TEACHERS GUIDE

SEMICONDUCTOR SCIENCE ACTIVITIES FOR HIGH SCHOOL PHYSICS

PHYSICS

MARICOPA COMMUNITY COLLEGES

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MARICOPA COMMUNITY COLLEGES

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PHYSICS

Semiconductor Science Activities for High School Physics

The student activities in this packet are designed to be incorporated into a standard high school physics curriculum. The intent is to provide the student with an introduction to study of the electronic facets of physics as they apply to semiconductor technology.

Physics component of "Semiconductor Science" flow sheet:

Day 1: The N-type and P-type Junction, Lecture and Discussion

Day 2: Investigation 1. A Simulation of Electron Migration.
Investigation 2. What happens when an outside voltage or source of EMF, Electromotive Force, is added to a pn device?

Day 3: Discussion of lab findings and finish with an overview of the N-P junction material covered.

Day 4: The Diode, Lecture and Discussion

Day 5: Investigation 1. What does a diode do?

Day 6: Discuss lab findings and begin investigation 2A. "How is the voltage applied across a resistor related to the current that passes through the resistor?

Day 7: Discuss lab findings and begin investigation 2B. "How is the current that passes through a diode related to the voltage across the diode?"

Day 8: Discuss lab findings and finish with an overview of the Diode material covered.

Day 9: The Transistor, Lecture and Discussion

Day 10: Investigation 1. "What type of logic gate is this?" (Inverter)

Day 11: Discussion of findings and begin investigation 2. "What type of logic gate is this?" (NOR gate)

Day 12: Discussion of findings and begin investigation 3. "What type of logic gate is this?" (OR gate)

Day 13: a) Discussion of findings in investigations 1-3.
b) Begin investigation 4, the AND gate.
c) Challenges (critical thinking).

Day 14: a) Discuss lab findings for investigation 4 and the challenges.
b) "What is an Integrated Circuit and how does it work?"
c) Begin the integrated circuit activity, investigation V.

Time frame for this schedule is based on class periods that meet for 50 minutes.

The N-P Junction

PHYSICS

The Physics of Semiconductor Manufacturing

The Building of a Microchip.

(These lessons can be incorporated with the *Electricity Unit* to introduce the concepts of the microchip.)

LESSON 1. The p-type and n-type junction.

Objectives: *To develop a basic understanding of:*

I. Electron migration.
II. The formation of the pn junction.
III. The effects of an EMF on the pn junction.

Previous knowledge:

I. Types of dopants. (p and n types)
II. Types of doped materials. (Si and Ge)
III. Ohm's principle

Background:

Silicon (Si) or Germanium (Ge) wafers, in their purest forms carry no charge.

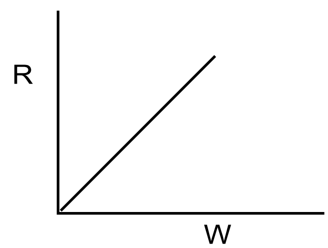
To develop n or p type wafers, n and p type dopants are used. The n-type materials carry a negative charge, due to excessive electrons that they acquire from Group 5 like Arsenic (As). The p-type materials carry a positive charge, due to excessive holes that they acquire from Group 3 elements like Boron (B).

Separately, these two types of materials are nonfunctional. When they are joined they form a useful device. They form a semi-conductive unit. Note that the P and N materials can not be put together like a sandwich but must be grown together chemically using one of the various semiconductor processes.

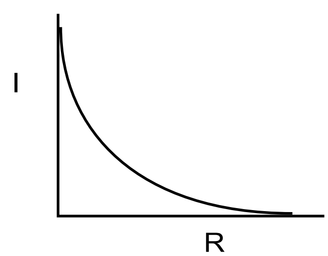
When joined, the excessive electrons in the n-type material migrate to the available holes that are found in the nearby p-type material. As this migration continues, the net charge on both materials begins to change. As the n-type material loses electrons, it gains a net positive (+) charge. As the p-type material loses holes (by gaining electrons) it gains a net negative (-) charge. During this migration of electrons, a region that is depleted of carriersis formed. This region is called the *depletion zone*. This zone separates the positive and negative areas of the semi-conductive unit and forms a internal potential difference, also known as the barrier potential. The barrier potential acts as a single cell battery, even though we can not measure this potential across the terminals of a non-powered device. Depending upon the **substrate** (doped) material, the electromotive force (EMF) varies (0.7 v for Si and 0.3 v for Ge). This internal voltage creates an internal electric field that stops the electron flow across the pn junction until a larger net voltage is applied from an outside source. As the semiconductor junction is being formed the electrons in the N-type material migrate over and fill the holes in the P-type material. The holes can be considered as empty spaces in the chemical structure of the P-type material. These holes exist because the P-type dopant, even though it chemically fits in the substrate structure, leaves a space where an electron can come to rest. When this happens, the P-type material has gained an electron on the P side of the junction so it has become negative by one electron charge. Since the P-type material has many billions of dopant atoms, you could conclude that it will get very negative.

However,as the process continues, the P-side gets negative enough that it begins to repel electrons from the N-type material rather than attracting them. On the N-side, electrons have been leaving. As a result the N-side is getting more positive as the process continues. Therefore, the N-side is trying to keep electrons from going over to the P-type material. This is a perfect example of the electrical force of repulsion and attraction being balanced by the chemical force of the P-Type dopant atoms wanting to have the equivalent of eight electrons in there outer shell to complete the crystal structure. This is call **equilibrium.**

The usefulness of this semi-conductive unit improves because we are able to control the width of the depletion region. By controlling the width, the resistivity of the unit can also be controlled. The relationship between the resistivity (R) and the width of the depletion area (W) is illustrated as:



Controlling the resistivity also determines the current (I) through the device for a particular value of applied voltage. This effect is demonstrated by Ohm's Principle; V=IR, hence the relationship between the current (I) through a device and the resistivity (R) of the device is:



The current (I) or the voltage (V) that is applied to the device to obtain a desired mode of operation is known as the **bias**. This electric potential is used to control the width of the depletion region. There are two common biases, **forward** and **reverse**. Forward biased pn junctions are created by applying an electric potential to:

a. the n-type material that is more negative than the p-type material potential. When this occurs, the electrons in the n-type material are pushed towards the junction by the negative terminal potential.

b. the p-type material that is more positive than the n-type material potential. When this occurs, the holes in the p-type material are pushed toward the junction by the positive terminal potential. Actually, the positive potential on the p-type material is attracting electrons into the p-side of the junction. Since electrons are leaving via the positive lead, more holes are created. The holes migrate toward the junction where they pick up an electron.

The device that is forward biased uses an electric potential to reduce the resistance across the pn junction and increase its conductivity. Typically the pn junction will show an exponential rise in current with increasing voltage up to its physical **power dissipation** limits. When the power dissipation limits of a semi-conductor device are exceeded the device gets too hot (above 200 degrees celcius) and begins to respond erratically.

Reverse biased pn junctions are created by applying an electric potential to:

a. the n-type material that is more positive than the p-type material potential. When this occurs the electrons of the n-type material head towards the positive terminal of the source.

b. the p-type material that is more negative than the n-type material potential. When this occurs, the holes of the p-type material move toward the negative terminal of the source.

The device that is reverse biased uses an electric potential to widen the depletion region and increase the resistivity of the pn junction and lower the conductivity to near zero. This increases the depletion region resistance to a very high value so that the device acts as an open circuit, hence, the current through the pn junction will approach zero.

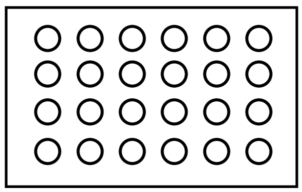
INVESTIGATION 1: A Simulation of electron migration

Query: How are pn junctions formed?

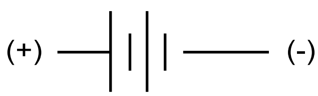
Hypotheses: (Student generated list)
Teacher's note: If necessary lead students to the idea that electrons migrate towards the more positive area.

Materials: (2 students per group)

2 - 10 cm x 30 cm cards with the following design:



1 - 10 cm x 10 cm card with the following design:



This card represents the electromotive source, such as a battery.

21 - 2 cm (outside diameter) washers. Pennies may be used.

Procedure:

1. Fill one of the cards with the washers or pennies. This card now represents the n-type material. The washers and pennies represent the excessive electrons from the n-dopant.
   Card 2, "free" of electrons, represents the p-type material. It has an excess of "holes" from the p-dopant.

2. Join the n-type and p-type materials by allowing the common borders to touch.

3. Move the first column of "electrons" to fill the first column of available holes on the p-type material. What you have formed is known as the pn junction and the depletion zone. When the pn junction is formed the migration of electrons stops.

