Electronics Technology and Robotics III
Control and Navigation 7 – Transistors

- **Administration:**
  - Prayer
- **Introduction:** As noted earlier in Lesson 20, a microcontroller's Input/Output (I/O) pins can source or sink a small amount of current, in the order of 25 – 40 mA. This capacity falls far short of the current requirements for most of the systems on an ROV. The output current from a microcontroller can be amplified using two devices: transistors or relays. Before examining transistors, we must first learn about semiconductor materials.
- **Basic Semiconductor Crystal Structure:**
  - The electrical conductivity of semiconductors is less than metal conductors but more than insulators. Introducing a small amount of impurities into a pure semiconductor material improves its conductivity. This process is known as doping. The conductivity of a doped semiconductor (called an extrinsic semiconductor) is dependent primarily upon the number of impurity atoms that have been added to the semiconductor. Doping makes it possible for semiconductors to be engineered with just the right levels of conductivity for the purpose at hand. Silicon is the most widely used semiconductor material in the electronics industry, so it will be our focus in this lesson.
  - A chemically pure semiconductor material (known as an intrinsic semiconductor) is a poor conductor. Figure 1 represents the crystal structure of pure silicon.

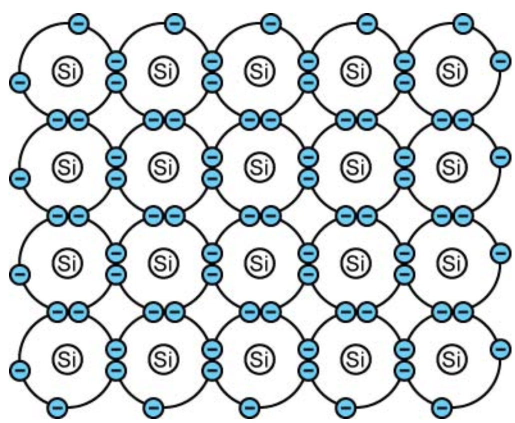


Figure 1: Representation of the Outer Electrons of a Pure Silicon Crystal

In a pure silicon crystal, there are no free electrons available to move from place to place as an electrical current. To produce conduction in a semiconductor, two types of impurities can be inserted into a semiconductor; one produces an n-type semiconductor and the other a p-type semiconductor.

- n-type Semiconductors:
  - Impurities such as arsenic (As), phosphorus (P), bismuth (Bi), or antimony (Sb) can replace silicon atoms in the crystal structure (a process called doping). These atoms have five valence electrons; the fifth electron easily detaches from this "donor" atom and becomes a conduction electron (Figure 2).
  - Because electrical conduction occurs by the additional negatively charged electrons provided by doping, the doped semiconductor is called "n-type."

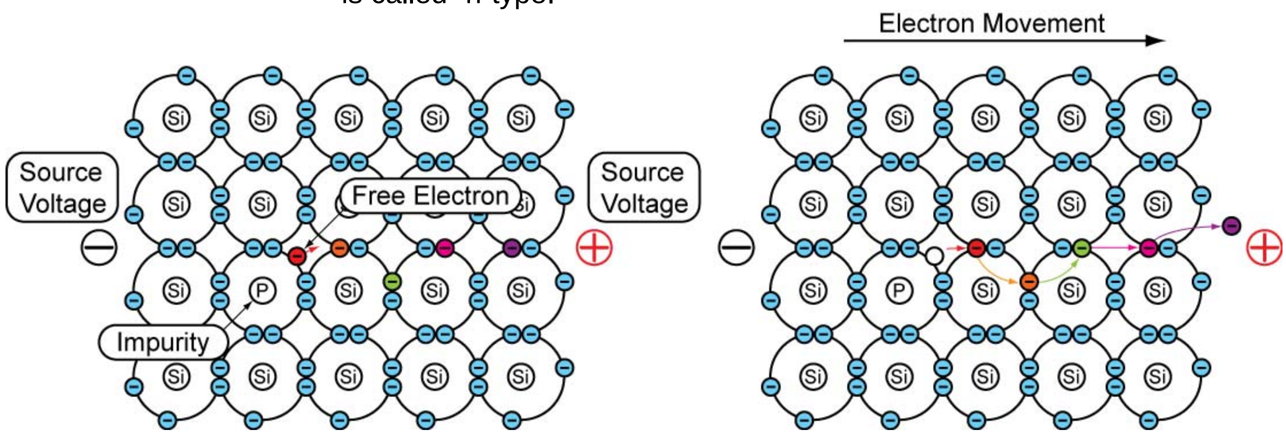


Figure 2: Electron Movement in n-type Semiconductor - Impurities Contribute Free Electrons for Current

- p-type Semiconductors:
  - Alternatively, you can replace silicon atoms in the crystal structure with impurity atoms that have only three valence electrons, such as boron (B), aluminum (Al), or gallium (Ga). These impurity atoms (called "acceptor" atoms) create holes that can accept valence band electrons from nearby silicon atoms. The nearby silicon atom is then left with a hole that soon pulls in an electron from another close silicon atom. The holes move in the opposite direction to the electrons (Figure 3). Holes are considered positively charged carriers even though they do not carry a physical charge.
  - Because the holes act like positively charged particles, the doped semiconductor is called "p-type."

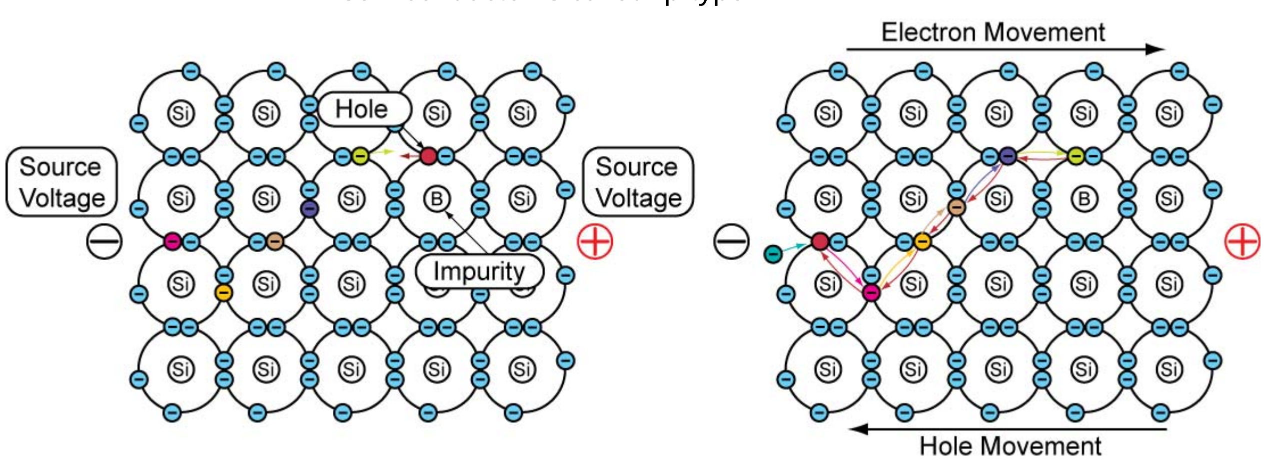


Figure 3: Hole and Electron Movement in p-type Semiconductor - Impurities Contribute Holes that Accept Electrons

- **Forward and Reverse Bias:**
    - p-n Junction: A p-n junction is formed by joining p-type and n-type semiconductors together. The p-type semiconductor has many holes; the n-type semiconductor contains many free electrons. Holes and electrons are current carriers because they both transport electric charge in an electric current. A semiconductor device containing one p-n junction, such as the one illustrated in Figure 4, is called a diode. The p-type region of a diode is called the anode; the n-type region is called the cathode.

