

DC Fundamentals

FACET[®]



Student Workbook

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

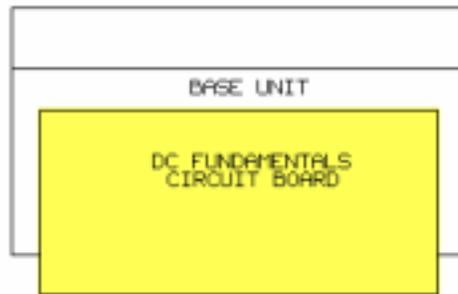
The **Appendix** includes safety information.

UNIT 1 – TRAINER FAMILIARIZATION

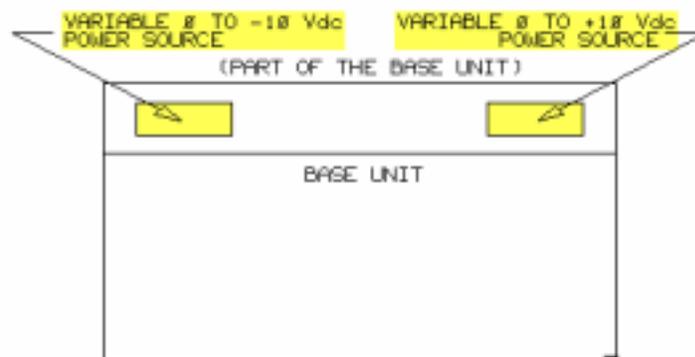
UNIT OBJECTIVE

At the completion of this unit, you will be able to set up the F.A.C.E.T. system by using standard lab procedures.

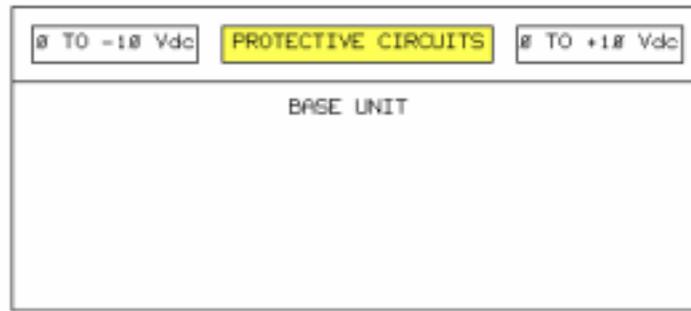
UNIT FUNDAMENTALS



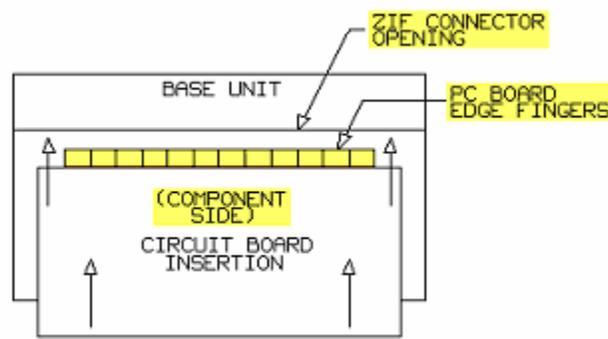
The first course in the F.A.C.E.T. system, or the Fault Assisted Circuits for Electronics Training system, consists of a base unit and a plug-in board of **dc circuits** called DC FUNDAMENTALS.



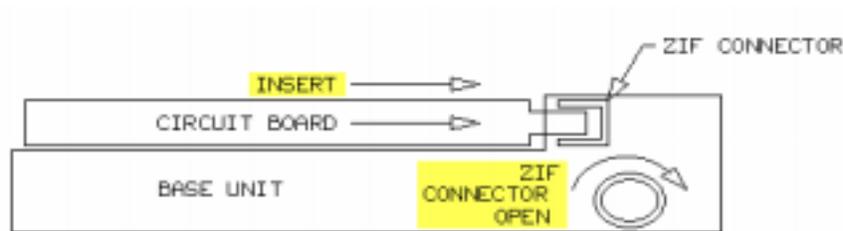
The base unit has built-in variable +10 Vdc and -10 Vdc regulated power supplies.



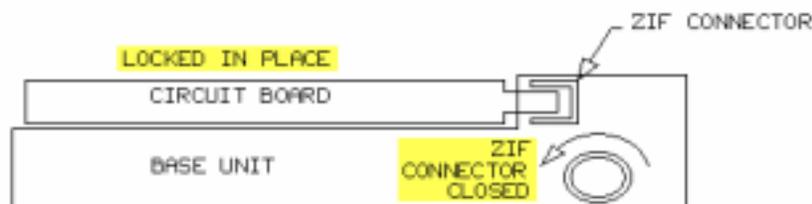
Additional protective **circuits** within the base unit guard against over voltage, over current, and reverse voltage in any **circuit board**; connected to the base unit.



Circuit boards are inserted into the base unit through the use of a Zero Insertion Force (ZIF) connector.

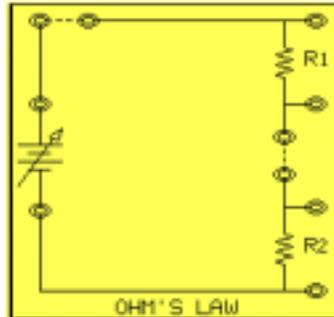


When open, the ZIF connector allows circuit boards to be inserted without any friction.



When closed, the ZIF connector provides power and other electrical signals to the circuit board.

The base unit contains twenty circuit modification (CM) read relays that modify an existing circuit. The base unit also contains twelve fault read relays that insert a fault in a circuit. These circuit faults, used in the troubleshooting unit, provide student training and assessment.



The schematic of each circuit on your trainer is drawn on the circuit board. Standard industrial components are used on the circuit boards.

NEW TERMS AND WORDS

dc circuits - direct current circuits; a flow of electrons in one direction along an electrical path.

circuits - paths for current to flow.

circuit board - specially constructed board containing many electrical circuits.

power sources - devices that supply electricity to an electrical circuit; also called power supplies.

cells - basic sources of power that produce electricity through chemical action.

schematic - drawing that uses standard symbols to show electrical paths and components.

symbol - a simple representative drawing of a component.

crowbar - a circuit that rapidly shorts the output voltage to ground.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC FUNDAMENTALS circuit board

Multimeter

Exercise 1 – Instrument Familiarization

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to activate a power source on the F.A.C.E.T. system. You will verify your results by measuring the output voltage of the power source with a multimeter.

DISCUSSION

- Multimeters measure electrical quantities of current: resistance, and voltage.
- An analog multimeter has numbers printed on a scale that, in conjunction with a range switch, covers the measurement values possible with the multimeter.
- A digital multimeter directly displays the value measured.
- Digital multimeters are recommended for this exercise.

Exercise 2 – F.A.C.E.T. Base Unit Familiarization

EXERCISE OBJECTIVE

When you have completed this exercise, you will discover the operating features of the base unit and DC FUNDAMENTALS circuit board. You will verify your results with an operational test.

DISCUSSION

- The base unit contains CM and fault read relays, power supply controls, LEDs (light-emitting diodes), and a ZIF connector that accepts circuit boards.
- Power is applied to the base unit when the AC cord is plugged in and the power switch is on.
- The base unit's power switch should be in the off position when inserting circuit boards.
- On the base unit are LEDs indicating the presence of the plus and minus 15 Vdc internal supplies. The LEDs are located above the control knobs of the negative and positive variable supplies.
- When power is applied to the base unit, the LEDs illuminate.
- One or both LEDs will be off should a base unit and protective circuit activate (to crowbar the base unit's power source).
- To remove the crowbar condition on a base unit, correct the problem, and turn the POWER switch on.
- Each of the internal variable power supplies are adjusted with COARSE and FINE knobs (concentric shaft) located on either end of the base unit.
- The left controls adjust the negative variable supply between 0 Vdc and -10 Vdc.
- The right controls adjust the positive variable supply between 0 Vdc and +10 Vdc.
- There are twenty computer-controlled CM read relays, numbered through 20, in the base unit.
- Initially, CMs are made inactive by the computer.
- When a CM is activated, a selected circuit located on the circuit board is modified.
- There are twelve computer-controlled fault read relays in the base unit.
- Initially, all faults are made inactive by the computer.
- Each fault, when activated, inserts a malfunction in a selected circuit located on the circuit board.

Exercise 3 – DC Board Familiarization

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to use specific trainer functions on the DC FUNDAMENTALS circuit board. You will verify your results with voltage and current measurements.

DISCUSSION

- The DC FUNDAMENTALS circuit board is divided into 10 training areas called circuit blocks.
- Each circuit block consists of circuits designed to introduce the student to electronic principles
- Each circuit block has a drawing or schematic that shows how every component in the circuit block is electrically connected.
- Test points are located at each end of the circuit blocks and accept test leads directly. Terminal posts and alligator clips are provided for those test leads that do not readily connect.
- Dashed lines between two test points show that no electrical connection exists. A two-post connector can be used to complete the connection.
- Each circuit block has a title to identify the circuit type and function.
- Most current measurements in this volume will be in the milliamperere range.

UNIT 2 – SAFETY

UNIT OBJECTIVE

At the completion of this unit, you will be able to identify safe working conditions in a typical electronic laboratory by using the illustrations and information presented in this unit.

UNIT FUNDAMENTALS

Safety is everyone's responsibility. Everyone must cooperate to create the safest possible working conditions.

Where your personal life and good health are concerned, safety becomes your responsibility.

Safety rules are common sense ideas that help prevent injury. When you work with electricity, treat it with respect. If electricity is properly used, it will work for you. Abuse it and you may have trouble!

NEW TERMS AND WORDS

None

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC FUNDAMENTALS circuit board

UNIT 3 – ELECTRONIC QUANTITIES

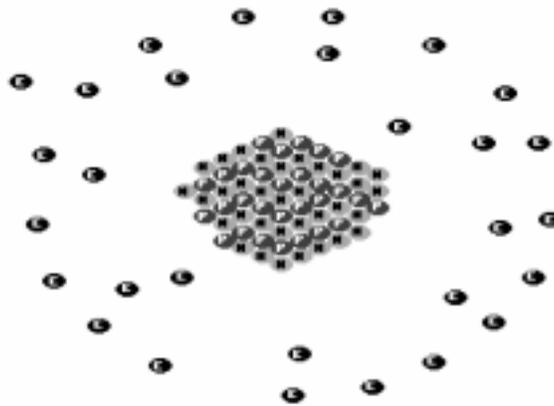
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe voltage, current, and resistance by using simple electronic circuits.

UNIT FUNDAMENTALS

We can make and use electricity because there is a basic force in nature called electrostatic force. The force is responsible for **charge** in an **atom**.

All atoms are made from three basic things: **protons**, **electrons**, and **neutrons**.

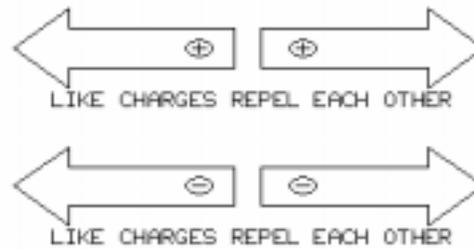


Protons and neutrons are at the center of the atom (the nucleus). Protons (P) give the nucleus a positive charge. Neutrons (N), as the name suggests, are neutral (possess neither positive nor negative charge).

Electrons (E) possess a negative charge. The amount of charge an electron has is an important part of the description of electricity. The unit of measure for charge is the **coulomb**.

Because the charge of a single electron is very tiny, a coulomb includes the combined charge of 6,280,000,000,000,000 electrons.

However, the **ampere (A)**, not the coulomb, is the most common measure of electricity (electron flow). One ampere is the flow of one coulomb of electrons in one second past a given point. This flow is commonly called **current (I)**.



A charge has the ability to act on another charge with either attraction or repulsion.

Two charges of the same polarity repel each other.



Two charges of unlike polarity attract each other.

NEW TERMS AND WORDS

charge - a type of electric energy. The basic electric charges are the negative charge of the electron and the positive charge of the proton.

atom - a basic building block of nature consisting of electrons, protons, and neutrons. Each element in the universe is formed from its own type of atom. There are over one hundred different types of atoms.

protons - positively charged subatomic particle.

electrons - negatively charged subatomic particles.

neutrons - subatomic particles that possess a neutral charge.

coulomb - the unit of measure for charge (equal to the combined charge of 6.28×10^{18} electrons).

ampere (A) - the unit of measure for current. One ampere is the movement of one coulomb past a given point in one second.

current (I) - a flow of electrons (therefore, the flow, or movement, of a charge).

electromotive force (emf) - the force that causes current to flow.

volts (V) - the unit of measure for voltage (and, therefore, emf). An electromotive force of one volt produces a current flow of one ampere through a resistance of one ohm.

voltage (E) - another term for electromotive force.

potential difference - a difference in charge between two points. Potential difference is measured in volts.

resistance (R) - the opposition to current flow in an electric circuit. When current flows through a resistance of one ohm, there is a potential difference of one volt across the resistor.

ohm - the unit of measure for resistance. 1000 ohms is one kilohm.

Exercise 3 – Circuit Resistance

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to describe and measure resistance by using a simple circuit. You will verify your results with a multimeter.

DISCUSSION

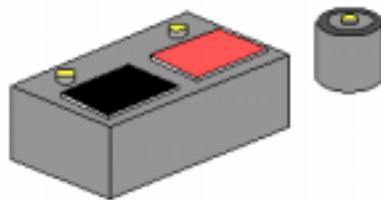
- The amount of voltage needed to cause current flow through a conductor varies with the physical and electrical properties of the conductor.
- The property of the conductor that resists the flow of current is called resistance.
- The unit of measure for resistance is the ohm (Ω).
- One ohm of resistance is present in a conductor when one ampere of current flows under one volt of potential difference.
- Resistors are devices designed to insert a specified amount of resistance into a circuit. There are four common types of fixed resistors: carbon composite, deposited carbon film, deposited metal film, and wire wound.
- Color bands are used to code the value of resistors.
- Conductance has a reciprocal relationship with resistance and measures the lack of resistance.
- The unit of measure for conductance is the siemen (S).
- The physical size of a resistor determines how much current can flow through it because current flow generates friction that causes heat.
- The watt is a measure of power.
- The physical size of a resistor is a measure of how many watts of power it can dissipate in the form of heat.

UNIT 4 – DC POWER SOURCES

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate battery circuits by using the DC FUNDAMENTALS circuit board.

UNIT FUNDAMENTALS

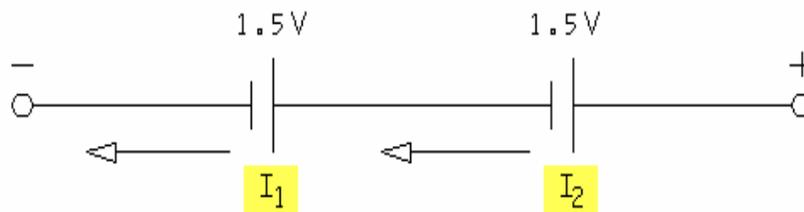


A basic source of electricity with which almost everyone is familiar is the battery. Although batteries come in many types and sizes, two of the most common types are the **storage battery**, used in automobiles, and the **dry cell**, used in transistor radios and flashlights.

Examples of battery types and voltages are carbon-zinc or alkaline (1.5 Vdc), nickel-cadmium (1.25 Vdc), and lead-acid (2 to 2.2 Vdc).

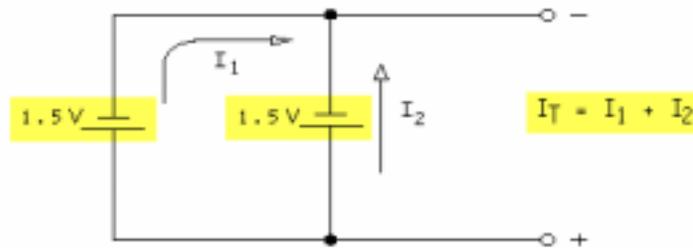
A battery is composed of two or more **voltaic cells**. A cell is one unit consisting of a positive and negative plate.

A battery is normally composed of two or more cells that are assembled in a single working package. Cells can be classified as primary or secondary. A **primary cell**, such as a carbon-zinc dry cell, cannot be recharged. **Secondary cells**, such as automobile batteries, can be recharged.



When cells or batteries are connected in series (positive to negative), their voltages are added, and current is the same through each.

$$I_T = I_1 = I_2$$



When cells or batteries are connected in parallel (negative to negative and positive to positive), the current capability of each is added, while the voltage remains the same.

$$I_T = I_1 + I_2$$

NEW TERMS AND WORDS

storage battery - a cell that can be recharged.

dry cell - a cell containing a moist electrolyte that cannot be spilled. The dry cell can be operated in any position.

voltaic cells - a device made of three interactive materials that generates electricity.

primary cell - a cell that cannot be recharged.

Secondary cells - a cell that can be recharged.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC FUNDAMENTALS circuit board

Multimeter

Exercise 1 – Series and Parallel Battery Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine voltage by using batteries connected in series and in parallel. You will verify your results with a voltmeter.

DISCUSSION

- When the positive terminal of one cell is connected to the negative terminal of another cell, the cells are connected in series and form a battery.
- The voltage appearing at the two ends of the series of cells is the sum of the individual cell voltages.
- The current flowing through cells in series is the same.
- When the positive terminal of one cell is connected to the positive terminal of another cell and the negative terminals are connected together, the cells are connected in parallel.
- When cells are connected in parallel, the voltage remains the same for each cell, but the current capability of each cell is added to find the total current capability.
- Batteries can be connected in series/parallel combinations. Each portion of the circuit (series and parallel) is simplified prior to determining the total circuit voltage and current.

UNIT 5 – SWITCHES AND SWITCHING CONCEPTS

UNIT OBJECTIVE

At the completion of this unit, you will be able to identify types of switches and demonstrate switch circuit operation by using a multimeter and LEDs.

UNIT FUNDAMENTALS

Switches are devices used to close, open, or change the connections in an electric circuit. Open is the OFF, or break, position, and closed is the ON, or make, position. The switch is usually placed in series with the voltage source and its load.

In the ON position, the closed switch has very little resistance, allowing maximum current to flow in the load with very little voltage (typically less than 0.5V) dropped across the switch.

When the switch is OFF, or open, the switch has infinite resistance, no current flows in the circuit, and there is maximum voltage dropped across the switch.

NEW TERMS AND WORDS

pole - the current-carrying moveable part or parts of a switch that closes and opens an electrical circuit.

contacts - the current-carrying part of a switch that closes and opens an electrical circuit.

SPST - abbreviation for Single Pole Single Throw switch; switch with two terminals used to connect one terminal to the other terminal.

DPST - abbreviation for Double Pole Single Throw switch; a switch with four terminals used to connect one pair of terminals to the other pair of terminals.

SPDT - abbreviation for Single Pole Double Throw switch; switch with three terminals used to connect one terminal to either of the other two terminals.

DPDT - abbreviation for Double Pole Double Throw switch; a switch with six terminals used to connect one pair of terminals to either of the other two pairs.

PBNO - abbreviation for PushButton Normally Open; switch whose terminals are connected when its pushbutton is depressed.

PBNC - abbreviation for PushButton Normally Closed; switch whose terminals are connected when its pushbutton is not depressed.

EQUIPMENT REQUIRED

F.A.C.E.T base unit

DC FUNDAMENTALS circuit board

Multimeter

Exercise 1 – Identify Types of Switches

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to identify switch functions by using a multimeter. You will verify your results with information found in this exercise.

DISCUSSION

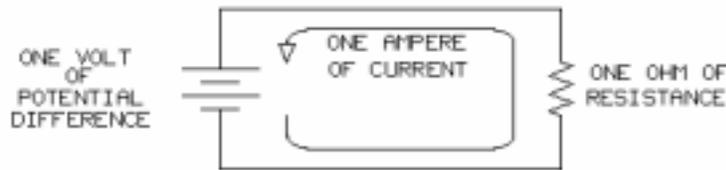
- All switches contain one or more poles.
- A pole consists of one complete set of contacts that opens or closes an electric switch.
- A single-pole single-throw switch connects only one point with another.
- Double-pole switch controls two circuits or both sides of one circuit.
- When the switch contacts make two points with one another, the switch is called a double-pole single-throw switch.
- A double-throw switch controls two circuit loads. Control only one conductor in the circuit with a single-pole double-throw switch. Use a double-pole double-throw switch to control two conductors in two circuit loads.
- The slide switch has a mechanism that actually slides back and forth on a track, causing the switch contacts to make or break a circuit connection.
- Slide switches are available as single or multiple poles and in normally open or normally closed configurations.

UNIT 6 – OHM'S LAW

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the relationship of resistance, current, and voltage by using Ohm's law.

UNIT FUNDAMENTALS

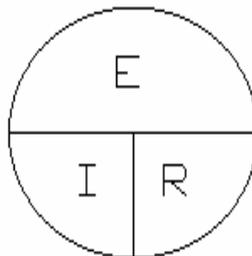


Electric potential difference is expressed in volts (V), the rate of electron flow is measured in amperes (A), and the resistance to electron flow is measured in ohms (Ω).

VOLT (V) - the electric potential difference required to produce one ampere of current in a circuit having one ohm of resistance.

AMPERE (A) - the current that exists when a potential difference of one volt is applied to a circuit having one ohm of resistance.

OHM (Ω) - the resistance required to limit the current to one ampere when a potential difference of one volt is applied.



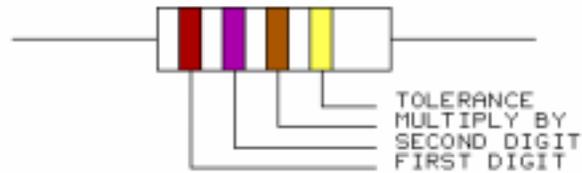
$$E = I \times R$$

$$I = E/R$$

$$R = E/I$$

The diagram indicates the **Ohm's law** relationship between voltage (E), current (I), and resistance (R). You should use this diagram as an aid in finding E, I, or R when the other two terms are known.

Resistance is a physical property that can be predicted and measured against manufactured values.



Manufacturers place color bands on the bodies of resistors to indicate their value. These color bands follow a standard resistor color code, which was discussed in the "Electronic Quantities" unit.

NEW TERMS AND WORDS

Ohm's law - In any dc electric circuit, the current is directly proportional to the voltage and inversely proportional to the resistance. In its simplest form, Ohm's law is expressed mathematically as $E = IR$ (voltage equals current times resistance).

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
DC FUNDAMENTALS circuit board
Multimeter

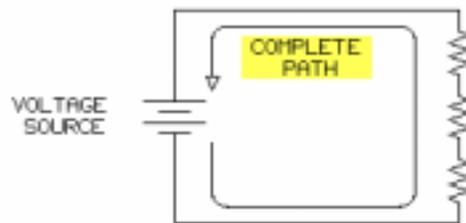
UNIT 7 – SERIES RESISTIVE CIRCUITS

UNIT OBJECTIVE

At the completion of this unit, you will be able to determine the values of resistance, current, and voltage in a series resistive circuit by using Ohm's law.

UNIT FUNDAMENTALS

A series circuit is one in which circuit components, such as resistors, are connected end-to-end to form a complete path from the voltage source, through the resistors, and back to the voltage source.

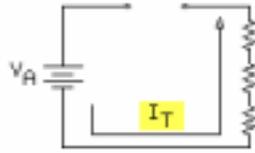


We call this a series circuit because the components are connected one after another, and there is only one path for current as it runs through all the parts of the circuit.



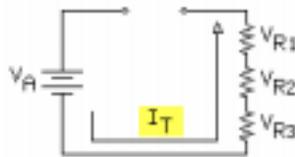
Resistance in series circuits is cumulative. The total resistance equals the sum of the circuit resistances.

$$R_T = R_1 + R_2 + R_3$$



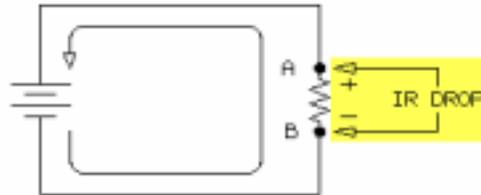
In a series circuit, current is the same through each part of the circuit.

$$I_T = V_A / R_T$$



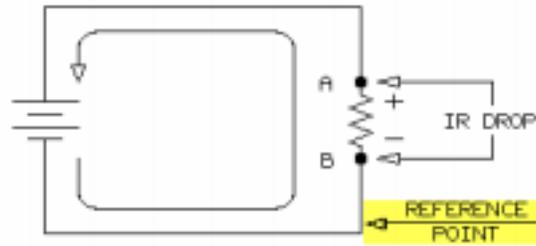
In a series circuit, the applied voltage equals the sum of each **voltage drop**.

$$V_A = V_{R1} + V_{R2} + V_{R3}$$



In a one-resistor series circuit, all of the applied voltage is dropped across the resistor. The voltage drop (also commonly referred to as IR drop) has the same polarity as the voltage source: negative where electrons enter the resistor and positive where electrons leave the resistor.

In this circuit, point A is said to be positive with respect to point B, or point B is negative with respect to point A.



In most electronic circuits, a reference point is used. This reference may be called a **reference point** or **with respect to**.

In this circuit, if point A is positive with respect to point B, then point B is the circuit reference point.



When the circuit has more than one resistor, the same principle applies. The polarity of all voltages in a series circuit corresponds with the polarity of the current flow.

In this circuit, point A is positive with respect to point B. Point C is positive with respect to point D. Point A is the most positive point of the circuit. Point D is the most negative point of the circuit.

NEW TERMS AND WORDS

voltage drop - the amount of voltage across any resistor in a circuit; also called IR drop.

series string - a combination of two or more resistances in series.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC FUNDAMENTALS circuit board

Multimeter

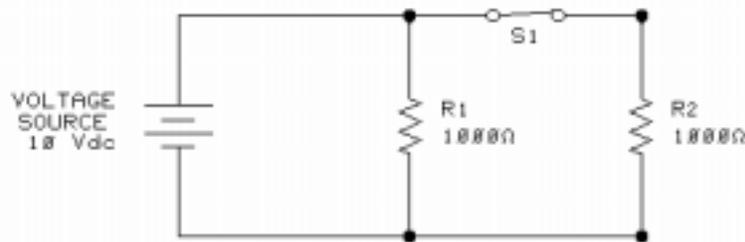
UNIT 8 – PARALLEL RESISTIVE CIRCUITS

UNIT OBJECTIVE

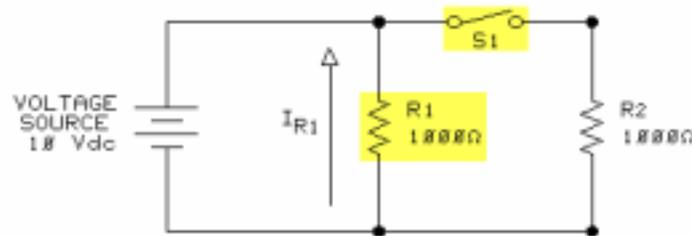
At the completion of this unit, you will be able to determine resistance, current, and voltage in a parallel resistive circuit by using a formula.

UNIT FUNDAMENTALS

- A **parallel circuit** is a circuit in which two or more components are connected across a voltage source.
- The major difference between series and parallel circuits is the path current takes.
- In a series circuit, the same current flows through all the components in the string. The current through each component is identical.
- In a parallel circuit, each parallel branch provides a separate path for current flow. The current through each branch need not be identical to any other branch current.

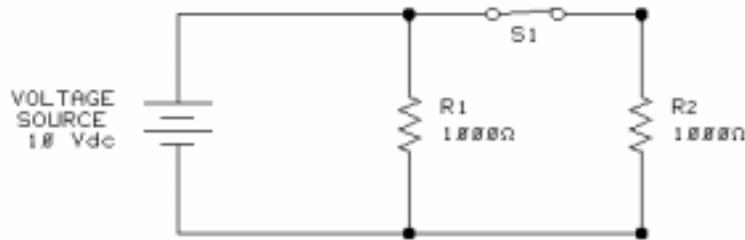


A parallel circuit with two resistors is shown. The voltage source is common to (across) both resistors.

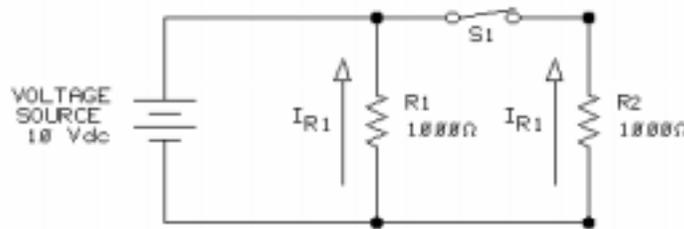


With S1 open, R1 provides a 1 kΩ load to the voltage source. Use Ohm's law to find current through R1 (I_{R1}):

$$I_{R1} = V_{R1} / R1 = 10/1000 = 0.01A = 10 \text{ mA}$$

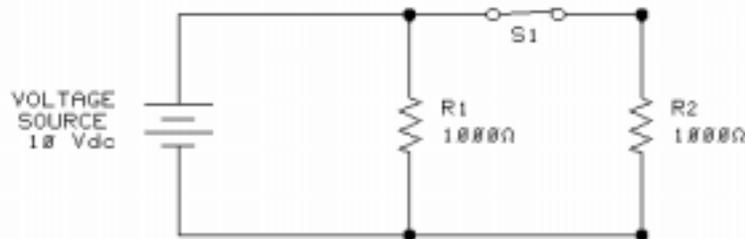


When S1 is closed, a second 1 kΩ resistor, R2, is connected in parallel with R1 to provide an additional path (I_{R2}) for current. Because R2 is connected across the voltage source in the same way as R1, the voltage source causes current to flow through R2.



In a parallel circuit, total current (I_T) equals the sum of the branch currents.

With two current paths, the total current (I_T) supplied by the source is the sum of the two branch currents ($I_T = I_{R1} + I_{R2}$).



Total circuit resistance equals the voltage source divided by total circuit current. To calculate total resistance, apply the **product-over-sum** formula.

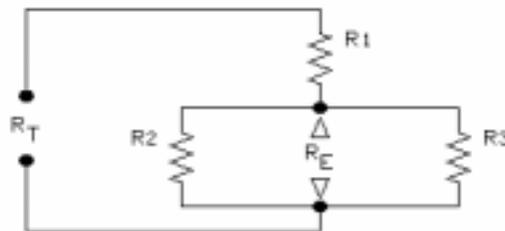
UNIT 9 – SERIES/PARALLEL RESISTIVE CIRCUITS

UNIT OBJECTIVE

At the completion of this unit, you will be able to find values for resistance, voltage, and current in a series/parallel resistive circuit.

UNIT FUNDAMENTALS

The rules for evaluating resistance, voltage, and current in a series/parallel circuit are a combination of the rules you used to evaluate series and parallel circuits.



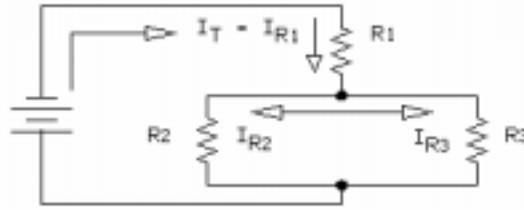
A series/parallel circuit is shown. R_1 is the series element of the circuit; R_2 and R_3 are the parallel elements (R_E). R_T is the combined resistance of R_1 , R_2 , and R_3 .

R_1 : series element

R_2 and R_3 : parallel elements

R_E : combined R_2 and R_3 value

R_T : combined R_1 and R_E value

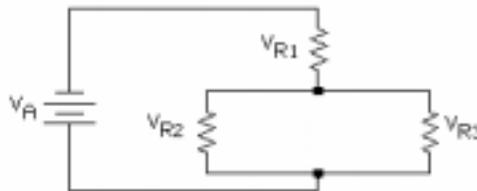


Total circuit current flows through series element R1. Total current divides between parallel elements R2 and R3.

I_T and I_{R1} are identical.

I_{R1} divides between R2 and R3 based on their values.

$$I_T = I_{R1} = I_{R2} + I_{R3}.$$



The voltage across series elements need not be identical. Voltages across each resistor of a parallel branch are identical.

$$V_A = V_{R1} + V_{R2} \text{ or } V_{R1} + V_{R3}$$

$$V_{R2} = V_{R3}$$

NEW TERMS AND WORDS

None

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC FUNDAMENTALS circuit board

Multimeter

UNIT 10 – POWER IN DC CIRCUITS

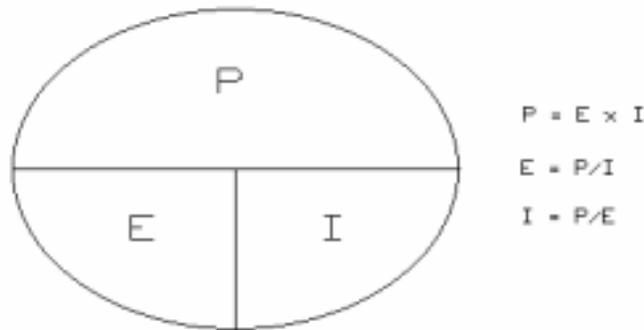
UNIT OBJECTIVE

At the completion of this unit, you will be able to determine power in series, parallel, and series/parallel resistive circuits.

UNIT FUNDAMENTALS

Electric **power** is the rate of doing work per unit time. The unit of power measurement is the watt (W). 1W of power equals the work done in 1 second by 1V of potential difference in moving 1C (electron flow) of charge.

1C of charge per second is 1A of current flow. Therefore, power in watts can be defined as the product of voltage and current: $P = E \times I$. In a resistor, power ($E \times I$) **dissipates** in the form of heat.



Ohm's law may be modified to accommodate the relationship between power, voltage, and current.

Power is also related to the square of current or voltage.

$$P = E \times I$$

$$= I \times R \times I$$

$$= I^2 \times R$$

$$P = E \times I$$

$$= E \times E/R$$

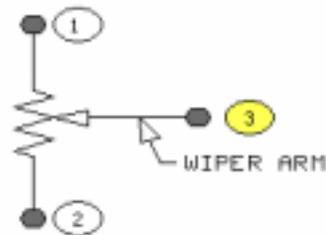
$$= E^2/R$$

UNIT 11 – POTENTIOMETERS AND RHEOSTATS

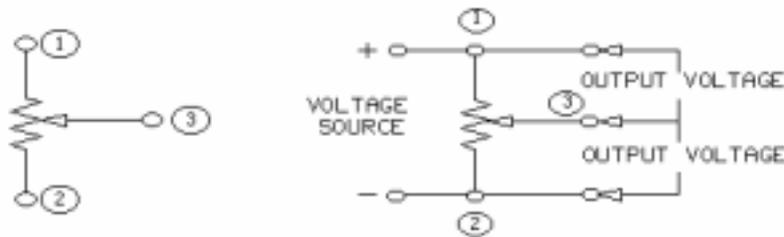
UNIT OBJECTIVE

At the completion of this unit, you will be able to identify and demonstrate the use of a potentiometer and a rheostat.

UNIT FUNDAMENTALS

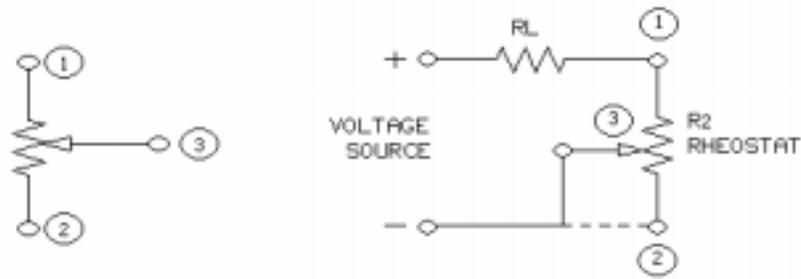


A variable resistor consists of a resistive element that is electrically connected to a pair of terminals (1 and 2). The center terminal (3) is connected to the wiper arm, which, when moved by shaft rotation, changes the resistance between the center terminal and the other two terminals.



A variable resistor using three external terminals to connect into a circuit is a **potentiometer** (pot).

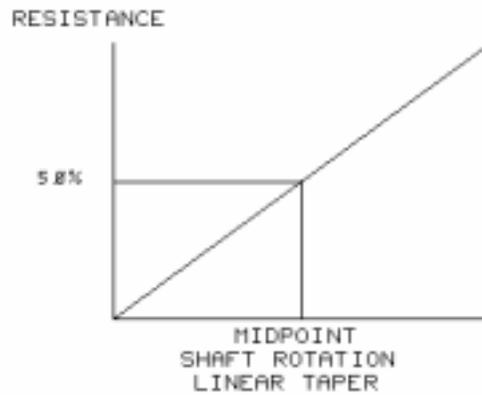
A pot controls voltage to a circuit.



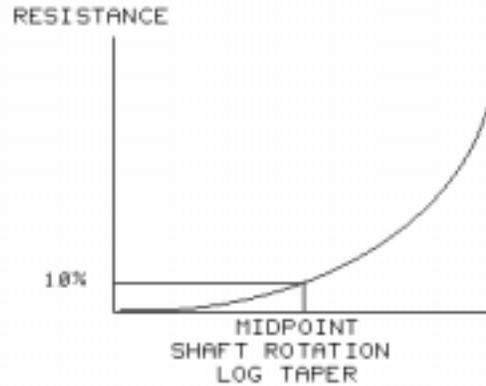
A variable resistor using the wiper arm (center terminal) and only one end of the resistive element is called a **rheostat**.

Rheostats are placed in series in a circuit to control circuit current.

Variable resistors are designed so that resistance varies when the shaft (or other adjusting device) is rotated. The variation of resistance in relation to shaft rotation defines the **taper** of the variable resistor.



With a **linear** taper, one-half rotation changes the resistance by one-half the maximum value. Resistance change is linear (in a straight line) with respect to shaft rotation.



With a **logarithmic** (log) taper, one-half rotation changes the resistance by 10% of the total amount. Resistance change is nonlinear (not in a straight line) with respect to shaft rotation.

There are three basic types of variable resistors: carbon composition, wirewound, and metal film.

Carbon composition types are available in wide resistance ranges, are inexpensive, and are generally used in low power applications.

Wirewound types are available in low resistance ranges, are more expensive, and have wide power ranges.

Film types are a compromise between carbon and wirewound elements in cost, resistance ranges, and power.

NEW TERMS AND WORDS

potentiometer - A variable resistor connected with three terminals to provide a variable voltage.

rheostat - A variable resistor connected with only two terminals to provide a variable current.

taper - Variation in resistance of a variable resistor due to changes in the angle of shaft rotation.

linear - A change or control that varies at a uniform rate through the entire range of adjustment.

logarithmic - A change or control that varies at a different rate through its range of adjustment; also called nonlinear.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC FUNDAMENTALS circuit board

Multimeter

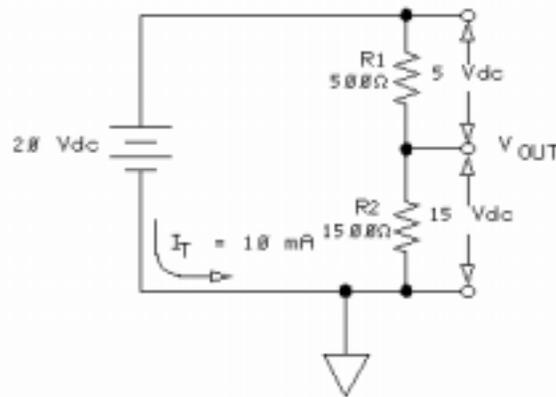
UNIT 12 – VOLTAGE AND CURRENT DIVIDER CIRCUITS

UNIT OBJECTIVE

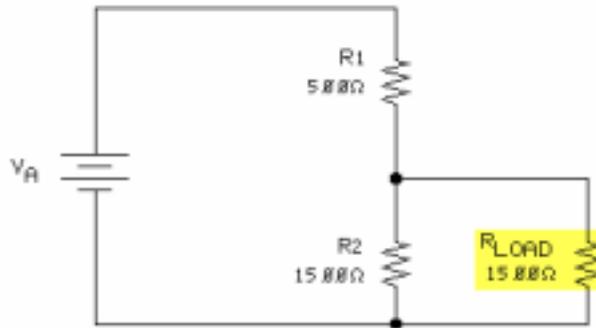
At the completion of this unit, you will be able to demonstrate voltage distribution, current distribution, and the effect of a load on a voltage divider by using voltage and current divider circuits.

UNIT FUNDAMENTALS

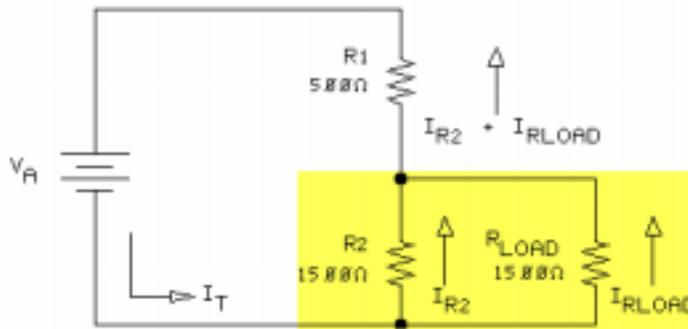
The resistive **voltage divider** provides a number of voltages from a single power source.



A series resistive circuit forms a voltage divider. This circuit is connected across the power source to provide the necessary output voltage. The voltage drop across each resistor is proportional to the resistor value.



When a load is added to a voltage divider, it is connected in parallel with one or more of the resistances in the series string. Adding a load to the output of a voltage divider reduces the voltage of the divider.



The load resistor in parallel with R_2 forms a **current divider**. The parallel circuit of R_2 and R_{LOAD} can be called a resistive **bank**.

NEW TERMS AND WORDS

voltage divider - A string of resistors designed to produce various voltages less than the source voltage.

current divider - A bank of resistors designed to provide various currents less than the main-line current.

bank - A parallel circuit with two or more branch circuits.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC FUNDAMENTALS circuit board

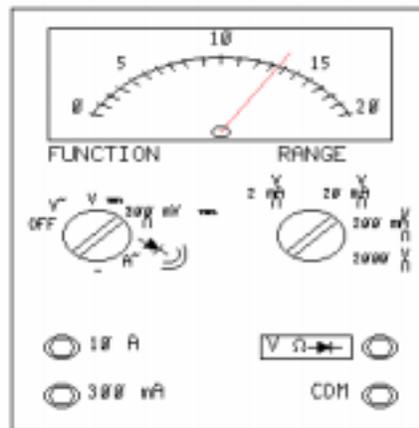
Multimeter

UNIT 13 – DIRECT CURRENT METERS

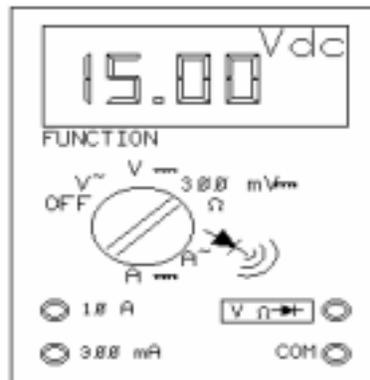
UNIT OBJECTIVE

At the completion of this unit, you will be able to determine how a meter movement can be used as an ammeter, an ohmmeter, or a voltmeter.

UNIT FUNDAMENTALS



One type of meter is the VOM (Volt-Ohm-Milliampere) meter. It is an analog meter because electrical values are continuously displayed on the scale of the meter by the pointer.



Another type of meter is the digital multimeter (DMM). This meter uses analog circuits to measure the electrical quantities of voltage, resistance, and current, but the results are displayed on the face of the meter numerically rather than with a pointer.

In an analog meter, the most common type of meter movement is the d'Arsonval meter movement, which uses a **moving coil**. The d'Arsonval meter movement consists of a **permanent magnet**, control springs, jewelled bearings, mounting hardware, and a moving element.

This moving element is wrapped by a coil of wire and has a pointer attached. In the d'Arsonval meter, the deflection of the pointer is directly proportional to the amount of current flowing through the coil.

The current required to deflect the pointer all the way to the right, to the last mark on the meter scale, is called **full-scale meter current (I_M)**. The wire used in the meter coil has some resistance. This resistance is the internal **meter resistance (R_M)**.

The specifications of the meter movement used in this unit are:

$I_M = 1$ mA full-scale current

$R_M = 2300$ ohms, $\pm 20\%$

Meter Type: moving magnet

Based on the specifications, the meter coil will drop 2.3 volts at full-scale deflection (1 mA x 2300 ohms).

A basic meter movement combined with other components can be made to indicate voltage, current, or resistance.

When a meter movement is configured to read current, the external circuit generally provides a parallel or shunt path to bypass excess current (greater than I_M) around the meter coil.

When the meter movement is configured to read voltage or resistance, the external circuit generally provides a series resistance to limit current to the value of I_M (at full-scale deflection).

NEW TERMS AND WORDS

moving coil - The part of a meter having a pointer that deflects with current.

permanent magnet - A magnet that retains its magnetism after the magnetizing force has been removed.

full-scale meter current (I_M) - Specified current required for full-scale deflection.

meter resistance (R_M) - The ohmic resistance of the wire making up the moving coil.

sensitivity - The ratio of the total resistance of an instrument to the full-scale meter deflection.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

DC Network Theorems

FACET[®]



Student Workbook

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Edition 4



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FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

UNIT 1 – DC NETWORK THEOREMS

UNIT OBJECTIVE

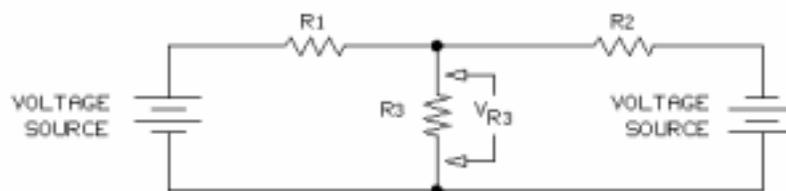
At the completion of this unit, you will be able to locate and identify the major components on the DC NETWORK THEOREMS circuit board.

UNIT FUNDAMENTALS

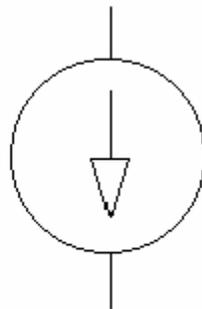
The DC NETWORK THEOREMS circuit board consists of 9 training circuit blocks and a **CONSTANT CURRENT SOURCE** generator block.

The board is designed to enhance your knowledge of voltage and current distribution in dc circuits.

Theorems are used to determine voltage and/or currents in circuits where Ohm's law cannot easily be applied.

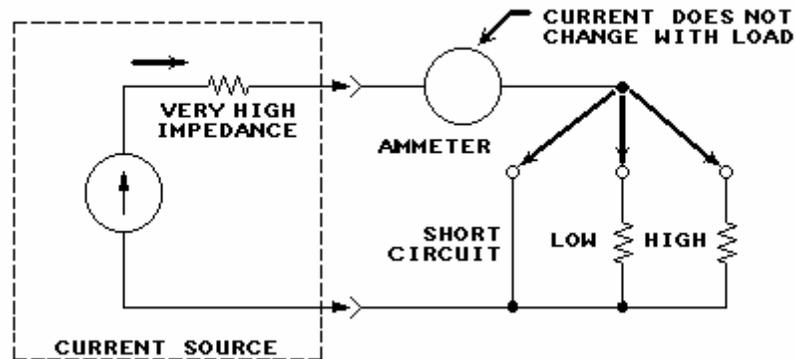


For example, Ohm's law cannot easily be applied in a circuit having two voltage sources applied in different branches. The voltage drop across R3 cannot easily be determined.



CONSTANT CURRENT SOURCE SYMBOL

One circuit block on the board is a constant current source. A constant current source circuit provides fixed current values that are independent of load changes.



Load changes do not affect the output current of the constant current source.

NEW TERMS AND WORDS

constant current source - a circuit designed to provide a fixed current that does not vary with changes in load.

theorems - statements or methods that propose verifiable solutions of voltage and/or current within a network.

networks - groups of components that form interrelated circuits.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC NETWORK THEOREMS circuit board

Multimeter

Exercise 1 – Component Location/Identification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to locate the major circuit blocks of the DC NETWORK THEOREMS circuit board. You will verify your results by correctly identifying circuits and components.

DISCUSSION

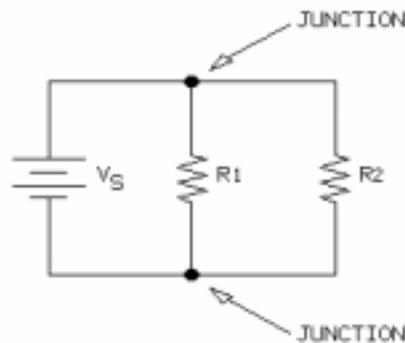
- The DC NETWORK THEOREMS circuit board provides examples of **networks** that can be solved with various theorems.
- The circuit board is organized into the following 9 circuit blocks:
 - KIRCHHOFF'S CURRENT LAW
 - KIRCHHOFF'S VOLTAGE LAW
 - KIRCHHOFF'S LAWS COMBINED
 - SUPERPOSITION
 - THEVENIN CIRCUITS
 - THEVENIZING A BRIDGE CIRCUIT
 - THEVENIN / NORTON CONVERSION
 - Δ TO Y OR Y TO Δ
- A tenth block is configured as a CONSTANT CURRENT SOURCE.
- Three types of resistors are used on the DC NETWORK THEOREMS circuit board. The resistors are carbon composition, carbon film, and metal film types.
- Fixed and variable power sources are used on the board.

UNIT 2 – KIRCHHOFF'S CURRENT LAW

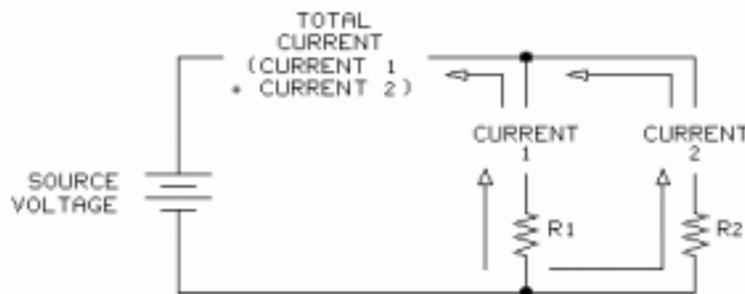
UNIT OBJECTIVE

At the completion of this unit, you will be able to analyze dc circuits by using Kirchhoff's current law.

UNIT FUNDAMENTALS

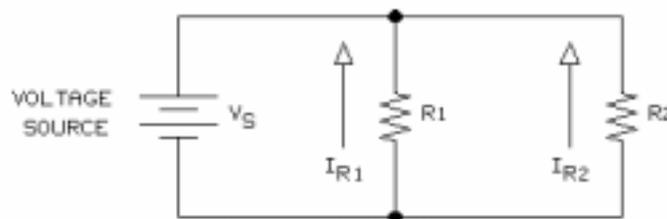


Kirchhoff's current law can be used to determine current into or out of circuit **junction**

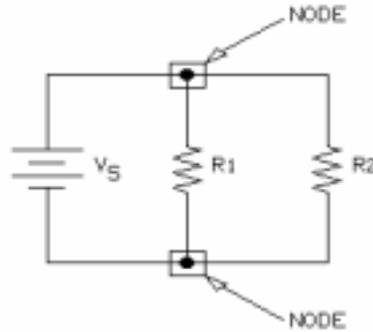


Kirchhoff's current law provides a solution for determining current in **parallel branch** circuits.

Each parallel branch, R1 and R2, allows current to flow from the power source.

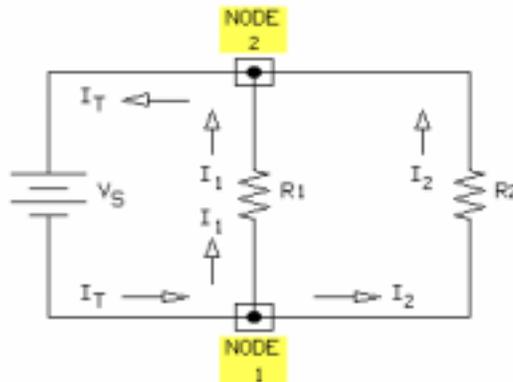


Each branch circuit provides a current path. Resistor R1 in this circuit is one branch. Resistor R2 in this circuit is another branch.

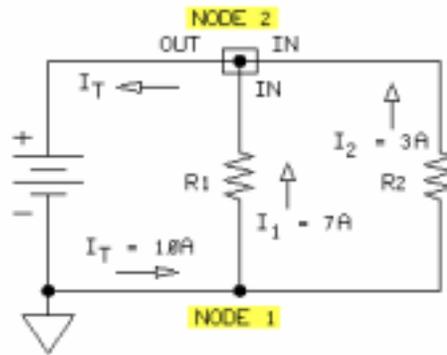


Kirchhoff's current law deals with currents at circuit points called **nodes**. A node is a junction, or a circuit point, where components are joined. Current enters and exits each node.

Kirchhoff's current law deals with the relationship of circuit currents and circuit nodes.



Circuit current flows into and out of each node of a two-branch circuit. I_T flows into NODE 1. Two currents (I_1 and I_2) leave NODE 1. Therefore, I_T equals $I_1 + I_2$. I_1 and I_2 combine at NODE 2. The combination of I_1 and I_2 results in I_T at NODE 2. Therefore, I_T from the power source is the same as I_T to the power source.

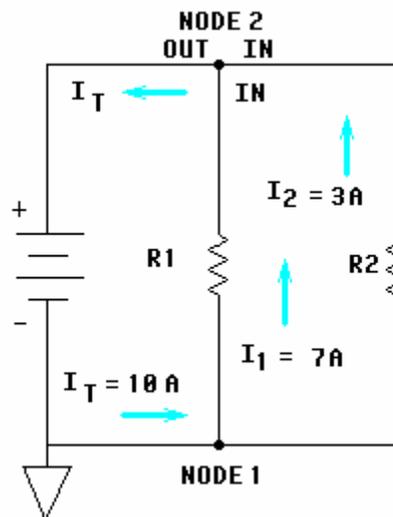


The connection on each side of the power source is represented by a node (NODE 1 and NODE 2).

Kirchhoff's current law can be stated in two ways:

1. The sum of the currents leaving a node in a circuit equals the sum of the currents entering the node.
2. The **algebraic sum** of the currents at any node in a circuit must equal zero.

If your calculations show a net gain or loss of node current, you have made an error.



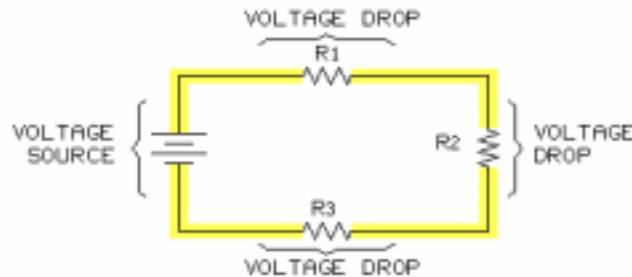
When applying an algebraic equation to node current, you must give a + or - sign to the current. In dealing with current flow, consider currents flowing into a node as negative (-), such as I_1 and I_2 into NODE 2. Consider currents leaving a node as positive (+), such as I_T out of NODE 2.

UNIT 3 – KIRCHHOFF'S VOLTAGE LAW

UNIT OBJECTIVE

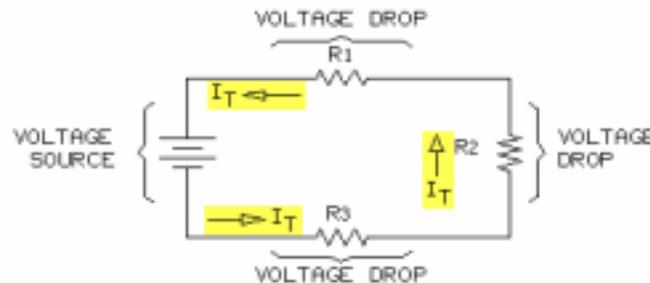
At the completion of this unit, you will be able to analyze dc circuits by using Kirchhoff's voltage law.

UNIT FUNDAMENTALS

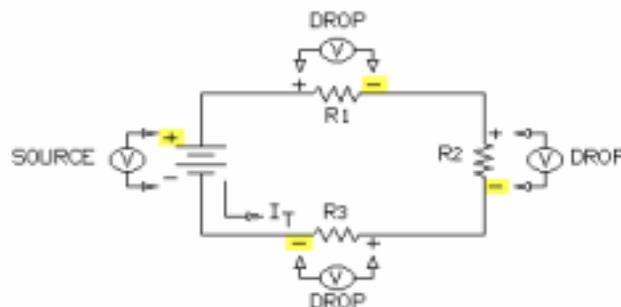


Kirchhoff's voltage law provides the solution of voltage drops and voltage sources around a closed loop.

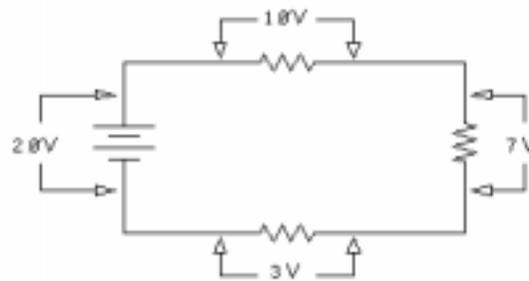
A solution for determining voltage is applied to series circuits, such as the circuit shown here.



The same current flows throughout the series circuit. As the current passes through each resistor, it generates a voltage drop. The sum of all voltage drops equals the value of the circuit voltage source.



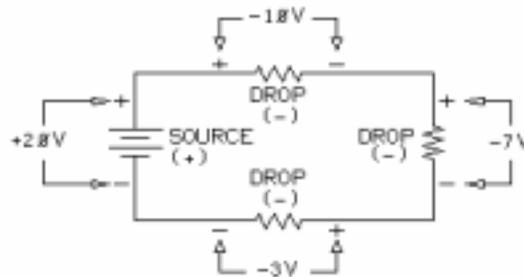
This drawing illustrates the polarities of voltages generated around a closed series circuit. Consider voltage drops negative (-) and voltage sources positive (+). Kirchhoff's voltage law deals with the relationship of the circuit voltage drops to the source voltage and to one another.



Kirchhoff's voltage law may be stated in two ways.

1. The sum of all the voltage drops in a series circuit equals the circuit applied (source) voltage.

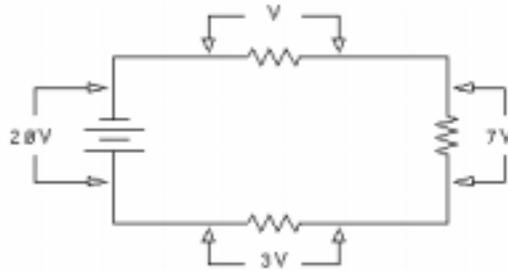
For example, in this circuit, the sum of all voltage drops is 20V (10 + 7 + 3). The source voltage is also 20V. Because the sum of the voltage drops equals the source voltage, the first requirement of Kirchhoff's law is met.



Kirchhoff's voltage law may be stated a second way.

2. The algebraic sum of the voltage source(s) and voltage drops in a series circuit equals zero.

For example, in this circuit, voltage drops are assigned a negative (-) polarity, and the voltage source is assigned a positive (+) polarity. Combining all voltages algebraically results in 0 (+20 - 10 - 7 - 3 = 0). Because the algebraic sum of all voltages in the loop is zero, the second requirement of Kirchhoff's law is met.



Due to the relationship of the circuit voltages, you can determine any one voltage drop or voltage source if you know all other voltages. The missing voltage (V) in this circuit must be the difference between the sum of the known voltage drops and the circuit source voltage.

Determine V (the missing voltage) by using Kirchhoff's voltage law and the following equation, where the source voltage equals 20V and the known voltage drops equal 3V and 7V.

$$\begin{aligned}
 20 &= 3 + 7 + V \\
 20 &= 10 + V \\
 20 - 10 &= V \\
 10 &= V
 \end{aligned}$$

NEW TERMS AND WORDS

Kirchhoff's voltage law - The algebraic sum of the voltages around a closed loop must equal zero. The sum of the voltage drops around a closed loop must equal the source voltage.

closed loop - A complete path or circuit for current flow.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
 DC NETWORK THEOREMS circuit board
 Multimeter

UNIT 4 – KIRCHHOFF'S LOOP EQUATIONS

UNIT OBJECTIVE

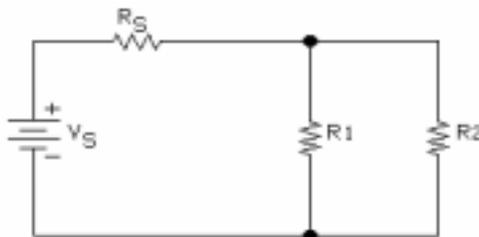
At the completion of this unit, you will be able to use loop equations by applying Kirchhoff's laws to a series/parallel circuit.

UNIT FUNDAMENTALS

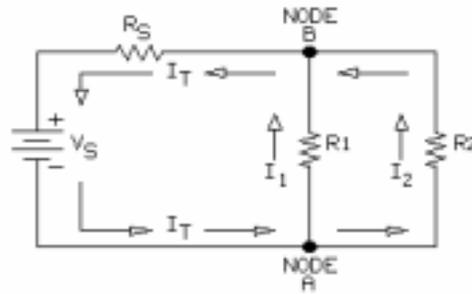


A loop is a closed circuit path. Shown is one example of a loop, where a single path is the only possible loop for the series circuit.

Kirchhoff's voltage law states that the algebraic sum of voltages in a closed loop equals zero.



A series/parallel circuit, such as this one, consists of more than one loop. To generate loop equations, use the voltages around each loop. One loop is from the - side of V_S , through R_1 and R_S , and back to V_S . The loop equation, therefore, is $V_{R1} + V_{RS} = V_S$.



Another loop is from the - side of V_S , through R_2 and R_S , and back to V_S . The relationship of the current, loops, and nodes of a series/parallel circuit is shown. The sum of the currents into NODE A equals the total circuit current (I_T). The sum of the currents out of NODE B also equals the total circuit current (I_T). I_T equals the sum of the I_1 and I_2 currents. Total circuit current (I_T) flows through R_S . Kirchhoff's laws and the loop equations can be combined to define a series/parallel circuit.

NEW TERMS AND WORDS

None

EQUIPMENT REQUIRED

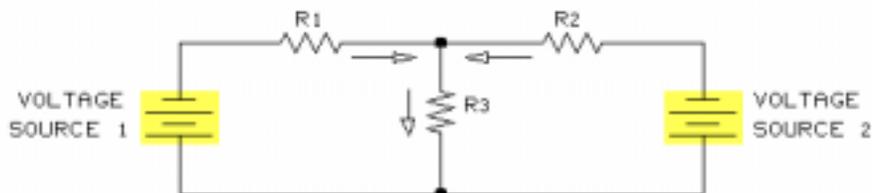
F.A.C.E.T. base unit
DC NETWORK THEOREMS circuit board
Multimeter

UNIT 5 – KIRCHHOFF'S SOLUTION WITH 2 SOURCES

UNIT OBJECTIVE

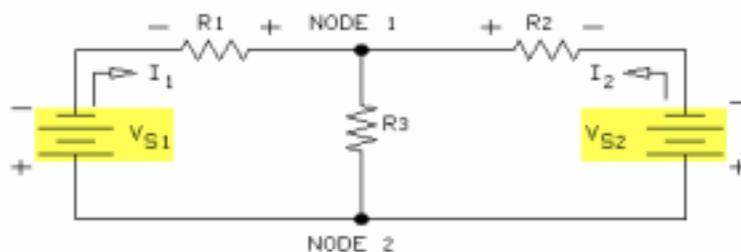
At the completion of this unit, you will be able to find voltage and current in circuits with two voltage sources by using Kirchhoff's laws. You will verify your results by comparing measured and calculated values.

UNIT FUNDAMENTALS

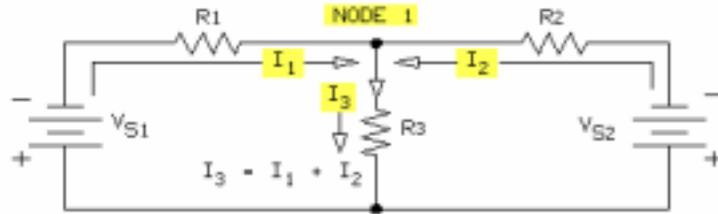


This circuit has two voltage sources. For each voltage source, current is assumed to flow in the direction shown.

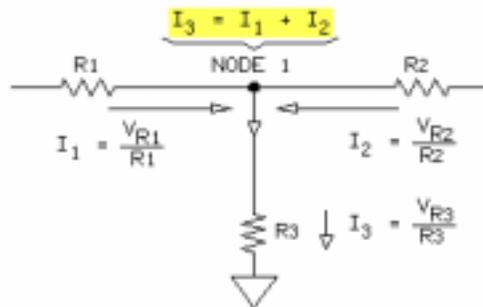
The application of Kirchhoff's laws to the circuit gives you the current through R_3 . The direction of the current is determined by the sign (+ or -) of the current. A negative (-) sign for current through R_3 indicates an incorrect assumption about the initial current direction. The problem is to find the voltage drops and the current flow through each resistor. You can apply Kirchhoff's laws to determine these circuit solutions.



This is a two-source circuit (V_{S1} and V_{S2}). There are 3 loops in this circuit, but only two are required for Kirchhoff's voltage law application.



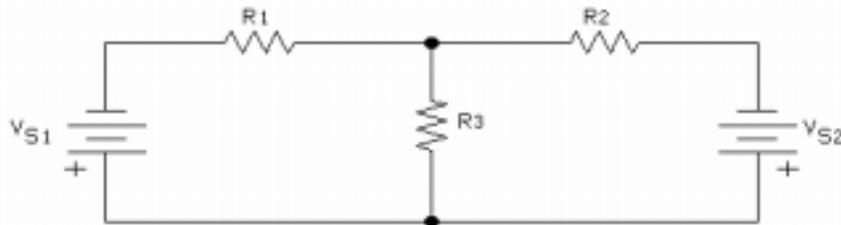
Based on Kirchhoff's current law, the current into NODE 1 ($I_1 + I_2$) must equal the current out of NODE 1 (I_3). Therefore, $I_3 = I_1 + I_2$.



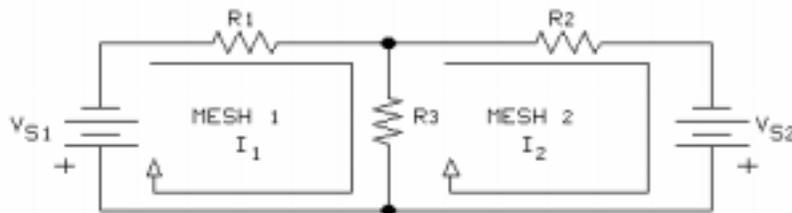
The currents can now be stated in terms of voltage drops.

$$I_1 + I_2 = I_3$$

$$(V_{R1} / R1) + (V_{R2} / R2) = V_{R3} / R3$$



Another method of applying Kirchhoff's laws is to implement a solution by using **mesh** currents. A mesh is the simplest possible closed path within a circuit.



The following **mesh equations** are based on this circuit.

FOR MESH 1

$$(I_1 \times R1) + (I_1 \times R3) - (I_2 \times R3) = VS1$$

FOR MESH 2

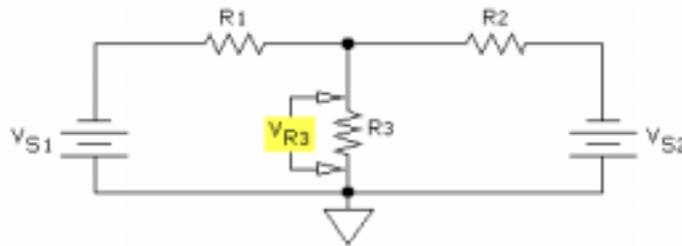
$$(I_2 \times R2) + (I_1 \times R3) - (I_2 \times R3) = -VS2$$

UNIT 6 – SUPERPOSITION AND MILLMAN'S THEOREMS

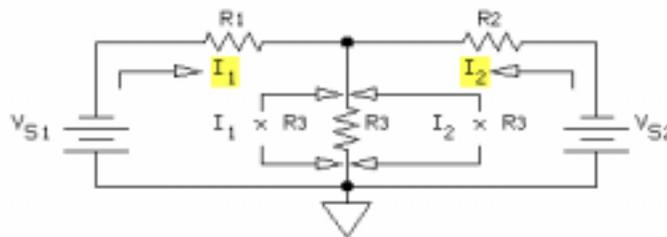
UNIT OBJECTIVE

At the completion of this unit, you will be able to determine voltages and currents by using the superposition theorem and Millman's theorem.

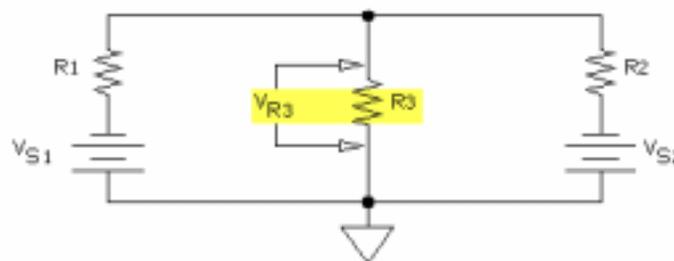
UNIT FUNDAMENTALS



The **superposition theorem** allows for a solution of V_{R3} when V_{S1} , V_{S2} , $R1$, $R2$, and $R3$ are known. In this circuit, $R3$ is common to each voltage source (V_{S1} and V_{S2}). When finding V_{R3} , you can determine all circuit voltages and currents by applying Ohm's law.



Each voltage source causes a current (I_1 and I_2) through $R3$. Based on Ohm's law, each current generates a voltage drop across $R3$. The two voltage drops are algebraically combined to determine the actual voltage across $R3$: $V_{R3} = (I_1 \times R3) + (I_2 \times R3)$.



Millman's theorem provides another method of determining the voltage drop across the common circuit element ($R3$). The circuit perspective is changed to make the junction of $R3$, $R2$, and $R1$ one side of the circuit, and the junction of $R3$, V_{S1} , and V_{S2} the other side of the circuit.

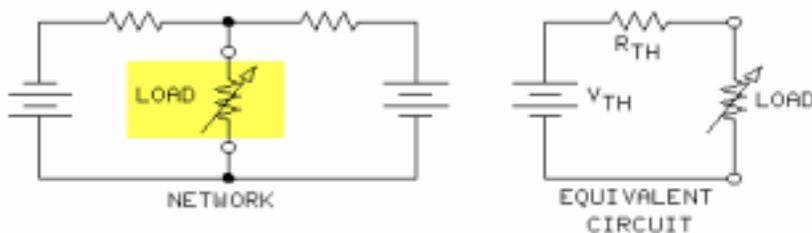
UNIT 7 – THEVENIN CIRCUITS

UNIT OBJECTIVE

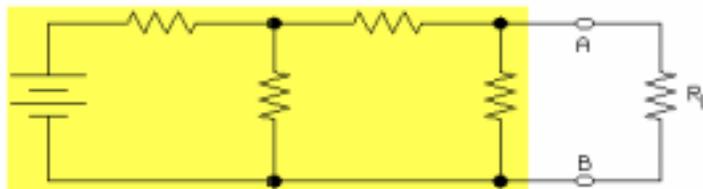
At the completion of this unit, you will be able to simplify one- and two-source circuits by using Thevenin's theorem.

UNIT FUNDAMENTALS

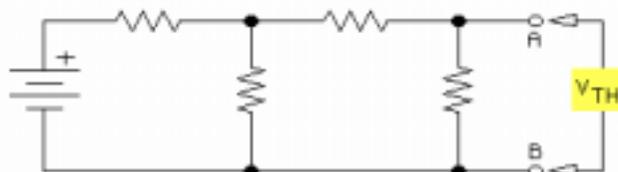
Thevenin's theorem named after the French engineer M.L. Thevenin, allows for the reduction of a network into an equivalent voltage and resistance. The equivalent voltage is called V_{TH} . The equivalent resistance is called R_{TH} .



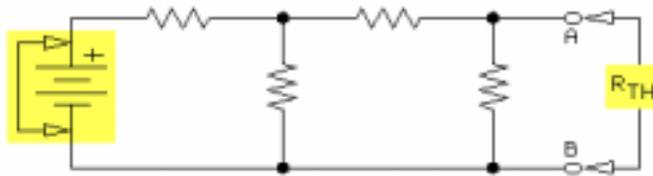
Thevenizing a circuit allows you to see the effects of changing load conditions without the need for repeating many Ohm's law equations for each load change. On the equivalent circuit, a simple voltage divider replaces the more complex network circuit.



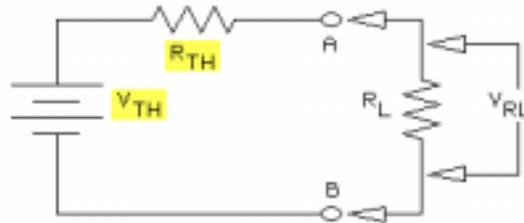
Thevenin's theorem reduces the circuit network into V_{TH} and R_{TH} . The reduction occurs with respect to A and B, the network output terminals. The circuit network is composed of a voltage source and 4 resistors. R_L represents the circuit load.



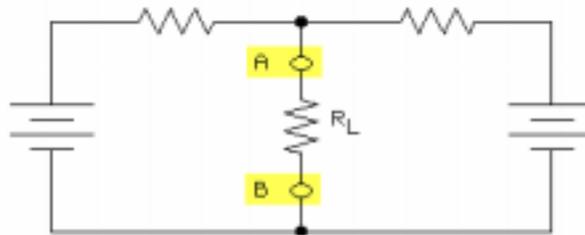
To calculate V_{TH} , remove R_L and apply Ohm's law to determine the output voltage of the network: V_{TH} between A and B. The polarity of V_{TH} is identical to the polarity of the network source voltage: A positive with respect to B.



To determine R_{TH} , replace the source voltage with a short circuit, and calculate the total resistance between terminals A and B of the network.



V_{TH} and R_{TH} make up the equivalent circuit. The original load is connected across terminals A and B. V_{TH} and R_{TH} develop the same load voltage and load current as that of the original network.



Two-source networks are thevenized in the same way. However, the superposition theorem can be used to determine V_{TH} .

NEW TERMS AND WORDS

Thevenin's theorem - a network can be represented by an equivalent V_{TH} and a series R_{TH} circuit with respect to a selected pair of output terminals.

V_{TH} - the Thevenin equivalent voltage of a network without a load.

R_{TH} - the Thevenin equivalent resistance of a network without its source voltage.

Thevenizing - applying Thevenin's theorem to a network.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC NETWORK THEOREMS circuit board

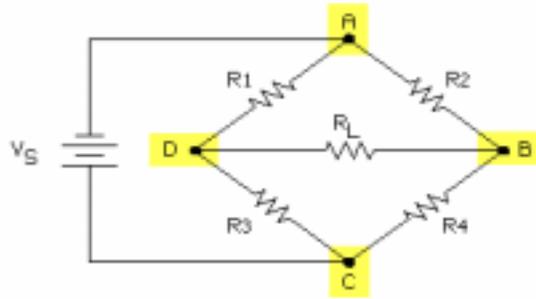
Multimeter

UNIT 8 – THEVENIZING A BRIDGE CIRCUIT

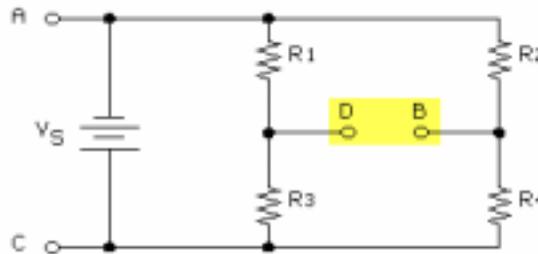
UNIT OBJECTIVE

At the completion of this unit, you will be able to thevenize a resistive bridge circuit by using the resistor divider equation.

UNIT FUNDAMENTALS

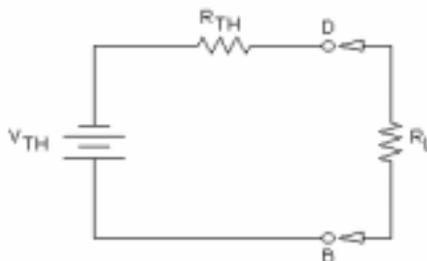


A resistive **bridge circuit** has 4 terminals, here labeled **A** through **D**. The source voltage (V_S) is applied across 2 opposing terminals (A and C). The output voltage is taken across the load resistor (R_L) connected between terminals D and B.



In this circuit, the bridge components are rearranged. Terminals D and B are the bridge output. You can use the voltage divider equation or Ohm's law to determine the bridge output voltage between D and B. This voltage is the Thevenin voltage of the bridge circuit.

To find the Thevenin resistance, replace the voltage source with a short circuit, and calculate R_{TH} between terminals D and B.



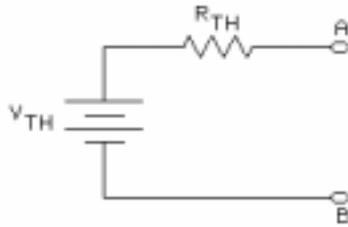
With the Thevenin voltage and the Thevenin resistance, the bridge circuit is simplified into a Thevenin equivalent circuit. You can now use Ohm's law to determine the load voltage (V_{RL}) and the load current (I_{RL}) for any value of R_L .

UNIT 9 – THEVENIN/NORTON CONVERSION

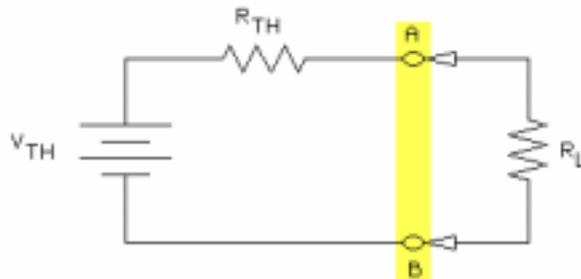
UNIT OBJECTIVE

At the completion of this unit, you will be able to convert networks into equivalent voltage and current sources by using Thevenin's and Norton's theorems.

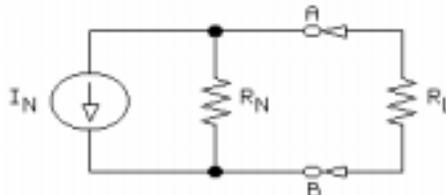
UNIT FUNDAMENTALS



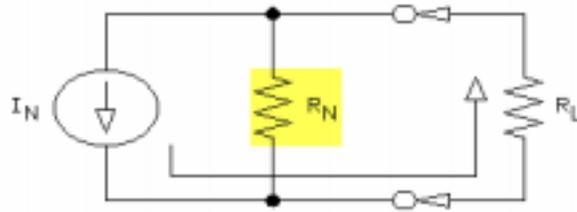
You can use Thevenin's theorem to reduce a network into an equivalent circuit called a **voltage source**. V_{TH} is the voltage source. R_{TH} is the internal source resistance. Terminals A and B are the output terminals of the source.