Discussion Questions:

1. Draw a scaled replica of the pn device and label the location of the pn junction.

2. Why did the electrons of the n-type material moved to the "holes" of the p-type material?

3. Why does the migration of electrons stop?

4. How did the migration of electrons change the physical characteristic of the n-type and p-type materials?

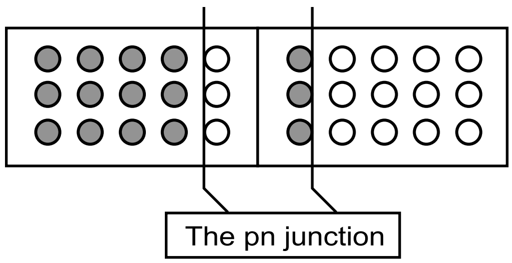
5. How would you best describe the pn junction?

6. Why is the pn junction also known as the depletion zone?

7. What would be needed to continue electron migration across the depletion zone?

Answers to Questions:

1.



2. Electrons have a natural tendency to flow towards the more positive area.

3. Migration ceases when the available carriers have formed the depleted “barrier” or depletion zone.

4. The n-type material now contains “holes” and carries a positive (+) charge and the p-type material now contains electrons and carriers a negative (-) charge. Forming a semi-conductive device in a state of equilibrium.

5. The pn junction is the immediate area of the n-type : p-type border where migrating electrons left “holes” in the n-type material and filled the immediate “holes” of the p-type material with electrons.

6. The immediate area of the pn junction is known as the depletion zone or region because it is free of available carriers.

7. An electric potential known as the barrier potential exists across the depletion zone. This potential is material specific. Silicon’s barrier potential is ~0.7v and Germanium’s barrier potential is ~0.3v. To continue the migration of electrons across the depletion zone, an outside EMF that has a larger electric potential than the barrier potential must be used.

This lesson is used to illustrate how two differently doped materials that are electrically neutral can be chemically joined to form a simple electronic semi-conductive device. This device is the foundation of the semiconductor industry as it has the capabilities of regulating the electric current and the direction that the current flows.

INVESTIGATION 2. What happens when an outside EMF source is added to a pn device?

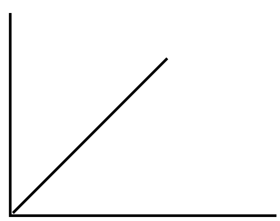
Background Information:

The width of the depletion zone is determined by the thickness of the dopant layer. The more available “holes” in the p-type material, the greater the opportunity for the migration of electrons to occur. In general, the more dopant, the wider the depletion zone. The manufacturing processes for diodes and transistors in the early years of semi-conductors produced wide depletion regions which limited high frequency operation. Now depletion regions in some devices are only a few tens of atoms thick.

When a voltage source, or electromotive force, EMF, that has a larger potential than the “barrier potential” of a device is used the device demonstrates a specific mode of operation. This is known as a forward **bias**. The bias, which is the current or voltage that is applied to a device is used to control the width of the depletion zone. This, in turn, regulates the resistivity of the device. The resistivity controls the current through the device.

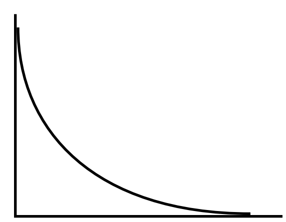
The relationship between the resistance and current is related to the width of the depletion zone. These relationships are approximately illustrated as:

Resistance (R)



Width

Current (I)



Width

Mathematically, R α W and I α W^{-1}

There are two types of bias, they are forward bias and reverse bias. The forward biased pn junction is formed when the outside EMF source causes the n-type material to be more negative than the p-type material. The negative pole of the EMF source is connected to the n-type material and the positive pole of the EMF source is connected to the p-type material. With this application, the depletion zone is reduced. The applied EMF moves electrons, in the n-type material, towards the p-n border. Simultaneously, the “holes” in the p-type material are also moving towards the pn border. With this reduction of the depletion zone, the resistivity is lowered and the electric current is increased. Another way of stating the method of forming a forward biased pn junction is to apply an EMF to the p-type material that is more positive than that of the n-type material.

A reversed biased pn junction is formed when the applied EMF causes the n-type material to become more positive than the p-type material. This application causes the electrons in the n-type material and the “holes” in the p-type material to migrate away from the pn junction causing the depletion zone to enlarge. With this increase width of the depletion zone, the resistivity of the device is increased and the value of the electric current approaches zero. Another way of stating the method of producing a reverse biased pn junction is to apply an EMF to the p-type material that is more negative than that on the n-type material.

Objectives:

Students will model the formation of forward and reversed biased pn junctions.

Students will recognize the effect that forward and reversed biased pn junctions have on current flow.

Materials:

Use the same materials as in investigation 1. Also add to this the cutout of the EMF source.
Two lengths of string, each 30cm long.
Scotch Tape.

Procedure A: For the forward biased pn junction.

1. Attach a length of string to each pole of the EMF source. The string represents the wire leads that are attached to the EMF.

2. Setup a pn junction that is three columns wide on each side.

3. Attach the negative lead to the n-type material and the positive lead to the p-type material. You now have a closed circuit. (Remember that electrons flow from the negative terminal towards the positive terminal.)

4. On the p-type card, move the outermost column of "electrons" of the depletion zone towards the positive lead wire. Remove these electrons from the board. (This represents the electrons passing through the positive lead and moving towards the EMF positive lead and back to the battery where they will be recycled back to the negative side of the EMF source, the negative lead.

5. On the n-type card, shift all columns of "electrons" one step towards the pn junction. Fill the open holes with the "electrons" that have passed through the wire leads. Note the width of the depletion zone.

6. Draw a scaled representation.

7. Repeat steps 4, 5 and 6.

Procedure B: For reverse biased pn junction.

1. Setup as in steps 1 and 2, from procedure A.

2. Attach the negative lead, from the EMF, to the p-type material. Attach the positive lead to the n-type material. (Again remember that electrons flow from the negative pole to the positive pole of the battery or EMF source.)

3. Move all columns of "electrons" on the n-type card one step towards the positive lead. (One column of "electrons" will move off of the board. These electrons represent the electrons that are moving through the positive lead towards the EMF source.)

4. Fill the next open column of "holes", on the p-type card, with the "electrons" that have passed through the wire leads. Note the width of the depletion zone.

5. Draw a scaled representation.

6. Repeat steps 3-5.

Discussion Questions:

1. Why does the depletion zone shrink in a forward biased pn junction?

2. How does a forward biased pn junction change the conductivity of the device? Please explain your answer.

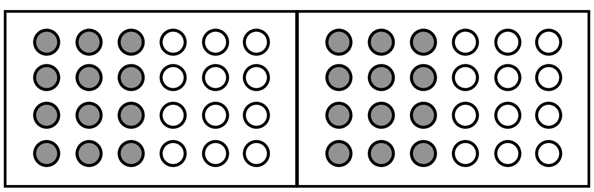
3. Why does the depletion zone enlarge in a reverse biased pn junction?

4. How does a reverse biased pn junction change the resistivity of the device? Please explain your answer.

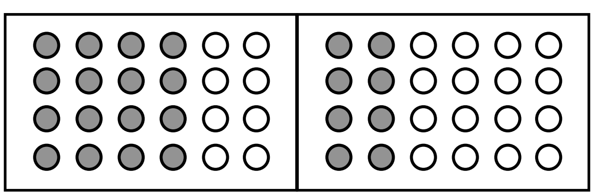
Drawings for Simulation and Answers to Questions.

Drawings for *forward biased pn junction*.
(Left side: n-type, Right side: p-type)

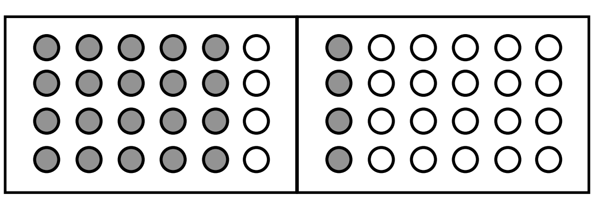
Before EMF is added.



After EMF is applied 1.



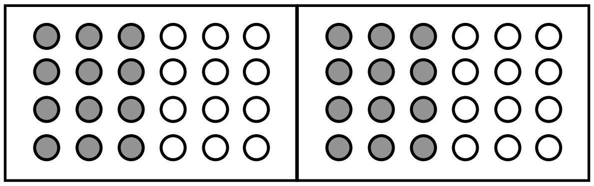
After EFM is applied 2.



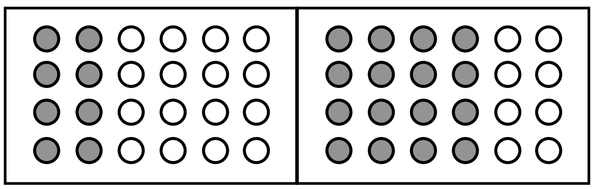
In both cases, the EMF, electromotive force, is pushing electron current through the n-type material towards the p-type material and to the positive side of the EMF. The net voltage, from the EMF, provides and excessive amount of electrons on the n-type material large enough that it can overcome the barrier potential of the pn junction. This causes the electrons and “holes” to migrate towards the pn boarder. This action reduces the depletion zone and increases the conductivity of the device.

