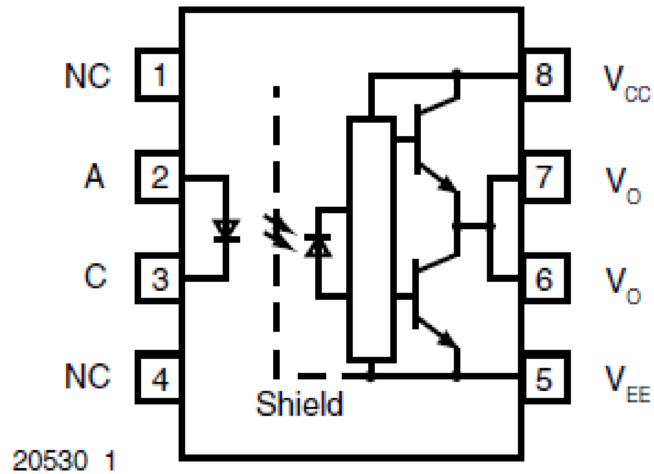
Images:
http://www.jach.hawaii.edu/ets/mech/JCMT/carousel/rcds_11.jpg
http://makezine.com/2013/02/10/prison-door-system-built-using-only-timers-and-relays/

SOLID-STATE RELAYS ALSO PROVIDE SWITCHING CAPABILITIES

- May switch AC or DC
- May use optical coupling

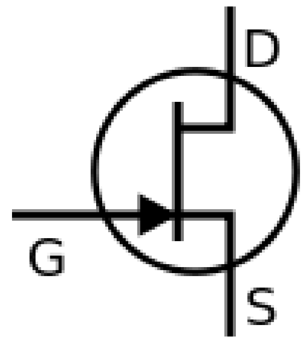




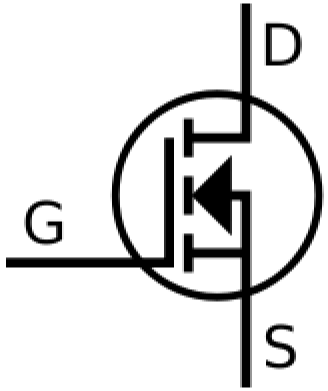


FIELD-EFFECT TRANSISTORS (FET) ARE USUALLY EITHER JFET OR MOSFET

- JFET = Junction FET

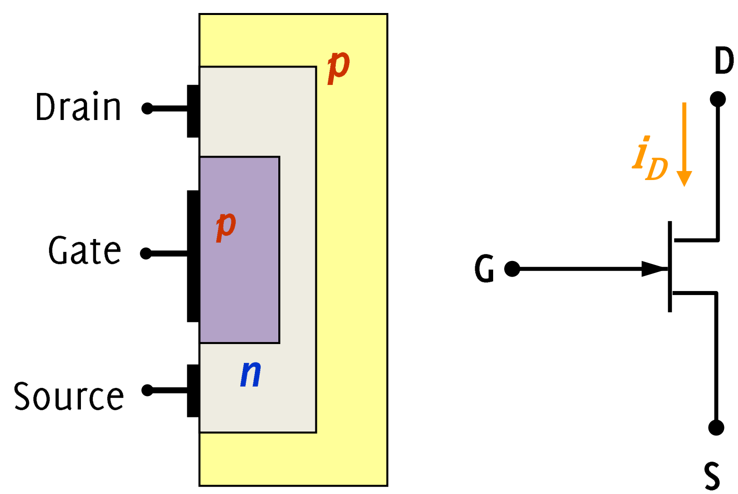


- MOSFET = Metal-Oxide-Semiconductor FET



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)