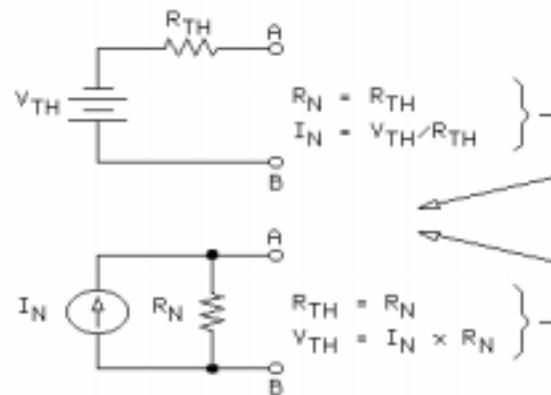
In a practical circuit, the no-load output voltage equals V_{TH} . When a load (R_L) is connected across terminals A and B, the output voltage equals $V_{TH} - V_{R_{TH}}$ because R_{TH} and R_L form a voltage divider.



You can use **Norton's theorem** to reduce a network into an equivalent circuit called a **current source**. I_N is the current source and is represented by an arrow in a circle. R_N is the internal source resistance. Terminals A and B are the output terminals of the source.



In an ideal situation, R_N is infinite [conductance (G) = 0]. Therefore, output current is constant, and terminal voltage varies with load resistance or load conductance.



You can use the formulas shown to convert between a Thevenin voltage source and a Norton current source. Each source generates the same load voltage and current as the network represented.

NEW TERMS AND WORDS

voltage source - a circuit that provides a constant voltage at its output terminals.

Norton's theorem - a network can be represented by an equivalent current source and parallel resistor with respect to a pair of output terminals.

current source - a circuit that provides a constant current at its output terminals.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DC NETWORK THEOREMS circuit board

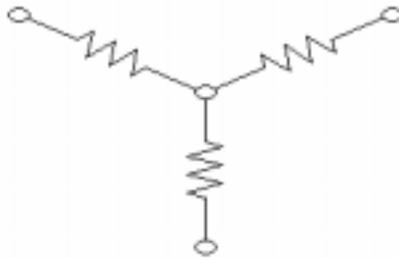
Multimeter

UNIT 10 – DELTA AND WYE NETWORKS

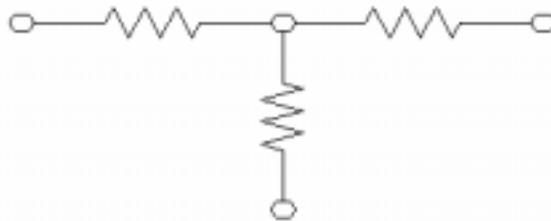
UNIT OBJECTIVE

At the completion of this unit, you will be able to simplify a resistive bridge network by using delta and wye transformations.

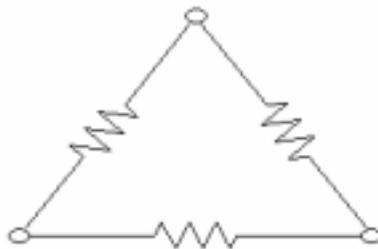
UNIT FUNDAMENTALS



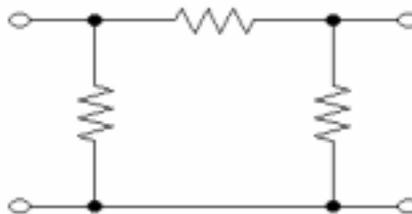
This configuration in the shape of a Y is a **wye** network.



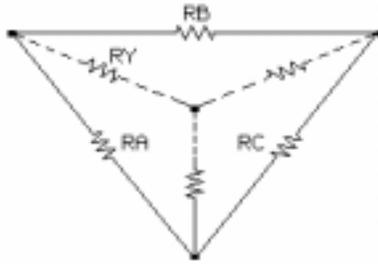
This configuration in the shape of a T is a **tee** network.



This configuration in the shape of the Greek letter Δ is a **delta** network.

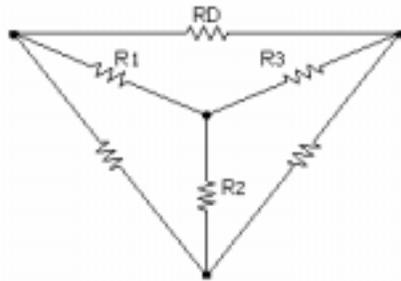


This configuration in the shape of the Greek letter π is a **pi** network.



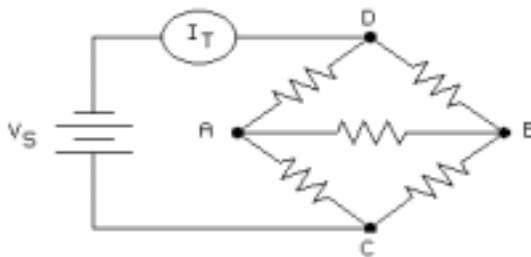
Conversion from delta to wye generates a wye circuit that is electrically identical to the delta network. To determine each wye resistor, divide the product of the two adjacent delta resistors by the sum of all the delta resistors.

$$R_Y = \frac{\text{PRODUCT OF 2 ADJACENT } R_s \text{ IN DELTA}}{\text{SUM OF } R_s \text{ IN DELTA}}$$



Conversion from wye to delta generates a delta circuit that is electrically identical to the wye network. To determine each delta resistor, divide the sum of all **cross products** in the wye network by the opposite resistor in the wye network.

$$R_D = \frac{\text{SUM OF ALL CROSS PRODUCTS IN Y}}{\text{OPPOSITE } R \text{ IN Y}}$$



Delta to wye transformation simplifies bridge circuit calculations. To easily determine total circuit current (I_T), convert one bridge delta section to a wye. This conversion results in a series/parallel circuit in which total current equals the supply voltage divided by the total circuit resistance ($I_T = V_S/R_T$).

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

AC 1 Fundamentals

FACET®



Student Workbook

FOURTH EDITION

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (FACET) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

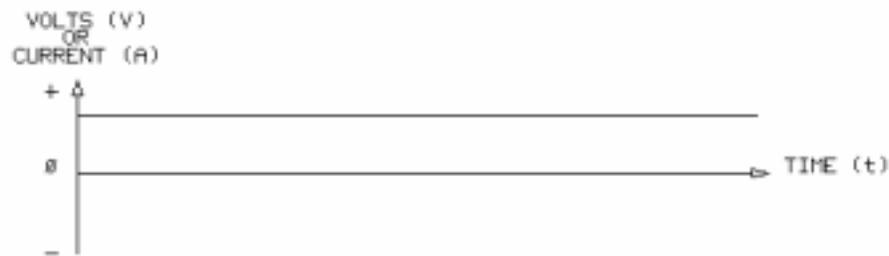
UNIT 1 – THE AC WAVEFORM GENERATOR

UNIT OBJECTIVE

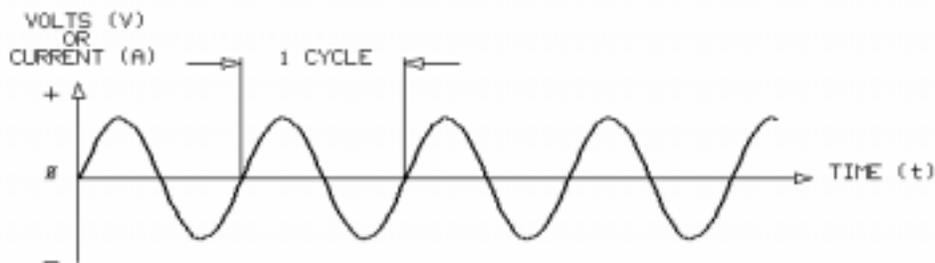
At the completion of this unit, you will be able to operate a basic ac waveform generator by using equipment provided.

UNIT FUNDAMENTALS

Alternating current (ac) differs from direct current in that it constantly changes in level and polarity.



The level and polarity of a dc **waveform** remain constant over time, as shown.



An ac waveform is produced when current or voltage changes in polarity over time. These changes usually occur in a repeating pattern. A common ac sine wave is shown.

The current or voltage level of an ac waveform is referred to as the **amplitude**. Amplitude, as in dc, is measured in volts (V) for emf and amperes (A) for current.

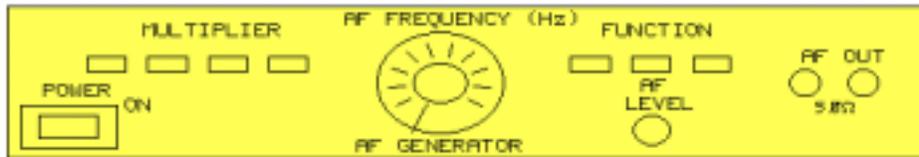
One complete repetition of a waveform is called a **cycle**, and the number of cycles that occur in one second is called the **frequency (f)**. Frequency is measured in hertz (Hz).

In dc circuits, opposition to current flow is resistance. In ac circuits, opposition to current flow is referred to as **impedance (Z)**. For ac circuits, Ohm's law is written:

$$\text{Voltage} = \text{Current} \times \text{Impedance}$$

or

$$E = I \times Z$$



An **ac waveform generator** produces an ac waveform. There are many types of ac waveform generators for many types of applications. Each waveform generator is unique, but all have similarities in operation and control.

NEW TERMS AND WORDS

Alternating current (ac) - a flow of electricity that first increases to maximum, then decreases to zero, reverses polarity, and reaches maximum in the opposite direction.

waveform - the shape of an electric wave as the amplitude is graphed over time.

amplitude - the level, or magnitude, of an alternating voltage or current.

cycle - one complete alternation of an ac current or voltage.

frequency (f) - the number of complete cycles in one second of alternating voltage or current; measured in hertz (Hz).

impedance (Z) - the total opposition a circuit offers to the flow of alternating current at a given frequency.

ac waveform generator - an electronic device that produces ac voltage of a desired frequency, wave shape, and amplitude.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

AC 1 FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Generator, sine wave

Exercise 1 – AC Waveform Generator Familiarization

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to operate an ac waveform generator by using equipment provided. You will verify your results by observing generator waveforms on the oscilloscope.

DISCUSSION

- Several types of waveform generators exist: examples include function generator, and af (audio frequency) generator.
- The following is a partial list of similarities between the different types of waveform generators.
 - all generate an ac waveform
 - all can vary the frequency of the generated waveform
 - all can vary the amplitude of the generated waveform
 - all exhibit a characteristic output impedance
- The controls that adjust the frequency of the waveform are labeled MULTIPLIER or RANGE, and FREQUENCY.
- The RANGE or MULTIPLIER control determines the span of frequencies the generator produces. The knob is marked: X1, X10, X100, X1K, X10K, X100K.
- The FREQUENCY controls the specific output frequency within the range established by the MULTIPLIER. The knob is graduated from 1 to 200.
- The actual frequency of the waveform is determined by the product of the frequency control setting and the multiplier control setting.
- The generator controls produce approximate frequency settings. The oscilloscope is used to produce an accurate frequency reading.
- The FUNCTION or WAVEFORM knob controls the type of output waveform produced by the generator.
- The output waveform amplitude is established using the LEVEL, AMPLITUDE, or AMPL control knob.
- A schematic diagram that has a generator symbol drawn using dotted lines means that an external generator connection is required.

UNIT 2 – AC MEASUREMENTS

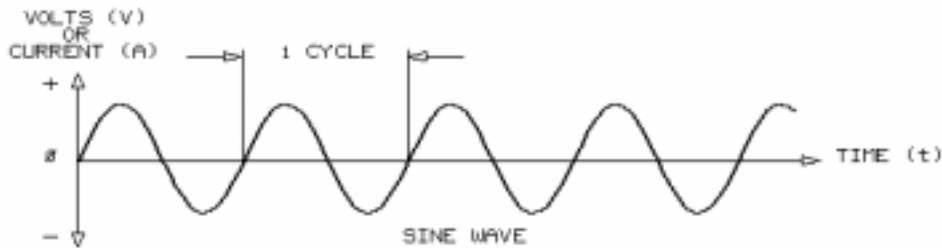
UNIT OBJECTIVE

At the completion of this unit, you will be able to take amplitude, frequency, and phase measurements of ac waveforms by using an oscilloscope.

UNIT FUNDAMENTALS

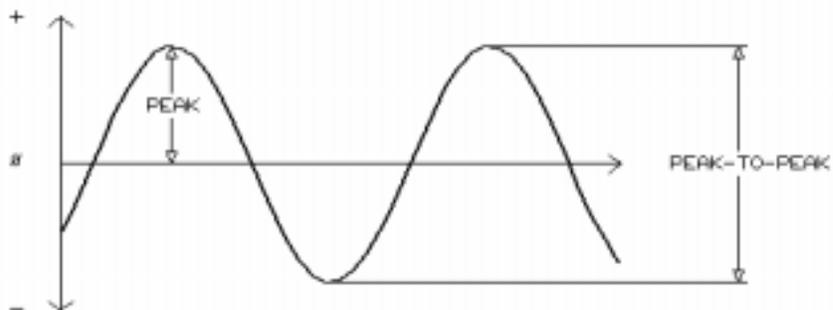


In dc circuits, voltage and current values do not change polarity.

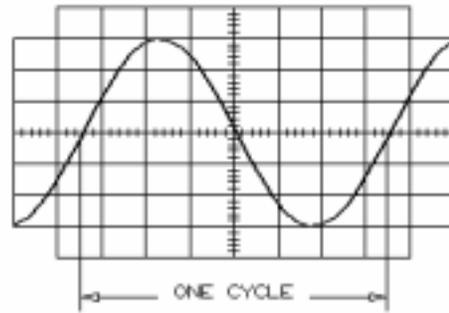


In ac circuits, however, circuit values are constantly changing polarity and amplitude over time. With ac, time as well as amplitude must be considered when measurements are made.

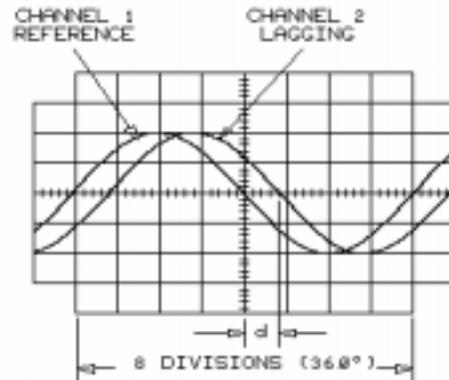
There are three basic ac measurements.



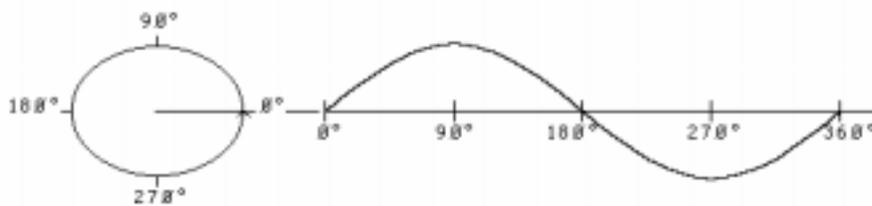
The first measurement is the **amplitude** of voltage or current.



The second type of measurement is the time-related measurement of **frequency**. Frequency is the number of cycles of a given waveform that occur in one second.



The last measurement, **phase angle**, is a time-related measurement used to compare two sine waves of identical frequency.



The sine wave bears a direct relationship to circular rotation. Like a circle, it is divided into 360 degrees. Each cycle of the sine wave equals one complete circular rotation.

As in a circle, one complete cycle of a sine wave equals 360 degrees.

Exercise 1 – AC Amplitude Measurement

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to measure the amplitude of ac waveforms by using an oscilloscope. You will verify your results with a multimeter.

DISCUSSION

- The number of voltage or current units between the maximum point (positive peak) of the ac waveform and the minimum point (negative peak) of the ac waveform is referred to as the peak-to-peak value.
- The subscript pk-pk is used to designate peak-to-peak amplitude measurements.
- An amplitude measurement from the horizontal axis to either the positive peak or the negative peak is designated as the peak value.
- The subscript pk is used to designate these amplitude values.
- The peak value of a waveform is one half the peak-to-peak measurement.
- Oscilloscopes are used to measure the peak or peak-to-peak amplitude of an ac signal. The amplitude scale should be expanded to display the largest possible signal. This provides the ability to make a more accurate measurement.
- A measured value indicating that an ac signal has the same heating power as an equivalent dc value is called the effective or rms (root mean square) value.
- Subscripts (V_{ac} , V_{rms} , or V_{eff}) are used to designate specific amplitude measurements.
- The product of the peak amplitude of a sine wave and 0.707 gives the rms value ($V_{rms} = V_{pk} \times 0.707$).
- When using the ac function of a general-purpose digital or analog multimeters, the reading is in rms. If the multimeter is analog, it may also have a “peak ac” scale. Many modern multimeters are usable to 100 kHz and above.
- The average value (indicated by a subscript of avg) of the amplitude of the ac waveform is calculated using this equation:
$$V_{avg} = 0.637 \times V_{pk}$$

Exercise 2 – Measuring With an Oscilloscope

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to measure voltage by using an oscilloscope and determine current and impedance by using Ohm's law. You will verify your results with information found in this exercise.

DISCUSSION

- A current-sensing resistor (R_2) is present on this circuit board. It is placed in series with the circuit under test and is a small enough value not to affect circuit performance.
- When the two-post connector is removed, the voltage drop across R_2 is measured and, using Ohm's law, the current can be calculated.
- Once the circuit current is determined, the circuit impedance can be calculated using Ohm's law and the source voltage (V_{GEN}).
- The oscilloscope, generator, and power source all have a common ground reference.
- Two scope probes and the ADD-INVERT method are used to measure the voltage of a component in order to prevent R_2 and L_2 from being shorted out.
- Follow these steps to perform the ADD-INVERT method:
 - Place both channel vertical input attenuators on the same setting.
 - Connect the channel 1 input to the side of the component with the greatest potential.
 - Connect the channel 2 input to the opposite side of the component.
 - Connect both oscilloscope probe ground clips to the generator common.
 - Invert channel 2.
 - Switch the vertical mode to ADD.
 - Record the voltage.
- If the ADD-INVERT method is used, even though one end of a component is connected directly to ground, the oscilloscope can be safely placed directly across the component.

UNIT 3 – INDUCTANCE

UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the effect of inductance on a circuit by using an oscilloscope.

UNIT FUNDAMENTALS

The property of a conductor that opposes a change in current flow is **inductance (L)**

The magnetic field surrounding a conductor produces an opposing electromotive force (emf) in response to a changing current. This opposing emf is called **counter electromotive force (cemf)**

The amount of cemf produced by a conductor depends on the rate at which the current changes and on the amount of inductance. The frequency of the applied ac current is the rate of change. The higher the frequency, the more cemf produced.

The measure of inductance depends largely upon how well the magnetic field surrounding the conductor is concentrated. A higher concentration results in a higher, more measurable amount of inductance.

A straight piece of wire has its magnetic field spread over a large area (less concentration). However, if we were to wind the wire into a coil, the magnetic field would then be concentrated into a much smaller area (greater concentration).

Because of its inductive properties, the coil is called an **inductor**.



The figure shows the symbol for an inductor as shown on a schematic. Inductors are usually labeled with the capital letter **L**.

The **henry (H)** is the unit of measure for inductance. An inductor measuring one henry produces one volt of cemf when one ampere of ac current at one hertz is applied to it. For most applications, however, inductors are in the millihenry (mH) and microhenry (μH) ranges.

The lower the total inductance, the higher the value of circuit current.

The higher the total inductance, the lower the value of circuit current.

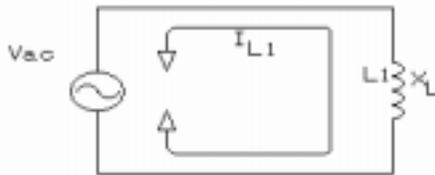
UNIT 4 – INDUCTIVE REACTANCE

UNIT OBJECTIVE

At the completion of this unit, you will be able to determine the characteristics of resistive-inductive (RL) circuits by using an oscilloscope and given information.

UNIT FUNDAMENTALS

There are many similarities and differences between capacitive reactance (X_C) and inductive reactance (X_L). They work in opposition to each other when subjected to an ac signal. Inductive reactance (X_L) will be studied first.



The amount of opposition an inductor (L) offers to ac circuit current is measured by the resistance it offers to the power source (V_{ac}).

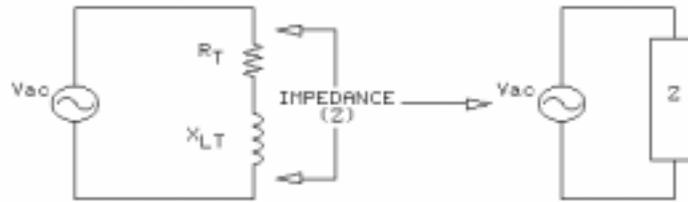
$$X_L = \frac{V_{ac}}{I_{L1}}$$

This apparent resistance is called **inductive reactance (X_L)** and is measured in ohms.

If inductance increases (larger inductor value), inductive reactance (X_L) increases; if inductance decreases, X_L decreases.

Increases in the frequency of the power source (V_{ac}) increase the inductive reactance (X_L); if frequency decreases, X_L decreases.

Inductive reactance (X_L) does not depend on the amplitude of the power source.



The total opposition to current flow in a circuit containing resistance (resistors) and inductive reactance (inductors) is known as impedance (Z) and is measured in ohms.

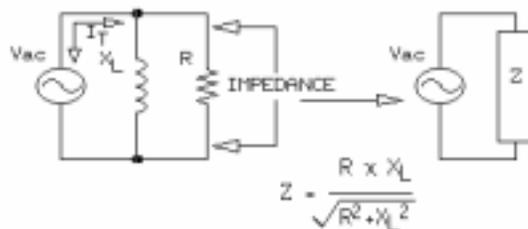
You cannot directly add resistance (R) and inductive reactance (X_L) to obtain the impedance value (Z).

In a series circuit with resistance and inductive reactance, impedance (Z) is determined from the following formula.

$$Z = \sqrt{R^2 + X_L^2}$$

A more practical approach to finding the impedance (Z) of X_L and R in series is to divide the total circuit current (I_T) into the applied voltage (V_{ac}).

$$Z = \frac{V_{ac}}{I_T}$$

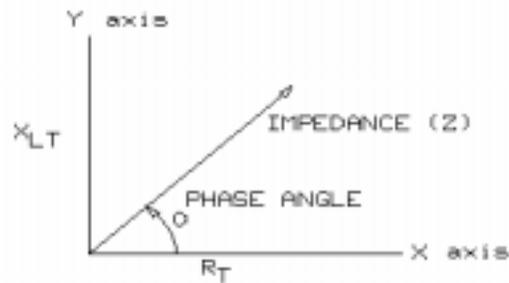


In a parallel circuit with resistance and inductive reactance, Z is determined from the following formula.

$$Z = \frac{R \times X_L}{\sqrt{R^2 + X_L^2}}$$

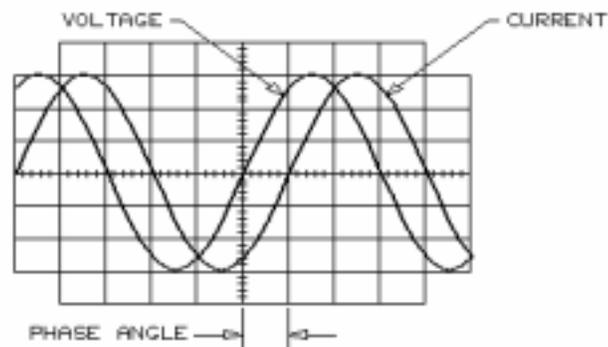
Again, a more practical approach to finding the impedance (Z) of X_L and R in parallel is to divide the total circuit current (I_T) into the applied voltage (V_{ac}).

$$Z = \frac{V_{ac}}{I_T}$$



Impedance (Z) is a phasor. Resistance (R_T) and inductive reactance (X_{LT}) are the components of the impedance phasor.

Being a phasor, impedance also has a phase angle.



The angle between the generator voltage and current is the phase angle of the circuit. The impedance angle is equal to this phase angle.

NEW TERMS AND WORDS

inductive reactance (X_L) - the opposition to the flow of alternating current by the inductance of a circuit. It is measured in ohms.

phasor - a quantity consisting of magnitude and direction used to describe an ac waveform.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
 AC 1 FUNDAMENTALS circuit board
 Multimeter
 Oscilloscope, dual trace
 Generator, sine wave

Exercise 2 – Series RL Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine characteristics of series RL circuits by using calculated and measured values. You will verify your results with an oscilloscope.

DISCUSSION

- Total resistance of a series circuit is the sum of the individual resistors. Resistance increases as the number of resistors increase, causing lower circuit current.
- Inductors connected in series behave in a similar manner. Total inductive reactance is the sum of the individual reactance. Inductive reactance increases as the number of series inductors increase, resulting in lower circuit current and higher circuit impedance.
- Impedance (Z) is measured in ohms and is the total opposition to current flow; it includes both inductive reactance and resistance.
- Resistance and inductive reactance cannot be added directly to obtain impedance.
- In an RL series circuit total impedance is found using this equation:

$$Z = \sqrt{R_T^2 + X_{LT}^2}$$

- A practical method of finding Z is to measure the total circuit current (I_T) and divide it into the applied voltage (V_{ac}). $Z = V_{ac}/I_T$
- In RL circuits, applied voltage is the square root of the sum of the squares of the voltage drops. $V_{GEN} = \sqrt{V_{RT}^2 + V_{XLT}^2}$
- Since impedance is a phasor, there is a phase angle associated with it. The phase angle is found with this equation: $\theta = \arctan (X_{LT}/R_T)$

Exercise 3 – Parallel RL Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine characteristics of parallel RL circuits by using calculated and measured values. You will verify your results with an oscilloscope.

DISCUSSION

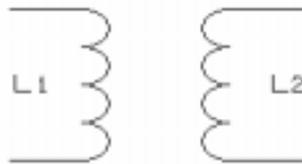
- Total parallel inductance, like total parallel resistance, is found by taking the inverse of the sum of the reciprocals. When just two inductors are in parallel, use the product-over-sum method.
- Inductive reactance decreases as the number of parallel inductors increases, causing an increase in circuit current and a decrease in circuit impedance.
- Once the parallel elements have been summed, the circuit is simplified to a parallel RL circuit that consists of one resistive branch and one reactive branch.
- The voltage across each parallel component is the same as the applied voltage.
- Branch currents are determined by using Ohm's law.
- In parallel RL circuits, total circuit current is not the sum of the branch currents. Total circuit current is the square root of the sum of the each individual branch current squared.
- The circuit impedance is calculated using this formula
$$Z = (R \times X_L) / [\text{sqrt}(R^2 + X_L^2)].$$
- A more practical method of finding the circuit impedance is to divide the total current into the applied voltage.
- When inductance is decreased, the inductive reactance decreases, resulting in increased current flow through the reactive branch. Phase angle between the applied voltage and circuit current decreases.

UNIT 5 – TRANSFORMERS

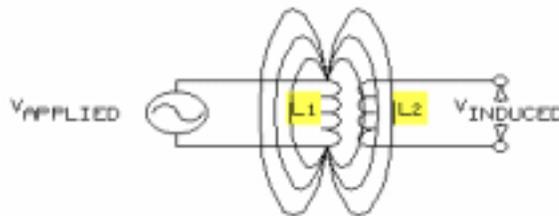
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the transfer of electrical energy from one circuit to another by mutual inductance.

UNIT FUNDAMENTALS

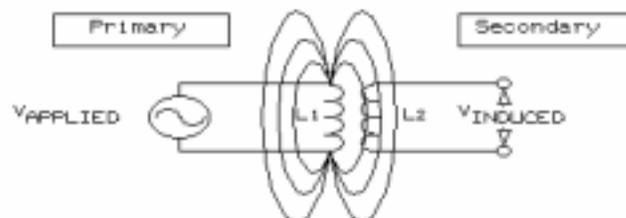


Suppose two inductors are placed in close proximity to one another, but no electrical connection exists between them.



Suppose also that an ac voltage is applied to one of the inductors. As shown, the magnetic field surrounding the inductor with the applied voltage (L1) induces a voltage into the other inductor (L2).

This phenomenon is known as **mutual inductance**. Inductor coils arranged in this manner result in a common electrical device called a **transformer**.



The coil, or winding, with the applied voltage is the **primary**. The coil that develops voltage from the magnetic field is the **secondary**.

The amount of voltage induced in the secondary depends on the ratio of turns of wire between the two windings.

The coils of a transformer are often wound around an iron or **ferrite** core that concentrates the magnetic field. This core improves the transfer of energy, or **coupling**, from the primary to the secondary.



Above are various transformer schematic symbols.

The presence or absence of lines between the coils indicates the type of core used.



This figure shows an iron-cored transformer with a tapped secondary. This **tap** may be used to alter the turns ratio between the two coils.



A transformer may contain one or several taps on the primary, on the secondary, or on both windings.

Transformers come in all sizes. The transformer you will use in this unit weighs only a few ounces. However, some transformers used by power companies weigh several tons.

NEW TERMS AND WORDS

mutual inductance - the ability of one coil to induce voltage into another coil in close proximity by way of a fluctuating magnetic field.

transformer - a device used to couple energy from one circuit to another through mutual inductance.

primary - a transformer winding connected to the source voltage.

secondary - a transformer winding connected to the load.

coupling - the transfer of energy from one circuit to another.

tap - a fixed electrical connection to a specified position on the winding of a transformer.

autotransformer - a transformer consisting of one winding that acts as both primary and secondary.

step-down transformer - a transformer whose applied primary voltage is greater than the secondary voltage.

step-up transformer - a transformer whose secondary voltage is greater than the applied primary voltage.

ferrite - a nonconductive, powdered, compressed, magnetic, iron-based material.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

AC 1 FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Generator, sine wave

Exercise 1 – Transformer Windings

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the coil resistances of a transformer by using a multimeter. You will verify your results with information found in this exercise.

DISCUSSION

- Inductors have an inherent resistance because they are made of wire. The same is true for transformer windings.
- The resistance of the transformer windings can be measured using a multimeter.
- Since the two windings (primary and secondary) are electrically isolated, an open circuit condition exists.
- Resistance in each winding will depend on the number of turns (length), wire gauge, and the type of wire.
- An autotransformer consists of one continuous tapped winding that acts as both primary and secondary.
- Transformer taps may be placed anywhere along the windings. The most common place is at the center (dividing the windings in half); this type of transformer is referred to as a center-tapped transformer.

Exercise 3 – Transformer Turns and Voltage Ratios

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the turns and voltage ratios of a transformer by using calculated and measured values. You will verify your results with an oscilloscope.

DISCUSSION

- A ratio of the number of turns of wire in the primary windings (N_P) to the number of turns of wire in the secondary windings (N_S) is called a turns ratio.
- The ratio of the primary side voltage (V_P) to the secondary side voltage (V_S) is equal to the turns ratio.
$$N_P/N_S = V_P/V_S$$
- Transformers that have a larger primary voltage than secondary voltage are called step-down transformers.
- Transformers that have a smaller primary voltage than secondary voltage are called step-up transformers.
- Since ratios are unitless quantities, the voltage ratio is independent of the amplitude of the applied signal.
- The tap on a center-tapped transformer divides the number of turns in half resulting in a choice of two different turns ratios and voltage ratios.

Exercise 4 – Transformer Secondary Loading

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the effect of secondary loading by using a typical transformer. You will verify your results with an oscilloscope.

DISCUSSION

- A ratio of the current through the primary (I_P) and the secondary (I_S) is called the current ratio.
- The current ratio is equal to the inverse of the voltage and turns ratio.
$$I_S/I_P = V_P/V_S = N_P/N_S$$
- The relationship between the current and voltage ratio shows that when voltage is stepped up by a certain factor, the current is stepped down by the same factor.
- Transformers are self-regulating devices. The transformer will automatically increase or decrease the primary current to accommodate for changes in the load (RL). (The load is placed across the secondary of the transformer.)
- In an ideal transformer the power delivered by the primary is equal to the power delivered by the secondary.
- In practical transformers typical efficiency of a transformer is 90% efficient.
$$\% \text{ efficiency} = (P_S/P_P) \times 100$$

UNIT 6 – CAPACITANCE

UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the effect of capacitance on a circuit by using an oscilloscope.

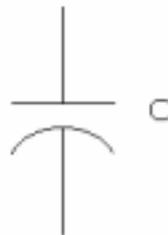
UNIT FUNDAMENTALS



Suppose two metal plates separated by an insulating material were placed in close proximity to one another. If a voltage were applied to the plates, a charge would develop between them.



Even if the voltage source were removed, the charge would still remain. The ability to store electric charge is called **capacitance (C)**. An electrical component with a predicted measure of capacitance is a **capacitor**.



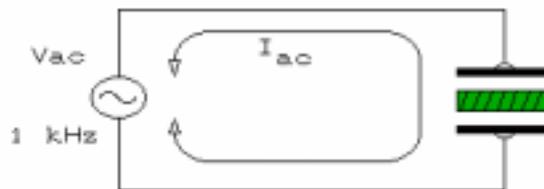
This is the symbol for a capacitor as shown on a schematic. Capacitors are usually labeled with the capital letter C.

The **farad (F)** is the unit of measure for capacitance. A farad equals one coulomb of charge stored at a potential of one volt. The farad, however, is a rather large value for most applications, so more common capacitor values are in the picofarad (pF) and microfarad (μ F) ranges.



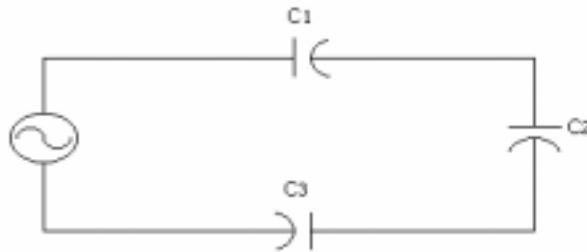
A capacitor charges when dc is applied to it. While the capacitor is charging, current flows until the capacitor is fully charged. At that time, current flow stops and the voltage across the capacitor equals the applied dc voltage.

Therefore, a capacitor blocks dc current when fully charged. As you continue your study of electronics, you will see that the ability to block dc is very useful.

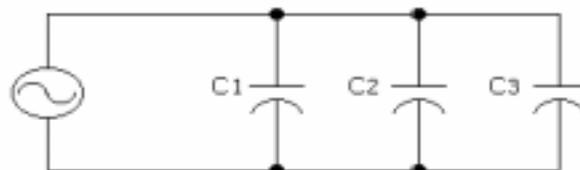


A capacitor will not block ac current because the voltage level and polarity are constantly changing.

Although ac passes through a capacitor, the capacitor does create opposition (impedance) to current flow. This impedance depends on the value of the capacitor and the frequency of the applied signal.



Total capacitance decreases as the number of capacitors in series increases.



Total capacitance increases as the number of capacitors in parallel increases.

Exercise 1 – Capacitors

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to describe the effect a capacitor has on dc and ac circuits by using measured values. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

- When dc is applied to a capacitor, it begins to charge and current flows. Once fully charged, the voltage across the capacitor is equal to the applied voltage, and the current flow stops. A very small amount of current (leakage current) actually does “leak” through the capacitor.
- A capacitor, once charged, remains at that voltage level when the applied dc is removed.
- Creating a complete circuit path between the leads of a charged capacitor will discharge it.
- When an ac source is applied to a capacitor, the signal is passed but with opposition in the form of impedance.
- The amount of impedance produced by a capacitor will depend on the capacitance and the frequency of the applied ac signal.
- When capacitance increases, impedance decreases and total circuit current increases.
- When the ac signal frequency is increased, impedance decreases and total circuit current increases.
- Capacitance affects the phase relationship between the applied voltage and current.
- The voltage across a capacitor lags the current by 90 degrees, or current through the capacitor leads the voltage by 90 degrees.

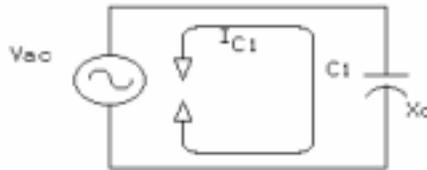
UNIT 7 – CAPACITIVE REACTANCE

UNIT OBJECTIVE

At the completion of this unit, you will be able to determine the characteristics of resistive-capacitive (RC) circuits by using an oscilloscope and given information.

UNIT FUNDAMENTALS

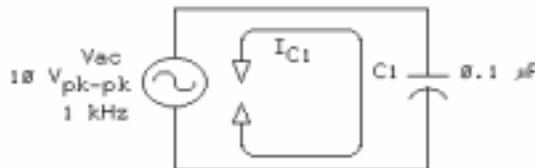
There are many similarities and differences between capacitive reactance (X_C) and inductive reactance (X_L). They work oppositely to each other in many respects when subjected to an ac signal.



The amount of opposition a capacitor (C) offers to ac circuit current is measured by the resistance it offers to the power source (Vac).

$$X_C = \frac{V_{ac}}{I_{C1}}$$

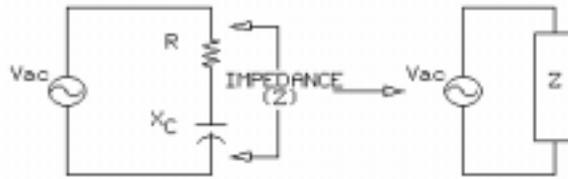
This apparent resistance is called **capacitive reactance**(X_C) and is measured in ohms.



If capacitance increases (larger capacitor value), capacitive reactance (X_C) decreases; if capacitance decreases, X_C increases.

Increases in the frequency of the power source (Vac) decrease capacitive reactance (X_C); if frequency decreases, X_C increases.

Capacitive reactance (X_C) does not depend on the amplitude of the power source.



The total opposition to current flow in a circuit containing resistance (resistors) and capacitive reactance (capacitors) is known as impedance (Z) and is measured in ohms.

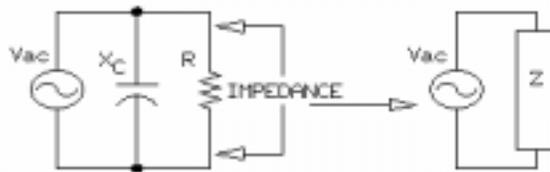
You cannot directly add resistance (R) and capacitive reactance (X_C) to obtain the impedance value (Z).

In a series circuit with resistance and capacitive reactance, impedance (Z) is determined by the following formula.

$$Z = \sqrt{R^2 + X_C^2}$$

A more practical approach to finding the impedance (Z) of X_C and R in series is to divide the total circuit current (I_T) into the applied voltage (V_{ac}).

$$Z = \frac{V_{ac}}{I_T}$$

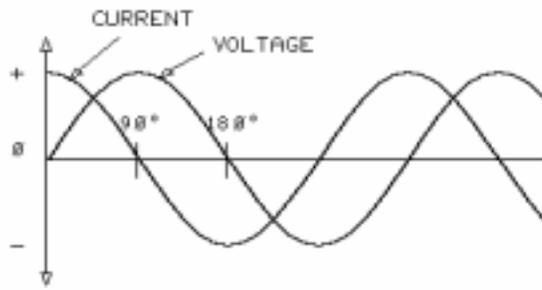


In a parallel circuit with resistance and capacitive reactance, Z is determined by the following formula.

$$Z = \frac{RX_C}{\sqrt{R^2 + X_C^2}}$$

Again, a more practical approach to finding the impedance (Z) of X_C and R in parallel is to divide the total circuit current (I_T) into the applied voltage (V_{ac}).

$$Z = \frac{V_{ac}}{I_T}$$



In RC circuits, voltage and current are not in phase (as they are in a circuit that contains only resistors).

NEW TERMS AND WORDS

capacitive reactance - the opposition to current flow due to capacitance.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
AC 1 FUNDAMENTALS circuit board
Oscilloscope, dual trace
Generator, sine wave

Exercise 1 – Capacitive Reactance

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine capacitive reactance (X_C) by using calculated and measured values. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- Capacitors pass ac current but present an opposition to current flow in the form of an impedance.
- The impedance produced by a capacitor is referred to as capacitive reactance (X_C) and is calculated using this equation.
$$X_C = 1/(2\pi fC)$$
where X_C is the reactance measured in ohms
 f is frequency in hertz
 C is capacitance in farads
 2π is a constant that indicates that the equation is valid for sine waves only.
- Capacitive reactance depends on the frequency of the signal and the capacitance.
- Capacitive reactance and circuit capacitance are inversely proportional.
- Capacitive reactance is independent of the amplitude of the applied signal.

Exercise 2 – Series RC Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine characteristics of series RC circuits by using calculated and measured values. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- Capacitive reactance, like resistance, increases as the number of series capacitors increases. The total capacitive reactance is the sum of the individual reactances.
- Capacitive reactance increases result in lower circuit current and higher circuit impedance.
- The current in a series circuit flows through each series component.
- The total opposition to current flow is impedance (Z); it is measured in ohms.
- Total impedance is found with this formula: $Z = \sqrt{R^2 + X_C^2}$
- Impedance is a phasor; the total resistance lies on the x-axis and the total active reactance lies on the y-axis.
- In RC circuits the applied voltage equals the square root of the sum of the squares of the voltage drops.
- The phase angle of the circuit impedance is found with this equation:
$$\theta = \arctan (X_{CT}/R_T)$$

Exercise 3 – Parallel RC Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine characteristics of parallel RC circuits by using calculated and measured values. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

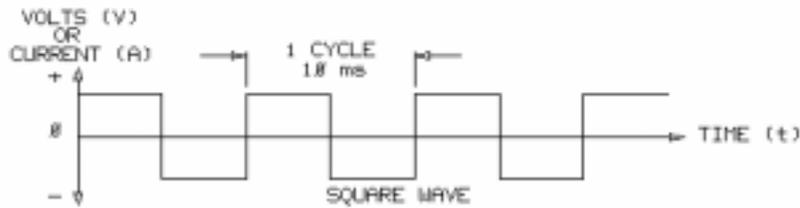
- In a parallel RC circuit, total capacitive reactance is found by taking the inverse of the sum of the reciprocals.
- If only two capacitors are in parallel, the product-over-sum method can be used.
- Capacitive reactance decreases as the number of capacitors in parallel increases; this results in higher circuit current and lower circuit impedance.
- The equivalent circuit has two distinct branches: one resistive and one reactive.
- Voltage drop across parallel branches are equal. Ohm's law is used to find the branch currents.
- Total circuit current is the square root of the sum of the squares of the branch currents.
- Circuit impedance is found by using this formula: $Z = (R \times X_C) / [\text{sqrt}(R^2 + X_C^2)]$
- The phase angle between the applied voltage and circuit current increases as capacitance is increased.

UNIT 8 – TIME CONSTANTS

UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the effects of time constants on ac and dc circuits by using calculated and measured values.

UNIT FUNDAMENTALS



In this unit, we will use square waves when applying ac to a circuit. The square wave shown has a period of 10 ms, which results in a **fundamental frequency** of 100 Hz (frequency = 1/period).



Exact multiples of the fundamental (first) frequency are called the **harmonic frequencies**. For example, the first harmonic frequency of the 100 Hz square wave is:

$$100 \text{ Hz} \times 1 = 100 \text{ Hz}$$

(first harmonic)

This first harmonic frequency is the fundamental frequency.

The second and third harmonic frequencies are:

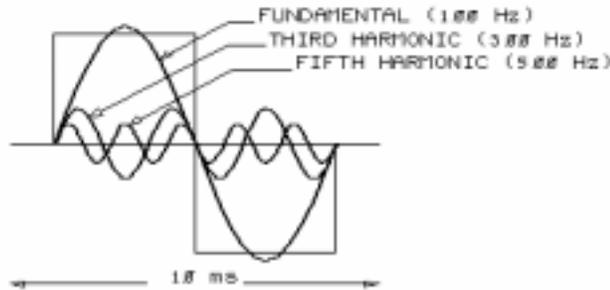
$$100 \text{ Hz} \times 2 = 200 \text{ Hz}$$

(second harmonic)

$$100 \text{ Hz} \times 3 = 300 \text{ Hz}$$

(third harmonic)

Harmonic frequencies that are even multiples of the fundamental frequency (second, fourth, sixth, etc.) are **even harmonics**.



The 100 Hz square wave is actually a composite waveform made up of many sine waves. These sine waves consist of odd harmonic frequencies of the square wave fundamental frequency.

NEW TERMS AND WORDS

fundamental frequency - the principal component of a wave; the component with the lowest frequency or greatest amplitude. For example, the fundamental frequency of a 100 Hz square wave is 100 Hz.

harmonic frequencies - sinusoidal waves having frequencies that are integral (positive whole number) multiples of the fundamental frequency. For example, a wave with twice the frequency of the fundamental is called the second harmonic.

even harmonics - harmonic frequencies that are even multiples of the fundamental frequency. For example, 200 Hz and 400 Hz waves are even harmonics of a 100 Hz wave.

odd harmonics - harmonic frequencies that are odd multiples of the fundamental frequency. For example, 300 Hz and 500 Hz waves are odd harmonics of a 100 Hz wave.

time constant - time required for voltage or current to rise or fall by 63 percent. It results from the ability of inductance (L) and capacitance (C) to store energy.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
 AC 1 FUNDAMENTALS circuit board
 Multimeter
 Oscilloscope, dual trace
 Generator, sine wave

Exercise 1 – RC Time Constants

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the time constant of an RC circuit by using calculated and measured values. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- The time constant (τ) of a circuit is the amount of time required for current (inductive circuit) or voltage (capacitive circuit) to reach 63% of its maximum value.
- An RC circuit time constant (in seconds) is the product of the circuit resistance (in ohms) and capacitance (in farads).
- An RL circuit time constant is the division of the circuit resistance divided into the inductance (in henries).
- Five time constants are required for the component to reach 99% maximum.
- There are no time constants for a purely resistive circuit because the circuit reacts to changes in voltage or current instantaneously.
- Universal time constant charts are used to determine the amount of voltage across a capacitor or current through an inductor when the time constant is known.
- Charging and discharging curves are equal and opposite.

Exercise 2 – RC and RL Wave Shapes

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the effects of time constants on RC and RL circuits by using square waves as the applied ac waveforms. You will verify your results with a universal time constant chart.

EXERCISE DISCUSSION

- A square wave input signal is used to constantly charge and discharge the capacitor in a simple RC circuit.
- The frequency of the square wave has been selected to provide a long enough period for the capacitor to fully charge and discharge.
- Current flow is maximum when the charge on the capacitor is zero. Current flow is minimum when the capacitor is fully charged. The current flow is in the opposite direction when the capacitor discharges.
- A sawtooth waveform is produced when the circuit resistance is increased. The larger resistance increases the time constant. The period of the input square wave is now too short for the capacitor to fully charge or discharge.
- Since the time constant of a simple RL circuit is much smaller than that of an RC circuit, a square wave input at a higher frequency (shorter period) can be used.
- Maximum voltage across an inductor and minimum current flow result when an inductor begins to charge. Since inductors oppose changes in current flow, the same conditions are present when an inductor begins to discharge.
- Current flow decreases at a rate governed by the RL time constant.
- Decreasing inductance shortens the charge and discharge time in relation to the period of the applied square wave. This condition causes positive voltage spikes on the rising edge and negative voltage spikes on the falling edge of the applied signal.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The FACET computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the FACET equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the FACET Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

AC 2 Fundamentals

FACET®



Student Workbook



FOURTH EDITION

Third Printing, May 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

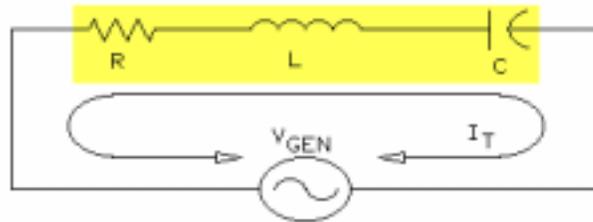
UNIT 1 – RLC CIRCUITS

UNIT OBJECTIVE

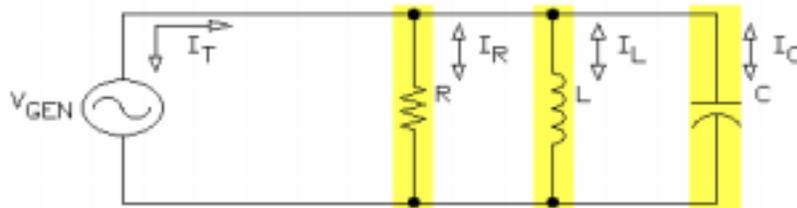
At the completion of this unit, you will be able to analyze series and parallel RLC circuits by using calculations and measurements.

UNIT FUNDAMENTALS

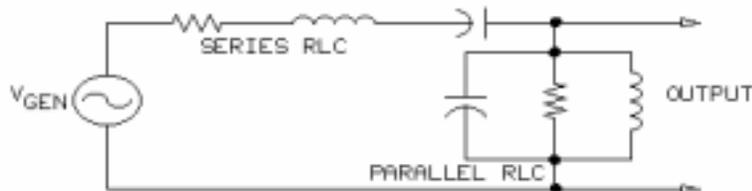
Many electronics circuits are made up of resistors (R), inductors (L), and capacitors (C). Such networks are referred to as **RLC circuits**. There are many ways that resistors, inductors, and capacitors can be connected.



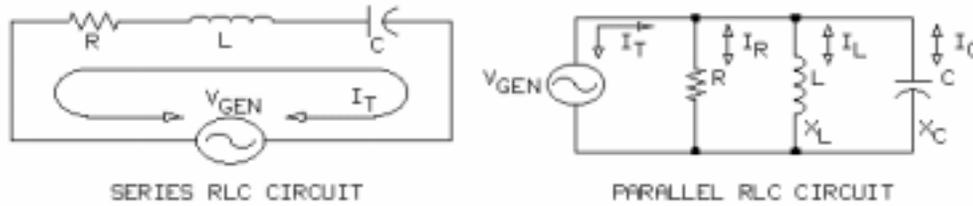
One way to connect these three components is in **series**.



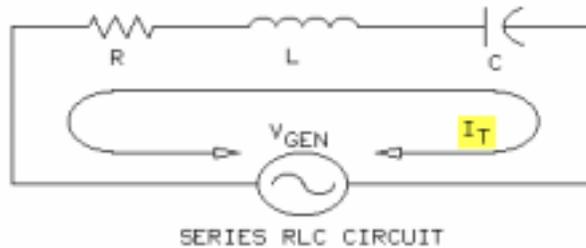
Another way to arrange these three components is in parallel.



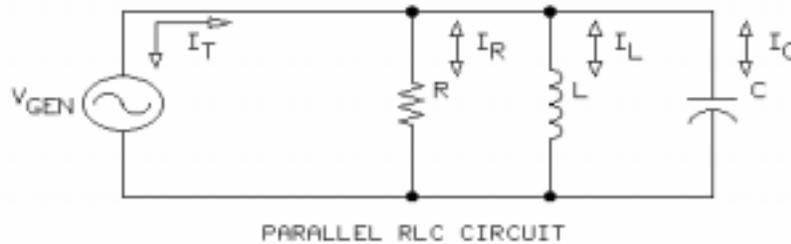
More complex RLC circuits are made up of combinations of series and parallel RLC circuits. Varying the frequency of the applied voltage (V_{GEN}) causes both the inductive (X_L) and capacitive (X_C) reactances to change which results in the total circuit current (I_T) changing.



At some frequencies, the RLC circuits act capacitively. The current (I_T) leads the applied voltage (V_{GEN}). At other frequencies, the RLC circuits act inductively, and I_T lags V_{GEN} .



In a series circuit, the same current flows in all three components. Given the current (I_T), you use Ohm's law to calculate the voltage drops across the individual circuit components.



In a parallel circuit, V_{GEN} appears across each of the components. Given V_{GEN} , you use Ohm's law to calculate the current through each of the three circuit branches.

NEW TERMS AND WORDS

RLC circuits - networks created by resistors (R), inductors (L), and capacitors (C) connected in various ways to perform some useful function such as filtering, phase shifting, or impedance matching; also called LCR circuits.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
 AC 2 FUNDAMENTALS circuit board
 Oscilloscope, dual trace
 Generator, sine wave

Exercise 1 – Series RLC Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to analyze series RLC circuits by using calculations and measurements. You will verify your results with an oscilloscope.

DISCUSSION

- In a series RLC circuit, the total impedance is the combination of the oppositions contributed by each component. Total impedance (Z) consists of a resistive and reactance component.
- Net reactance is the difference between the two reactances.
- The equivalent circuit behaves as a series RL or RC circuit, depending on which reactive component is larger.
- Once total impedance is known, Ohm's law can be used to determine circuit current.
- Voltage across each component is found using Ohm's law and series circuit basics.
- In a series RLC circuit, total voltage is found with this equation:

$$V_{\text{GEN}} = \text{sqrt} [V_{\text{R}}^2 + (V_{\text{C}} - V_{\text{L}})^2]$$

- The impedance phase angle is found using one these equations:

$$Z_{\theta} = \arctan (X_{\text{NET}}/R)$$

$$\theta = \arctan (V_{\text{NET}}/V_{\text{R}})$$

where X_{NET} is the total reactance

V_{NET} is the total reactive component voltage

- Since the amount of reactance is frequency dependent, circuit values will vary with changes in the frequency of the applied voltage.

Exercise 2 – Parallel RLC Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to analyze parallel RLC circuits by using calculations and measurements. You will verify your results with an oscilloscope.

DISCUSSION

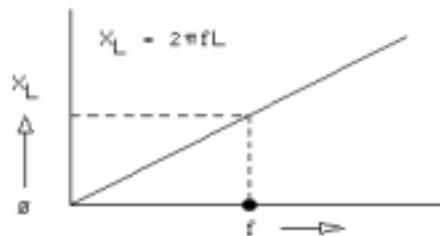
- In parallel RLC circuits, components are connected in parallel with the applied voltage source; each component forms an individual parallel branch.
- Consistent with parallel circuit theory, each branch voltage is equal to the applied voltage.
- Ohm's law and the branch resistance or reactance is used to determine individual branch currents.
- Total circuit current is not the sum of the branch currents. Use the following equation to calculate total current: $I_T = \text{sqrt} [I_R^2 + (I_C - I_L)^2]$
- Characteristics of the equivalent circuit depend on the dominant reactive component. The component with the lowest reactance, or highest current, is dominant.
- Equivalent capacitance or inductance can be determined from the appropriate reactance formula once component reactance has been determined by Ohm's law.
- Phase angle is calculated from the following equation: $\theta = \arctan (I_{NET}/I_R)$
- Since the amount of reactance is frequency dependent, circuit values will vary with changes in the frequency of the applied voltage.

UNIT 2 – SERIES RESONANCE

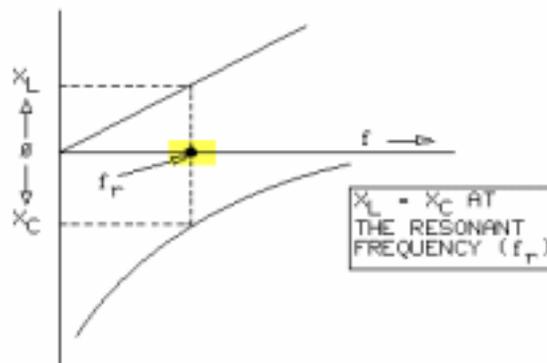
UNIT OBJECTIVE

At the completion of this unit, you will be able to analyze series resonant RLC circuits by using calculations and measurements.

UNIT FUNDAMENTALS

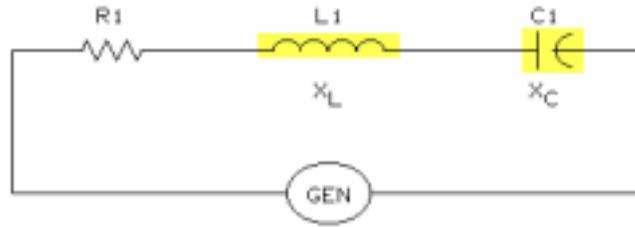


An increase in frequency (f) causes the inductive reactance (X_L) to increase. A decrease in frequency causes the inductive reactance (X_L) to decrease.

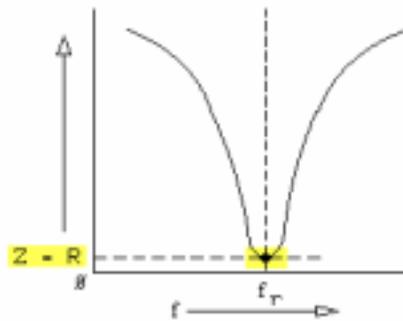


At some frequency, the inductive and capacitive reactances are equal in a series RLC circuit. This frequency is called the **resonant frequency** (f_r). To calculate resonant frequency, apply the following formula.

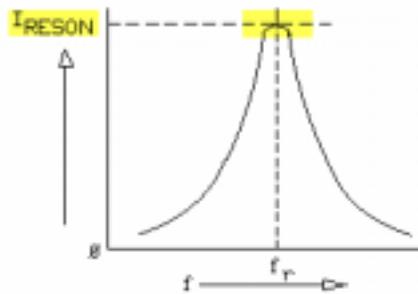
$$f_r = \frac{1}{2\pi\sqrt{LC}}$$



At **resonance**, the reactances are equal, so they cancel one another ($X_L - X_C$). The total circuit impedance of a series RLC circuit at resonance is simply the circuit resistance (R_1).

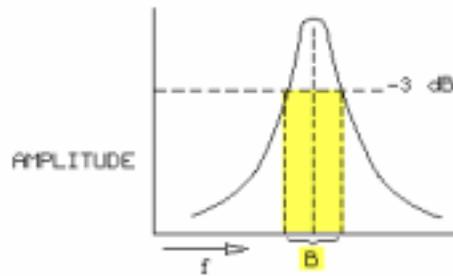


This response curve shows that as frequency increases, the circuit impedance (Z) decreases until it reaches a minimum point (R), then it increases again.

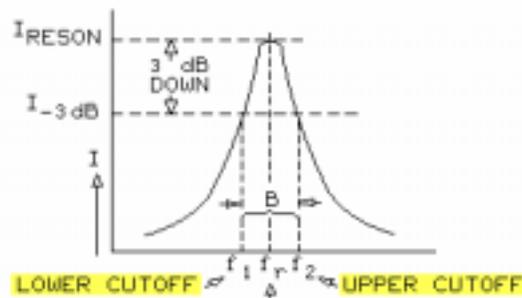


This response curve shows that as frequency increases, the circuit current (I_T) increases until it reaches a maximum point (I_{RESON}), then it decreases again.

RLC series circuits are widely used in radio, TV, and communications equipment for **tuning** and **filtering** because they allow a large peak current at the resonant frequency and provide a high opposition to current flow at all other frequencies. This ability to select a desired frequency while rejecting other frequencies is known as **selectivity**.



The selectivity of a circuit is determined by the **bandwidth (B)** of the circuit.



The bandwidth is determined by the upper and lower **cutoff frequencies** of the circuit ($B = f_2 - f_1$).

The selectivity and bandwidth of a series RLC circuit depends on the circuit **Q** ($Q = X_L/R$).

NEW TERMS AND WORDS

resonant frequency (f_r) - the frequency at which the inductive and capacitive reactances in an RLC circuit are equal.

resonance - the condition where the inductive and capacitive reactances in any RLC circuit are equal and cancel one another.

tuning - varying the inductance or capacitance in an RLC circuit in order to set the resonant frequency and select or reject specific signals.

filtering - the process of either passing or rejecting specific frequencies.

selectivity - the measure of the ability of a tuned circuit to pass selected frequencies or bands of frequencies and reject all others.

bandwidth (B) - the range of frequencies that will be passed or rejected by a resonant circuit; the difference between the upper and lower cutoff frequencies.

cutoff frequencies - the frequencies above and below the resonant frequency of a tuned series circuit where the current is 70.7% of, or 3 dB down from, its peak value; also known as the half power points.

Q - the ratio of inductive reactance to resistance ($Q = X_L/R$).

Exercise 2 – Q and Bandwidth of a Series RLC Circuit

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to calculate the bandwidth and Q of a series RLC circuit by using standard formulas. You will verify your results with an oscilloscope.

DISCUSSION

- Resonant RLC circuits are often used for tuning and filtering input signals.
- Selectivity, in series RLC circuits, is the ability to produce a high current (I_{RESON}) at resonance and high impedance at all other frequencies.
- Highly selective circuits are responsive to a limited range of frequencies.
- The bandwidth (B) of a resonant circuit determines the selectivity.
- Bandwidth is determined by the upper and lower cutoff frequencies of the circuit.
$$B = f_2 - f_1$$
- Upper and lower cutoff frequencies occur where circuit current is 3 dB down from the maximum current (I_{RESON}).
- Resonant circuit selectivity is characterized by a factor called Q. The Q of a circuit is calculated from this equation: $Q = X_L/R$
- Circuits with high Q values have a high selectivity. Q values have a wide range, a Q below 10 is very low, while a Q larger than 250 is very high.
- The higher the Q the smaller the bandwidth. $B = f_r/Q$
- Q of the resonant circuit can determine the voltage across L or C using this relationship:
 $V_C \text{ or } V_L = Q \times V_{\text{GEN}}$

UNIT 3 – PARALLEL RESONANCE

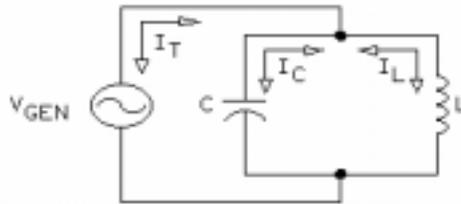
UNIT OBJECTIVE

At the completion of this unit, you will be able to analyze parallel resonant LC circuits by using calculations and measurements.

UNIT FUNDAMENTALS

Resonance occurs in series and parallel circuits. The resonant frequency (f_r) of a parallel resonant circuit is calculated with the same formula used for series resonant circuits.

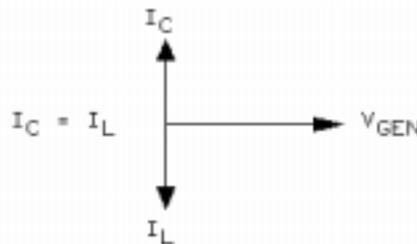
$$f_r = 1/2\pi\sqrt{LC}$$



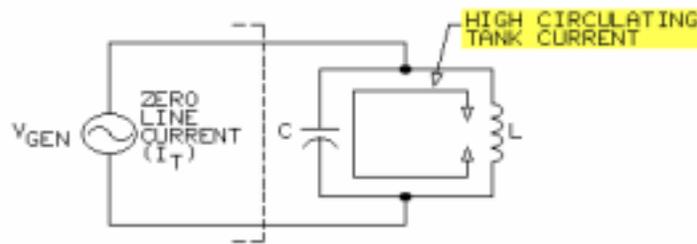
In a parallel LC circuit, the generator voltage (V_{GEN}) is applied across each component. The component currents (I_C and I_L) are determined from the following equations.

$$I_C = V_{GEN}/X_C$$

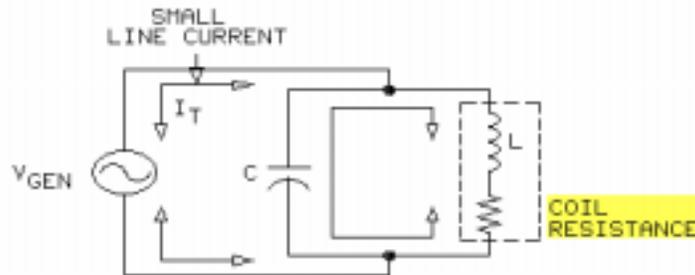
$$I_L = V_{GEN}/X_L$$



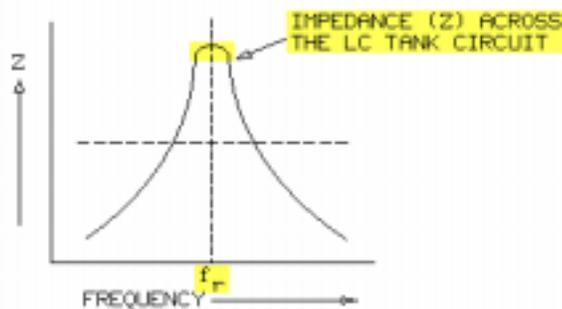
The current in the capacitor (I_C) leads the generator voltage (V_{GEN}) by 90° . The current in the inductor (I_L) lags the generator voltage by 90° . At resonance, the currents (I_C and I_L) are equal and opposite in their effect, so they cancel one another. The total current drawn from the generator is the **line current** (I_T).



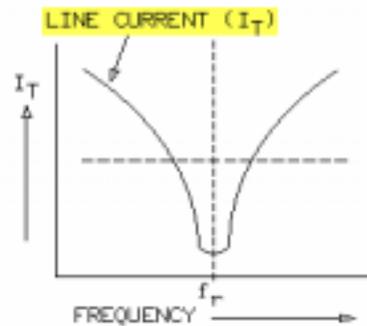
The inductor and capacitor effectively exchange energy. The current exchange between the capacitor and inductor is referred to as the **circulating current**. A parallel circuit consisting of inductors and capacitors that exchange circulating current is referred to as a **tank circuit**. Circulating current flows inside the tank as the inductor and capacitor exchange energy, but no current is drawn from the generator. At resonance, the circulating current is maximum while the total line current (I_T) is 0.



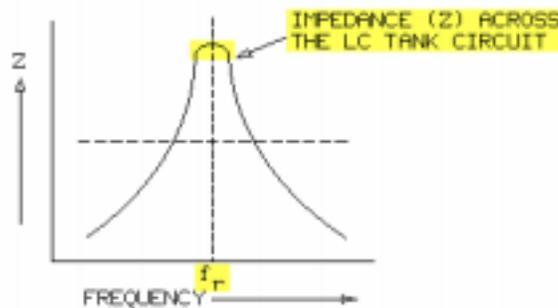
In a practical parallel resonant LC circuit, the small series resistance in the inductor (R_L) causes the inductor current (I_L) to be slightly lower than the capacitor current (I_C). Because of the coil resistance, inductor current (I_L) does not equal capacitor current (I_C), and a small amount of line current flows. Circuit impedance (Z) is still very high and resistive.



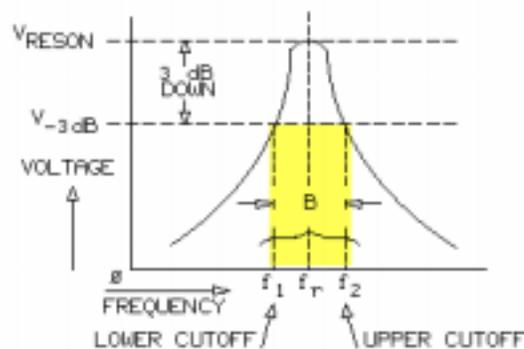
This response curve shows that as frequency increases, the circuit impedance (Z) increases until it reaches a maximum point, then it decreases again.



This response curve shows that as frequency increases, the circuit current (I_T) decreases until it reaches a minimum point, then it increases again. The relationship between impedance and line current in a parallel resonant circuit is exactly opposite to the relationship between impedance and total current in a series resonant circuit. At resonance, circuit current and voltage are in phase (impedance is resistive) for series and parallel LC circuits.



Parallel resonant circuits are used in tuning and filtering circuits because they provide a high impedance at the resonant frequency and a low impedance at all other frequencies.



As in series resonant circuits, the Q determines the selectivity of a parallel resonant circuit, and the bandwidth (B) is a measure of selectivity.

Exercise 1 – Parallel Resonant Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to compute the resonant frequency, total circuit current, and impedance of a parallel LC circuit by using standard electronics formulas. You will verify your results with an oscilloscope.

DISCUSSION

- At the resonance frequency, inductive and capacitive reactance are equal in a parallel LC tank circuit.
- The equation $f_r = 1/[2\pi(\text{sqrt}(LC))]$, is used to calculate the resonant frequency for both parallel and series resonant circuits.
- At resonance, an LC tank circuit has a very high impedance and exhibits resistive characteristics.
- Ohm's law is used to determine total line current, which, at resonance, is minimal.
- Voltage (V_{RESON}) across the tank circuit, at resonance, is maximal.
- At resonance, the reactive components are equal and opposite therefore canceling one another.
- The applied voltage and total current are in phase when the circuit is at resonance.

Exercise 2 – Q and Bandwidth

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to calculate the Q and the bandwidth of a parallel resonant circuit by using standard formulas. You will verify your results with an oscilloscope.

DISCUSSION

- Resonant circuit selectivity is characterized by a factor called Q.
- The Q of an individual inductor is the inductive reactance divided by the internal resistance of the inductor.
- This internal resistance can be represented as an equivalent parallel resistance (R_{LP}) found by using the equation $R_{LP} = Q^2 \times R_L$.
- Practical parallel resonant circuits have a current limiting resistor in series with the signal generator, prior to the LC parallel network. Here the overall circuit Q is a much lower value than the Q of the inductor.
- Reducing the above circuit to a simple parallel resonant circuit produces an equivalent shunt resistance (R_E). The Q is then calculated by dividing R_E by X_L (R_E/X_L). R_E is the parallel combination of ($R_{GEN} + R_I$) and R_{LP} .
- The bandwidth (B) of a resonant circuit defines its selectivity.
- Bandwidth is determined by the upper and lower cutoff frequencies of the circuit.
$$B = f_2 - f_1$$
- Upper and lower cutoff frequencies occur where circuit voltage is 3 dB down from the maximum voltage (V_{RESON}).
- The higher the Q the smaller the bandwidth. $B = f_r/Q$
- Q can be calculated from the circuit bandwidth. $Q = f_r/B$

UNIT 4 – POWER IN AC CIRCUITS

UNIT OBJECTIVE

At the completion of this unit, you will be able to calculate and measure the apparent power, real power, reactive power, and power factor in ac circuits.

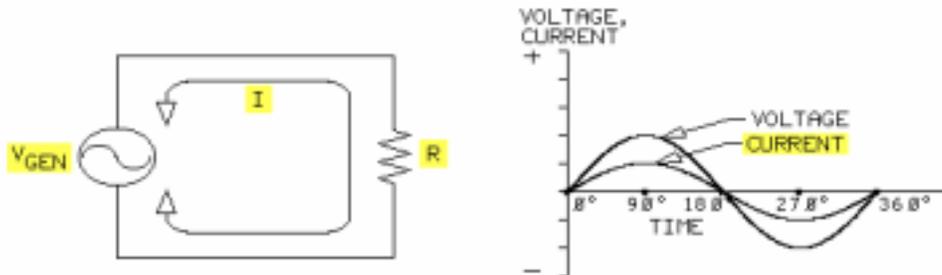
UNIT FUNDAMENTALS

Power is the rate at which work is done. Power is energy expended over a period of time to accomplish useful work. In an electrical circuit, energy moves electrons. This energy is dissipated in the form of heat when electrons flow through a resistance. A watt is the unit of electrical power. **Real power (P)** is dissipated only in a resistance.

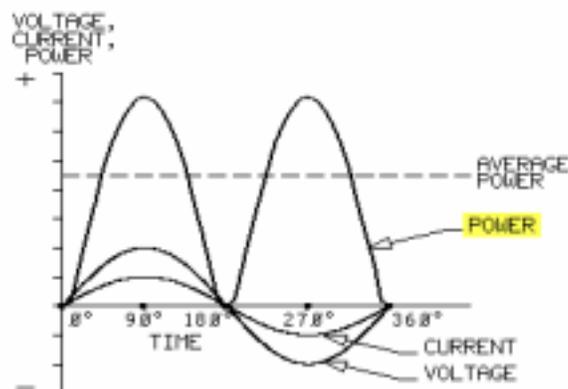
Three basic formulas are used to compute real power in a resistance.

$$P = I \times E \quad P = I^2 \times R \quad P = E^2/R$$

In these formulas, P is power in watts, I is the current through the resistance in amperes, E is the voltage across the resistance in volts, and R is the resistance in ohms.

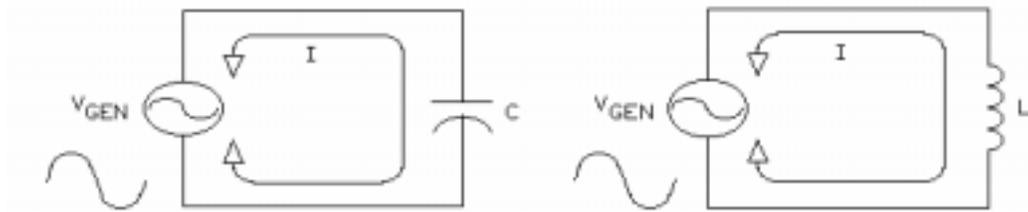


In this circuit, the sine wave of voltage (V_{GEN}) produces a sine wave of current (I) through the resistor (R).

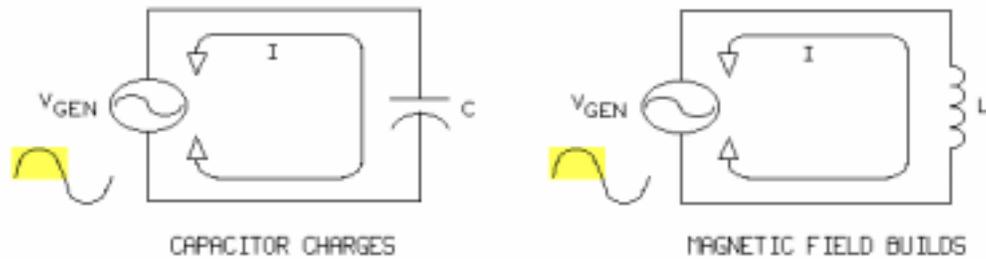


Multiplying the instantaneous current value by the corresponding voltage produces the power curve shown. The average power is indicated by the horizontal dashed line. When calculating the average power, use the rms values of current and voltage.

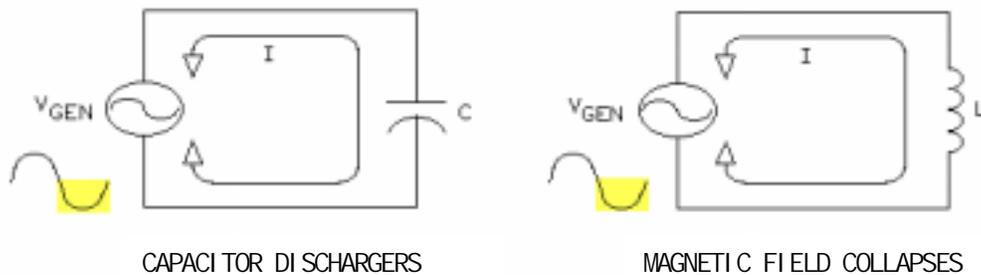
$$P = I \times E \quad P = I^2 \times R \quad P = E^2/R$$



An ideal capacitor or inductor does not convert energy to heat. The reactive component stores the energy delivered to it from the generator (V_{GEN}), then returns that energy to the circuit.



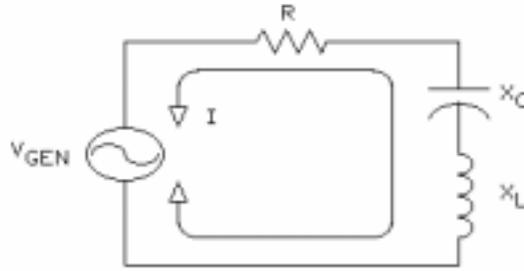
For one half-cycle of the generator's (V_{GEN}) sine wave, the reactive component draws energy from the generator.



During the other half-cycle, the reactive component returns power to the generator. The power consumption of the reactive component exactly equals the amount of power returned to the circuit.

Power not converted into another form of energy, such as heat, is called reactive power (Q).

Reactive power is the product of the voltage across and the current through a reactive component. The unit for reactive power is the voltampere reactive (var). NOTE: The unit for real power is the watt (W).



In circuits containing resistance and reactance (X_L or X_C), the generator must supply both the real power (P) and the reactive power (Q).

To determine this generator power, called the **apparent power (S)**, multiply the generator voltage (V_{GEN}) by the circuit current (I). $S = V_{GEN} \times I$

Only a percentage of the generator's apparent power (S) is converted to real power (P) and is dissipated in the circuit resistance as heat.

The generator also supplies reactive power (Q) to the reactive components, which alternately consume and supply power (Q).

The ratio of real power (P) to apparent power (S) is the **power factor (PF)**.

$$PF = P/S$$

The power factor (PF) is a measure of the real power (P) actually delivered to the circuit from the generator.

NEW TERMS AND WORDS

real power (P) - power that is converted from one form of energy to another; the power dissipated in a resistor as heat; the product of the applied voltage and circuit current in a resistance, expressed in watts; also called true power.

reactive power (Q) - power not converted into another form of energy; the product of the voltage across and the current through a reactive component such as an inductor or a capacitor. The unit of measure for reactive power is the voltampere reactive (var).

apparent power (S) - the product of an rms voltage across and an rms current through an impedance (Z). The unit of measure for apparent power is the voltampere (VA).

power factor (PF) - the ratio of the true power to the apparent power in a circuit; the cosine of the phase angle between circuit current and applied voltage.

Exercise 1 – Power Division

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine ac power division among the components of an RLC circuit by using standard power formulas. You will verify your results with an oscilloscope.

DISCUSSION

- Real power (P_T) is drawn by resistive components and dissipated as heat.
- Reactive components draw apparent power (S) from the generator during one half-cycle and supply reactive power (Q) during the second-half cycle.
- Apparent power (S) is calculated using this equation: $S = V_{GEN} \times I$
where V_{GEN} is the generator voltage (V_{rms})
 I is the circuit current (I_{rms})
- Since the reactive components introduce a phase shift, apparent power will be greater than the real power.
- Total reactive power (Q_T) is the sum of the inductive component power minus the sum of the capacitive component power.

Exercise 2 – Power Factor

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the power factor of ac circuits by using standard electronic formulas. You will verify your results with an oscilloscope.

DISCUSSION

- A power triangle can be used to represent real power (P), reactive power (Q), and apparent power (S).
- Real power is drawn on the horizontal axis and represents the total real power in units of watts.
- Reactive power is represented on the vertical axis in units of vars.
- Apparent power is the resultant, or hypotenuse, of the triangle in units of VA.
- Power factor (PF) is a ratio of the circuit's real power to the apparent power.
- The cosine of the angle (θ) equals the ratio of real power to apparent power and represents the phase angle between the voltage and current of an ac circuit.
- Apparent power multiplied by the power factor ($\cos \theta$) equals the real power of the ac circuit.
$$P = \cos \theta \times S$$
- Power factor defines what portion of the apparent power is real power.

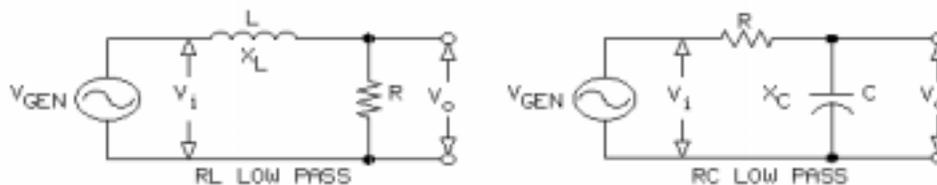
UNIT 5 – LOW- AND HIGH-PASS FILTERS

UNIT OBJECTIVE

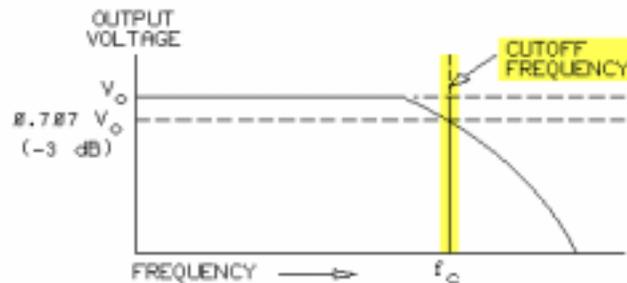
At the completion of this unit, you will be able to determine the cutoff frequencies and attenuations of RC and RL low- and high-pass filters by using test circuits.