Drawings for *reverse biased pn junction*.
(Left side: n-type, Right side: p-type)

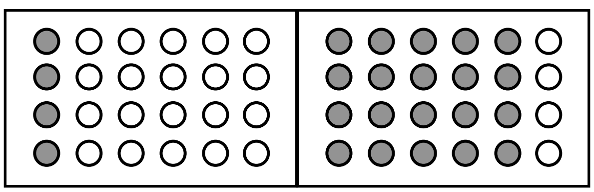
Before EMF, voltage, is added.



After EMF is applied 1.



After EMF is applied 2.



In this case the EMF is moving positive electric charges in the p-type material away from the junction. The availability of excess electrons at the negative side of the EMF allows the electrons to migrate further into the p-type material making the P-type material even more negative. The electrons in the n-type material are attracted toward the positive side of the EMF source and as a result the n-type material becomes even more positive. In this case the EMF is moving negative electric charges in the n-type material away from the junction. Since the charge carriers are being pulled further apart the depletion zone has widened and the resistivity has increased.

Answers to questions:

1. When the negative and positive potentials (poles) of the EMF are applied to the n-type and p-type materials, respectively, the negative potential of the EMF pushes the electrons in the n-type material towards the junction. The holes, of the p-type material, are also pushed towards the junction by the positive potential of the EMF. The combined effects cause the width of the junction to be reduced.

2. With this reduction of the pn junction and assuming that the applied voltage is greater than that of the barrier potential, the electrons in the n-type material will gain enough energy to break through the depletion zone. When this occurs, the electrons are free to fill the “holes” in the p-type material and conduction occurs.

3. When the negative and positive potentials (poles) of the EMF are applied in reverse on the pn device, the electrons in the n-type material move towards the positive terminal of the EMF and the “holes” in the p-type material migrate towards the negative terminal of the EMF. In this situation, the depletion zone has widened.

4. With an increase of the width depletion zone, the electrons have a formidable barrier that prevents ready migration across the junction. This barrier increases the resistivity of the junction and the conductivity of the device is close to zero.

Supplemental Information:

If you would like to learn more about chemical doping and electron migration across pn devices check out this web site:

http://www.irf.com/technical-info/guide/semi.html

PHYSICS

The Diode

LESSON 2. The Diode.

Query: *What is a diode and how does it work?*

Objectives:

I. Identify and draw the accepted schematic diagram of a diode.
II. Identify the terminals of a pn-junction diode.
III. Determine the function of a diode.
IV. Determine the direction of electrons through the diode.
V. Determine the relationship between the current and the applied voltage for a diode.

Previous knowledge:

I. Electron migration
II. The pn-junction
III. Forward and reverse biased junctions.

Background Information:

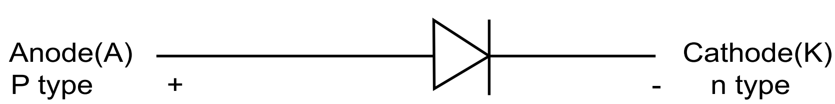
The N-P or P-N junction.

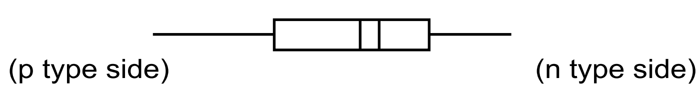
When n-type (n-cell) and a p-type (p-cell) materials combine to form a junction, the excessive electrons in the n-type material passively flow to the p-type material (uni-directional). As this flow (recombination process) proceeds it forms what is known as the *depletion zone*. The formation of the depletion zone occurs in a matter of microseconds.

The orientation of the combined cells (N-P or P-N) is based on the amounts of dopant used. If n-dopant > p-dopant, then the junction is N-P. If p-dopant > n-dopant, then the junction is P-N. This orientation determines the behavior of the electrical current through the semiconductor.

Basic diode design.

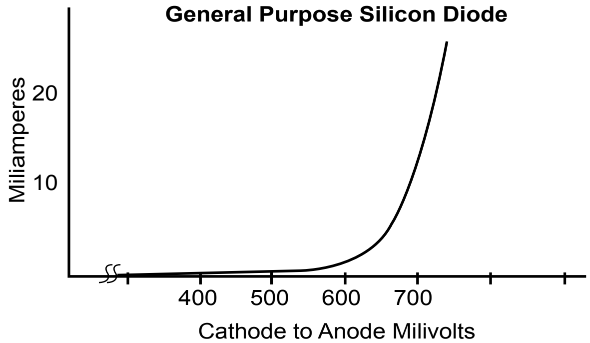
The P-N cell represents the basic design for a diode. What is needed is an EMF to drive a continuous electron flow through the cell (diode). The following schematic illustrates the basic design.





The pn device, as it relates to the above diode.

A diode is a two electrode device that acts as a one way conductor. The pn junction diode is the basic diode. The forward biased diode will conduct electricity and the reverse biased will not. Diodes are formed from semi-conductive materials, primarily silicon. The type of material determines the voltage vs current characteristic of the device. The resistivity of the diode is not constant as you can tell from the changing slope of the curve below. Unlike the *linear* relationship shown previously as Ohm's Law, the curve below illustrates a *non-linear* relationship between the current and the voltage.



Here, the graphical model tells us that I α V^n. The value of n > 1.

Supplemental Information:

If you'd like to learn more about diodes check out this web site:

http://www.ee.duke.edu/~cec/final/node84.html

INVESTIGATION 1: The Diode

Query: What does a diode do?

Hypothesis: (Student generated. If necessary, lead students to the idea that diodes may determine the direction of the flow of electrons.)

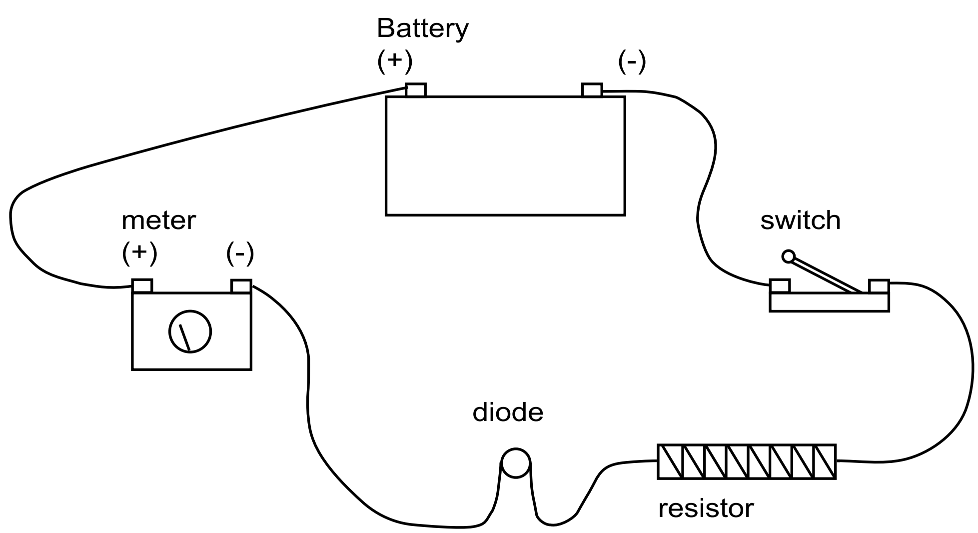
Materials:

Three diodes: 2 standard diodes and an LED
A 470 Ω resistor
A battery pack. (9v)
Multi-meter or ammeter
A proto-board
Insulated bell wire
Switch

Note: If multi-meters or ammeters are not available, use LED's (Light emitting diodes) If proto-boards are not available, use wire leads with 'alligator' clips to make connections.

Procedure:

1. Set up a simple circuit as illustrated.



2. Close circuit by closing the switch. Record the reading on the meter.

3. Open the circuit by opening the switch.

4. Reverse the terminal attachment, of the diode, in the circuit. To do this, attach the wire leads to the opposite electrodes. Close the circuit and record the reading on the meter.

5. Open the circuit.

6. Replace diode with another diode and repeat steps 2 – 5. Repeat this process with a light emitting diode (LED).

Data:

Diode	Meter Reading (mA)
D_1	
D_1 (reversed)	
D_2	
D_2 (reversed)	
LED	
LED (reversed)	

Conclusion:

Discussion Questions

1. What is a diode?

2. Are diodes unidirectional in regards to current flow? Please explain your answer.

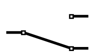
3. What physical characteristic, of a diode, identifies the direction of the current flow?