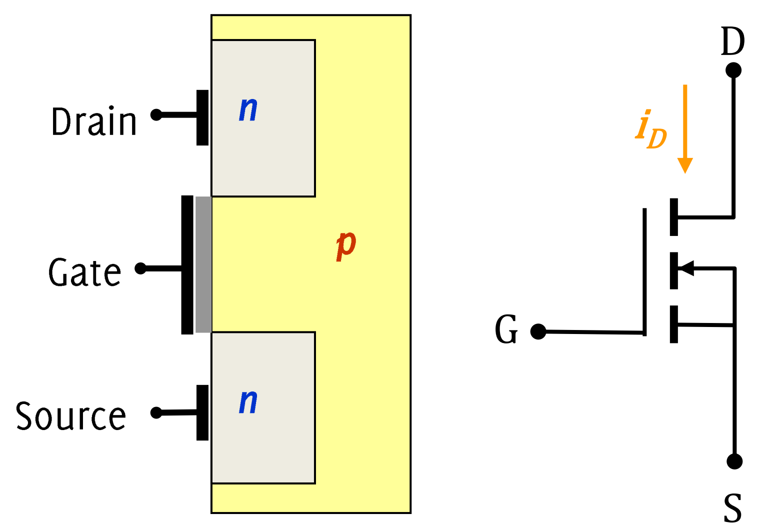
n-channel JFET

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

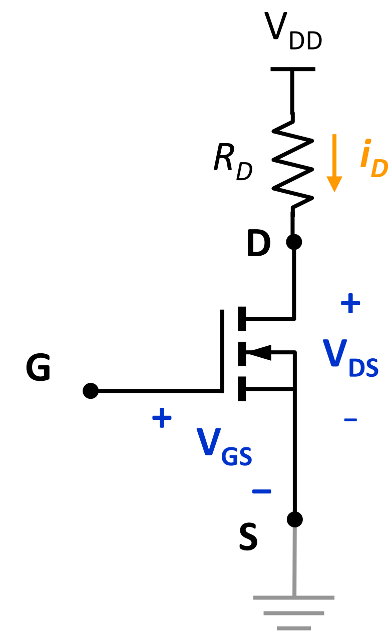
- Devices available that can operate in either *enhancement mode* (gate-source voltage forward biased) or *depletion mode* (gate-source voltage reverse-biased)
- Very high input impedance at the gate – good for digital applications



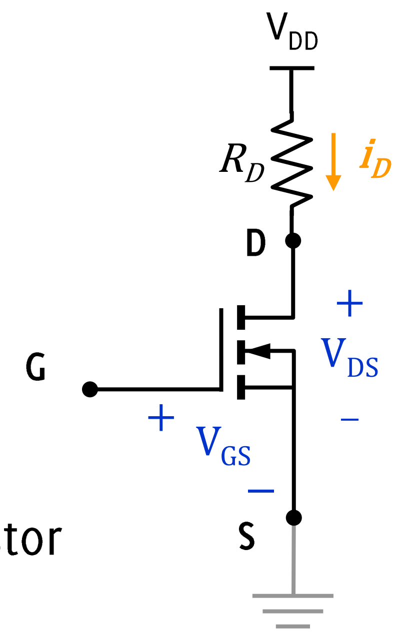
Enhancement mode
n-channel MOSFET

THRESHOLD VOLTAGE DEFINES MOSFET OPERATION

- 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 $V_{GS(\mathrm{on})}$ and is typically between 1 and 5 V.



MOSFETS (ENHANCEMENT-MODE) HAVE FOUR OPERATING REGIONS



- Cutoff state – Transistor is turned OFF

  $V_{GS} < V_T \Longrightarrow i_D \approx 0; \quad V_{DS} \approx V_{DD}$

- Ohmic state – Linear (or triode) region

  $(V_{GS} > V_T \ \& \ V_{DS} < V_{GS} - V_T \ll V_{DD}) \Longrightarrow i_D \approx V_{DD}/R_D$;