UNIT FUNDAMENTALS

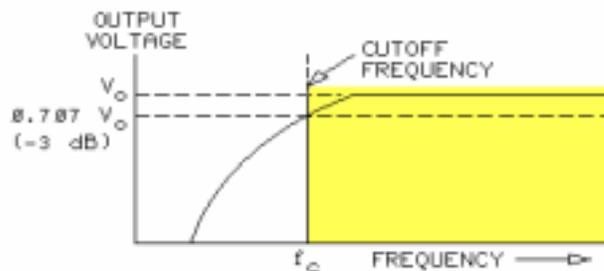
A filter is a frequency-selective circuit that permits signals of certain frequencies to pass while it rejects signals at other frequencies.



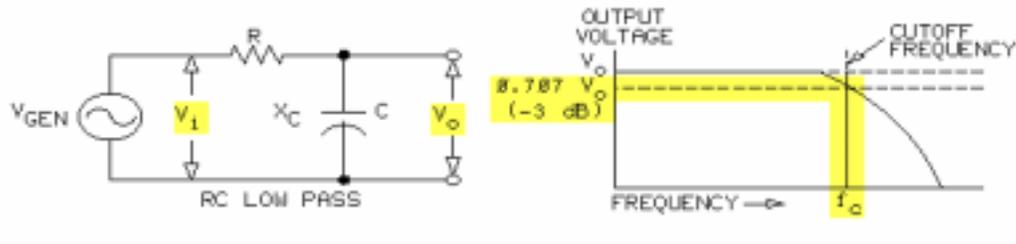
A low-pass filter, as its name implies, passes low frequencies but rejects high frequencies.



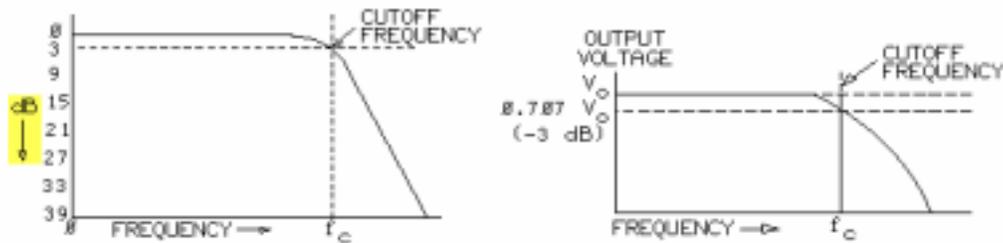
The dividing line between the passing of low frequencies and the rejecting of high frequencies is the cutoff frequency (f_c), or -3 dB point. In a low-pass filter, signals lower than the cutoff frequency pass essentially unmodified. Frequencies higher than the cutoff frequency are greatly attenuated, or reduced.



In a high-pass filter, signals higher than the cutoff frequency pass essentially unmodified. Signals lower than the cutoff frequency are greatly attenuated, or reduced.



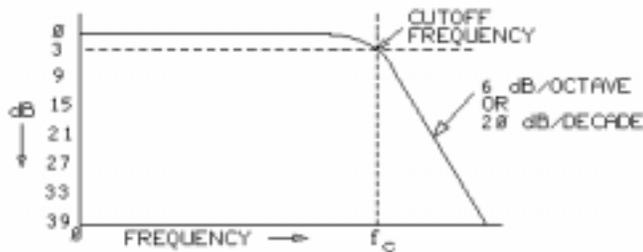
The cutoff frequency (f_c) is the point where the output voltage (V_o) drops to 70.7% of, or 3 dB down from, the input voltage.



Frequency response data may be expressed in terms of output voltage but is usually expressed in decibels (dB). Decibels are units that express or measure the gain or loss (attenuation) in a circuit. The decibel can be based on the ratio of the output voltage (V_o) to the input voltage (V_i).

$$\text{Attenuation (dB)} = 20 \log_{10} \frac{V_o}{V_i}$$

NOTE: In the type of filters studied in this volume, the output voltage (V_o) is always less than the input voltage (V_i).



The rate of attenuation, or loss, beyond the cutoff frequency (f_c) is highly predictable. This attenuation is **6 dB per octave** or **20 dB per decade**. An attenuation rate of 6 dB per **octave** is the same rate as 20 dB per **decade**.

Exercise 1 – Low-Pass Filters

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to calculate the cutoff frequencies and attenuations of RC and RL low-pass filters. You will verify your results with an oscilloscope.

DISCUSSION

- Several ways exist for the implementation of low-pass filters, each of which consist of a voltage-divider network containing a resistor and a frequency-varying component (inductor or capacitor).
- Output voltage from the filters is “tapped off” the voltage divider.
- Changes in the frequency of the supply voltage cause changes in the circuit reactance, resulting in output voltage variations.
- In RC filters, the capacitive reactance is high at low frequencies compared to the resistance, causing most of the input voltage to appear across the output capacitor.
- Capacitive reactance decreases as the generator frequency increases, causing larger voltage drops across the R and decreasing the voltage across the output capacitor.
- Low-pass filters are designed so that frequencies below the cut-off frequency are passed while higher frequencies are attenuated.
- In low-pass RL filters, the inductive reactance is small at low frequencies compared to the resistance, and most of the input voltage falls across the output resistor.
- Inductive reactance increases as the generator frequency increases; therefore, more and more voltage is dropped across the inductor and less across the output resistor.
- Cutoff frequency is defined as the frequency where the output signal is 3 dB down, or $0.707 \times V_o$.
- For RC circuits: $f_c = 1/2\pi RC$
- For RL circuits: $f_c = R/2\pi L$

Exercise 2 – High-Pass Filters

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to calculate and measure the cutoff frequencies and observe the attenuation rates of RC and RL high-pass filters. You will verify your results with an oscilloscope.

DISCUSSION

- Several ways exist for the implementation of high-pass filters, each of which consist of a voltage divider network containing a resistor and a frequency-varying component (inductor or capacitor).
- Output voltage from the filters is tapped off the voltage divider formed by the series resistor and reactive component.
- Changes in the frequency of the supply voltage cause changes in the circuit reactance, resulting in output voltage variations.
- In high-pass RC filters, the capacitive reactance is low at frequencies above cutoff compared to the resistance, causing most of the input voltage to appear across the output resistor.
- Capacitive reactance increases as the generator frequency decreases causing larger voltage drops across the C and decreasing the voltage across the output resistor.
- In high-pass RL filters, the inductive reactance is large at high frequencies compared to the resistance, and most of the input voltage falls across the output inductor.
- Inductive reactance decreases as the generator frequency decreases; therefore, more and more voltage is dropped across the resistor and less across the output inductor.
- Cutoff frequency is defined as the frequency where the output signal is 3 dB down, or $0.707 \times V_o$.
- For RC circuits: $f_c = 1/2\pi RC$
- For RL circuits: $f_c = R/2\pi L$

UNIT 6 – BANDPASS AND BANDSTOP FILTERS

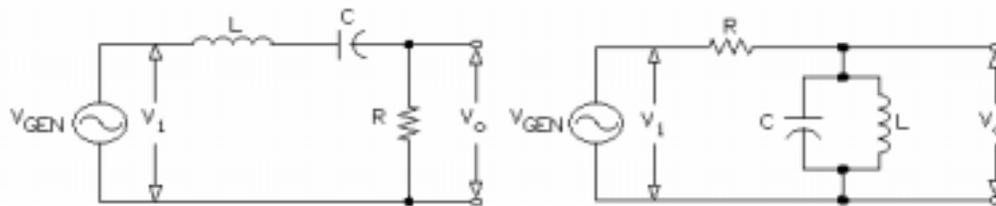
UNIT OBJECTIVE

At the completion of this unit, you will be able to analyze the operation of bandpass and bandstop filters by using standard electronics formulas.

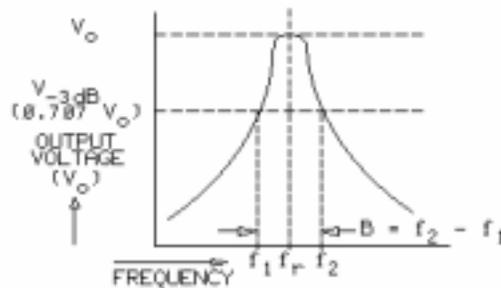
UNIT FUNDAMENTALS

Various combinations of inductors, capacitors, and resistors can be used to produce low-pass, high-pass, bandstop, and bandpass filters.

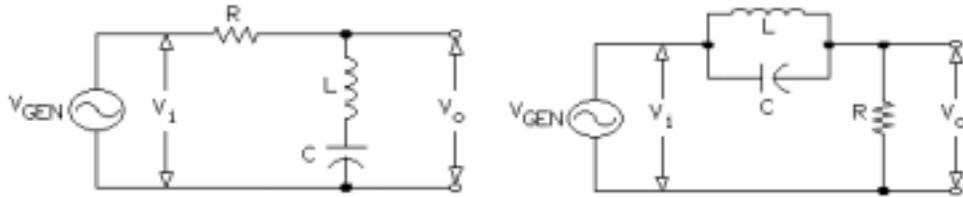
Bandpass filters and **bandstop filters** select a specific range of frequencies. The types of bandpass and bandstop filters studied in this unit use resonant circuits.



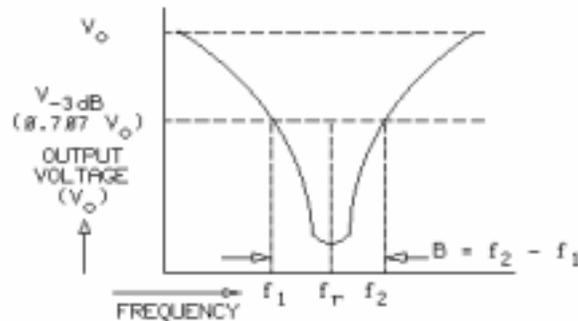
Bandpass filters can be implemented by connecting a series or parallel resonant circuit with a resistor. This combination forms a voltage divider across the generator (V_{GEN}).



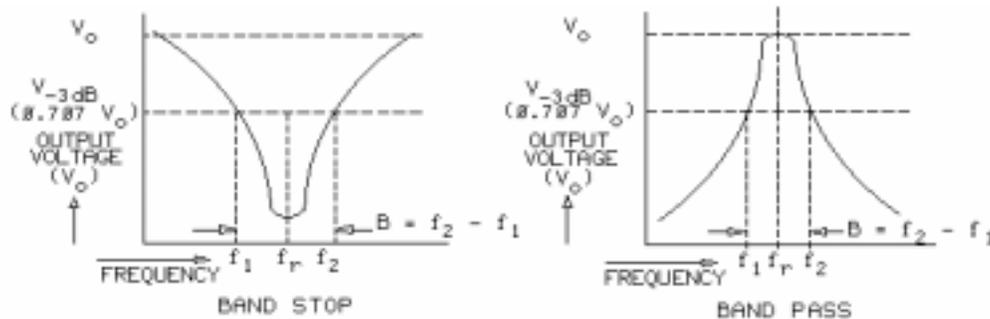
A bandpass filter allows a narrow band of frequencies to pass but rejects frequencies above and below that band. The range of frequencies passed by a band pass filter is the bandwidth (B), which depends on the upper (f_2) and lower (f_1) cutoff frequencies.



Like bandpass filters, bandstop filters can be implemented by connecting a series or parallel resonant circuit with a resistor.



A bandstop filter, or band reject filter, rejects a narrow range of frequencies but passes frequencies above and below that range. The range of frequencies rejected by a bandstop filter is the bandwidth (B), which depends on the upper (f_2) and lower (f_1) cutoff frequencies.



Resonant bandpass and bandstop filters select a specific range of frequencies.

NEW TERMS AND WORDS

bandpass filters - a circuit that passes frequencies over a narrow range, or band, of frequencies and rejects those above and below this range.

bandstop filters - a circuit that rejects frequencies within a narrow band and passes those above or below this band; also called a band reject filter.

center frequency - resonant frequency.

Exercise 1 – BandPass Filters

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to calculate and measure the center frequency and bandwidth of series and parallel bandpass filters. You will verify your results with an oscilloscope.

DISCUSSION

- The bandpass filter consists of a series LC resonant network wired in series with an output resistor. Input voltage is applied across this voltage divider configuration.
- Inductive and capacitive reactance cancel one another at the resonant frequency resulting in a circuit with resistive characteristics. Under these conditions circuit current is maximum.
- At resonant frequency the output voltage is maximum. This point on the response curve is called the bandpass filter center frequency.
- Center frequency of bandpass filters, series or parallel, is computed using this equation:
$$f_c = 1/[2\pi(\text{sqrt}(LC))]$$
- The series RLC band pass filter has capacitive characteristics below resonance (V_o decreases) and inductive characteristics above resonance (V_o increases).
- Bandwidth of a bandpass filter is the range of frequencies the filter will pass, and depends on the upper and lower cutoff frequencies.
- Parallel LC networks connected to a series resistor create another bandpass filter configuration. Input voltage is applied across this voltage divider and the output voltage is taken across the parallel LC tank circuit.
- At resonance, the parallel tank network has a high impedance and the output voltage is maximum.
- The parallel bandpass filter acts inductively (V_o decreases) at frequencies below resonance and capacitively (V_o increases) at frequencies above resonance.

Exercise 2 – BandStop Filters

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to calculate and measure the center frequency and bandwidth of series and parallel bandstop filters. You will verify your results with an oscilloscope.

DISCUSSION

- The band stop filter consists of a series LC resonant network wired in series with a resistor. Input voltage is applied across this voltage divider configuration and the output is taken across the series LC circuit.
- At resonant frequency, the output voltage is minimal since the impedance of the LC circuit is small. This point on the response curve is the center frequency.
- Center frequency of bandstop filters, series or parallel, is computed using this equation:
$$f_c = 1/[2\pi(\text{sqrt}(LC))]$$
- The series RLC bandstop filter has capacitive characteristics below resonance (V_o increases) and inductive characteristics above resonance (V_o increases).
- Bandwidth of a bandstop filter is the range of frequencies which the filter will attenuate, and depends on the upper and lower cutoff frequencies.
- Parallel LC networks connected to a series resistor create another bandstop filter configuration. Input voltage is applied across this voltage divider and the output voltage is taken across the resistor.
- At resonance, the parallel tank network has a high reactance and the output voltage is minimal.
- The parallel bandstop filter acts inductively (V_o increases) at frequencies below resonance and capacitively (V_o increases) at frequencies above resonance.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

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4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Magnetism and Electromagnetism

FACET®



Student Workbook

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Edition 2



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SECOND EDITION

Third Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

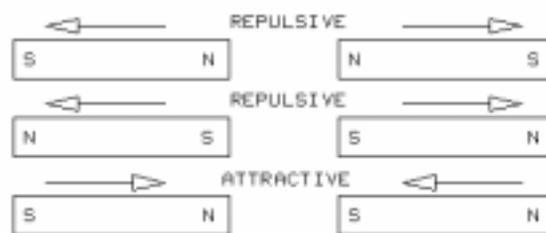
UNIT 1 – MAGNETISM

UNIT OBJECTIVE

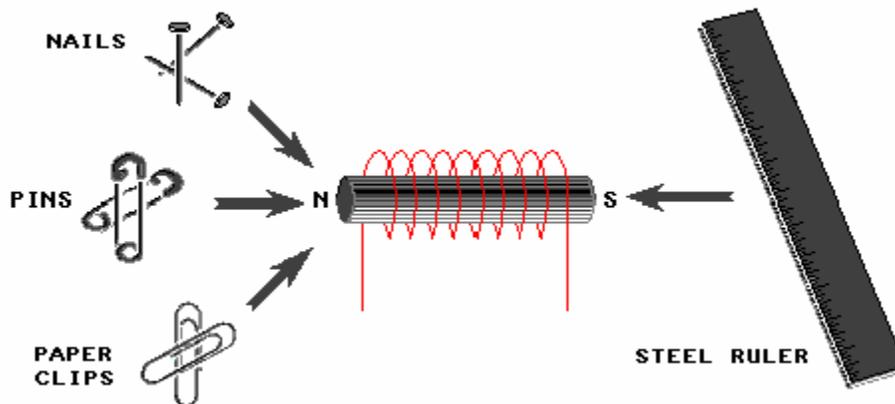
At the completion of this unit, you will be able to describe and demonstrate the effects of magnetism by using magnets and a compass.

UNIT FUNDAMENTALS

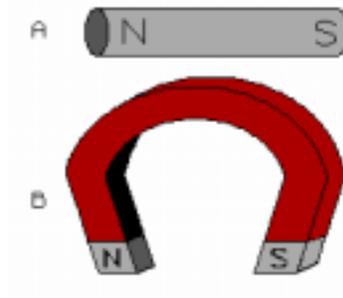
Magnetism is a phenomenon that occurs naturally in some metallic materials. It can also be produced by electrical currents (electromagnetism). In this unit, you will learn about natural magnets.



Magnets exert a force on other magnets. This force may cause the magnets to attract each other (**attractive force**) or to repel each other (**repulsive force**).

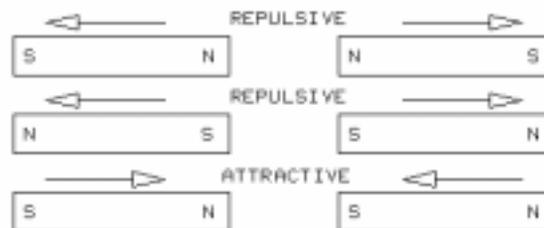


Magnets also exert a force on other magnetic materials that are not magnets themselves. These materials will be discussed later.



Two of the most familiar types of magnets are the bar magnet (A) and the horseshoe magnet (B). Their names reflect their physical shape.

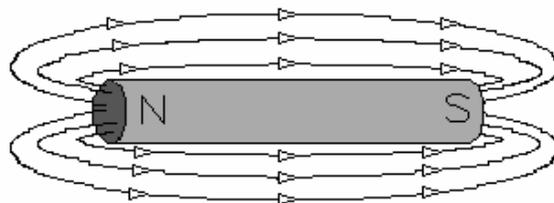
A magnet's **pole** is the area where its magnetic force is strongest. Magnets of virtually any shape have a north (N) pole at one end and a south (S) pole at the other. The type of pole determines whether the magnet will attract or repel a particular pole of another magnet.



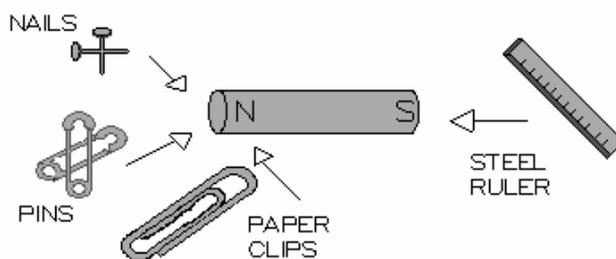
These arrows represent the direction of the attractive or repulsive magnetic forces. If a pole of one magnet is moved toward the similar pole of a second magnet (north to north or south to south), the magnets repel, or push away from, each other. If a pole of one magnet is moved toward the opposite pole of a second magnet (north to south), the magnets attract, or pull toward, each other. This relationship can be stated simply: opposite poles attract and like poles repel.



Breaking a magnet in half results in two smaller, weaker magnets, each with its own north and south pole. It does not result in one magnet having just a north pole and the other having just a south pole.



The direction of a bar magnet's force is shown here by **lines of force** which originate from the north pole and travel to the south pole. The lines of force closest to the magnet represent the strongest magnetic force. The force becomes progressively weaker for the lines of force further away from the magnet. You can't see a magnet's lines of force, but you can see their effects.



A magnet also exerts a force on objects that are not magnets themselves but that are made of iron or have an iron content. The force is attractive only, and it is exerted by both the north and south poles of the magnet. Magnets are used in many electric and electronic devices, including telephones, televisions, radar, audio speakers, alarms, and motors. Magnets come in all sizes. Some are small enough to hold in your hand, and others, such as the large electromagnets found in junkyards, are powerful enough to lift several tons of scrap metal.

NEW TERMS AND WORDS

magnets - objects having a magnetic field that attracts or repels magnetic materials.

attractive force - a force that tends to pull 2 objects toward each other. A magnet's pole attracts magnetic objects or the opposite pole of another nearby magnet.

repulsive force - a force that tends to push 2 objects away from each other. A magnet's pole repels the similar pole of another nearby magnet.

pole - the area on a magnet where magnetic force is strongest. Every magnet has 1 north pole and 1 south pole.

lines of force - invisible lines that represent the strength and density of a magnetic materials.

magnetic field - an area where magnetic force is present.

permanent magnets - pieces of hardened steel or other magnetic material which has been so strongly magnetized that they retain the magnetism indefinitely.

temporary magnet - a magnet whose field quickly loses its magnetic power.

Exercise 1 – The Compass

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to explain and demonstrate the function of a compass by using a bar magnet. You will verify your results with a compass.

DISCUSSION

- One of the most familiar applications of a magnet is the compass.
- A compass needle is actually a small magnet that is loosely suspended at its center so there is as little friction as possible to impede movement.
- Earth itself is actually a large magnet.
- The north pole of the compass needle, when not affected by other nearby magnetic forces, always points to Earth's geographic north pole.
- The south pole of Earth's magnet is commonly called **magnetic north** because it attracts a compass needle's north pole.
- Similarly, the north pole of Earth's magnet is commonly called **magnetic south**.
- Because of the compass's magnetic relationship to Earth's poles, it has been used for centuries as a navigational device.
- When a bar magnet is suspended loosely from a string or rubber band, it simulates the action of a compass needle.
- A loosely suspended bar magnet moves so that its north pole points to magnetic north and its south pole points to magnetic south.

Exercise 2 – Magnetic Fields

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to identify the invisible field around a magnet by using iron filings. You will verify your results by observing patterns formed by the filings.

DISCUSSION

- A magnet has lines of force that originate at its north pole and flow to its south pole.
- The lines of force surrounding a magnet make up its **magnetic field**.
- The lines near the magnet's poles have the highest density (are closest together), so the magnetic force is strongest here.
- Midway between the poles, the lines are farthest apart, so the magnetic force here is weakest.
- The lines of force for a horseshoe magnet are strongest where the poles are closest to each other.
- Weaker lines of force radiate outward between the poles.
- Additional weaker lines travel completely around the outside of the magnet's shape.
- A common way to demonstrate the configuration of a magnetic field is with iron filings.
- In the presence of a magnet, iron filings align themselves with the magnet's field.

Exercise 3 – Making a Magnet

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to make a magnet by using parts included with the MAGNETISM/ELECTROMAGNETISM circuit board. You will verify your results with an ordinary paper clip.

DISCUSSION

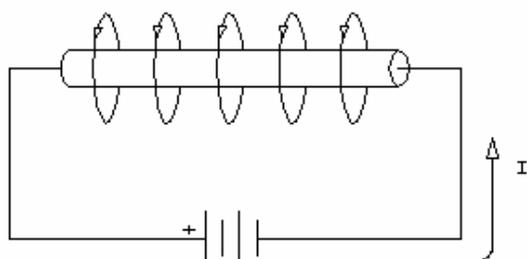
- The types of magnets discussed in the previous exercises, such as bar magnets and horseshoe magnets, are **permanent magnets** because they are always surrounded by their own magnetic field.
- A **temporary magnet** is an object that becomes a magnet only when placed in a magnetic field.
- A temporary magnet retains its own magnetic field for a short period of time, then loses it.
- You can make a temporary magnet from an object made of iron or one that has an iron content, such as an iron nail.
- The north pole of the bar magnet creates a south pole at the adjacent end of the nail.
- The south pole of the bar magnet creates a north pole at the opposite end of the nail.
- A nail magnetized in this way retains a weaker magnetic field of its own even after the permanent magnet is removed.
- The nail loses its magnetic field if it is subjected to a sharp blow or dropped on a hard surface.

UNIT 2 – ELECTROMAGNETISM

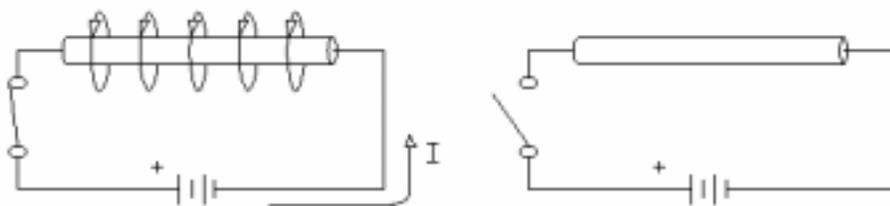
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe and demonstrate electromagnetism by using electromagnetic devices. You will verify your results with a solenoid and a relay.

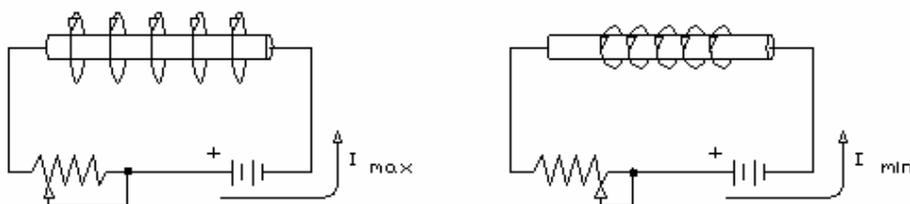
UNIT FUNDAMENTALS



Electromagnetism is a form of magnetism created when current flows through a conductor. When current is present, it generates a magnetic field around the conductor similar to that of a permanent magnet. When current is removed, the magnetic field disappears.



One way an electromagnet differs from a permanent magnet is that you can switch an electromagnet's field on and off by simply switching current on and off.



You can also vary the strength of an electromagnet's field by increasing or decreasing the applied current.

Electromagnets are used extensively for recording media such as magnetic tapes and disks. They are also used in the automotive, communications, scientific, and many other industries. Familiar examples of electromagnets are relays, solenoids, alarm bells, car alternators, and electric motors.

NEW TERMS AND WORDS

Electromagnetism - the magnetic field around a wire or other conductor when current passes through it.

left-hand rule - when the left hand is placed around a current-carrying conductor so that the thumb points in the direction of current (electron) flow, the other fingers will point in the direction of the magnetic field; when the fingers of the left hand are placed around an electromagnet in the direction of current (electron) flow, the thumb will point to the north magnetic pole.

field intensity - the strength of a magnetic field.

solenoid - an electromagnet with a sliding core.

plunger - the sliding core of a solenoid.

stroke - the range of motion of a solenoid's sliding core.

relay - an electromechanical device with contacts that are opened and closed by an electromagnet.

armature - a relay's moving element, which is attracted by an electromagnet.

hysteresis - the difference between a device's response to an increasing signal and a decreasing signal.

isolation - the separation between a device's response to an increasing signal and a decreasing signal.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

MAGNETISM/ELECTROMAGNETISM circuit board

Exercise 1 – The Electromagnet

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to explain the operation of an electromagnet by using a coil of wire. You will verify your results with a compass and an iron nail.

DISCUSSION

- An electromagnet is an electrical conductor that generates a magnetic field around itself when current passes through it.
- To determine the direction of the field lines, you can use a convention known as the **left-hand rule**.
- When you grasp the conductor with your left hand so that your thumb points in the direction of current (electron) flow, the magnetic field flows in the direction that your other fingers curl around the conductor.
- A conductor formed into a loop has a more concentrated magnetic field at the center of the loop.
- The field can be concentrated further by winding the conductor into a coil and inserting an iron core in the center.
- The strength, or intensity, of the magnetic field is proportional to the applied current and the number of turns of the coil. It is also inversely proportional to the length of the coil.
- Just like the permanent magnet, the electromagnet has a north and a south pole, and it attracts only objects made of iron or that have an iron content.
- You can use the left-hand rule to determine the poles of an electromagnet.
- When you grasp the coil with your left hand so that your fingers curl in the direction of current (electron) flow, your thumb points to the electromagnet's north pole.
- You can reverse the north and south poles by reversing either the direction of current flow or the direction in which the wire is wound around the coil.

Exercise 2 – The Solenoid

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to describe and demonstrate the operation of a solenoid by using an electromagnet. You will verify your results by visual observations.

DISCUSSION

- An iron core partially inserted into an electromagnet's coil is pulled into the coil when you apply current.
- This device, called a solenoid, can be very useful in electromechanical systems because it translates electrical power into a mechanical motion.
- In practice, an iron core slightly smaller than the coil's inside diameter is used in a solenoid. This allows the core to slide freely back and forth in a straight line.
- The moving core of a solenoid is also called a **plunger**.
- In many cases, a return spring is attached between the movable plunger and a fixed point.
- The plunger travels back and forth between two distinct points.
- The plunger's range of motion is called its **stroke**.
- Practical solenoids have strokes ranging from a fraction of an inch up to 3 inches.
- This two-position linear motion is useful in many practical applications such as operating a valve, opening and closing one or more electrical circuits, engaging gears, and operating clutches and brakes.
- Solenoids are designed in a variety of sizes, configurations, and strokes. They are available for a wide range of ac and dc voltages.

Exercise 3 – The Relay

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the operations of a relay by using several relay circuits. You will verify your results with visual observations.

DISCUSSION

- A **relay** is a type of switch operated by an electromagnet.
- The relay's electromagnet has a stationary core.
- The **armature** is a moving element that is attracted to the core when the coil is energized.
- When the coil is de-energized, the magnetic field disappears, and a spring returns the armature to its original position.
- When the armature moves up and down, it operates a set of switch contacts.
- The common contact is mounted to the armature. It alternately connects to the normally open (NO) and normally closed (NC) contacts.
- You can configure relays to have many other multiple-pole switches by stacking additional contacts on the armature.
- Like the solenoid, the relay translates electrical power into mechanical motion.
- Since the relay coil is an inductor, it is often represented schematic-ally by the inductor symbol.
- Another way to represent the coil is by a rectangle with two leads for the coil connections.
- The schematic symbol for relay contacts is similar to that of standard switch contacts.
- A dashed line indicates a mechanical connection (the spring-loaded armature) between the coil and the contacts.
- A relay coil has a nominal voltage rating (V_N) for ideal operation; however, the relay also operates at voltages below the nominal rating.
- If you start from 0V and increase voltage, you will reach the point at which the armature pulls in. This is the pull-in voltage (V_P).
- If you start from V_N and decrease voltage, you will reach a point at where armature is released. This is the dropout voltage (V_D).
- Pull-in (V_P) and dropout (V_D) occur at different voltages. The window between the pull-in and dropout is called **hysteresis**.
- If switching occurred at the same point for increasing and decreasing voltage (without hysteresis), the relay would chatter, which means it would turn on and off with every small change in voltage.
- An important feature of relays is the isolation between the input and output circuits. This means that no electrical connection exists between the coil and the switch contacts.

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2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Semiconductor Fundamentals

FACET[®]



Student Workbook

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Edition 4



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FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

UNIT 1 – INTRODUCTION TO SEMICONDUCTORS

UNIT OBJECTIVE

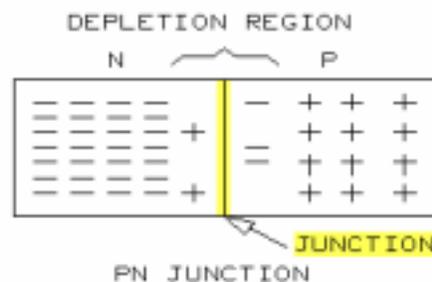
At the completion of this unit, you will be able to describe a semi-conductor, identify semiconductor devices, and demonstrate their operation by using circuits on the SEMICONDUCTOR DEVICES circuit board.

UNIT FUNDAMENTALS

Diodes, transistors, integrated circuits, and other so-called "solid state" devices are made from crystals of a **semiconductor** material, usually silicon or germanium. At room temperature, the crystals of pure silicon and germanium are neither good insulators nor good conductors. This is why they are called semiconductors.



Introducing an impurity into a semiconductor crystal through **doping** reduces the electrical resistance. Semiconductor material doped with impurities containing excess electrons is called **N type material** (negative). If the impurity has too few **valence ring** electrons, the doped semiconductor is called **P type material** (positive). **Free electrons** are the **majority carriers** in N type material, and positive charges, called **holes** are the majority carriers in P type material.



Doping adjacent areas of a semiconductor crystal with N type and P type impurities, respectively, forms a **PN junction**. In a region close to the junction, a few electrons migrate to the P material and a few positive charges migrate to the N material. Because these migrated charges tend to neutralize each other, an arrow depletion region is created.

The SEMICONDUCTOR DEVICES circuit board has eight circuit blocks. Each circuit block consists of an arrangement of diodes and/or transistors that gives you an understanding of how a semiconductor functions in a practical application. This unit introduces you to semiconductors and the functional circuit blocks on the SEMICONDUCTOR DEVICES circuit board. Subsequent units are dedicated to each of the eight circuit blocks and to troubleshooting semiconductor circuits.

NEW TERMS AND WORDS

diodes - semiconductor devices consisting of P type material and N type material.

transistors - devices consisting of NPN or PNP semiconductor layers. Transistors allow a small current to control the flow of a larger current.

semiconductor - a material, usually silicon or germanium, doped with impurities to create a compound whose electrical resistance is greater than that of conductors but less than that offered by insulators.

doping - the deliberate introduction of a specific type of impurity into very pure base material. Doping is accomplished by many different processes, but it is always carefully controlled to produce semiconductors with specific properties.

N type material - pure semiconductor material which has been doped with an impurity that introduces free electrons into the semiconductor. The atoms of the doping material, sometimes referred to as donor material, usually have a valence ring that contains one electron more than those required to complete covalent bonds with base material atoms.

valence ring - the outermost electrons surrounding the nucleus of any atom. These electrons interact with the valence electrons of neighboring electrons and are the main influences on the electrical characteristics of the element.

P type material - pure semiconductor material which has been doped with an impurity that introduces apparent positive charges (holes) into the semiconductor. The atoms of the doping material, sometimes called acceptor material, usually have a valence ring that lacks one electron from those necessary to complete covalent bonds with base material atoms.

free electrons - "extra" valence ring electrons that are not incorporated into covalent bonds. These electrons result from doping pure base material with an N type impurity. They act as current carriers in N type semiconductor material.

majority carriers - charges deliberately introduced into semiconductors to act as current carriers. Electrons are the majority carriers in N type material; holes are considered to be the majority carriers in P type material.

holes - positive charges in semiconductors resulting from incomplete covalent bonds. Holes occur when pure base material is doped with a P type impurity.

anode - the diode region doped with P (positive) type material.

cathode - the diode region doped with N (negative) material.

zener - a diode designed to maintain a relatively constant voltage drop over a range of current flows. Zeners are supplied in the same packages as "ordinary" diodes, but they operate in a different way.

light-emitting diodes - (LED) a diode constructed to release energy in the form of light when supplied with an electric current. The materials used in the construction of an LED determine the color and brightness of the light.

Exercise 1 – Semiconductor Component Identification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to identify various semiconductor devices. You will verify your knowledge by locating diodes and transistors on the SEMICONDUCTOR DEVICES circuit board.

DISCUSSION

- Diodes and transistors are the two classes of semiconductors covered in this exercise.
- Diodes are generally constructed of germanium or silicon and consist of only one PN junction.
- Diodes are constructed with an anode (positive, P-type material) and a cathode (negative, N-type material).
- Schematic diagrams for common diodes, LEDs, and zener diodes are illustrated in the exercise. Common types of diode packaging are shown, also.
- Diodes are usually identified on schematic diagrams by the letters CR followed by a number. For example: CR12.
- Specialized diodes, designed for specific tasks, include the Zener diode, which can maintain a constant voltage, and the Light Emitting Diode (LED), which emits light under specific circumstances.
- Transistors belong to two major families, Field-Effect Transistors (FET) and Junction Transistors (JT). Only junction transistors, also called bipolar transistors, are discussed in this course.
- Transistors have two PN junctions; therefore, they have three regions. Each region consists of either N-type or P-type material. The three regions can be formed two ways: as P-type material sandwiched between N-type material (NPN) or by N-type material sandwiched between P-type material (PNP).
- Junction transistors have a terminal (lead) connected to each of the three regions. The center region is designated the base. The outer regions are designated emitter and collector, respectively.
- Schematic diagrams for PNP and NPN type junction transistors are illustrated in the exercise. Transistors are usually identified by the letter Q, followed by a number, on circuit diagrams. For example: Q2.

Exercise 2 – Circuit Location and Identification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the functional circuit blocks on the SEMICONDUCTOR DEVICES circuit board. You will verify your circuit knowledge by identifying the circuit blocks and operating a transistor circuit.

DISCUSSION

- The following eight circuit blocks are present on the SEMICONDUCTOR DEVICES circuit board.
 1. DIODES AND 1/2 WAVE RECTIFICATION circuit block
 2. FULL-WAVE RECTIFICATION WITH POWER SUPPLY FILTERS circuit block
 3. ZENER DIODE REGULATOR circuit block
 4. DIODE WAVESHAPING circuit block
 5. VOLTAGE DOUBLER circuit block
 6. TRANSISTOR JUNCTION circuit block
 7. PNP DC BIAS circuit block
 8. TRANSISTOR LOAD LINES AND GAIN circuit block

- The first five circuit blocks contain diode circuits only. Each block demonstrates the following diode functions.
 - Block 1. diode polarity, voltage drop required for a diode to conduct, and how a diode circuit functions as a half-wave rectifier.
 - Block 2. full-wave bridge rectification with and without filtering
 - Block 3. voltage drop characteristics of a zener diode
 - Block 4. clipping and clamping circuits
 - Block 5. ac to dc rectification resulting in an output voltage which is twice the input voltage (peak voltage)

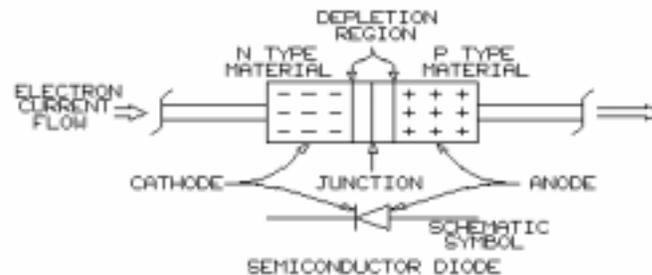
- The last three blocks demonstrate the following:
 - Block 6. forward and reverse biasing of transistors, as well as a comparison of diode and transistor junctions
 - Block 7. transistors as switches
 - Block 8. transistor characteristics such as base-emitter voltage, base current, collector current, and dc load lines

UNIT 2 – DIODES AND HALF-WAVE RECTIFICATION

UNIT OBJECTIVE

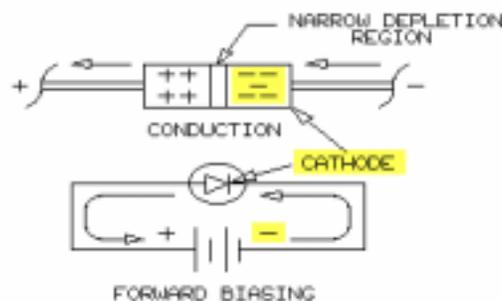
At the completion of this unit, you will be able to demonstrate the principles of semiconductor diode operation and diode half-wave rectification by using diode test circuits.

UNIT FUNDAMENTALS

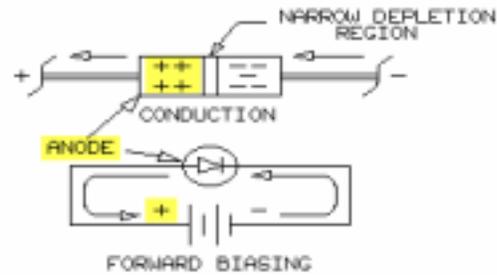


Diodes normally permit electron current flow in only one direction, as illustrated. When N type semiconductor material is joined to P type material, a depletion region is formed near the junction. An additional voltage potential is required to pass current through the depletion region of the diode junction.

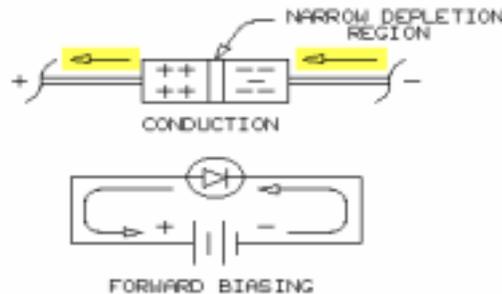
The extra voltage potential required at the depletion region of a diode semiconductor junction is the **barrier voltage**. The barrier voltage for germanium diodes is about 0.3V and for silicon diodes is about 0.6V (0.5V to 0.7V). The barrier voltage is also called the diode **forward voltage drop (VF)**.



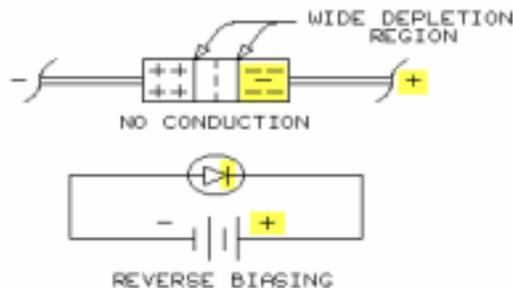
When a negative voltage is applied to the cathode of the diode, electrons in the N type material are forced closer to the junction.



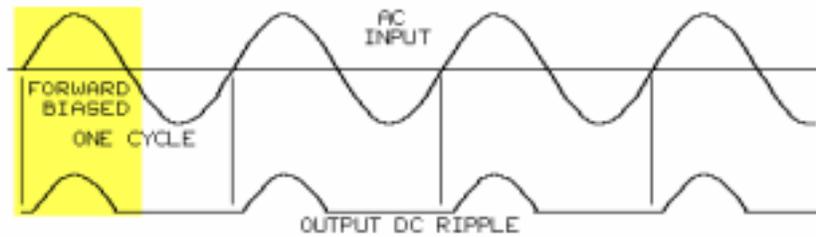
Similarly, the positive charges in the P type material of the anode are attracted toward the junction by the increased negative charge across the barrier.



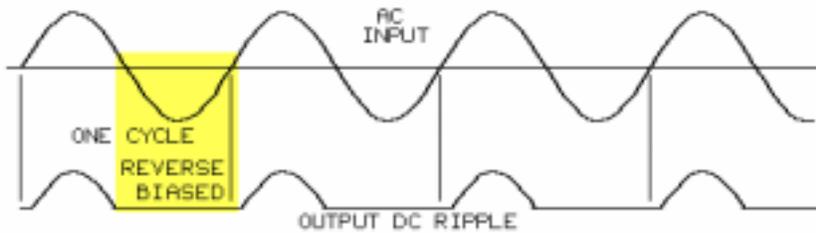
When the applied voltage overcomes the barrier voltage, the depletion region width is reduced, and electrons move across the junction toward the positive terminal of the voltage source. As long as the applied voltage exceeds the barrier voltage, electron flow continues and the diode is fully **forward biased**, or in the on state.



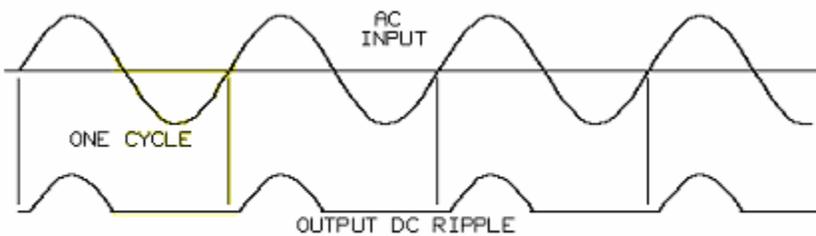
When a positive voltage is applied to the cathode and a negative voltage to the anode, electrons in the N type material are attracted away from the junction toward the voltage source positive terminal. Positive charges in the P type material are also attracted away from the junction toward the negative terminal of the voltage source. These charge movements increase the width of the depletion region, causing the diode to be **reverse biased** (in its off state) with almost no current flow.



If an ac voltage large enough to overcome the barrier voltage is applied to a diode, the diode conducts during alternations when the ac voltage is in the forward biased direction.



The diode cannot conduct during alternations when it is reverse biased.



The resulting output voltage or current is a **pulsating dc** current called **ripple** which flows in one direction or not at all. The process of converting a half-cycle of an ac voltage to a pulsating dc voltage is **half-wave rectification**.

NEW TERMS AND WORDS

barrier voltage - the voltage potential required for current flow through the depletion region of a diode junction. The barrier voltage must be overcome by the forward bias voltage before current can flow in a diode.

forward voltage drop (V_F) - the condition that exists when the cathode of a diode is negative with respect to its anode, and forward current flows.

forward biased - the condition that exists when the cathode of a diode is negative with respect to its anode, and forward current flows.

reverse biased - the condition that exists when the anode of a diode is negative with respect to the cathode.

pulsating dc - the rectifier output pulses of one polarity that corresponds to half-cycles of the rectifier ac input voltage when the diode is forward biased.

ripple - the pulsations appearing in the output voltage of a rectifier circuit.

half-wave rectification - rectification in which output current flows only during half-cycles of the ac input.

characteristic curve - a graphic representation of diode current flow versus diode voltage drop.

leakage current - the very small current that flows through a reverse biased diode.

minority carriers - free electrons in P type material, and holes (positive charges) in N type material. Minority carriers are caused by the presence of tiny quantities of natural impurities in the base semiconductor material. They are responsible for most reverse (leakage) current through a semiconductor.

breakdown voltage - the reverse voltage that causes a diode to conduct heavily and destructively in the "wrong" direction. Diodes should be selected to have a breakdown voltage greater than any normally applied reverse voltage.

dynamic forward resistance (r_F) - the apparent resistance of a conducting diode; calculated from a measured change in diode voltage drop divided by a measured change in current.

rectification - the process of converting an alternating current into a pulsating direct current.

reverse recovery time (t_{RR}) - the time required for a diode to stop conducting after forward bias is removed. Reverse recovery time is due primarily to stored charges.

stored charges - positive and negative charges temporarily existing in a forward biased semiconductor due to current flow. Stored charges reduce the efficiency of common semiconductors at high frequencies because they increase the time required for a junction to switch from the forward to reverse biased state.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

SEMICONDUCTOR DEVICES circuit board

Multimeter

Oscilloscope, dual trace

Generator, sine wave

Exercise 1 – Diode DC Characteristics

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to test a diode in a typical diode circuit by using a diode dc characteristic curve. You will verify your results with a multimeter.

DISCUSSION

- Diode characteristic curves graph the current flow versus applied voltage. The right side of the graph shows the diode operating in the forward bias condition. The left portion of the graph illustrates the reverse bias condition.
- Voltage and current scales on the characteristic curve vary by region, ranging from milliamps to picoamps or millivolts to volts.
- Forward voltages below the barrier voltage will not forward bias the diode. In silicon diodes, conduction begins when the forward voltage reaches between 0.5 and 0.7V. Germanium diodes require a forward voltage of about 0.3V.
- Once forward voltage produces conduction, small increases in voltage produce large current increases. This nearly constant voltage is called the forward voltage drop (V_F).
- Reverse biased diodes will have very small current flows. The current flow is due to the presence of minority carriers and is referred to as leakage current.
- Breakdown voltage is the reverse voltage that causes large current flow through reverse biased diodes. The current can be large enough to damage the diode.
- In general, for calculations, the forward voltage drop of a silicon diode is 0.6V, and 0.3V for a germanium diode.
- Forward resistance is the ratio of the increase in voltage drop divided by the increase in forward current.
- Since forward resistance, or dynamic forward resistance, of a diode is very small, a resistor is included in the circuit to prevent damage to the diode.
- The highest current value that can pass through the diode without causing damage is referred to as maximum forward current ($I_{F(max)}$).
- Ohmmeters cannot accurately measure the resistance of a diode junction therefore, diode junctions are tested by checking for continuity only. A forward biased junction will register a very low resistance indicating continuity. A reverse biased junction, or damaged diode, will indicate a very high resistance or an overload, indicating a lack of continuity.
- Included in this exercise are instructions for testing diodes with the following meters:
 - LAB-VOLT DIGITAL MULTIMETER
 - DIGITAL MULTIMETER WITH A DIODE TEST FUNCTION
 - ANALOG OHMMETER

Exercise 2 – Half-Wave Rectification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate how a diode functions as a half-wave rectifier by using a typical half-wave rectifier circuit. You will verify your results with an oscilloscope and a multimeter.

DISCUSSION

- Half-wave rectification converts an ac output to a pulsating dc output. The circuit consists of a diode and a load resistance.
- Either positive or negative pulsating dc output can be produced, depending on the way the diode is connected to the circuit.
- Rectification is the process of converting ac to dc. Half-wave rectification occurs when conduction is for only one half of every ac cycle.
- Dc output can be significantly lower than the ac input since the forward voltage drop of the diode must be reached before conduction occurs and voltage appears across the load.
- Half-wave rectification will be observed on an oscilloscope. Oscilloscope voltage measurements are peak-to-peak; therefore, the following conversion factor is used to convert the observed voltages to rms or average values.

$$\text{For average voltage} \quad V_{o(\text{avg})} = 0.318 \times V_{o(\text{pk})}$$

$$\text{For rms voltage} \quad V_{o(\text{rms})} = 0.707 \times V_{o(\text{pk})}$$

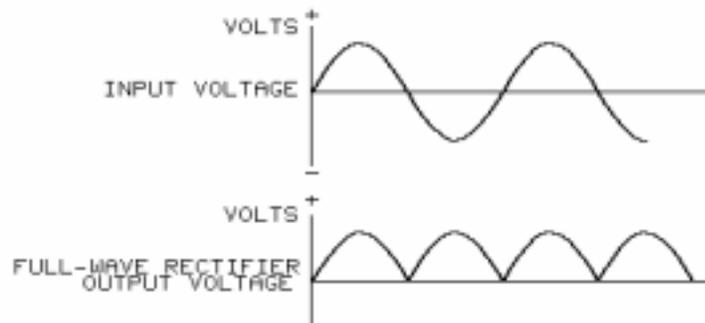
- These conversion factors are for the full half-cycle, so the calculated value will be less than the value measured with a multimeter.
- Variations in the pulsating dc output of a half-wave rectifier are referred to as ripple.
- Half-wave voltage rectifiers have ripple that is the same frequency as the input voltage frequency.
- The reverse recovery time (t_{RR}) of the diode can have an adverse affect on the output of a half-wave rectifier at frequencies larger than 1 kHz. Reverse recovery time causes an output voltage pulse in a direction opposite that of the normal half-wave pulse.

UNIT 3 – FULL-WAVE RECTIFICATION AND FILTERING

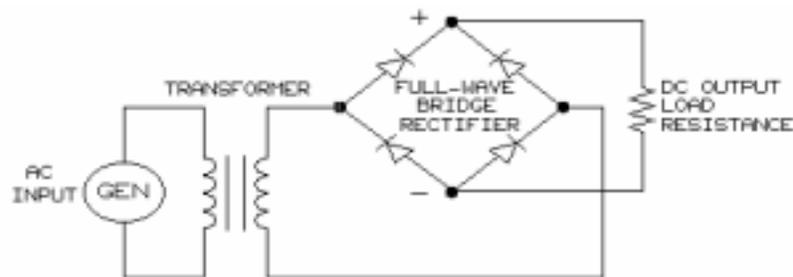
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate full-wave rectification, filtering and voltage doubling by using calculated and measured circuit conditions.

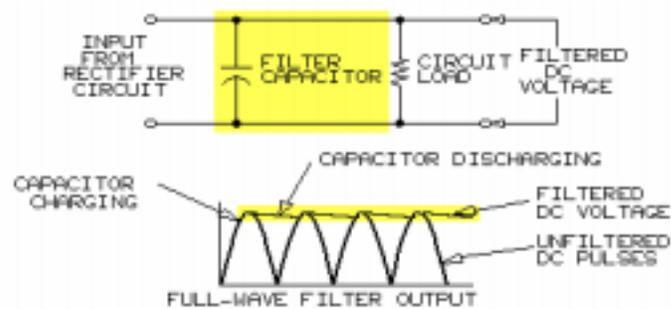
UNIT FUNDAMENTALS



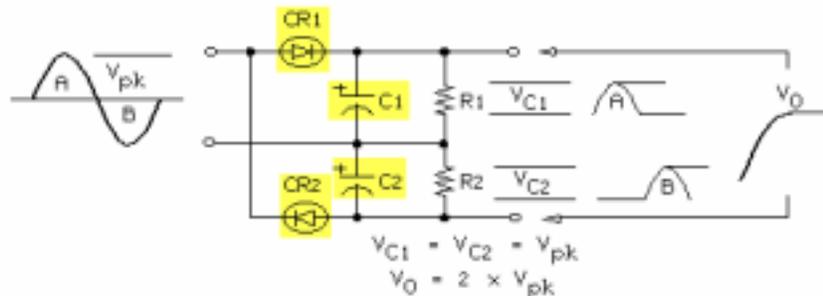
A **full-wave rectifier** converts positive and negative alternations of an ac signal into a pulsating dc signal, as shown above.



A full-wave **bridge rectifier** is a circuit that performs full-wave rectification. The input to the bridge rectifier circuit is usually the secondary coil of a power transformer. The transformer isolates the bridge rectifier from the ac source and serves to step up (increase) or step down (decrease) the ac input to the bridge rectifier.



The large ripple of the dc pulses from a full-wave bridge rectifier are reduced to a relatively smooth dc signal by an **electrolytic capacitor** across the output of the rectifier. The **capacitor filter** charges up quickly and discharges slowly to reduce the rectifier dc output ripple.



A **voltage doubler** composed of two pairs of diodes and capacitors, produces a full-wave rectified, filtered dc output (V_O) equal to two times the ac input peak voltage (V_{pk}). The capacitors are connected in series so that the capacitor charges are added at the output.

NEW TERMS AND WORDS

full-wave rectifier - a diode configuration in which positive and negative alternations of an ac input signal are converted into a pulsating dc output signal.

bridge rectifier - a type of full-wave rectifier circuit.

electrolytic capacitor - a high-capacity capacitor that is polarized and used in power supply filter applications.

capacitor filter - a capacitor used to average the output pulses of a rectifier circuit.

voltage doubler - a circuit designed to rectify, filter, and double the value of a peak ac input voltage.

Exercise 1 – Full-Wave Diode Bridge Rectification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate full-wave rectification by using a full-wave bridge rectifier circuit. You will verify your results with an oscilloscope and a multimeter.

EXERCISE DISCUSSION

- Two types of circuits that utilize diodes for full-wave rectification are illustrated. One employs a center-tapped full-wave rectifier while the second uses a full-wave bridge rectifier. The full-wave bridge circuit is used in this exercise.
- Diode bridges contain four diodes, designated D1 through D4, configured so that two diodes conduct during each half-cycle of the input ac signal and produce a pulsating dc output.
- The pulsating dc output flows through the load resistance in one direction, independent of which ac cycle the current is derived.
- Two input terminals, usually labeled with a sine wave symbol, and two output terminals, labeled with positive and negative symbols, are present on the bridge rectifier.
- Diodes D1 and D3 are forward biased during the positive half-cycle of the ac input signal.
- Diodes D2 and D4 are forward biased during the negative half-cycle of the ac input signal.
- Each diode pair conducts for one half-cycle of the ac input signal, resulting in full-wave rectification.
- Since there are two dc pulses for one complete cycle of the input ac waveform, the output pulse frequency of a full-wave rectifier is twice the ac input frequency.
- The following relationships apply to full-wave diode bridge rectifiers.
Peak output voltage ($V_{o(pk)}$) equals the peak input voltage ($V_{i(pk)}$) minus the forward voltage drop (V_F) of the two conducting diodes.

$$V_{o(pk)} = V_{i(pk)} - 2V_F$$

Output rms voltage ($V_{o(rms)}$) equals 0.707 times the peak output voltage.

$$V_{o(rms)} = 0.707 \times V_{o(pk)}$$

Output average ($V_{o(avg)}$) voltage equals 0.636 times the peak output voltage.

$$V_{o(avg)} = 0.636 \times V_{o(pk)}$$

Exercise 2 – Power Supply Filtering

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate how a filter significantly reduces the ripple of a pulsating dc output to a relatively smooth dc voltage by using a capacitive input filter circuit. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

- Most electronic equipment requires a smooth dc voltage; therefore, filters are required after a rectifier to reduce ripple. Ripple present in the volt range can be reduced to the millivolt range.
- One example is the capacitive input filter which is implemented by placing an electrolytic capacitor across the bridge rectifier output and in parallel with the load resistor.
- Under no-load conditions the capacitor charges rapidly to the peak full-wave rectifier voltage output. Since there is no discharge path, the capacitor remains charged, maintaining the rectifier output when the rectifier input drops to zero.
- With a load present, the capacitor discharges through the load, maintaining a near-constant load voltage. Another output pulse recharges the capacitor before the capacitor can fully discharge.
- Discharge rate of a capacitor is longer than the charge time and depends on the RC (load Resistance times Capacitance) time constant.
- Discharge time, for constant frequencies, will affect the magnitude of the ripple. Increases in the capacitance and/or load resistance reduces ripple. Ripple is also reduced as frequency increases.
- Other types of filters are configured with inductors or combinations of resistors, capacitors, and inductors.
- Additional filter sections remove a portion of the rectifier ripple content.
- The circuit used in this exercise is not a regulated power supply. Parallel load resistance reduces the peak output voltage of the rectifier.

Exercise 3 – Voltage Doubler

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate how to obtain a filtered dc voltage equal to double the peak ac input voltage by using a voltage doubler circuit. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

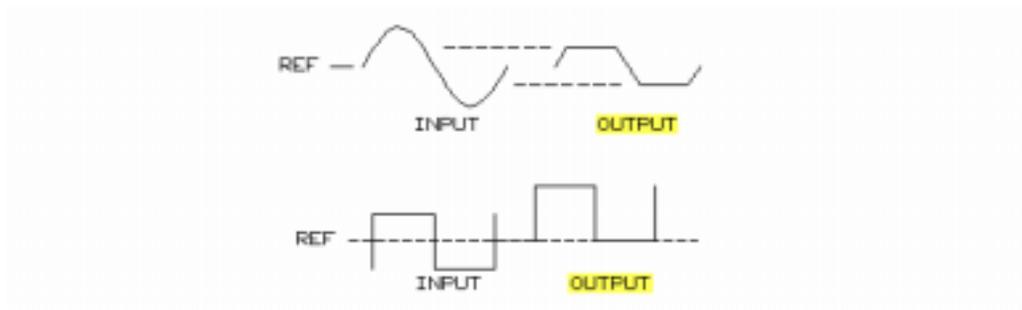
- Voltage doubler circuit rectifies the ac input signal and filters the output producing a dc output voltage twice the peak ac input voltage minus the forward voltage drop of the diode.
- A typical full-wave voltage doubler circuit consists of two diodes and two series filter capacitors.
- Total voltage across series capacitors is the sum of the capacitor voltage drops. The addition of these voltage drops produce the voltage doubling effect of the circuit.
- Resistors R1 and R2 are equalizing resistors that evenly divide the capacitor voltages within the circuit.
- Full-wave voltage doubler use both the positive and negative half-cycle of the ac input signal. One diode and one capacitor are paired per half-cycle.
- Diode (CR1) and capacitor (C1) function for the positive half-cycle. Diode (CR2) and capacitor (C2) function for the negative half-cycle.
- Since the discharge time constant is large, the capacitors maintain a charge close to the maximum charged voltage between charging cycles.
- Output ripple frequency of a full-wave voltage doubler is twice the ac input frequency.
- Input peak voltage is reduced during the capacitor charging period because the voltage doubler input is supplied by an unregulated power supply.

UNIT 4 – DIODE WAVE SHAPING AND ZENER REGULATION

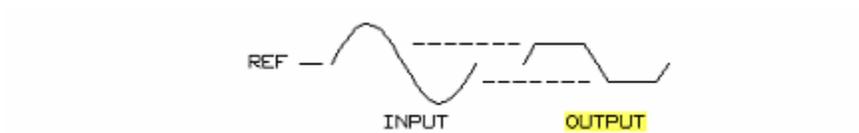
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate wave shaping, zener diode operation, and zener diode voltage regulation by using diode circuits.

UNIT FUNDAMENTALS



Diode circuits can be configured to output a waveform with a different shape than the input waveform.



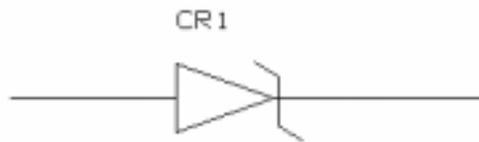
A **limiter** (or clipper) circuit removes all or part of the input alternation, as shown.



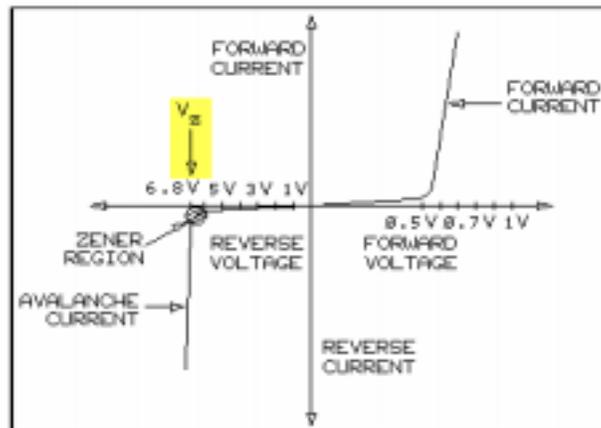
A **clamper** circuit shifts the positive or negative amplitude extreme of an input waveform to a different dc output voltage reference level, as shown.



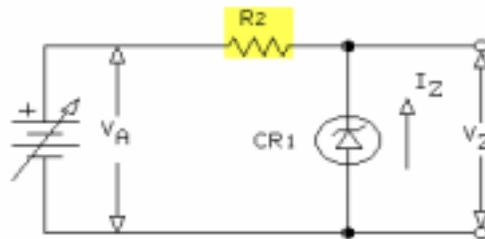
Limiter and clamper circuits take advantage of the diode forward bias voltage drop to set the clipping or clamping voltage level.



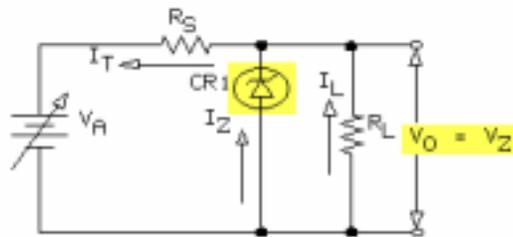
A **zener diode** is designed to operate safely at the reverse breakdown voltage. The symbol for a zener diode is shown above.



The breakdown voltage of a zener diode is called the **zener voltage** (V_Z). The zener voltage can be from 3V to 200V. At the zener voltage region, the reverse current (zener current) increases very rapidly for a very slight increase in zener voltage.



In circuits, the zener current (I_Z) is limited to a safe value by a resistor (R_2) in series with the zener (CR_1).



A zener diode (CR_1) can be configured in a circuit to control the out-put voltage (V_O) so that it equals the zener voltage (V_Z). The zener diode **voltage regulator** maintains the output voltage (V_O) equal to the zener voltage for changes in the input (line) voltage (V_A) and load current (I_L).

NEW TERMS AND WORDS

limiter - circuits that prevent voltage above or below a specified point from appearing at circuit output terminals.

clammer - circuits that shift the reference level of a waveform from input to circuit output.

zener diode - a diode designed to operate in the avalanche region, maintaining a relatively constant voltage drop over a range of current flows. The avalanche operating area of a diode occurs when the cathode is positive with respect to the anode.

zener voltage - the nearly constant voltage produced by a zener diode.

voltage regulator - an IC that maintains a constant output voltage when both input voltage and output loads change.

dc restorers - circuits that duplicate their input voltage at their output terminals but move or shift the signal reference level; also called level shifters.

positive clamper - a circuit that sets or clamps the negative peaks of an input waveform.

negative clamper - a circuit that sets or clamps the positive peaks of an input waveform.

avalanche - the reverse voltage point where a PN junction breaks down to pass high values of current.

Exercise 1 – Diode Wave Shaping

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate limiting and clamping by using diode circuits. You will verify your results with an oscilloscope.

DISCUSSION

- Limiter or clipper circuits remove positive and/or negative portions of a waveform. Sine waves can be converted to a rectangular wave using a limiter.
- Diode limiters are classified as series or parallel.
- Series diode limiters, shown in this exercise are half-wave rectifiers.
- Parallel diode limiters are composed of a series resistor, diode and load resistance in parallel with the diode. When the diode is forward biased the output is limited to the diode forward voltage. The half-cycle input voltage appears at the output when the diode is reversed bias.
- A limiting circuit with a variable voltage bias at the diode is illustrated in this exercise. The point where limiting occurs is controlled by the amount of bias added to the circuit by a positive variable voltage supply.
- Clamping circuits shift the unwanted positive or negative portions of an input waveform to a different output dc voltage reference level.
- Clamping circuits are also referred to as restorers or baseline stabilizers.
- Clamping circuits with capacitors must have short charge time constants and long discharge time constants compared to the period of the input signal or the output waveform will be distorted.

Exercise 2 – The Zener Diode

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the operation of a zener diode by using a dc characteristic curve. You will verify your results with a multimeter.

DISCUSSION

- Reverse biased resistance of a diode is very large, so there is little current flow until breakdown voltage is reached (where reverse current increases rapidly). Breakdown voltage is also called avalanche or zener voltage and ranges from 3V to 200V.
- Zener diodes are PN junction diodes designed to operate at the avalanche voltage.
- The schematic symbol for a zener diode has a Z-shaped line at its cathode.
- A zener diode has a forward voltage the same as a conventional diode.
- Dc characteristic curve for a zener diode, in forward bias, is the same as a rectifier diode. In reverse bias direction, current flow is very small until zener voltage is reached. The knee of the curve is the zener region (breakdown point).
- Zener test current, specified by the manufacturer, is the current at which the zener voltage is within the tolerance range.
- The part of the curve where the current increases slowly with increases in the zener voltage is the soft region.
- At the stiff region of the curve, the current increases rapidly with very small increases in the zener voltage.

Exercise 3 – Zener Diode Voltage Regulation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate voltage regulation by using a zener diode voltage regulator. You will verify your results with a multimeter.

DISCUSSION

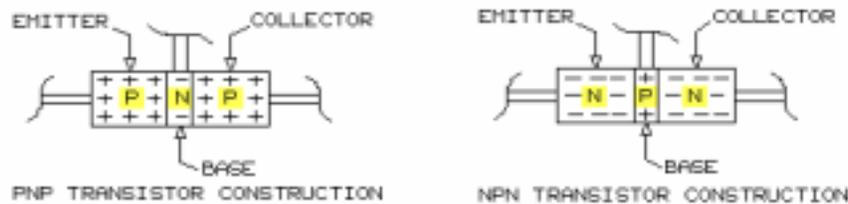
- Zener diodes are used in voltage regulator circuits because of the nearly constant zener voltage.
- The zener diode maintains an output voltage that is equal to the zener voltage, regardless of variations of the supply voltage and load resistance.
- Total current in a zener diode voltage regulator circuit is the sum of the zener current and the load current.
- Zener diodes function well for voltage regulation because I_Z can vary significantly with small changes in applied voltage when operating in the breakdown region.
- Increases in load current are compensated for by equal decreases in zener current; this characteristic provides the load regulation property of a voltage regulator.
- Percent load regulation is a measure of the voltage change across the load due to a change in load.

UNIT 5 – TRANSISTOR JUNCTIONS & PNP DC BIAS

UNIT OBJECTIVE

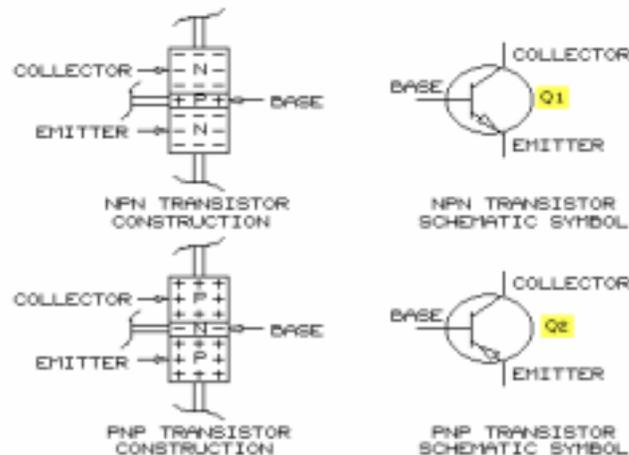
At the completion of this unit, you will be able to test transistors and demonstrate a transistor switch by using PNP and NPN transistor circuits.

UNIT FUNDAMENTALS

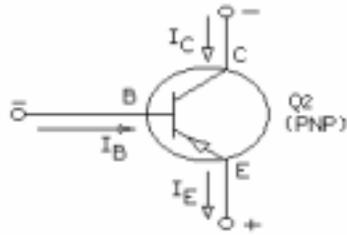


When another section of P or N type material is added to a PN diode junction, a three-section device containing two **junctions** is formed. This three-section semiconductor device is a bipolar transistor. The three sections are the emitter (E) and collector (C) on the ends and the base (B) in the middle.

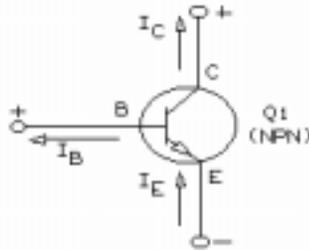
Transistors are classified by the arrangement of the P (positive) and N (negative) type materials. Transistors are either **PNP** or **NPN** types, as shown. Each of the two PN junctions of a transistor have forward and reverse voltage/current characteristics similar to a diode PN junction.



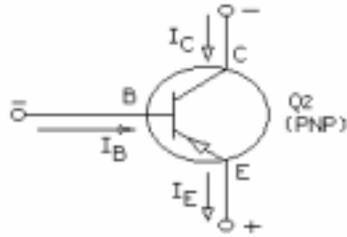
Q is the letter used to identify a transistor. The emitter arrows in the NPN and PNP transistor symbols show the direction of conventional current flow. Electron current flow, which is in the opposite direction of conventional current flow, is used in this course.



The PNP transistor shown has the base and collector terminals negative with respect to the emitter terminal. Because the negative (N) base material has a more negative voltage than the emitter, the PN junction is forward biased and permits current to flow from the base to the emitter. The current arrows indicate electron current flow. The base current permits collector current to flow to the emitter because the collector is more negative than the emitter.



The NPN transistor shown has the base and collector terminals positive with respect to the emitter terminal. Because the positive (P) base material has a more positive voltage than the emitter, the PN junction is forward biased and permits current to flow from the emitter to the base. The base current permits collector current from the emitter because the collector is more positive than the emitter.



A transistor is a current-controlling device; the base-emitter junction has to be forward biased for transistor current to flow. A small change in base current causes a large change in collector current; this transistor property is current gain. The emitter current is the sum of the base and collector currents: $I_E = I_B + I_C$

NEW TERMS AND WORDS

junctions - the points of contact between the emitter and base or the base and collector sections of a transistor.

PNP - a transistor type that has an N type material sandwiched between two P type materials.

NPN - a transistor type that has P type material sandwiched between two N type materials.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

SEMICONDUCTOR DEVICES circuit board

Multimeter

Exercise 1 – Testing the Junctions of a Transistor

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to test a transistor by forward biasing and reverse biasing the junctions. You will verify your results with an ohmmeter.

DISCUSSION

- A transistor is operating properly if it amplifies correctly, does not go into breakdown under operating voltages, and leakage current is within tolerance.
- Commercial transistor testers exist; however, an ohmmeter can also be used to test a transistor.
- Simple ohmmeter tests can show if a transistor is open or shorted, is a PNP or NPN type, or has excessive leakage.
- Transistors, for testing, can be considered to consist of two diodes — the base-emitter PN junction and the base-collector PN junction.
- A good NPN transistor has base-emitter and base-collector junctions that conduct when forward biased and do not when reverse biased. No current flow should be present between the collector and emitter.
- The same is true for a PNP transistor; however, care should be taken when connecting the ohmmeter. For example: to forward bias the base-emitter junction, connect the positive lead to the emitter and the negative lead to the base.
- If an ohmmeter indicates “overload” or off-scale when connected to forward bias a junction, the transistor is damaged.
- If an ohmmeter reading indicates current flow (low resistance) when connected to reverse bias a transistor junction, the transistor is damaged.
- A very low ohmmeter reading across the collector and emitter indicates a short or high leakage current and, therefore, a damaged transistor.
- Directions for testing with LAB-VOLT DIGITAL MULTIMETER, DIGITAL MULTIMETER WITH A DIODE TEST FUNCTION, and an ANALOG OHMMETER are presented in this exercise.

Exercise 2 – PNP Transistor Current Control Circuit

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate transistor current control by using a PNP transistor circuit. You will verify your results with a multimeter.

DISCUSSION

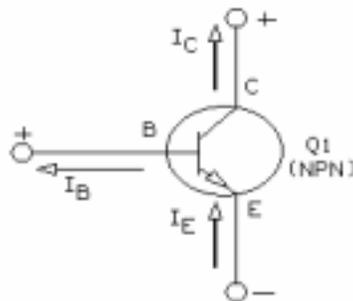
- A bipolar transistor can operate as a switch by changing the base current from zero to the maximum value.
- To forward bias a base-emitter junction, the base, of a silicon PNP transistor must be about 0.5 Vdc to 0.8 Vdc more negative than the emitter.
- Collector-emitter junction resistance depends upon the base current.
- A forward biased base-emitter junction causes the collector-emitter resistance to be very low allowing current to flow in the transistor collector circuit. Analogous to a closed switch.
- When the forward bias is removed (base-emitter junction is reverse biased) the base current becomes zero. Zero base current causes the collector-emitter resistance to be very high, which blocks the flow of current in the transistor collector circuit. Analogous to an open switch.
- When maximum collector current flows, the transistor is said to be in saturation and V_{CE} is nearly zero volts.
- When the base current is zero and there is no collector current flow, the transistor is said to be in cut-off and V_{CE} is equal to the supply voltage.
- The emitter current is equal to the sum of the base current and the collector current. Since the base current is negligible, the collector current and emitter current are virtually equal.

UNIT 6 – TRANSISTOR LOAD LINES AND GAIN

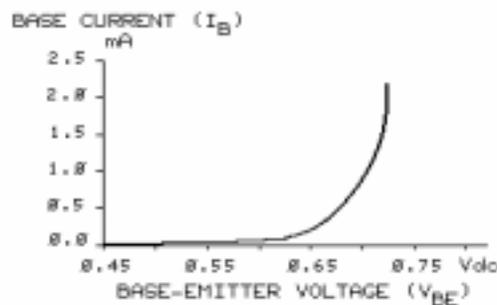
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate how operating conditions and gain affect transistor circuit currents by using a transistor dc or load line.

UNIT FUNDAMENTALS



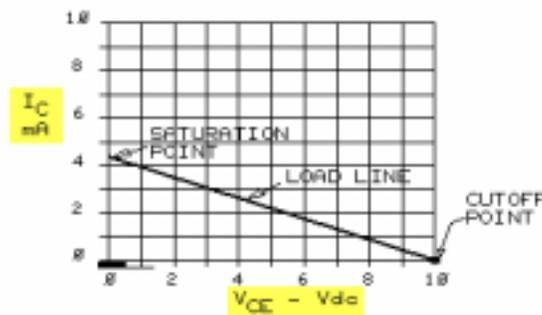
A transistor is a current-controlling device. A small base current (I_B) controls a large collector current (I_C). The collector current equals the emitter current minus the base current: $I_C = I_E - I_B$.



The base-emitter junction must be forward biased for base current to flow. When the base-emitter voltage (V_{BE}) is in the range of 0.5 Vdc to 0.75 Vdc, the base current (I_B) starts to increase very rapidly with small increases in V_{BE} . When the base-emitter junction is forward biased and the base-collector junction is reverse biased, the collector current (I_C) is proportional to the base current (I_B). The ratio of the collector current (I_C) to the base current (I_B) is the current gain (β_{DC}). The current gain (β_{DC}) for a transistor can be in the range from 50 to 300.

	BASE-EMITTER JUNCTION	BASE-COLLECTOR JUNCTION
SATURATION	FORWARD BIASED	FORWARD BIASED
ACTIVE	FORWARD BIASED	REVERSE BIASED
CUTOFF	REVERSE BIASED	—

The above table shows the base-emitter junction and base-collector junction voltage bias necessary for the transistor to be in the saturation, active, or cutoff states.



A dc **load line** is a plot of the collector current (I_C) versus the collector-emitter voltage (V_{CE}). The active region is between the **saturation point** and **cutoff point**.

NEW TERMS AND WORDS

load line - a plot of collector current versus collector voltage used to determine the best transistor operating point.

saturation point - the operating point at which maximum collector current is flowing in a forward biased transistor.

cutoff point - the operating point of a reverse biased transistor (not conducting).

quiescent point - the dc operating point of a transistor equal to about half of the supply voltage.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

SEMICONDUCTOR DEVICES circuit board

Multimeter

Exercise 1 – Base-Emitter Bias Potentials

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the relationship between the transistor base-emitter voltage and the base current by using a transistor circuit. You will verify your results with a multimeter.

DISCUSSION

- Forward bias and reverse bias dc conditions of the transistor base-emitter junction are similar to those of a diode PN junction.
- Silicon transistors have a forward voltage drop between 0.5 Vdc and 0.75 Vdc. Germanium transistors have forward voltage drops between 0.15 Vdc and 0.3 Vdc.
- Once forward voltage has been reached, forward current begins to flow and increases very rapidly with small increases in forward voltage.
- Most transistor base-emitter junctions can not tolerate reverse voltages greater than 5 Vdc to 6 Vdc.
- Transistor base-collector junctions, which are normally reverse biased, can tolerate reverse voltages of in the range of 60 Vdc to 75 Vdc. This maximum reverse bias voltage is documented in the transistor specification sheet and is referred to as the breakdown voltage.
- Exceeding the breakdown voltage will damage the transistor.
- When the base-emitter junction is forward biased and base current flows through the junction, current also flows through the base-collector junction regardless of its bias.
- A transistor with a forward biased base-emitter junction and a reverse biased base-collector junction is operating in the linear region.
- A transistor in saturation has maximum current flow through the collector.
- This exercise will demonstrate the relationship between the base-emitter voltage drop and the base current with the collector open.
- Subscript BEO represents Base-Emitter with the collector terminal Open.

Exercise 2 – Collector Current Versus Base Current

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the relationship of collector current to base current by using a transistor circuit. You will verify your results with a multimeter.

DISCUSSION

- The circuit used in this exercise has two voltage supplies: one biases the base and the other supplies the collector current.
- Vary base current by adjusting the potentiometer (R2).
- The base-emitter junction is forward biased and the base-collector junction is reverse biased.
- The emitter current is equal to the sum of the base and collector currents.
- The base region is thin and lightly doped compared to the collector and emitter. This condition allows current to flow between the base and collector junction even when the junction is reversed biased.
- Dc current gain is the ratio of collector-base currents (I_C/I_B) when the transistor is operating in the linear region and is represented by the symbols β_{DC} or h_{FE} .
- Beta can be between 10 and 500 and will increase with changes in the operating temperature of the transistor. The transistor used in this exercise has a beta of between 50 and 300.
- Gain is the transistor property that allows a small base current to control a much larger collector current.
- Gain defines the degree to which a transistor amplifies small input signals into large output signals.