4. Draw the schematic symbol for a diode and label the terminals.

5. Using the appropriate schematic symbols, draw the circuit used for the experiment.

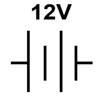
Switch :

switch



Battery (EMF):

12V



Meter:

Resistor:

470Ω

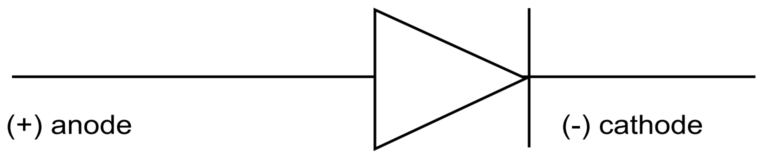
Answers to Questions

1. A diode is a two terminal electronic device that acts as a one-way conductor.

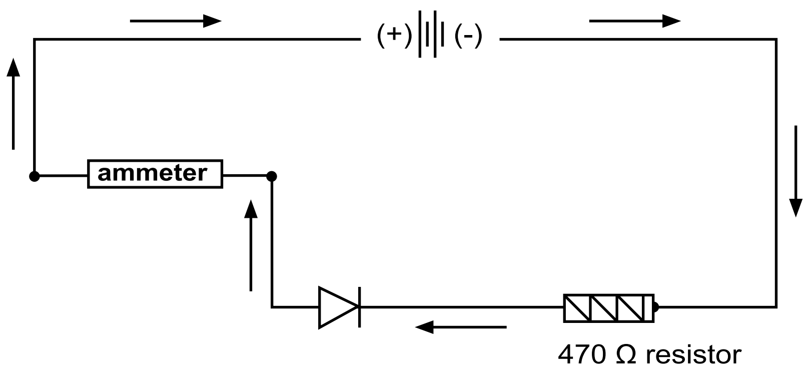
2. Yes, from the data, the diodes conduct electricity only when they have the proper polarity applied. In some cases, the initial setup of the diode prevented a current flow and by simply switching the terminal positions current was allowed to flow.

3. LEDs have terminals of different lengths. The long lead is the anode (+) and short terminal is the cathode (-). Others have a terminal with a flattened portion, this is the cathode (-)with the other being the anode (+). Or the casing has a flattened side, here the terminal that is closes to the flattened side is the cathode (-). Other diodes have (+) and (-) markings to signify specific electrodes as either the anode (+) or the cathode (-). The most common marking is a band near the cathode end of the diode. When placing a diode into a circuit, attach the device leads so that the cathode is attached to the most negative potential and the anode to toward the positive potential. This will keep the diode forward biased.

4. Schematic showing forward biased diode:



5.



Note:

The arrows (⟶) indicate the direction of electron current flow.

In many electronics and physics textbooks, the current flow is shown going in the opposite direction. The current moving from the (+) terminal to the (-) terminal is known as **conventional current flow**.

LESSON 2. INVESTIGATION 2A.

Query: How is the voltage (V) that is applied to the resistor related to the current (I) that passes through the resistor?

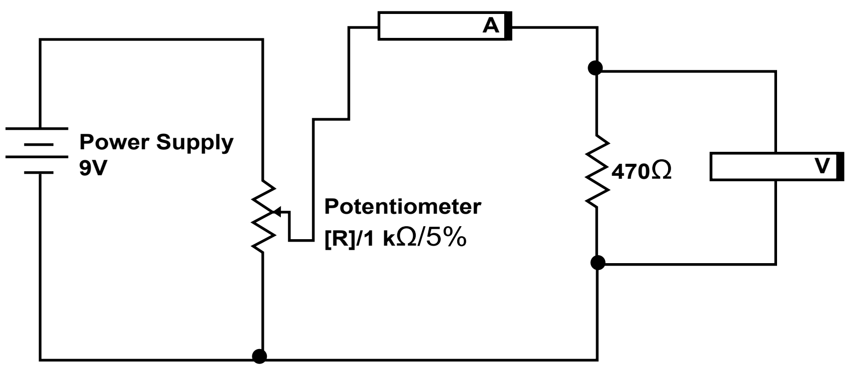
Hypotheses: (Student generated). Since the data that is collected will be graphed, students can list their hypothesis as a graphical representation.

Materials:

Bread board with 9v- battery hook up
Voltmeter (0-10 volts scale)
Ammeter with milli-amp scale
1 - 1kΩ potentiometer
1 - resistor: 470Ω

Procedure:

1. Construct the test circuit following the electronic schematic diagram shown below. R_1 is the poteniometer and the resistor is 470 OHMS.



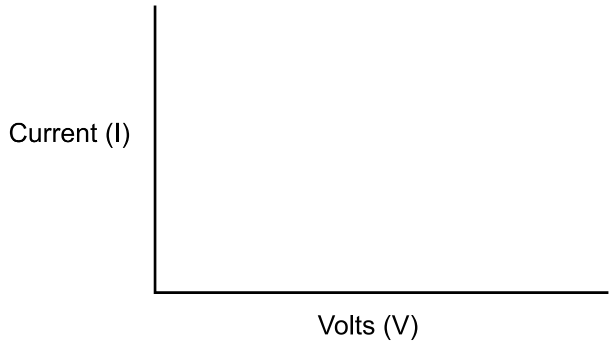
2. By adjusting R_1 (turning the dial) you will see changes in the voltmeter and ammeter scales.

3. Change the R_1 position in seven equal increments and record the resistor voltage and amperage.

4. Graph your results as I v. V.

Voltage (V)	Current (mA)

Evaluation of data: *Graphical Analysis*



Conclusion: (Students should conclude that the current in the circuit is directly dependent upon the voltage applied to the resistance.)

Discussion Questions:

1. What is the constant in this exercise?

2. What is the function of the potentiometer?

3. What does your data suggest about the resistive value of the 470 OHM resistor?

4. Write the mathematical model that is illustrated by your graph.

5. Using Ohm's Principle, calculate the experimental resistive value of the 470 OHM resistor. How does it compare to the accepted range of values for the 470 OHM resistor?

Answers to Questions:

1. The resistance of resistor, 470 OHMS, is constant.

2. The potentiometer is used to adjust the voltage applied to the resistor. It behaves as a potentiometer in that it provides a variation in potential from 0 to 9 volts from the 9 volt supply.

3. The value of the 470 OHM resistor is constant.

4. Current $\alpha\alpha$ Voltage. The mathematical model: V = I(k). Where k, the constant, is the resistance (R). Therefore, V = IR, Ohm's Principle.

5. The experimental value of the resistor should be within 10% of the color-coded value.

LESSON 2. INVESTIGATION 2B.

Query: How is the current (I) that flows through a diode related to the voltage (V) across the diode terminals?

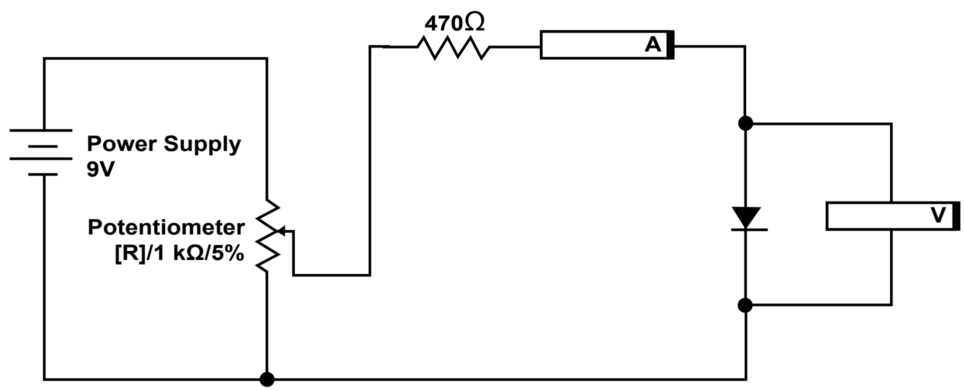
Hypotheses: (Student generated). Since the data that is collected will be graphed, students can list their hypothesis as a graphical representation.

Materials:

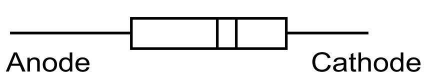
Bread board with 9v- battery hook up
Voltmeter (0-10 volts scale)
Ammeter with milli-amp scale
1 - 1N4148 small-signal diode or 1N4001 power diode
1 - 1kΩ potentiometer
1 - 470 ΩΩ resistor

Procedure:

1. Construct the test circuit following the electronic schematic diagram shown below. R_1 is the potentiometer and R_2 is the resistor. Find the 470 OHM resistor and mark it as R_2 on the schematic diagram.



Note: On a small signal diode the terminal closest to the distinctive colored band is the cathode.



2. By adjusting R_1 (turning the dial) you will see changes in the voltmeter and ammeter scales.

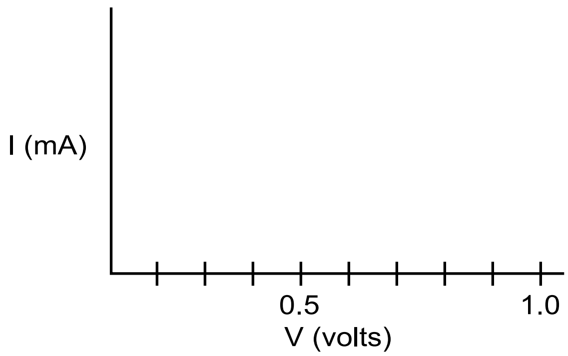
3. Change the R_1 position in seven relatively equal increments and record the voltage and current at each R_1 position. As you increase the voltage from zero, also record the diode voltage when current first begins to flow.