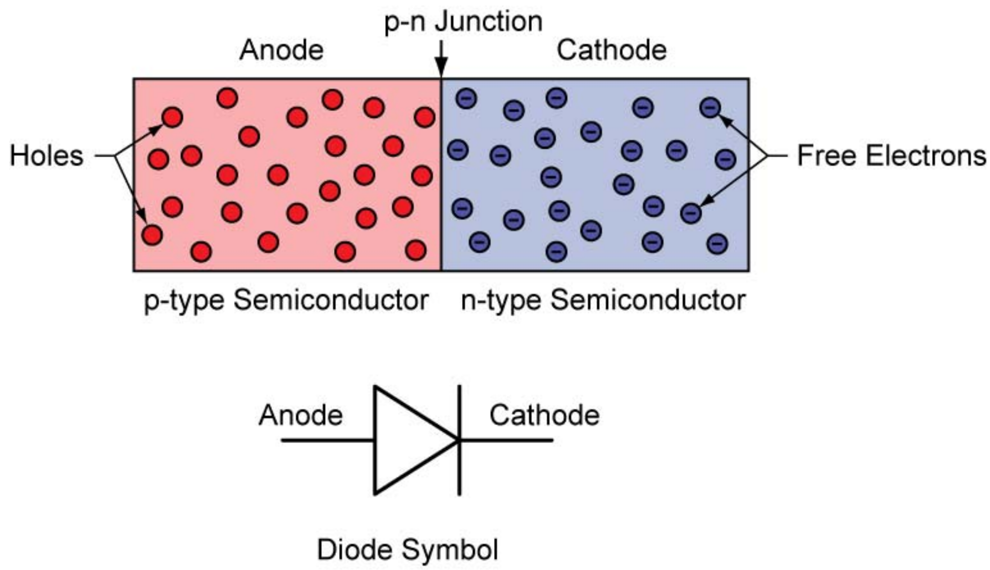


Figure 4: p-n Junction as the p-type and n-type Semiconductors Come in Contact

- Depletion Region: The depletion region is the region at the juncture of p-type and n-type semiconductors, in which there is neither an excess of electrons nor of holes (Figure 5). The electrons from the n-type semiconductor that are close to the p-n junction defuse across the p-n junction, combining with the holes from the p-type semiconductor. The depletion region is formed very quickly when the p-type and n-type semiconductors come in contact with each other. When there is not a power source connected to the diode, the depletion region is very thin compared to the p-type and n-type semiconductors.

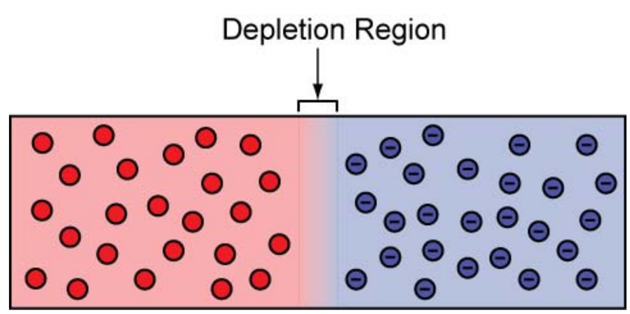


Figure 5: Depletion Region between the p-type and n-type Semiconductors

- Forward Bias:
  - Forward bias occurs when a voltage is applied to a diode where the anode is at a large enough positive voltage compared to its cathode. Before current can flow through a diode, a minimum voltage (barrier voltage) must be applied. This voltage for silicon is approximately 0.6 volts, and for germanium it is approximately 0.2 volts. After the voltage exceeds these values, the diode will conduct.
  - When a diode is forward biased, the electrons in the cathode and the holes in the anode (current carriers) are forced toward the p-n junction by the applied voltage. The electrons and holes then combine and current flows through the diode (Figure 6).

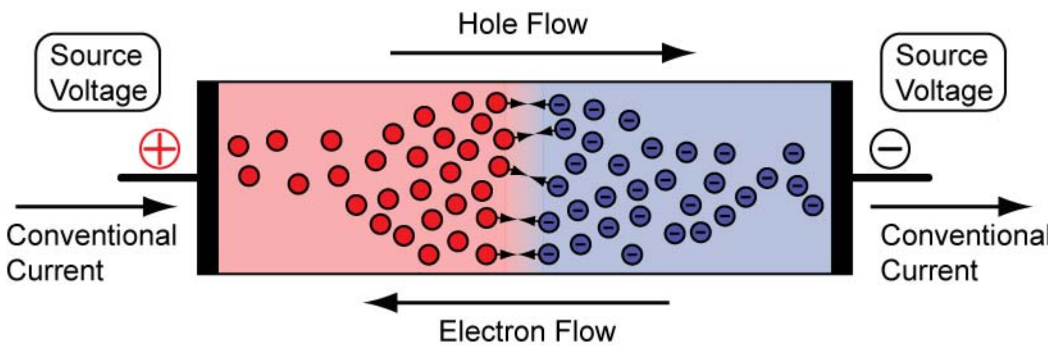


Figure 6: Current Flows when the p-n Junction Diode is Forward Biased

  - Equivalent Switch Circuit:

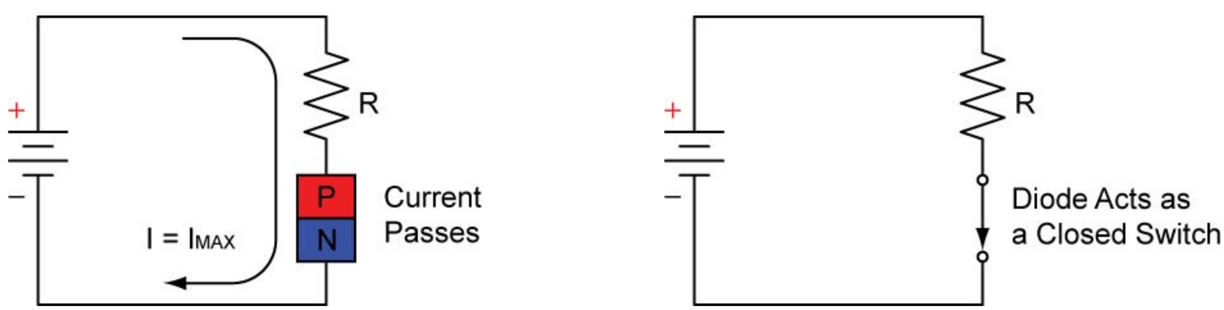


Figure 7: A Forward Biased Diode is Equivalent to a Closed Switch

- Reverse Bias:
  - Reverse bias happens when a voltage is applied to a diode that causes the cathode to reach a positive voltage compared to its anode.
  - When a diode is reverse biased, the electrons in the cathode are attracted to the positive diode terminal and the holes in the anode are pulled toward the negative diode terminal. The result is an expanded depletion region which lacks current carriers and prevents current flow (Figure 8). A large depletion region inhibits current flow.