Exercise 3 – Transistor Circuit DC Voltages

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate dc operating conditions of a transistor circuit by using an NPN transistor. You will verify your results with a multimeter.

DISCUSSION

- Three possible dc voltage conditions for a transistor circuit are (1) at the saturation point, (2) in the active (linear) region, or (3) at the cutoff point.
- An NPN transistor circuit is used in this exercise. The base voltage supply is 15 Vdc, and the collector circuit supply is 10 Vdc.
- All voltage measurements are referenced to the emitter voltage. Since there is no emitter resistor, the following is true: $V_B = V_{BE}$ and $V_C = V_{CE}$
- Base current is set by adjusting potentiometer R2.
- Saturation conditions are present when the base-collector junction is forward biased. $V_{CE} = 0$ Vdc. In this state the transistor behaves like a closed switch. Collector current is at maximum and is equal to the collector supply voltage divided by the total collector circuit resistance. At saturation, collector current does not equal the base current times beta.
- A transistor circuit operating in the active region can have an operating point anywhere between saturation and cutoff.
- In the active region, the base-emitter junction is forward biased and the base-collector junction is reverse biased. Collector current is linearly proportional to the base current. Collector current is equal to the base current times beta.
- Cutoff occurs when the base voltage and current become zero because the base-emitter junction is no longer forward biased. Collector current is zero and V_{CE} is equal to the collector supply voltage. The transistor circuit behaves as an open switch.

Exercise 4 – Transistor Load Lines

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the dc load line for a transistor circuit. You will verify your results with a multimeter.

DISCUSSION

- Collector current characteristic curves are graphs of collector current versus collector-emitter voltage as a function of base current.
- Since beta is almost constant in the transistor active region, a plot of collector current versus collector-emitter voltage with a constant base current is a curve that increases very slightly.
- Dc load lines intersect the Y-axis at the saturation point and the X-axis at the cutoff point.
- The Q-point or operating point is the point at which the load line intersects I_B and is determined by the dc bias conditions of the transistor circuit.
- Transistor circuits used for small signal amplification are usually designed to have the Q-point in the center of the load line. This gives an active region operating range for the applied ac signal.
- Load line determination will be effected with changes in collector voltage supply or the value of the collector resistor.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Transistor Amplifier Circuits

FACET®



Student Workbook

FOURTH EDITION

Second Printing, March 2005

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Appendix A – Safety A-ii

Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

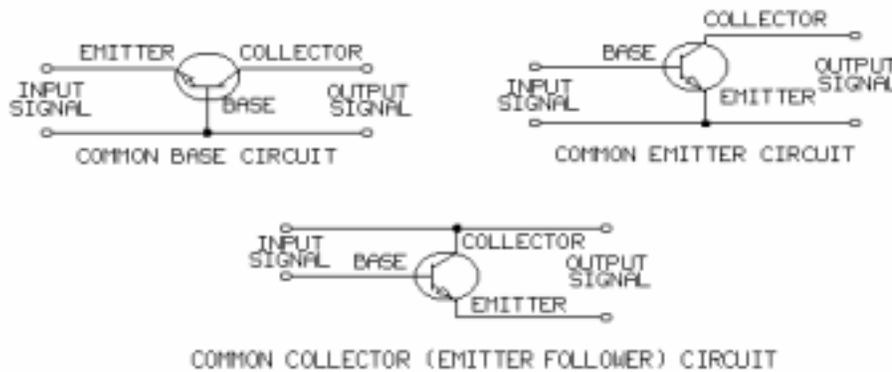
UNIT 1 – INTRODUCTION TO TRANSISTOR AMPLIFIERS

UNIT OBJECTIVE

At the completion of this unit, you will be able to identify, connect, and operate circuit blocks and their major components on the TRANSISTOR AMPLIFIER CIRCUITS circuit board.

UNIT FUNDAMENTALS

This unit describes the circuit blocks on the TRANSISTOR AMPLIFIER CIRCUITS circuit board and presents some background on transistor amplifiers.



Transistor amplifiers are grouped into one of three basic circuit configurations depending on which transistor element is common to input and output signal circuits.

1. Common base
2. Common emitter
3. Common collector

Each circuit configuration has its own characteristics and, therefore, its own applications.

Multistage transistor amplifiers include more than one transistor. The output of the first stage is connected (coupled) to the input of the second stage. The output of the second stage is coupled to the input of the third stage, and so forth.

The three methods of coupling amplifier stages on the TRANSISTOR AMPLIFIER CIRCUITS circuit board are RC coupling, transformer coupling, and direct coupling.

Exercise 1 – Circuit Location and Identification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to locate and identify the functional circuit blocks on the TRANSISTOR AMPLIFIER CIRCUITS circuit board. You will observe the operation of two basic amplifier circuits by using an oscilloscope.

DISCUSSION

- Amplifiers are circuits that increase the voltage, current, or power of an input signal.
- An amplifier consists of an active circuit component and a source of power.
- Transistors are the active components used on this circuit board. The power source is the external power supply.
- Five amplifier circuit blocks, which can be configured for seven different circuits, are present on the TRANSISTOR AMPLIFIER CIRCUITS circuit board.
- The five amplifier circuit blocks are the:
 - COMMON BASE / EMITTER circuit block
 - RC COUPLING/TRANSFORMER COUPLING circuit block
 - COMMON COLLECTOR circuit block
 - BIAS STABILIZATION circuit block
 - DIRECT COUPLING circuit block
- Potentiometer R4 is the load resistor on the COMMON COLLECTOR circuit block.
- The BIAS STABILIZATION circuit block does not use a sine wave generator, instead, it uses a positive, variable, dc power supply. In addition, this circuit block has a resistor, labeled HEATER which is located near the transistor, that is powered by a separate dc power supply.
- The RC COUPLING/TRANSFORMER COUPLING and the DIRECT COUPLING circuit blocks include components that are used to demonstrate two-stage amplification.
- All transistors on the TRANSISTOR AMPLIFIER CIRCUITS circuit board are NPN except for the second stage PNP transistor on the DIRECT COUPLING circuit block.

Exercise 2 – Multistage Amplifier Introduction

EXERCISE OBJECTIVE

When you have completed this exercise, you will have observed the operation of a two-stage transistor amplifier circuit. You will view your results on an oscilloscope.

DISCUSSION

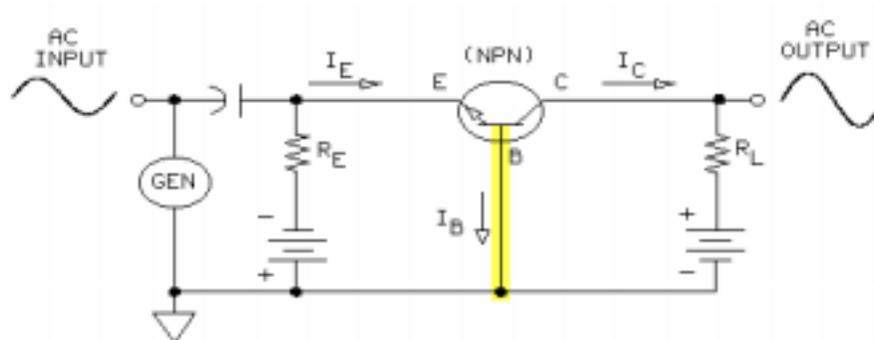
- Multistage transistor amplifiers utilize multiple transistors to produce voltage, current, or power gains greater than those provided by a single transistor.
- Multistage transistor amplifiers are identified by the method used to couple the signal between amplifier stages.
- Resistor-capacitor (RC) coupling uses a resistor to develop an output signal and a capacitor to pass the signal from the output of one stage to another.
- Transformer coupling uses a transformer to couple signals between the primary and the secondary side of the coil.
- In multistage amplifiers, capacitors are used to isolate the dc bias levels and simplify the design.
- All amplifiers are designed for a specific frequency range and an input/output signal amplitude range.
- An input signal that is too large or outside the frequency range of an amplifier will produce a distorted output signal.

UNIT 2 – COMMON BASE CIRCUIT

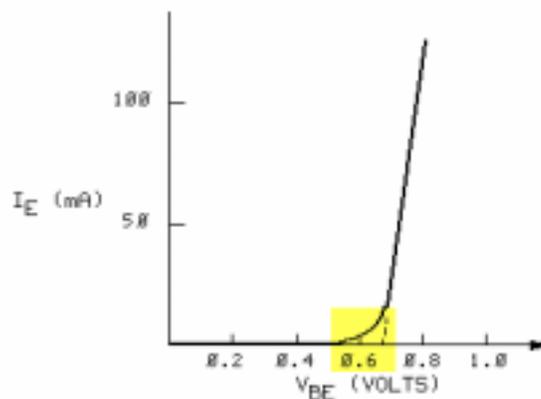
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of the common base transistor amplifier circuit by using calculated and measured circuit conditions.

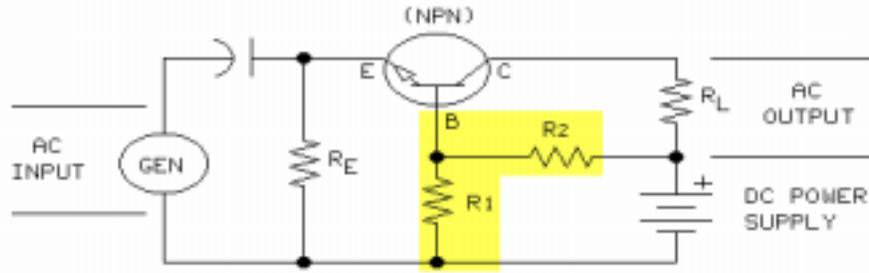
UNIT FUNDAMENTALS



The base terminal is common to the input and output signals in the common base (CB) transistor circuit. The ac output signal of a common base (CB) circuit is in phase with the input signal. For a PNP or NPN transistor to function normally in any type of amplifier circuit, the base-emitter junction is forward biased, and the base-collector junction is reversed biased.



The emitter current (I_E) increases very rapidly after the transistor is forward biased [base-emitter voltage (V_{BE}) of about 0.6 Vdc].



Proper biasing of a CB transistor circuit can be provided by a connection between the base terminal and a voltage divider circuit across a single dc power supply.

NEW TERMS AND WORDS

active region - the region on the transistor load line between the saturation point and the cutoff point.

Q-point (quiescent point) - the dc steady state operating point set by the dc bias conditions.

cutoff point - the point on the load line where the collector current is essentially zero.

saturation point - the point on the load line where the collector current is maximum.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine wave

TRANSISTOR AMPLIFIER CIRCUITS circuit board

Exercise 1 – Common Base Circuit DC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the dc operating conditions of a common base (CB) transistor circuit by using a typical CB circuit. You will verify your results with a multimeter.

DISCUSSION

- In common base amplifier circuits the base terminal is common to both the input and output signals.
- The voltage divider network provides the fixed dc base voltage required to forward bias the base-emitter junction of the transistor.
- The voltage divider equation can be used to calculate the base voltage (V_B).
- V_{BE} , base-emitter voltage, of a forward biased silicon transistor is approximately 0.6 V.
- The emitter voltage (V_E) is the difference between the base voltage and the base-emitter voltage.
$$V_E = V_B - V_{BE}$$
- Ohm's law is used to calculate both emitter current (I_E) and collector current (I_C).
- Collector current can be found in two other ways: First the collector current is approximately equal to the emitter current. Second the collector current is the difference between the emitter current and the base current.
$$I_C = I_E - I_B$$
- Transistor characteristic curves and dc load lines are used to determine the Q (quiescent) point, dc-point, or operating point of the transistor circuit.
- Saturation occurs when the base-collector voltage is zero.

Exercise 2 – Common Base Circuit AC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine ac operating characteristics of a common base (CB) amplifier by using a typical CB circuit. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

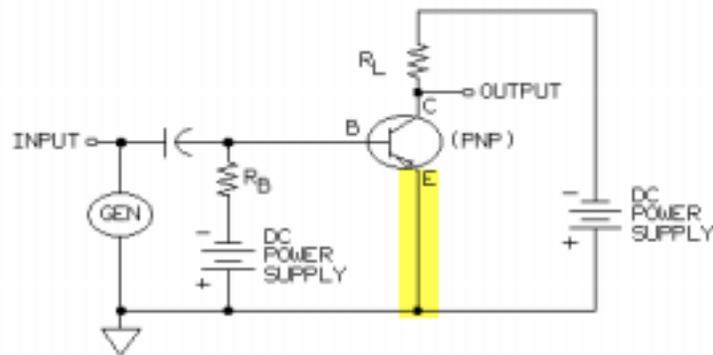
- The sine wave generator provides the ac input signal.
- Ac signals at the base are shorted to ground by capacitor C2.
- The ac output signal is between capacitor C3 (located at the collector of Q1) and ground.
- The input impedance of the common base configuration is very low while the output impedance is very high.
- Low input impedance causes loading of the input signal.
- The high ratio of output to input impedance creates a circuit with high gains.
- Common base transistor circuits are used in applications which require high output gains.
- The ac output signal is in phase with the input signal.
- Voltage gain of the common base circuit is the ratio of the output voltage to the input voltage, or the ratio of the load and input impedance.

UNIT 3 – COMMON EMITTER CIRCUIT

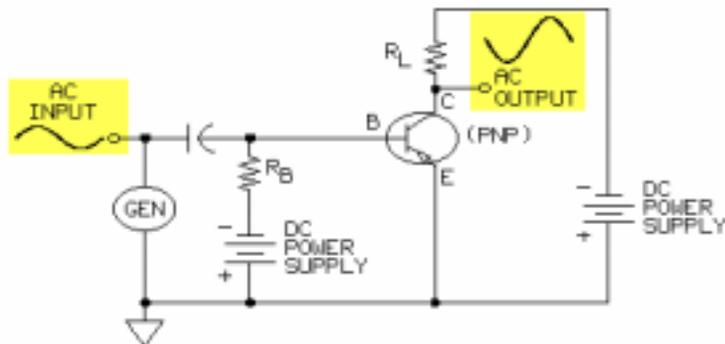
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a common emitter transistor amplifier circuit by using calculated and measured circuit conditions.

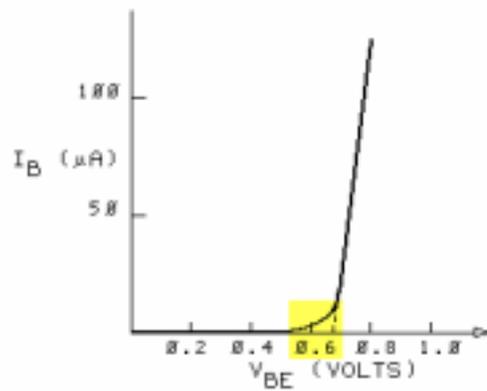
UNIT FUNDAMENTALS



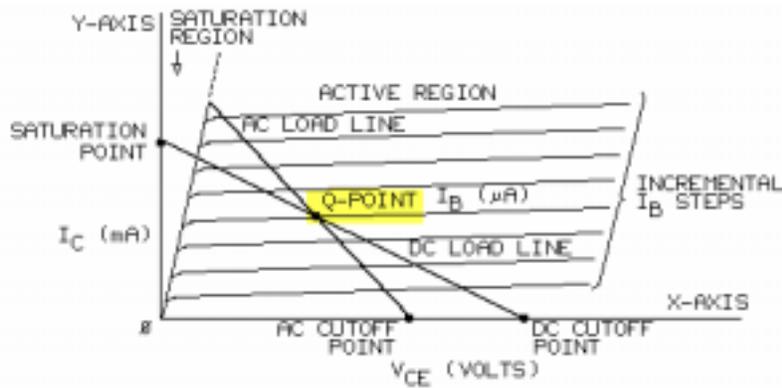
The emitter terminal is common to the input and output signals of the common emitter (CE) transistor circuit.



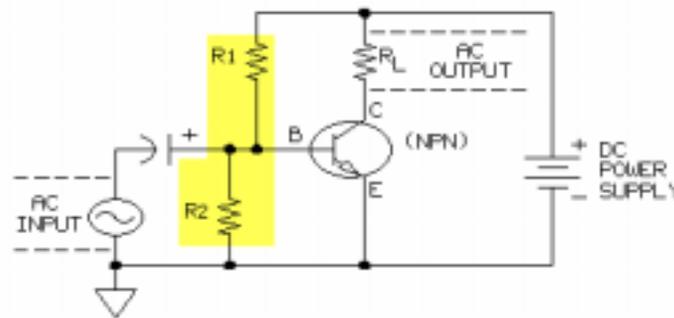
The ac output signal of a CE circuit is 180° out of phase with the ac input signal.



After a base-emitter voltage (V_{BE}) of about 0.6 Vdc, the base current (I_B) increases very rapidly.



The transistor circuit ac and dc load lines intersect at the Q-point on the collector current characteristic curves.



A voltage divider circuit uses a single dc power supply to provide a constant base terminal voltage for the CE transistor. The CE circuit has high current, voltage, and power gains. The input and output impedances are high.

Exercise 1 – Common Emitter Circuit DC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the dc operating conditions of a common emitter (CE) transistor circuit by using a typical CE circuit. You will verify your results with a multimeter and calculations.

DISCUSSION

- The emitter terminal is common to both the input and output signals.
- Base voltage (V_B) can be calculated from the voltage divider equation.
- Ohm's law is used to calculate the emitter current (I_E).
- The emitter current and collector current (I_C) are nearly equal. The exact collector current can be found by subtracting the base current from the emitter current.
- Current gain is the ratio of dc collector current to base current. Dc current gain is represented by beta (β_{dc}) or h_{FE} and usually ranges in value between 10 and 500.
- Design criteria for a common emitter circuit specifies a collector voltage (V_C) about halfway between the power supply voltage (V_A) and the emitter voltage (V_E).
- The saturation point occurs when the collector-emitter voltage (V_{CE}) is zero and collector current is maximum ($I_{C(SAT)}$).
- Cutoff occurs when collector current is approximately zero.
- The area on a transistor characteristic curve between saturation and cutoff is called the active region.
- The Q-point of a transistor is determined by its dc bias conditions. Q-point is the where the dc load line intersects the base current, collector current, and the collector-emitter voltage curves.
- The ideal location of the Q-point is at the midpoint of the dc load line.

Exercise 2 – Common Emitter Circuit AC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the ac operating characteristics of a common emitter (CE) amplifier by using a typical CE transistor circuit. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

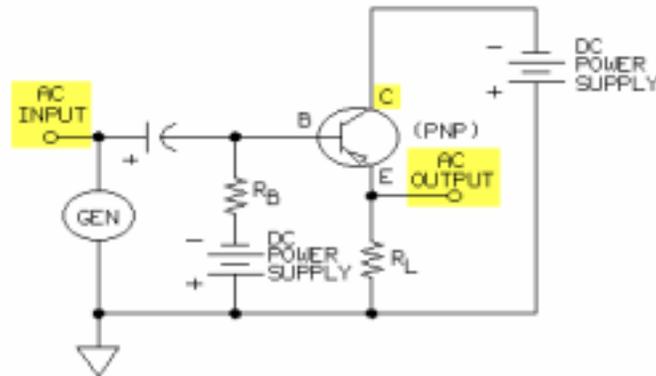
- The ac input signal is provided by the sine wave generator. The ac output signal is taken between the collector terminal and ground. The parallel resistance of R4 and R6 is the load.
- The ac output voltage is larger and 180° out of phase with the input signal.
- As base voltage increases, base current increases, this results in an increase in the collector and emitter currents.
- The voltage gain of a common emitter circuit is the ratio of the ac output voltage to the ac input voltage. $A_v = -V_o/V_i$ (where the negative sign indicates that there is a 180° phase shift.)
- The gain of a CE circuit where an emitter resistor is not bypassed by a capacitor is equal to the ratio of the collector load (R_L) to the emitter resistor (R_5). $A_v = -R_L/R_5$
- Connecting the Q-point with the $I_{C(SAT)}$ point and drawing a line to the X-axis provides the value of the ac cutoff voltage and the ac load line.
- Large ac input signals, which are so large that the peak output voltage exceeds the maximum allowed by the cutoff point, cause clipping at the output.
- The optimum Q-point is at the center of the ac load line.

UNIT 4 – COMMON COLLECTOR CIRCUIT

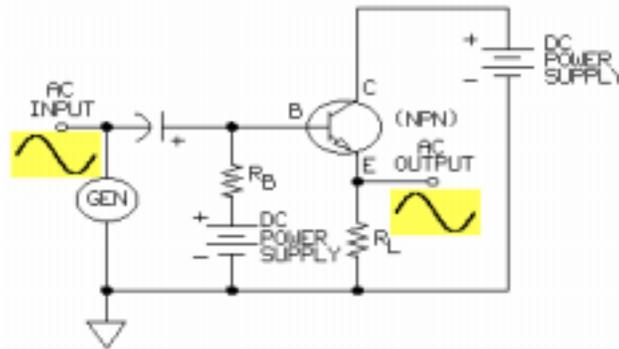
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a common collector transistor amplifier circuit by using calculated and measured circuit conditions.

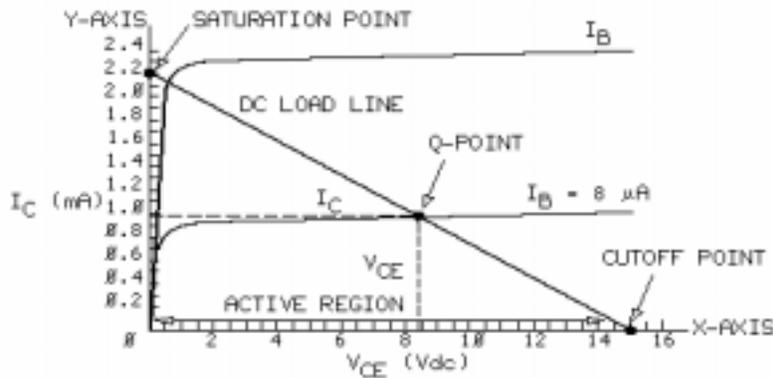
UNIT FUNDAMENTALS



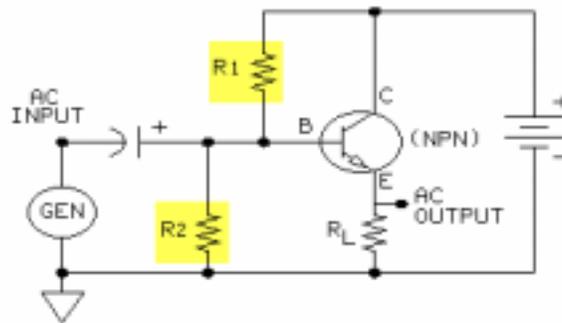
The collector terminal is common to the input and output signals of the common collector (CC) transistor circuit.



The ac output signal of a CC circuit is in phase with the input signal.



The CC transistor circuit base and collector current characteristic curves are similar to the CE circuit curves.



A CC transistor voltage divider circuit biases the base terminal with a single dc power supply. The CC circuit has a voltage gain less than 1.0 and has current gains between 10 and 500.

High input impedance and low output impedance make the CC transistor circuit desirable for applications between a high impedance source and a low impedance load.

NEW TERMS AND WORDS

None

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine wave

TRANSISTOR AMPLIFIER CIRCUITS circuit board

Exercise 1 – Common Collector Circuit DC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the dc operating conditions of a common collector (CC) transistor circuit by using a typical CC circuit. You will verify your results with a multimeter and with calculations.

DISCUSSION

- In common collector transistor circuits the collector terminal is common to both the input and the output signals.
- Since no collector resistor is present the collector voltage (V_C) equals the dc power supply voltage (V_A).
- Base voltage (V_B) is calculated using the voltage divider equation.
- Emitter voltage (V_E) is about 0.6 Vdc less than the base voltage when the transistor is operating normally.
- Ohm's law is used to calculate the emitter current (I_E).
- Collector current (I_C) is the emitter current minus the base current.
- The dc load line passes through the saturation point, Q-point, and the cutoff point.
- Cutoff occurs when V_{CE} is equal to the supply voltage and I_C equals 0 mA.
- Saturation occurs when V_{CE} equals 0 Vdc and the I_C is at maximum value.

Exercise 2 – Common Collector Circuit AC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine ac operating characteristics of a common collector (CC) amplifier by using a typical CC transistor circuit. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

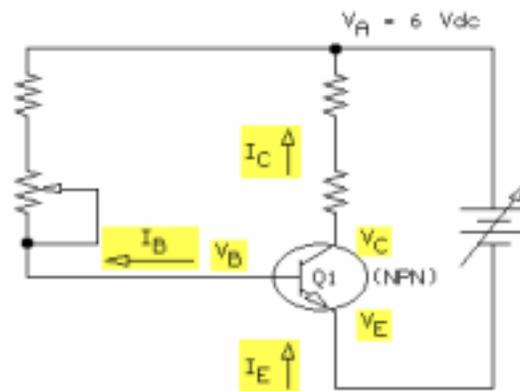
- The ac input is provided by a sine wave generator.
- The ac output is taken between the emitter terminal and ground.
- Voltage gain of the common collector transistor circuit is the ratio of the ac output voltage to the ac input voltage. The voltage gain is always less than one.
- The input and output signal are in phase.
- The common collector transistor circuit is also called an emitter follower because the output signal follows the input signal.
- Input impedance (Z_i) is equal to the combined parallel resistance of R_1 , R_2 , and $\beta \times (R_3 + r_e')$. Since $\beta \times (R_3 + r_e')$ is more than 100 times as large as R_1 in parallel with R_2 , this parallel combination equals the input impedance.
- This circuit block allows the student to measure output impedance (Z_o) by connecting potentiometer R_4 in parallel with R_3 and adjusting R_4 until the output signal is half that of the original.

UNIT 5 – BIAS STABILIZATION

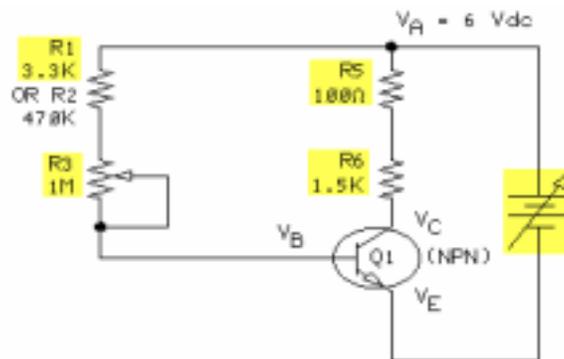
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the effect of a temperature increase on transistor bias by using typical transistor amplifier bias circuits.

UNIT FUNDAMENTALS

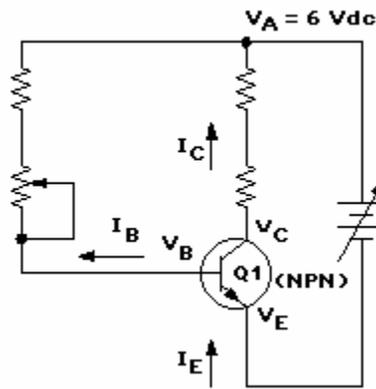


Transistor bias refers to the dc operating conditions: the base, collector, and emitter dc voltages and currents.

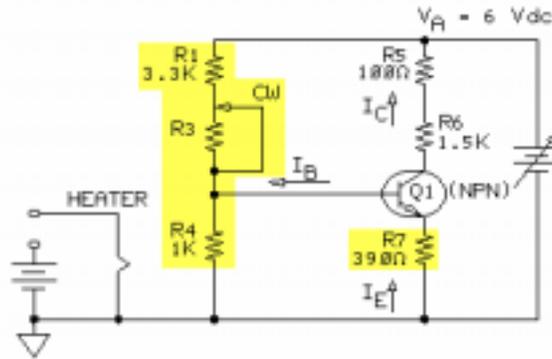


Transistor bias depends on the dc voltage supply and on the values and configuration of the circuit resistors.

The Q-point of the load line is determined by the transistor bias. Transistors are heat-sensitive devices. A change in transistor temperature can adversely affect the output signal quality.



If a circuit is not designed to overcome the effects of temperature change, the location of the Q-point can move toward the saturation or cut-off points causing signal distortion.



A transistor amplifier circuit with a base voltage divider and an emitter resistor fixes the bias voltage levels and, therefore, has good bias temperature stability. The stability factor (S) is a measure of a transistor circuit's bias stability with changes in temperature.

NEW TERMS AND WORDS

collector leakage current (ICBO) - current caused by the reverse bias voltage between the collector and the base. ICBO increases with temperature.

EQUIPMENT REQUIRED

- F.A.C.E.T. base unit
- Multimeter
- Clock
- TRANSISTOR AMPLIFIER CIRCUITS circuit board

Exercise 1 – Temperature Effect on Fixed Bias

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to describe the effect of temperature on a fixed bias circuit by using a typical transistor circuit. You will verify your results with a multimeter, a clock, and calculations.

DISCUSSION

- Increased transistor temperature creates an increase in the value of beta (β , current gain) and the collector leakage current (I_{CBO}).
- Collector leakage current (I_{CBO}) is caused by the reverse bias voltage. I_{CBO} is measured from the base to the collector with the emitter open.
- Collector leakage current is normally in the nanoampere range, but doubles with every 10° C increase.
- In a fixed bias circuit, changes in beta have the greatest effect on the collector current.
- Large temperature increases can cause collector current to reach the saturation point or create a thermal runaway condition that could damage the transistor.
- A measure of transistor temperature stability is referred to as the stability factor (S). The stability factor is a ratio of the change in collector current to the change in collector leakage current.
- Stability factors can range in value from one to as high as beta. A low stability factor indicates a temperature stable transistor. Values less than 10 are considered good.
- Fixed bias, or simple bias, circuits have poor temperature stability. The stability factor is equal to beta.
- In a fixed bias circuit, increased temperature causes V_{BE} to decrease resulting in an increase of both the voltage drop across R_3 and the base current.
- Base current increase cause an increase in collector current. Increases in beta and collector leakage current compound the collector current increase.
- Fixed bias circuits are usually used for transistor circuits that provide a switching function. The circuit operates at saturation and cutoff.

Exercise 2 – Temperature Effect on Voltage Divider

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to describe the temperature effects on a voltage divider bias circuit by using a typical transistor circuit. You will verify your results with a multimeter, a clock, and calculations.

DISCUSSION

- The collector current is almost independent of beta in a voltage divider bias circuit. Therefore when beta changes with temperature, it has little effect on circuit bias.
- When the resistors in the voltage divider network are selected correctly, the base voltage is essentially constant. Constant base voltage and the feedback from the emitter resistor give the voltage divider bias circuit good temperature stability.
- Increasing temperatures cause an increase in the collector and emitter currents. Larger emitter currents increase the emitter voltage which opposes and slightly increases base voltage. A slight increase in base voltage creates a decrease in base current thus counteracting the collector and emitter current increase.
- Feedback is the effect on the base voltage caused by the increase in emitter voltage.
- The larger the emitter resistance the better the temperature stability of the circuit.
- Too large an emitter resistor will limit the voltage gain of the circuit and bring the Q-point closer to the saturation point, limiting the ac signal operating range.
- The stability factor (S) of the voltage divider bias circuit is approximately equal to the ratio of R_4 to R_7 . A stability factor of ten or less is desirable.

UNIT 6 – TRANSISTOR SPECIFICATION SHEET

UNIT OBJECTIVE

At the completion of this unit, you will be able to cite transistor parameters by using a transistor specification sheet.

UNIT FUNDAMENTALS

A transistor parameter is a physical or an electrical property whose value determines the characteristics or behavior of the transistor. The transistor specification (data) sheet summarizes all the transistor parameters and technical data that the manufacturer considers important for the user. The user should refer to the specification sheet when selecting a transistor for a specific circuit application.

A typical transistor specification sheet contains:

1. A listing of the manufacturer's transistor identification numbers and transistor casing types.
2. Maximum ratings.
3. Electrical characteristics.
4. Characteristic curves.
5. Mechanical features.

Some important transistor parameters include:

1. Current gain (h_{FE}).
2. Maximum power dissipation (P_D).
3. Saturation voltages ($V_{CE(sat)}$ and $V_{BE(sat)}$ are measures of conductivity).
4. Collector leakage (cutoff) current (I_{CBO}).
5. Breakdown voltage ($V_{(BR)CEO}$, $V_{(BR)CBO}$, $V_{(BR)EBO}$).
6. Switching characteristics.
7. Noise (NF).

Transistor specification sheets are contained in the manufacturer's technical information book. Such books usually cover the family of devices to which a transistor belongs.

NEW TERMS AND WORDS

None

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

TRANSISTOR AMPLIFIER CIRCUITS circuit board

Exercise 2 – Using the Transistor Specification Sheet

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to locate maximum ratings, dc characteristics, and operating parameters by using a typical transistor specification sheet. You will verify your results by successfully completing all tasks.

DISCUSSION

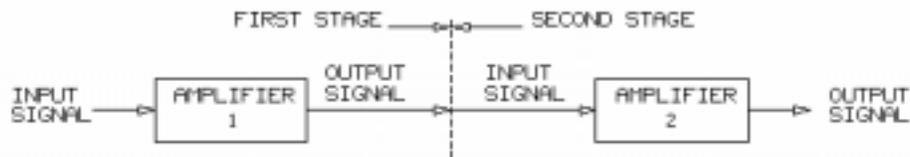
- Manufacturer's of transistors publish technical manuals which include the transistor specification (data) sheets.
- The manual usually contains an alphanumeric index indicating the page number where data on a specific transistor is located.
- Manuals, also, include information to help select the correct transistor for the application and tables that compare specific transistor performance for general design or applications groupings.
- Specification sheets include sections for maximum ratings, electrical characteristics, and characteristic curves.
- Included in the data sheet are the transistor identification numbers, casing types, applications, transistor configuration, and material.
- Maximum ratings section provides operating parameters when a transistor is at its maximum rating.
- The Electrical Characteristics section consists of the following categories that provide maximum and minimum parameter values required for circuit design.
 - Off characteristics
 - On characteristics
 - Small-signal characteristics
 - Switching Characteristics

UNIT 7 – RC COUPLING

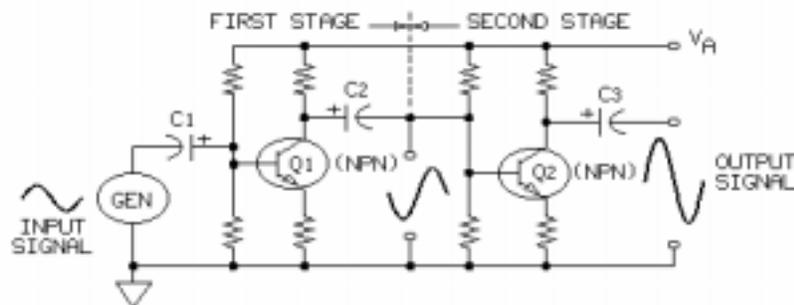
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a two-stage RC-coupled amplifier by using measured circuit conditions.

UNIT FUNDAMENTALS



Two amplifiers are **cascaded** when the output of the first amplifier is connected to the input of the second amplifier. In a cascaded system, the first amplifier is called the first stage. The second amplifier is called the second stage. Cascaded amplifiers achieve an overall gain higher than that possible with one amplifier.



When a capacitor and one or more resistors connect the output of the first stage to the input of the second stage, the amplifiers are RC (resistance-capacitance) coupled. With common-emitter circuits, each amplifier inverts the input signal so that the output of the second stage is in phase with the input of the first stage. The manner in which gain varies with the frequency of the input signal is called **frequency response**.

Exercise 2 – AC Voltage Gain and Phase

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the ac voltage gain and the input/output phase relationship of an RC-coupled amplifier by using measured and calculated values. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

- The sine wave input is applied to the base of the first amplifier.
- The output of the first amplifier depends on the ac output load resistance of Q1. Since C2 passes ac signals, the ac load resistance (R_{L1}) consists of the parallel combination R3, R4, R8, and the Q2 $\beta \times (R_{10} + r'_e)$.
- Q2 $\beta \times (R_{10} + r'_e)$ is large and may be eliminated from the calculation.
- The first amplifier has a voltage gain (A_{v1}) which is the ratio of the output to input signal (V_{o1}/V_{i1}). The gain has a negative sign since this stage inverts.
- The ratio of load resistance to the emitter resistance approximates the voltage gain of the first amplifier.

$$A_{v1} = -R_{L1}/R_5$$

- The ac output load resistance of Q2 is equal to the value of the collector resistor (R9).
- Voltage gain of the second amplifier is expressed using this equation:

$$A_{v2} = -V_{o2}/V_{i2} = -R_{L2}/R_{10} = -R_9/R_{10}$$
- Overall circuit gain is the product of the amplifier gain.

Exercise 3 – Frequency Response

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the frequency response of an RC-coupled amplifier by using measured values. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

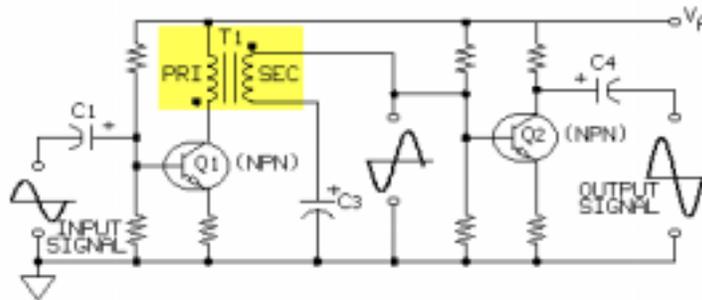
- Amplifier gain varies as the input signal frequency varies. This behavior is referred to as the frequency response.
- The amplifier circuit used in this exercise experiences decreases in gain at frequencies below 20 Hz and above 100 kHz.
- The bandwidth of an amplifier is the range of input signal frequencies over which the amplifier gain remains constant.
- In general, a 15% decrease in amplifier gain indicates that the amplifier is at the end of its bandwidth range.
- Frequency response curves for audio amplifiers should be relatively flat between 20 Hz and 20 kHz.
- The coupling capacitor value may affect frequency response (at the lower frequencies) of the amplifier.
- Upper limit frequency bandwidth is affected by the frequency-dependent transistor parameters and the stray capacitance of circuit elements.

UNIT 8 – TRANSFORMER COUPLING

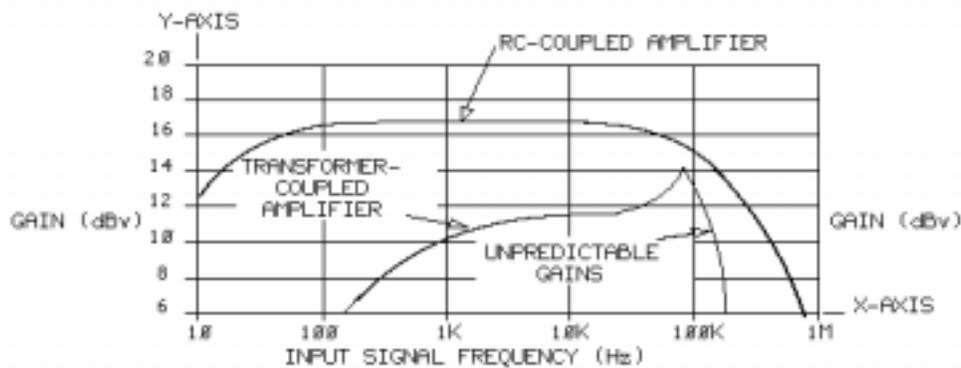
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a transformer-coupled two-stage amplifier by using measured circuit conditions.

UNIT FUNDAMENTALS



When a transformer connects the output of the first-stage amplifier to the input of the second-stage amplifier, the amplifiers are transformer-coupled. The transformer matches the high output impedance of the first-stage amplifier (Q1) with the low input impedance of the second-stage amplifier (Q2). A transformer-coupled amplifier uses less power than an RC-coupled amplifier does because the dc voltage drop across a transformer winding is less than that of a collector resistor, permitting a smaller dc supply voltage.



The frequency response of a transformer-coupled amplifier is normally poorer than that of an RC-coupled amplifier.

Exercise 1 – DC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the dc operating conditions of a transformer-coupled two-stage amplifier by using measured values. You will verify your results with a multimeter.

DISCUSSION

- The transformer-coupled amplifier circuit consists of two NPN common emitter amplifiers (Q1 and Q2).
- The transformer T1 has its primary winding connected between the power supply and the collector terminal of the first stage amplifier.
- The secondary winding of the transformer is connected to the base terminal of the second-stage amplifier and to ground through a dc current-blocking capacitor (C3).
- Transformer (T1) blocks dc current flow between the two amplifier stages. This isolates the dc bias for each stage.
- Transformers are circuit devices used for ac signals only.
- Resistor R7, which is connected in parallel with the transformer secondary winding, maintains the impedance specification of this coil.
- The amplifiers have identical voltage divider circuits and emitter resistors causing V_B and V_E of each transistor to have about the same value.
- The resistance of the primary winding is small; therefore, the collector voltage of the first stage (V_{C1}) is slightly less than the dc supply voltage (V_A).
- The second stage of the amplifier has a collector resistor (R9) which produces a collector voltage (V_{C2}) of about 9 Vdc.

Exercise 2 – AC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the ac voltage gain, impedance matching, and input/output phase relationship of a transformer-coupled amplifier by using measured and calculated values. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

- The ac input signal to the base of the first amplifier stage is provided by the sine wave generator.
- Transformer T1 has its primary connected between the power supply and the collector of the first stage amplifier.
- The secondary is connected to the base of the second-stage amplifier and to ground through a dc blocking capacitor (C3).
- The transformer provides impedance matching between the low impedance of the second-stage base circuit and the high impedance of the first stage collector output.
- The primary winding impedance (Z_P) is represented as: $Z_P = Z_S \times (N_P/N_S)^2$
 where Z_S is the impedance of the secondary
 N_P/N_S is the turns ratio of the transformer
- The impedance of the second-stage base circuit is equal to the parallel combination of R7, R8, and $\beta \times (r_e + R10)$.
- The turns ration of this transformer is 1.96.
- The ac peak-to-peak voltage between the primary and secondary coils is reduced (stepped down) by the transformer. The reduction is proportional to the turns ratio.
- The dot on the bottom of the primary and the dot on the top of the secondary indicate that the signals at these points are in phase.
- The voltage gain of the first-stage is equal to the ratio of the output voltage to the input voltage. $A_{v1} = -V_{o1}/V_{i1}$ Note: The negative sign indicates a phase inversion.
- The ac output signals of each amplifier are measured from their respective bases.
- The first stage output signal is smaller than the first stage collector signal because the transformer steps down the signal.
- The collector resistor R9 is the ac output load of Q2.
- The voltage gain of the amplifier's second stage can be expressed by any of the following equations:

$$A_{v2} = -V_{o2}/V_{i2}$$

$$A_{v2} = -R_{L2}/R10$$

$$A_{v2} = -R9/R10$$
- The overall amplifier gain is the product of the gains of the individual amplifier stages.
- The output signal of stage 2 is not quite in phase with the input signal of stage 1. This is caused by the inductive reactance of the transformer.
- The ac cutoff of V_{ce} is higher than the dc supply voltage because of the transformer action.

Exercise 3 – Frequency Response

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the frequency response of a transformer-coupled amplifier by using measured values. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

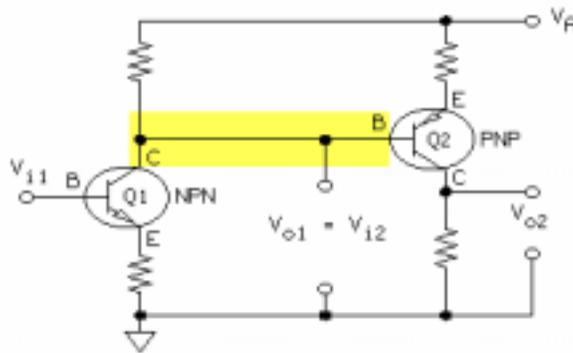
- Voltage gain can be expressed using a logarithmic scale, the unit of logarithmic voltage gain is decibels (dB).
- This equation is used to convert voltage gain into its logarithmic equivalent:
$$A_{\text{vdB}} = 20 \log_{10} (V_o/V_i) = 20 \log_{10} (A_v)$$
- Decibels are used because human hearing has a logarithmic response.
- Doubling the decibel level is the equivalent to a tenfold increase in arithmetic gain.
- Voltage gain in dBs is plotted against the frequency of the input signal, the resulting curve is referred to as the frequency response.
- Transformer-coupled amplifiers have a poorer frequency response than RC-coupled amplifiers. This occurs because the transformer frequency response is limited in comparison to an RC coupling circuit.
- The transformer used on the TRANSISTOR AMPLIFIER CIRCUITS circuit board has a frequency response spec of ± 2 dB between 200 Hz and 10 KHz.

UNIT 9 – DIRECT COUPLING

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a direct-coupled, two-stage amplifier by using measured circuit conditions.

UNIT FUNDAMENTALS



When the output of the first-stage amplifier (Q1) is directly connected to the input of the second-stage amplifier (Q2), the amplifiers are direct coupled.

The frequency response at low frequencies is very good for direct-coupled amplifiers. The dc conditions of each amplifier stage are not isolated. A direct-coupled amplifier is temperature sensitive and requires stabilizing circuits to minimize drifting of the dc bias.

NEW TERMS AND WORDS

None

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
 Multimeter
 Oscilloscope, dual trace
 Generator, sine wave
 TRANSISTOR AMPLIFIER CIRCUITS circuit board

Exercise 1 – Direct-Coupled Amplifier DC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the dc operating conditions of a direct-coupled, two-stage amplifier by using measured values. You will verify your results with a multimeter.

DISCUSSION

- The direct-coupled two-stage amplifier circuit consists of two transistors configured as common emitters. The first stage, Q1, uses an NPN transistor and the second stage, Q2, uses a PNP transistor.
- The output of Q1 (the collector) connects directly into the input of Q2 (the base). The collector voltage of Q1 is equal to the base voltage of Q2. ($V_{C1} = V_{B2}$)
- The emitter voltage (V_{E2}) is about 0.6 Vdc more positive than the base voltage (V_{B2}) when the base-emitter junction of Q2 is forward biased.
- The collector voltage (V_{C2}) is less positive than the base voltage (V_{B2}) since the base-collector junction is normally reverse biased.
- The first stage has a voltage divider network to set the dc bias. The collector voltage of this stage sets the base voltage of the second stage.
- The second stage does not use a voltage divider to establish the dc bias; the resulting bias is more sensitive to temperature changes.
- The emitter resistor in the second stage generates feedback that counteracts dc bias drift due to temperature. But, it is not as effective as voltage divider bias.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Transistor Power Amplifiers

FACET[®]



Student Workbook

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Edition 4



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FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

UNIT 1 – CIRCUIT BOARD FAMILIARIZATION

UNIT OBJECTIVE

At the completion of this unit, you will be able to identify the circuit blocks and their major components on the TRANSISTOR POWER AMPLIFIERS circuit board. You will connect some circuits and observe their operation.

UNIT FUNDAMENTALS

Radio and television receivers, public address systems, tape recorders, and other electronic devices use transistor power amplifiers.

This unit describes the circuit blocks on the TRANSISTOR POWER AMPLIFIER circuit board. Other units include exercises that will help you understand the principles of each type of power amplifier on the circuit board.

NEW TERMS AND WORDS

None

EQUIPMENT REQUIRED

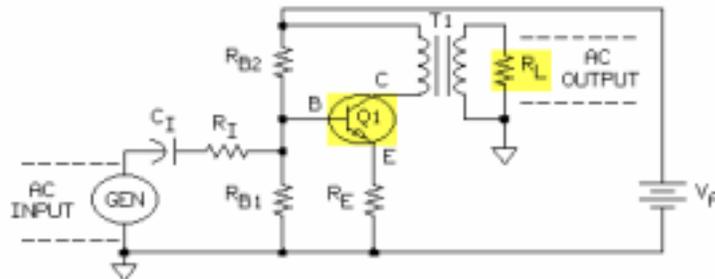
F.A.C.E.T. base unit
TRANSISTOR POWER AMPLIFIERS circuit board
Multimeter
Oscilloscope, dual trace
Generator, sine wave

UNIT 2 – SINGLE-ENDED POWER AMPLIFIER

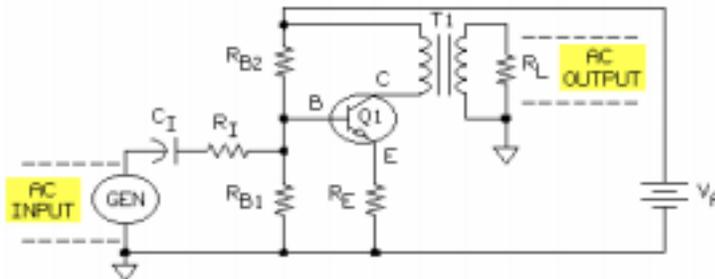
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation of a single-ended power amplifier by using ac and dc measurements.

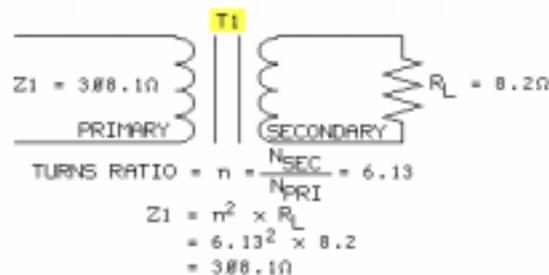
UNIT FUNDAMENTALS



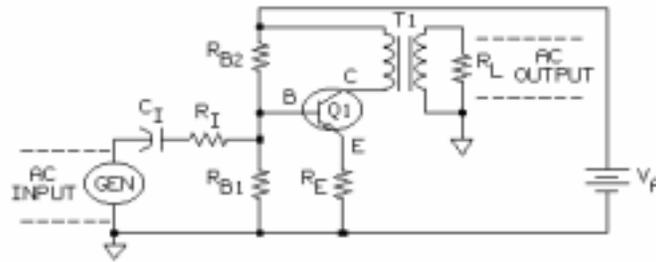
A single-ended **power amplifier** circuit is shown. It has a single transistor (Q1) controlling a current through a load (R_L).



The ac signal is input at R_I to the base of Q1; the output signal is across R_L in the secondary coil of the transformer (T1).



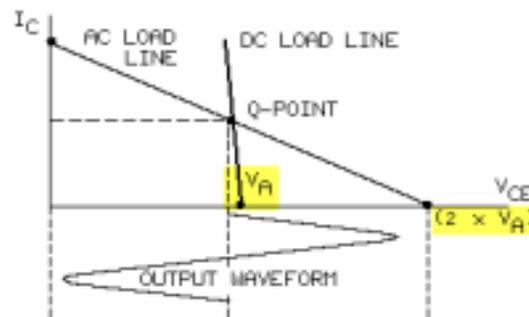
The transformer (T1) is used as an impedance matching device. T1 matches the relatively high impedance ($Z_1 = 308.1\Omega$) of the Q1 collector circuit in the T1 primary coil with a low impedance load ($R_L = 8.2\Omega$) in the T1 secondary coil.



Power gain (A_p) is determined by the ratio of the output power (P_o) to the input power (P_i) or the product of voltage gain (A_v) and current gain (A_i).

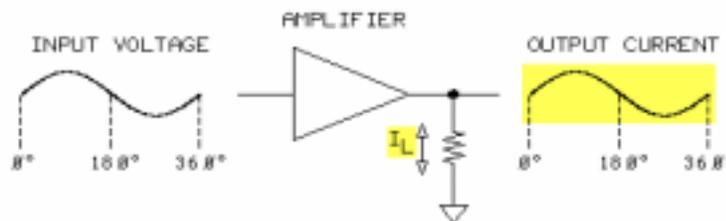
$$A_p = P_o/P_i = A_v \times A_i$$

Power amplifiers have high power gain but low voltage gain.



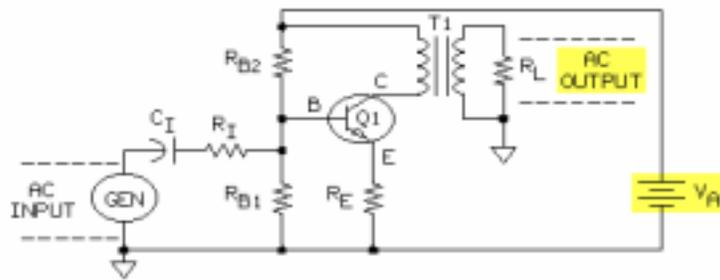
The peak of the collector-emitter voltage (V_{CE}) may exceed the dc supply voltage (V_A) by a factor of two, as shown in the figure.

When a single-ended power amplifier is designed, V_{CE} must not exceed the transistor specification.



Amplifiers can be classified as class A, B, or C. The single-ended power amplifier is biased for continuous current flow (I_L), which causes class A operation.

Because output current flows continuously, class A is the least efficient class of amplifier, but it produces an output signal with practically no amplitude distortion.



A power amplifier's efficiency is determined by the ac output power of the load (R_L) divided by the dc power of the supply (V_A).

NEW TERMS AND WORDS

power amplifier - amplifier that increases the signal power from the input to the output.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
TRANSISTOR POWER AMPLIFIERS circuit board
Multimeter
Oscilloscope, dual trace
Generator, sine wave

Exercise 2 – AC Voltage, Current, and Power Gains

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to identify single-ended power amplifier ac characteristics by determining ac voltage, current, and power gains. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

- Due to the class A operation, there is no distortion or clipping between the input and output
- Calculation of average ac power requires the conversion of the peak-to-peak (pk-pk) ac voltages to root mean square values (rms):

$$V_{\text{rms}} = (V_{\text{pk-pk}} \times 0.707) / 2$$

- The average input ac power to the amplifier (P_i) is the product of the rms values of the ac voltage (V_i) and current (I_i) at the base of Q1:

$$P_i = V_i \times I_i$$

- The output power is the power consumed by load resistor R5. It is the product of the rms voltage drop across (V_o) and rms current through (I_o) R5:

$$P_o = V_o \times I_o$$

- Another form of the power formula may be used when voltage and resistance are known:

$$P_o = V_o^2 / R5$$

- Amplifier voltage, current, and power gains are the ratios of the output values to the input values:

$$\text{Voltage Gain} \quad A_v = V_o / V_i$$

$$\text{Current Gain} \quad A_i = I_o / I_i$$

$$\text{Power Gain} \quad A_p = P_o / P_i$$

- Power gain is also equal to the product of the voltage gain and current gain:

$$A_p = P_o / P_i = (V_o \times I_o) / (V_i \times I_i) = A_v \times A_i$$

- The voltage gain of a power amplifier is low, but the power gain is high because the current gain is very high.

UNIT 3 – PHASE SPLITTER

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate and describe the operation of a transistor phase splitter circuit by using dc and ac measurements.

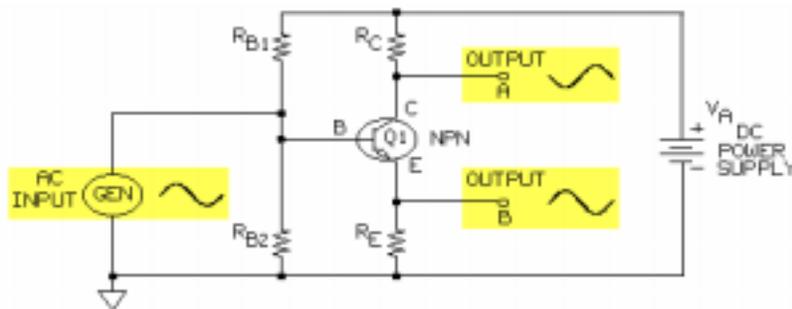
UNIT FUNDAMENTALS



A block diagram of a phase splitter is shown above.

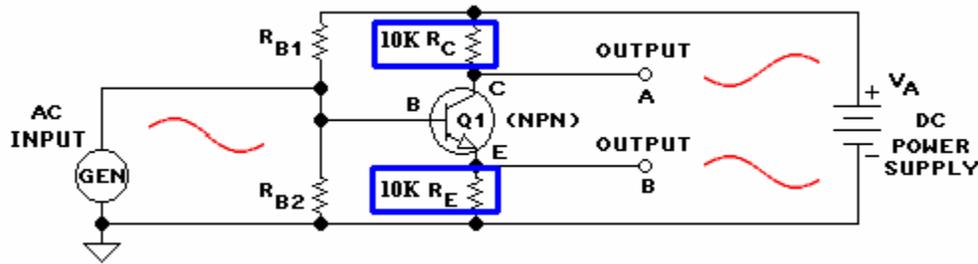
A phase splitter can be a transformer or a transistor circuit.

A phase splitter is a circuit that receives a single input signal and provides two equal amplitude output signals that are 180° out of phase



A **transistor phase splitter** circuit is shown above. The input is at the base of Q1, and the outputs are at the Q1 collector (C) and emitter (E) terminals. The voltage divider circuit (R_{B1} and R_{B2}) across the dc power supply sets a base voltage (V_B) that maintains a stable forward bias for Q1.

Because the voltage divider circuit forward biases the transistor (Q1), the phase splitter operates as a class A amplifier



In a transistor phase splitter circuit, the emitter resistor (R_E) and collector resistor (R_C) are equal. When R_C and R_E are equal, the voltage drop across the collector circuit equals the emitter circuit voltage drop.

Because the emitter (R_E) and collector (R_C) resistors are equal, the voltage gains at outputs A and B of the transistor phase splitter are equal and slightly less than 1.0.

To summarize, a transistor phase splitter is a common-emitter circuit that converts the input signal into two output signals that are 180° out of phase with peak-to-peak voltages essentially equal to the input signal.

NEW TERMS AND WORDS

transistor phase splitter - a transistor circuit that generates two equal signal out of phase, from a single input signal.

EQUIPMENT REQUIRED

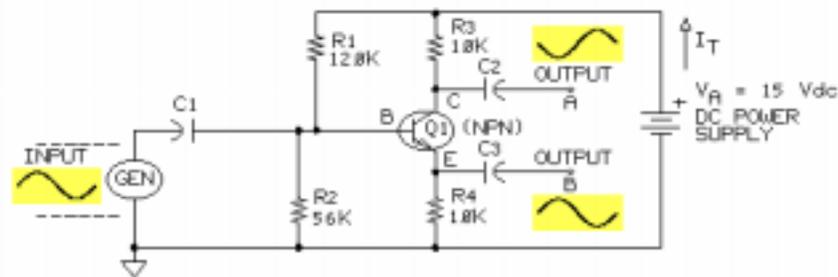
F.A.C.E.T. base unit
 TRANSISTOR POWER AMPLIFIERS circuit board
 Multimeter
 Oscilloscope, dual trace
 Generator, sine wave

Exercise 2 – Voltage Gain and Phase Relationships

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to measure phase splitter voltage gain and phase relationships by using a typical phase splitter circuit. You will verify your results with an oscilloscope and a multimeter.

DISCUSSION



- The input signal is in phase with output signal B at the emitter.
- The input signal is out of phase with output signal A at the collector.
- The ac currents at the input, emitter, and collector are in phase.
- When calculated from circuit resistances, the gain of the phase splitter circuit is less than one even though the measured gain appears to equal one.

$$A_V (\text{output B}) = R_E / R_E + r_e$$

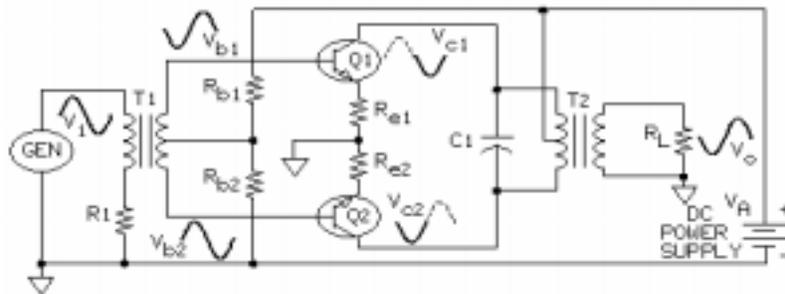
- The outputs at the emitter and collector are equal in magnitude but 180 degrees out of phase.

UNIT 4 – THE PUSH-PULL POWER AMPLIFIER

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a typical push-pull power amplifier by using ac and dc measurements.

UNIT FUNDAMENTALS



A **push-pull power amplifier** circuit is shown. It offers greater power gain and better efficiency than a single-ended amplifier circuit does.

The two transistors (Q1 and Q2) of a push-pull power amplifier require input signals at the base that are equal in amplitude but 180° out of phase.

A push-pull transistor amplifier can use a center-tapped transformer (T1), as shown above, or a phase splitter circuit to provide the two equal 180° out-of-phase input signals.

Because the ac inputs to each transistor are 180° out of phase and the dc bias is near the cutoff point, each transistor conducts during opposite halves of the input signal (V_i). The transistor collector signals are combined into one output signal (V_o) by the output transformer (T2).

Crossover distortion of the output signal is prevented by each transistor being biased near the cutoff point.

Because each transistor operates as a class AB amplifier, the output (V_o) of the push-pull amplifier is a class A signal.

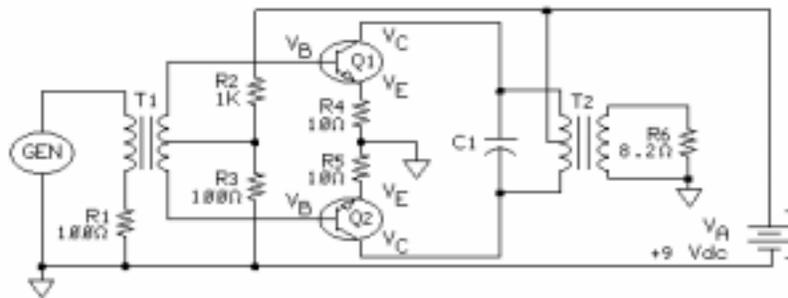
The power gain of the push-pull power amplifier is high because the current gain is very high; the voltage gain is low (less than 1.0).

Exercise 1 – DC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the dc operation of a push-pull power amplifier by using a typical push-pull power amplifier circuit. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION



- Two class AB amplifiers connected back-to-back in a common emitter configuration form a push-pull power amplifier
- Base resistor R2 and R3 form a voltage divider circuit to provide the base voltage for forward biasing the transistors.
- The voltage drop across each transistor is slightly less than the power supply voltage
- The transistors are biased near the cutoff point so that the collector power dissipated is minimum under no-signal conditions.
- Collector current for each of the two class AB transistors flows only during a portion of the input signal; consequently, the total dc circuit current is affected by an ac input signal.
- Transformer T2 matches the relatively high output impedance of the transistors to the low impedance of the load.

Exercise 2 – AC Voltage and Power Gains

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to measure push-pull power amplifier voltage and power gains by using a typical push-pull power amplifier circuit. You will verify your results with an oscilloscope.

DISCUSSION

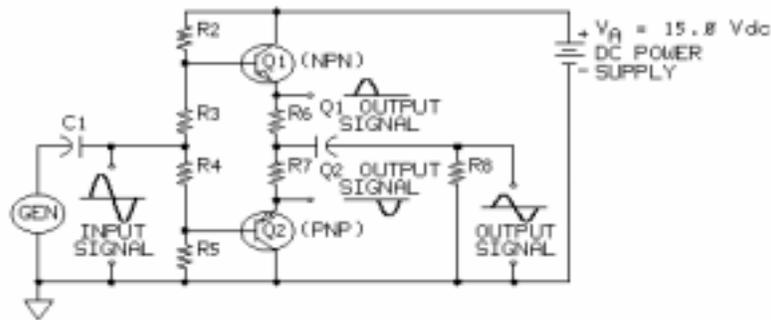
- The input transformer (T1) is used as a phase splitter to develop two signals that are equal in amplitude but opposite in phase to transistors Q1 and Q2.
- Transistor Q1 amplifies the negative half of the input signal, and transistor Q2 amplifies the positive half.
- These half-signals from the transistors are then combined in output transformer T2 to restore the sine wave, which is 180° degrees out of phase with the input signal to T1.
- A small collector current is needed to flow at all times to prevent a type of waveform distortion called cross-over distortion.
- Transistors Q1 and Q2 conduct for more than 180° but less than 360° of the input signal, permitting continuous collector current.
- The power gain is high, but the voltage is not.
- These transistors are considered class AB.

UNIT 5 – THE COMPLEMENTARY POWER AMPLIFIER

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a complementary power amplifier by using measured circuit conditions.

UNIT FUNDAMENTALS



A complementary power amplifier circuit is shown.

A complementary power amplifier consists of an NPN transistor and a PNP transistor connected in series across a dc power supply. The transistors are configured in common collector circuits.

Each transistor operates as class AB, resulting in an output from the complementary power amplifier that is nondistorted.

NPN and PNP transistors have **complementary symmetry**; the biasing is arranged so that the input signal polarity needed to turn on the NPN is opposite that needed for the PNP.

Complementary power amplifiers have high input impedance, low output impedance, high power gain, and good efficiency.

Exercise 2 – AC Voltage and Power Gains

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine voltage and power gains by using a typical complementary power amplifier circuit. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

- The NPN Q1 transistor conducts during the positive half-cycle of the input signal (V_i).
- The PNP Q2 transistor conducts during the negative half-cycle of the input signal (V_i).
- Each transistor conducts for a slightly more than 180 degrees of the input signal, producing an output signal with no cross-over distortion; this is class AB operation.
- The output signal is in phase with the input signal.
- The high power gain is the product of a voltage gain less than 1.0 and a very high current gain.

$$A_p = A_v \times A_i$$

$$P_{in} = V_i \text{ (rms)} \times I_i \text{ (rms)}$$

$$\text{where: } I_i \text{ (rms)} = V_{R1} \text{ (rms)} / R1$$

$$P_{out} = V_o \text{ (rms)} \times I_o \text{ (rms)}$$

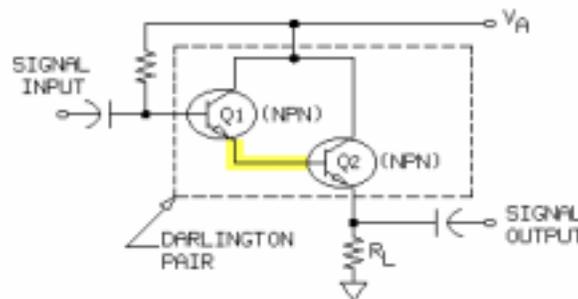
$$\text{where: } I_o \text{ (rms)} = V_o \text{ (rms)} / R6$$

UNIT 6 – THE DARLINGTON PAIR

UNIT OBJECTIVE

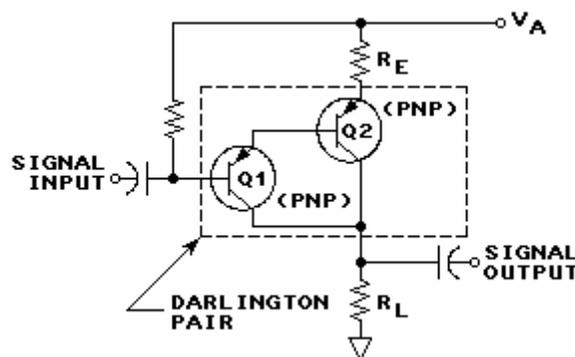
At the completion of this unit, you will be able to demonstrate the operation of a typical Darlington pair by using measured circuit conditions.

UNIT FUNDAMENTALS



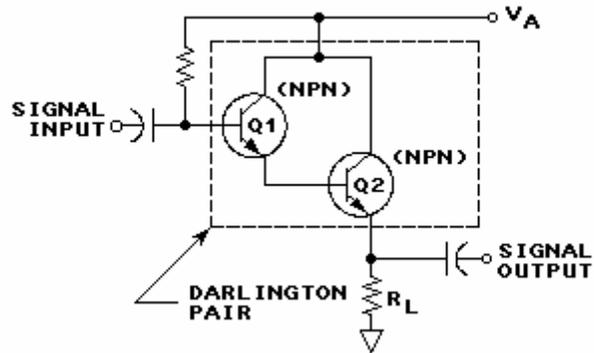
Transistors can be connected in many ways to allow you to take advantage of different characteristics or to make best use of a particular parameter.

A Darlington pair consists of two NPN or PNP transistors (NPN shown) with the emitter of the first stage directly connected to the second stage base.



This circuit shows a PNP Darlington pair in a common emitter configuration.

The Darlington pair acts as a single transistor with an overall current gain (β_D) equal to the product of the individual transistor current gains (β).



The input impedance of a Darlington pair is very large.

When the Darlington pair is connected in a common collector configuration, the output impedance is very small.

The two transistors of a Darlington pair are often mounted in the same case so that both transistors undergo exactly the same changes in temperature and applied voltage.

NEW TERMS AND WORDS

None

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
 TRANSISTOR POWER AMPLIFIERS circuit board
 Multimeter

Exercise 1 – Current Gain Characteristics

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the current gain of a Darlington pair by using measured values. You will verify your results with a multimeter.

DISCUSSION

- A Darlington pair has the emitter of the first stage transistor directly connected to the base of the second stage transistor.
- In a Darlington pair, the Q2 base current (I_{B2}) equals the Q1 emitter current (I_{E1}) or essentially equals the collector current (I_{C1}):

$$I_{B2} = I_{C1}$$

- The Q1 and Q2 betas equal the ratio of the collector and base currents:

$$\beta_1 = I_{C1} / I_{B1}$$

$$\beta_2 = I_{C2} / I_{B2}$$

- The Darlington pair current gain (β_D) equals the Q2 collector current (I_{C2}) divided by the Q1 base current (I_{B1}):

$$\beta_D = I_{C2} / I_{B1}$$

- The Darlington pair current gain (β_D) equals the product of the betas of each stage:

$$\beta_D = \beta_1 \times \beta_2$$

- If the two transistors in a Darlington pair are very carefully matched to have equal betas, the Darlington pair beta (β_D) equals the square of the transistor beta:

$$\beta_D = (\beta)^2$$

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Transistor Feedback Circuits

FACET[®]



Student Workbook

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Edition 4



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FOURTH EDITION

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

UNIT 1 – INTRODUCTION TO THE CIRCUIT BOARD

UNIT OBJECTIVE

At the completion of this unit, you will be able to locate and identify the major circuit blocks on the TRANSISTOR FEEDBACK CIRCUITS circuit board.

UNIT FUNDAMENTALS

The TRANSISTOR FEEDBACK CIRCUITS circuit board consists of 4 circuit blocks:

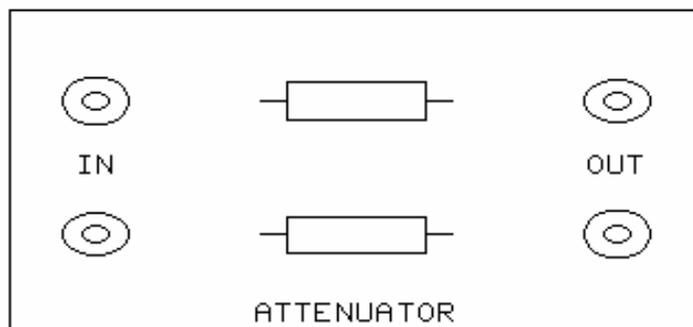
SERIES FEEDBACK/SHUNT FEEDBACK circuit block

MULTISTAGE SHUNT-SERIES FEEDBACK circuit block

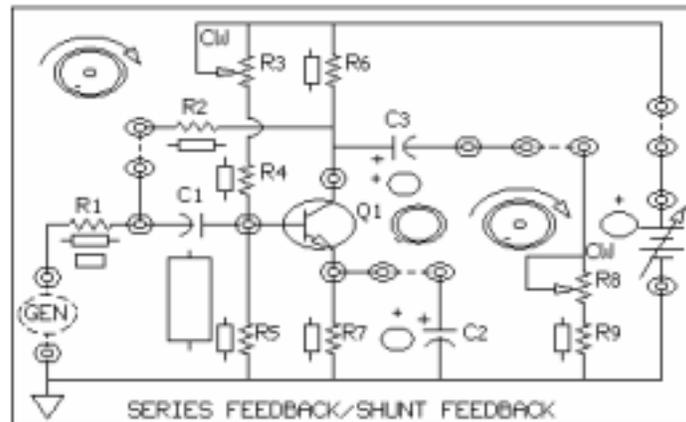
MULTISTAGE SERIES-SHUNT FEEDBACK circuit block

DIFFERENTIAL AMPLIFIER circuit block.

A GENERATOR BUFFER circuit and an ATTENUATOR circuit are also included on the circuit board. Three of the circuit blocks introduce various **feedback** methods. The fourth circuit block is a **differential amplifier**.



The **attenuator** can be used to attenuate or reduce the magnitude of an input signal.



To become familiar with a feedback circuit on the TRANSISTOR FEEDBACK CIRCUITS circuit board, you will set up a typical circuit and use test equipment to look at its operation.

Two-post connectors allow circuit configuration changes and circuit power application.

NEW TERMS AND WORDS

feedback - the return of a portion of an amplifier's output to its input.

differential amplifier - an amplifier whose output signal is proportional to the algebraic difference between two input signals.

attenuator - a passive network that reduces the level of a signal.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine wave

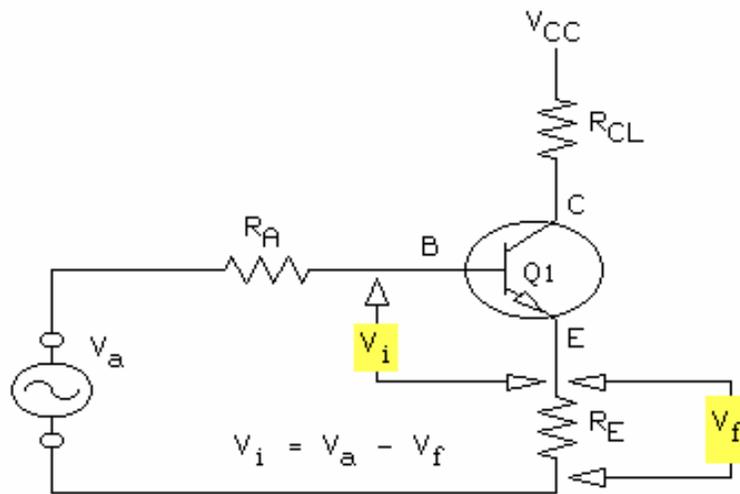
TRANSISTOR FEEDBACK CIRCUITS circuit board

UNIT 2 – SERIES FEEDBACK

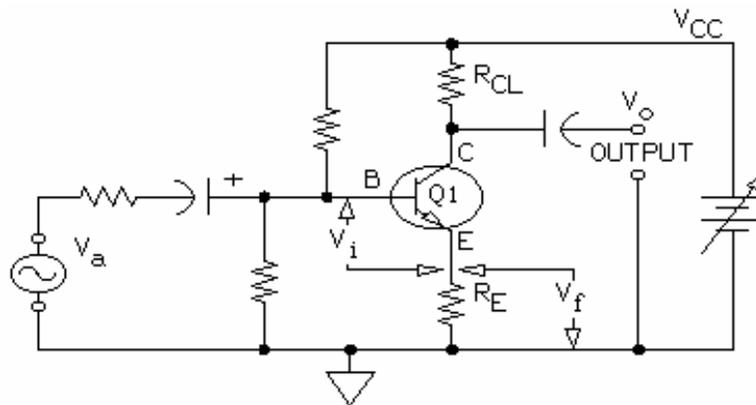
UNIT OBJECTIVE

At the completion this unit, you will be able to describe the effect of a series feedback circuit by using ac and dc measurements.

UNIT FUNDAMENTALS

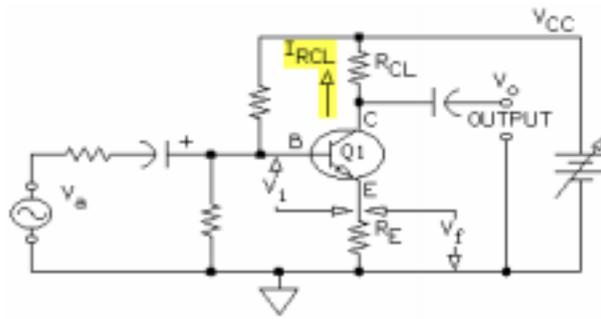


Degenerative feedback also known as inverse feedback or negative feedback, is produced when a portion of an amplifier's output signal is transferred to and opposes the effect of the input.



Negative feedback decreases the gain, increases the bandwidth, and affects the **input impedance** and the **output impedance** of an amplifier. **Series feedback** is applied in series with the input (V_a).

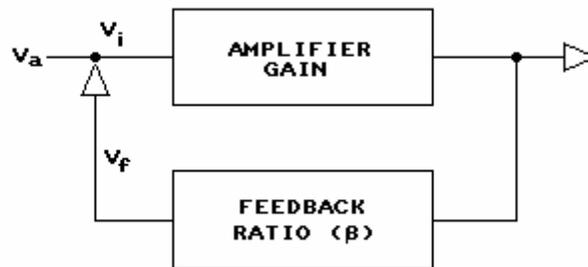
Current feedback is a feedback current that is proportional to output current (I_{RCL}).



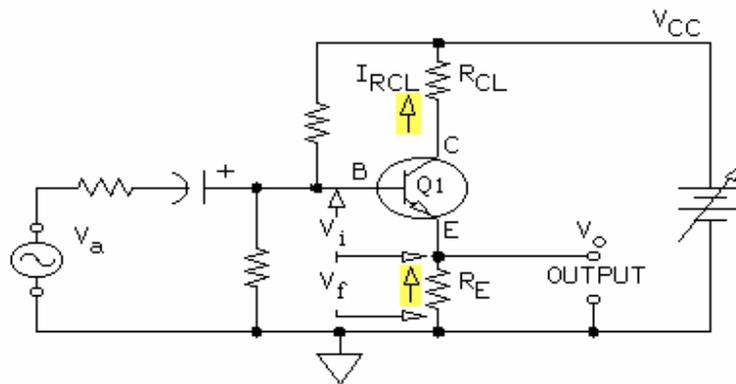
The output current (I_{RCL}) flows through the emitter feedback resistor (R_E).

I_{RCL} through R_E develops a feedback voltage (V_f).

V_f opposes the input voltage (V_a).



The **feedback ratio (β)** is the fractional part of the output voltage that is fed back to the input.



To understand the feedback ratio (β) in a common emitter amplifier such as this one, consider the output taken across the emitter resistor (R_E).

Since all of the output voltage (V_O) is fed back to the input ($V_f = V_O$), the feedback ratio (β) would be 1.

The gain relationship for any type of amplifier with feedback is determined by the following equation, where A_f is the gain with feedback and A is the gain without feedback.

$$A_f = \frac{A}{1 + (A \times \beta)}$$

In case of negative feedback, β is a negative quantity, and you need to take the minus sign into account when you calculate gain.