4. Graph your results as I v. V.

Data:

Voltage (V)	Current (mA)

Evaluation of data: *Graphical Analysis*



Conclusion: (Students should conclude that the current of the circuit is dependent upon an exponential function of the voltage.)

Discussion Questions:

1. Can Ohm's principle be applied to current and voltage across a diode?
2. What does your data suggest about the resistance of the diode?
3. Write the mathematical model that is illustrated by your graph.

Answers to Questions:

1. No, it cannot. Ohm's principle illustrates a direct relationship between the current and the voltage in a circuit. The analysis of the data shows on exponential rather than a direct relationship.
2. The resistance of the diode is not constant.
3. The mathematical model is; I α V^n , where $n>1$.

PHYSICS

The Transistor

The Transistor

Objectives:

I. Introduce the concept of the basic transistors: the NPN and NPN types.
II. Identify the parts of the transistor.
III. Draw and label the schematic of a transistor.
IV. Recognize the transistor as a "switch".
V. Apply Ohm's Principle to an electronic circuit that includes diodes and transistors.
VI Apply the Voltage Divider Principle to electronic circuits that include diodes and transistors. Introduce the concept of logic gates and truth tables.
VII Draw the schematic of a NOT, NOR and an OR gate and calculate the current flow through the system.
VIII. Build and test a simple NOT gate, NOR gate, OR gate and AND gate.

Previous Knowledge:

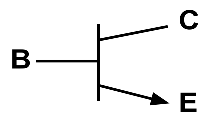
I. Ohm's Principle.
II. Voltage Divider Principle.
III. The diode.
IV Basic schematic symbols and design.

Background information:

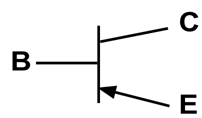
Transistors are electronic devices that at the most basic level are composed of three regions of doped material. Two common transistors are the NPN and the PNP types these are known as **bipolar junction transistors** *(BJT)*. These devices use relatively small amounts of electric current (I) to control large amounts of current (I) within the same device. BJT devices are three terminal units. There are many types of transistor packages and each package may have one of several terminal orientations. For small signal transistors one of the common packages is cylindrical with a flattened area. The terminals may be arranged in several configurations. For example, the TO-92 package used for many small signal transistors, has the shape described above. With the flat side facing you and the leads pointing downward, the terminal on your right is the **collector terminal**, the middle terminal is the *base* **terminal** and the terminal on your left is the **emitter terminal**. Note that you should always find a collector current terminal diagram for each semi-conductor device that you are using. NPN transistors have a p-type base terminal and n-type collector and emitter terminals. PNP transistors have a n-type base terminal and p-type collector and emitter terminals. The base terminal is used to control the collector current. The ability of the base current to control collector current is one of the main transistor parameters known as Beta (β). Beta is the ratio of collector current to base current. It can vary from 20-30 for power transistors to over 400 for small signal transistors. The value is usually between 100 and 200. Since it is the ratio of collector current to base current, the number for Beta has no units.

The symbols for the BJT are:

For the NPN transistor,



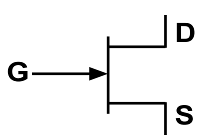
For the PNP transistor,



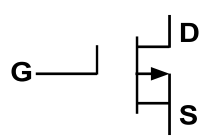
The base terminal (B) is the **on** and **off** switch for the transistor. When the switch is on, current flows from emitter to collector. When it is off, there is no flow. The base terminal usually acts as the input of the transistor. When the **input** is low or off, its value is 0. When the input is high or on, its value is 1. The same holds true for the **output**, if current is flowing through the output device then the device is on. If there is no flow of current then the output device is off.

In addition to the BJT's described above, there is another category of three terminal semiconductors called Field Effect Transistors (FETs). Field Effect Transistors and Metal Oxide Semi-conductor FETs (MOSFETs) are the primary type of transistors that are used in the micro-processing industry. These transistors are controlled by voltage rather than current. FETs and MOSFETs require much less control current to operate as compared to their BJT counterpart. There are several configurations of field effect devices. The schematics of an n-channel FET and a p-channel MOSFET are shown below.

FET



MOSFET



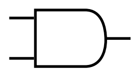
G is the **gate** of the transistor and it is equivalent to the base of a BJT.
D is the **drain** of the transistor and it is equivalent to the collector of the BJT.
S is the **source** of the transistor and it is equivalent to the emitter of the BJT.

The conditions that allow a gate to turn on or off can be calculated by using Ohm's principle, V = IR, and the voltage divider principle. The voltage divider principle allows one to calculate the voltage at the junction of two resistors in a series combination when you know the applied voltage and the individual resistance values. When measuring voltage, attach the voltmeter across (parallel to) the terminals of the device being measured. When measuring resistance, attach the ohmmeter across (parallel to) the device (only after removing the power from the device being measured.) When measuring amperage (current), of a circuit element, it is important that the ammeter or milli-amp meter be placed in line (series) with that particular element of the circuit.

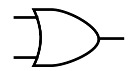
In combination, transistors can form what are known as **logic gates**. Logic gates are used to translate electric current into either a zero (0) or a one (1). This numeration is known as the **binary language** or computer mathematics. As computer functions become more complex, the binary signals that are processed by computers involve in processing large series of 0s and 1s. A **decoder** “reads” the signal and causes the appropriate switches to be activated or a command to be activated. The **ASCII** code is a list of binary sequences for various keyboard functions and characters like for example the letter A, which is 0001100.

There are five common gates: the AND gate, the OR gate, the NOT gate, the NAND gate and the NOR gate. Two additional but not so common gates are the exclusive OR and the exclusive NOR gate. Each gate has its own unique symbol and function.

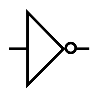
The AND gate:



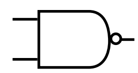
The OR gate:



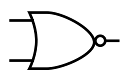
The NOT gate:



The NAND gate:



The NOR gate:



(For most gates, the inputs are on the left side and there is only one output on the right)

Notice that the NOT gate has only one input terminal. A NOT gate is known as a unary gate. The other gates have two or more input terminals and are known as binary gates. The output for each type of gate is determined by the input value (0 or 1) on each input terminal. Each gate has a predictable output value that can be determined by developing a **truth table** for the particular device. This table lists all possible input and output combinations for each type of gate.

One must remember that the math being used is binary mathematics, which is based on **Boolean Algebra**. Truth tables are also used to determine the output of a particular multi-gate design. The values from the truth table combined with Boolean Algebraic Equations and **Karaungh tables** are used to determine the best gate circuit design.

The number of input terminals, also known as variables, determines the dimensions of the truth table. The number of columns is the sum of inputs and the output. The header for each column will be input or output. The number of rows in the truth table is based on the number of inputs to the table. This simple mathematical relationship is the number of rows = $2^{(\text{number of variables})}$. Thus, a four-input truth table will have 16 rows to specify all possible combinations of the four variables.

The truth tables for the common gates are:

NOT gate

Input (x)	Output (z)
0	1
1	0

OR gate

Input (x)	Input (y)	Output (z)
0	0	0
0	1	1
1	0	1
1	1	1

AND gate

Input (x)	Input (y)	Output (z)
0	0	0
0	1	0
1	0	0
1	1	1

NAND gate

Input (x)	Input (y)	Output (z)
0	0	1
0	1	1
1	0	1
1	1	0

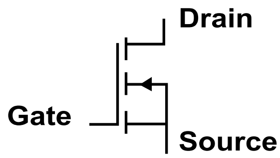
NOR gate

Input (x)	Input (y)	Output (z)
0	0	1
0	1	0
1	0	0
1	1	0

The type of gate is determined by its electronic construction. Its electrical output is determined by the gate inputs. The truth table is helpful in making sure that all the possible combinations have been considered. A simple and common gate is the **inverter**, it is also known as the NOT gate. A NOT gate can be constructed of one transistor and three resistors. This device recognizes only two input values: 0 and 1. These values are dependent upon specific voltage signals from the system controls or from other gates within the system. If the voltage is present, then the input value is 1. If not, then the value is 0. With inverters, the value of the output is opposite (inverted) that of the input.

OR gates are commonly found in a simple integrated circuit (IC). They involve at least two transistors within the device and either transistor may be either ON or OFF. As you can see from the OR gates truth table, its output will be ON if either or both inputs are ON.

When a groups of gates are used to control a system, there will be an output from each group that will control a specific function. The final driven elements will respond to the sequence of (1s) and (Os) by turning ON or OFF their respective electrical mechanical process controls. This coded sequence may also be converted into a real number by using binary mathematics or used to begin a specific digital function. A keystroke on a computer keyboard or on the number pad of a calculator may produce a sequence that sets the system up to add two numbers together. Simple gates are usually packaged in groups of two or more per package. These packages are called integrated circuits (ICs). For example an IC package called a hex inverter has six inverter gates inside.