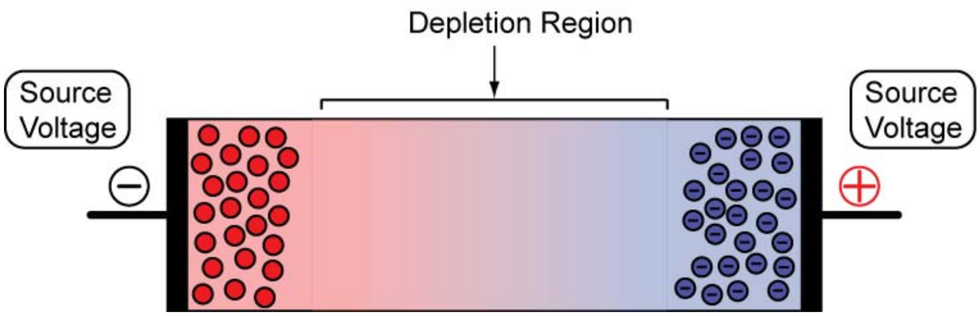


Figure 8: Current Is Stopped When the p-n Junction Diode is Reverse Biased

  - Equivalent Switch Circuit:

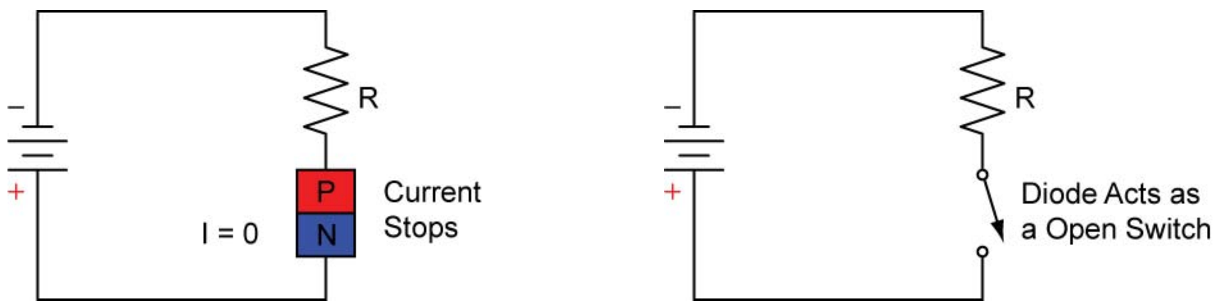


Figure 9: A Reverse Biased Diode is Equivalent to an Open Switch

- **Transistors:**
  - Active Components: A transistor is an example of an "active" electronic component. An active component injects power into a circuit. A transistor produces an output signal that has more power than the input signal. It is able to increase the power of a signal because it injects power from an electrical power source that is separate from the signal (Figure 10). A passive component has no power gain, in fact, they often cause power to be lost (example: resistor).

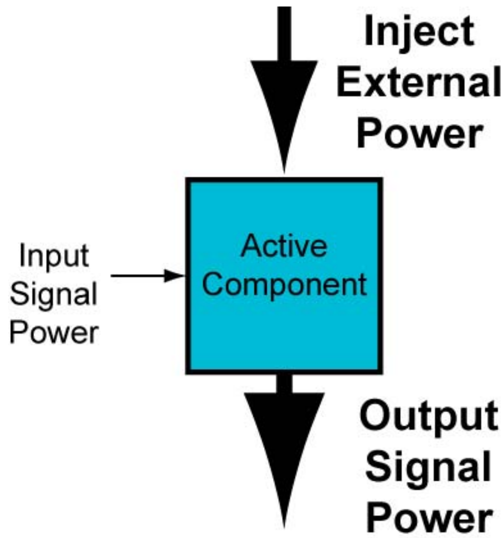


Figure 10: An Active Electronic Component Injects Power into a Circuit

- Introduction to Bipolar Junction Transistors: A bipolar junction transistor (BJT) is a semiconductor component with three terminals called the collector, base, and emitter. BJTs can be used as amplifiers, switches, or in oscillators. BJTs can be found either as individual discrete components, or in large numbers as parts of integrated circuits.
- Bipolar Junction Transistor Schematic Symbols:

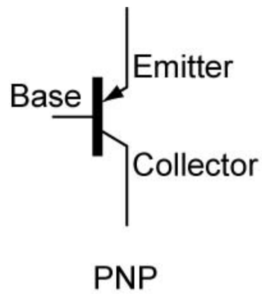


Figure 11: PNP Transistor Symbol

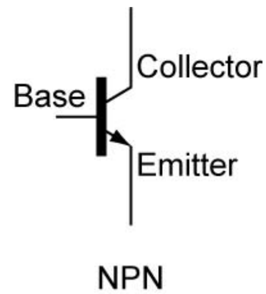


Figure 12: NPN Transistor Symbol

For a PNP transistor, the arrow points toward the base; for the NPN transistor, the arrow points away from the base (**NPN** – “**N**ot **P**ointing i**N**”). In both symbols, the arrow indicates the direction of conventional current flow - toward ground.

- Transistor Construction:
  - A transistor is made of three doped regions. Figure 13 represents a PNP transistor and an NPN transistor construction. For both types of transistors, the narrow base region is sandwiched between the collector and emitter regions.

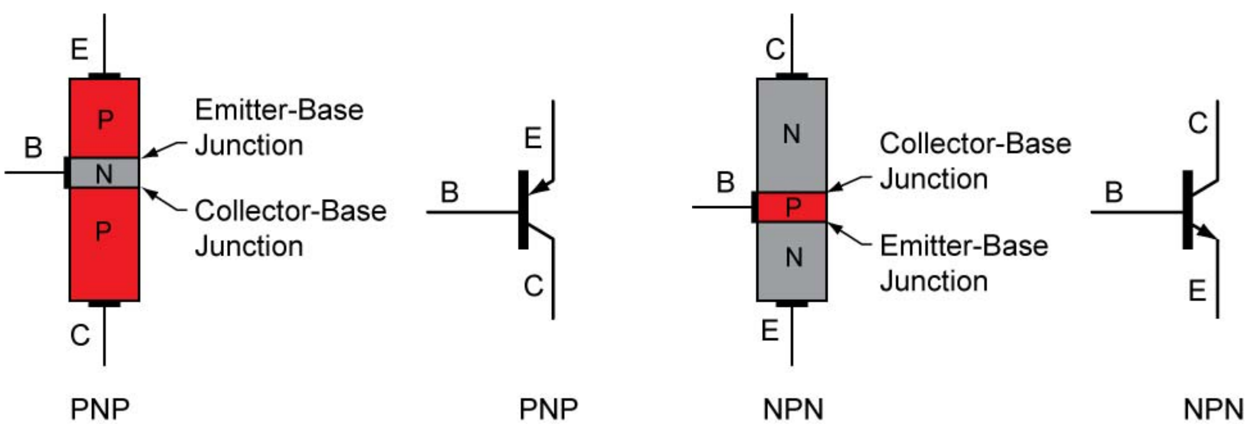


Figure 13: Transistor Construction with Three Doped Regions and Matching Symbols

- Summary of Transistor Structure Regions: Table 1 lists each region in the structure of a transistor and their respective features.
  - Remember that current carriers are electrons or holes that transport the electric charge in an electric current.

Region	Doping	Size of Region	Function
Emitter	Heavy	Large	Emits current carriers into the base
Base	Light	Very Thin	Receives a small number of current carriers from the emitter and controls the current carriers going to the collector
Collector	Moderate	Largest	Collects most of the current carriers from the emitter

Table 1: Transistor Region Features

- o Bipolar Transistor Operation: Bipolar transistors have distinct regions of operation that are defined by the voltages applied to the BJT junctions See the graph in Figure 14.