NEW TERMS AND WORDS

degenerative feedback - a mode of feedback in which a portion of the output is fed back to and opposes the input; also called inverse feedback or negative feedback.

input impedance - the impedance across the input terminals of an amplifier.

output impedance - the impedance across the output terminals of an amplifier; also called source impedance.

series feedback - a feedback signal applied in series with the input signal.

current feedback - a feedback signal that is proportional to output current.

feedback ratio - the portion of the output voltage that is fed back to the input; also referred to as feedback factor.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine wave

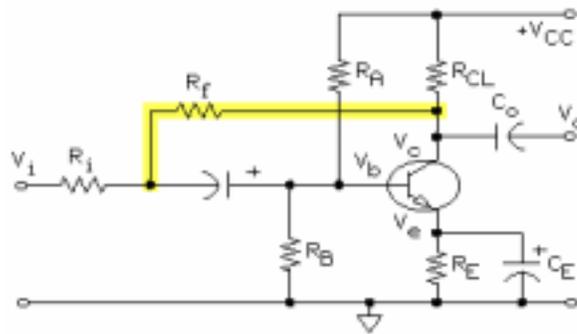
TRANSISTOR FEEDBACK CIRCUITS circuit board

UNIT 3 – SHUNT FEEDBACK

UNIT OBJECTIVE

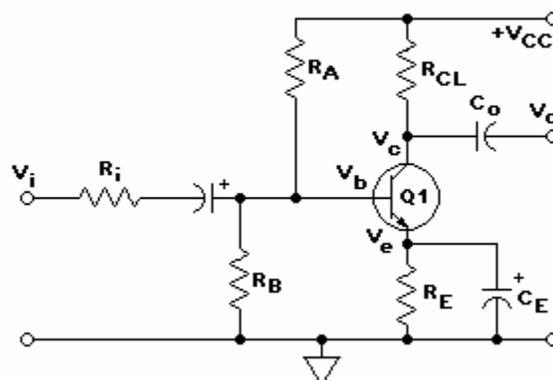
At the completion of this unit, you will be able to describe the effects of shunt feedback on ac gain, bandwidth, input impedance, and output impedance by using a typical shunt feedback circuit.

UNIT FUNDAMENTALS



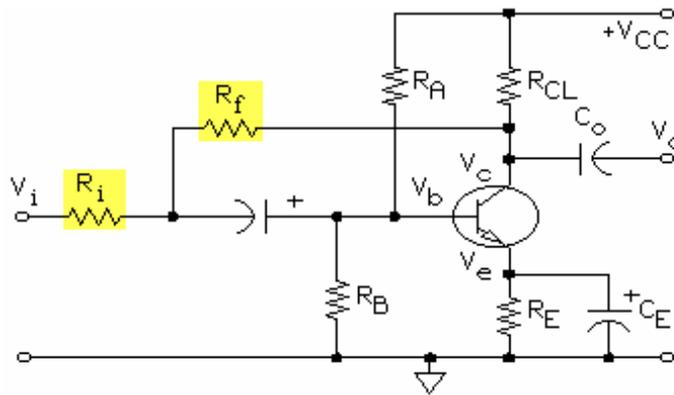
Shunt negative feedback places a portion of an amplifier's output voltage in shunt (parallel) with the input voltage.

Shunt feedback effectively shunts the input and the output of an amplifier.



For a transistor amplifier without feedback, the gain (A) depends on the transistor ac gain (β). For the transistor used in this circuit, β can vary from 50 to 300.

$$A_v = \beta$$



The gain (A_f) of a shunt feedback amplifier equals the ratio of the feedback resistor (R_f) to the series input resistor (R_i).

$$A_f = R_f/R_i$$

For shunt feedback, the feedback ratio (β) is the reciprocal of A_f .

$$\beta = R_i/R_f$$

Therefore, this equation applies.

$$\beta = 1/A_f$$

Negative shunt feedback decreases gain but increases the bandwidth.

NEW TERMS AND WORDS

Shunt feedback - feedback voltage that is effectively applied in parallel with the input signal.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine/square wave

TRANSISTOR FEEDBACK CIRCUITS circuit board

Exercise 2 – Effect of Feedback on Bandwidth

EXERCISE OBJECTIVE

When you have completed this exercise, you will understand the effect of shunt negative feedback on bandwidth by using a typical shunt feed-back circuit. You will verify your results with an oscilloscope.

DISCUSSION

- Bandwidth defines the breadth of input frequency for which the output amplitude remains constant, within prescribed limits
- Limits are usually defined as upper and lower cutoff frequency
- Cutoff frequency is where the gain of an amplifier falls to 3 dB of its average gain
- Average gain means the midrange gain: the gain at the center of its bandwidth
- A square wave can be used to measure bandwidth of an amplifier by checking certain characteristics of the square wave at the output of the amplifier
- As viewed on an oscilloscope, the lower cutoff frequency is the time (T) it takes the square-wave leading edge to reach 63 percent of its final level
- As viewed on an oscilloscope, the upper cutoff frequency is the time it takes the output to fall 63 percent
- Simplified equation for lower (or upper) cutoff frequency is: f_1 (or f_2) = $0.159/T$

Exercise 3 – Effect of Feedback on Impedance

EXERCISE OBJECTIVE

When you have completed this exercise, you will understand the effect of shunt negative feedback on input and output impedance by using a typical shunt feedback circuit. You will verify your results with an oscilloscope.

DISCUSSION

- Bandwidth defines the breadth of input frequency for which the output amplitude remains constant, within prescribed limits
- Limits are usually defined as upper and lower cutoff frequency
- Cutoff frequency is where the gain of an amplifier falls to 3 dB of its average gain
- Average gain means the midrange gain: the gain at the center of its bandwidth
- A square wave can be used to measure bandwidth of an amplifier by checking certain characteristics of the square wave at the output of the amplifier
- As viewed on an oscilloscope, the lower cutoff frequency is the time (T) it takes the square-wave leading edge to reach 63 percent of its final level
- As viewed on an oscilloscope, the upper cutoff frequency is the time it takes the output to fall 63 percent
- Simplified equation for lower (or upper) cutoff frequency is: f_1 (or f_2) = $0.159/T$

UNIT 4 – MULTISTAGE AMPLIFIER FEEDBACK

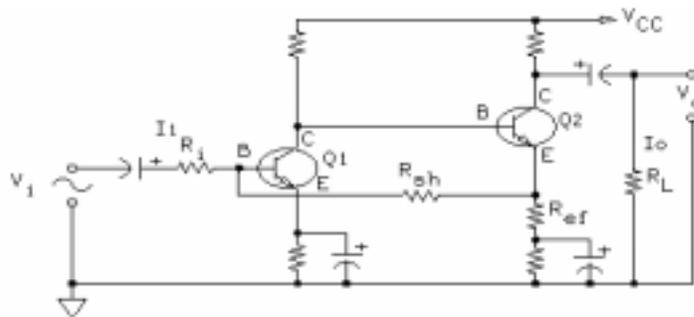
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation and characteristics of two types of multistage feedback amplifiers by using ac and dc measurements.

UNIT FUNDAMENTALS

Multistage feedback is in an amplifier circuit that has more than one stage. This feedback is across the entire amplifier circuit.

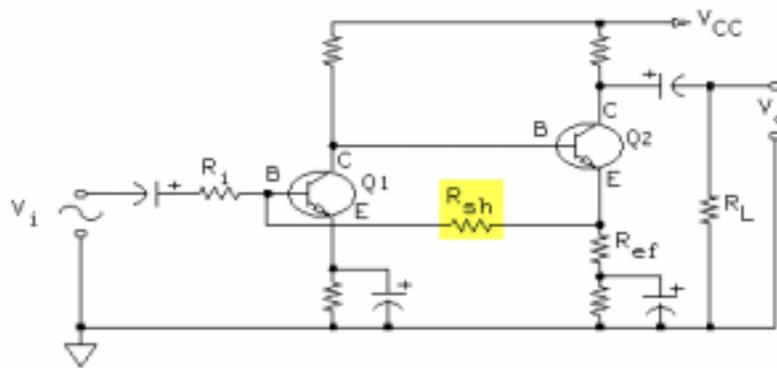
There are two basic types of multistage amplifier feedback: **shunt-series** and **series-shunt**.



Shown is a shunt-series feedback circuit. Resistor R_{sh} provides shunt feedback to the input stage.

Resistor R_{ef} provides series feedback to the output stage.

In a multistage amplifier with shunt-series feedback, the feedback ratio of R_{sh}/R_{ef} determines the ac current gain ($A_i = R_{sh}/R_{ef}$).



Shown is a series-shunt feedback circuit.

Resistor R_{ef} provides series feedback to the input stage.

Resistor R_{sh} provides shunt feedback to the output stage.

In a series-shunt multistage amplifier, the feedback ratio of R_{sh}/R_{ef} determines the voltage gain ($A_v = R_{sh}/R_{ef}$).

NEW TERMS AND WORDS

shunt-series - a multistage amplifier in which the input stage has shunt feedback.

series-shunt - a multistage amplifier in which the input stage has series feedback.

constant current source - a high impedance source that delivers the same load current

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine wave

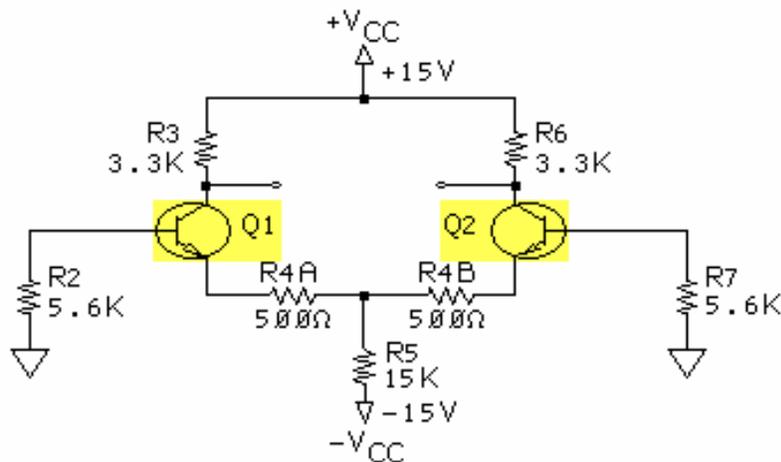
TRANSISTOR FEEDBACK CIRCUITS circuit board

UNIT 5 – DIFFERENTIAL AMPLIFIERS

UNIT OBJECTIVE

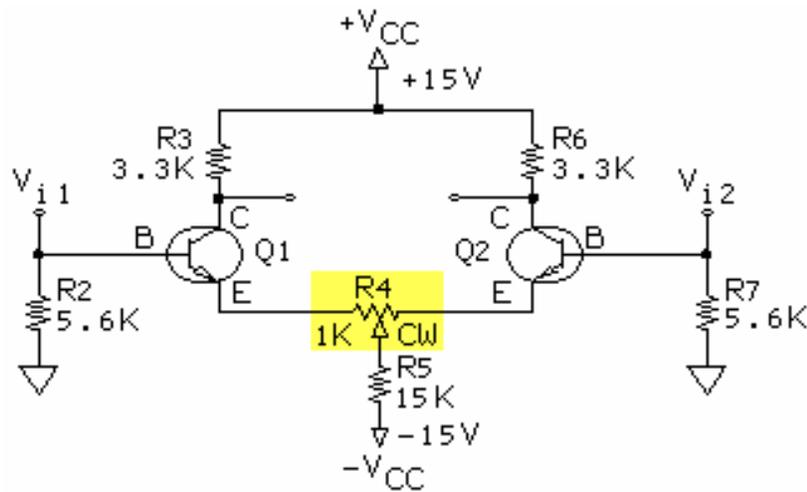
At the completion of this unit, you will be able to describe the operation of a differential amplifier by using ac and dc measurements.

UNIT FUNDAMENTALS



This circuit is a **differential amplifier**. It has two transistors (Q1 and Q2) with equal gains.

The two emitter resistors (R4A and R4B) are tied together and connect to a common emitter resistor (R5). R5 sets the circuit operating current, which divides equally between the two transistors.



A differential amplifier has several modes of operation. You can take the output between the two collectors or from either transistor collector to ground.

The output taken from one collector with respect to ground is called a **single-ended output**. The output taken between the two collectors is called a **double-ended output**, or more commonly, a **differential output**.

A differential amplifier can also have a **single-ended input** signal at either input or a **differential input**, which is applied between the two inputs and is not referenced to ground.

NEW TERMS AND WORDS

differential amplifier - an amplifier whose output signal is proportional to the algebraic difference between two input signals.

single-ended output - an output that is referenced to ground or circuit common.

differential output - an output circuit in which the signal is taken between two levels which are floating; there is no ground (common) reference.

single-ended input - an input that is referenced to ground or circuit common.

differential input - an input circuit that amplifies the difference between two input terminals.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine wave

TRANSISTOR FEEDBACK CIRCUITS circuit board

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Power Supply Regulators

FACET[®]



Student Workbook

91568-00
Edition 4



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FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

UNIT 1 – CIRCUIT BOARD FAMILIARIZATION

UNIT OBJECTIVE

At the completion of this unit, you will be able to identify the circuit blocks and major components on the POWER SUPPLY REGULATION CIRCUITS circuit board.

UNIT FUNDAMENTALS

Most electronic devices require power supply regulation circuits.

A power supply regulation circuit provides a constant voltage or current to a system when changes in the line voltage or load resistance occur.

NEW TERMS AND WORDS

integrated circuit (IC) - any electronic device in which active and passive elements are contained in a single package.

discrete - an individual circuit component, complete in itself, such as a resistor, diode, capacitor, or transistor, used as an individual and separable circuit element.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

POWER SUPPLY REGULATION CIRCUITS circuit board

Exercise 1 – Circuit Location and Identification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the functional circuit blocks on the POWER SUPPLY REGULATION CIRCUITS circuit board. You will use the circuit board to locate and identify circuit components.

DISCUSSION

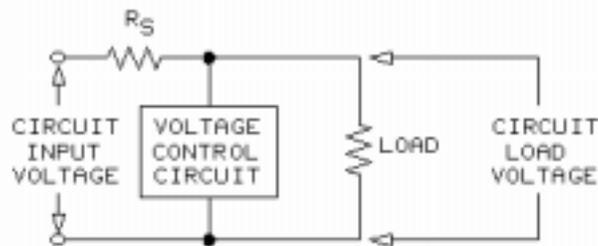
- The six power supply regulation circuits on the POWER SUPPLY REGULATION CIRCUITS circuit board are:
 - Shunt Voltage Regulator
 - Series Voltage Regulator
 - Current Regulator
 - Voltage Feedback Regulation
 - IC Regulator
 - DC to DC Converter
- The SHUNT VOLTAGE REGULATOR consists of a transistor in parallel with the load. Two-post connectors are used to energize the input and select the load resistor.
- The SERIES VOLTAGE REGULATOR consists of a transistor in series with the load. Two-post connectors are used to energize the input and select the load resistor.
- The CURRENT REGULATOR requires a two-post connector to energize the circuit, and a second two-post connector to provide a series connection between the PNP transistor and the circuit load.
- The VOLTAGE FEEDBACK REGULATOR is an enhanced version of a series voltage regulator. This regulator has circuits which provide overload protection and output voltage adjustment.
- The IC REGULATOR has an adjustable three-pin regulator which can be configured as a fixed or an adjustable voltage or current regulator.
- The DC to DC CONVERTER utilizes a switching regulator IC. The IC uses an inductor to increase the applied voltage.
- Both the IC REGULATOR and the DC to DC CONVERTER require a two-post connector to energize the input circuits.

UNIT 2 – SHUNT VOLTAGE REGULATOR

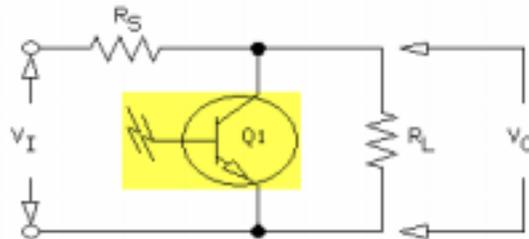
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation, line regulation, and load regulation of a shunt voltage regulator.

UNIT FUNDAMENTALS



A shunt regulator is designed to maintain a nearly constant load voltage for changes in line (input) voltage or load resistance.



A **shunt voltage regulator** uses a regulating device, usually a transistor, in parallel (or in **shunt**) with the circuit output.

The transistor forces more or less current through R_S as a means to control the load, or output, voltage (V_O).

Transistor current is added to the load current. Total circuit current flows through R_S .

The performance of a shunt regulator is determined by its ability to maintain a constant load voltage.

Line regulation expressed as a percentage, indicates the ability to maintain a constant load voltage for variations in circuit line (input) voltage.

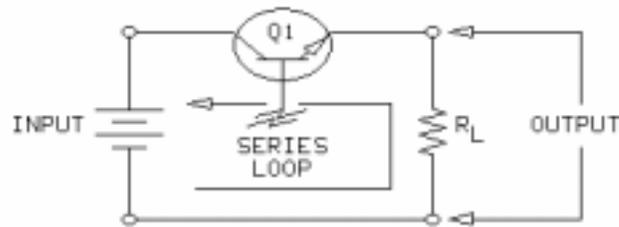
Load regulation expressed as a percentage, indicates the ability to maintain a constant load voltage for variations in circuit load resistance.

UNIT 3 – SERIES VOLTAGE REGULATOR

UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation, line regulation, and load regulation of a series voltage-regulating circuit.

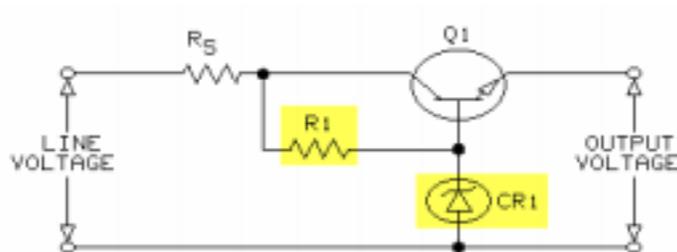
UNIT FUNDAMENTALS



A **series regulator** has a regulating transistor ($Q1$) in series with the output (circuit load R_L).

$Q1$ is referred to as the series **pass transistor** because all of the load current must pass through the transistor.

The series regulating configuration shown is also referred to as an **emitter follower** circuit.

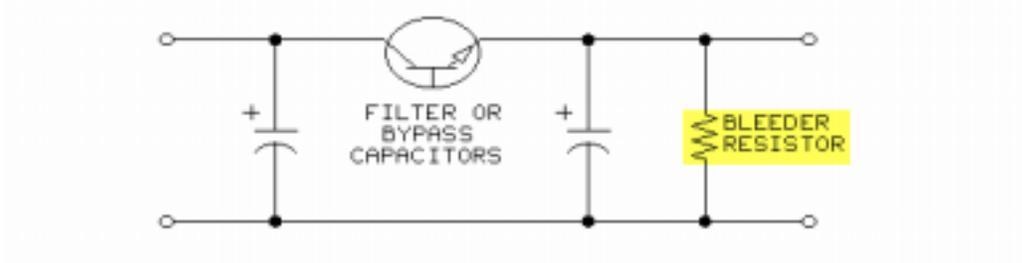


In the series regulator, the voltage drop across $Q1$ is varied to maintain a nearly constant output voltage.

R_S , in series with $Q1$, reduces the power dissipation of $Q1$.

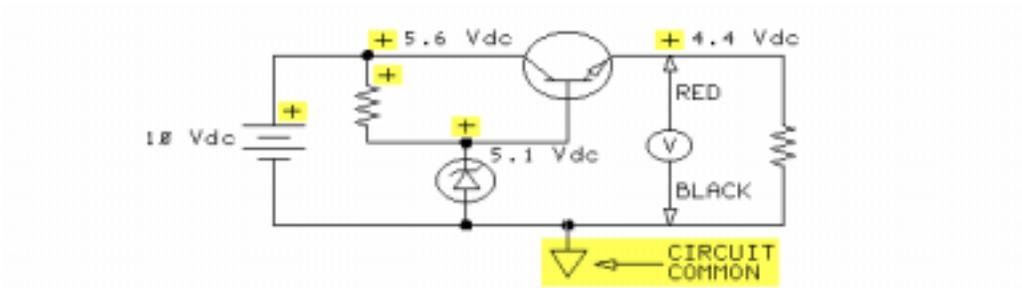
$R1$ provides the base current for $Q1$ and the bias current for zener diode $CR1$.

$CR1$ provides the circuit reference voltage.



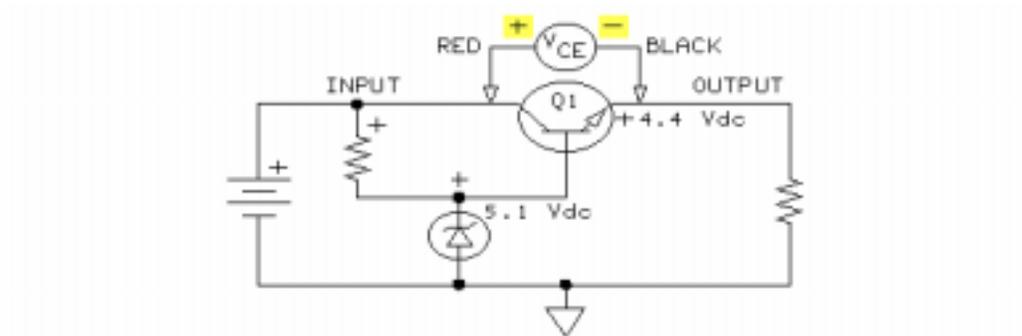
In typical applications, input and output bypass capacitors are used to provide stability (prevent undesired oscillations) to the circuit.

A **bleeder resistor** is used to maintain a minimum circuit load current.

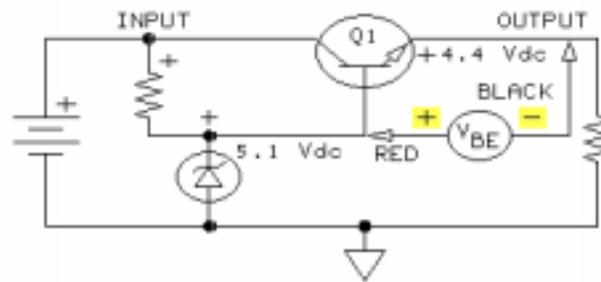


The polarity of a specific voltage is determined by the reference point selected.

Unless noted, all voltages are with respect to circuit common.



Since the input (collector) of Q1 (an NPN transistor) is more positive than the output (emitter) of Q1, V_{CE} of Q1 is measured as shown.



The voltage at the base of Q1 is more positive than the voltage at the emitter of Q1. V_{BE} of Q1 is measured as shown.

NEW TERMS AND WORDS

series regulator - a voltage-regulating circuit that uses a series pass transistor.

pass transistor - a name commonly applied to a series regulating element because all output current must pass through this device.

bleeder resistor - a resistor that is connected across a circuit to provide a minimum circuit load.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

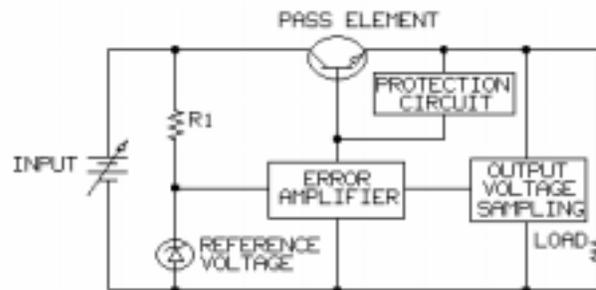
POWER SUPPLY REGULATION CIRCUITS circuit board

UNIT 4 – VOLTAGE FEEDBACK REGULATION

UNIT OBJECTIVE

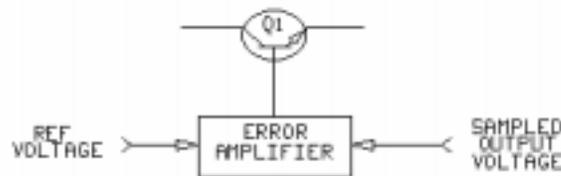
At the completion of this unit, you will be able to demonstrate the operation of a voltage feedback regulator circuit that uses active foldback current limiting.

UNIT FUNDAMENTALS



This is a block diagram of the series pass feedback voltage regulator used in this unit.

With exception to the error amplifier, output voltage sampling, and protection circuit, the regulator functions as an emitter follower (standard series pass regulator).



The circuit output voltage is controlled by varying the conduction of Q1, the series pass transistor.

The conduction of Q1 is controlled by the error amplifier circuit, which varies the base current of Q1.

Should an overload or short circuit occur, the active protection circuit reduces the output (load) current and voltage.

An activated **foldback** protection circuit draws current away from the base of the pass transistor to reduce its conduction.

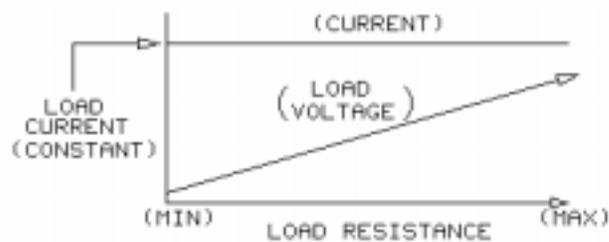
UNIT 5 – CURRENT REGULATOR

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a current regulator.

UNIT FUNDAMENTALS

An ideal **current source** provides a constant load (output) current regardless of line (input) or load changes.



Based on Ohm's law ($E = I \times R$), a constant current through a variable load resistance generates a load voltage directly related to the value of the resistance.

Transistors can be configured to generate a constant current output.

Within design limits, practical current sources can provide line regulation and load regulation (maintain a near constant output current).

NEW TERMS AND WORDS

current source - a power source whose output is stated in terms of current. A current source provides a fixed value of current independent of the load.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

POWER SUPPLY REGULATION CIRCUITS circuit board

Exercise 2 – Current Regulator Line Regulation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to calculate the percentage of current regulator line regulation. You will verify your results with a multimeter.

DISCUSSION

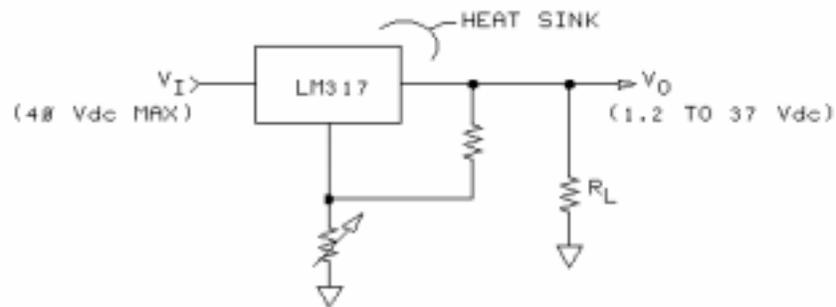
- A current regulator with good line regulation maintains nearly constant load current when variations of input voltage occur.
- Determine line regulation by maintaining a constant load resistance as the input voltage is varied between specific limits.
- This equation is used to calculate percentage line regulation:
$$\text{Line regulation} = [I_{L(\max)} - I_{L(\min)}] / I_{L(\min)} \times 100$$
- The constant current is determined by the voltage drop across R1.
- Variations in line voltage affect the current and voltage of CR1. Zener diode voltage variations affect the voltage across R1 and V_{BE} of Q1.
- V_{BE} is nearly constant; therefore, it is the voltage drop across R1 that varies and determines whether circuit current increases or decreases.

UNIT 6 – THREE-PIN IC REGULATOR

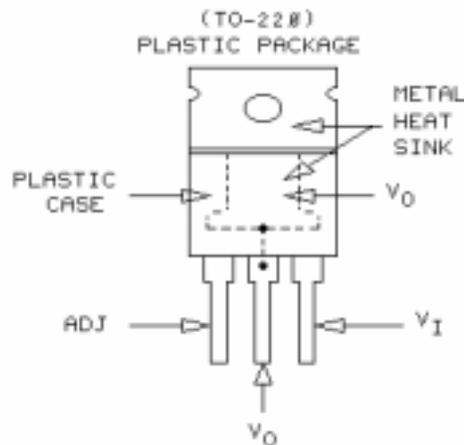
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of an adjustable three-pin integrated circuit power supply regulator.

UNIT FUNDAMENTALS

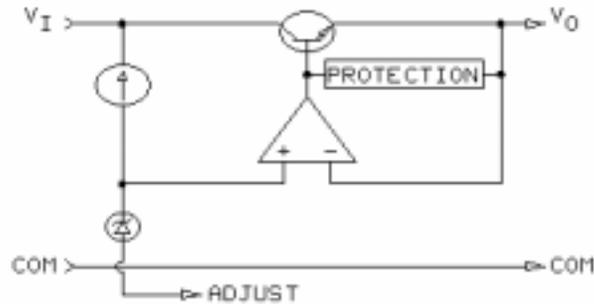


The LM317 adjustable three-pin **integrated circuit (IC)** regulator is designed to provide an adjustable positive output voltage.



The LM317 IC is housed in a TO-220 type plastic package. It can provide a maximum load current of 1.5A and dissipate 15W of power.

A heat sink, which is a metal tab attached to the internal chip, removes heat from the device.

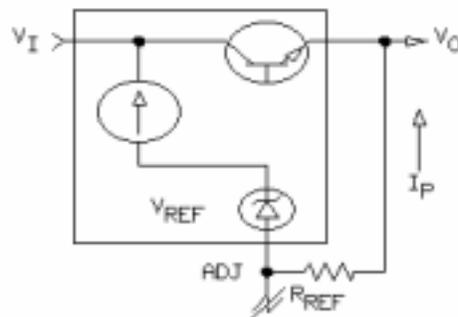


The functional diagram of the regulator illustrates its similarity to the voltage feedback series pass regulator. Output voltage (V_O) is compared against the circuit reference voltage (zener diode) by the operational amplifier (error amplifier). The op amp output drives the base of the series pass transistor.

The internal reference zener diode current is provided by a constant current source. The current source buffers the zener diode from variations of line voltage. Protective circuits, which shut down the pass transistor, ensure that the regulator is not stressed beyond its maximum operating limits. The three-pin IC regulator can be configured as a voltage or current regulator with fixed or variable outputs.

Adjustability is derived from the application of Ohm's law to the voltage reference (ADJ terminal) of the IC.

Based on Ohm's law, a resistor in series with a voltage causes current to flow: $I = E/R$.



The programming current (I_P) required to operate the LM317 regulator is obtained from the IC ADJ voltage and an external resistance (R_{REF}).

$$I_P = V_{ADJ}/R_{REF}$$

For this regulator family, the programming current is essentially constant because V_{ADJ} is constant.

Exercise 2 – Current Regulation and Power Efficiency

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate three-pin IC current regulation and determine IC power dissipation. You will verify your results with a multimeter.

DISCUSSION

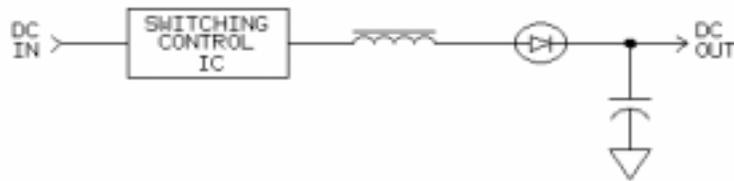
- An LM317 can be configured as a constant current source (current regulator).
- R_P is selected for a specific current output and the reference voltage of the IC is essentially constant.
- Current regulation is maintained by the combined internal reference voltage and op amp producing a constant voltage across R_P .
- Current regulation and voltage regulation depend on a constant voltage across R_P .
- Voltage regulator configuration uses the programming current flowing through R_2 to set the circuit output voltage. Once set, the output voltage is constant and the output current varies depending on the load resistance.
- Current regulator configuration uses the programming current as the circuit constant current output and flows through R_2 . Output current is constant and the output voltage varies depending on the load resistance.
- Power is dissipated by the regulator. $\text{Power} = V_D \times I_{RL}$ (where $I_{RL} = V_{REF}/R_P$ or I_K of the circuit).
- Power consumed by the IC regulator is not available to the load. Therefore, power efficiency is less than 100%.
- Power efficiency is the power consumed divided by the line power. Multiply by 100 to obtain percentage.
$$\%PE = (P_{LOAD} / P_{LINE}) \times 100.$$

UNIT 7 – DC TO DC CONVERTER

UNIT OBJECTIVE

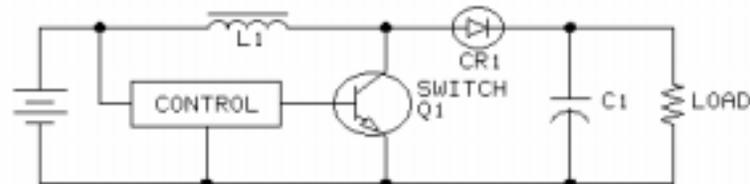
When you have completed this unit, you will be able to demonstrate the operation of an IC switching regulator configured as a dc to dc converter.

UNIT FUNDAMENTALS

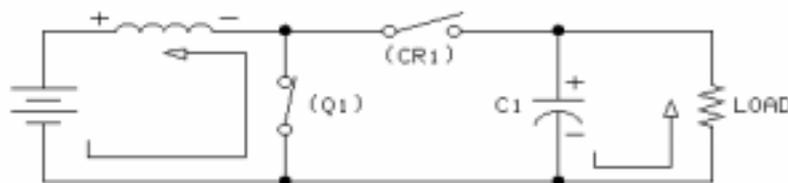


A dc to dc converter transforms a dc input voltage from one level to a different level.

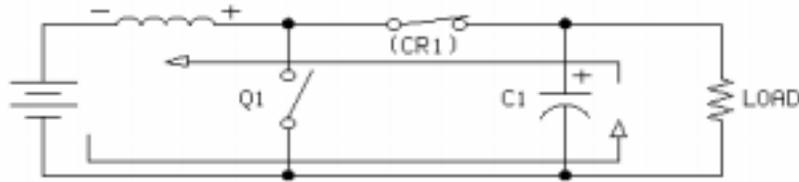
The output voltage may be higher or lower than the input voltage, and the output polarity may be the same as or opposite to that of the input.



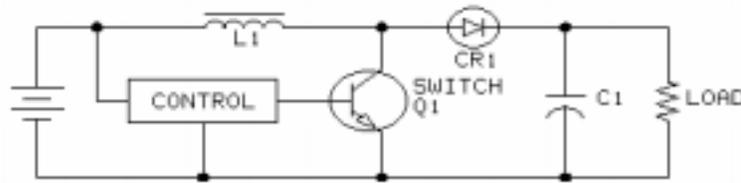
In general, dc to dc converter circuits control a transistor switch (Q1) that is used to charge an inductor (L1) with energy.



When transistor switch Q1 is turned on, energy is stored in the inductor, CR1 is reverse biased (off), and C1 supplies (discharges) energy to the load.

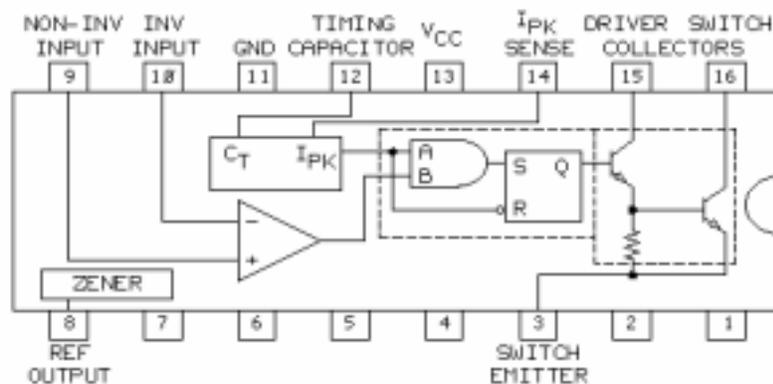


When transistor switch Q1 is turned off, energy from the inductor flows through CR1 (now forward biased) into C1 and the load.



A typical dc to dc converter circuit uses a transistor switch to chop up the dc line voltage into high frequency **pulses**. The pulses are rectified and filtered to provide a dc output voltage.

Due to the high frequency pulses (25 kHz or higher), the rectifier and filter components are generally smaller in size than required in conventional linear power supplies.



On your circuit board, a 78S40 type of universal switching regulator subsystem, housed in a 16-pin molded DIP package, is used for the dc to dc converter circuit block.

The 78S40 is a monolithic regulator subsystem consisting of the active building blocks required for a dc to dc converter circuit.

Exercise 1 – Operating Characteristics

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the operating characteristics of a dc to dc converter. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- The dc to dc converter on the circuit board has three sections:
 - Switching regulator subsystem - controls the voltage switching action of Q1.
 - Inductive storage element and rectifier/filter section - generates a dc output voltage
 - Resistive divider - sample the output voltage and provide feedback control voltage
- The switching regulator subsystem comprises several active circuit blocks (the inductor is an external passive component).
- The oscillator block provides a free-running 25 kHz square wave that drives the transistor switch.
- An error amplifier (comparator) uses the reference voltage and feedback voltage to generate a control voltage.
- A control circuit block modifies the duty cycle of an oscillator circuit that provides the base drive for the transistor switch.
- If the on duty cycle of the free-running oscillator waveform were increased, the transistor switch would remain on longer and the inductor would charge proportionally longer.
- The two-transistor configuration of the transistor switch is referred to as a darlington stage.
- The IC provides a very stable internal band-gap voltage reference (1.25 Vdc nominal) at pin 8.
- Initial circuit output voltage (V_O) is determined by the ratio between R4 and R3 and is expressed by the following: $V_O = 1.25 \times [1 + (R4/R3)]$
- An IC SENSE voltage (V_{R1}) of about 0.3V limits the output current by modifying the switching regulator duty cycle.
- A capacitor connected to pin 12 is used to select the frequency of the internal free-running oscillator.
- R2 provides collector current for the IC driver transistor.
- Inductor L1 charges from V_{CC} through R1 when the transistor switch is on and discharges into the load when the switch is off.
- CR1, a steering diode, ensures that the energy into and out of L1 is properly directed.
- The circuit output voltage appears across R5 and R6. C3 provides output voltage filtering (reduces ripple voltage).
- The R3/R4 voltage divider sets the output voltage by providing a sample (feedback) voltage.
- C2 bypasses the IC reference voltage. This action prevents stray pickup from the IC oscillator from disrupting the circuit regulation.

Exercise 2 – Voltage Regulation and Efficiency

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate regulation and power efficiency of a dc to dc converter. You will verify your results with a voltmeter and an oscilloscope.

EXERCISE DISCUSSION

- Since V_{REF} is a constant reference voltage, the output voltage (V_O) is a function of the R_4/R_3 ratio.
- Initial output voltage is determined as follows: $V_O = V_{REF} \times [(R_4/R_3) + 1]$
- Output voltage is related to the energy transferred by the inductor. Therefore, V_O can also be expressed in terms of the switching transistor on/off ratio.
- Based on the transistor duty cycle, output voltage is determined as shown:
 $V_O = V_I \times [(t_{on}/t_{off}) + 1] - 0.8$. Where: V_I is the circuit input (V_{CC}), and 0.8 V represents the voltage drop of diode CR1.
- Regulation occurs because output voltage variations cause proportional changes in the feedback voltage, V_{R3} .
- A change in V_{R3} is detected by the comparator. The comparator modifies the on/off ratio of Q1, restoring the circuit output voltage.
- The output voltage of the converter varies between a maximum and minimum value. The peak-to-peak variation of the voltage is called ripple.
- There are two major operating areas for the switching regulator IC:
Area A - the output is below a specified limit and must be boosted, or charged, to its proper level.
Area B - the output voltage is above a specified limit and must be allowed to discharge to its proper level.
- Ripple voltage comprises two frequency components:
 1. - The high frequency component, which occurs during boost time, is generated by the switching action of the IC transistor.
 2. - The low frequency component, which occurs because of discharge time, equals the sum of the boost time and discharge time.
- The power efficiency (PE) of your circuit, expressed as a percentage, relates the power consumed by the load (P_L) to the total input power (P_I) required by your circuit.
 $\%PE = (P_L/P_I) \times 100$

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

FET Fundamentals

FACET[®]



Student Workbook

FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

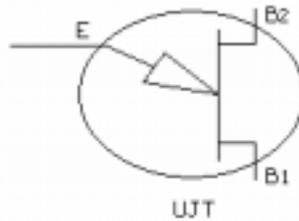
UNIT 1 – CIRCUIT BOARD FAMILIARIZATION

UNIT OBJECTIVE

At the completion of this unit, you will be able to identify the circuit blocks and major components of the FET FUNDAMENTALS circuit board by using the given information.

UNIT FUNDAMENTALS

The FET FUNDAMENTALS circuit board explores the field-effect transistor (FET), the unijunction transistor, and three **transducer** devices. Two types of field-effect transistors (FETs) are discussed: the **junction** FET and the dual gate **metal oxide semiconductor** FET.



A unijunction transistor has only one PN junction. Training is provided on this device by connecting the UNIUNCTION TRANSISTOR circuit block as a **relaxation oscillator**.

Transducers convert energy from one form to another, such as a heat to resistance change. Three transducers, a **thermistor**, a **photoresistor**, and a **fiber optic link** are explored in this unit.

NEW TERMS AND WORDS

transducer - a device that converts energy from one form to another; for example, current to light (LED) or heat to resistance(thermistor).

relaxation oscillator - a type of oscillator in which the active control device turns off (relaxes) for part of the cycle.

thermistor - a device whose resistance varies as the amount of the heat on the device changes.

photoresistor - a device whose resistance varies as the amount of light on its surface changes.

fiber optic link - a path that uses light energy to transmit information.

gate (G) - the FET terminal that corresponds to the base of a transistor.

emitter (E) - the current injection terminal of a UJT.

drain (D) - the FET terminal that corresponds to the collector of a transistor.

fiber optic cable - a low loss cable made of glass fibers. It is used as a path way (or conductor) for the passage of light.

Exercise 1 – Circuit Location and Identification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the functional circuit blocks on the FET FUNDAMENTALS circuit board. You will use the circuit board to locate and identify components.

DISCUSSION

- Five circuit blocks explore a field-effect transistor.
JFET
JFET AMPLIFIER
JFET CURRENT SOURCE
DUAL GATE MOSFET
HARTLEY/COPITTS OSCILLATORS
- One circuit block explores a unijunction transistor.
- Three circuit blocks explore transducers.
THERMISTOR
PHOTORESISTOR
FIBER OPTIC LINK

Exercise 2 – Unijunction Oscillator Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to activate a typical circuit block by applying power to the UNIJUNCTION TRANSISTOR circuit block. You will verify your results with an oscilloscope.

DISCUSSION

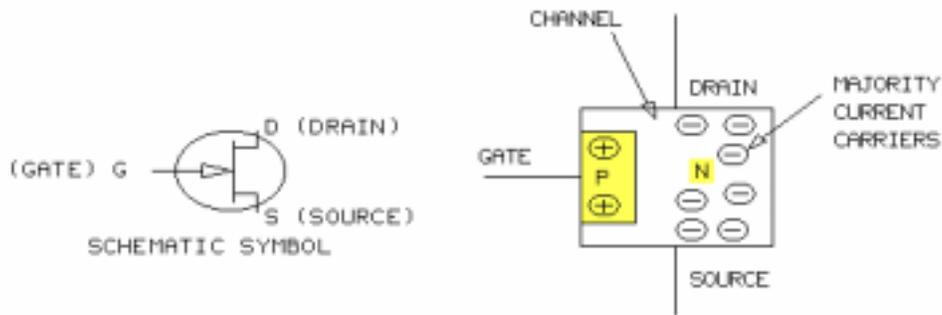
- The circuit produced by the unijunction transistor is called a relaxation oscillator.
- A timing circuit, consisting of an RC network, determines the frequency of the output signal.
- A repeating waveform is produced at each terminal of the UJT when the timing components and power are properly connected.

UNIT 2 – JUNCTION FETS

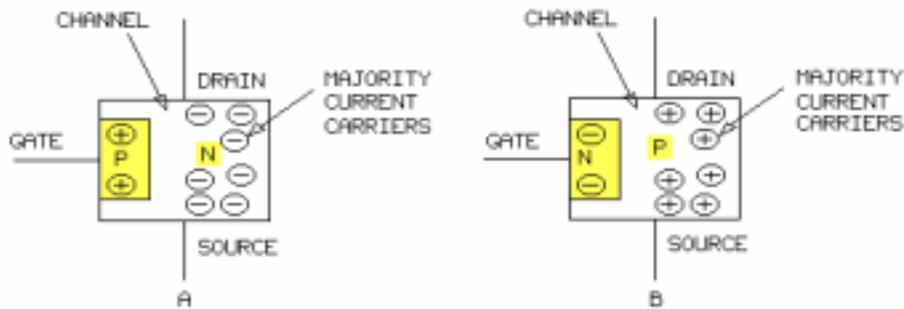
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation of a junction field-effect transistor (JFET) by using dc and ac measurements.

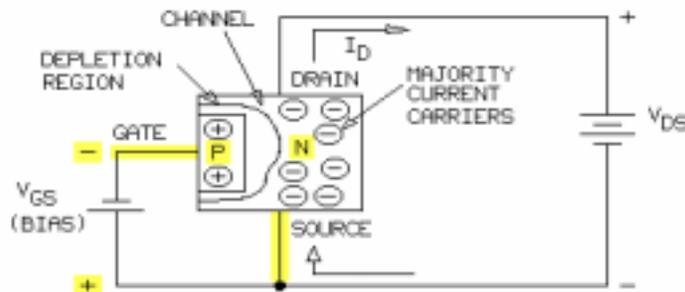
UNIT FUNDAMENTALS



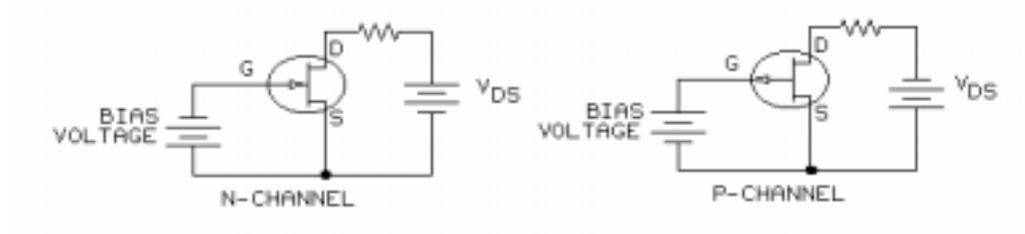
A JFET has three terminals: **gate (G)**, **source (S)**, and **drain (D)**.



JFETs are either **N-channel** or **P-channel** semiconductor devices.



The figure shows the proper bias for an N-channel JFET. JFETs are voltage-operated, current-controlling devices. A reverse bias voltage, applied between the gate and source terminals, produces a depletion region. The width of the depletion region, determined by the amount of bias, controls the amount of current flow through the **channel**.



Shown are the schematic symbols and proper bias voltages of an N-channel and a P-channel JFET.

NEW TERMS AND WORDS

gate - the FET terminal that corresponds to the base of a transistor.

source - the FET terminal that corresponds to the emitter of a transistor.

drain - the FET terminal that corresponds to the collector of a transistor.

N-channel - an FET device with a P type (doped) gate material.

P-channel - an FET device with an N type (doped) gate material.

channel - the source to drain controlled path for current flow through an FET device.

ohmic region - the linear operating area between a JFET's off and saturated limits.

pinch-off - FET saturation or constant current region; an operating point at which an increase in drain to source voltage does not produce a change in the drain to source current.

avalanche region - the destructive breakdown area of an FET. It results from excessive drain to source circuit voltage.

pinch-off - FET saturation or constant current region; an operating point at which an increase in drain to source voltage does not produce a change in the drain to source current.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

FET FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Generator, sine wave

UNIT 3 – JFET AMPLIFIER

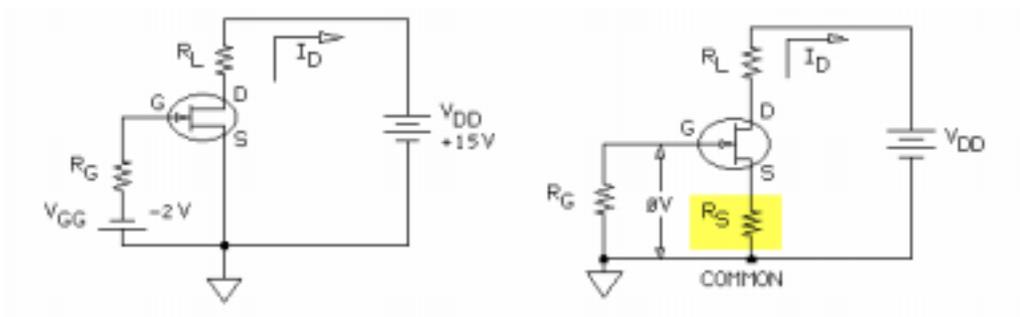
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation of a JFET voltage amplifier by using dc measurements and observed waveforms.

UNIT FUNDAMENTALS

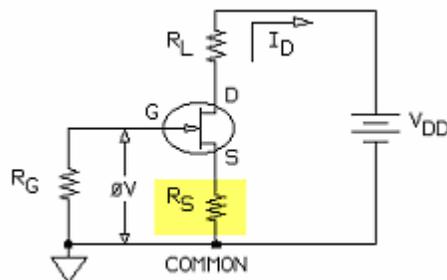
JFET **amplifiers** must be biased correctly to:

1. establish dc voltages around which undistorted sine waves can occur.
2. stabilize circuit performance against wide device variations between JFETs of the same type.

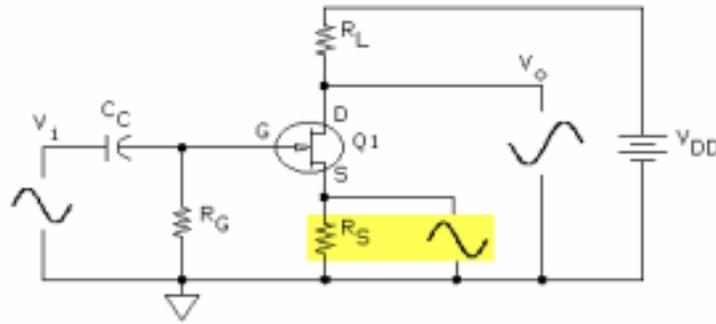


In **common source amplifiers**, two basic methods of bias are used:

1. **fixed bias** (gate bias)
2. **source bias** (self bias)



Source bias improves circuit stability and requires only one power source, V_{DD} .



The ac voltage drop across the bias source resistor (R_S) produces a **degenerative feedback** (reduced circuit gain).

NEW TERMS AND WORDS

amplifiers - circuits that increase the level of an input signal without distortion.

transconductance - a measure of the amplification capability of a JFET, stated in micromhos.

common source amplifiers - circuits having an input signal applied to the gate and an output signal taken from the drain (both with respect to circuit common).

degenerative feedback - feedback that reduces circuit gain but increases circuit bandwidth.

source bypass - capacitive bypass of a source resistor.

fixed bias - a JFET that requires a fixed level of dc bias voltage between the gate and source terminals of the device.

source bias - a JFET bias that requires a resistor in series with the source terminal.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

FET FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Generator, sine wave

UNIT 4 – JFET CURRENT SOURCE

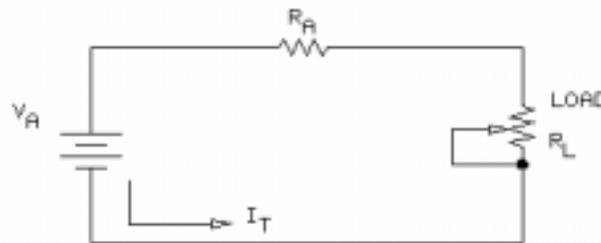
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation of a JFET current source by using dc measurements.

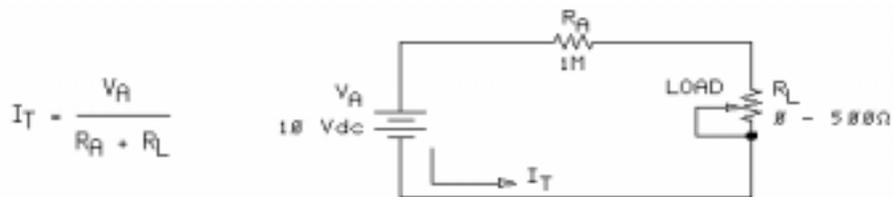
UNIT FUNDAMENTALS



A **constant current source** supplies a fixed value of current to a varying load resistance.



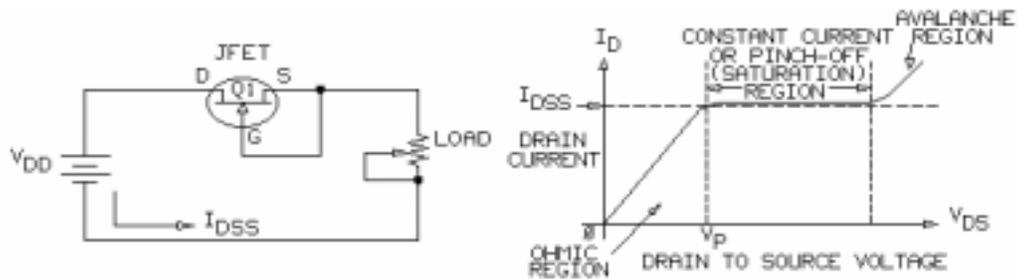
This circuit illustrates the constant current source principle.



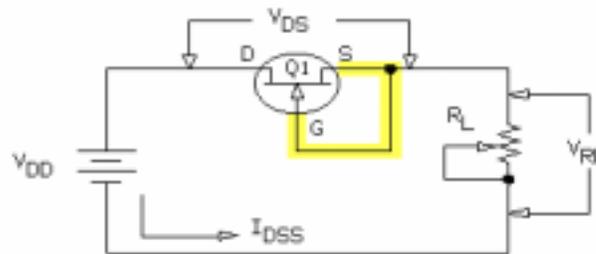
In this circuit, R_A ($1\text{ M}\Omega$) is so much larger than R_L (0Ω to 500Ω) that the circuit current (I_T) is mainly controlled by R_A . Therefore, I_T is determined by the equation below.

$$I_T = V_A / R_A$$

Changes in the load resistor have little or no effect on I_T .



You may connect a JFET as a constant current source by operating it in its pinch-off region.



The JFET current source studied in this unit uses zero gate bias; the gate and source terminals are shorted together.

The **drain saturation current (I_{DSS})** is constant when V_{DS} exceeds the JFET **pinch-off voltage specification**.

NEW TERMS AND WORDS

constant current source - a circuit that supplies a fixed current to a varying load resistance.

drain saturation current (I_{DSS}) - zero gate drain current of a JFET operated in the pinch-off region.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

FET FUNDAMENTALS circuit board

Multimeter

UNIT 5 – DUAL GATE MOSFET

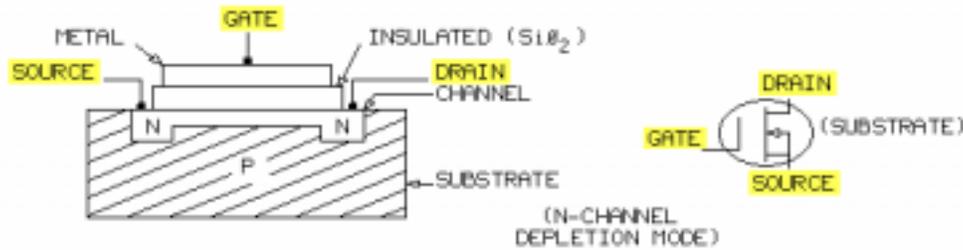
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation of a metal oxide semiconductor field-effect transistor (MOSFET) by using ac and dc measurements.

UNIT FUNDAMENTALS



MOSFETs are either N-channel or P-channel devices.



Similar to a JFET, a single gate **MOSFET** has 3 terminals: gate, source, and drain.

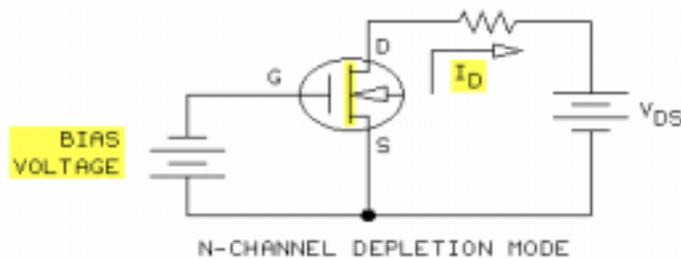
A MOSFET is also known as an insulated gate FET (**IGFET**). The gate is physically and electrically insulated from the device **channel** by a layer of glass-like material (**silicon dioxide**) with excellent insulation properties.



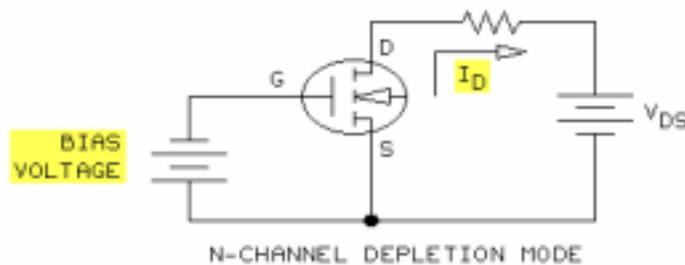
When a MOSFET has two gates, it is known as a dual gate MOSFET.



MOSFETs can operate in either the depletion or enhancement mode. Some devices operate in both modes. The dashed lines in the schematic symbol represent the enhancement mode.



Depletion mode devices are considered to be on until they are depleted, or biased off.



Enhancement mode devices are considered to be off until they are enhanced, or biased on. In this circuit, increasing the positive bias increases drain current (I_D).

NEW TERMS AND WORDS

MOSFET - metal oxide semiconductor field-effect transistor.

IGFET - insulated gate field-effect transistor.

channel - a part of a MOSFET that is continuous from drain to source and is embedded in oppositely doped substrate material.

silicon dioxide - a glass-like oxide insulator used between the gate and channel of a MOSFET device.

Exercise 2 – MOSFET Voltage Amplifier

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the operating characteristics of an N-channel MOSFET amplifier by using a typical test circuit. You will verify your results with an oscilloscope.

DISCUSSION

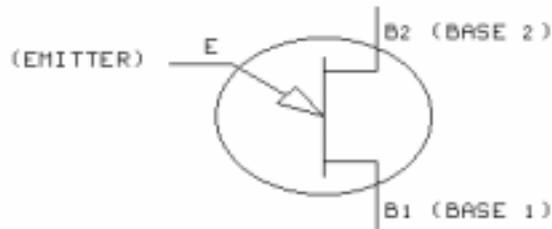
- The circuit shows an N-channel enhancement / depletion mode MOSFET configured for combination fixed bias.
- A combination fixed bias is provided by the source resistor and the fixed bias adjust (R_{ADJ}).
- The fixed bias adjust (R_{ADJ}) varies the gate bias voltage, which establishes the value of the dc drain current.
- When a MOSFET amplifier is properly biased, the drain voltage is approximately half of V_{DD} .
- An N-channel common source MOSFET amplifier amplifies an input sine wave with minimum distortion. The output signal is 180° out of phase.
- A disadvantage of source bias is that it reduces the circuit gain. This effect is reduced by using a capacitor to short the source resistor.
- A coupling capacitor prevents any external dc voltages from upsetting the combination bias.
- The bias divider resistors can be large because the gate terminal draws very little current.
- The MOSFET amplifier is a voltage-control device. Input signal variations in amplitude create variations in drain current which develop a signal voltage across the load resistor.
- The ac voltage gain (A_v) is determined by the ratio of the output voltage (V_o) to the input voltage (V_i). $A_v = V_o/V_i$
- In this circuit configuration the input signal is at gate 1, while a dc level is applied to gate 2 to control the output signal.

UNIT 6 – UNIJUNCTION TRANSISTORS

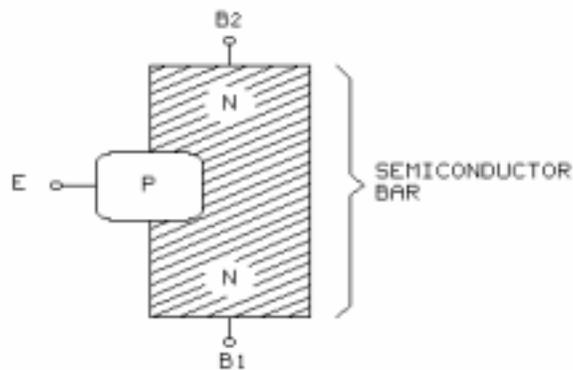
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the dc and ac operation of a relaxation oscillator by using a unijunction transistor test circuit.

UNIT FUNDAMENTALS

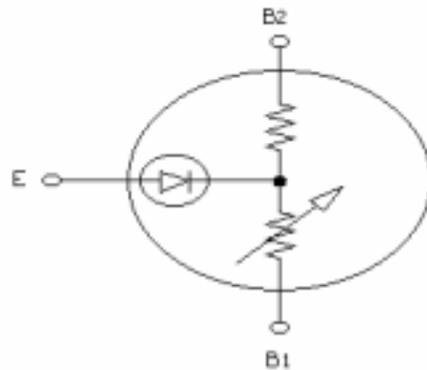


This is the schematic symbol of a unijunction transistor (UJT).

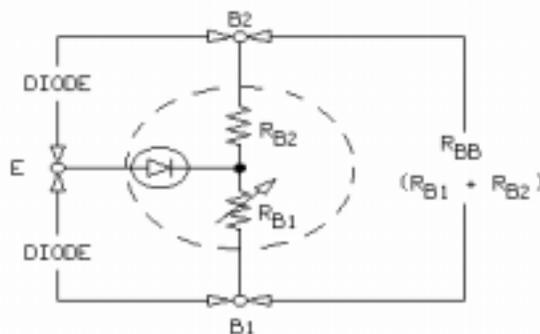


The construction (simplified) of a UJT is shown. A unijunction transistor is a two-layer device. It is constructed with P type material and N type material.

The large bar of N type semi-conductor material joins with a small portion of P type material. The junction of both materials forms a PN junction.



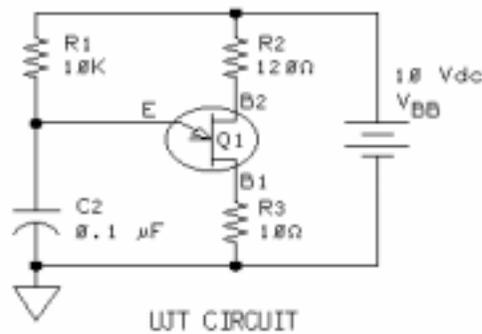
The bar of semiconductor material has resistive characteristics. It can be compared to two resistors connected in series. The PN junction is represented as a diode because it has the same characteristics. The diode (PN junction) connects at a point along the resistance (N type material).



A variable resistor represents the resistance below the diode connection (R_{B1}) because its resistance value initially decreases as the **emitter current** (I_E) increases; the UJT has a **negative resistance** characteristic. When the saturation current is reached, the variable resistance starts to increase again.

The connection between B1 and B2 (R_{BB}) behaves like a resistor. The connection between the emitter (E) and B2 or B1 behaves like a diode (PN) junction.

Values of R_{B2} and R_{B1} are related by a device specification called the **intrinsic standoff ratio**, which is represented by the Greek letter eta (η).



This is a UJT **relaxation oscillator** circuit. A UJT is a nonlinear device that typically switches between on and off states as the voltage at E increases and decreases with the charging and discharging of the timing capacitor (C2).

The UJT is used for timing, triggering, sensing, and wave-form generation circuits such as a relaxation oscillator.

NEW TERMS AND WORDS

emitter current - the base 1 to emitter current that flows after the UJT is fired (conducting).

negative resistance - the unique characteristic of a UJT in which the base 1 resistance and voltage decrease as the base 1 current increases.

intrinsic standoff ratio - a ratio used to determine the firing voltage (V_p) of a UJT; represented by η .

relaxation oscillator - an oscillator that has positive feedback and that switches between off and on states. The off time is called its relaxation time.

graduated voltage drop - the voltage distributed along a bar of semiconductor material (similar to the voltage drops along a string of series resistors); also called voltage gradient.

firing voltage (V_p) - the emitter terminal voltage, with respect to base 1, required for the UJT to conduct emitter current.

valley voltage (V_v) - the emitter terminal voltage at which the UJT moves to its off state

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

FET FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Exercise 1 – UJT Operating Characteristics

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the operating characteristics of a unijunction transistor by using a UJT test circuit. You will verify your results with a multimeter and an oscilloscope.

DISCUSSION

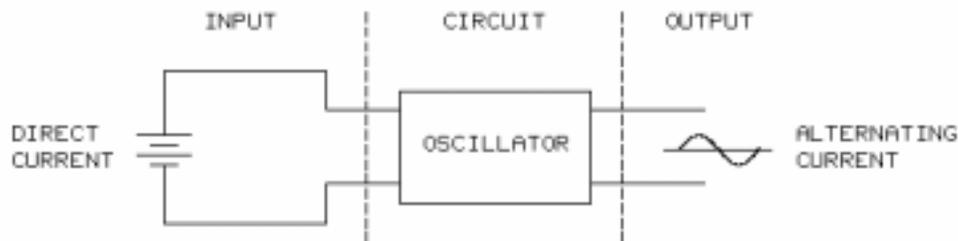
- The diode in the equivalent circuit represents the PN junction.
- The interbase resistance ranges from 4.7 k Ω to 9.1 k Ω for this UJT.
- The emitter voltage (V_E) must be able to overcome the junction voltage (V_J) and the diode drop (V_D) for emitter current to flow.
- Emitter current flows from B1 to the emitter providing a regenerative (positive feedback) effect.
- The regenerative effect gives a UJT its unique negative resistance characteristic.
- No emitter current flows in the cutoff region.
- Once firing voltage is reached at the emitter terminal, emitter current starts to increase (milliampere range).
- Emitter voltage decreases because of the negative resistance effect between the emitter and B1.
- Beyond the saturation region, emitter current increases with emitter voltage and the resistance effect becomes positive again.
-

UNIT 7 – HARTLEY AND COLPITTS OSCILLATORS

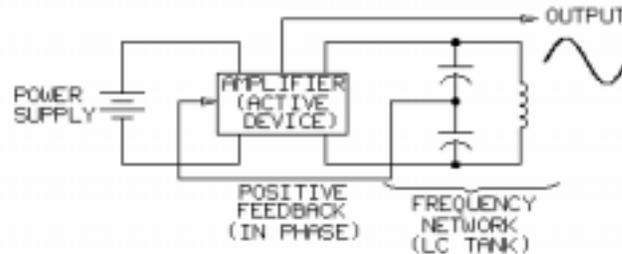
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of JFET Hartley and Colpitts oscillators by using an oscillator test circuit.

UNIT FUNDAMENTALS



An **oscillator** is a circuit that converts direct current to alternating current with a specific frequency.



There are four requirements for a circuit to be an oscillator.

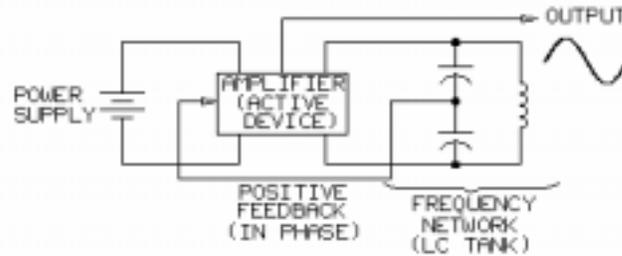
1. a dc power supply
2. an amplifier (active device)
3. a frequency-determining network (such as an LC tank)
4. **positive feedback**(in phase) or **regenerative feedback** which causes a circuit gain greater than 1

The operating frequency of oscillators can range from less than one cycle per second (< 1 Hz) to billions of cycles per second (gigahertz, or GHz).

Hartley and Colpitts oscillators usually operate from about 100 kHz to 100 MHz; a Colpitts oscillator is usually used for the higher frequencies.

The active device (amplifier) of an oscillator may be a bipolar transistor or a FET. The Hartley and Colpitts oscillators in this unit use a JFET as the active device.

When the level of the **feedback signal** is above a critical level and essentially in phase with the amplifier input signal, the circuit oscillations become **self-sustaining**, or self-driven.

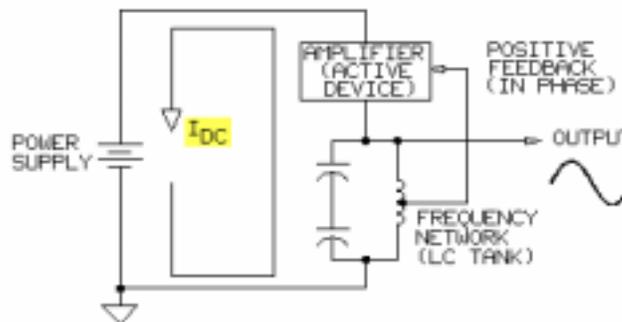


A practical oscillator uses a frequency-determining network to make it oscillate at a predetermined frequency.

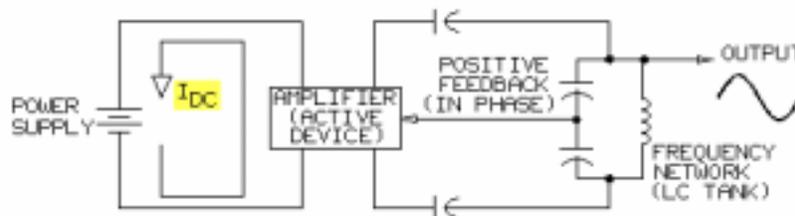
The frequency-determining network, or **tank circuit**, could be a resonant LC (inductor/capacitor) network or an RC (resistor/capacitor) phase shift network.

The frequency-determining network could also be a quartz **crystal** or a **mechanical resonator**

Oscillator circuits may be varied over a range of frequencies if part of the tank circuit is adjustable.



Depending upon the dc power supply configuration, the two general types of oscillator circuits are series fed and shunt fed. In the **series fed oscillator** circuit shown, the dc supply current passes through the amplifier and all or part of the tank circuit.



In a **shunt fed oscillator**, the dc supply current does not flow through the tank circuit.

NEW TERMS AND WORDS

oscillator - a circuit that can convert dc current to ac current at a predictable rate.

positive feedback - a signal returned to the circuit input which is in phase with the circuit input signal.

regenerative feedback - positive feedback.

feedback signal - the part of the circuit output signal returned to the circuit input.

self-sustaining - having sufficient feedback to maintain circuit oscillations without external stimulus.

tank circuit - the frequency-determining components of an oscillator circuit.

crystal - a component made from quartz material. It can be cut or shaped to resonate (oscillate) at very precise and stable frequencies.

mechanical resonator - a nonelectrical component that can oscillate at a predetermined frequency. Examples are springs, pendulums, or tuning forks.

series fed oscillator - a circuit that has direct current within the tank circuit.

shunt fed oscillator - a circuit in which direct current is not present within the tank circuit.

buffer circuits - circuits that have a high input impedance and therefore do not load down the tank circuit of an oscillator.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

FET FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Exercise 1 – Hartley Oscillator Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the operation of a typical JFET Hartley oscillator by using a test circuit. You will verify your results with a multimeter and an oscilloscope.

EXERCISE DISCUSSION

- This JFET Hartley oscillator is shunt fed and uses an LC tank circuit to set the oscillator frequency.
- C1 and C2 are dc blocking capacitors and prevent dc current from flowing through the tank circuit.
- C_S and L1 are used to decouple the dc power supply to prevent circuit oscillations on the power supply (V_{DD}).
- For ac signals the impedance of C_S is low and the impedance of L1 is high.
- The JFET in this circuit is the active component and is a source-biased amplifier.
- The oscillator circuit frequency is determined by the components of the tank circuit (C3, C4, L2 and L3). The resonant frequency can be determined using this formula. $f_r = 1 / (2\pi\sqrt{LC})$ where $L = L2+L3$ and $C = (C3 \times C4) / (C3+C4)$
- The ac feedback signal is from the inductor divider circuit (L2 and L3) within the tank circuit. The ac voltage across L3 is the available feedback. The amount of feedback is set by the feedback adjust circuit (R2 and R3).
- The oscillator becomes self-driven when enough signal is fed back and the feedback is regenerative.
- JFET source bias is developed across R1 and is essentially in phase with the output voltage.
- External circuit connections to the LC tank will cause loading effects. In practical oscillators, the LC tank circuits are isolated to prevent loading.
-

Exercise 2 – Colpitts Oscillator Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the operation of a typical JFET Colpitts oscillator by using a test circuit. You will verify your results with a multimeter and an oscilloscope.

EXERCISE DISCUSSION

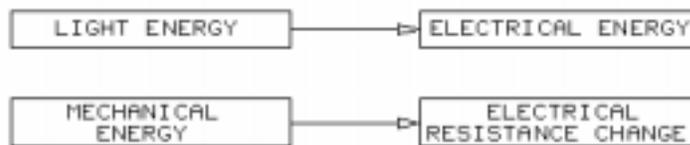
- This JFET Colpitts oscillator is shunt fed and uses an LC tank circuit to set the oscillator frequency.
- C1 and C2 are dc blocking capacitors and prevent dc current from flowing through the tank circuit.
- C_S and L1 are used to decouple the dc power supply to prevent circuit oscillations on the power supply (V_{DD}).
- For ac signals, the impedance of C_S is low and the impedance of L1 is high.
- The JFET in this circuit is the active component and is a source-biased amplifier.
- The oscillator circuit frequency is determined by the components of the tank circuit (C3, C4, L2 and L3). The resonant frequency can be determined using this formula. $f_r = 1 / (2LC)$ where $L = L2+L3$ and $C = (C3 \times C4) / (C3+C4)$
- The ac feedback signal is from the capacitor divider circuit (C3 and C4) within the tank circuit. The ac voltage across C4 is the available feedback. The amount of feedback is set by the feedback adjust circuit (R2 and R3).
- The oscillator becomes self-driven when enough signal is fed back and the feedback is regenerative.
- JFET source bias is developed across R1 and is essentially in phase with the output voltage.
- External circuit connections to the LC tank will cause loading effects. In practical oscillators, the LC tank circuits are isolated to prevent loading.
-

UNIT 8 – TRANSDUCERS

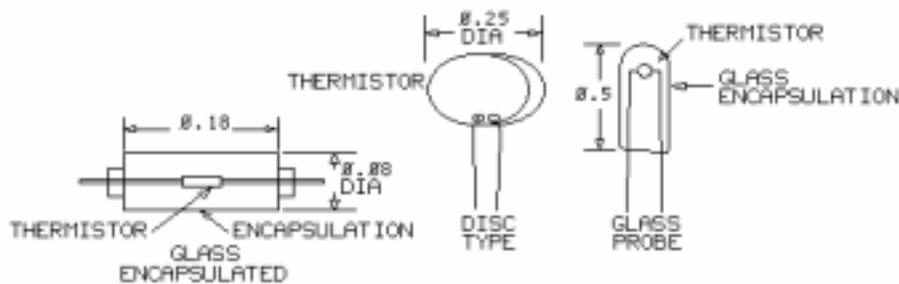
UNIT OBJECTIVE

At the completion of this unit, you will be able to identify and describe the operation of several types of transducers by using a thermistor, photoconductive cell, and fiber optic link.

UNIT FUNDAMENTALS

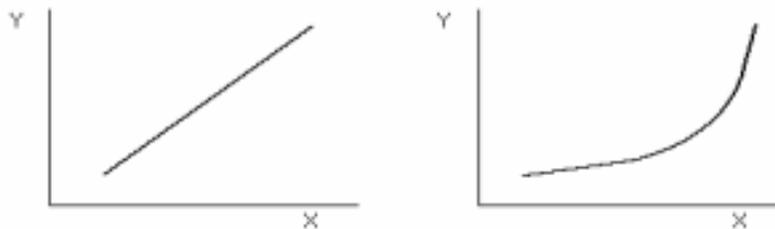


A **transducer** converts one form of energy into a more usable form of energy that is used primarily for measurement and control. Transducers are used for many different applications. They convert a temperature change to a resistance change, a light intensity change to a resistance change, a current to a light source, a light source to a current, and a physical movement to a current.



NOTE: All dimensions are in inches.

Transducers come in many shapes and sizes. They can be very different both physically and electrically.



Transducers may have **linear characteristics** or **nonlinear characteristics**.

Some examples of transducers and their applications are shown.

TRANSDUCER	APPLICATION; METHOD OF OPERATION
Antenna	Communications: converts electromagnetic fields into electric current or converts current into fields.
Bimetallic Strip	Home heating and air conditioning: converts temperature into physical movement.
Crystal	Communications: a quartz material converts physical motion into electrostatic charge or voltage change.
Fiber Optic Link Pair	Communications: converts electrical current into light and light back to electrical current.

Additional examples of transducers and their applications are shown.

TRANSDUCER	APPLICATION; METHOD OF OPERATION
Light-Emitting Diode	Signal indicators: converts electrical current into visible light.
Load Cell	Weighing: converts a push or pull force into a voltage or resistance change.
Photoresistor	Light detector: converts changes in light energy into changes of ohmic resistance.
Strain Gauge	Failure analysis: converts mechanical stress into a resistance change
Thermistor	Temperature control and sensing: converts change of temperature into changes of ohmic resistance.

NEW TERMS AND WORDS

transducer - a device that can transform or convert one form of energy into another form. For example, a transducer (load cell) can convert motion to resistance.

passive device - a device that does not require the application of an external power source.

active device - a device that requires the application of an external power source.

linear characteristics - a type of response where one quantity, such as current, varies directly with a second quantity, such as voltage. A plot of this relationship produces a straight line.

nonlinear characteristics - a type of response where one quantity varies indirectly with a second quantity. A plot of this relationship does not produce a straight line.

thermistor - a component whose resistance is affected by the amount of heat energy to which it is exposed.

self heating - the internal power dissipation generated when current flows through a thermistor.

cold resistance - the resistance of a thermistor at a reference temperature where there is no current flow and therefore a zero self-heating effect.

photoconductive - a material or device whose conduction characteristics are sensitive to changes in light intensity.

Exercise 1 – Thermistor Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the relationship between thermistor resistance and temperature by using self-heated and externally-heated test circuits. You will verify your results with a multimeter.

EXERCISE DISCUSSION

- A thermistor is a thermally-sensitive resistor whose primary function is to exhibit a change in resistance with a change in body temperature.
- Thermistors are used for precise temperature detection, measurement, compensation, or control.
- Thermistors are typically nonlinear and have negative temperature coefficients.
- Thermistors are made by heat-treating, under pressure, a mixture of metallic oxides. The process used is called sintering.
- Thermistors are more sensitive than thermometers. Some thermistors show a resistance change of several thousand ohms per degree of temperature.
- Thermistors respond quickly to changes in temperature; therefore they have a fast time constant.
- Thermistors can be used in passive or active circuits

Exercise 2 – Photoconductive Cell Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the effects of light on the resistance of a photoconductive cell by using a test circuit. You will verify your results with a multimeter.

EXERCISE DISCUSSION

- A photoconductive cell is made of photosensitive semiconductor material whose resistance changes with light intensity.
- Photoresistor is another name for a photoconductive cell.
- In the absence of light the resistance of the cell is very high. When the cell is exposed to light, its resistance decreases.
- The sensitivity of a photoconductive cell is the change in cell resistance when there is a change in cell illumination.
- Photoconductive cells are usually made of a layer of photoconductive semiconductor material, such as cadmium sulfide (CdS) or cadmium selenide (CdSe), on a ceramic substrate. The cell does not have a PN junction.
- When used as part of a voltage divider, photoconductive cells provide a voltage output which is directly or inversely related to light intensity.
- Applications of photoconductive cells include light control and measurement, alarm and relay controls, photometers and photographic exposure control.
-

Exercise 3 – Fiber Optic Light Transmission

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate fiber optic light transmission by using a fiber optic transmitter, cable, and receiver. You will verify your results by observing the status of LEDs at the transmitter and receiver.