N – Channel Enhancement Mode FET. (N-CH-EN-MOSFET)

The ICs that are used in microchips are described as VLSI (Very Large Scale Integration) and are much more sophisticated and delicate than the ones described above. Field-effect transistors (FET) and Metal-Oxcide-Semi-conductor FET (MOSFET) are the most commonly used systems in micro-processing ICs. These integrated circuits with more sophisticated design allows them to do more complex tasks. There are several types of MOSFETs. Schematically a N channel Enhancement Mode MOSFET is symbolized as:
In the communications industry transistors are used as amplifiers to increase the strength of an alternating current (ac) signal. In digital computer electronics specialized transistors are used as high speed electronic switches. These switches are capable of switching between two operating commands in a matter of nanoseconds. (A nanosecond is a billionth of a second). A computer micro-processing chip, about a quarter the size of a postage stamp, may contain five million transistors!!! The more transistors on a chip, the more gates. This leads to having a greater number of possible numerical sequences which are needed for the newer generation computers to perform more complicated functions. Try to imagine the processing chip in a four- function calculator and that of a graphing scientific calculator.

To learn more about logic gates and computer mathematics check these sites:

http://www.proaxis.com/~iguanalabs/1stled.htm

http://cs.ru.ac.za/func/boolJava/index.htm

http://www.mc.edu/courses/csc/110/index.html

To get a sampling of ASCII codes and tables check these sites:

http://www.physics.udel.edu/wwwusers/watson/scen167/ascii.html

http://www.pcwebopedia.com/ASCII.html

LESSON 3. INVESTIGATION 1: Boole's Logic

Query: What type of logic gate is this?

Hypothesis: (The students have been introduced to the five common gates and should choose one of the five as a possible answer.)

Materials:

1 – Bread board with 9v attachment
1 – LED
1 – 9v battery
1 – MOSFET Transistor
2 – 1000 ohm resistors
1 – 1 M Ω resistors
1 – 470 Ω resistors
An assortment of wire connectors

Background Information On Circuit Construction Precautions

N-channel Enhancement Mode Mosfet Inverter

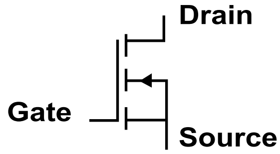
The inverter circuit will be your first gate circuit to construct. There are three definite PRECAUTIONS when working with the MOSFET (metal oxide semiconductor field effect transistor).

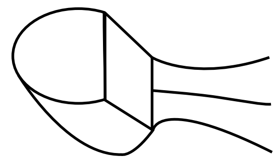
ONE (MOST important), the device is very static sensitive. A very small static charge can wipe out (punch through) the very thin (atoms thick) gate insulation which is silicon dioxide. The MOSFETs come with their terminals inserted in a black conductive foam material. Do NOT put the MOSFETS in any other type of foam as most other types create static as the leads are inserted. Probably the best way to proceed is to build the circuit and then carefully insert the MOSFET into the circuit. Mark three connector banks on your circuit board with the designation of GATE, SOURCE and DRAIN respectively, then build the circuit carefully and finally transfer the MOSFET to the circuit board. Before you remove the MOSFET from the conductive foam, remove your body static electricity by touching a relatively large metal object or the case on a power supply. Then remove the MOSFET from its conductive foam, adjust the position of the leads so that it will fit in your circuit, touch your circuit SOURCE and GATE terminals with your finger and then insert the MOSFET. Touching the circuit with your finger will bring the circuit, you and the MOSFET to the same potential so the MOSFET will not experience any static high voltage when it is inserted in the breadboard.

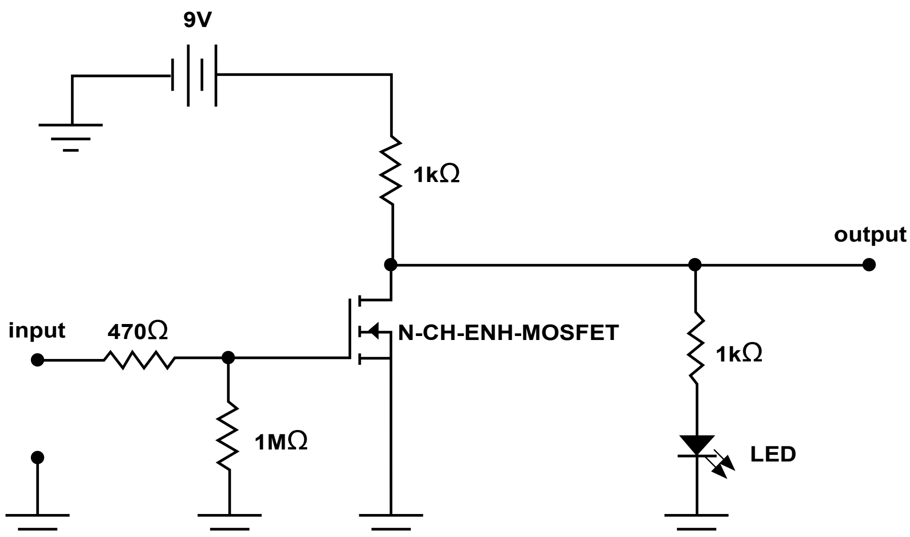
TWO, apply the proper polarity voltage to the circuit.

THREE, pay close attention to the names of the leads of the MOSFET. It can be quite confusing when looking in a data book, so refer to the schematic and pictorial diagrams that follow this information. You are encouraged to look up the device in a data book to see if you can determine the pin names and numbers from that source. Remember that most data books show the device with the leads pointing toward you. You have to look at the leads and the orientation of the device features such as a FLAT surface to accurately determine the lead designations. In this case you will be looking for the SOURCE, GATE and DRAIN leads.

The enhancement mode MOSFET is an open circuit between its source (lower terminal) and its drain (upper terminal) when its gate (center terminal) is close to ground potential. If the gate voltage rises to about one-half of the drain supply voltage then the MOSFET becomes a closed circuit.   This is nearly equivalent to turning a SPST (single pole single throw) switch in the OFF position to the ON position. You will notice upon analyzing the circuit that the LED will be ON when there is no input a (0) in digital language. Placing an input of six or more volts DC on the gate will cause the MOSFET to turn ON and therefore the voltage at the drain terminal will be almost (0) volts. In this case the LED will not have enough voltage to turn it ON. Therefore, you can see that the sense of the input is reversed in the output.







Procedure:

1. Set up the circuit as illustrated by the schematic diagram shown above.
2. Be sure to follow the rules about static protection:
3. Check your circuit before you begin data collection.
4. Develop truth table for this circuit.
5. From the truth table determine the type of gate.

Data Table: (Student developed truth table)

Instructor reminder: The number of rows in a truth table is determined by the number input terminals (variables). The number of rows is equal to $2^{(\text{number of variables})}$. The number of columns is the sum of the number of inputs plus the output.

Example: The AND gate has 2 inputs and an output. This means that this truth table will have three columns; Input-1, Input-2 and the Output. With two variables (inputs) the number of rows will be 4. ($2^2=4$). And the table will look like this: (next page)

Input 1	Input 2	Output

Conclusion:

Discussion Questions:

1. What type of circuit does the truth table indicate?

2. Draw the schematic symbol for the gate used.

3. What would be a function of this type of gate?

Answers to Lab and Questions:

1. The circuit demonstrates a NOT gate or an **inverter**. The truth table should reflect the NOT gate values.

2. The diagram is the schematic symbol for the NOT gate.

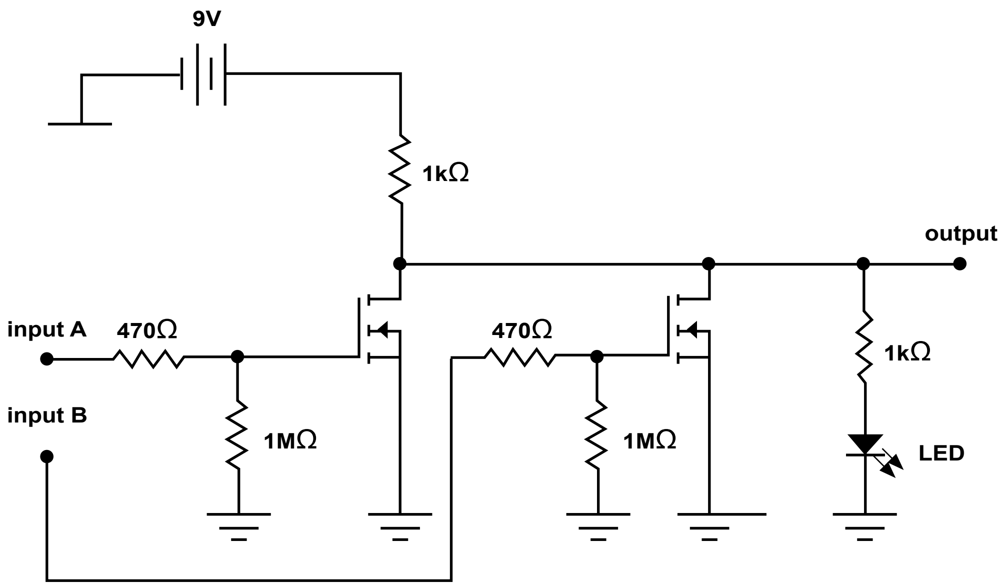
3. A function would be to open or close a switch when another switch needs to be closed or opened. Hence, the name: Inverter.