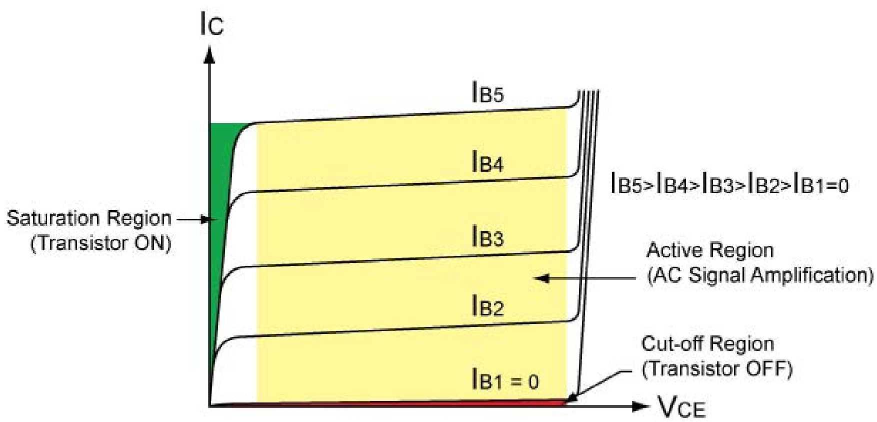


Figure 14: Bipolar Junction Transistor (BJT) Regions of Operation Shown on a Transistor Characteristic Graph

- Saturation Region: The region of operation where the maximum base current is applied resulting in the maximum collector current. The transistor acts like a closed switch from the collector to the emitter.
- Cut-off Region: The region of operation where the transistor acts like an open switch, zero input base current and nearly zero output collector current.
- Active Region: The region where the transistor acts like an amplifier because a near linear relationship exists between the base current (I_B) and the collector current (I_C).

This lesson focuses on one of the main applications for transistors: acting as a solid state SPST ON/OFF switch in digital circuits. In Figure 8, the regions of operation for a transistor switch are known as the saturation and cut-off regions. The active region of BJT operation shown in Figure 8 is used for linear amplification in analog circuits; this topic will not be discussed in this lesson.

- Transistor Currents:
    - Most of the current carriers coming from the emitter and entering the base are attracted to the collector and pass right through the base. Only a small portion of the emitter current carriers flow into the base lead. See Figure 15.

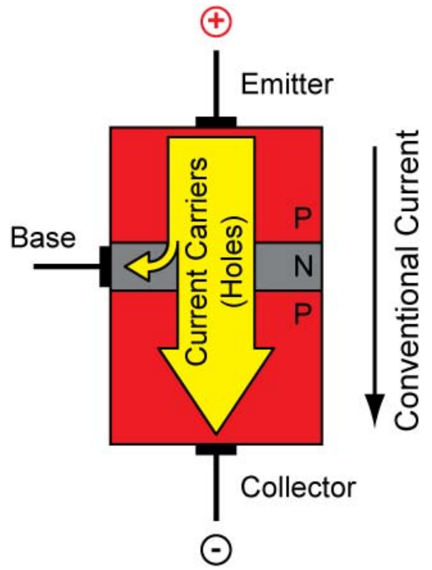


Figure 15: Current through a PNP and an NPN Transistor

- A BJT is a current amplifier so it can be used as a controlling device. A small controlling current flowing through the base (for example 1 mA) can control a much larger current flow through the collector (often 100 mA or more). See Figure 16.

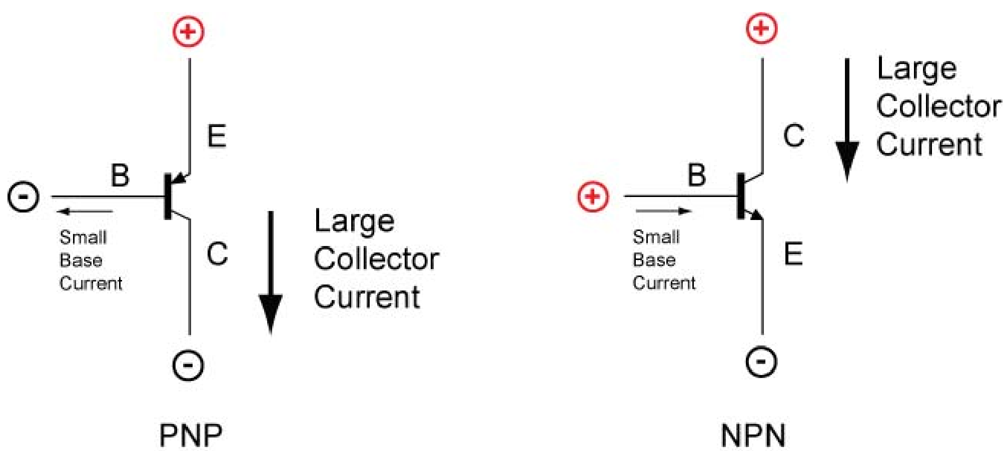


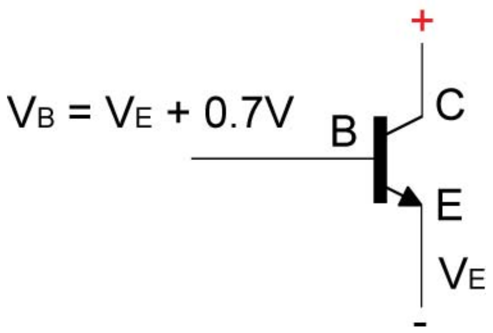
Figure 16: A Small Base Current Controls a Large Collector Current

Note that in the PNP transistor, the base current flows out of the base while in the NPN transistor, the base current flows into the base.

Also note that the transistor does not generate the collector current. It acts as a valve controlling the current that can flow through it. The source of current (and power) is the power supply that feeds the collector or emitter terminals.

The most important thing to remember about the two different types of transistors is that the emitter-base voltage of the PNP transistor has the same controlling effect on collector current as that of the NPN transistor.

- o Base/Emitter Voltages for a BJT:
    - In a NPN transistor, there is a 0.7 volt voltage drop between the base and the emitter (Figure 17). V_B must be 0.7 volts greater than V_E or the transistor will not permit collector-emitter current to flow. In a PNP transistor, there is a 0.7 volt voltage rise between the base and the emitter (Figure 18).



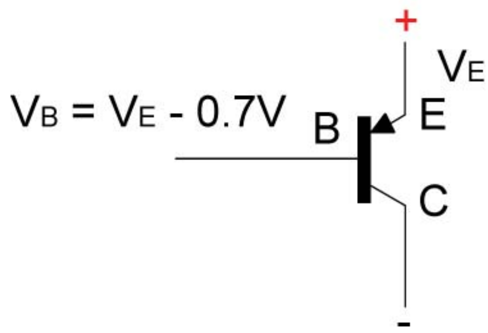


Figure 17: V_{BE} for an NPN Transistor **Figure 18: V_{BE} for an PNP Transistor**

- o Transistors as Switches:
    - Both the NPN & PNP type bipolar transistors can be made to operate as an "ON/OFF" type solid state switch for controlling high power devices such as motors, solenoids, heaters, or lamps. Rather than being mechanically controlled like a manual switch, a transistor is controlled by an electronic signal driving the base terminal.
    - ON/OFF switching in a transistor is controlled by the voltage applied (bias) to the transistor's base-to-emitter junction.
    - NPN Transistor in the OFF Condition: If the base input voltage is reduced to zero, the base current (I_B) will also be zero since the base-emitter junction is not forward biased. From the transistor characteristic graph in Figure 14, the collector current (I_C) is cut-off to near zero making it act as an open switch. See Figure 19.

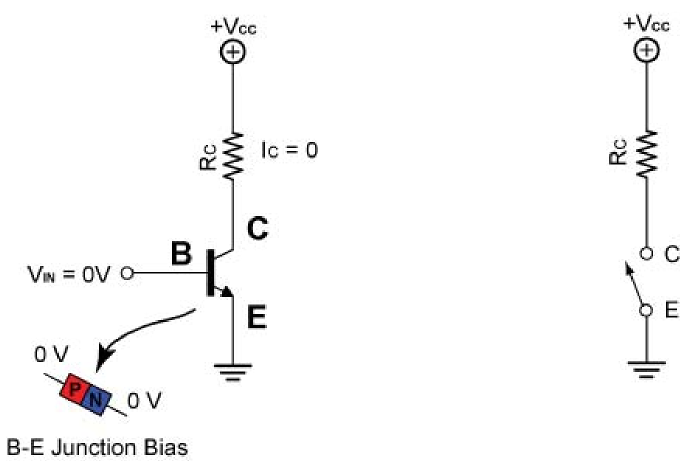


Figure 19: NPN Transistor Switch in the OFF Condition

- NPN Transistor in the ON Condition: If the base-to-emitter junction is forward biased and the base current is made large enough, the collector current is forced to saturation. The collector and emitter terminals are equivalent to a closed switch (Figure 20).