EXERCISE DISCUSSION

- Fiber optic technology uses light to transmit electronic signals from sources such as voice, data, and video.
- The electronic signal is multiplexed, modulated, and encoded.
- The groomed electronic signal is converted into an optical signal by the fiber optic transmitter.
- Transmission of optical signals occurs through fiber optic cables, which are composed of glass or plastic fibers with a protective plastic coating.
- The fiber optic receiver converts the optical signal into an electronic signal which is decoded, demodulated, and demultiplexed by the signal processor.
- A light-emitting diode (LED) enclosed within a protective housing functions as the fiber optic transmitter.
- A phototransistor, an amplifier and an open collector transistor driver are the fiber optic receiver.
- The fiber optic cable is terminated with color-coded connectors that match the transmitter and receiver receptacles.
-

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Lab-Volt[®] Basic Electricity & Electronics

Thyristor & Power Control Circuits

FACET[®]



Student Workbook

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Edition 4



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FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

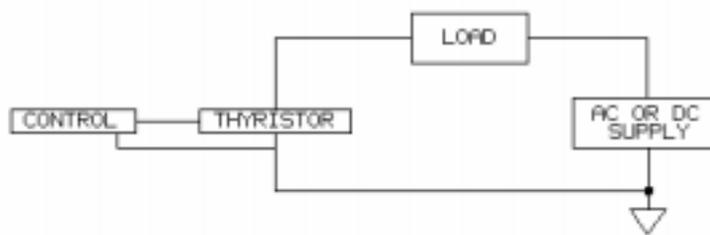
The **Appendix** includes safety information.

UNIT 1 – THYRISTORS & POWER CONTROL CIRCUITS

UNIT OBJECTIVE

At the completion of this unit, you will be able to identify the thyristors and connect and operate circuits on the THYRISTOR & POWER CONTROL CIRCUITS circuit board by applying the information presented in this unit.

UNIT FUNDAMENTALS



A **thyristor** is a semiconductor device. Electronically controlled switches use thyristors in industrial, military, aerospace, commercial, and consumer applications.

Thyristors can control power to many kinds of loads, such as a simple lamp, power supplies, voltage regulators, and industrial motors. Circuits using ac or dc can use thyristors for power control.

Following are the two most commonly used thyristors for power control:

1. the **silicon controlled rectifier (SCR)**, which is a reverse blocking triode thyristor, and
2. the **triac**, which is a bidirectional triode thyristor.

In the following two exercises, you will identify thyristors and connect and operate thyristor circuits on the THYRISTOR & POWER CONTROL CIRCUITS circuit board.

NEW TERMS AND WORDS

thyristor - a bistable semiconductor device made of 3 or more junctions that can be switched from the off state to the on state or vice versa.

silicon controlled rectifier (SCR) - a gate triggered 3-terminal thyristor that has positive anode to cathode voltages and exhibits a reverse blocking state for negative anode to cathode voltages.

triac - a gate triggered, 3-terminal thyristor that switches for either positive anode to cathode voltages or negative anode to cathode voltages.

Exercise 1 – Thyristor Component Familiarization

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to identify thyristors and components in the circuit blocks on the THYRISTOR & POWER CONTROL CIRCUITS circuit board. You will verify your knowledge by answering the questions in the exercise.

EXERCISE DISCUSSION

- There are five circuit blocks on the THYRISTOR & POWER CONTROL CIRCUITS circuit board.
- The following four circuit blocks contain thyristors:
SILICON CONTROLLED RECTIFIER (SCR)
TRIAC AC POWER CONTROL
SCR DC GATE HALF-WAVE AND FULL-WAVE
SCR AC GATE AND UJT HALF-WAVE AND UJT HALF-WAVE AND FULL-WAVE / MOTOR
- The DRIVER circuit block contains a circuit that interfaces an external signal generator with the ac input to three of the circuit blocks.
- Thyristors are labeled with the letter Q followed by a number (for example, Q1)
- The silicon controlled rectifier (SCR) is sometimes called a reverse blocking triode thyristor. The SCR is primarily used for switching in ac and dc power control. The SCR is a three terminal device.
- An SCR is very useful for switching because a few milliwatts applied at the gate (G) can control hundreds of watts to a load.
- Triacs are three terminal, gate (G) controlled thyristor switches. The triac is bi-directional and behaves like two inversely parallel connected SCRs.
- The triac conducts with positive or negative voltage at either terminal (MT1 and MT2) and is triggered by a gate (G) current of either polarity.
- A diac is another thyristor type. The diac is a 2-terminal, bi-directional thyristor switch which is generally used in SCR gate triggering applications. The diac operates like two inversely parallel connected diodes.
- The Unijunction transistor (UJT) is a single junction, three terminal transistor that can be used for delaying the triggering signal at the SCR gate.
- Thyristor specification sheets include all of the significant parameters unique to a particular thyristor and are very important tools when designing thyristor circuits.

Exercise 2 – Circuit Block Familiarization

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to connect thyristor circuits by using the circuit blocks on the THYRISTOR & POWER CONTROL CIRCUITS circuit board. You will verify your results with a multimeter and an oscilloscope.

EXERCISE DISCUSSION

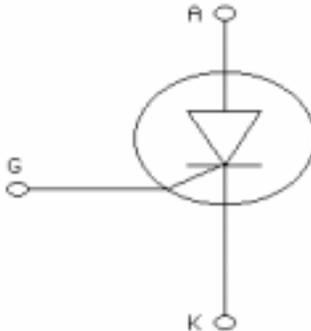
- The DRIVER circuit block contains a transformer and amplification circuitry that amplifies the ac signal from an external signal generator.
- The signal generator connects to the DRIVER circuit block input at the terminals marked GEN.
- The DRIVER circuit block is used with thyristor circuits that have ac signal input. The DRIVER output is hardwired to the ac inputs identified by the ac source symbol on the circuit blocks.
- When you connect the generator to the DRIVER circuit block, the generator connects to the circuit block ac input through the DRIVER circuitry.
- All measurements for adjusting the signal generator (magnitude and frequency) are made at the circuit block ac input.
- The THYRISTOR & POWER CONTROL CIRCUITS circuit board has four thyristor circuit blocks. Each block uses at least one thyristor as the active circuit element.
- You can configure several types of thyristor circuits from the components in each circuit block.
- The SCR circuit block which includes provisions for monitoring different parameters of an SCR (Q1).
- The SCR DC GATE HALF-WAVE AND FULL-WAVE circuit block uses a dc voltage at the gate (G) to control turn-on of the SCR (Q1). You can configure SCR Q1 as a half-wave rectifier, to control a half-wave rectifier (CR1), or to control a full-wave bridge rectifier (CR2).
- When SCR Q1 controls half-wave rectification, diode CR1 is the half-wave rectifier.
- When SCR Q1 controls full-wave rectification, bridge rectifier CR2 is the full-wave rectifier.
- The SCR AC GATE AND UJT HALF-WAVE AND FULL-WAVE/MOTOR circuit block uses ac voltage with or without a UJT (Q1) at the gate (G) of an SCR (Q2).
- The SCR (Q2) controls conduction of a full-wave rectifier (CR3) to either a resistive load (R8) or a motor load (MOT). The circuit can also be configured for Q2 to function as a half-wave rectifier.

UNIT 2 – SILICON CONTROLLED RECTIFIER

UNIT OBJECTIVE

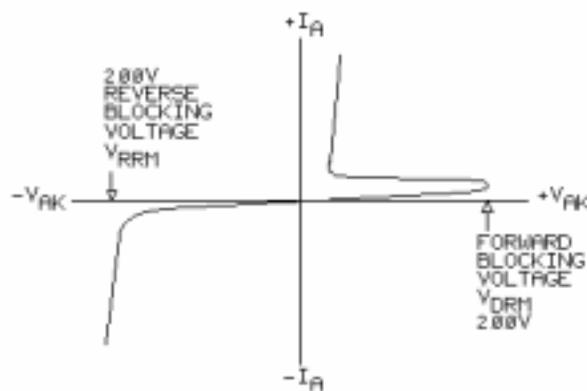
At the completion of this unit, you will be able to demonstrate the fundamental operation of a silicon controlled rectifier (SCR) by using dc measurements.

UNIT FUNDAMENTALS



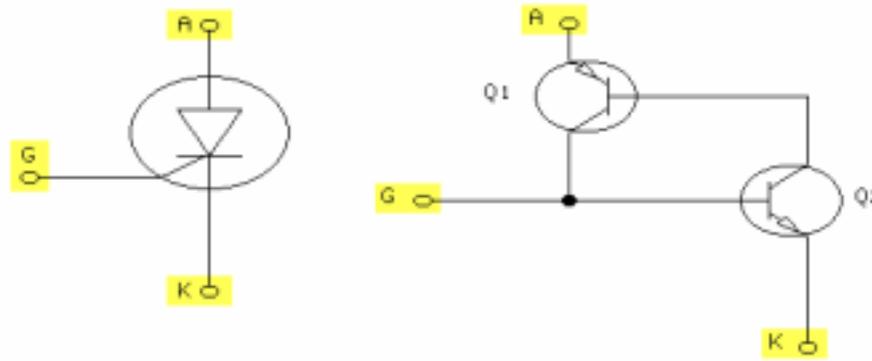
A thyristor is any semiconductor switch. A **silicon controlled rectifier (SCR)** is one type of thyristor. A **silicon controlled rectifier (SCR)** is a 3 terminal, unidirectional thyristor. The 3-terminals are the anode (A), the gate (G), and the cathode (K).

An SCR conducts when the anode to cathode is forward biased and a gate trigger signal is applied. After an SCR is turned on, it remains on as long as it has a minimum anode current. This minimum anode current that maintains conduction is the **holding current (IH)**.

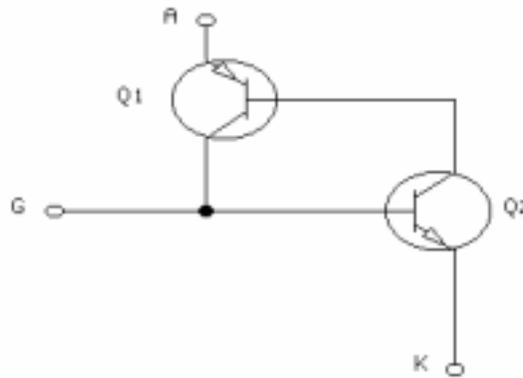


Shown are the voltage/current characteristics of an SCR with no gate current applied and with a forward and **reverse blocking voltage** rating of 200V.

When the **forward blocking voltage** is reached, the SCR turns itself on. The anode to cathode voltage decreases, and the anode current increases.



Internally, the SCR is similar to 2 cross-connected transistors. Above is the SCR symbol and its equivalent transistor circuit.



A gate trigger signal turns on transistor Q2. Q2 then forward biases the Q1 base-emitter junction, and both transistors turn on, providing a current path from the anode to the cathode. Both transistors are then latched on until the anode current is removed.

NEW TERMS AND WORDS

holding current (I_H) - the minimum current required to keep an SCR conducting.

reverse blocking voltage - the maximum reverse voltage that may be applied without turning on an SCR.

forward blocking voltage - the maximum forward voltage that may be applied with turning on an SCR.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine wave

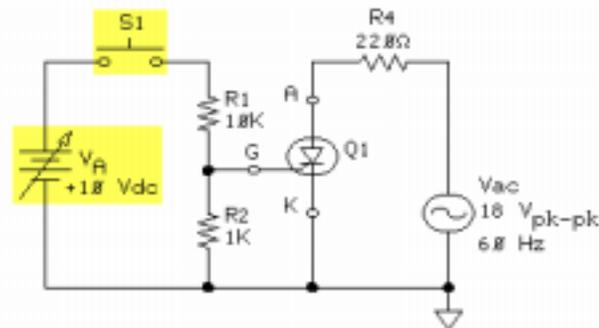
THYRISTOR & POWER CONTROL CIRCUITS circuit board

UNIT 3 – SCR DC CONTROL

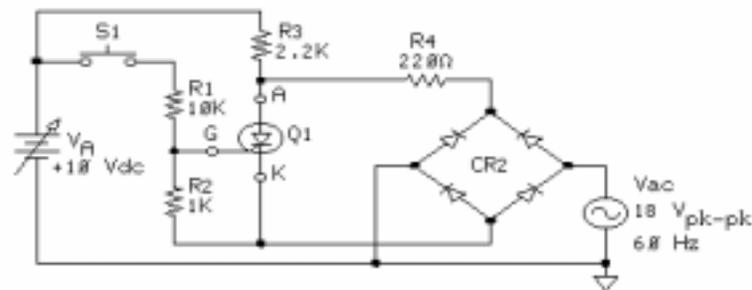
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the dc control of typical rectification circuits by using an SCR.

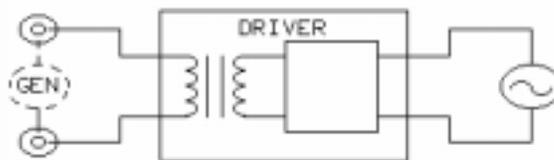
UNIT FUNDAMENTALS



In this circuit, the SCR is a half-wave rectifier that is controlled by S1 and the dc supply (V_A). The SCR turns off every negative half-cycle because the SCR becomes reverse biased.



In this circuit, the SCR is a switch in series with load resistor R4. When S1 is closed, V_A supplies the gate trigger voltage and turns on the SCR. The SCR then acts like a closed switch, and a full-wave rectified waveform appears across R4.



You will use the DRIVER circuit block in this unit to amplify the generator signal. You can then use the signal generator as the ac power source needed for the thyristor circuits.

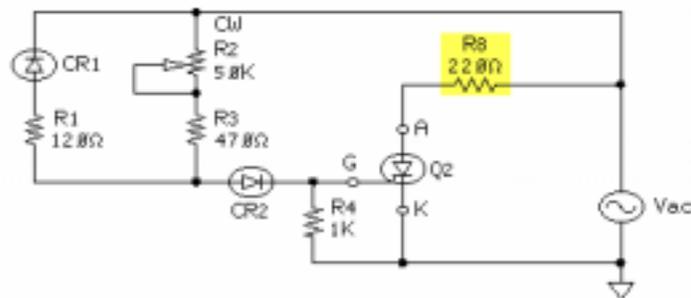
UNIT 4 – SCR AC CONTROL

UNIT OBJECTIVE

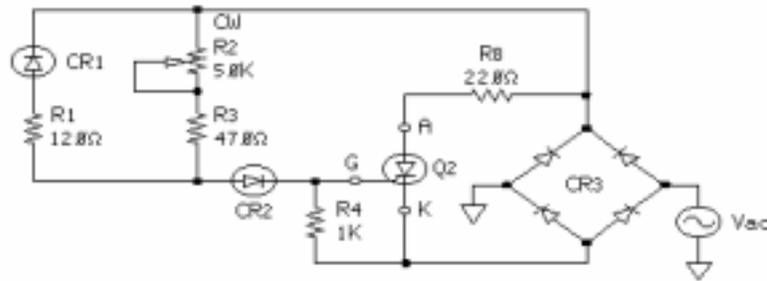
At the completion of the unit, you will be able to demonstrate ac control of an SCR by using half-wave and full-wave phase control circuits.

UNIT FUNDAMENTALS

A phase control circuit controls the SCR **conduction angle**. The SCR conduction angle of a full-wave **phase control** circuit is shown. A phase control circuit can also be used with a half-wave rectifier.



This circuit is a half-wave SCR phase control circuit. Power to the load (R8) can be controlled during the positive half of the input cycle.



In this circuit, power to the load (R8) can be controlled on both halves of the input cycle. Therefore, the maximum power to the load is twice that of the half-wave circuit.

NEW TERMS AND WORDS

conduction angle - the time an SCR conducts during one cycle of the source voltage measured in degrees.

phase control - control of the SCR conduction angle through controlling the phase of the SCR trigger signal with respect to the source voltage.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Generator, sine wave

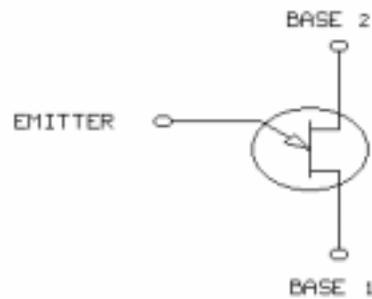
THYRISTOR & POWER CONTROL CIRCUITS circuit board

UNIT 5 – UJT TRIGGERED SCR POWER CONTROL

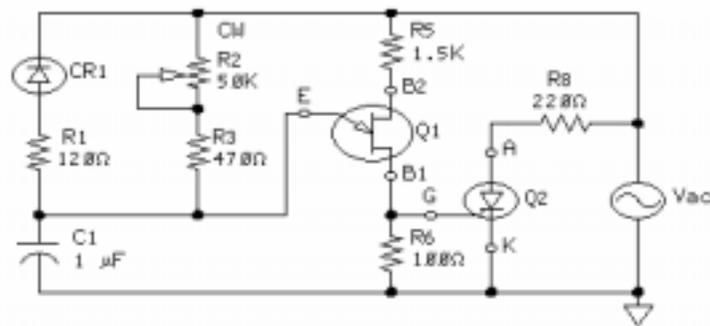
UNIT OBJECTIVE

At the completion of this unit, you will be able to use a unijunction transistor (UJT) as the trigger device for an SCR by using a typical UJT-SCR circuit.

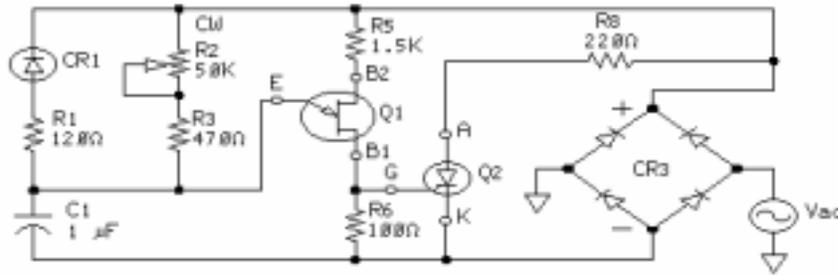
UNIT FUNDAMENTALS



This is the symbol for a **unijunction transistor (UJT)**. The UJT has 1 PN junction and 3 terminals. In this unit, you will use the UJT to control the conduction angle of an SCR.



In this circuit, a UJT phase control is used with a half-wave rectifier.



The UJT makes a good trigger device for the SCR because it generates a sharp pulse at the B1 terminal. When the UJT is used with a variable RC phase control circuit, you can easily adjust the phase angle at which the B1 pulse occurs.

NEW TERMS AND WORDS

unijunction transistor (UJT) - a 3-terminal device with 1 PN junction.

firing voltage (V_P) - the maximum emitter voltage at which the UJT turns on; also called the peak-point emitter voltage.

valley voltage (V_V) - the minimum emitter voltage just before the UJT turns off also called the valley-point emitter voltage.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Oscilloscope, dual trace

Generator, sine wave

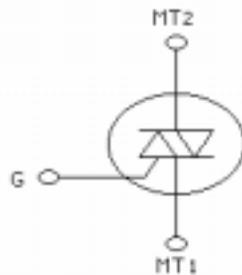
THYRISTOR & POWER CONTROL CIRCUITS circuit board

UNIT 6 – TRIAC DEVICES

UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation of typical triac devices by using dc measurements.

UNIT FUNDAMENTALS



A triac is a 3-terminal **bidirectional** thyristor. A thyristor is any solid state switch. The triac is a thyristor that, unlike the SCR, is capable of conducting in either direction between its main terminals.

A triac can be triggered on if **MT2** is positive with respect to **MT1** or if **MT2** is negative with respect to **MT1**.



Similar to the SCR, a triac requires a minimum **MT2** current to remain in conduction. This minimum current is the holding current.

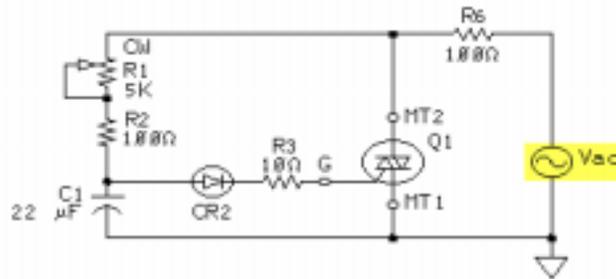
A triac has 4 trigger modes. It can be triggered on with either a positive or negative gate trigger signal, with **MT2** being either positive or negative.

UNIT 7 – TRIAC AC POWER CONTROL

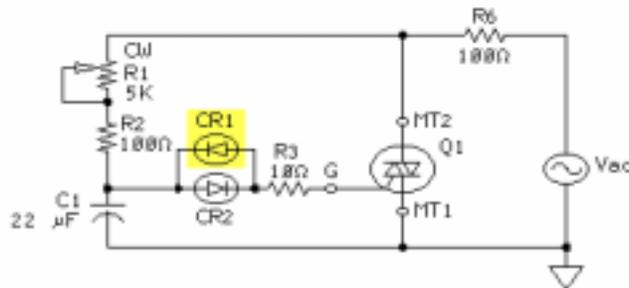
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate ac power control by using typical triac control circuits.

UNIT FUNDAMENTALS



This is a half-wave triac circuit. The triac can be turned on only when V_{ac} is positive.



By adding CR1 to the circuit, it becomes a full-wave circuit. Since the triac can conduct on the positive and negative half-cycles, it is bidirectional.

NEW TERMS AND WORDS

None.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Operational Amplifier Fundamentals

FACET®



Student Workbook

FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

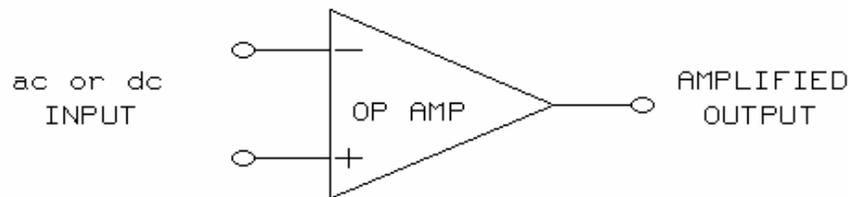
The **Appendix** includes safety information.

UNIT 1 – THE OPERATIONAL AMPLIFIER

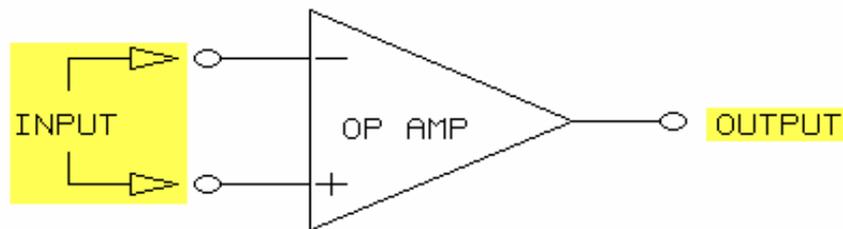
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the basic characteristics of operational amplifiers.

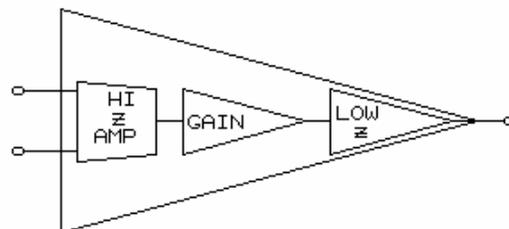
UNIT FUNDAMENTALS



An **operational amplifier (op amp)** is an **integrated circuit (IC)** used to amplify ac and dc input voltages.

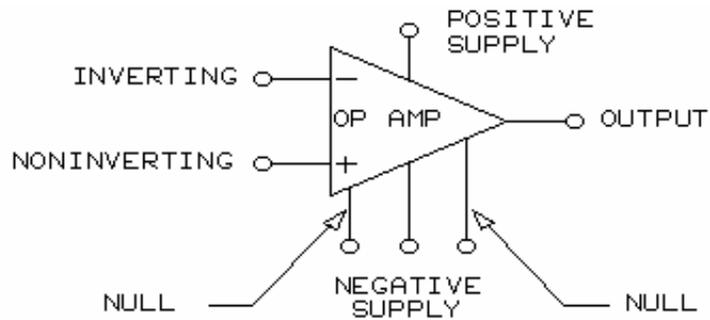


An op amp provides a linear output voltage proportional to the difference between the op amp input terminals.

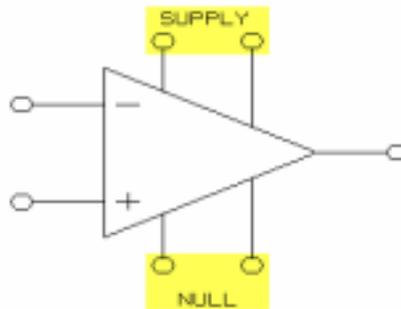


Internally, typical op amps are constructed with three basic building blocks.

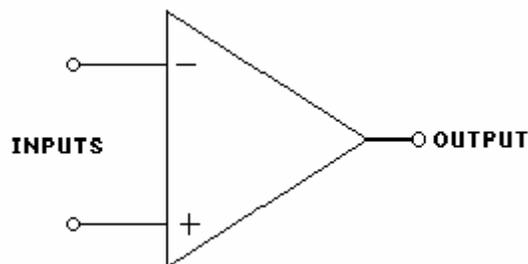
1. A differential amplifier with high input impedance buffers, or prevents loading of, the signal source.
2. A high gain amplifier boosts the output signal from the differential amplifier.
3. A low impedance, or output, buffer prevents loading of the gain stage by an external circuit load.



Typical op amps use several types of signal functions. Positive and negative supply terminals connect to the system power supply rails and provide operating power. Null, or nulling, terminals connect to an external voltage and allow for op amp offset voltage adjustment. **Inverting (-)** and **noninverting (+)** terminals connect to the circuit input voltages. An output terminal drives the external circuit load.

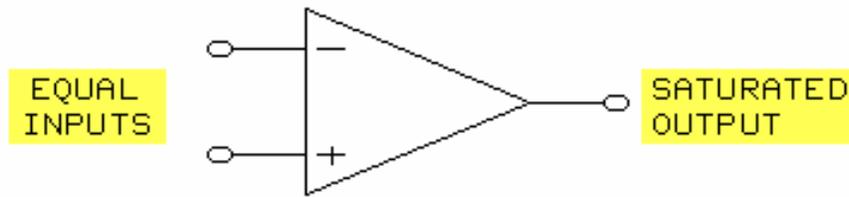


On many circuit drawings, the voltage supply terminals and the nulling terminals are not shown.

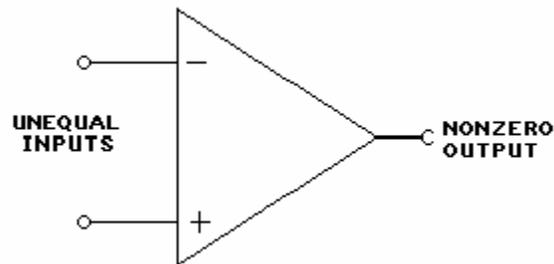


An op amp in the **open loop mode** has no feedback path between its output and input connections.

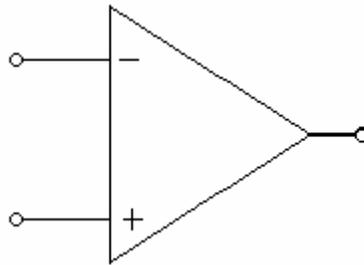
For an ideal op amp, open-loop gain is infinite.



If the voltages at the noninverting and inverting inputs are equal, the op amp output is saturated.



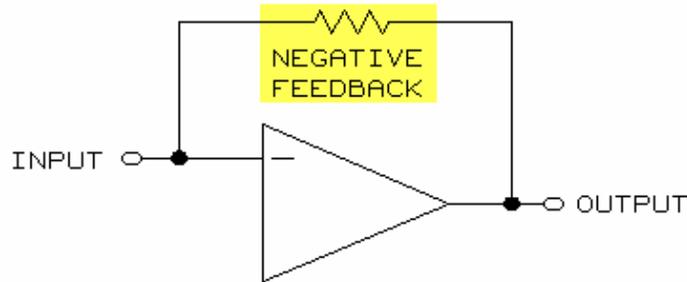
Due to the extremely high open-loop gain, a small voltage difference between the op amp inputs causes the output voltage to swing toward one of the power supply levels (voltage).



The output voltage polarity of an op amp is identical to the polarity of the voltage at the noninverting input terminal.

NOTE: Typically, voltage polarity is with respect to circuit common. However, op amp inputs can be referenced to one another.

Closed-loop mode operation is established by a resistor connected between the op amp output and inverting input terminals. The resistor allows a portion of the output voltage to be fed back as negative, or degenerative, feedback.



Negative, or degenerative, feedback reduces the gain (from the open-loop value) of an op amp.

Although circuit gain is reduced, negative feedback improves circuit stability by preventing unwanted oscillation and distortion.

NEW TERMS AND WORDS

operational amplifier (op amp) - a linear device used to generate an output voltage proportional to the differential input voltage.

integrated circuit (IC) - an interconnected array of components (resistors, transistors, etc.) contained on a single chip of a host substrate material.

Inverting (-) - the input terminal of an op amp which reverses the polarity of the applied input voltage.

noninverting (+) - the input terminal of an op amp which does not reverse the polarity of the applied input voltage.

open loop mode - an op amp configuration without external feedback between output and input.

Closed-loop mode - an op amp configuration that feeds back a portion of the output voltage to the inverting input.

input bias current - the current entering into both inputs of an op amp.

output-offset voltage - the output error voltage present when the input voltage is 0 Vdc.

drift - the change in offset current and offset voltage generated by a change in temperature.

input-offset current - the difference between the two input bias currents when the output voltage is zero.

input-offset voltage - the voltage that must be applied to the two inputs of an op amp in order to produce an output voltage of zero.

offset nulling - the process of balancing an op amp and adjusting its output voltage to zero.

Exercise 1 – Op Amp Types and Packages

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to recognize different op amp packages. You will verify your knowledge through observation and recognition.

EXERCISE DISCUSSION

- Op amps are available in a variety of package styles.
- Op amp package material can be metal, ceramic, or plastic.
- Not all IC pins connect electrically to the op amp.
- "No connection" (NC) pins add stability and ruggedness to the package.
- From a bottom view, pin count progresses in a clockwise (CW) direction
- From a top view, pin count progresses in a counterclockwise (CCW) direction.
- On a TO-5 (top hat) package, pin 1 is located adjacent to the package tab.
- On the flat pack, pin 1 is located adjacent to the dot or round indentation on the top side of the package.
- On the DIP package, pin 1 is located adjacent to the dot or half round notch on the top side of the package.
- ICs are available in single or multiple op amp configurations: typically one, two (dual), or four (quad) per package.
- The LF441 used on the circuit board is a single op amp package type.
- The LF441 DIP outline shows the IC pin assignments. These assignments are set by the device manufacturer and cannot be altered.
- Since each op amp type is unique, the device manufacturer stamps a part number on the top surface of each IC.
- The TO-5 LF441 op amp outline shows the same pin assignments as the DIP, but in a circular pattern.
- Dual and quad style LF441 op amps have specific pin assignments. Note the absence of null inputs.

Exercise 2 – Op Amp Circuit Board Familiarization

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the operation of the OPERATIONAL AMPLIFIER FUNDAMENTALS circuit board. You will verify your results by observation and measurements.

EXERCISE DISCUSSION

- Three basic op amp configurations are used on your circuit board.
- Only the open-loop configuration does not require a feedback path (resistor).
- Inverting and non-inverting configurations generally require a feedback resistor to provide negative feedback.
- There are eight training circuit blocks on the op amp board.
- Three other general purpose blocks are also required to support the training procedure.
- The three general purpose blocks are labeled FOR GENERATOR BUFFER, ATTENUATOR, and VOLTAGE DIVIDER.
- The ATTENUATOR circuit block reduces an input voltage, or signal, by a factor of 10 ($OUT = IN/10$).
- Certain procedural steps require a low-amplitude input signal. The ATTENUATOR allows you to precisely adjust the output amplitude of a signal generator.
- The VOLTAGE DIVIDER circuit block generates a variable low-voltage output between +2.5 Vdc and -2.5 Vdc.
- If a two-post connector is inserted into the circuit block, the range of output voltage is reduced to between +0.5 Vdc and -0.5 Vdc.
- The circuit block labeled FOR GENERATOR BUFFER is used with an optional generator buffer plug-in module. This module interfaces devices without 50 Ω output impedance to the circuits on your circuit board.

Exercise 3 – Basic Op Amp Characteristics

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with fundamental op amp characteristics. You will verify your results by performing offset null adjustments.

EXERCISE DISCUSSION

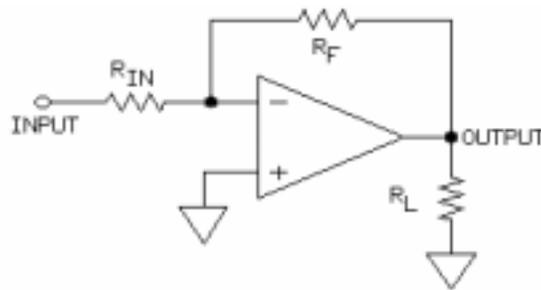
- Three fundamental op amp characteristics are high input impedance, high voltage gain, and low output impedance.
- Ideal op amps have infinite input impedance. Practical op amps have typical input impedances of 1 M Ω or more.
- Ideal op amps have infinite open-loop gains. Practical op amps have typical open-loop gains of 200,000 or more.
- Ideal op amps have zero output impedance. Practical op amps have typical output impedances of 10 Ω or more.
- Practical op amps possess a small input current called the input bias current.
- Input bias currents generate output error voltages called output-offset voltage.
- Shifts in temperature change offset current, which changes offset voltage. These changes are referred to as **drift**.
- If the **input bias current** of an op amp is low, its offset voltage will be small.
- If the inputs of a practical op amp are at the same potential, output voltage should be zero. However, due to input bias current, an output- offset voltage is generated.
- The effects of input bias current can be reduced significantly by the introduction of an **input-offset current** or an input-offset voltage. This process is referred to as **offset nulling**.
- Offset nulling, or op amp trim adjust, uses an adjustable external voltage to set the op amp output to near 0V.
- High gain op amps, unless properly bypassed, may oscillate. To prevent this undesirable condition, power supply connections must exhibit low impedance characteristics.
- Bypass, or decoupling, capacitors are used to ensure op amp stability.

UNIT 2 – THE INVERTING AMPLIFIER

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the dc and ac characteristics of an inverting operational amplifier by measuring circuit performance.

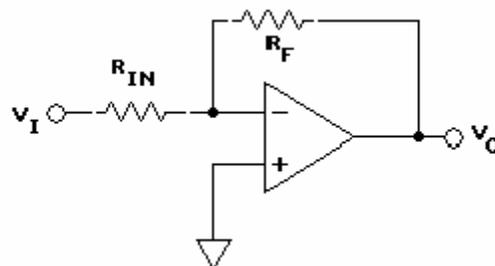
UNIT FUNDAMENTALS



An **inverting amplifier** is a closed-loop op amp circuit in which feedback is applied to the inverting input through the feedback resistor (R_F).

The circuit input is applied to the inverting terminal of the op amp through the input resistor (R_{IN}).

The circuit output, developed across R_L , is amplified and inverted with respect to the circuit input.

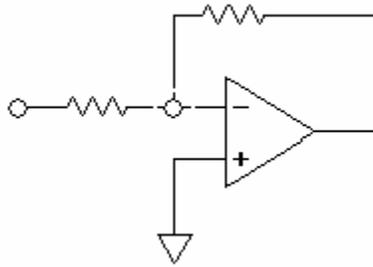


Circuit gain (A_v) is function of the ratio between R_F and R_{IN} .

$$A_v = R_F / R_{IN}$$

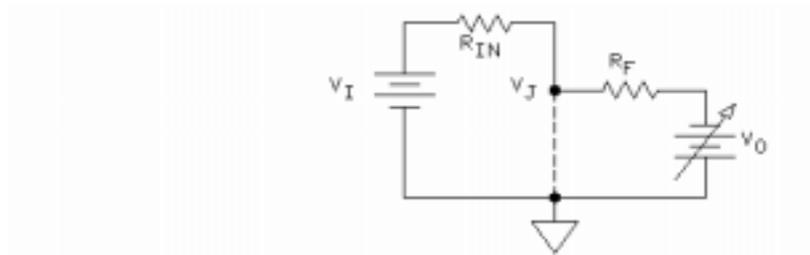
Output voltage is calculated by multiplying the input voltage by the circuit gain value. The (-) sign indicates inversion, not that the output voltage must be negative.

$$V_O = - (V_I \times A_v)$$



Since the op amp has high gain and feedback is provided, the inverting op amp terminal is maintained at **virtual ground**.

For this circuit configuration, the inverting op amp terminal serves as the circuit **summing point**.



In the circuit shown, V_O represents the action of an op amp. The junction V_J is maintained at virtual ground (0V) because V_O varies as V_I varies.

Since V_J is held at virtual ground, it is also the circuit summing junction: $V_J = V_I - V_O$.

NOTE: Virtual ground and summing junction concepts will be extensively explored in this and other units.

NEW TERMS AND WORDS

inverting amplifier - a circuit using an active device to amplify and invert (180-degree phase shift) an input signal.

virtual ground - a circuit point that behaves like circuit common or has near zero potential with respect to circuit common.

summing point - a node where two or more voltages or currents meet and algebraically combine.

phase shifted - the difference between two signals; measured in units of time or degrees.

Gain-bandwidth product - the product of the closed-loop gain of an op amp and its corresponding closed-loop bandwidth.

Exercise 1 – Inverting Amplifier DC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to operate an inverting amplifier. You will verify circuit operation by using a voltmeter.

EXERCISE DISCUSSION

- An inverting amplifier inverts and amplifies the input voltage.
- Output voltage is determined by: $V_O = -[V_I \times (R_F/R_{IN})]$.
- The junction of R_{IN} , R_F , and the inverting terminal is the summing point of the circuit.
- The circuit input resistance equals the value of R_{IN} since the summing junction is at virtual ground.
- A circuit is zero-base referenced because the noninverting terminal is connected to circuit common.
- Zero-based reference circuits change their output voltage polarity from plus-to-minus or minus-to-plus as the input voltage passes through zero (circuit common).
- Use Ohm's law to determine the magnitude of electron flow through circuit parts.
- Current through the input resistor, which is connected to virtual ground at one end, is $I_{R_{IN}} = V_I/R_{IN}$.
- Feedback current (I_{R_F}) equals V_{R_F}/R_F or V_O/R_F .
- Load current (I_{R_L}) equals V_O/R_L .
- When a positive input voltage is applied to the inverting input of an op amp, current flows (electrons flow) out of the output terminal of the op amp. The value of the current is $I_{R_F} + I_{R_L}$.
- When a negative input voltage is applied to the inverting input of an op amp, current flows (electrons flow) into the output terminal of the op amp. The value of the current is $(I_{R_F} + I_{R_L})$; the minus sign indicates direction, not negative current.

Exercise 3 – Inverting Amplifier Response

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to relate the gain and bandwidth of an op amp inverting amplifier. You will measure bandwidth with an oscilloscope.

EXERCISE DISCUSSION

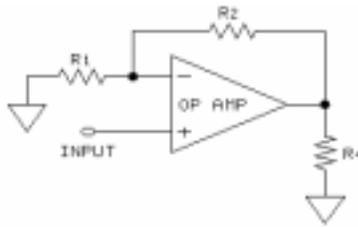
- Gain-bandwidth product and slew rate are op amp parameters that affect the operation of an inverting amplifier.
- Gain-bandwidth (GBW) is an op amp parameter that does not depend on op amp configuration.
- Gain multiplied by circuit bandwidth equals the GBW of an op amp.
- The GBW product is also called the unity-gain bandwidth since GBW is specified at a gain of one.
- A general plot shows that bandwidth (B or bw) and gain are inversely proportional.
- Bandwidth decreases as gain increases.
- Bandwidth = GBW product/circuit gain
- The LF441 op amp has a specified GBW of 1 MHz (at unity gain).
- The bandwidth of an inverting amplifier is reduced by placing a capacitor across the feedback.
- As frequency increases, capacitive reactance decreases. At a specific frequency, capacitive reactance equals R_F . This frequency is called the breakpoint frequency.
- At the breakpoint frequency, an output signal drops 3 dB.

UNIT 3 – THE NONINVERTING AMPLIFIER

UNIT OBJECTIVE

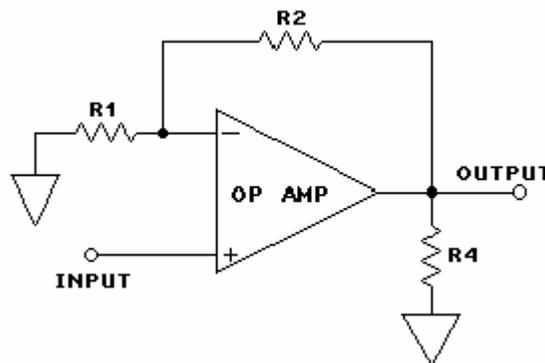
At the completion of this unit, you will be able to demonstrate the dc and ac characteristics of a noninverting operational amplifier by measuring circuit performance.

UNIT FUNDAMENTALS

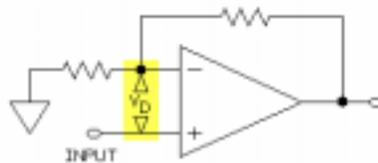


A **noninverting amplifier** is a closed-loop op amp configuration. Feedback through R2 is applied to the inverting terminal of the op amp. The input signal of the noninverting circuit is applied to the noninverting terminal of the op amp.

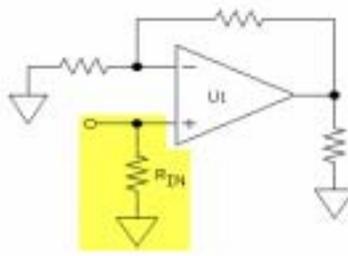
Resistor R1 connects the inverting terminal of the op amp to circuit common. Circuit gain (A_v) equals $1 + (R2/R1)$. If R1 and R2 are equal, circuit gain equals 2.



In a noninverting configuration, the output and input voltage polarities are identical.

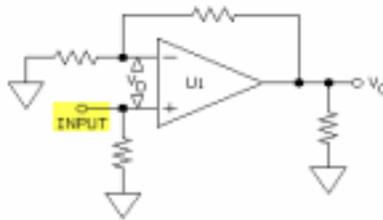


For proper operation (not in saturation), the differential input voltage (V_D) of the op amp is maintained at 0V. If the op amp is driven into saturation, V_D cannot be maintained at 0V.

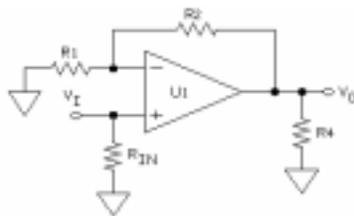


Due to the very high input impedance of the op amp, a resistor (R_{IN}) is usually connected between the positive terminal and circuit common. R_{IN} prevents op amp saturation should the circuit input voltage (V_I) be disconnected (referred to as a floating input). The input impedance of the circuit shown essentially equals the ohmic value of R_{IN} .

A noninverting op amp displays all the attributes of op amps in general: high input impedance, low output impedance, and high gain.



The circuit input voltage is applied to the positive op amp input. This means that the circuit summing junction is not at virtual ground but at a potential required to hold the differential input voltage (V_D) at 0V.



To determine the circuit current distribution, apply Ohm's law.

NOTE: $V_{R_{IN}}$ is the same as V_I , V_{R_4} is the same as V_O , and R_1 and R_2 form a voltage divider.

Exercise 1 – Noninverting Amplifier DC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to operate a noninverting operational amplifier using dc inputs. You will verify circuit operation with a multimeter.

EXERCISE DISCUSSION

- The noninverting amplifier is a closed-loop op amp configuration.
- Circuit gain (A_v) is based on the ratio of R_2 to R_1 : $A_v = 1 + (R_2/R_1)$.
- Due to the noninverting operation, the output and input voltages have the same polarity.
- R_3 is adjusted to balance, or null, the circuit output (V_O) to 0V. The circuit input must be connected to circuit common.
- A noninverting op amp amplifies an input voltage and does not invert the input voltage polarity.
- Since the circuit gain (A_v) is 10, output voltage is +10 Vdc.
- For nonsaturated operation, the differential input voltage (V_D) must be 0V.
- Since the op amp (+) input is at +1 Vdc, sufficient voltage is fed back (through R_2) to maintain V_D at nearly 0V.
- With respect to circuit common, both the (+) and (-) op amp inputs are at +1 Vdc.
- To determine circuit current distribution, apply Ohm's law.
- When the circuit input voltage (V_I) is positive, electrons flow into the output terminal of the op amp.
- When V_I is negative, electrons flow out of the output terminal of the op amp.

Exercise 3 – Noninverting Amplifier Response

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the gain/bandwidth characteristics of a noninverting operational amplifier. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- Gain-bandwidth (GBW) product and slew rate (SR) are two op amp specifications that affect the operation of a noninverting amplifier. Slew rate will be examined in another unit.
- For a noninverting amplifier, circuit gain multiplied by circuit bandwidth cannot exceed the specified GBW product of the circuit op amp.
- As the gain of the amplifier increases, circuit bandwidth decreases.
- As the gain of the amplifier decreases, circuit bandwidth increases.
- If the amplifier bandwidth is limited, its output voltage falls off (is reduced or attenuated), and the waveform may be distorted.
- The LF441 op amp has a specified GBW product of 1 MHz.
- A capacitor placed across the circuit feedback resistor reduces the bandwidth ac gain of the amplifier and ac gain becomes frequency dependent.
- The breakpoint frequency of this circuit occurs at the frequency where X_C (in ohms) equals the value of R_2 .
- The breakpoint is referred to as the -3 dB point of the circuit and defines the circuit bandwidth frequency.
- At the -3 dB point of a circuit, the output voltage is attenuated by the factor 0.707 ($0.707 \times V_O$).
- The formula $\text{dB} = 20 \log (V_{\text{NEW}}/V_{\text{INITIAL}})$ expresses the change in output voltage.
- V_{NEW} is the final output voltage at the operating frequency, such as 100 kHz, where the output voltage has decreased by 0.707.
- V_{INITIAL} is the starting output voltage at the reference frequency, such as 1 kHz.

UNIT 4 – THE VOLTAGE FOLLOWER

UNIT OBJECTIVE

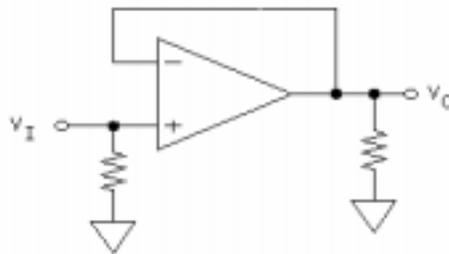
At the completion of this unit, you will be able to operate an operational amplifier circuit configured as a voltage follower or a gain-of-one inverting amplifier.

UNIT FUNDAMENTALS

A **voltage follower** circuit has unity gain, which means it has a gain of 1.

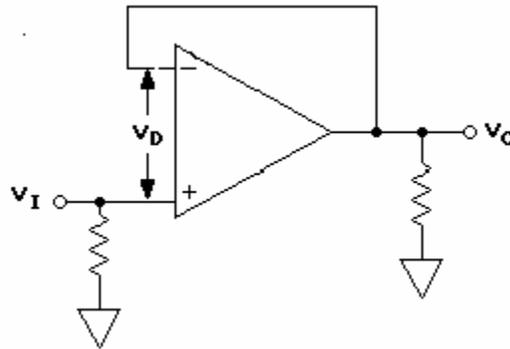
A voltage follower is also called a **unity gain amplifier**.

Advantages of a voltage follower are high input impedance, low output impedance (good impedance matching characteristics), wide bandwidth, and fast response.



In a voltage follower configuration, the op amp output terminal is directly connected to the op amp inverting input terminal. As a result, all of the output voltage is fed back.

Due to the input/output connection, the output voltage (V_O) follows the circuit input voltage (V_I) in magnitude and polarity.



The voltage at the op amp inverting terminal equals the output voltage (V_O).

V_O follows the circuit input voltage (V_I).

V_D , the op amp differential input voltage, is 0V.

The GBW product of an op amp is specified at unity gain.

A voltage follower circuit operates with unity gain. Therefore, the circuit bandwidth essentially equals the specified op amp GBW product (1 MHz for the LF441 op amp).

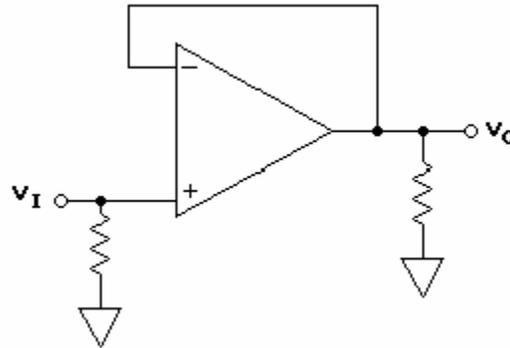
The ability of an op amp voltage follower to accurately duplicate an input voltage is related to levels of operation called **small-signal** and **large-signal**.

Typically, **small-signal** refers to voltages with amplitudes equal to or less than $1 V_{pk-pk}$.

Typically, **large-signal** refers to voltages with amplitudes between $10 V_{pk-pk}$ and $20 V_{pk-pk}$.

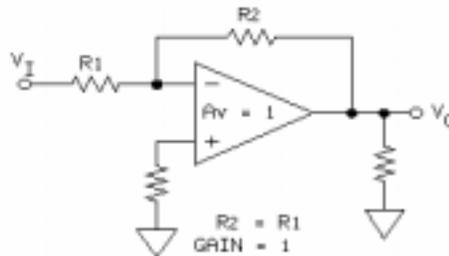
Small-signal operation is primarily related to the GBW product of an op amp.

Large-signal operation is primarily related to op amp slew rate and **full-power bandwidth**.

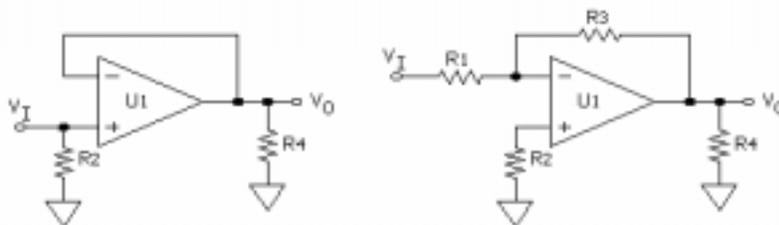


This voltage follower configuration is used to measure the effects of op amp slew rate and full-power bandwidth on an input signal.

A voltage follower configuration generates an output signal (V_O) equal to and in phase with the circuit input signal (V_I).



However, some applications require unity gain **with** phase inversion. An op amp configured as a unity gain inverting amplifier meets this requirement.



On your circuit board, the VOLTAGE FOLLOWER circuit block can be configured for either noninverting or inverting operation.

Due to the low output offset voltage values of the LF441 op amp, the VOLTAGE FOLLOWER circuit block does not require a nulling circuit.

Exercise 2 – Inverting Gain-of-One Amplifier

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to operate an inverting gain-of-one amplifier using dc voltages. You will verify circuit operation with a voltmeter.

EXERCISE DISCUSSION

- An inverting amplifier can be configured to provide unity gain.
- Circuit gain equals R_3/R_1 . If R_3 and R_1 are equal in value, the circuit gain equals one.
- Resistor R_2 is added to the circuit to reduce the input bias current effect. The value of R_2 equals the parallel combination of R_3 and R_1 : $R_2 = (R_3 \times R_1)/(R_3 + R_1)$.

NOTE: Input bias current flowing through R_1 generates a voltage (V_{R1}) that appears at the output.

- Fractional gain, a gain of less than one, results if the value of R_3 is less than the value of R_1 .
- Since the circuit output voltage is less than the circuit input voltage, the configuration acts as an attenuator.
- To determine the current distribution of the gain-of-one inverting amplifier, apply Ohm's law ($I = V/R$) to the circuit.
- A positive input voltage to an inverting gain-of-one amplifier generates a negative output voltage. Electrons flow out of the op amp output terminal.
- When $U1$ is not saturated, V_O tracks V_I , and V_D is at 0V.
- $U1$ is zero-based (R_2 connected to common); therefore, the inverting terminal of $U1$ is at virtual ground and serves as the circuit summing junction.
- If $U1$ is saturated (V_O greater than 10 Vdc), V_O cannot track V_I , and V_D is greater than 0V.

Exercise 3 – Voltage Follower AC Characteristics

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the effects of slew rate and full-power bandwidth on a voltage follower. You will observe the effects on an oscilloscope.

EXERCISE DISCUSSION

- Slew rate (SR) specifies maximum rate-of-change in output voltage over a period of time. Mathematically, SR is equivalent to the slope of a waveform.
- Slew rate (SR) is defined as a change in output voltage divided by the time interval during which the voltage change occurs. For this pair of parameters, SR is given in units of volts/time.
- The graph illustrates how slew is measured. The calculation determines the slope of the line. SR is given in volts/microsecond ($V/\mu s$).
- If, for example, output voltage changes by 10V in 10 μs , the slew rate of the circuit is 1 $V/\mu s$
- Ideal op amps have an infinite slew rate: the output would instantaneously follow any change at the input.
- An ideal square wave has instantaneous rise and fall times.
- The LF441 op amp used on the circuit board has a specified slew rate of 1 $V/\mu s$. Generally, this means that the op amp output voltage cannot change faster than 1V in less than 1 μs .
- Slew rate decreases rise and fall times of a square wave. For a slew rate of 1 $V/\mu s$, it would take 10 μs for a 10V swing to occur.
- If an op amp circuit has an SR of 5 $V/\mu s$ and its square wave input has rise and fall times of 1 μs , the circuit can duplicate the input waveform.
- When the circuit SR is equal to or greater than the rate of change in the input waveform, the circuit output waveform tracks (reproduces) the input waveform.
- When circuit SR is less than the rate of change of an input waveform, the output waveform does not fully track (reproduce) the input waveform. The "squareness" of the waveform is reduced.
- For a given slew-rate-limited circuit, an output waveform becomes triangular and decreases in amplitude as input frequency increases.
- Slew rate limitations also affect sinusoidal waveforms. On a sinusoidal waveform, the slope is maximum at the zero crossing points and zero at the peak points of the waveform.
- The slope of a sinusoidal waveform always changes.
- Slope defines a rate of change (volts per unit of time). Therefore, slope is also frequency dependent. If the frequency of a constant amplitude sinusoidal waveform increases (period decreases), the slope of the waveform increases.

UNIT 5 – THE INVERTING SUMMER

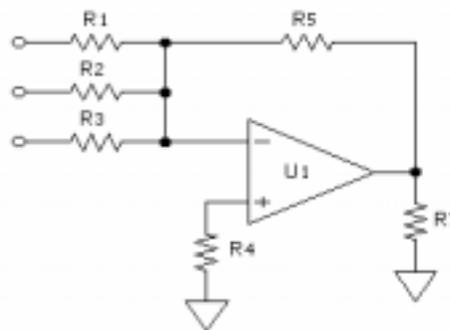
UNIT OBJECTIVE

At the completion of this unit, you will be able to describe the operation of an inverting summing amplifier using a three-input op amp summing configuration.

UNIT FUNDAMENTALS

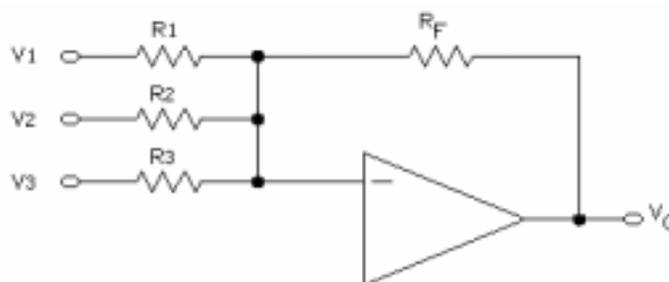
An **inverting summing amplifier** is a multiple input inverting op amp circuit. The circuit output voltage is proportional to the algebraic sum of the input voltages.

The polarity of the circuit output voltage is opposite that of the summed input voltages.



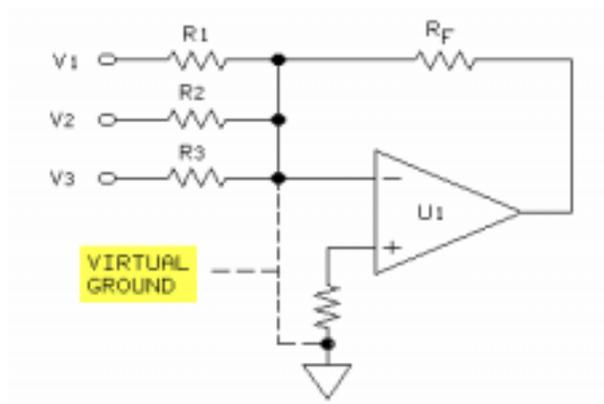
The junction formed by the input resistors, feedback resistor, and the op amp inverting terminal is the circuit summing point.

Direct summation of the input voltages and feed-back voltage occurs at the circuit summing junction. The circuit summing junction is at virtual ground (the op amp is zero based) because the noninverting terminal is referenced to circuit common.

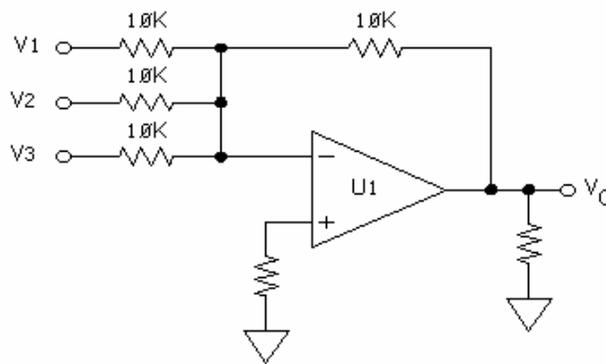


Circuit output voltage is proportional to the sum of each input voltage multiplied by the ratio of R_F to the respective input resistor (R_x).

$$V_O = -\{[(R_F/R_1) \times V_1] + [(R_F/R_2) \times V_2] + [(R_F/R_3) \times V_3]\}$$

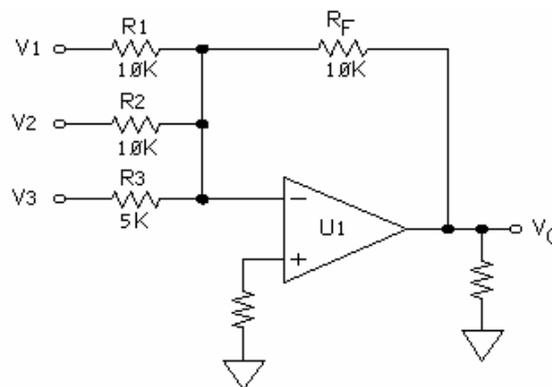


Input impedance for each circuit input voltage equals the value of the respective input resistor. The impedance is based upon a virtual ground at the circuit summing junction.

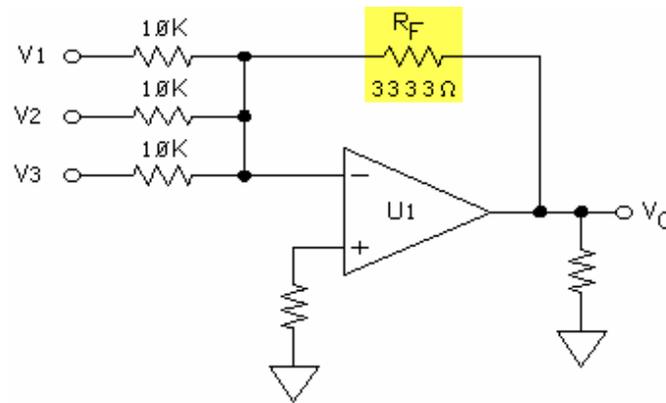


If the input and feedback resistors equal each other, the circuit performs a summing (algebraic addition) operation.

$$V_O = -(V_1 + V_2 + V_3)$$



In a **scaling, or weighted configuration**, if R_1 , R_2 , and R_F equal each other but not R_3 , V_3 is scaled (or weighted) differently than V_1 and V_2 . Scaling can be similarly applied to R_1 or R_2 .



If R_3 , R_2 , and R_1 equal each other but R_F equals the average value of the input resistors, V_O equals the average value of the input voltages.

$$V_O = -[(V_1 + V_2 + V_3)/3]$$

Op amp saturation levels limit the maximum circuit output voltage. If the product of any one input voltage and its respective circuit gain factor is excessive, the op amp saturates.

NEW TERMS AND WORDS

inverting summing amplifier - an inverting op amp configuration that algebraically combines two or more input voltages.

scaling, or weighted configuration - a summing amplifier configuration that allows a certain input voltage to have more influence on the output voltage than another input voltage.

summing configuration - a summing amplifier configuration that generates an output voltage equal to the algebraic sum of the input voltages.

averaging configuration - a summing amplifier configuration that generates an output voltage equal to the average value of the circuit input voltages.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

OPERATIONAL AMPLIFIER FUNDAMENTALS circuit board

Exercise 1 – Amplifier Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to operate an inverting summing amplifier. You will verify circuit operation with a multimeter.

EXERCISE DISCUSSION

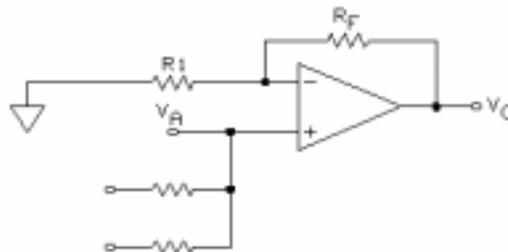
- A summing amplifier combines multiple input voltages and applies individual gain factors to each input.
- To minimize summing errors, R4 is added to the circuit. R4 equals the parallel combination of R1, R2, R3, and R5.
- The summing configuration generates an output voltage equal to the algebraic sum of each circuit input voltage multiplied by its respective circuit gain factor.
- Due to the inverting configuration, the polarity of the summed input voltages is inverted at the circuit output.
- U1, working through the feedback path, keeps the differential input voltage (V_D) at 0V.
- If V_D is greater than 0V (positive or negative), U1 is driven into saturation.
- One of the circuit inputs can be used to null, or trim, the circuit offset voltage to 0V.
- Circuit input, feedback, and load current distribution depend on the magnitude and polarity of the input and output voltages.
- Apply Ohm's law to determine the magnitude of each current.
- For positive input voltages, the summed voltage polarity is positive, and electrons flow out of the op amp output terminal.
- For negative input voltages, the summed voltage polarity is negative, and electrons flow into the op amp output terminal.
- If the circuit input voltages are positive and negative, electrons flow in either direction.
- The direction of the op amp output terminal current is based on the resultant polarity of the summed input voltages.

UNIT 6 – THE NONINVERTING SUMMING AMPLIFIER

UNIT OBJECTIVE

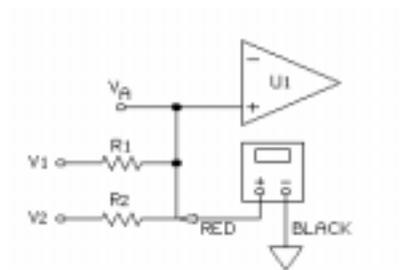
At the completion of this unit, you will be able to describe the operation of a noninverting summing amplifier.

UNIT FUNDAMENTALS



In a **noninverting summing amplifier**, the (-) terminal acts as the op amp summing junction. The (+) terminal acts as the summing point (V_A) of the individual circuit input voltages.

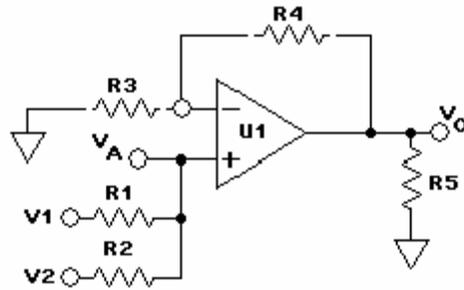
V_A is multiplied by the circuit gain factor $[1 + (R_F/R_1)]$ to generate the output voltage (V_O).



Due to the high impedance of U_1 , V_A is determined by the superposition theorem. However, if R_1 and R_2 are equal in value, $V_A = (V_1 + V_2)/2$.

NOTE: V_1 , V_2 , and V_A are measured with respect to circuit common.

U_1 is not zero based because the (+) input terminal is not returned to circuit common. V_A can be greater than 0V (positive) or less than 0V (negative).

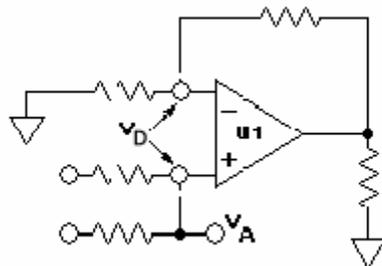


In this circuit, gain equals $1 + (R4/R3)$ and cannot be equal to or less than 1.

Output voltage (V_O) equals $V_A \times [1 + (R4/R3)]$.

If $R1$ equals $R2$, V_A equals $(V1 + V2)/2$. Therefore, the circuit applies the gain factor $[1 + (R4/R3)]$ to the average of the input voltages.

$$\begin{aligned} V_O &= (V1 + V2)/2 \times [1 + (R4/R3)] \\ &= V_A \times [1 + (R4/R3)] \end{aligned}$$



In a noninverting summing amplifier, V_D is 0V when U1 is not saturated. When V_D is greater than 0V, U1 is saturated.

V_A can be any value that when multiplied by the circuit gain factor does not drive U1 into saturation.

NEW TERMS AND WORDS

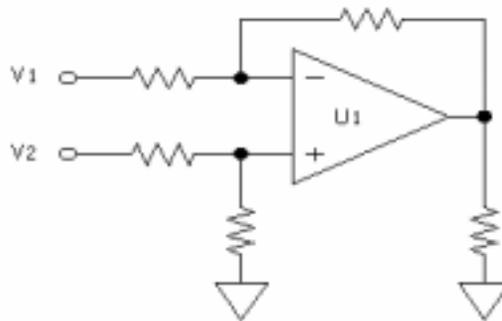
noninverting summing amplifier - an op amp configuration that algebraically combines input voltages and does not invert the sum voltage polarity.

UNIT 7 – THE DIFFERENCE AMPLIFIER

UNIT OBJECTIVE

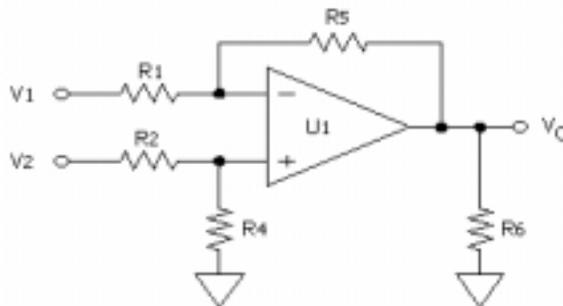
At the completion of this unit, you will be able to describe the operation of a difference amplifier by using a typical operational amplifier circuit.

UNIT FUNDAMENTALS



The **difference amplifier** shown is a two-input circuit that amplifies the difference between V_1 and V_2 .

V_1 is connected to the inverting side of U_1 , and V_2 is connected to the noninverting side of U_1 .



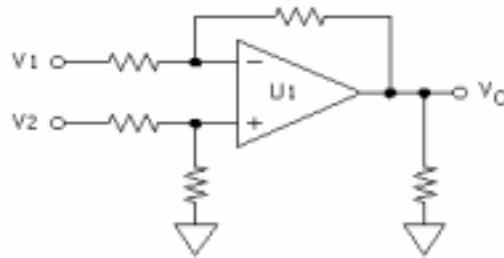
When R_1 , R_2 , R_4 , and R_5 are equal in value, the difference amplifier subtracts V_1 and V_2 .

$$V_O = V_2 - V_1$$

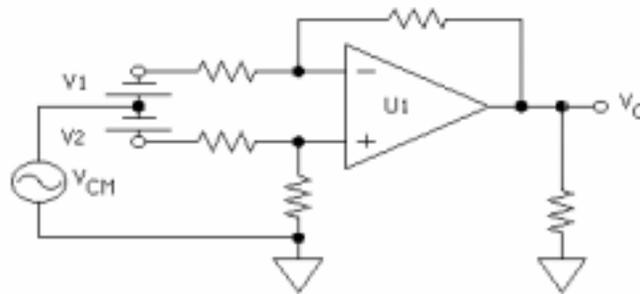
In practice, the input impedance for V_1 equals the ohmic value of R_1 . The input impedance for V_2 equals the ohmic value of $R_2 + R_4$. A difference amplifier circuit combines the gain effect from the inverting and noninverting resistor ratios.

For V_1 , V_O equals $-[V_1 \times (R_5/R_1)]$.

For V_2 , V_O equals $\{R_4/(R_2 + R_4)\} \times [1 + (R_5/R_1)]$.



A difference amplifier can combine dc and ac voltages. A difference amplifier exhibits a characteristic called **Common-mode rejection (CMR)**. CMR is the ability to cancel input voltages that simultaneously appear at both circuit inputs.



In this circuit, the sine wave generator applies an unwanted **common-mode input voltage** (V_{CM}) to both circuit inputs. Due to the common-mode rejection of U1, the sine wave does not appear at V_O .

Common-mode rejection ratio (CMRR), usually given in dB, measures the ability to cancel (attenuate or reduce) common-mode voltages. The amplitude of the unwanted signal appearing at the circuit output (V_{OCM}) equals $(A_v/CMRR) \times V_{CM}$: CMRR must be converted from dB form to numeric form. V_{OCM} is the remaining common-mode input signal appearing at the amplifier output.

NEW TERMS AND WORDS

difference amplifier - A circuit that amplifies the difference between two or more input voltages.

Common-mode rejection (CMR) - the ability of a difference amplifier to attenuate a signal appearing simultaneously at both inputs of the circuit.

common-mode input voltage - a voltage appearing simultaneously at both inputs of an amplifier.

Common-mode rejection ratio (CMRR) - a measure (usually in dB) of the amount of common-mode input voltage that appears at the circuit output.

Exercise 2 – Difference Amplifier AC Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to operate a difference amplifier using ac voltages. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- The difference amplifier combines input waveforms and accounts for amplitude and phase.
- If R_1 , R_2 , R_4 , and R_5 are equal in value, V_o equals $V_2 - V_1$.
- If V_2 and V_1 are identical (in amplitude and phase) ac waveforms, V_o is essentially 0V.
- V_o is 0V because of the common-mode rejection capability of U_1 .
- The common-mode rejection capability of an op amp is an advantage because a common-mode input voltage has a small effect on circuit output voltage.
- If V_2 has greater amplitude than V_1 , V_o is in phase with V_2 and lower in amplitude than either V_2 or V_1 .
- If V_2 has less amplitude than V_1 , V_o is in phase with V_1 and lower in amplitude than either V_2 or V_1 .
- If V_2 and V_1 have equal amplitudes and are 180° out of phase, then V_o is in phase with V_2 . In addition, V_o equals $2 \times V_1$ or $2 \times V_2$.
- When V_2 and V_1 are out of phase, V_1 (the inverting input) adds to the magnitude of V_2 (the noninverting input). V_2 dominates V_1 , and V_o is in phase with V_2 .
- Based on the $V_2 - V_1$ relationship of a difference amplifier, out-of-phase inputs (not common-mode) are **added**.

UNIT 8 – VOLTAGE COMPARATORS

UNIT OBJECTIVE

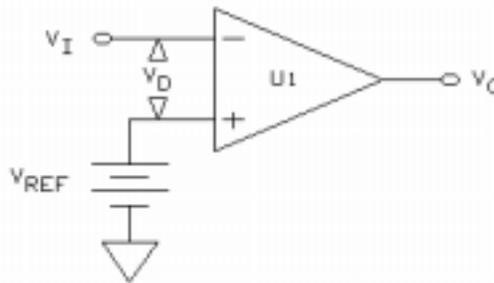
At the completion of this unit, you will be able to describe the operation of an operational amplifier comparator circuit.

UNIT FUNDAMENTALS

A **voltage comparator** circuit compares an input voltage to a reference voltage and indicates whether the input is greater than, equal to, or less than the reference voltage.

Voltage comparators are typically used as **level detectors** or squaring circuits.

Level detectors indicate when a voltage crosses a specific set point. Squaring circuits convert slow rise or fall time wave-forms into high slewing waveforms.

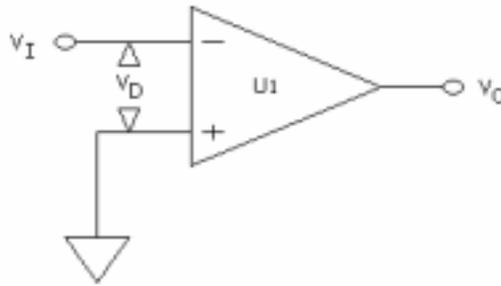


On this open-loop comparator, V_I is compared to the reference voltage (V_{REF}). V_{REF} is connected to the non-inverting terminal of U1. Therefore, U1 is not zero based, but has a trigger point equal to V_{REF} .

In this circuit, U1 tends to saturate due to the very high open-loop gain. V_D is not 0V if U1 is saturated.

When V_I is more positive than V_{REF} , V_D is greater than 0V, and V_O switches to $-V_{SAT}$.

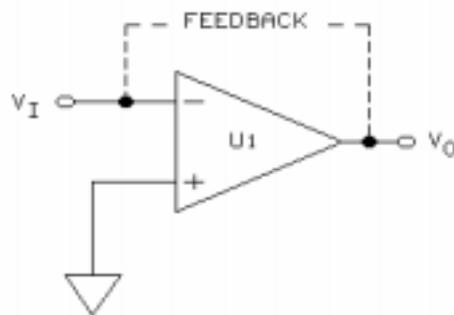
When V_I is more negative than V_{REF} , V_D is greater than 0V, and V_O switches to $+V_{SAT}$.



This circuit illustrates zero crossing operation: U1 is zero based because its (+) input is connected to circuit common.

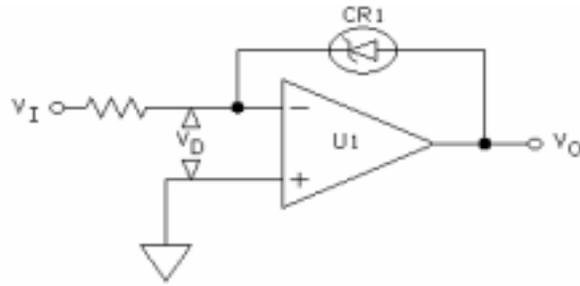
If V_I equals 0V, then V_D equals 0V, and U1 is not saturated.

If V_I is slightly above or below 0V (circuit common), V_O is at negative or positive saturation, and V_D is greater than 0V.



Open-loop comparator configurations are not practical because of the saturation characteristics of op amps: slew rate limits and large voltage swings.

Op amp comparators can operate in closed-loop configurations. Feedback limits the level of voltage change and introduces **hysteresis**.

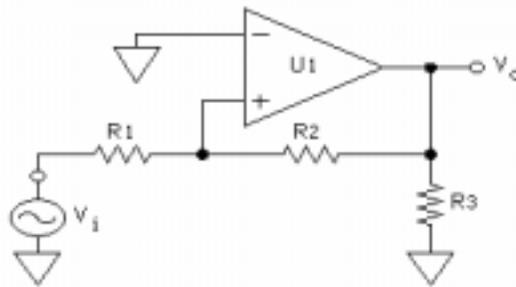


Zener diode CR1 provides a feedback path to limit the voltage swing of V_O , thus preventing U1 saturation.

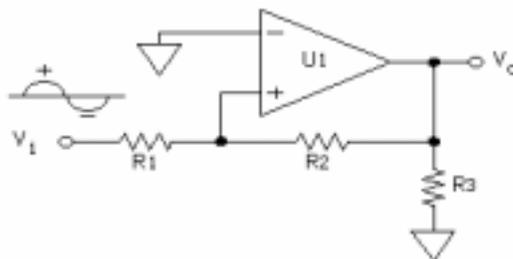
If V_I equals 0V, V_D equals 0V. V_O is not 0V because of the characteristics of CR1 when it "sees" insufficient current.

If V_I is positive, V_O equals $-V_Z$ (CR1's zener voltage), but V_D equals 0V.

If V_I is negative, V_O equals $+V_F$ (CR1's forward diode drop), but V_D equals 0V.



This circuit uses the noninverting input side of U1 as the circuit input. If V_i is positive, V_O is positive; if V_i is negative, V_O is negative.



Positive feedback through resistor R2 generates hysteresis. Hysteresis prevents false triggering of U1 around the zero crossing points of V_i by increasing the width of the **threshold voltage**

Exercise 3 – Square Wave Converter

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to operate a sine wave to square wave converter. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- U1 is configured as an open-loop comparator that uses positive feedback and is referred to as a Schmitt trigger.
- V_i is converted from a sine wave into a square wave. V_o switches between $+V_{SAT}$ and $-V_{SAT}$ and is in phase with V_i .
- Positive feedback voltage (V_{TH}) is provided by hysteresis resistor R_H . Two trigger points are established by the positive feedback.
- V_{TH} provides a voltage at the noninverting input of U1. Therefore, the circuit is not zero based.
- Hysteresis, or positive feedback, creates a window, or band, through which V_i must cross before the comparator switches V_o .
- Based on a specific hysteresis level, a switch in V_o occurs at trigger points A and B.
- V_o cannot switch back until V_i crosses a trigger point. Within the window, variations of V_i do not cause U1 to switch.
- The voltage difference between points A and B, labeled $+V_{TT}$ and $-V_{TT}$, equals the circuit hysteresis voltage.
- An increase of positive feedback increases the width of the hysteresis window.
- A decrease of positive feedback decreases the width of the hysteresis window.
- Hysteresis reduces the sensitivity of a comparator, increasing the noise immunity of the circuit.
- Based on V_i , a zero based comparator (no hysteresis) generates many changes in V_o . The number of transitions in V_o decreases as hysteresis increases.
- Two equations, based on the saturation level of U1, define the circuit trigger voltages
- ($+V_T$ and $-V_T$).

$$+V_T = +V_{SAT}/(R2/R1)$$

$$-V_T = -V_{SAT}/(R2/R1)$$
- The trigger voltages are based on the saturation voltage of U1. Therefore, the trigger points are not symmetrical and vary from op amp to op amp.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Operational Amplifier Applications

FACET[®]



Student Workbook

FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

The **Appendix** includes safety information.

UNIT 1 – INTRODUCTION TO THE CIRCUIT BOARD

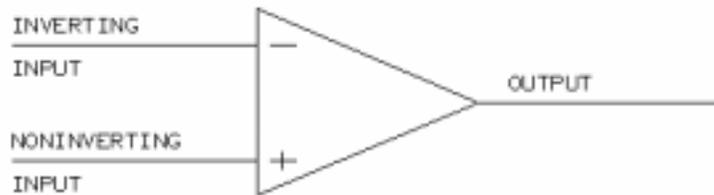
UNIT OBJECTIVE

At the completion of this unit, you will be able to locate and identify the major components on the OPERATIONAL AMPLIFIER APPLICATIONS circuit board.