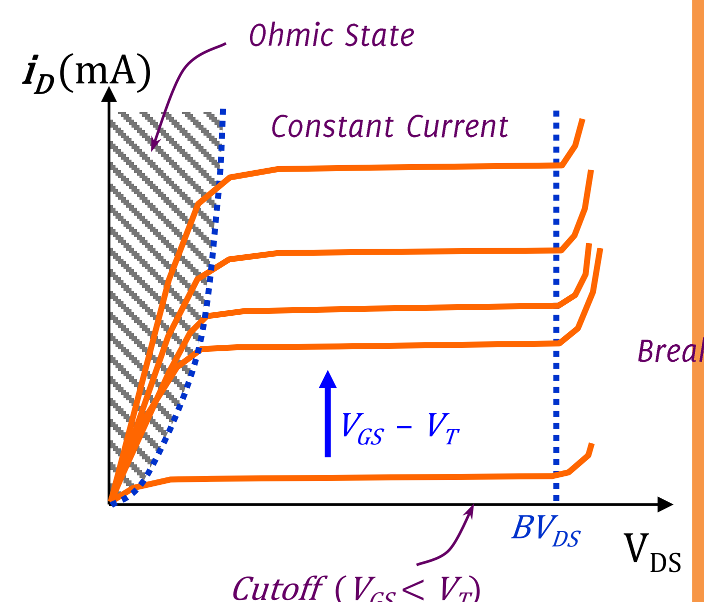
  - i_D controlled by drain circuit
  - Connection from D to S acts as a small voltage-controlled resistor

- Constant current – Active region

  $(V_{GS} > V_T \ \& \ V_{DS} > V_{GS} - V_T) \Longrightarrow i_D \propto (V_{GS} - V_T)^2$

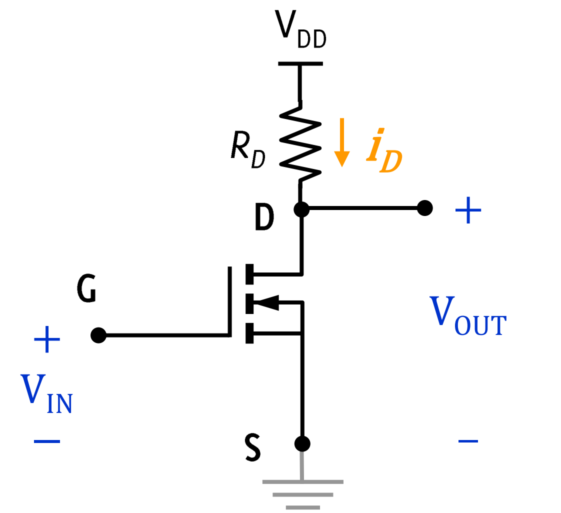
  - i_D controlled by gate-source voltage
  - Power dissipated: $P = i_D \cdot V_{DS}$

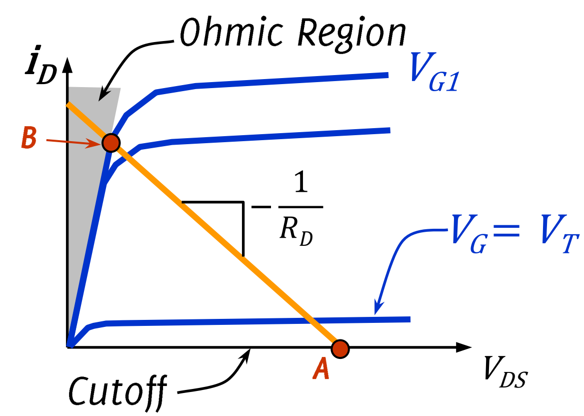
- Breakdown – Transistor will get VERY HOT!

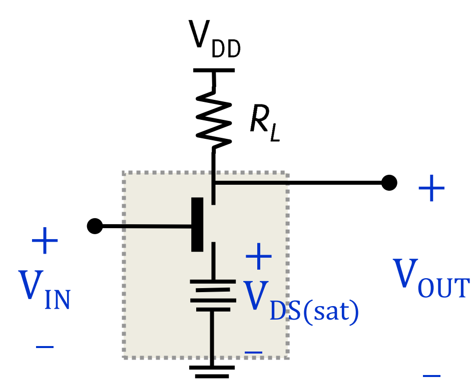


GATE VOLTAGE CAN TOGGLE MOSFET SWITCH

- ***Point A*** ($V_{IN} < V_T$)
  - transistor is cutoff
  - $i_D \approx i_S \approx 0 \Longrightarrow V_{OUT} \approx V_{DD}$
  - Switch open!
- ***Point B*** ($V_{IN} > V_T$)
  - transistor is in Ohmic region
  - $V_{OUT} = V_{DD} - V_{DS} = V_{DD} - i_D(V_{G_1}) \cdot R_D$
  - Switch closed!