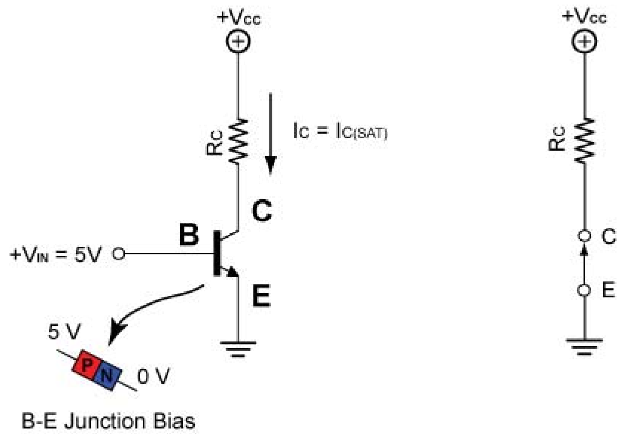


Figure 20: NPN Transistor Switch in the ON Condition

- For a discussion about PNP transistor switches, see Control and Navigation 7 – Transistors – Lab 1 Bipolar Junction Transistor Switch
- When a transistor is on, it is driven into saturation, i.e., the base bias voltage is increased to such a point that any further increase in bias voltage will not cause any further increase in current through the collector and emitter. The base current is high enough to give a collector-emitter voltage of near 0 volts resulting in maximum collector current flowing; the device is switched fully on.
- A transistor is not a perfect switch. Even in saturation there will be a voltage across the transistor between the collector and the emitter. This voltage is known as $V_{CE(SAT).}$ This will usually range between .3V and 1V, depending on the voltage and currents. In many circuits $V_{CE(SAT).}$ can be ignored.
- The lesson is continued on the next page.

- It was noted earlier that a current of 1 mA flowing through the base of a transistor can control a collector current of 100 mA or more (current gain (symbol h_{fe}) = I_C/I_B = 100mA/1mA = 100). Although this is correct for at lower collector currents, the gain reduces at higher collector currents. The graph in Figure 16 illustrates the point. The graph is a plot of the base current, collector current, and collector-emitter voltage in the saturation region of an MPS2222A which is the Motorola model of the 2N2222A NPN transistor in the TO-92 case. At the red dot, I_C = 150mA, $V_{CE(SAT)}$ = 0.3V, and the base current is 1.5 mA; the current gain = 150mA/1.5mA = 100. At the blue dot, I_C = 500mA, $V_{CE(SAT)}$ = 0.3V, and the base current is 15 mA; the current gain = 500mA/15mA = 33. To ensure that a transistor is driven into saturation, a current gain of 10 (I_C/I_B = 10) is used when determining component values.
- Also note in Figure 21 that at a given collector current, if the base current driving the transistor is too small, the collector-emitter voltage (V_{CE}) rises dramatically above the $V_{CE(SAT)}$. As a result, the performance of the transistor as a switch drops off because of the increase voltage drop across the collector-emitter terminals.

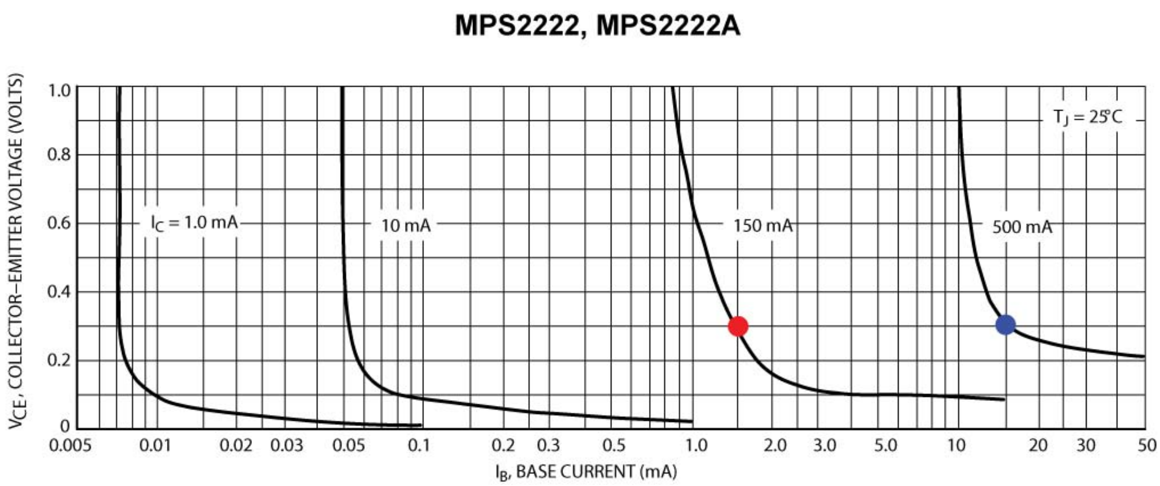


Figure 21: Base and Collector Currents in the Saturation Region of a MPS2222A

- o Calculating the base resistor value for a transistor switch circuit in Figure 22:

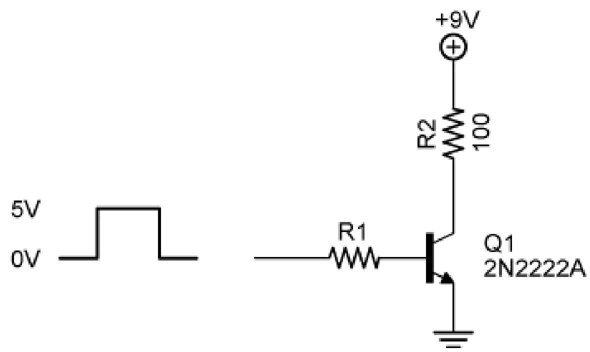


Figure 22: Determining Base Resistor Example

1. Using the circuit above, calculate the collector current assuming the transistor switch is on.

$$I_C = I_{R2} = V_{R2}/R_2$$

Where: I_C = Collector current
V_{R2} = Voltage drop across R_2
R_2 = Resistance of R_2

From the 2N2222A datasheet, the collector-emitter voltage at saturation ($V_{CE(SAT)}$) equals 0.3V.

$I_C = V_{R2}/R_2$
$I_C = (9V – 0.3V) / 100\ \Omega$
$I_C = 8.7V / 100\ \Omega$
$I_C = 87$ mA.

2. There is a rule of thumb to reliably drive a single transistor into saturation; the base-emitter current (I_B) should be 1/10 collector-emitter current (I_C).

$I_B = I_C / 10$
$I_B = 87$ mA / 10
$I_B = 8.7$ mA

3. Now calculate the value of R1. Take into account the 0.7 volt drop across the base-emitter junction.

$R_1 = V_{R1} / I_{R1}$
Since $I_{R1} = I_B$,
$R_1 = (5V – 0.7V) / 0.0087$ A
$R_1 = 4.3V / 0.0087$ A
$R_1 = 494\ \Omega$

Use a 470 Ω resistor.