UNIT FUNDAMENTALS

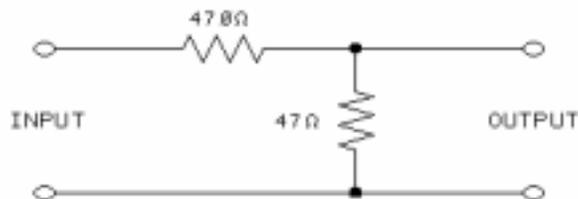
The OPERATIONAL AMPLIFIER APPLICATIONS circuit board consists of 6 training circuit blocks:

- INTEGRATOR
- DIFFERENTIATOR
- LOW PASS FILTER
- HIGH PASS FILTER
- BAND PASS FILTER
- FULL-WAVE BRIDGE DRIVER/CONVERSION



Each circuit block is designed around an LF441 integrated circuit operational amplifier (op amp). The schematic symbol for an op amp is shown.

Each op amp is installed in a plug-in DIP socket. This makes it easy to replace the op amps if they become damaged.

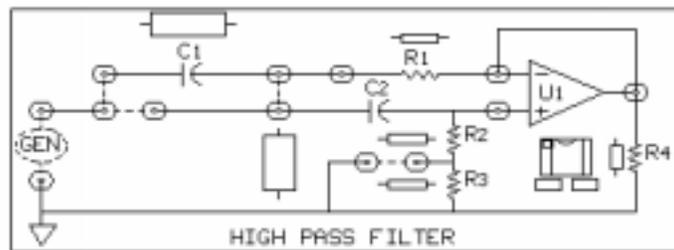


The circuit board provides an **ATTENUATOR** circuit block for use with input signals whose amplitude is too large for the test circuits.

Attenuation is a reduction of a signal's amplitude. In this circuit, the attenuation factor is 11:1 based on the resistor ratio of 470Ω to 47Ω .



This symbol represents the signal generator connected to each circuit block input. The dotted lines indicate that it is not permanently wired to the circuit, so you must make the connections yourself.



Two-post connectors are used to change circuit configurations.

NEW TERMS AND WORDS

Attenuator - a circuit that reduces a signal's amplitude.

Attenuation - the reduction of a signal's amplitude.

decouple - to use capacitors to bypass (provide a low ac impedance path to circuit common) the power supply lines of an amplifier.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

Signal generator

OPERATIONAL AMPLIFIER APPLICATIONS circuit board

Exercise 1 – Component Location and Identification

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to locate the major circuit blocks on the OPERATIONAL AMPLIFIER APPLICATIONS circuit board. You will verify your results by correctly identifying these circuits and their major components.

DISCUSSION

- Each op amp is an 8-pin integrated circuit (IC) installed in a DIP socket.
- The op amp IC has a small “dimple” in the upper left corner which identifies pin 1. The pin numbers are counted consecutively in a counterclockwise (CCW) direction, starting at the “dimple”.
- Bypass capacitors are located below each op amp.
- Decoupling provides a local low ac impedance path to ground. This improves the stability of the amplifiers.
- Additional electronic components are present to allow each circuit block to be configured for specific applications.
- Most op amp applications have output load resistors. The exception is the FULL-WAVE BRIDGE DRIVER/CONVERSION circuit block.

Exercise 2 – Circuit Block Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to connect the signal generator to operate the various circuit blocks. You will determine circuit function by using the oscilloscope to analyze input and output waveforms.

DISCUSSION

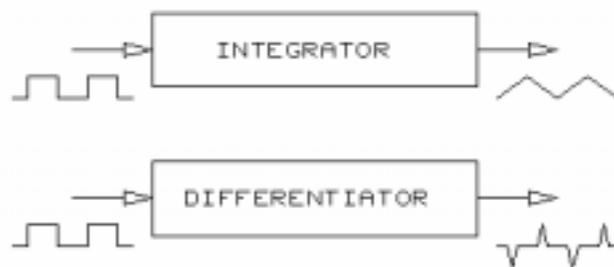
- Three circuit blocks are filter circuits. They are the HIGH PASS FILTER, LOW PASS FILTER, and BANDPASS FILTER.
- Filters are used to pass input signals of specific frequencies and reject, (filter out or block) input signals of other frequencies.
- The configuration of the circuit resistors and capacitors determine the filter application.
- The value of the resistors and capacitors determines the frequencies to be filtered or passed.
- HIGH PASS FILTERS pass high frequency input signals and reject (attenuate) low frequency input signals.
- LOW PASS FILTERS pass low frequency input signals and reject (attenuate) high frequency input signals.
- BANDPASS FILTERS pass a range of frequencies. Input signals with frequencies which are within that range are passed to the output. Frequencies above or below the filter's range are rejected.

UNIT 2 – INTEGRATION AND DIFFERENTIATION

UNIT OBJECTIVE

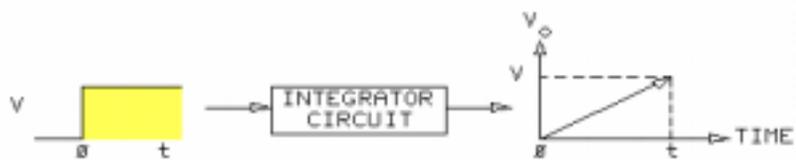
At the completion of this unit, you will be able to determine the effects of an active integrator and differentiator circuit on an input waveform. You will verify your results with an oscilloscope.

UNIT FUNDAMENTALS

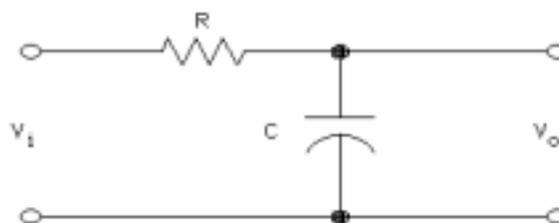


Integrators and **differentiators** are signal conditioning circuits that change the shape of an input waveform.

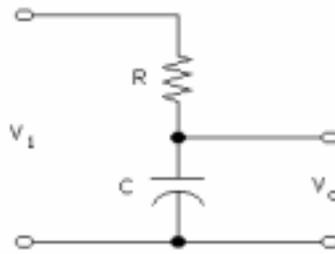
The modified output signals can then be used to perform different functions.



The output of an integrator is a voltage equal to the **area under the input waveform** over a specified period of time.

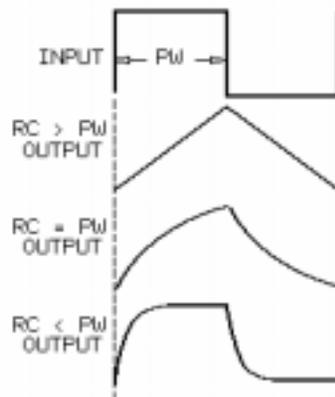


This **passive integrator** network is called "passive" because it does not include any active component that is capable of amplification, such as a transistor or an op amp.



You can also think of a passive integrator as a voltage divider with the output taken across the capacitor.

Increasing the frequency of an integrator's input signal causes the output amplitude to **decrease**.



The top waveform in this group represents an input pulse to a passive integrator.

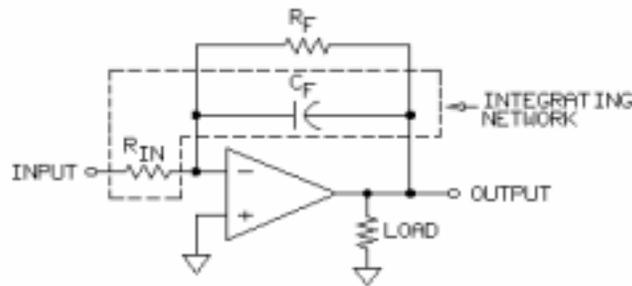
The remaining waveforms are the resulting output for different relationships of input pulse width (PW) to the RC time constant.

For the first output, the RC time constant is **larger than the pulse width**. The input pulse ends before the capacitor charges completely.

For the second output, the RC time constant approximately **equals the pulse width**. The slight rounding at the top of the waveform is due to the exponential nature of the capacitor's charging action.

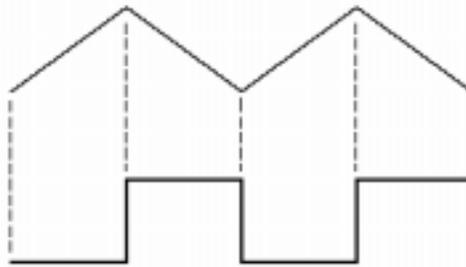
For the third output, the RC time constant is much **smaller than the pulse width**. The capacitor charges up relatively quickly and has finished charging long before the input pulse ends.

In practice, a common use of the integrator is to produce a linear ramp waveform from a square wave.



The integrating network is formed by the feedback capacitor (C_F) and the input resistor (R_{IN}).

For low frequencies and dc, C_F can be ignored, and the circuit acts like a linear inverting amplifier.

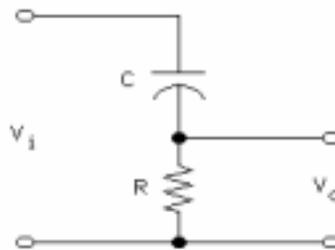


The output of a differentiator circuit is a voltage that is proportional to the **change in slope** of the input waveform. The example shown is a ramp input waveform that differentiates into a square wave output.

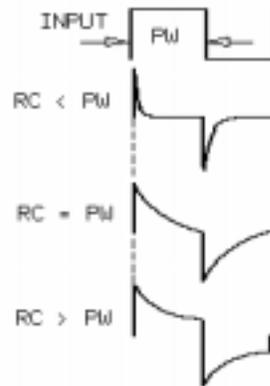
The rising portion of the input wave-form represents a **constant slope**. Since there is no change in the slope, the corresponding portion of the differentiator output is a horizontal line.

When the input slope goes negative, the output transition is positive due to the inverting amplifier configuration.

Conversely, when the input slope goes positive, the output transition is negative.



Increasing the differentiator's input frequency causes the output amplitude to **increase**.



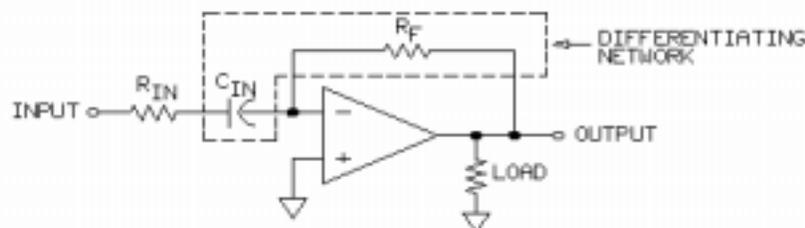
The top waveform in this group represents an input pulse to a passive differentiator. The remaining waveforms show the resulting output for different relationships of input pulse width (PW) to the RC time constant.

For the first output, RC is much **smaller than the pulse width**. This results in a relatively quick charging of the capacitor and a relatively quick discharging through the resistor, as the narrow pulse width indicates.

For the second output, RC approximately **equals the pulse width**. The output pulse widens as the discharging time of the capacitor increases.

The third output shows the result of the time constant being **larger than the input pulse width**. The output pulse width has increased to a point where the capacitor has not fully discharged by the time the input pulse ends.

In practice, the most common use of a differentiator is to produce a short pulse from a relatively long pulse.



In this **active differentiator circuit**, the op amp is the active element. The differentiator network consists of a feedback resistor (R_F) and an input capacitor (C_{IN}).

At very high input frequencies, the reactance of C_{IN} approaches zero. An input resistor (R_{IN}) is placed in series to limit the closed loop voltage gain at high frequencies.

Exercise 1 – The Integrator

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the effects of an active integrator on an input waveform. You will verify your results with an oscilloscope.

DISCUSSION

- This is an active integrator circuit. The op amp (U1) is the active component.
- The integrating network is formed by R_1 and C_1 .
- No feedback resistor is needed in an ideal active integrator. In practice the feedback resistor (R_3 in this circuit) establishes the dc and low frequency gain of the op amp. The feedback resistor, also, prevents saturation due to input offset voltages.
- The op amp acts like an inverting amplifier.
- R_2 reduces the effects of input offset currents.
- The load resistor is R_4 .
- The integrator has a low frequency phase shift of 180° . At higher frequencies the phase shift decreases from 180° because of the reactance of the feedback capacitor.
- This active integrator, within a certain range of frequencies, has the basic characteristics of a low pass filter which are: Low frequencies are passed to the output with high gain and high frequencies are attenuated.
- The cutoff frequency (f_C) is the frequency at which attenuation begins.
- The breakpoint frequency is the frequency at which the feedback capacitor's reactance equals the feedback resistance ($R_F = X_{CF}$).
- Integration occurs above the breakpoint frequencies. Below the breakpoint frequencies, high capacitive reactance causes the circuit to act like a simple inverting amplifier.
- Breakpoint frequency (f_C) is calculated using this equation:
$$f_C = 1/(2\pi \times R_3 \times C_1)$$

Exercise 2 – The Differentiator

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the effects of an active differentiator on an input waveform. You will verify your results with an oscilloscope.

DISCUSSION

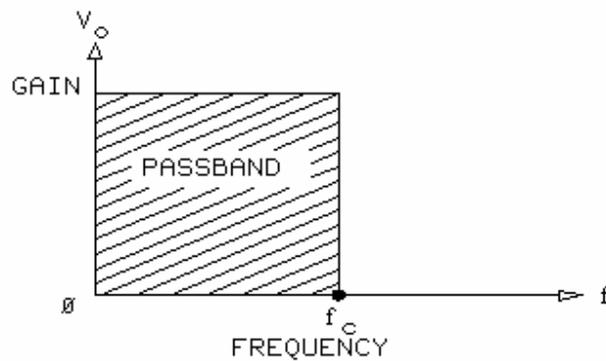
- This is an active differentiator circuit. The op amp (U1) is the active component.
- The differentiating network is formed by R_2 and C_1 .
- The op amp acts like an inverting amplifier.
- R_1 limits the high frequency gain of the circuit.
- The load resistor is R_3 .
- When square wave inputs are applied, the differentiated output is inverted with respect to the input.
- Triangle input waveforms are differentiated into square waves.
- Low frequency sinusoidal input signals are differentiated into a 90° phase shifted sinusoidal waveform.
- The phase shift approaches 180° as the frequency increases to the breakpoint.
- Output signal amplitude increases as frequency increases. Therefore, for sinusoidal input signals, the active differentiator tends to pass high frequencies.
- The breakpoint frequency is the frequency at which the feedback capacitor's reactance equals the resistance ($R_1 = X_{C1}$).
- The active differentiator has two distinct operating regions, which can be seen by viewing the gain versus frequency curve.
- Frequencies below the breakpoint, differentiation occurs and gain increases with increasing frequency. At and above the breakpoint frequency, the signal is passed with maximum gain.
- For practical differentiators, choose a relatively high breakpoint frequency to make use of the widest possible differentiator region.

UNIT 3 – LOW PASS FILTER

UNIT OBJECTIVE

At the completion of this unit, you will be able to determine the operating characteristics of low pass filters by analyzing the performance of a single and double pole op amp filter circuit. You will verify your results with an oscilloscope.

UNIT FUNDAMENTALS



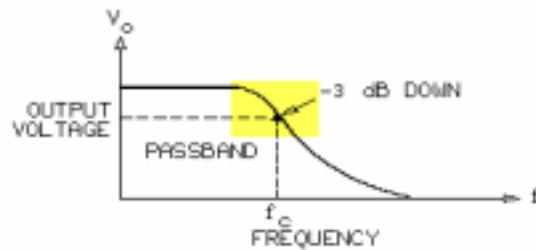
A **low pass filter** is a circuit that passes input signals below a certain frequency and blocks higher frequency signals.

The gain versus frequency characteristics of an ideal low pass filter are shown.

The point at which the filter stops passing and begins blocking input signals is the **cutoff frequency (f_c)**.

The range of frequencies passed by the filter is the **passband**.

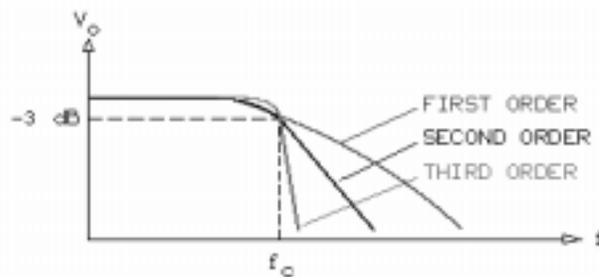
The range above the cutoff is the **stopband**.



The characteristics of a practical low pass filter show a more gradual transition from passband to stopband. You will see in a later discussion that it is possible to alter the circuit to make the characteristics approach the ideal response.

The cutoff frequency is also called the **corner frequency** or break frequency and is the point at which the output voltage equals 70.7% of the passband level. This corresponds to a -3 dB attenuation and is also known as the **3 dB down point**.

The rate at which gain decreases beyond f_c is the filter's **rolloff**.

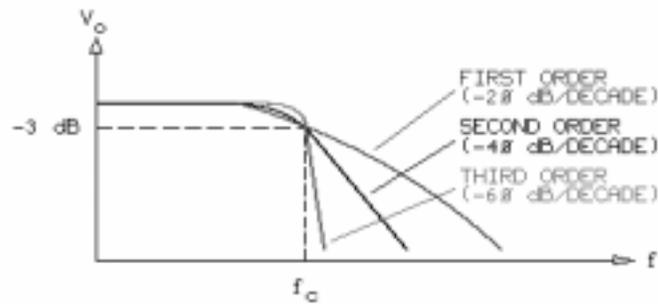


Low pass filters have a property called **order**. The order number corresponds to the number of poles a filter has. The number of poles is also the number of lag networks.

As a filter's order (number of poles) increases, it experiences a sharper rolloff, and its response curve approaches that of the ideal low pass filter.

Different types of low pass filters have different rolloff characteristics.

For example, the Butterworth filter responses shown exhibit an attenuation rate of $n \times (-20)$ dB per decade, where n is the number of poles.



These response curves show the attenuation rates for first, second, and third order Butterworth low pass filters.

NEW TERMS AND WORDS

overshoot - the amount by which a signal exceeds its final value.

undershoot - the amount by which a signal exceeds its final value in a direction opposite to the main transition.

ringing - a damped oscillation in a circuit's output signal resulting from a sudden change in the input signal.

settle time - the time required for ringing to diminish to a specific level.

damping - reduction of amplitude in oscillations.

overdamped - damped beyond the critically damped level.

critically damped - condition of a filter in which the damping level provides this.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Oscilloscope, dual trace

Signal Generator

OPERATIONAL AMPLIFIER APPLICATIONS circuit board

Exercise 1 – Low Pass Filter Frequency Response

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the frequency characteristics of an active low pass filter by using an oscilloscope to analyze input and output waveforms.

EXERCISE DISCUSSION

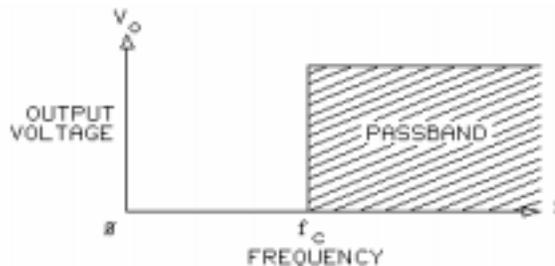
- Active low pass filters can be designed for different types of frequency response. Circuit component relationships define the type of frequency response.
- Chebyshev, Butterworth, and Bessel are three common types of active low pass filters.
- The Chebyshev filter has stopband characteristics that are close to those of an ideal low pass filter.
- Butterworth filters exhibit passband characteristics that are close to those of an ideal filter.
- Plot filter response curves on semilogarithmic graph paper to clearly illustrate rolloff characteristics of the filter. Output voltage (or dB gain) is assigned to the vertical (y) axis. The horizontal (x) axis is scaled logarithmically.
- A frequency decade is defined as a factor of 10, i.e.: 100, 1k, 10k.

UNIT 4 – HIGH PASS FILTER

UNIT OBJECTIVE

At the completion of this unit, you will be able to determine the operating characteristics of high pass filters by analyzing first order and second order op amp filter circuits. You will verify your results with an oscilloscope.

UNIT FUNDAMENTALS

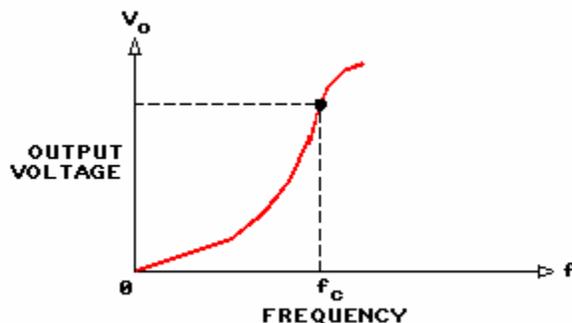


A **high pass filter** is a circuit that allows frequencies above a specified limit to pass but attenuates all frequencies below the limit.

For the ideal high pass filter characteristics shown, the point at which input signals begin to pass to the output is called the **corner frequency** (f_c).

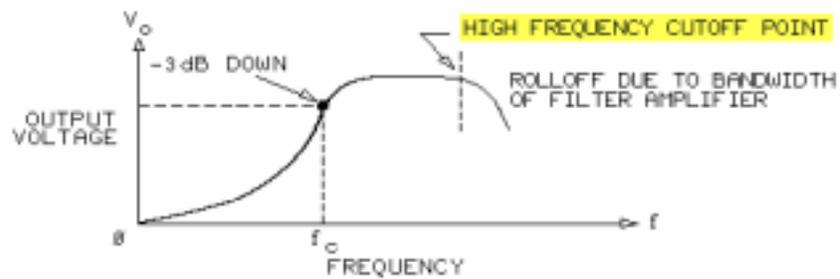
The range of frequencies passed by the filter (above f_c) is the passband.

The range of frequencies blocked by the filter is the stopband.



The response curve for a practical high pass filter shows a more gradual transition from stopband to passband.

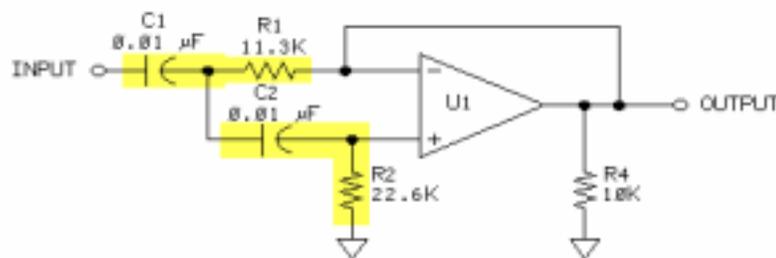
The corner frequency (f_c) is the point at which the output voltage is at 70.7% of the passband level, which corresponds to a -3 dB attenuation. This point is also called the **3 dB down point**.



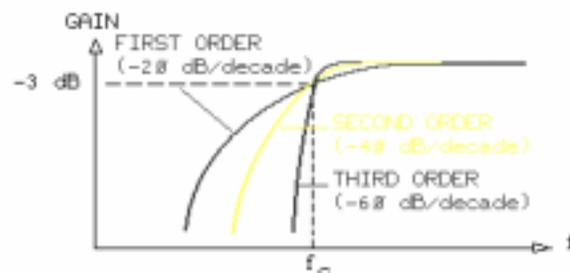
A practical high pass filter designed with an op amp also has a **high frequency cutoff** due to the op amp's bandwidth limitations.

The high frequency cutoff point depends on the specifications of the particular op amp.

High pass filters are classified by an order number, which corresponds to the number of **lead networks** in the circuit.



This high pass filter circuit has 2 lead networks: R2 and C2 and R1 C1.



The attenuation in a high pass filter's stopband increases as the order number increases, as shown in these Butterworth response curves.

Exercise 2 – Phase and Transient Response

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the phase and transient response characteristics of a high pass filter by analyzing input and output waveforms. You will verify your results with an oscilloscope.

DISCUSSION

- High pass filters cause phase shifts between the input and output signals. The phase shift characteristics depend on the type of response (Butterworth, Bessel, or Chebyshev, for example).
- Phase shift decreases as frequency increases.
- Phase shift increases as the order number increases.
- Transient response of a high pass filter is its ability to react to changes in the input signal.
- Transient signals to a high pass filter can produce output distortion; examples are overshoot, undershoot, and ringing.
- Damping is used to reduce or eliminate overshoot, undershoot, and ringing.
- Large amounts of damping can result in an overdamped output, which can severely delay the filter's response to step input signals.

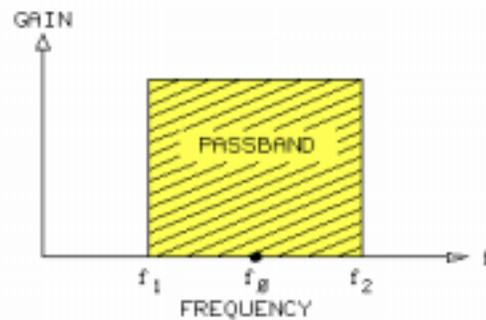
UNIT 5 – BAND PASS FILTER

UNIT OBJECTIVE

At the completion of this unit, you will be able to determine the operating characteristics of an active bandpass filter by analyzing input and output signals.

UNIT FUNDAMENTALS

A **band pass filter** is a circuit that passes frequencies within a certain range, or band. Frequencies above and below this band are attenuated.

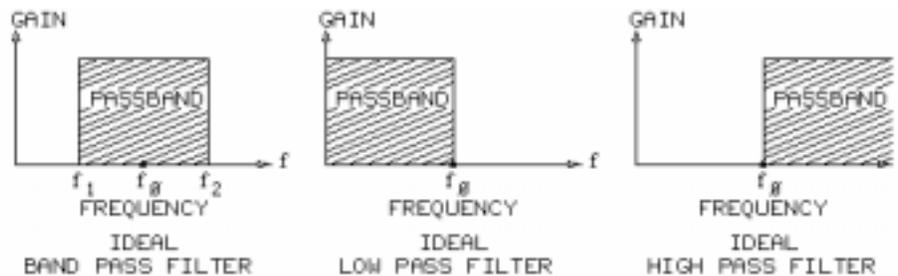


For the ideal frequency response shown, the range of frequencies passed by the filter is the passband.

The two frequency ranges attenuated by the filter are the upper and lower stopbands.

The midpoint of the passband is the **center frequency (f_0)**

The corner frequency at the leading edge of the passband is the **lower cutoff frequency (f_1)**.



These are the response curves of ideal band pass, low pass, and high pass filters.

In practice, a band pass filter is sometimes designed using a low pass filter in combination with a high pass filter.

Exercise 1 – Band Pass Filter Frequency Response

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the frequency response characteristics of an active bandpass filter by analyzing input and output signals. You will verify your results with an oscilloscope.

DISCUSSION

- The center frequency is at the midpoint of the passband.
- The lower cutoff frequency is the point below the center frequency at which the output is 3 dB below the maximum gain.
- The upper cutoff frequency is the point above the center frequency at which the output is 3 dB below the maximum gain.
- The passband is the frequency range between the lower cutoff frequency and the upper cutoff frequency.
- The bandwidth of the passband is determined using this equation: $BW = f_2 - f_1$
- Bandpass filters are classified as narrow-band or wide-band. If the bandwidth is less than or equal to 10% of the center frequency, the filter is a narrow-band type. If the bandwidth is greater than 10% of the center frequency, the filter is a wide-band type.
- Bandpass filters select a narrow range of frequencies from a relatively wide frequency spectrum. This selectivity is expressed by the bandpass filter's quality factor, or Q-factor.
- The Q-factor is defined by the equation: $Q = f_0/BW$
- A high-Q filter has a minimum Q of 10. Low-Q filters have a Q of below 10.

Exercise 2 – Band Pass Filter Phase Response

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the phase response of an op amp band pass filter circuit. You will verify your results with an oscilloscope.

DISCUSSION

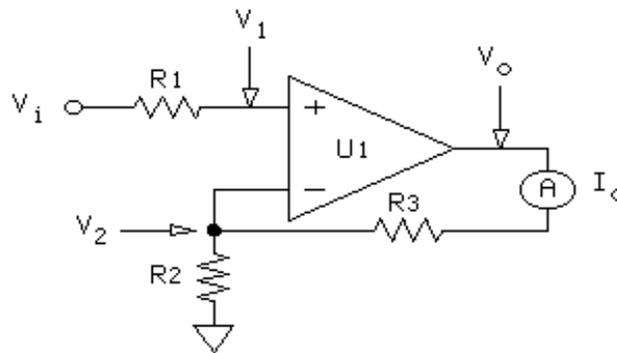
- The phase response of a bandpass filter is a combination of the phase responses of the low pass and high pass filters.
- Phase shift is about -45° at the corner frequency of the high pass filter or at the lower cutoff frequency of the bandpass filter. Phase shift increases toward -90° as frequency decreases.
- Phase shift is about $+45^\circ$ at the corner frequency of the low pass filter or at the upper cutoff frequency of the bandpass filter. Phase shift increases toward $+90^\circ$ as frequency increases.
- At the center frequency the bandpass filter has a net phase shift of about 0° .
- The bandpass filter used in this unit has a phase shift caused by the inverting op amp. The additional phase shift is -180° and is created by the reactive components in the op amp feedback and input circuit.
- The overall phase shift of the bandpass filter circuit is a combination of the op amp inversion and the individual capacitor phase shifts.

UNIT 6 – FULL-WAVE BRIDGE DRIVER/CONVERSION

UNIT OBJECTIVE

At the completion of this unit, you will be able to determine the operating characteristics of an op amp voltage-to-current converter by applying ac and dc input voltages. You will verify your results by measuring circuit output current.

UNIT FUNDAMENTALS

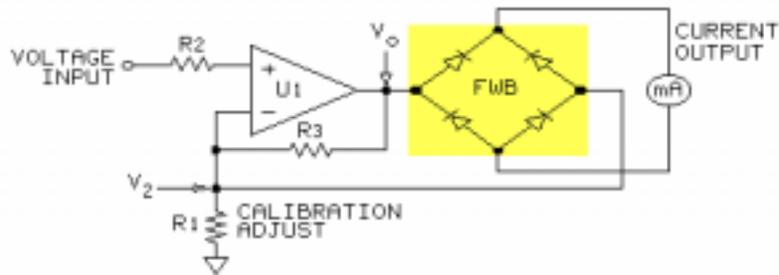


An op amp can be configured to convert an input voltage to a proportional output current. A typical noninverting **voltage-to-current converter** circuit is shown.

The op amp is configured as a noninverting voltage follower. The op amp's output constantly changes to maintain a zero voltage differential between the + and – inputs.

Since the meter is in the feedback loop, its voltage drop is compensated by the op amp.

You can determine the output current by dividing V_2 by R_2 ($I_0 = V_2/R_2$).



By adding a full-wave bridge (FWB) rectifier as shown, this circuit is still a voltage-to-current converter, but you can adjust R1 to calibrate the output current to the peak, rms, or average value of a sinusoidal input voltage.

An ac input signal results in an ac output signal from the op amp. This signal is rectified by the full-wave bridge before driving the milliammeter.

This circuit can also accept dc signals of either polarity.

The full-wave rectifier ensures that positive voltage always appears at the positive meter terminal.

NEW TERMS AND WORDS

voltage-to-current converter - a circuit whose output is a current proportional to its input voltage

conversion factor - a number that establishes the relationship of output current

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Milliammeter

Multimeter

Oscilloscope, dual trace

Generator, sine wave

OPERATIONAL AMPLIFIER APPLICATIONS circuit board

Exercise 1 – Op Amp Voltage-to-Current Conversion

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the operating characteristics of an op amp voltage-to-current converter by applying a dc input voltage. You will verify your results by measuring dc output current.

DISCUSSION

- Op amp (U1) is configured as a noninverting amplifier, has a high gain, and a very high input impedance.
- The op amp output voltage moves up or down to make the voltage drop across R1 (V1) equal to the input voltage (Vi). Current is generated through the feedback path.
- The output current can be adjusted by varying R1 since the voltage drop V1 matches the input voltage Vi.
- The four diodes form the full-wave bridge rectifier. CR2 and CR3 conduct when the input voltage is negative. CR1 and CR4 conduct when the input voltage is positive.
- The full-wave bridge rectifier maintains a one way flow of current through the meter. This allows ac input voltage and dc input voltage (of either polarity) to be converted.
- The calibration resistor (R1) can be used to adjust the circuit to any voltage-to-current factor (within the circuit limitations). The conversion factor is found using this equation:
$$FC = I_o/V_i$$
- The output current is found using this equation: $I_o = FC \times V_i$

Exercise 2 – Full-Wave rms and Average Converter

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the operating characteristics of an op amp voltage-to-current converter by applying a sinusoidal input voltage. You will verify your results by measuring circuit output current.

DISCUSSION

- A sinusoidal input signal is converted into a proportional dc current using a circuit that consists of a full-wave bridge and an op amp.
- The op amp is configured as a noninverting voltage follower. The op amp output is positive for the positive half-cycle of the input.
- The current through the meter always flows in the same direction because the full-wave bridge rectifier produces a signal with a constant polarity.
- R1 is used to establish the relationship of output current to input voltage. Adjusting R1 allows calibration of the meter to read peak-to-peak, average, or rms value of the input sine wave.
- Peak-to-peak voltage (V_{pk-pk}) of a sine wave is measured between its positive and negative peaks.
- Peak value (V_{pk}) is measured from 0V to the peak of one half-cycle. The peak value is half the peak-to-peak value.
- The average value (V_{avg}) of a sine wave is 0V because the portions of the curve above and below 0V are equal. The meter reads the value of the rectified waveform; therefore the average value will not be 0V.
- The average value of a full-wave rectified sine wave is 63.6% of the peak value.
 $V_{avg} = .636 \times V_{pk}$
- The rms value of a full-wave rectified sine wave is 70.7% of the peak value.
 $V_{rms} = .707 \times V_{pk}$
- Calibration of the meter is determined by adjusting the output current to 1 mA when the input voltage is set for the appropriate 1V equivalent. For example: set the input voltage to 2.83 V_{pk-pk} (the equivalent of 1 V_{rms}), adjust R1 for a 1 mA output and the meter is calibrated to display V_{rms} .

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Digital Logic Fundamentals

FACET[®]



Student Workbook



FOURTH EDITION

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

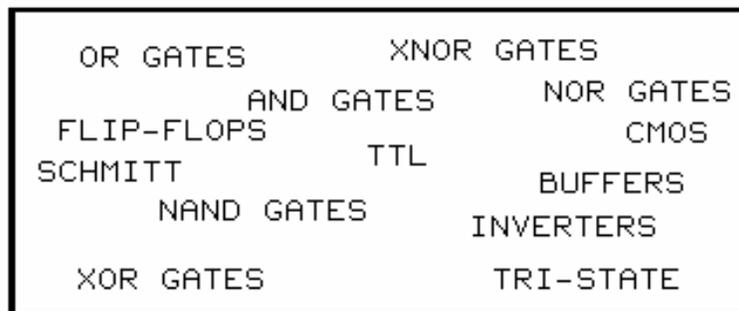
The **Appendix** includes safety information.

UNIT 1 – INTRODUCTION TO THE CIRCUIT BOARD

UNIT OBJECTIVE

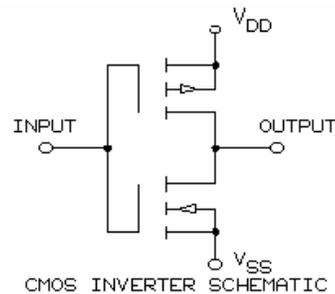
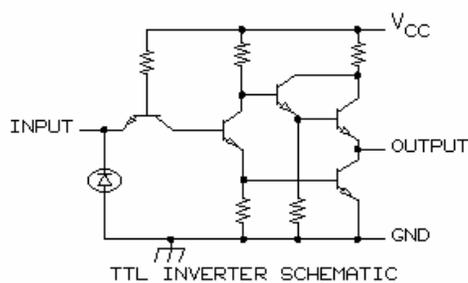
At the completion of this unit, you will be able to locate, identify, and connect digital circuits, and demonstrate digital logic states by using the DIGITAL LOGIC FUNDAMENTALS circuit board.

UNIT FUNDAMENTALS

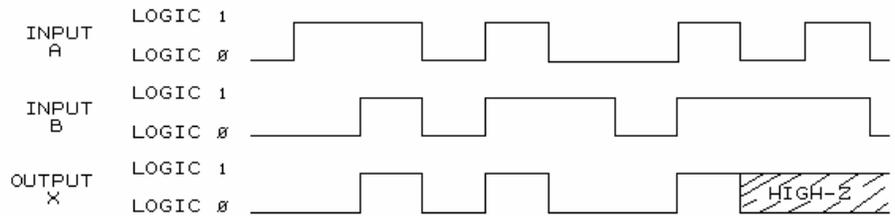


LOGIC GATES

The DIGITAL LOGIC FUNDAMENTALS circuit board is composed of ten circuit blocks that demonstrate different types of **logic gates**; there are also three voltage and signal support circuit blocks.



Logic gate circuits consist of transistors that act like on/off switches. Most of the gates on the circuit board are bipolar **TTL** (transistor to transistor logic) gates. A comparison of a bipolar TTL gate and a **CMOS** gate is made on the TTL/CMOS COMPARISON circuit block.



LOGIC STATES

The output logic state (level) of a gate depends on the logic state of the input(s). There are two logic states: logic 1, or high, and logic 0, or low.

The output of some gates can also be in a high-Z (high impedance) state, which is neither a high nor low logic state. The gate is disabled when the output is in a high-Z state; the inputs have no effect on the output.

The input and output logic states change voltage levels stepwise or almost instantaneously. Sequential (consecutive) change is the nature of digital signals.

The input and output logic states change voltage levels stepwise or almost instantaneously. Sequential (consecutive) change is the nature of digital signals. Analog signals change in a smooth continuous manner.

BOOLEAN ALGEBRA

The logic gates simulate equations of **Boolean algebra**. Boolean algebra equations are expressions that relate the output logic state to the input logic state(s).

$X = A$	<table style="border-collapse: collapse; margin: 0 auto;"> <tr> <td style="padding: 2px 5px;">INPUT A</td> <td style="padding: 2px 5px;">OUTPUT X</td> </tr> <tr> <td style="padding: 2px 5px;">1</td> <td style="padding: 2px 5px;">1</td> </tr> <tr> <td style="padding: 2px 5px;">0</td> <td style="padding: 2px 5px;">0</td> </tr> </table>	INPUT A	OUTPUT X	1	1	0	0
INPUT A	OUTPUT X						
1	1						
0	0						

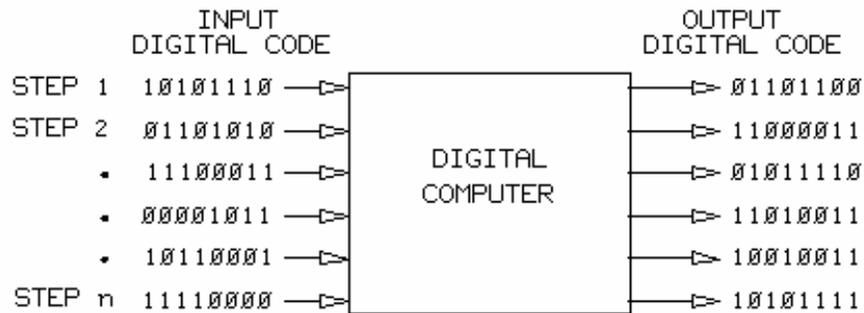
For example, the Boolean equation $X = A$ means that the output X will have the same logic state as the input A. This relationship is presented in a tabular form called a **truth table**. In a truth table, a 1 means logic 1, or high, and a 0 means logic 0, or low.

$X = \bar{A}$	INPUT A	OUTPUT X
	1	0
	0	1

Another example of a Boolean equation is $X = \bar{A}$. The truth table is shown above. The equation $X = \bar{A}$ means that X is the **complementary logic state** (opposite or inverted state) of A: when A is logic 1, X is logic 0 and vice versa.

NOT SYMBOL

The overbar (line over the letter **A**) is a NOT symbol that indicates a complementary condition. The Boolean equation $X = \bar{A}$ means that if A is logic 0, X is logic 1.



DIGITAL COMPUTER

A digital computer contains **integrated circuits (ICs)** that are com-posed of logic gates. The outputs and inputs of the logic gates are connected to perform the function of the digital computer.

Letters, numbers, and graphic symbols processed by a digital com-puter are represented by a **binary code** that consists of logic 1s and logic 0s.

The logic states of the gate inputs and outputs in a digital computer change state sequentially (consecutively). The sequential logic functions occur millions of times per second.

Understanding the fundamentals of digital logic circuits is the first step in learning about the operation of a digital computer.

NEW TERMS AND WORDS

logic gates - devices that perform logic functions.

TTL - Transistor-Transistor-Logic; a logic gate composed of bipolar transistors.

CMOS - devices constructed from a Complementary Metal Oxide Semiconductor process.

Boolean algebra - a logical expression that relates the output logic state of a gate to its input logic state(s).

truth table - a table that shows the relationship of output logic states to all combinations of input logic states.

complementary logic state - the binary opposite logic state; logic 1 is the complementary logic state of logic 0.

NOT symbol - an overbar symbol that indicates that the function is the complement.

integrated circuits (ICs) - devices that combine the actions of many transistors on one chip. There are many types of IC devices.

binary code - a method of representing numbers by using the two digits 0 and 1.

LED - Light-Emitting Diode; a semiconductor diode that emits light when forward biased.

pulse train - a free-running and repetitive waveform; usually refers to a square waveform.

dual-in-line package (DIP) - a type of IC package that has the same pin count on both sides of the device.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DIGITAL LOGIC FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Exercise 1 – Circuit Block Familiarization

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to locate and identify the circuit blocks and components on the DIGITAL LOGIC FUNDAMENTALS circuit board. You will verify your results by identifying logic circuits and making logic level measurements with a voltmeter and an oscilloscope.

EXERCISE DISCUSSION

- There are thirteen circuit blocks on the DIGITAL LOGIC FUNDAMENTALS circuit board connected to your base unit.
- Three of the circuit blocks are support circuits that are located in the upper left corner of the circuit board. The support circuit blocks include:
 - POWER SUPPLY REGULATOR (not labeled)
 - CLOCK
 - INPUT SIGNALS.
- The ten circuit blocks that contain digital logic circuits are:
 - AND/NAND circuit block
 - OR/NOR circuit block
 - XOR/XNOR circuit block
 - OPEN COLLECTOR circuit block
 - SET/RESET FLIP-FLOP circuit block
 - D-TYPE FLIP-FLOP circuit block
 - JK FLIP-FLOP circuit block
 - TRI-STATE OUTPUT circuit block
 - TTL/CMOS COMPARISON circuit block
 - DATA BUS CONTROL circuit block.
- The +5V LED indicates that 5 Vdc power is available to the circuit board.
- The CLOCK circuit block provides a 50 kHz square wave clock signal.
- The INPUT SIGNALS circuit block provides two outputs (A and B) for static high (logic 1) and low (logic 0) signals.
- The circuit board contains several ground terminals.
- The logic circuits on the circuit board are contained in dual-in-line (DIP) integrated circuit (IC) packages.

UNIT 2 – FUNDAMENTAL LOGIC ELEMENTS

UNIT OBJECTIVE

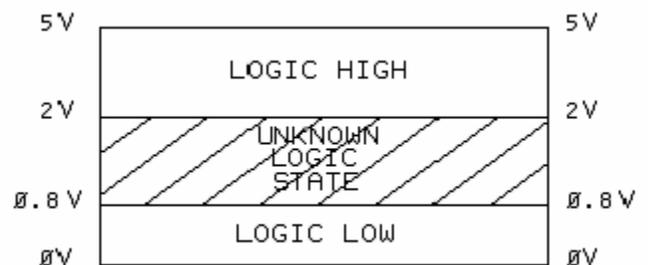
At the completion of this unit, you will be able to determine the input/ output relationship of AND, NAND, OR, and NOR logic gates by using the DIGITAL LOGIC FUNDAMENTALS circuit board.

UNIT FUNDAMENTALS

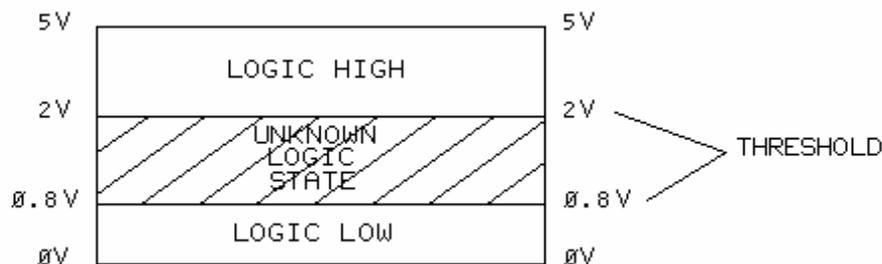
In TTL digital circuits, there are two fundamental voltage levels, or logic states:

1. a **high state**, called a logic high (logic 1) and equal to about +5 Vdc.
2. a **low state**, called a logic low (logic 0) and equal to about 0V.

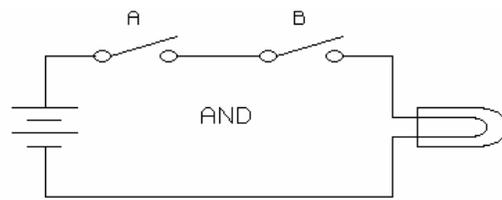
For practical circuits, each state consists of a minimum and a maximum voltage level. Outside of this range, the logic circuit cannot reliably determine which logic state to assign.



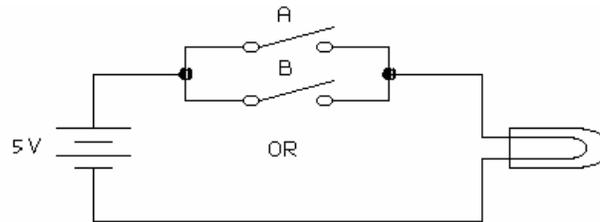
The figure illustrates the operating limits of typical TTL circuits. Logic high values, represented by logic 1, range between 2 and 5 Vdc. Logic low values, represented by logic 0, range between 0 and 0.8 Vdc. **Ones (1)** and **zeros (0)** define the truth tables of standard logic gates and circuits.



A voltage level between 0.8V and 2V represents an unknown logic state. Logic levels that are near the **threshold** can generate intermittent results. Any noise that adds to or subtracts from the signal can put a gate input in the unknown logic state.



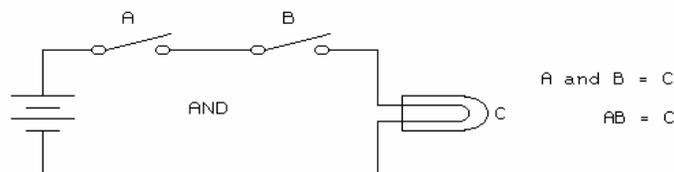
The circuit illustrates a fundamental logic concept. Switches A and B connected in series represent an **AND** function. Switches A and B must be closed to illuminate the lamp. If either switch is opened, the lamp goes off.



This circuit illustrates a second fundamental logic concept. Switches A and B connected in parallel represent an **OR** function. Either switch A or switch B can be closed to illuminate the lamp. Both switches must be opened to turn the lamp off.

SWITCH STATE	LOGIC	
	LEVEL	STATE
OFF	LOW	0
ON	HIGH	1

Switch positions can be related to logic levels. Logic levels are represented by highs (1) or lows (0).



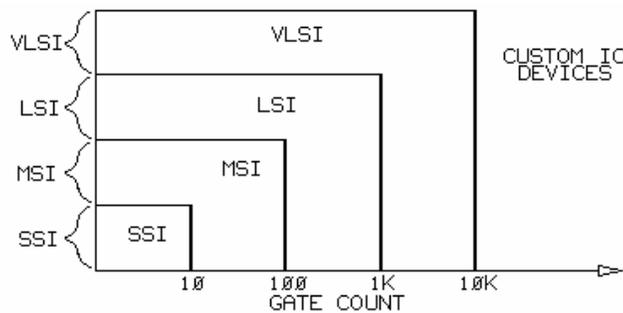
Boolean equations define the input/output relationships of logic circuits. In place of ones and zeros, Boolean equations take the form of $A \text{ and } B = C$, notated as shown above.

The Boolean equation **A and B = C** defines the circuit operation. The expression states that switches A and B must both be activated (on or high) to illuminate the lamp (C). If a lamp-on condition is considered a logic high, then both A and B must be high to generate a high output.

Basic logic functions can be complemented. The **complement** of a logic state is its opposite state. Logic high (1) and logic low (0) levels are complements of each other. Zero (0) is the **ones complement** of one (1), while 1 is the ones complement of 0.

The complexity of an IC package determines its classification. IC packages are classified as follows:

- SSI - small scale integration devices
- MSI - medium scale integration devices
- LSI - large scale integration devices
- VLSI - very large scale integration devices
- custom IC devices



The relationship between gate count and classification is illustrated above. For example, a LSI (large scale integration) device may contain from 101 to 1000 (1K) gates.

NEW TERMS AND WORDS

high state - a voltage level that is interpreted as a logic high.

low state - a voltage level that is interpreted as a logic low.

Ones (1) - represent logic high states; ones complement of 0.

zeros (0) - represent logic low states; ones complement of 1.

threshold - voltage values that define the low and high boundaries of their respective logic levels.

OR - ($A + B = C$) a logic function which generates a high logic level when any single input is at a high logic level.

AND - ($A \cdot B = C$ or $AB = C$) a logic function which generates a high logic level when all inputs are at a high logic level.

complement - opposite.

ones complement - the inverse of an initial logic state. Zero and one are ones complements of each other.

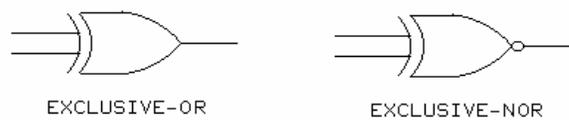
NAND - ($\overline{A \cdot B} = C$ or $\overline{AB} = C$) a logic function which generates a low logic level when inputs are at a high logic state.

UNIT 3 – EXCLUSIVE-OR/NOR GATES

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the input/output relationship of EXCLUSIVE-OR and EXCLUSIVE-NOR gates by using the XOR/XNOR circuit block on the DIGITAL LOGIC FUNDAMENTALS circuit board.

UNIT FUNDAMENTALS

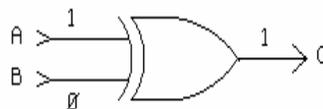


An exclusive type gate is used in arithmetic systems or where the input states are to be compared. Exclusive gates take two forms: **EXCLUSIVE-OR** and **EXCLUSIVE-NOR (XNOR)**. The schematic symbols are shown above.

The double curved lines at the gate inputs differentiate the exclusive function from a conventional OR or NOR function.



The output (C) of an XOR gate is logic 1 (high) when the inputs (A and B) are complementary (not equal to one another).



$$A \oplus B = C$$

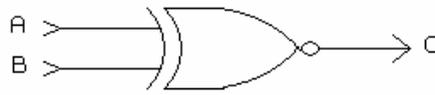
$$A\bar{B} + \bar{A}B = C$$

The Boolean equation for an XOR gate is $C = A\bar{B} + \bar{A}B$, or simplified as $C = A \oplus B$. A plus sign in a circle, \oplus , denotes an exclusive function in a Boolean equation.



The output (C) of an XNOR gate is logic 1 (high) when the gate inputs (A and B) are equal (both high or both low).

An XNOR gate has a circle on the output in addition to the double curved lines at the input.



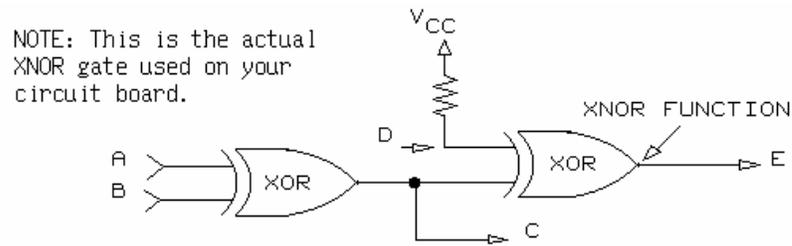
$$\overline{A \oplus B} = C$$

$$AB + \overline{A}\overline{B} = C$$

The Boolean equation for an XNOR gate is $C = AB + \overline{A}\overline{B}$, or simplified as $C = \overline{A \oplus B}$.

INPUT CONDITION	INPUTS		OUTPUTS	
	A	B	XOR	XNOR
EQUALITY	1	1	0	1
INEQUALITY	1	0	1	0
INEQUALITY	0	1	1	0
EQUALITY	0	0	0	1

Above is the truth table for the **XOR** and **XNOR** functions. The XOR circuit detects conditions of **inequality** at its input. The XNOR circuit detects conditions of **equality** at its input.



As shown above, two XOR gates can be connected to generate both XOR and XNOR output signals. The output of the second XOR gate (E) is the XNOR function of inputs A and B. The second XOR gate performs an XNOR operation due to the action of the pull-up resistor connected at D.

B	A	C (XOR)	D	E (XNOR)
1	1	0	1	1
1	0	1	1	0
0	1	1	1	0
0	0	0	1	1

The table is the truth table for the circuit shown above.

NEW TERMS AND WORDS

EXCLUSIVE-OR (XOR) - a logic gate that generates a low output level for conditions of equality or a high output level for conditions of inequality.

EXCLUSIVE-NOR (XNOR) - a logic gate that generates a high output level for conditions of equality or a low output level for conditions of inequality.

inequality - a condition in which input logic states are not equal (complementary).

equality - a condition in which input logic states are equal (not complementary).

open collector - a type of gate output that generally requires a pull-up resistor connected to the collector.

EQUIPMENT REQUIRED

F.A.C.E.T. DIGITAL LOGIC FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

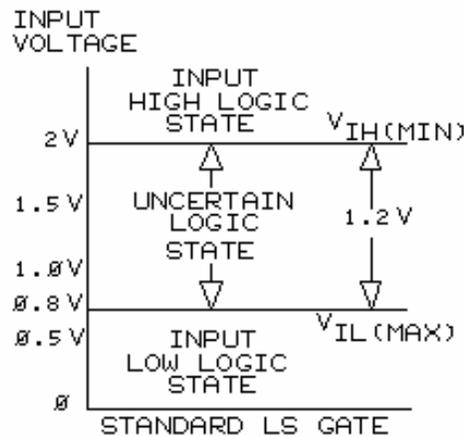
UNIT 4 – OPEN COLLECTOR AND OTHER TTL GATES

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operating characteristics of a Schmitt-trigger LS inverter, a standard LS inverter, and an open collector buffer by using the OPEN COLLECTOR circuit block.

UNIT FUNDAMENTALS

Standard input **Low Power Schottky (LS)** gates require input wave-forms with fast **rise times** and **fall times**. **Schmitt-trigger** LS gates allow input signals with slow rise and fall times or noise to drive TTL ICs without generating false output signals.



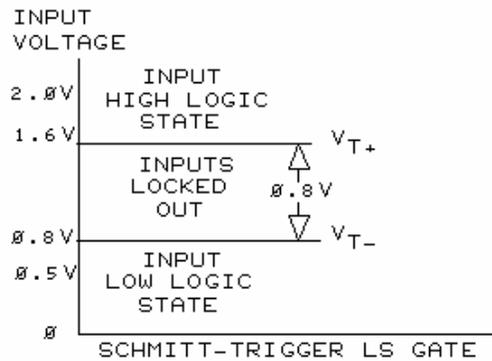
For a standard LS gate, the input voltage levels at which the input signal is in a low, uncertain, or high logic state are shown.

V_{IH} (voltage in high) and V_{IL} (voltage in low) represent the specification input voltage levels at which the output has a definite logic state (high or low).

At V_{IH} (2V) or greater, the output of a standard LS gate is high for a **buffer** and low for an **inverter**. At V_{IL} (0.8V) or less, the output of a standard LS gate is low for a buffer and high for an inverter.

The output logic state is un-certain between an input voltage of 0.8V and 2V.

Actually, the output changes state during a narrow, uncertain input voltage range that is between 0.8V and 2V.



For a Schmitt-trigger LS gate, the input voltage levels at which the input is in a low, locked out, or high logic state are shown.

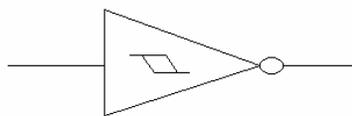
With a Schmitt-trigger gate, the output logic state will not change until the input voltage increases to the upper trip point of 1.6V. This is the positive-going threshold voltage (V_{T+}).

When the input voltage decreases, the output will not change until the input voltage decreases to the lower trip point of 0.8V.

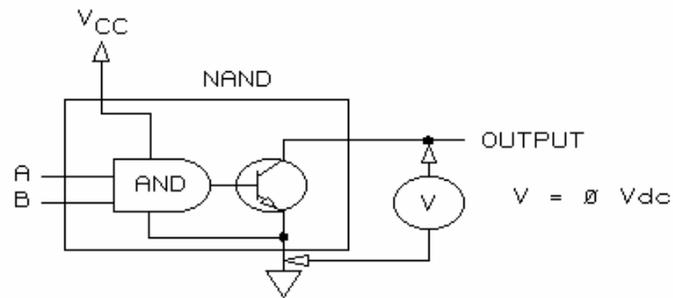
This is the negative-going threshold voltage (V_{T-}).

Positive feedback (**hysteresis**) is used in the Schmitt-trigger gate circuit.

Input voltages between V_{T-} and V_{T+} are locked out and will not cause false output states if the inputs have slow rise and fall times or if the input signal contains noise.

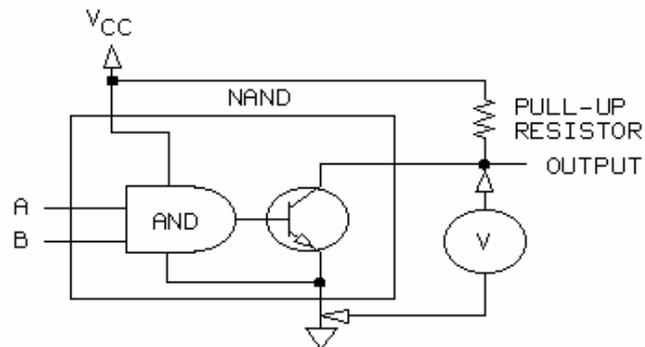


A Schmitt-trigger device is identified by a hysteresis loop on the device symbol, as shown.



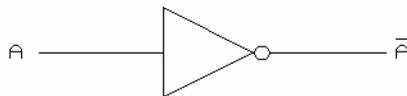
An open collector gate circuit has its output connected only to the collector of a transistor, as shown.

The output terminal is not connected to any internal source of power; therefore, as shown above, a voltmeter indicates 0 Vdc even if the transistor is off.

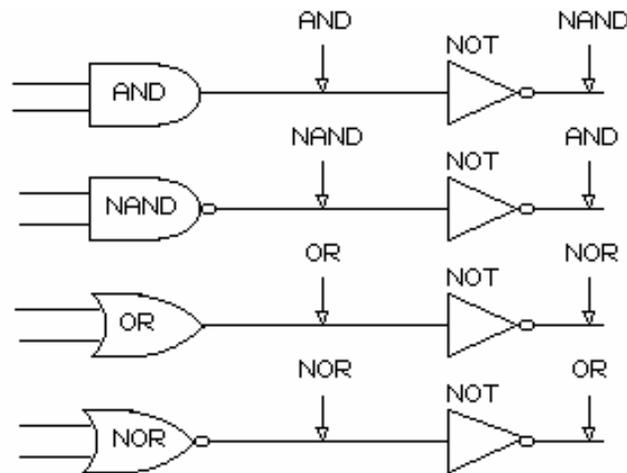


In general, an open collector device requires a pull-up resistor to V_{CC} (5 Vdc). The voltmeter reads 5 Vdc (V_{CC}) when the transistor is off and less than 0.5 Vdc when the transistor is on.

This circuit performs a NAND operation because the AND output is complemented (inverted) by the open collector transistor.



The symbol for a **NOT** gate, or **inverter**, is shown. The circle at the gate output indicates a NOT function. A logic gate that has an output complementary to the input is an inverter, or a NOT gate.



Shown are several combinations of logic gates and the effects of a NOT operation.

NEW TERMS AND WORDS

Low Power Schottky (LS) - a type of logic family that uses high speed/low voltage drop diodes to improve gate performance.

rise times - the period of time required for a signal to move from its 10% point to its 90% point. Also called the low to high transition time.

fall times - the period of time required for a signal to move from its 90% point to its 10% point. Also called the high to low transition time.

Schmitt-trigger - a type of gate that uses hysteresis to determine threshold points.

V_{IH} - minimum voltage for the input of a standard gate to be logic 1.

V_{IL} - maximum voltage for the input of a standard gate to be logic 0.

buffer - a logic gate with one input and one output, and the output logic state equals the input logic state.

inverter - a logic gate with one input and one output, and the output logic state is the complement of the input.

V_{T+} - the positive-going threshold voltage of a Schmitt gate.

V_{T-} - the negative-going threshold voltage of a Schmitt gate.

hysteresis - a type of positive feedback used to improve the response time of a gate driven by analog waveforms.

NOT - type of logic circuit used to generate a complement.

OR-TIE - a circuit function that allows more than one gate output to control one circuit point.

transfer characteristic - the relationship between the output and input voltage levels of a logic gate.

UNIT 5 – FLIP-FLOPS

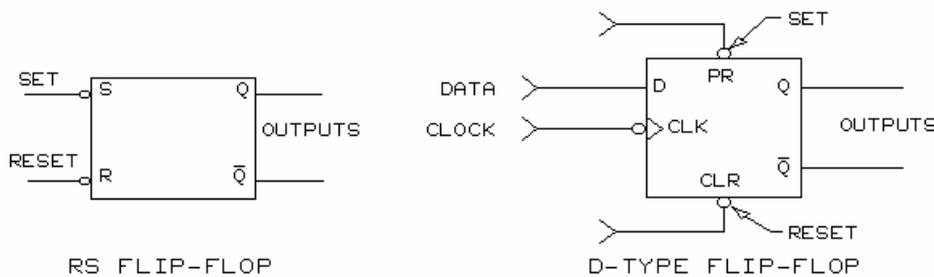
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a set/reset (RS) flip-flop and a D-type flip-flop on the DIGITAL LOGIC FUNDAMENTALS circuit board by using measured logic levels of the input and output signals.

UNIT FUNDAMENTALS

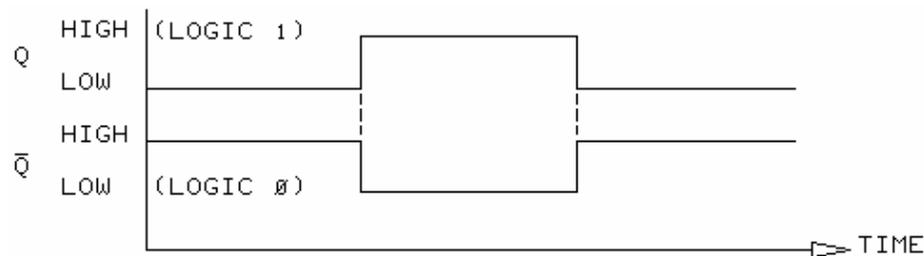
Flip-flop circuits have an output state of logic 1 (high) or logic 0 (low). Flip-flops are **bi-stable**: they remain in one logic state until switched to the complementary (opposite) state. Logic 1 (high) is the complement of logic 0 (low).

Flip-flops function as memory or storage elements, synchronizing circuits, dividers, and system reset elements. Flip-flop circuits are configured with basic logic gates or with an integrated circuit (IC) having many gates.

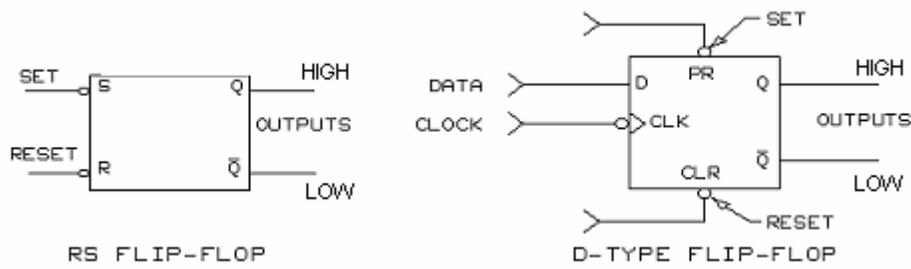


There are several types of flip-flop configurations. This unit demonstrates the **RS flip-flop** (set/reset) and **D-type flip-flop**. The schematic symbols are shown.

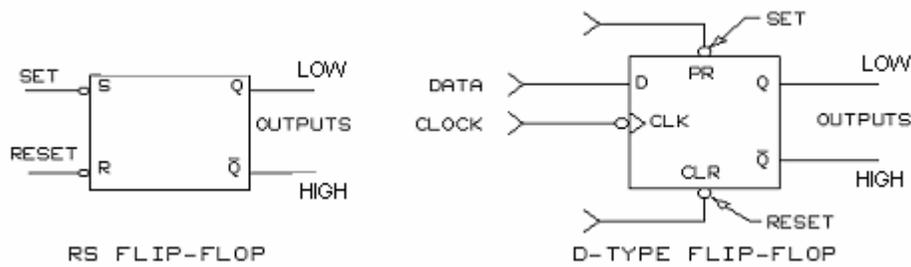
In general, flip-flop circuits have two outputs labeled **Q** and **Q**. The inputs include **set** (*preset*), **reset** (*clear*), data, and clock signals.



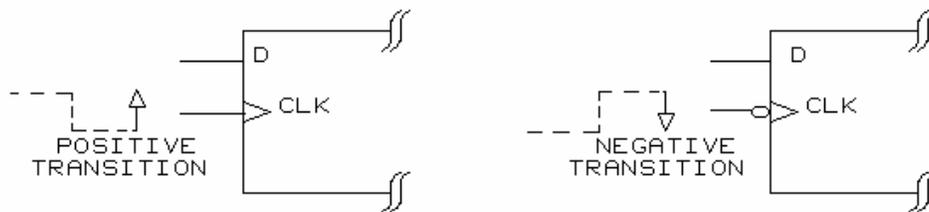
The Q and **Q** outputs are complementary: when Q is high (logic 1), **Q** is low (logic 0) and vice versa.



When a flip-flop is set or preset, the Q output is put in a high (logic 1) state.



Reset or clear puts the Q output in a low (logic 0) state.



Some flip-flops have inputs for a clock signal. A specific logic level (level-triggered) or a **transition** (edge-triggered) of the clock signal enables the flip-flop to respond to the logic level of the data signal.

Two types of clock signals that activate flip-flops are shown. A symbol at the clock (CLK) input identifies the clock signal.

The positive transition (edge) of the clock enables the flip-flop on the left to respond to the data input. The CLK symbol is a triangle.

The negative transition (edge) of the clock enables the flip-flop on the right to respond to the data input. A circle and a triangle represent the CLK symbol.

Exercise 1 – Set/Reset Flip-Flop

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the operating characteristics of a set/reset (RS) flip-flop by using cross-coupled NAND gates. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- A set/reset (RS) flip-flop has two inputs, S (SET) and R (RESET), and two complementary outputs, Q and \bar{Q} .
- The circles at S and R indicate that a logic low is required.
- This RS flip-flop does not require a clock signal; however, some RS flip-flops are configured with a clock input.
- A logic low at input S combined with a logic high at R sets the Q output to logic high and the \bar{Q} output to logic low.
- When the inputs are changed to a high at S and a low at R, the flip-flop is reset: output Q becomes low and \bar{Q} becomes high.
- An RS flip-flop is bi-stable because the outputs are latched, or stored, until switched to the complement logic states.
- The RS flip-flop consists of two NAND gates with cross-coupled outputs: one input connects to the output of the adjacent gate.
- The NAND gates in an RS flip-flop schematic are usually represented by the symbols for OR gates with negated inputs.
- An OR gate with negated inputs has the same output states as a NAND gate.
- Because Q connects to input B1 of NAND gate B, the two high inputs to gate B cause a low at \bar{Q} .
- Because \bar{Q} connects to input A2 of NAND gate A, input A2 is low.
- When the RS flip-flop is set, the Q output is high.
- When the switch is open, the Q output remains high and the \bar{Q} output remains low because the gates are cross-coupled.
- The feedback from gate B (\bar{Q}) maintains input A2 low, and the feedback from gate A (Q) maintains input B1 high.
- NAND gate A has a low input that is required for a high output (Q), and NAND gate B has two high inputs that are required for a low output (\bar{Q}).
- The RS flip-flop latches to the SET condition (high Q and low \bar{Q}) until the switch is placed in the RESET position.

- Placing the switch to RESET (R) puts a low at input B2. A low at either input of NAND gate B causes a high output (\bar{Q}).
- Because \bar{Q} connects to input A2 of NAND gate A, the two high inputs at gate A cause a low output (Q).
- Because Q connects to input B1 of NAND gate B, input B1 is low.
- When the RS flip-flop is reset, the Q output is low and the \bar{Q} output is high.
- When the switch is open, output \bar{Q} remains high and output Q remains low because of the feedback.
- NAND gate B has a low input that is required for a high output (\bar{Q}), and NAND gate A has two high inputs that are required for a low output (Q).
- The RS flip-flop latches to the RESET condition (high \bar{Q} and low Q) until the switch is placed in the SET position.
- When the position of a switch changes, it bounces (makes and breaks contact) a few times before making permanent contact.
- Because the Q and \bar{Q} outputs of an RS flip-flop become latched to a fixed state at initial switch contact to SET or RESET, switch bouncing does not affect the flip-flop output state.
- An RS flip-flop buffers a circuit from the effect of switch bouncing; the RS flip-flop can be used to debounce a switch contact.
- Switch bouncing does not change the RS flip-flop output state because Q and \bar{Q} become latched on initial contact to SET or RESET, and the NAND gates are cross-coupled.
- A high at the SET and RESET inputs (1,1) after setting or resetting the flip-flop represents placing the switch in the open position.
- Placing the switch in the open position after SET or RESET does not change the output state.
- This RS flip-flop circuit cannot have a low at the SET and RESET inputs simultaneously because of the switch arrangement.
- However, if a low were put at both the SET and RESET inputs, Q and \bar{Q} would be high. This state is prohibited because complementary outputs are desired.
- Putting a high to the SET and RESET inputs following the prohibited output state (two highs) causes a race condition between the Q and \bar{Q} outputs to an indeterminate complementary output condition.
- Putting a low at the SET and RESET inputs is prohibited in an RS flip-flop circuit because complementary outputs (Q and \bar{Q}) are desired.

Exercise 2 – D-Type Flip-Flop

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the characteristics of a D-type flip-flop by observing the logic states of the outputs in response to the input signals. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

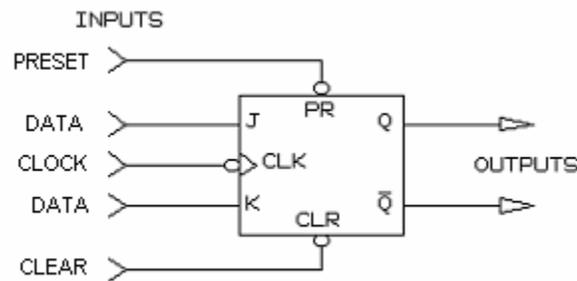
- The schematic symbol shows a typical D-type flip-flop. There is one data input (D) and a clock input (CLK).
- A PR (preset) input sets the flip-flop and a CLR (clear) input resets the flip-flop.
- The two outputs, Q and \bar{Q} , are complementary.
- A low (logic 0) at PR sets Q high (logic 1).
- A low at CLR resets Q low.
- If either the PR or CLR inputs remain in a low state, the flip-flop is locked in its set or reset state, respectively; data or clock signals have no effect on Q and \bar{Q} .
- A low (logic 0) at PR sets Q high (logic 1).
- The small circle and triangle at the CLK input indicate that the negative edge of the clock signal activates the data (D) input.
- The data input must be stable before and after the flip-flop is clocked.
- The logic state of the data is input to the D-type flip-flop only during the transition of the clock signal from high to low.
- This is a timing diagram showing the relationship between the data input (D), the outputs (Q and \bar{Q}), and the clock signal (CLK).
- Q equals the D input after the negative edge of the CLK. \bar{Q} is the complement of D and Q.
- Once a D-type flip-flop is clocked, changes to the logic state of D do not affect Q and \bar{Q} until there is another negative edge of the CLK signal.
- The Q output is logic 1. If input D is logic 0 during the next negative edge of the clock signal, the Q output changes to logic 0.
- For example, if PR is logic 1 and CLR is logic 0, the D-type flip-flop is reset: Q is logic 0 and \bar{Q} is logic 1. The logic states of D and CLK do not affect the outputs.

UNIT 6 – JK FLIP-FLOP

UNIT OBJECTIVE

When you have completed this unit, you will be able to demonstrate the operation and configurations of a JK flip-flop by using the DIGITAL LOGIC FUNDAMENTALS circuit board.

UNIT FUNDAMENTALS

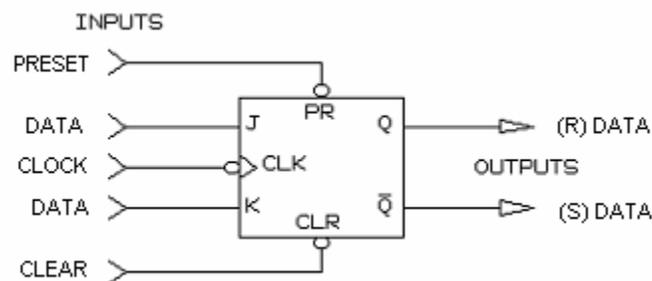


The schematic symbol shows a **JK flip-flop**. There are two data inputs (J and K) and a clock input. This JK flip-flop requires a negative clock edge signal; however, other JK flip-flops may require a positive clock edge, a logic 1, or a logic 0 clock signal.

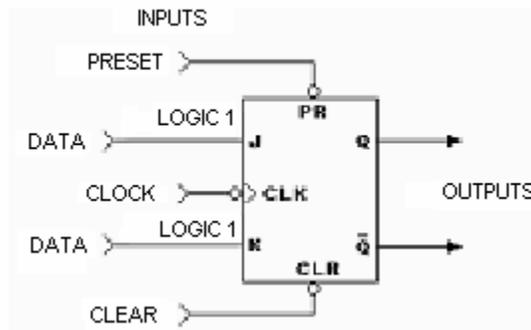
In addition, there usually are asynchronous preset and clear inputs to respectively set and reset the JK flip-flop. Either negative (as shown) or positive logic levels may be required at PR or CLR. The outputs, Q and \bar{Q} , are complementary.

The JK flip-flop is the most commonly used flip-flop because it is versatile.

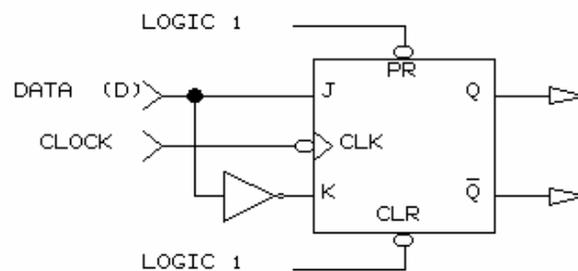
The JK flip-flop can be adapted to have the operating features of an RS flip-flop, a T flip-flop (toggle flip-flop), a D-type flip-flop, or a **master-slave JK flip-flop**.



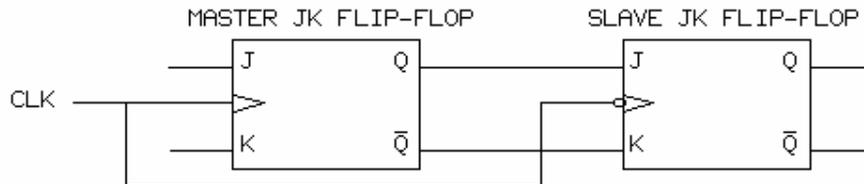
The basic JK flip-flop is essentially a clocked RS flip-flop; the J and K inputs are equivalent to the R and S inputs, respectively.



A T flip-flop is a JK flip-flop with J and K inputs set high (logic 1). The outputs of a T flip-flop change state at every clock signal.



A D-type flip-flop is a JK flip-flop with complementary J and K inputs.



A master-slave flip-flop is two JK flip-flops with the outputs of the master connected to the inputs of the slave. A master-slave flip-flop is useful in certain applications to prevent racing of the outputs.

NEW TERMS AND WORDS

JK flip-flop - a flip-flop with two data inputs (J and K) and one clock input.

master-slave JK flip-flop - a circuit that contains two flip-flops, a master and a slave. The outputs of the master connect to the inputs of the slave.

Exercise 1 – Static JK Flip-Flop Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the truth table for a JK flip-flop by measuring the output logic states for changes to the input logic states. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION

- The JK flip-flop used in this exercise is designated as an integrated circuit (IC) type 74LS76 flip-flop.
- The PR input presets (sets) the Q output to logic 1.
- The CLR input clears (resets) the Q output to logic 0.
- The data inputs are J and K.
- A negative clock edge is required for the outputs (Q and \bar{Q}) to respond to the logic states of the J and K data inputs.
- A logic 0 (L) at PR (PRESET) sets the JK flip-flop: Q is logic 1 (H) and \bar{Q} is logic 0 (L).
- A logic 0 (L) at CLR (CLEAR) resets the JK flip-flop: Q is logic 0 (L) and \bar{Q} is logic 1 (H).
- A logic 0 (L) at PR or CLR will override the J, K, and CLK inputs.
- A logic 0 (L) at the PR and CLR inputs causes Q and \bar{Q} to be logic 1 (H); this output condition is invalid.
- When PR and CLR are both logic 1 (H), the following three logic conditions at data inputs J and K cause the following Q and \bar{Q} output logic states after a negative edge of the clock signal.
 1. A logic 0 (L) at J and K results in no output change after the clock signal.
 2. A logic 1 (H) at J and a logic 0 (L) at K result in Q equal to logic 1 (H) and \bar{Q} equal to logic 0 (L) after the clock signal.
 3. A logic 0 (L) at J and a logic 1 (H) at K result in Q equal to logic 0 (L) and \bar{Q} equal to logic 1 (H) after the clock signal.
- When the J and K inputs have complementary logic states, the JK flip-flop functions basically as a clocked RS flip-flop.
- PR and CLR are logic 1, and J and K have complementary logic states. After the next negative edge of the clock signal, the Q output equals the J input logic state.
- A logic 1 (H) at J and K results in the outputs changing (togglng) after every negative edge of the clock signal.
- With J and K held at logic 1, the JK flip-flop is configured as a T flip-flop (toggle flip-flop).
- When the clock is logic 1 (H) or logic 0 (L), there is no output change.
- Inputs PR, CLR, J, and K are logic 1. After the next negative edge of the clock signal, the Q and \bar{Q} outputs will change logic states.

Exercise 2 – Dynamic Operation of a JK Flip-Flop

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to configure a JK flip-flop to operate as a toggle flip-flop or a D-type flip-flop by using the DIGITAL LOGIC FUNDAMENTALS circuit board. You will verify your results by comparing the input and output logic states.