INVESTIGATION 2: Boole's Logic II

Query: What type of logic gate is this?

Hypothesis: (The students have been introduced to the five common gates and should choose one of the five as a possible answer.)

Materials:
1–Breadboard with 9v attachment
1 - LED
1 – 9v battery
2 - MOSFET Transistors
2 – 1000 ohm resistors
2 – 1 MΩ resistors
2– 470 Ω resistors
An assortment of wire connectors



N-CH-EN-MODE MOSFET NOR GATE CIRCUIT

Upon careful comparison of the NOR gate and the INVERTER circuit you will find that the NOR gate is quite similar to the INVERTER. If either MOSFET has a high voltage on its gate (input A or B) then the transistor acts very much like a closed switch. Notice that if either MOSFET is ON the common line connecting their drain terminals to the output will be close to (0) volts and the LED will be OFF. Make a TRUTH table for the circuit and compare it to the other digital circuits you are building.

Procedure:

1. Set up the circuit as illustrated by the schematic diagram shown above:
2. Check your circuit before you begin data collection.
3. Draw the schematic symbol for the gate used.
4. Develop a truth table for this gate configuration.
5. Also determine the type of gate from the truth table.

Data Table: (Student developed truth table)

Student reminder: The number of input terminals (variables) determines the number of rows in a truth table. The number of rows is equal to $2^{(\text{number of variables})}$. The number of columns is the sum of the number of inputs plus the output.

Conclusion:

Discussion Questions:

1. What type of a gate does the circuit show?
2. What type of gate does the truth table show?
3. What is the function of this type of gate?

Answers to Lab and Questions:

1. The circuit demonstrates a NOR gate.
2. The truth table should reflect the NOR gate values.
3. A function would be to allow a series of devices that are linked together, to be turned on or off depending upon the input values. As an example, four computers that are linked to one printer. A NOR gate device sends signals to the printer that stops the flow of information from one computer as it prints information from another. Waiting computers are on hold until the printer signals the next computer to send its print data.

LESSON 3. INVESTIGATION 3: Boole's Logic III

Query: What type of logic gate is this?

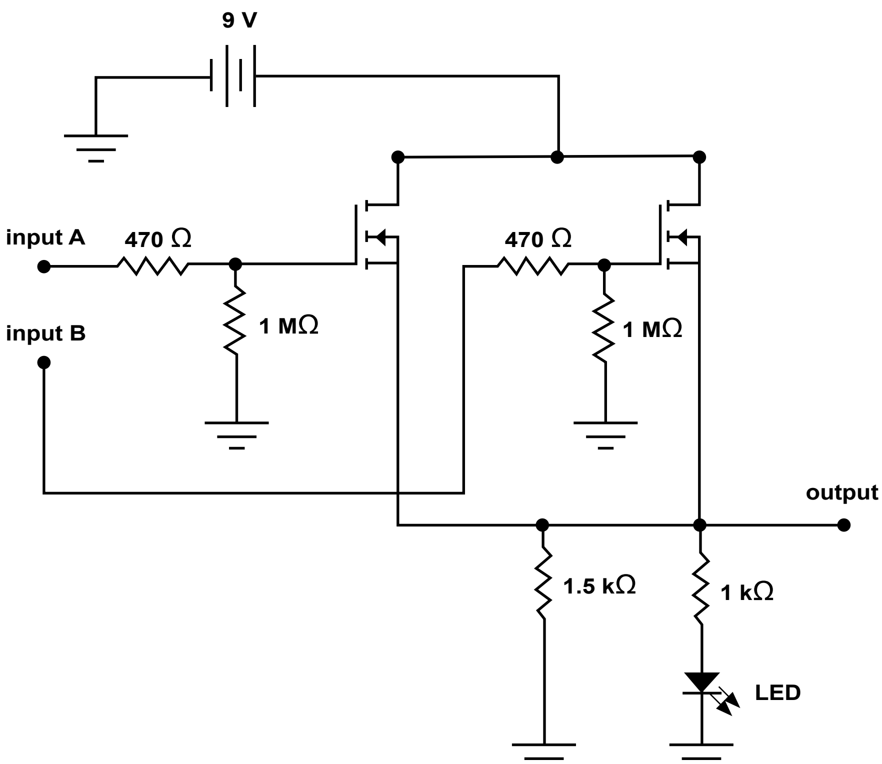
Hypothesis: (The students have been introduced to the five common gates and should chose one of the five as a possible answer.)

Materials:
1 – Breadboard with 9v attachment
1 – LED
1 – 9v battery
2 - MOSFET Transistors
2 – 1 M Ω resistors
1 – 1000 ohm resistor
1 – 1500 ohm resistor
2– 470 Ω resistors
An assortment of wires connectors

Procedure:

1. Set up a circuit as shown in the following schematic.

2. Check your circuit before you begin data collection.



3. Develop the truth table for this circuit.

4. Also determine the type of gate from the truth table.

Data Table: (Student developed truth table)

Conclusion:

Discussion Questions:

1. Draw the schematic diagram for this circuit.

2. Draw the schematic symbol for the gate used.

3. What would be a function of this type of gate.

Answers to Lab and Questions:

1. The circuit demonstrates an OR gate. One could also get an alternate schematic diagram by combining the circuits in investigations I and II.

2. The OR gate symbol should be shown. If data manuals are available the student should look up the alternate symbol for the OR gate.

3. A function would be to allow a series of devices that are linked together, to be turned on depending upon the input values. An example would be a security system for a house. The system is linked to all windows and doors. If any window or door is breached the alarm goes off. If two reed switches (SPST switches activated by a magnet) are available they could be used as inputs to the OR circuit to demonstrate the security alarm system.

LESSON 3. INVESTIGATION 4: Boole's Logic IV

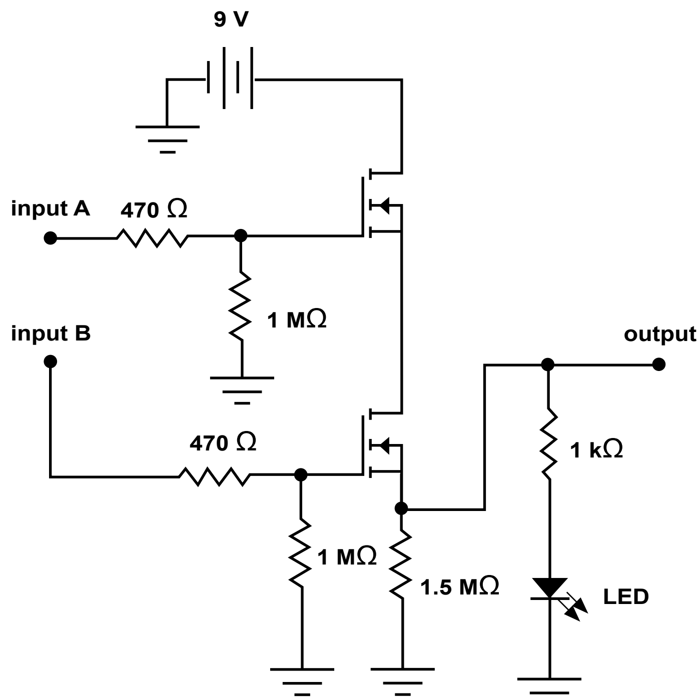
Query: What type of logic gate is this?

Hypothesis: (The students have been introduced to the five common gates and should choose one of the five as possible answers.)

Materials:

1 – Bread board with 9v attachment
1 – LED
1 – 9v battery
2 - MOSFET Transistors
2 – 1 M Ω resistors
1 - 1000 ohm resistor
1 - 1500 ohm resistor
2 - 470 Ω resistors
An assortment of wire connectors

Procedure:



1. Connect the circuit as shown above.
2. Check your circuit before you begin data collection.
3. Develop truth table for this circuit.
4. Also determine the type of gate from the truth table.

Data Table: (Student developed truth table)

Conclusion:

Discussion Questions:

1. Draw the schematic diagram for this circuit.
2. Draw the schematic symbol for the gate used.
3. What would be a function of this type of gate?

Answers to Lab and Questions:

1. The circuit should show a AND gate circuit.
2. The schematic symbol should reflect that of a AND gate.
3. This gate could be used to turn on an off the flow of data to a circuit. For example, a digital signal on the A input could be allowed to pass or not pass by making the B input to the gate either a HIGH to let the signal on the A input pass or by making the B input LOW to prevent the passage of the signal on the A input. As an inquisitive student, you might want to investigate the other gates you have studied to see if any of them can provide the same type of function.