- Summary of steps for calculating the base resistor value in a transistor switch circuit:

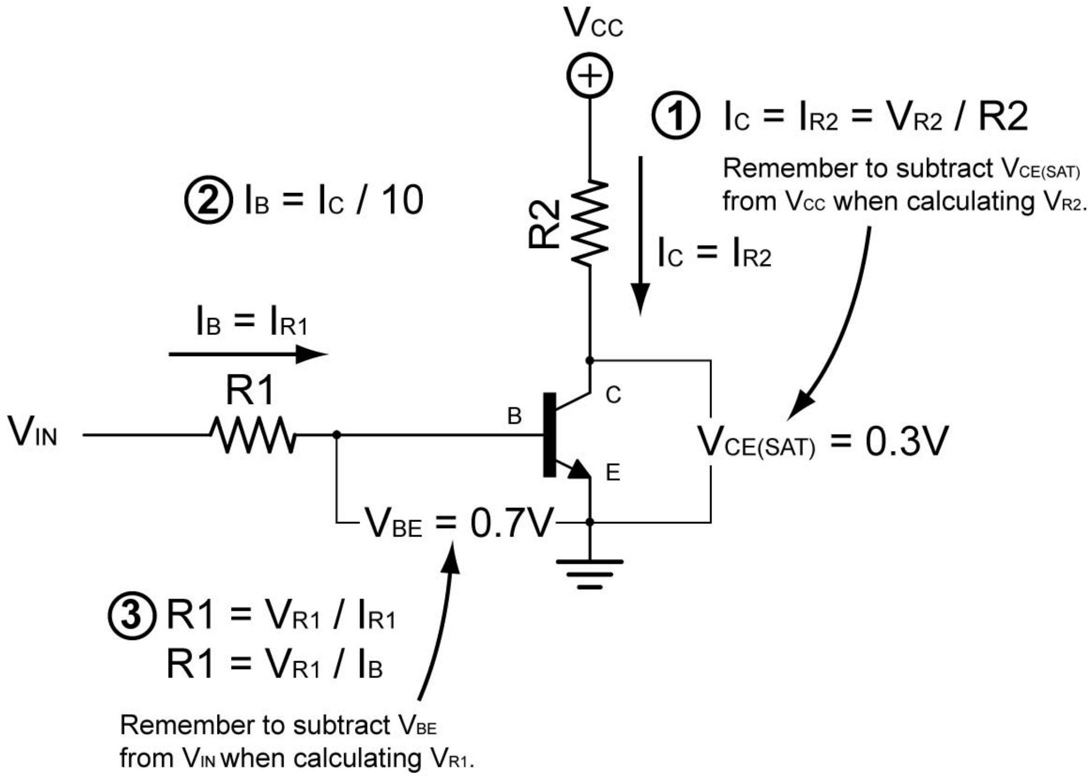


Figure 23: Steps for Calculating the Base Resistor

- Load Placement:
  - Sourcing and Sinking Currents:
    - Current sourcing is when a device (switch and PNP transistor switch in Figure 24) supplies an output voltage and can drive current through a load whose other side is connected to ground or system common. PNP transistors and P-channel FETs are used as current sources. The switch and PNP transistor switch in Figure 24 are acting as a “high side switch”.

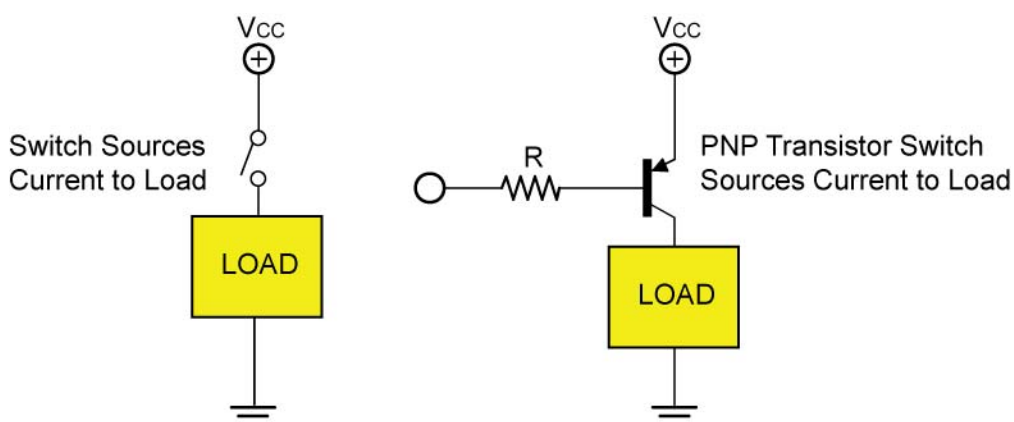


Figure 24: Sourcing Current with a Switch and a Transistor

- Current sinking is similar, except the load is connected to a power supply and the device completes the path from the load to ground or system common (Figure 25). NPN transistors and N-channel FETs are used as current sinks. The switch and NPN transistor switch in Figure 25 are acting as a "low side switch".

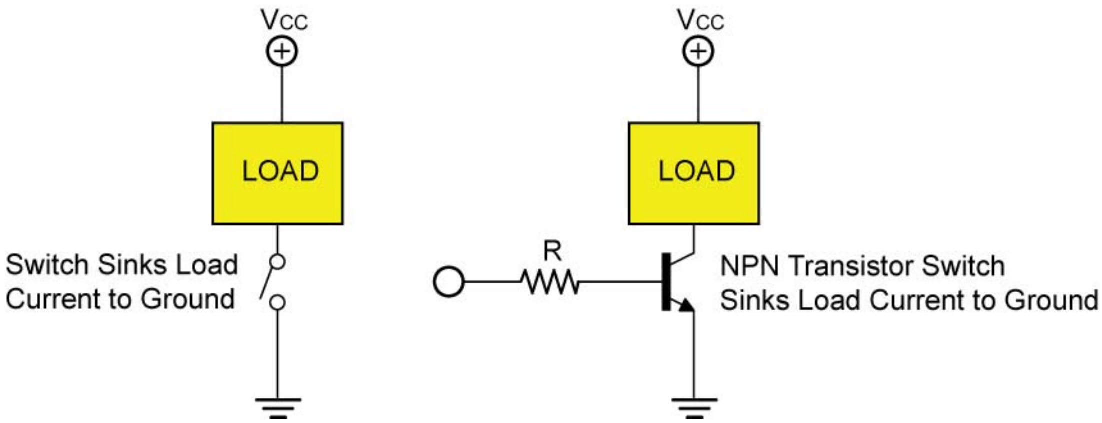


Figure 25: Sinking Current with a Switch and a Transistor

- NPN as a Source: When an NPN transistor is acting as a source, the load is placed between the emitter and ground (Figure 26). The problem with the load being placed between the emitter and ground is that current flows through load which creates a voltage drop across the load (V_{LOAD}). This raises the voltage at the emitter ($V_E = V_{LOAD}$) which causes the base voltage to rise to V_{LOAD} + 0.7V. To drive an NPN transistor as a source, the base voltage must be higher than if the NPN transistor is acting as a sink (Figure 27).