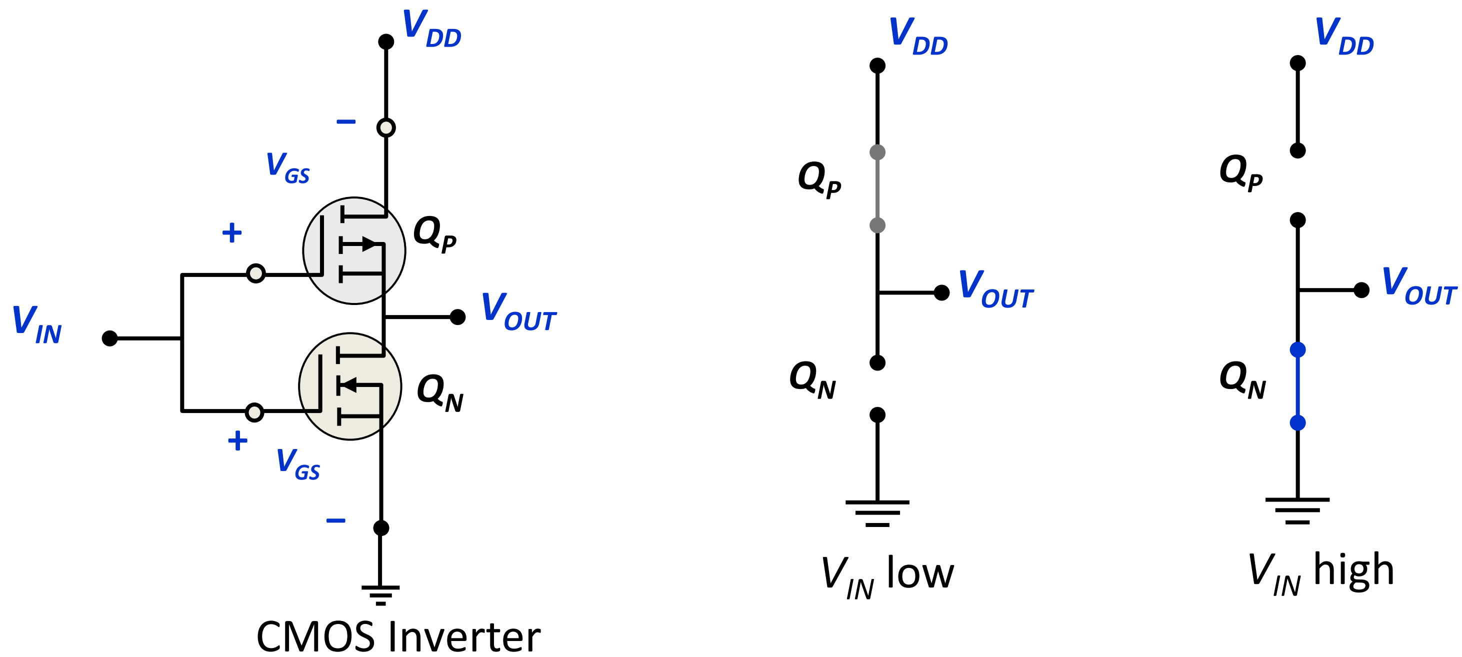






The MOSFET transistor can be viewed as a gate voltage controlled switch or it can also be viewed as an inverter!

EXAMPLE: CMOS INVERTER



Complementary Metal-Oxide Semiconductor (CMOS)

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)

- BJTs usually have larger current capacity than similar sized MOSFETs.
- BJTs have slower switching rates.
- BJTs 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