CHALLENGES:

You have now constructed four logic circuits. Re-study these circuits to make sure that you know exactly how they work.

1. Can you change the position of only one resistor in the AND circuit shown in investigation IV above, and make it into a NAND circuit?
2. Can you add and inverter circuit to the AND circuit shown in investigation IV and create a NAND gate in a different way that in challenge # 1 above? You may want to use a truth table in this and succeeding challenges.
3. Can you add another inverter to the inverter in investigation # 1 to produce a circuit that will have the same output as input? You might think that this is a relatively foolish thing to do. Seems like it just wastes parts. What you have created is a BUFFER. Buffers are used to build up an input that has a marginal voltage, to one that has the correct voltage to drive other circuits. Signal voltages may be to low because of to many connected gate inputs. In more complicated circuits care must be exercised to limit the number of inputs connected to one output. The term found in the specification sheets that indicated the maximum number of gates that can be connected to one output is referred to as FANOUT.
4. Here is your last challenge. You may want to think up some other challenges. If you put an inverter on each input of the NOR gate you produce another type of gate. What is the name of this gate? ____________ Try to determine the type of gate using a truth table. Then hook it up to prove or disprove your answer.

INVESTIGATION V: Integrated Circuits

The Integrated Circuit

Query: What is an Integrated Circuit and how does it work?

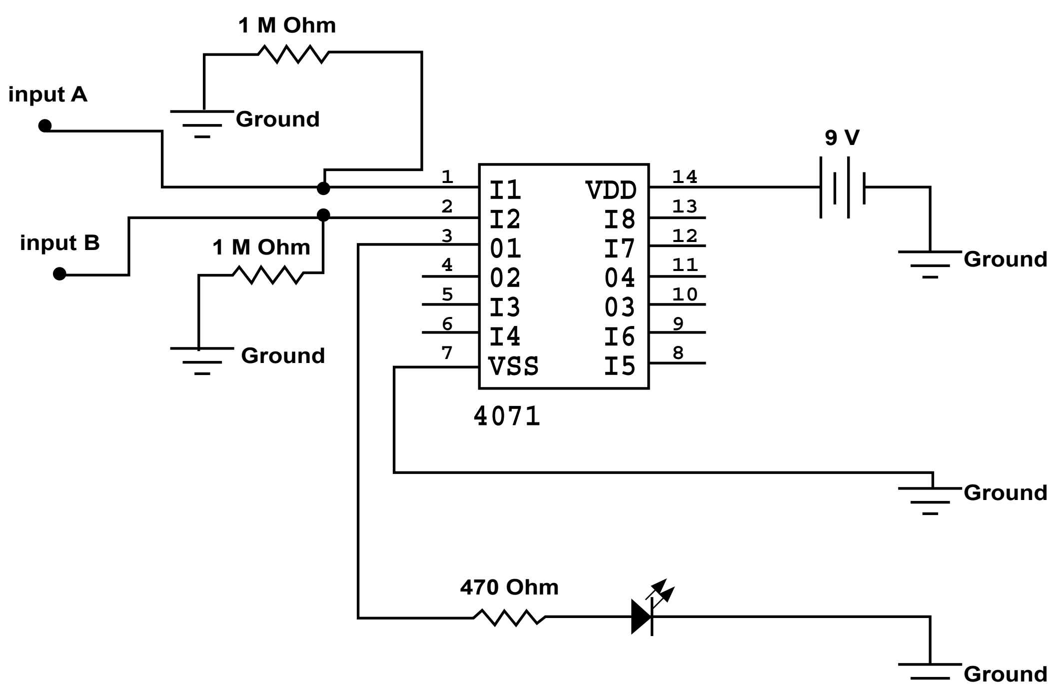
Hypothesis: Student generated

Materials:

1 – Breadboard with 9v attachment
2 – 1MΩΩ resistors
1 – 470 ΩΩ resistor
1 – LED
1- 4071 integrated circuit with its pin-out schematic symbol
An assortment of conductor wires

Procedure:

1. Insert IC into breadboard. Making sure that a "gutter" separates each terminal line. Make sure that the ground (VSS) and positive (VDD) connections are completed before powering either input. If the inputs are powered before the circuit power is applied the IC may be damaged. Generally it is best to connect the IC ground and positive connections to their respective power terminals on the breadboard so that when power is applied to the circuit from the battery of power supply the IC internal electronic circuits will be operating. Follow the schematic:



2. Develop truth table by trying all possible input combinations.

Data: (Student derived truth table. Table should represent that of the specific IC)

Conclusion: (Based on redundant data, students should recognize that this IC produces exactly the same result as the OR gate they built in one of the investigations above. The exception is that the commercial IC has multiple gates.)

Discussion Questions:

1. What are the advantages of the integrated circuit?

2. How are the resistors, wire connectors, transistors and diodes connected to the IC?

3. How do manufacturers fit three million transistors on a micro-processing chip that has a surface area of 1 cm^2 ?

Answers to Questions:

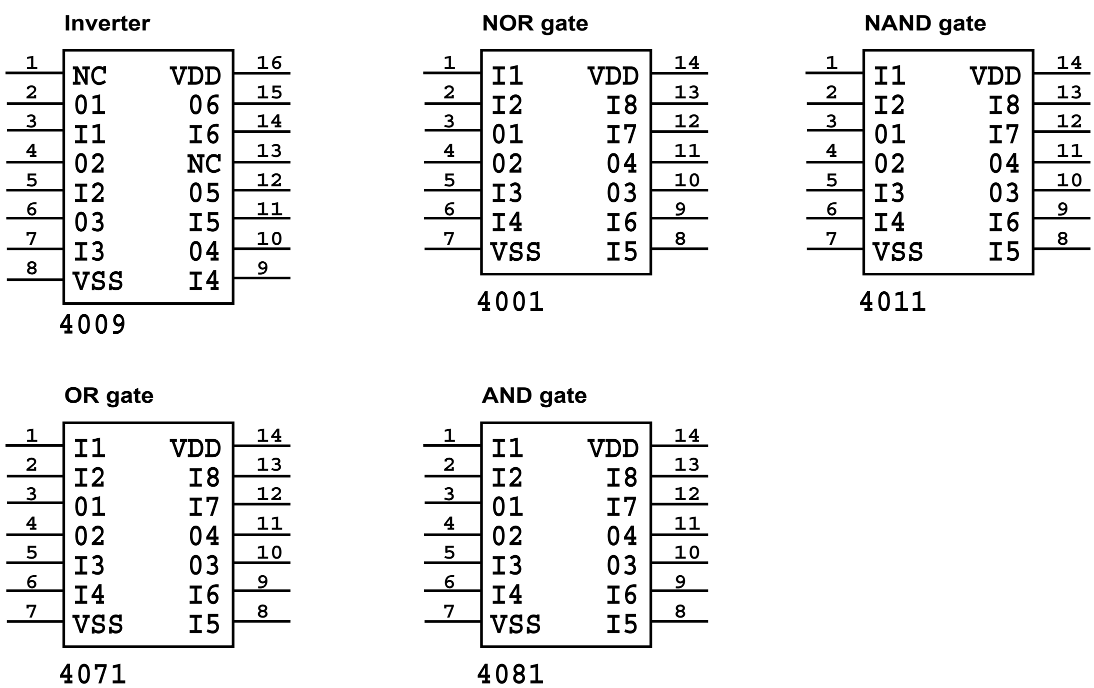
1. The advantages of the IC are cost effectiveness, miniaturization and multiple gates in one package.

2. Students may say that the resistors, diodes, etc. are made much smaller. The reality is that each device is made of N or P type materials that are literally grown onto a silicon wafer.

3. On a micro-processing chip, each device has been cut to a smaller scale using tools that have etching diameters in the micron and/or Angstrom range.

If time permits try a different integrated circuit. For example, connect the CD4011 in your kit of parts and repeat the above procedure. Does it act like a NAND gate? It should! Could you connect this NAND gate to make it act like an INVERTER?

The following diagrams represent a few of the types of Integrated Circuits being used.



The learning activities contained within these Instructional Units require the parts/materials listed below:

Physics Kit	Quantity
Breadboard	1
Resistors	
470 ohm	6
1K ohm	6
1.5K ohm	2
1 Meg ohm	6
1K potentiometer	1
Semiconductors	
N-Channel Enhancement Mode MOSFET	5
CD4011 NAND gate	2
CD4071 OR gate	2
1N4001 Silicon Diode	2
Red LEDs	3
9 volt battery clip	1
Assorted wires	15
2-short & 2-long RED	4
2-short & 2-long BLACK	4
3-YELLOW & 2 BLUE	5
2- Long multi-colored wires to cut as necessary	2
Battery not included. Use fresh 9 volt alkaline	
or well filtered 9-12 volt power supply.	
Digital Volt Meter (not included).	

*Complete kits are available through MATEC (each kit accommodates 2 students) @ $29.95 each.