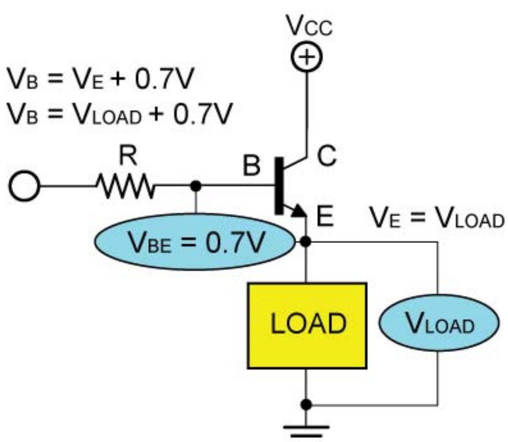


Figure 26: NPN Transistor as a Source

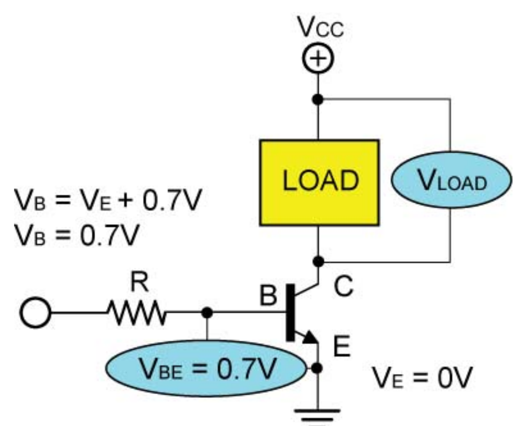


Figure 27: NPN Transistor as a Sink

- Let's see why this could be a problem. Suppose the load in the circuit is a 12V relay, and a 12V supply is connected to the collector (Figure 28). A 5V microcontroller controls the transistor so 5V is the maximum that can be supplied to the base. The emitter voltage is 0.7 V lower than the base, V_E = 4.3 V, which is too low to activate the 12V relay coil. The voltage can't go higher, because then there wouldn't be a base current anymore. So if the rated load voltage is higher than the control voltage you can't use a NPN transistor as a source.

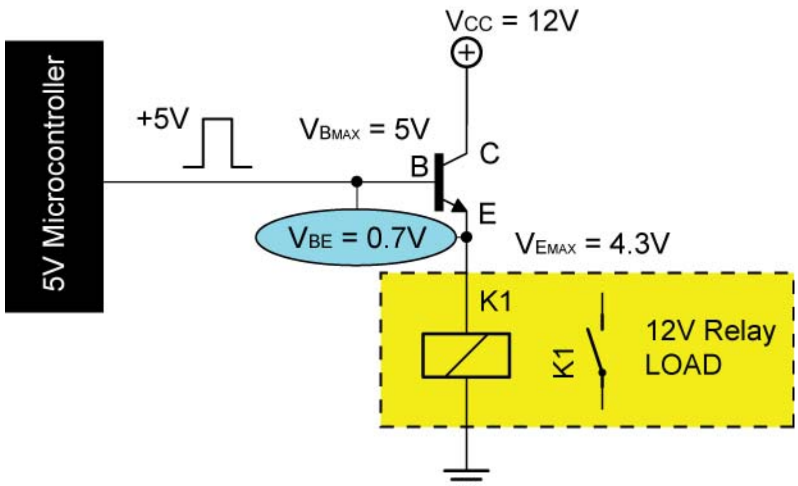


Figure 28: NPN Transistor Acting as a Source Cannot Drive the 12 Volt Relay Load

- The load should be placed between the power supply and collector in an NPN transistor switch circuit and between the collector and ground in a PNP transistor switch circuit.
- Perform Control and Navigation 7 – Transistors – Lab 1 Bipolar Junction Transistor Switches

MOSFET Transistor as a Switch:

- Introduction: Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) are a type of field effect transistors (FET) known for its ability to handle high currents while consuming very little power. It is frequently used as a transistor switch in H-bridges and motor controller circuits. A MOSFET is a semiconductor component with three terminals called the source, gate, and drain, with the source and drain regions kept apart by the gate. A voltage applied to the gate controls the flow of electrons from the source to the drain. The gate voltage establishes an electrostatic field that turns on and off the main source-drain current. MOSFETs are either NMOS (n-channel) or PMOS (p-channel) transistors. MOSFETs are the most common transistor used in digital and analog circuits, replacing the very popular BJTs.
- Enhancement MOSFET Schematic Symbols:

Figure 19: N-Channel **P-Channel**

- Differences between a BJT and a MOSFET:
  - Bipolar Junction Transistor (BJT) is a current-controlled device where the collector or emitter output current is dependent upon the current in the base. Basically, the mode of operation of a BJT is driven by the current at the base.
  - Metal Oxide Semiconductor Field-Effect Transistor (MOSFET) is a voltage-controlled device. MOSFETs control output current between the source and drain by varying the gate voltage. The gate draws almost no current because the gate input impedance is so large ($>10^{14}$ Ohms). In this transistor, a voltage on a gate electrode can generate a channel for conduction between the source and drain. What's great about MOSFETs is that they handle power more efficiently. They also have much faster switching speeds than the BJTs. Unfortunately, some types of MOSFETs are easier to damage than BJTs when handling.
- The MOSFET that we will be using is a logic level power MOSFET; the gate can be driven directly from the output of a microcontroller. A word of caution when ordering power MOSFETs. A MOSFET will turn on if the gate voltage is larger than a parameter known as the threshold voltage, V_{TH}. Low threshold type power MOSFETs may not switch "ON" until at least 3V or 4V has been applied to its gate. If the output from the logic gate is only +5V logic, it may be insufficient to fully drive the MOSFET into saturation. Using lower threshold MOSFETs designed for interfacing with TTL and CMOS logic gates that have thresholds as low as 1.5V to 2.0V are available.
- Damaging MOSFETs:
  - MOSFETs are very fragile. It is possible to destroy a MOSFET by walking across a room with carpet flooring and then touching the gate lead. Too much electrostatic discharge on the gate lead can break through the gate. It is necessary to remove all static electricity around the work area when handling MOSFETs to prevent electrostatic damage (ESD). Static prevention measures should be taken when working with the component or a printed circuit board containing MOSFETs.
  - Also remember that a motor is an inductive load so the MOSFET must be protected from inductive voltage surges. Modern high current MOSFETs have an internal high current diode which is wired to protect the main chip. If your MOSFET is not equipped with a current diode, install a flyback diode in parallel with the inductive load.
- Perform Control and Navigation 7 – Transistors – Lab 2 MOSFET Switch
- Differences between Enhancement and Depletion MOSFETS:

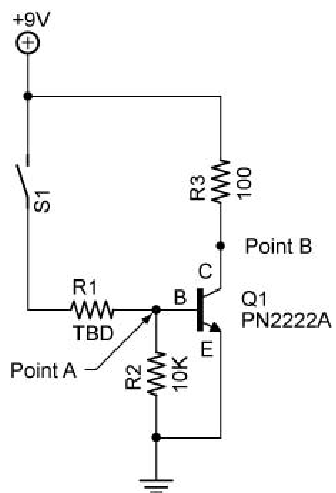
Enhancement-mode MOSFET	Depletion-mode MOSFET
More commonly used	Less commonly used
Acts as a normally open switch	Acts as a normally closed switch
OFF at 0V	OFF at -V
ON at +V	ON at 0V

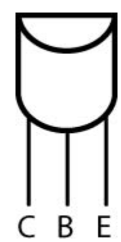
- **Purpose:** The purpose of this lab is to acquaint the student with basic BJT switching circuitry and operation.

- **Apparatus and Materials:**

    - 1 – Breadboard with +5V supply
    - 3 – Digital Multimeters
    - 1 – SPST Switch
    - 1 – PN2222A NPN Transistor
    - 1 – PN2907A PNP Transistor
    - 1 – 100 Ohm 5 Watt Resistor
    - 1 – 10K Ohm ¼ Watt Resistor
    - 2 – Base Resistors To Be Determined

- **Procedure:**
    - Wire the NPN transistor circuit shown below on your breadboard. The pinout diagram for the PN2222A transistor we use is also given.





NPN Switch Circuit **NPN Transistor Pinout**

- Using the DMM, measure and record the current at Points A and B when the switch is open and closed. Note the direction of the base current. Also measure and record the V_{CE} for each switch position.

- o Discussion about PNP Transistor Switches:
  - PNP Transistor in the OFF Condition: If the base input voltage is at the same potential as the emitter, the base current (I_B) will be zero since the base-emitter junction is not forward biased. The collector-emitter terminals of the PNP transistor act as an open switch. See the illustration below.

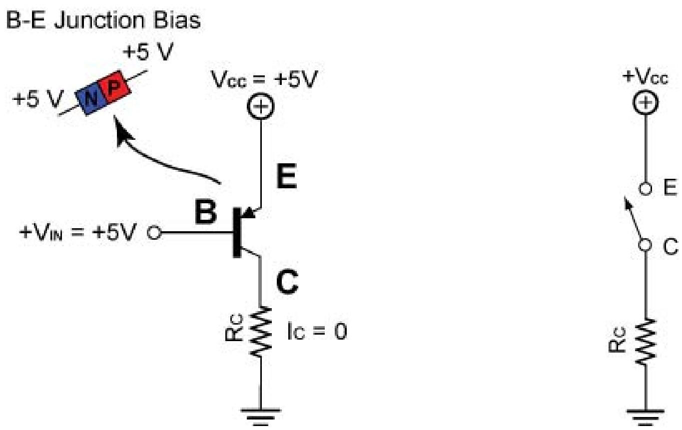
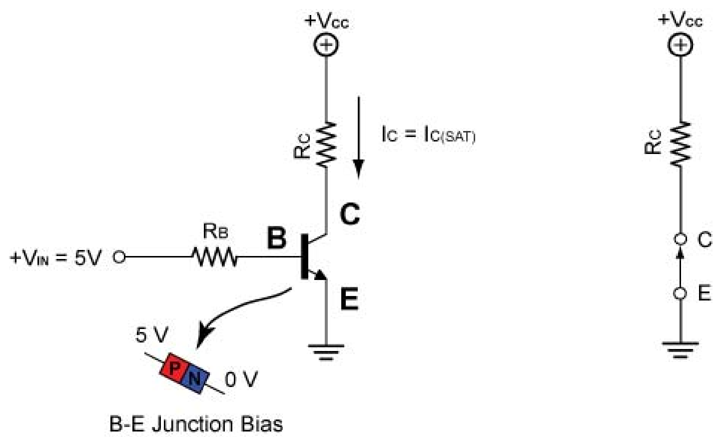
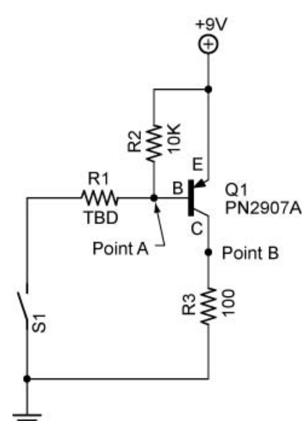


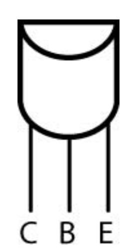
Figure 14: PNP Transistor Switch in the OFF Condition

  - PNP Transistor in the ON Condition: If the base-emitter junction is forward biased and the base current is made large enough, the collector current is forced to saturation. The collector and emitter terminals are equivalent to a closed switch. See the figures below.



- o Repeat the procedure for the PNP transistor switch circuit below.





PNP Switch Circuit **PNP Transistor Pinout**

- **NPN Transistor Switch Results:**
  - Which direction is the base current flow, into or out of the base?
  - Results Table for Open Switch:

Point	Current (mA)
A (I_B)	
B (I_C)	

V_{CE} (V)	

  - Results Table for Closed Switch:

Point	Current (mA)
A (I_B)	
B (I_C)	

V_{CE} (V)	

- **PNP Transistor Switch Results:**
  - Which direction is the base current flow, into or out of the base?
  - Results Table for Open Switch:

Point	Current (mA)
A (I_B)	
B (I_C)	

V_{CE} (V)	

  - Results Table for Closed Switch:

Point	Current (mA)
A (I_B)	
B (I_C)	

V_{CE} (V)	

- **NPN Transistor Conclusions:**
  - Based upon your results, is the base-collector junction forward or reverse biased?
  - Based upon your results, is the base-emitter junction forward or reverse biased?
  - Calculate the current gain due to the PN2222A transistor.

Current Gain = I_C/I_B

Current Gain =

- **PNP Transistor Conclusions:**
    - Is the direction of the base current the same for both types of transistors?

    - Based upon your results, is the base-collector junction forward or reverse biased?

    - Based upon your results, is the base-emitter junction forward or reverse biased?

    - Calculate the current gain due to the PN2907A transistor.

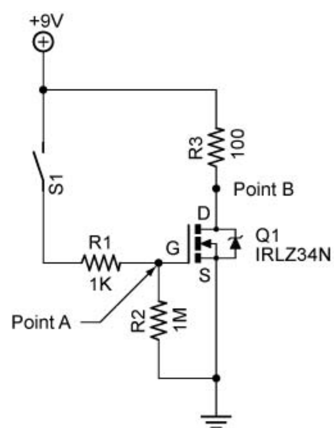
      Current Gain =

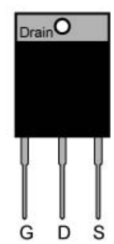
Control and Navigation 7 LAB 2 – MOSFET Switch

- **Purpose:** The purpose of this lab is to acquaint the student with MOSFET switching circuitry and operation.

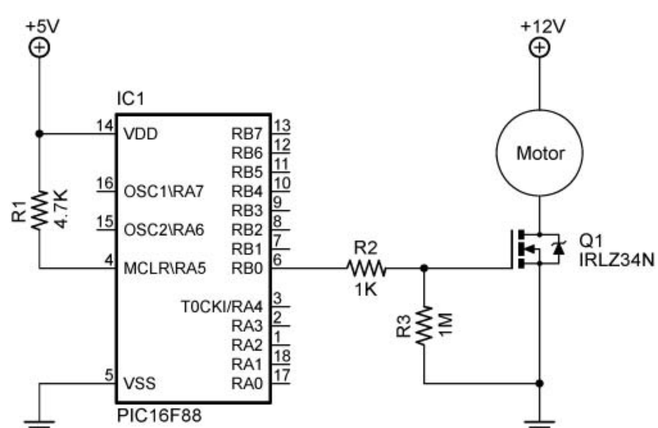
- **Apparatus and Materials:**
    - o 1 – Breadboard with +5V, +9V, and +12V supplies
    - o 3 – Digital Multimeters
    - o 1 – IRLZ34N MOSFET (or IRF3708)
    - o 1 – 100 Ohm 5 Watt Resistor
    - o 1 – 1K ¼ Watt Resistor
    - o 1 – 1M ¼ Watt Resistor
    - o 1 – 12V DC Motor

- **Procedure:**
    - o Wire the MOSFET circuit shown below on your breadboard. The pin configuration diagram for the IRLZ34N MOSFET is also given. The Philips IRLZ34N has integral zener diodes giving electrostatic discharge (ESD) protection up to 2kV on all pins.
    - o Using the DMM, measure and record the current at Points A and B when the V_{IN} = 0V and +9V. Also measure and record the V_{DS} for each switch position.





    - o Wire the PIC16F88 and motor circuit on your breadboard.
    - o Program the PIC with PWM1 from: http://cornerstonerobotics.org/picbasic.php#MotorPrograms16F88 under Servo and Motor Control Programs.



- **Results:**
  - Results Table for Open Switch with 100 Ohm Resistor Load:

Point	Current (mA)
A (I_G)	
B (I_D)	

V_{DS} (V)	

  - Results Table for Closed Switch with 100 Ohm Resistor Load:

Point	Current (mA)
A (I_G)	
B (I_D)	

V_{DS} (V)	

- **Conclusions:**
  - When the switch is closed, how does the gate current for the MOSFET compare to the base current for the NPN transistor in Lab 1?
  - Again, when the switch is closed, how does the V_{DS} for the MOSFET compare to the V_{CE} for the NPN transistor in Lab 1?