EXERCISE DISCUSSION

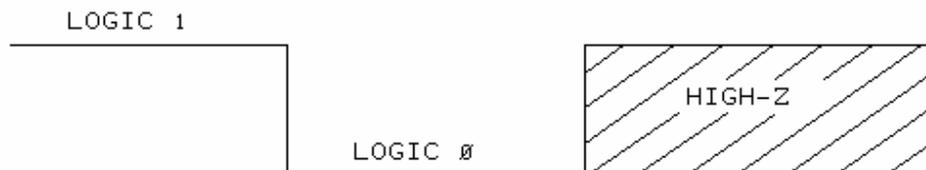
- The JK flip-flop is the most commonly used flip-flop because it can be configured to have the operating features of an RS flip-flop, a T flip-flop, or a D-type flip-flop.
- In the previous exercise, you observed that a JK flip-flop is essentially a clocked RS flip-flop.
- In this exercise procedure, you will configure the JK flip-flop as a T flip-flop and as a D-type flip-flop; a 50 kHz clock signal is used.
- When the J and K data inputs are each set at logic 1, the JK flip-flop functions as a T flip-flop.
- The Q and \bar{Q} outputs of a T flip-flop change state (toggle) at every negative edge of the clock signal.
- However, if the PR or CLR inputs are logic 0, the toggle action of the outputs with the clock signal is overridden, and the outputs are held in the set or reset state.
- The J, K, PR, and CLR inputs of the JK flip-flop are logic 1. The Q and \bar{Q} outputs will change state at every negative edge of the clock signal because the JK flip-flop is configured as a T flip-flop.
- A timing diagram shows the relationship between the CLK signal and the Q and Q-not output signals. Q and \bar{Q} toggle (change state) at every negative edge of the clock signal.
- Because Q and \bar{Q} are complementary, Q is logic 1 when \bar{Q} is logic 0 and vice versa.
- The Q and \bar{Q} signals have one cycle for every two clock cycles.
- The Q and \bar{Q} frequencies are each half of the CLK frequency because they change logic states only on the negative edge of CLK.
- During the positive edge of CLK, Q and \bar{Q} do not change logic states.
- If the frequency of the CLK signal is 50 kHz, the frequency of the Q and \bar{Q} outputs is 25 kHz.
- When the J input to the JK flip-flop is inverted and connected to the K input, the J and K inputs are always complementary.
- In Unit 5, you demonstrated that the Q output of a D-type flip-flop equals the logic state of the D input (J input) after every clock signal (negative edge).
- To configure a JK flip-flop as a D-type flip-flop, the J input is inverted and connected to the K input.

UNIT 7 – TRI-STATE OUTPUT

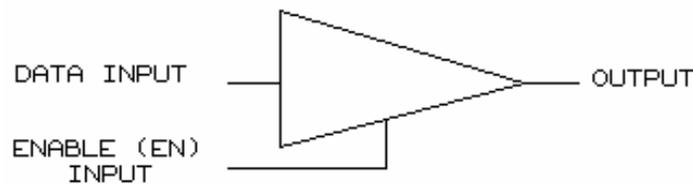
UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate the operation of a tri-state buffer by using the TRI-STATE OUTPUT circuit block on the DIGITAL LOGIC FUNDAMENTALS circuit board.

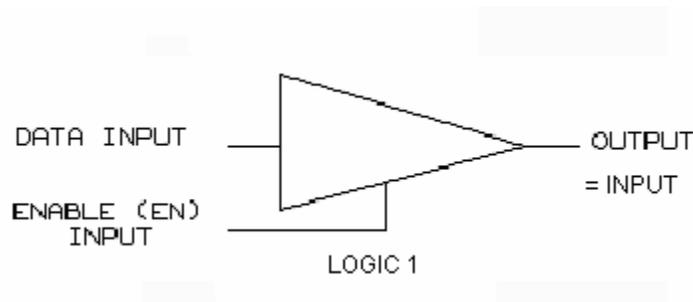
UNIT FUNDAMENTALS



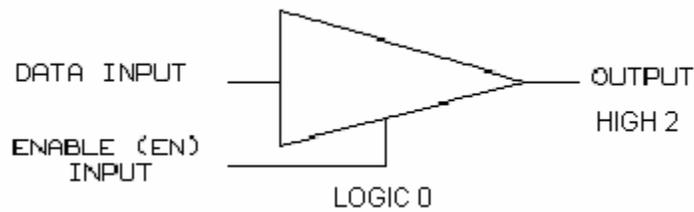
Tri-state logic devices have three distinct out-put states. In addition to the high (logic 1) and low (logic 0) output states, tri-state devices have a third output state called the **high-impedance** state, or **high-Z state**. The high-Z state is equivalent to an open circuit at the output of the device; the output is in a floating condition.



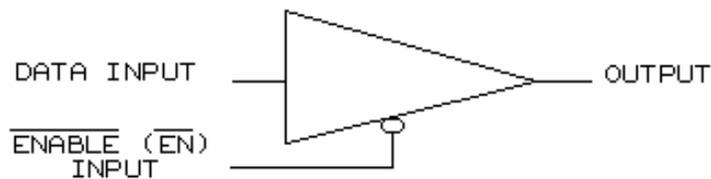
This is the schematic symbol for a tri-state buffer.



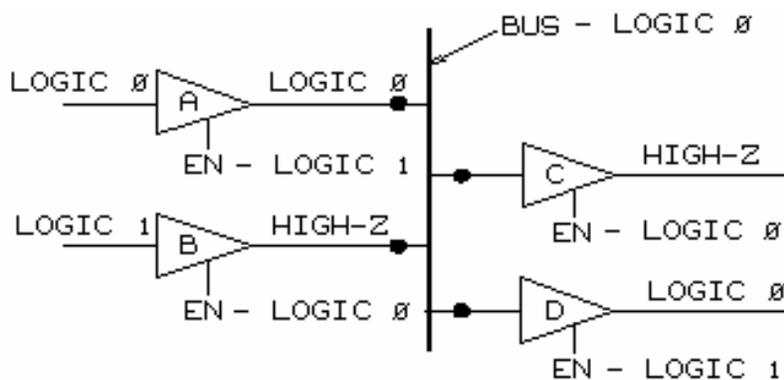
A logic 1 at the EN INPUT permits the buffer to operate normally: the output is the same logic state as the input.



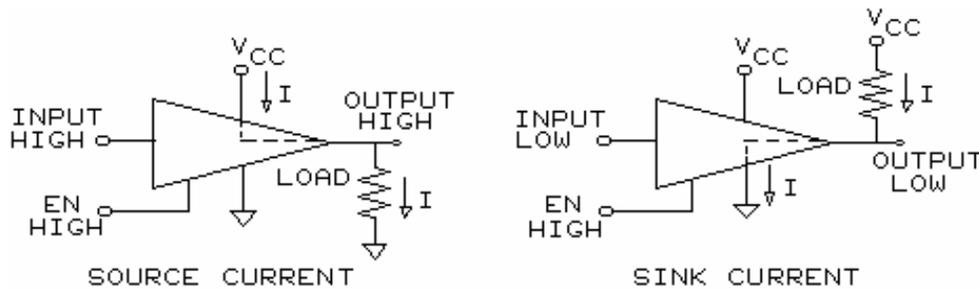
When the EN signal is logic 0, the buffer output is in the high impedance (high-Z) state: the data input has no effect on the output.



Some tri-state devices are configured to be enabled by a logic 0. The circle on the enable input indicates this condition, and the **ENABLE (EN)** INPUT has a not sign. The discussions and procedures in this unit are based on a tri-state buffer that requires a logic 1 to be enabled.

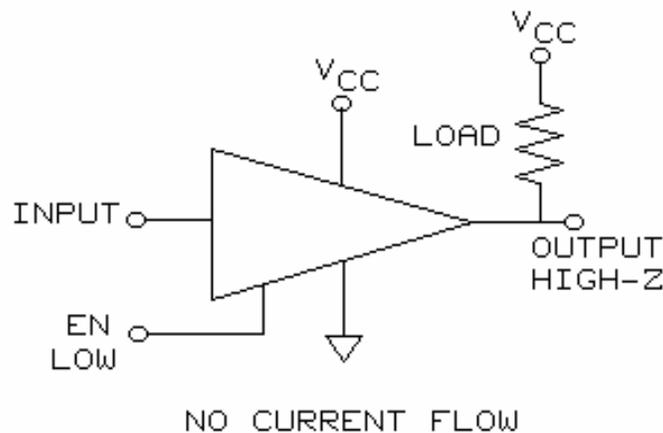


Tri-state logic devices are very useful for the transfer of data on a data **bus**. Many tri-state devices can connect to a data bus. Only the enabled tri-state device sends data to or receives data from the bus.



NOTE: CONVENTIONAL CURRENT FLOW IS SHOWN.

The output of a tri-state device can **source** or **sink** current. When the output is high, the tri-state device is a source of current. When the output is low, the tri-state device is a sink for current.



When the tri-state device is in the high-Z state, the output does not source or sink output current; the output current is zero.

The following devices can have tri-state logic:

- BUFFERS
- INVERTERS
- FLIP-FLOPS
- REGISTERS
- ALMOST ALL MICROPROCESSOR ICs.

7400 SERIES TTL GATES	4000 SERIES CMOS GATES
FASTER	LOW POWER CONSUMPTION
GOOD FOR HIGH CLOCK SPEEDS	MORE COMPACT IC'S
	BETTER NOISE IMMUNITY

A comparison between a 7400 series TTL gate and a 4000 series CMOS gate is made above.

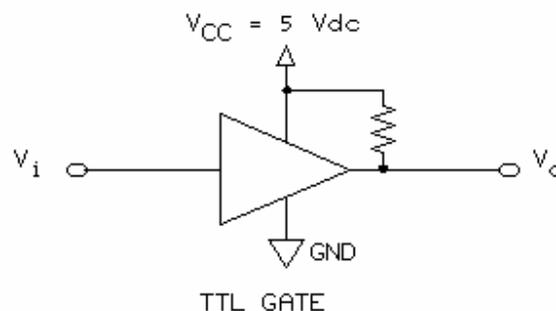
The input of a FET does not require current; consequently, a CMOS gate usually uses less power than a TTL gate at moderate clock frequencies.

However, at very high clock frequencies (switching rates) the power consumption of a CMOS gate increases to TTL consumption levels.

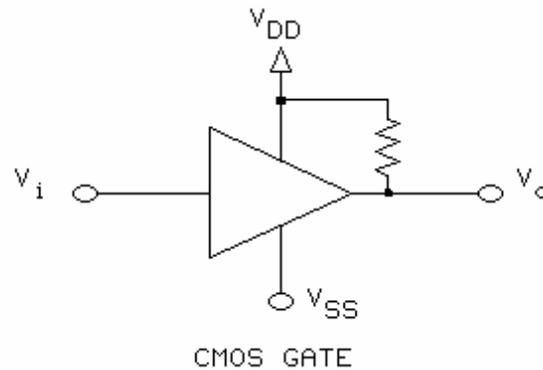
A TTL gate switches logic levels faster than a CMOS gate does. Therefore, you should weigh power savings against switching speed when deciding between a CMOS or TTL gate.

Because low power consumption means low heat generation, a CMOS has a higher packing density. Many more gates can be placed per unit of IC area.

Electrical noise can cause false output logic states. CMOS gates have a wider voltage range between the input low voltage (V_{IL}) and the input high voltage (V_{IH}) and, as a result, have better noise immunity than do TTL gates.



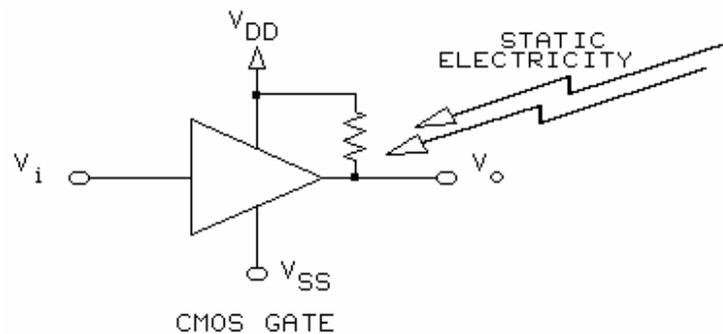
TTL gates have a nominal positive supply voltage (V_{CC}) of 5 Vdc (4.75 Vdc to 5.25 Vdc). The negative supply is ground.



CMOS gates have a nominal positive supply voltage (V_{DD}) of 5 Vdc, 10 Vdc, and 15 Vdc (3 Vdc to 18 Vdc). The negative supply voltage (V_{SS}) is less than the input or output voltages.

Special types of CMOS gates, called **high speed CMOS gates**, combine the speed of TTL gates with the low power requirements of CMOS gates.

CMOS devices are available in **B series** (buffered) or **UB series** (unbuffered) versions. UB devices are generally faster than B series devices, but they possess less ideal noise immunity and transfer characteristics.



HANDLING

TTL gates are not considered to be sensitive to static electricity. CMOS gates are very static sensitive devices that can be damaged or destroyed by improper handling.

NEW TERMS AND WORDS

V_{DD} - the higher potential (with respect to V_{SS}) power supply voltage of CMOS devices.

V_{SS} - the lower (in potential) of two supply voltages required for a TTL IC.

high speed CMOS gates - a family of devices that combines the speed of TTL circuits with the low power requirements for CMOS.

B series - CMOS gates that possess higher

UB series - CMOS gates that possess lower gain and less ideal transfer characteristics than buffered CMOS devices do.

transition time - the time it takes the output to go between 10% and 90% of the maximum output voltage; t_{THL} and t_{TLH} are the symbols for transition time.

propagation delay - the time between the 50% point of the input signal and the 50% point of the output signal; t_{PHL} and t_{PLH} are the symbols for propagation delay.

t_{THL} - the symbol for high-to-low transition time.

t_{TLH} - the symbol for low-to-high transition time.

t_{PHL} - the symbol for high-to-low propagation delay.

t_{PLH} - the symbol for low-to-high propagation delay.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

DIGITAL LOGIC FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Exercise 1 – Trigger Levels of TTL and CMOS Gates

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the input voltage at which the output of a TTL gate or a CMOS gate changes logic states by using the TTL/CMOS COMPARISON circuit block. You will verify your results with an oscilloscope and a multimeter.

EXERCISE DISCUSSION

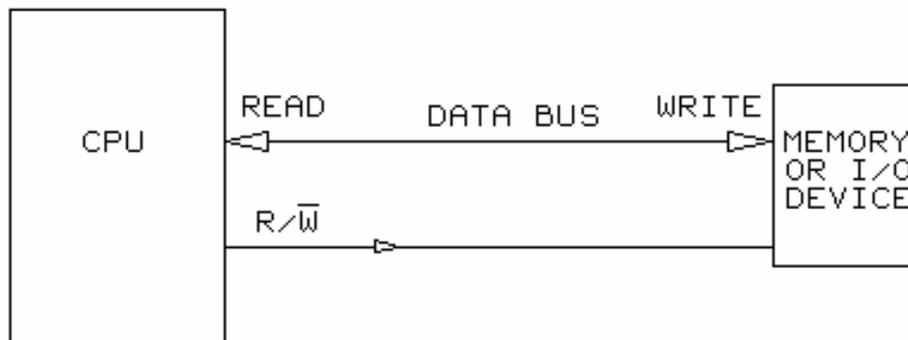
- TTL uses 5 Vdc and ground as the supply voltage.
- The CMOS supply voltage is 5, 10, or 15 Vdc.
- The CMOS input and output levels are between the supply voltages (V_{DD} and V_{SS}).
- At some voltage between V_{IL} and V_{IH} the gate output changes states.
- TTL levels are: $V_{IL} = 0.8$ Vdc and $V_{IH} = 2.0$ Vdc.
- CMOS levels are: $V_{IL} = 1.0$ Vdc and $V_{IH} = 4.0$ Vdc.
- CMOS has a better noise margin than TTL.
- CMOS is low power at low frequencies.
- CMOS power increases with frequency.
- Open collector TTL gates can generate CMOS logic levels when a resistor is used to pull the output to V_{DD} .

UNIT 9 – DATA BUS CONTROL

UNIT OBJECTIVE

At the completion of this unit, you will be able to demonstrate computer read and write data transfer operations by using the DATA BUS CONTROL circuit block.

UNIT FUNDAMENTALS



Via a **bidirectional data bus**, a computer transfers data between the **CPU (central processing unit)** and the memory or input/output devices.

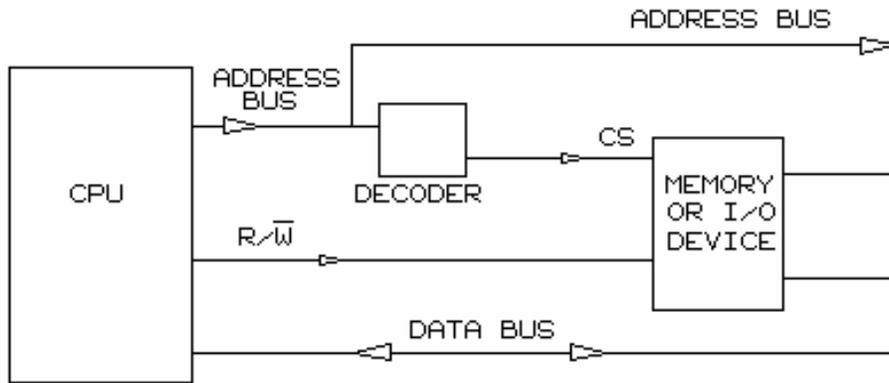
When the CPU is receiving data from a memory or input/output (I/O) device, it is in the **read** operating mode. When the CPU is sending data to a memory or I/O device, it is in the **write** operating mode.

A **R/W** (read/write) control signal is output by the CPU to control the direction of data transfer on the data bus.

When the **R/W** (designated **RD/WR** on the circuit board) signal is high, the CPU reads data from a memory or I/O device.

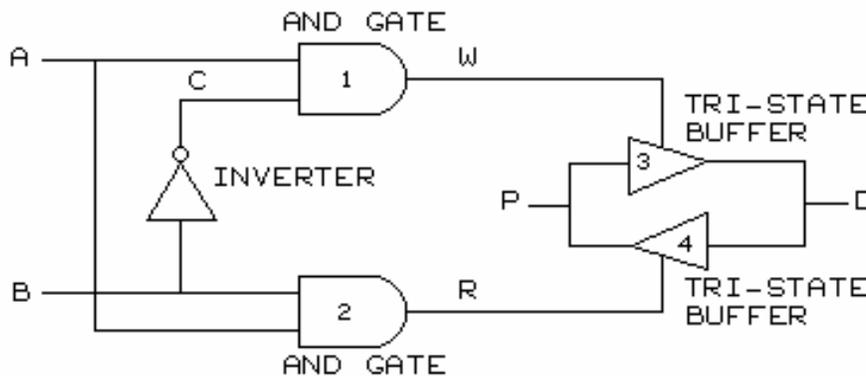
When the **R/W** signal is low, the CPU writes data to a memory or I/O device.

The read and write operations are related, respectively, to the direction of data flow from and to the CPU.



The CPU outputs information on the **address bus**. A decoder interprets the address and sends a **chip select (CS)** control signal to the device with which the CPU desires to communicate.

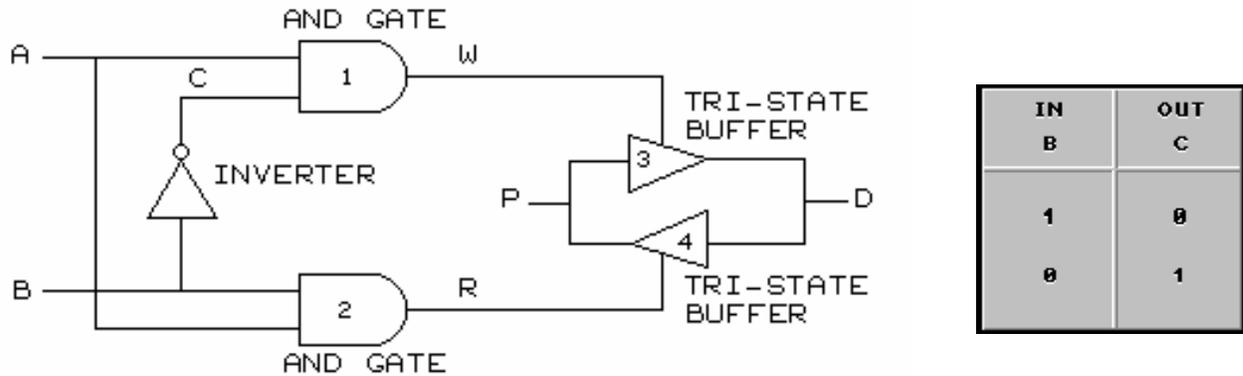
A high chip select (CS) control signal enables the device for a read or write operation from the CPU. CS and R/W signals control the flow of data, on the bidirectional data bus, between the CPU and the memory or I/O devices.



AND gates, tri-state buffers, and an inverter (NOT gate) are used in the digital logic circuitry that controls read and write operations.

In previous units, you demonstrated the operation of

1. an inverter,
2. an AND gate, and
3. a tri-state buffer.

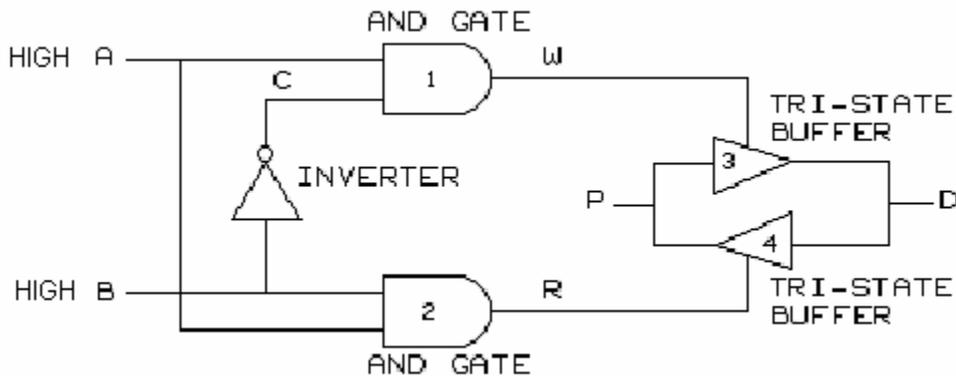


The output of an inverter is the complement of the input.

The output of an AND gate is high when both inputs are high.

When the enable input of a tri-state buffer is high, the output is the same as the input.

When the enable input is low, the output of a tri-state buffer is in a high impedance (high-Z) state; the output is effectively disconnected from the output circuit and the input has no effect on the output.



The operation of this circuit in controlling data transfer is discussed and demonstrated in the following two exercises.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Digital Circuit Fundamentals 1

FACET®



Student Workbook



FOURTH EDITION

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

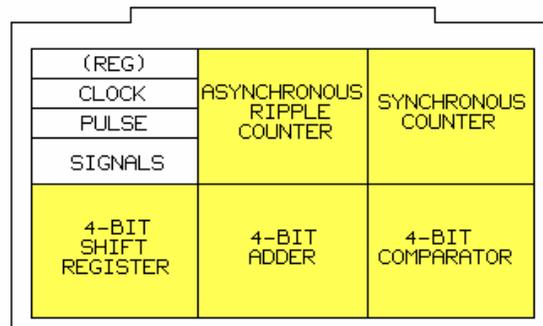
The **Appendix** includes safety information.

UNIT 1 – CIRCUIT BOARD INTRODUCTION

UNIT OBJECTIVE

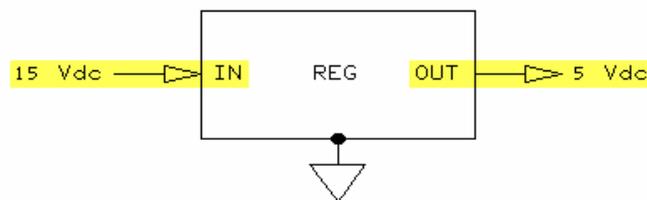
At the completion of this unit, you will be able to identify and operate the circuit blocks on the DIGITAL CIRCUIT FUNDAMENTALS 1 circuit board.

UNIT FUNDAMENTALS



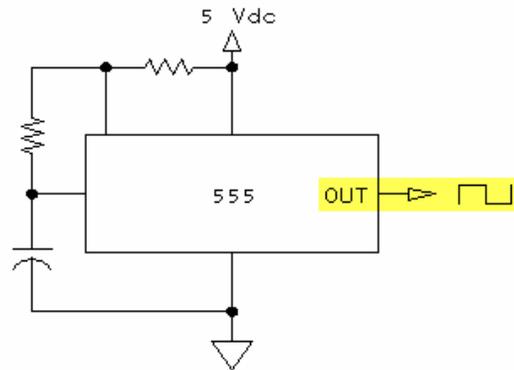
The DIGITAL CIRCUIT FUNDAMENTALS 1 circuit board consists of 5 training circuit blocks.

A general purpose circuit block consists of a 5V regulator, a square wave CLOCK generator, a PULSE GENERATOR circuit, and an INPUT SIGNALS generating set of toggle switches.



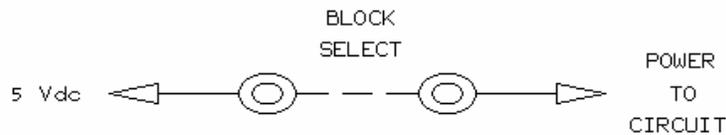
A **voltage regulator** converts the system's 15 Vdc power supply to 5 Vdc, which is required by the **integrated circuits (ICs)** on the circuit board.

Power supply voltages are **hardwired** to all ICs on the circuit board.



The **timer (555 type)** CLOCK circuit generates a square wave clock waveform. The PULSE GENERATOR toggle switch generates positive- and negative-going signal edges. The "at home" position of this toggle switch is in its UP position.

The INPUT SIGNALS toggle switches, labeled **A** through **D**, generate high and low **TTL** digital levels. The outputs of this section are hardwired to other points on the circuit board that are labeled **A** through **D**.



The BLOCK SELECT control powers specified circuits. Two-post connectors and patch leads (interconnecting leads) activate various circuit functions and interconnect circuit blocks.

NEW TERMS AND WORDS

voltage regulator - an IC that maintains a constant output voltage when input voltage or output load changes.

integrated circuits (ICs) - devices that combine the actions of many transistors on one chip.

hardwired - refers to permanent connections made in copper as opposed to connections that must be completed with a wire or test lead.

timer (555 type) - an IC used with external components to generate various waveforms, such as a pulse train.

TTL - transistor-transistor logic.

LED - light-emitting diode; a semiconductor diode that emits light when forward biased.

decoupling capacitors - capacitors that reduce the impedance between the power supply bus and the IC that the bus powers.

Exercise 2 – Operation of the General Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to use the general purpose circuits on the circuit boards. You will verify your knowledge by taking voltage and waveform readings.

DISCUSSION

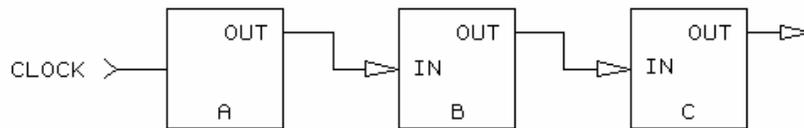
- The four general purpose circuits are the power supply regulator, CLOCK GENERATOR, PULSE GENERATOR, and INPUT SIGNALS.
- The power supply regulator uses a 5V voltage regulator to convert 15 Vdc to 5 Vdc. This supply powers all the ICs on the circuit board and the LED groups which have been activated with the BLOCK SELECT function.
- The CLOCK GENERATOR provides timing for several circuits on the circuit board. Using a 555 timer to generate a square wave and various timing components a clock signal of approximately 50 KHz is produced. The 1N4446 signal diode generates a duty cycle waveform of about 50%.
- The PULSE GENERATOR produces complementary pulse output waveforms which are used to ensure a “single-shot” edge (switch debounce) for each switch activation. The PULSE GENERATOR circuits use two 74LS03 gates and a toggle switch.
- INPUT SIGNALS circuit generates four separate TTL voltages labeled D through A. Each signal has two levels: high or low.

UNIT 2 – ASYNCHRONOUS RIPPLE COUNTER

UNIT OBJECTIVE

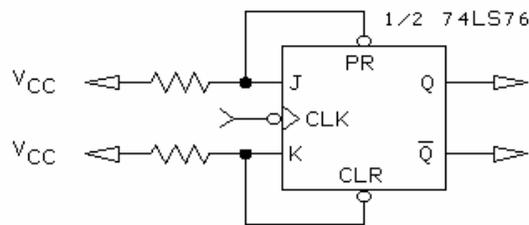
At the completion of this unit, you will have a working knowledge of an asynchronous ripple counter configured from JK flip-flops.

UNIT FUNDAMENTALS



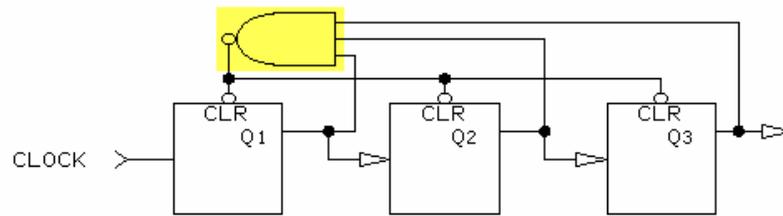
A **ripple counter** consists of 2 or more flip-flops connected so that the output of each flip-flop is wired to the input of the following flip-flop. The initial input is called **CLOCK**. The output of flip-flop A is connected to the input of flip-flop B. The output of B is connected to the input of C.

A ripple counter is also called an **asynchronous** counter because the circuit outputs do not change simultaneously with a common clock. The asynchronous counter is also referred to as a **serial counter** because each flip-flop is triggered one at a time.



A JK flip-flop used to construct a ripple counter is configured as a **T, or toggle, flip-flop**.

The J and K inputs are pulled to V_{CC} . Q and \bar{Q} are complements; therefore, ripple counters may have complementary outputs. Ripple counters can be set or cleared.



The maximum number of counts of a ripple counter may be controlled with feedback. This action, or controlling of the count, is the **modulus** (sometimes abbreviated MOD) of the counter.

NEW TERMS AND WORDS

ripple counter - an asynchronous or serial counter in which the sections are triggered one at a time, not simultaneously.

asynchronous - a related set of signals that do not change at the same period of time.

T, or toggle, flip-flop - a gate that alters its output state for each clock cycle.

modulus - the number of output states.

nibble - 4 bits of binary data.

word - 8 bits of binary data, or 2 nibbles.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

DIGITAL CIRCUIT FUNDAMENTALS 1 circuit board

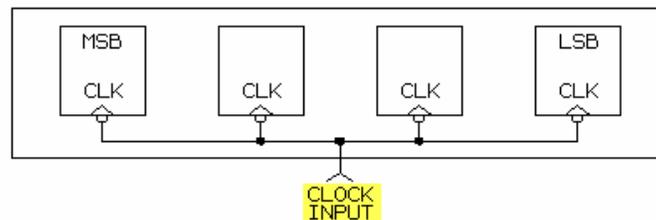
UNIT 3 – SYNCHRONOUS COUNTER

UNIT OBJECTIVE

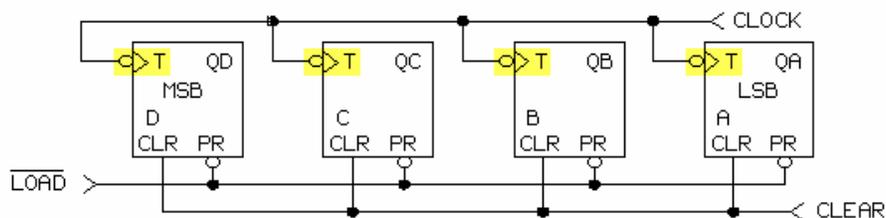
At the completion of this unit, you will have a working knowledge of an UP/DOWN synchronous counter.

UNIT FUNDAMENTALS

The 74LS193 is a **monolithic** synchronous reversible (up/down) counter constructed on a single IC substrate. The IC has a gate complexity of 55 equivalent gates, placing it in the MSI (medium-scale integration) category.

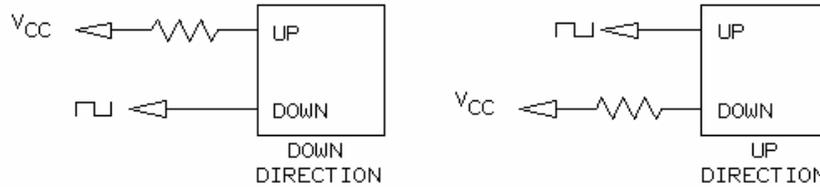


In the LS193 counter, **synchronous** operation is provided by simultaneous clocking of all flip-flops. This mode of operation ensures that the counter outputs change at the same time. A synchronous counter eliminates the output counting spikes normally associated with asynchronous (ripple-clocked) counters.

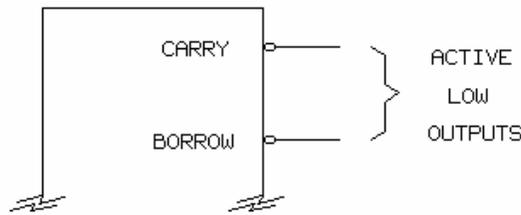


Each section of the LS193 counter is composed of a JK flip-flop configured as a T (toggle) flip-flop. Each counter stage provides a single output (QA through QD). The CLOCK input is common to each stage of the counter and updates all outputs simultaneously.

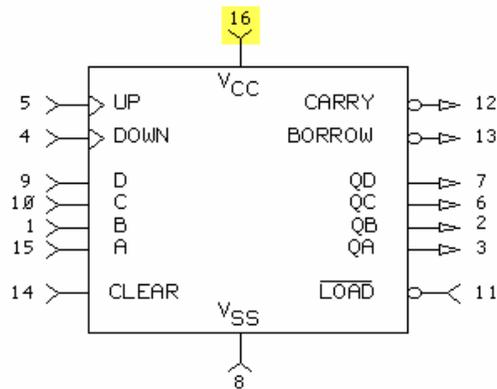
The **LOAD** input is common to each stage of the counter. **LOAD**, in conjunction with data inputs A through D, presets each counter stage. **CLEAR** is a common input that sets all Q outputs low.



The LS193 counter can count up or down. If UP is pulled to V_{CC} and DOWN is pulsed, the count direction is down (HEX B, A, 9, 8, etc.). If DOWN is pulled to V_{CC} and UP is pulsed, the count direction is up (HEX 8, 9, A, B, etc.).



The LS193 counter detects **overflow** (a count of 15 + 1) and **underflow** (a count of 0 - 1). Overflow detection generates an active CARRY output signal. Underflow detection generates an active BORROW output signal.



The pin-out structure of the 74LS193 serial counter indicates a 16-pin device. Your circuit board uses a DIP version.

Exercise 1 – Control Functions

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to control the functions of a synchronous counter. You will verify your results by operating a 4-bit counter.

DISCUSSION

- The BLOCK SELECT supplies power to the LEDs. Each LED represents a state of the IC output terminals. LED on = 1 (high state); LED off = 0 (low state)
- The four output bits are labeled QD (MSB) through QA (LSB).
- Inserting a two-post connector and momentarily pulling CLEAR low resets the counter outputs.
- Momentarily pulling LOAD low sets the counter outputs to the same level as the circuit inputs A through D. A through D are controlled by toggle switches which are located on the INPUT SIGNALS circuit.
- A two-post connector must be used to enable the COUNT input function. The connector allows the CLOCK input to be passed to the UP and DOWN inputs of the IC.
- When COUNT and UP are selected the counter increments. When only COUNT is selected the counter decrements.
- Use the STEP input function to override the free-run counting mode and allow single-step clocking. In this operating mode the CLOCK inputs are generated by the toggle switches located in the PULSE GENERATOR circuit.
- Activating the MOD option, with a two-post connector, uses a specific modulus to reset the counter. The MOD circuit point is not an actual modulus feedback signal. It enables a gate to pass the signal to the counter IC CLEAR input.
- The LS193 counter is binary, the 4-bit output represents counts between 0000_2 (\$0) and 1111_2 (\$F), and generates a CARRY and a BORROW.

UNIT 4 – 4-BIT SHIFT REGISTER

UNIT OBJECTIVE

At the completion of this unit, you will have a working knowledge of the 4-BIT SHIFT REGISTER circuit block.

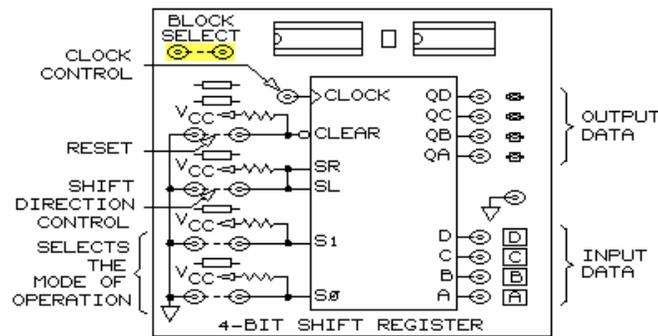
UNIT FUNDAMENTALS

The 74LS194 is a monolithic, **bidirectional** shift register. The IC has a gate complexity of 46 equivalent gates, placing it in the MSI (medium scale integrity) category.

OPERATION	FUNCTION
Parallel load	Preset outputs from inputs
Shift right	Data moves from QA toward QD
Shift left	Data moves from QD toward QA
Inhibit clock	Do nothing

OPERATIONAL MODES OF THE LS194

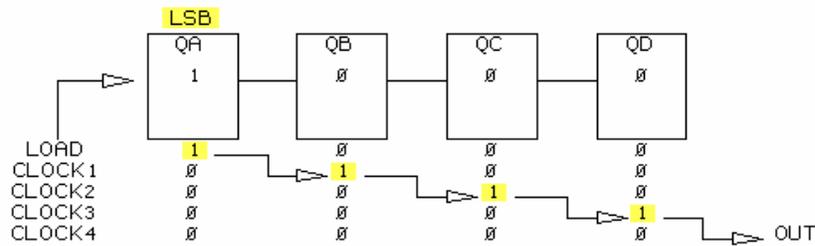
IC features include parallel inputs and outputs, **shift right** and **shift left** serial inputs, operating mode control inputs, and a direct overriding CLEAR (reset) input.



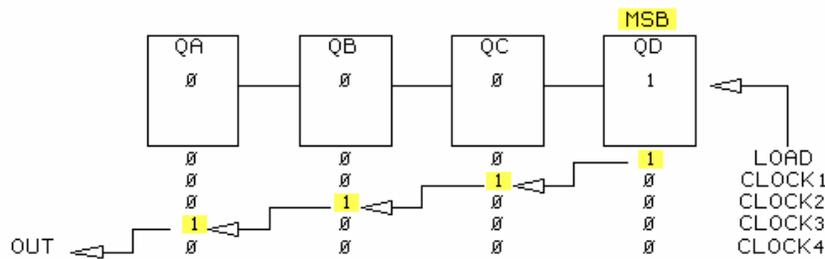
The BLOCK SELECT function, not a part of the IC, controls the application of power to the circuit block LEDs.

The CLOCK input (positive edge triggered) synchronously shifts data right or left. CLEAR, a reset for the shift register, places all outputs (QD through QA) in the LOW, or zero, state (LEDs OFF).

Synchronous parallel loading sets (presets) the register, placing the 4 data bits on the input lines (D through A) at the outputs (QD through QA). SR (serial right) and SL (serial left) input serial data to the IC. S0 and S1 are the register select inputs: 2 bits control 4 specific functions.



Shift right is defined as a bit or data movement toward QD: a bit of data is shifted from a less significant register toward a more significant register. 0 shifted into a flip-flop resets its output to 0. 1 shifted into a flip-flop sets its output to 1.



Shift left is defined as a bit or data movement toward QA: a bit of data is shifted from a more significant register toward a less significant register. 0 shifted into a flip-flop resets its output to 0. 1 shifted into a flip-flop sets its output to 1.

NEW TERMS AND WORDS

Inhibit - to prevent an action such as data shift.

bidirectional - moving in either of two directions (for example, left or right).

shift right - movement of data from a less significant register to a more significant register.

shift left - movement of data from a more significant register to a less significant register.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

DIGITAL CIRCUIT FUNDAMENTALS circuit board

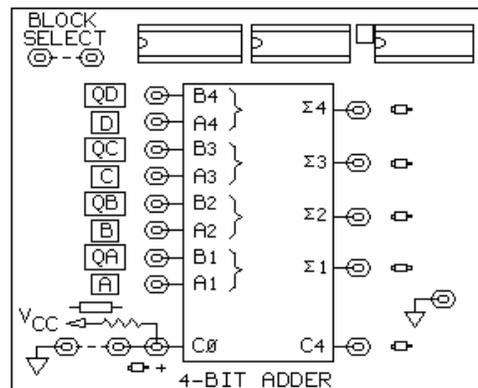
UNIT 5 – 4-BIT ADDER

UNIT OBJECTIVE

At the completion of this unit, you will have a working knowledge of a 4-BIT ADDER.

UNIT FUNDAMENTALS

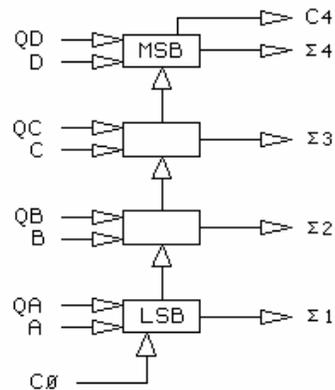
The 74LS283 adder adds two 4-bit binary words. This IC falls into the medium scale integration (MSI) category. The LS283, unlike the LS83 earlier version, has its V_{CC} and V_{SS} pins at diagonal corners of the IC, simplifying PCB interconnections.



There are 8 input terminals, labeled **A** through **D** and **QA** through **QD**. **A** through **D** comprise one 4-bit word. **QA** through **QD** comprise the second 4-bit word.

A and **QA** are the least significant bits (LSB) of the adder. **D** and **QD** are the most significant bits (MSB) of the adder. The outputs are referred to as **the sum of**, which is indicated by the symbol Σ ($\Sigma 1$ is the sum of **A** and **QA**).

The signal identifiers enclosed within the IC borders are the identifiers assigned by the device manufacturer. **C4** (output of the MSB stage of the counter) indicates an overflow, or a carry. The carry is generated when a binary 1 is added to a binary 1111. **C0** (input to the first, or LSB, stage of the counter) adds 1 to the input side of the adder.



The IC performs binary (or **base 2**) addition. The base 2 subscript, or **radix** indicates a binary weighted number written as number₂ (1000₂). Each stage adds its three inputs, generates an output, and internally sends carry information to the next stage in line.

The fundamental rules of binary addition are given below.

$$0 + 0 = 0$$

$$0 + 1 = 1$$

$$1 + 0 = 1$$

$$1 + 1 = 0 \text{ with a 1 carry or } 10$$

EXAMPLE

$$\begin{array}{r} 0010 \\ + 0101 \\ \hline 0111 \end{array}$$

EXAMPLE WITH A CARRY

$$\begin{array}{r} 0001 \\ + 0001 \\ \hline 0010 \end{array}$$

NEW TERMS AND WORDS

the sum of - a term indicating that numbers are added to generate a sum.

S - a symbol indicating the sum of T.

base 2 - a number expressed in binary form.

radix - a subscript that defines the base of a number.

Exercise 1 – Fundamental Binary Addition

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to predict the output of a 4-bit adder. You will verify your results by using a 4-bit adder to add two 4-bit words.

DISCUSSION

- The gates forming the 4-bit adder have additional logic circuit elements which ensure that gates B and C respond to unequal inputs.
- Carry detection is provided by gate A if inputs A and B are both 1.
- Gate B generates a 1 when $A = 0$ and $B = 1$. Gate C generates a 1 when $A = 1$ and $B = 0$.
- Two cascaded stages have the elements of a two 2-bit word adder.
- The circuit provided with the trainer does not show the internal carry or overflow bits (C1, C2, and C3) but they are included in the overall result.
- Stage A is the LSB stage of the adder. Stage D is the MSB stage of the adder.
- Outputs QD through QA of the SYNCHRONOUS COUNTER circuit block are hardwired as inputs to the 4-BIT ADDER circuit block.
- Inputs D through A of the 4-BIT ADDER circuit block are hardwired to toggle switches D through A of the INPUT SIGNALS circuit.
- Inputs to any one stage are paired: for example A and QA; and C and QC.
- A through D comprise one 4-bit word and QA through QD comprise the second 4-bit word.
- Addition occurs between words only. Addition does not occur within words.

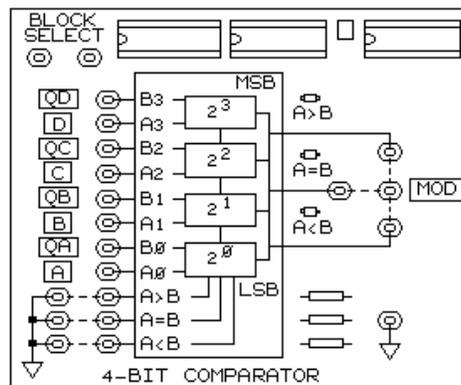
UNIT 6 – 4-BIT COMPARATOR

UNIT OBJECTIVE

At the completion of this unit, you will have a working knowledge of a 4-bit comparator.

UNIT FUNDAMENTALS

The 74LS85 IC used on your circuit board is a 4-bit **magnitude comparator**. The LSB inputs correspond to the A0 and B0 inputs. The MSB inputs correspond to the A3 and B3 inputs. This IC falls into the medium-scale integration (MSI) category.

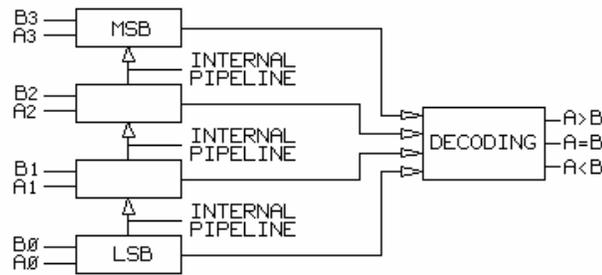


The LS85 comparator makes decisions about two 4-bit words with respect to word A. If A is greater than B, then the A>B output is activated. If A is less than B, then the A<B output is activated.

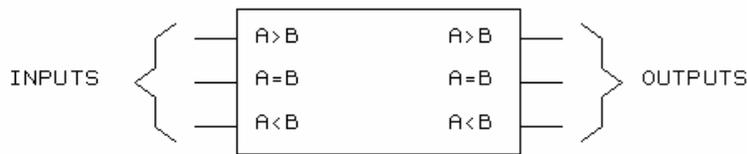
Two 4-bit words comprise the input of the comparator. On the circuit block, word A (A0 through A3) is labeled A through D, and word B (B0 through B3) is labeled QA through QD.

Inputs A>B, A=B, and A<B program the comparator. Programming determines at which state (high or low) the IC A=B output indicates equality. LEDs show the status of each output: on for high and off for low.

Connections between any one comparator output and the MOD point allow feedback to the SYNCHRONOUS COUNTER circuit block.



Each stage compares one bit of each word. The decision about each comparison is passed to the decoding stage, where all results are combined and placed on the comparator output terminals. Information between input comparison stages flows through an internal **pipeline**.



The LS85 comparator has a set of greater than (>), equal to (=), and less than (<) inputs and outputs. The inputs are used to select how a decision is represented at the comparator output.

WORD B	1 1 1 1	1 0 1 0	0 1 0 1	0 1 0 0	0 0 0 0
WORD A	1 1 1 1	1 0 1 1	0 1 0 0	0 0 0 1	0 0 0 0
A > B	0	1	0	1	0
A = B	1	0	0	0	1
A < B	0	0	1	0	0

This table shows comparisons between various 4-bit words.

NEW TERMS AND WORDS

magnitude comparator - an IC or circuit used to compare two words and to decide which word has a greater value.

pipeline - refers to a pathway over which data can flow.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

Digital Circuit Fundamentals 2

FACET[®]



Student Workbook



FOURTH EDITION

Second Printing, March 2005

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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

- ◆ The unit objective
- ◆ Unit fundamentals
- ◆ A list of new terms and words for the unit
- ◆ Equipment required for the unit
- ◆ The exercise objectives
- ◆ Exercise discussion
- ◆ Exercise notes

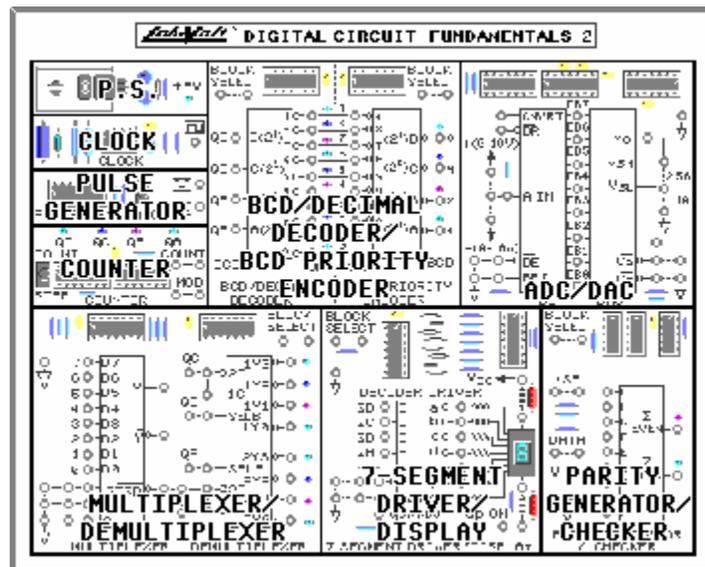
The **Appendix** includes safety information.

UNIT 1 – CIRCUIT BOARD FAMILIARIZATION

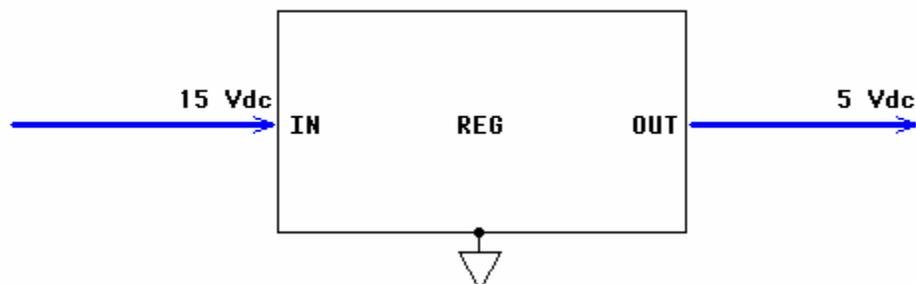
UNIT OBJECTIVE

At the completion of this unit, you will be able to identify and operate the circuit blocks on the DIGITAL CIRCUIT FUNDAMENTALS 2 circuit board.

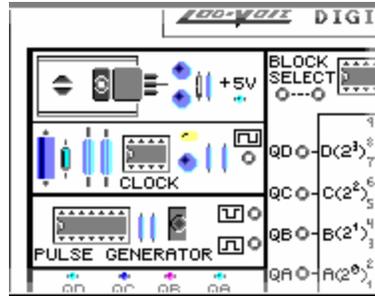
UNIT FUNDAMENTALS



The DIGITAL CIRCUIT FUNDAMENTALS 2 circuit board consists of 6 training circuit blocks. A general purpose circuit block consists of a 5V regulator, a square wave clock generator, a pulse generator, and a 4-bit counter.

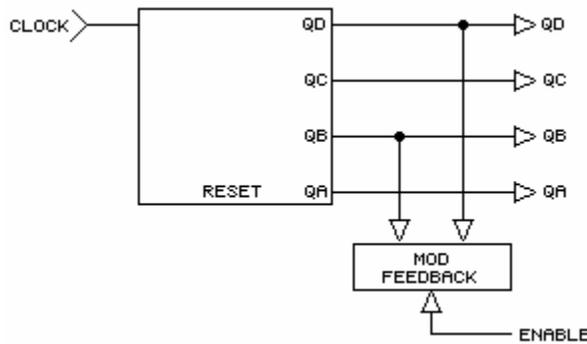


A **voltage regulator** converts the system's 15 Vdc power supply to 5 Vdc, required by the **integrated circuits (ICs)** on the circuit board. Power supply voltages are **hardwired** to all devices of the circuit board.



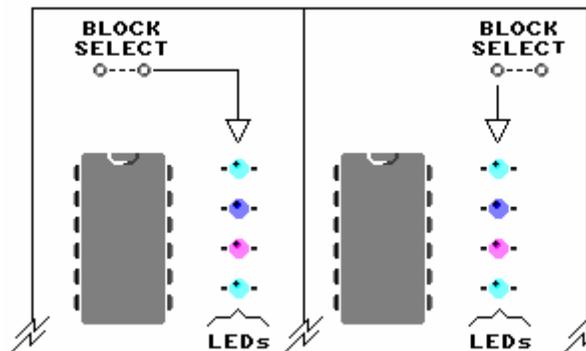
The 555 **timer** CLOCK circuit generates a square waveform, useful as an input signal generator.

The PULSE GENERATOR circuit's toggle switch generates positive-and negative-going signal edges. The "at home" position of this toggle switch is up.



The COUNTER circuit generates a 4-bit output with a count value between 0 and 15 (1111 in binary form).

If **MOD** is enabled, the counter modulus is 10 (output between 0 and 9). You can free-run or step the counter outputs (QD, QC, QB, and QA).



Placement of two-post connectors and interconnecting leads activates various circuit functions and connects circuit blocks. Inserting a two-post connector in the BLOCK SELECT terminals, for example, powers specific LED circuits.

ICs are mounted in dual-in-line sockets and are of the **TTLs**(74LSxx family) type. The **DAC** and **ADC** use I²L (integrated injection logic) technology.

Decoupling capacitors, which bypass ICs, and pull-up resistors, which determine logic levels, are incorporated into the design.

NEW TERMS AND WORDS

voltage regulator - an IC that maintains a constant output voltage when input voltage and output loads change.

integrated circuits (ICs) - devices that combine the actions of many transistors on one chip.

hardwired - refers to connections made in copper on a printed circuit board as opposed to connections that must be completed with a wire or test lead.

timer - IC (555 type) used in conjunction with external components to generate various waveforms, such as a pulse train.

MOD - the modulus of a counter; a circuit feedback used to set the maximum output value of a counter.

TTL - transistor-transistor logic.

LS - low power Schottky; a logic family that has high speed but low power consumption.

DAC - digital to analog converter; an IC that converts digital inputs to an equivalent analog output.

ADC - analog to digital converter; an IC that converts analog inputs to an equivalent digital output.

decoupling capacitors - a capacitor that reduces the impedance between the power supply bus and the IC that the bus powers.

pulse train - a free-running and repetitive waveform, usually refers to a square waveform.

dual-in-line packages (DIPs) - types of IC packages that have the same number of pins on both sides of the devices.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

DIGITAL CIRCUIT FUNDAMENTALS 2 circuit board

UNIT 2 – DECODER AND PRIORITY ENCODER

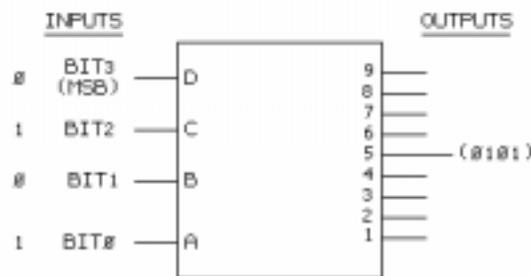
UNIT OBJECTIVE

At the completion of this unit, you will be able to locate, operate, and control a decoder and encoder circuit combination.

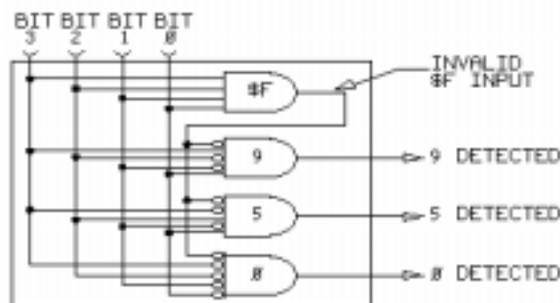
UNIT FUNDAMENTALS

BCD BIT CODE	DECIMAL VALUE
1111 THROUGH 1010	INVALID CODES IN BCD FORMAT
1000	0
1001	1
0111	2
0110	3
0101	4
0100	5
0011	6
0010	7
0001	8
0000	9

A **binary coded decimal (BCD) decoder** detects and indicates unique 8-4-2-1 bit combinations between 0 and 9 decimal, or **base 10** (indicated by 9_{10}). BCD information ranges between 0 and 9. Codes above 9 (10 through 15 for a 4-bit word) are invalid. These bit patterns are usually not decoded but generate some form of "out of limit" indication.

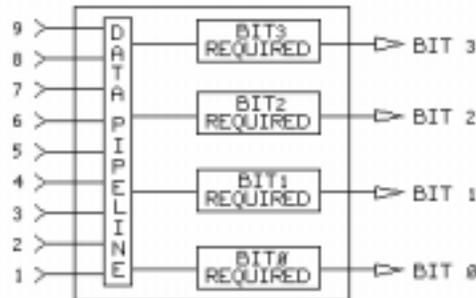


In the BCD decoder, only one output is active for a given input bit group. The active state can be high or low depending on the type of IC selected. A 4-bit BCD input activates one of the outputs (0101 activates 5, for example).

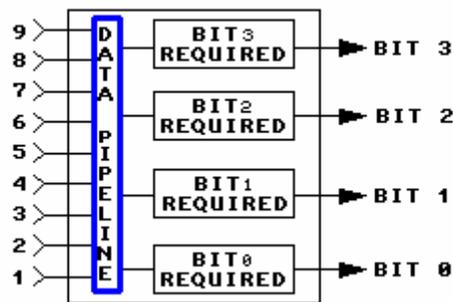


Each decoder section detects a specific input bit code. In this example, section 0 detects a 0000 input. Section 5 detects a 0101 input. Section 9 detects a 1001 input.

A binary-coded decimal **encoder** reverses the process of the BCD decoder. The encoder detects inputs between 9_{10} and 0 and generates unique 4-bit BCD codes. Because the encoder outputs represent BCD equivalents, more than one output at a time may be active.

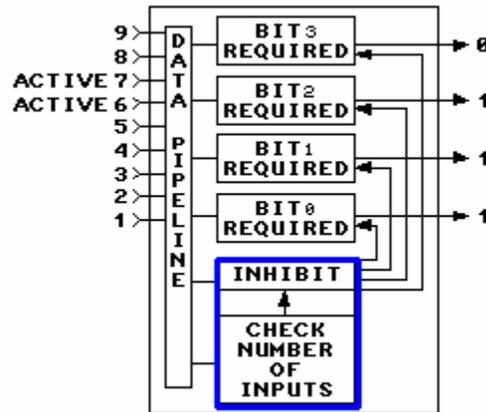


A BCD encoder has nine possible active inputs, 1 through 9. A 0 input is not required because inactive inputs generate inactive outputs.



Each bit section of an encoder is connected to a **data pipeline**, which distributes the input data. Each section decides if its bit is required to represent part of the 4-bit BCD code. If a specific bit is needed, that section activates its output. If a specific bit is not needed, that section deactivates its output. For example, an input of 6 requires a BCD output of 0110; therefore, sections BIT2 and BIT1 are active, and sections BIT3 and BIT0 are inactive.

Each encoder input represents a unique BCD code; therefore, two or more active inputs should cause an output error. If inputs 6 (0110) and 7 (0111) are both active, BIT0 cannot be inactive (xxx0) and active (xxx1) simultaneously.



Encoders use another operating section to determine input priority (called **priority detection**). Detecting more than one input activates the INHIBIT section. This section ensures that only output bits associated with the **higher** input value are encoded. Lower input values are locked out.

NEW TERMS AND WORDS

binary coded decimal - (BCD) a form of 4-bit coding representing decimal number between 9 and 0.

decoder - a circuit that generates one unique output in response to a set of input bit patterns.

base - indicates the numbering system; base 10 indicates decimal, base 2 indicates binary, and base 16 indicates hexadecimal.

disables - turns off, deactivates, inhibits, or makes nonresponsive.

enables - turns on, activates, or makes responsive.

encoder - a circuit that generates unique output bit patterns in response to a specific input.

data pipeline - a common data path used to distribute information throughout a circuit.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

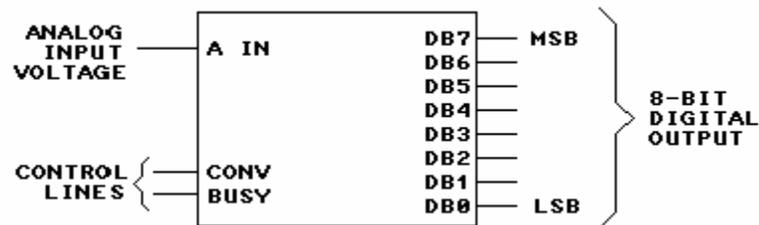
DIGITAL CIRCUIT FUNDAMENTALS 2 circuit board

UNIT 3 – ADC AND DAC OPERATION

UNIT OBJECTIVE

At the completion of this unit, you will be able to identify, operate, and control ADC and DAC circuits.

UNIT FUNDAMENTALS



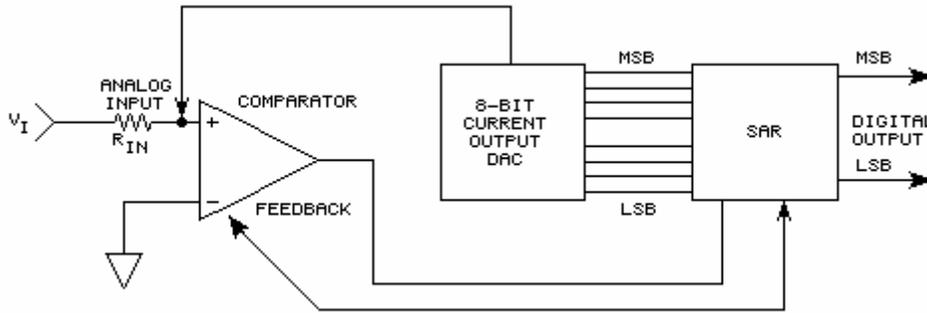
An **analog to digital converter** (ADC) generates a digital output code equivalent to the value of an analog input voltage. The analog input voltage is converted into an 8-bit digital output.

Generally, the digital output codes range from \$00 through \$FF (binary 0000 0000 through 1111 1111). DB7 is the most significant bit (MSB) of the ADC output, and DB0 is the least significant bit (LSB).

Binary numbers, such as 1010 0101, are written with the MSB at the left side.

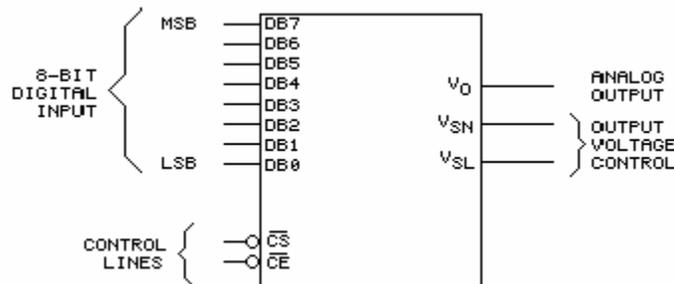
MSB	LSB
1 0 1 0	0 1 0 1

For the ADC used on your circuit board, input voltage is either **unipolar** or **bipolar**. A unipolar input voltage ranges from 0 through +10 Vdc and generates an output code from \$00 to \$FF, respectively. Mid-scale occurs at 5 Vdc. A bipolar input voltage ranges from -5 Vdc through +5 Vdc and also generates an output code from \$00 to \$FF, respectively. However, mid-scale occurs at 0 Vdc.



The AD673 ADC studied in this unit uses a **successive approximation register (SAR)** to process an analog input voltage. An SAR essentially compares two currents and in the process of making the currents identical, generates the ADC 8-bit output.

An SAR conversion circuit has a comparator, an 8-bit current output DAC, and the SAR register. The comparator output stimulates the SAR to sequence the 8-bit current output DAC from MSB to LSB. At each bit point, a current is fed back to the comparator. If the **sum** value is greater than the input current, the respective bit is turned off; if the sum value is less, the respective bit is turned on. This process continues until 8 output bits are generated.



A **digital to analog converter (DAC)** generates an analog output voltage equivalent to the value of a binary code input. The 8-bit digital input is converted into an analog output. Generally, the digital input codes range from \$00 through \$FF (binary 0000 0000 through 1111 1111).

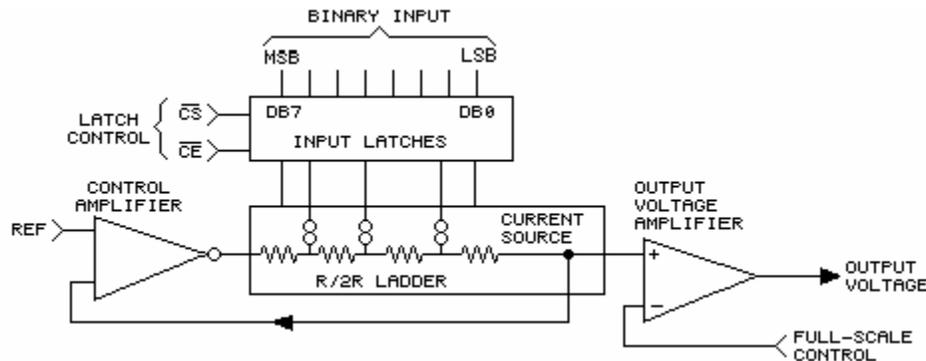
DB7 is the MSB of the DAC, and DB0 is the LSB.

Binary numbers, such as 1010 0101, are written with the MSB at the left side.

MSB	LSB
1 0 1 0	0 1 0 1

V_{SN} and V_{SL} select a full-scale output voltage of 10 Vdc or 2.5 Vdc. A 10V full-scale output has a mid-scale value of about 5V. A 2.5V full-scale output has a mid-scale value of about 1.27V.

The AD558 DAC studied in this unit uses 8 **current sources** (3 are shown) switched into an **R/2R ladder** to process a digital binary input code. The current source and the R/2R ladder null the reference (REF) voltage and generate an analog output voltage in the process.



As current is switched into the R/2R ladder, a voltage drop is developed. The voltage drives the control amplifier and the output voltage amplifier.

The control amplifier buffers the internal **band-gap** reference voltage and controls the amplitude of current through the ladder. The input latches store the binary input codes.

NEW TERMS AND WORDS

analog to digital converter - an IC or process that generates a binary output code equivalent to the value of an analog input voltage.

unipolar - possessing one polarity (+) or (-) with respect to circuit common (zero).

bipolar - possessing positive (+) or negative (-) polarity with respect to circuit common (zero).

successive approximation register - a circuit, used in conjunction with a current output DAC, which generates a binary-coded output equivalent to the value of a current input.

digital to analog converter - an IC or process that generates an analog output voltage equivalent to the value of a binary input code.

current sources - a circuit designed to provide a fixed and stable current output.

R/2R ladder - a resistive network in which each resistor has a 2:1 (larger or smaller) relationship to the value of a binary input code.

band-gap - a very accurate and temperature-stable voltage reference source.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

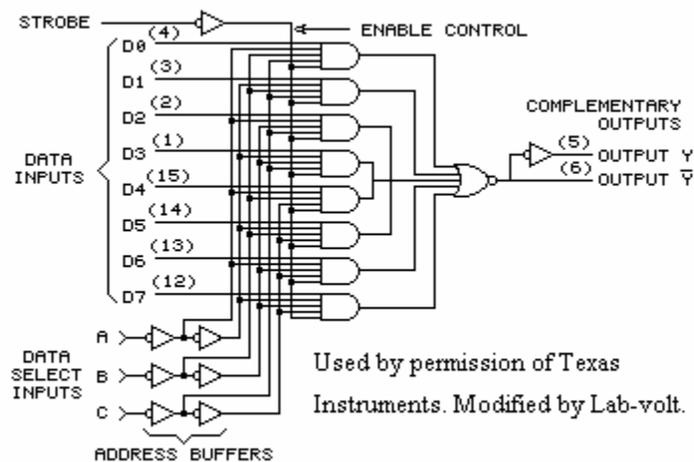
DIGITAL CIRCUIT FUNDAMENTALS 2 circuit board

UNIT 4 – MULTIPLEXER AND DEMULTIPLEXER

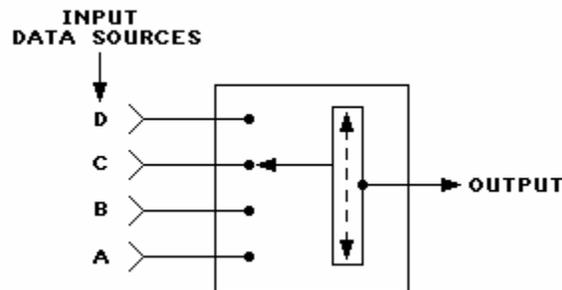
UNIT OBJECTIVE

At the completion of this unit, you will be able to operate and control a multiplexer and demultiplexer circuit.

UNIT FUNDAMENTALS

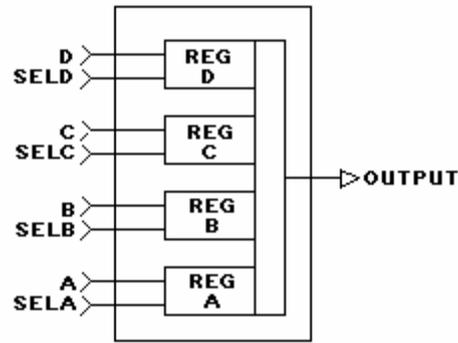


The 74LS151 **multiplexer** on your circuit board is a 1-of-8 data selector. It is an MSI device with a gate complexity of 17 equivalent gates.



A multiplexer allows the selection of one data source from a group. You can connect the output to any of the input data sources (A through D) by positioning the multiplexer pointer.

In this multiplexer, input data source C is selected. This input passes through the multiplexer pointer to the output. Data sources A, B, and D have no effect on the multiplexer output.

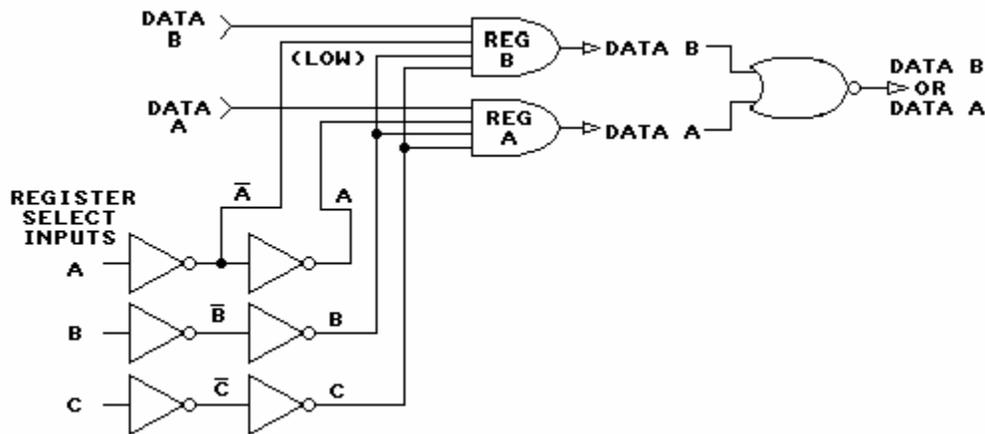


On the 74LS151 multiplexer, pointer movement is provided electrically through a register select process. Internal registers (REG) allow the selection of a specific data input. Each register is enabled by a select (SEL) line.

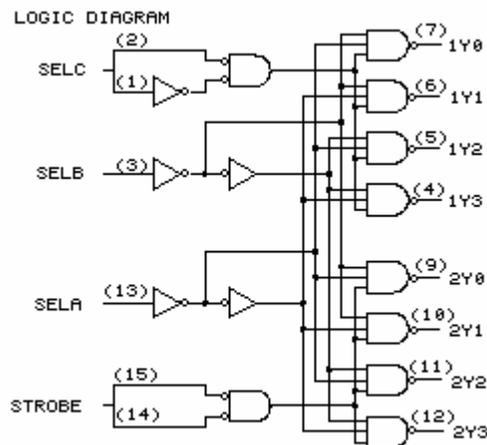


Part of the selection process deals with an output-enable control line called a **strobe (STRB)**. On the 74LS151, the strobe input disables or enables all data registers simultaneously.

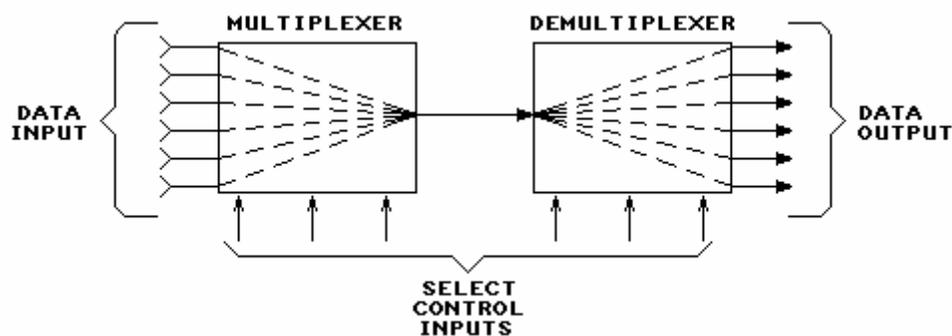
DATA A and SELA have no effect on the output if the **STRB** input is high. **STRB** high disables the output of REGISTER A. If **STRB** is low, the register is enabled, and DATA A can be passed to the output.



This circuit illustrates two internal pathways of the 74LS151 multiplexer. Register A is enabled when the register select inputs equal binary 111. REG B is disabled because A is high and \bar{A} is low.



The 74LS155 on your circuit board is a dual 2-4 line decoder configured as a 1-line-to-8-line data **demultiplexer**. It is an MSI device with a gate complexity of 15 equivalent gates.



The demultiplexer allows one data source to selectively drive individual elements of a group. In this demultiplexer, lines of data (data input) are multiplexed down to 1 line. In turn, the data on this line is placed on 1 of 6 lines.

NEW TERMS AND WORDS

multiplexer - a circuit that selectively connects one data line of a group to one output line.

strobe (STRB) - the input data line of a multiplexer or demultiplexer.

demultiplexer - a circuit that selectively connects one data line to a specific output line of a group.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

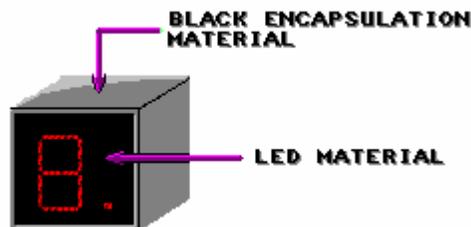
DIGITAL CIRCUIT FUNDAMENTALS 2 circuit board

UNIT 5 – 7-SEGMENT DRIVER/DISPLAY

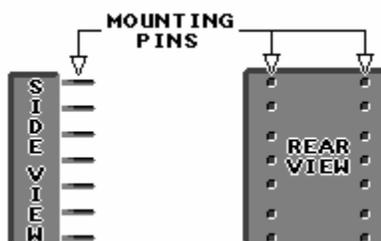
UNIT OBJECTIVE

At the completion of this unit, you will be able to control a 7-segment LED display by using a decoder/driver IC.

UNIT FUNDAMENTALS

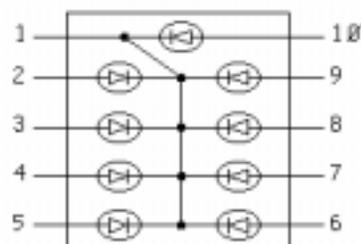


A **7-segment LED display** is constructed with 7 bars of semiconductor material capable of emitting light when stimulated by a drive voltage. The individual LEDs are encapsulated in an opaque material that serves as the device housing. In general, 7-segment displays are available in red, high efficiency red, green, or yellow. Each color denotes a specific **luminous intensity** at a given test current.

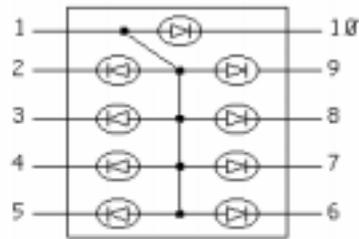


The number of pins varies with the specific IC selected. Typically, there are an equal number of pins on both sides of the dual-in-line housing.

Package dimensions are about the same as those of a dual-in-line, 14-pin TTL IC. The 7-segment display can be socket mounted or directly soldered to a PCB.

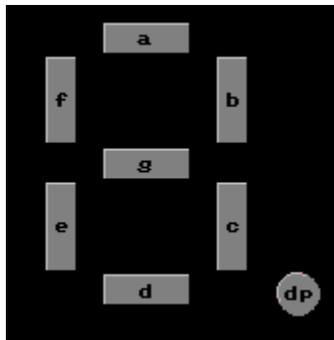


This configuration is called a **common cathode** display because all the cathodes are connected together.

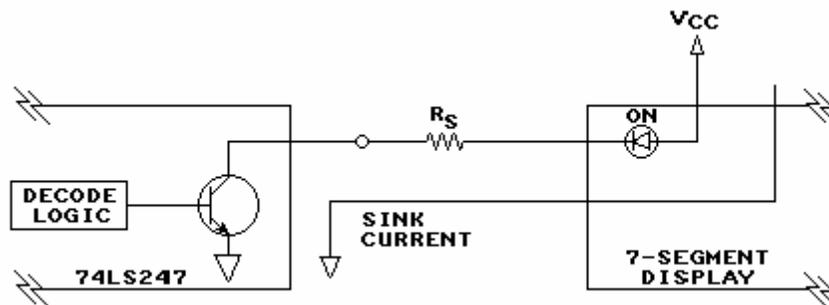


This configuration is called a **common anode** display because all the anodes are connected together.

For both configurations, the total current of the display (sum of the segment currents) flows through the common terminal of the package.

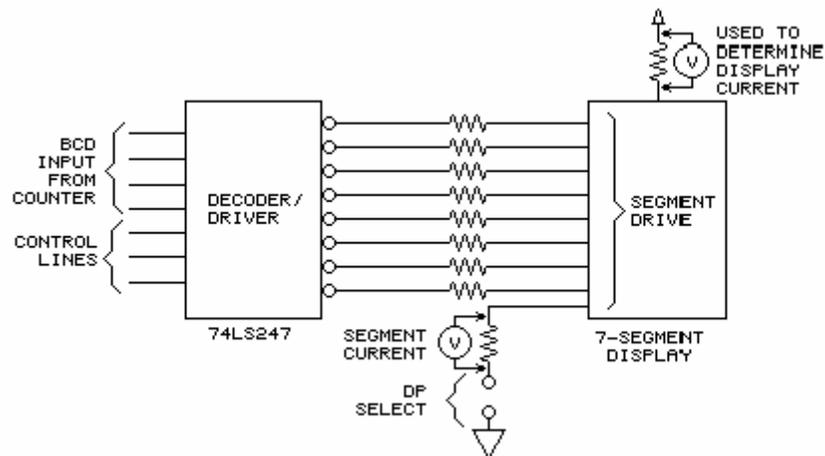


Each display segment is assigned an identifier (a through g). Groups of segments are driven to produce specific figures or symbols. For example, segments e, f, a, b, c, and g (on) produce the letter A.



The 74LS247 **decoder/driver** used in this unit drives a 7-segment (outputs a through g) display. This type of IC, a **BCD-to-7-segment decoder/driver** provides internal logic that can select (decode) the proper group of segments needed to display a given character.

The 74LS247 also provides output drivers (buffers) that supply the **sink current** for each segment of the display.



The 74LS247 uses a 7-segment display to generate the symbols 0 through 9. Although the 7-segment display can be configured to generate symbols from 0 through 9, A through F, and other unique symbols, the 74LS247 can decode only symbols 0 through 9.

You will use sensing resistors to determine display, or digit, current and segment current:

$I = V/R$. BCD inputs (hardwired to the COUNTER circuit) and control inputs condition the 74LS247 decoder/driver. The 7-segment display indicates the equivalent BCD code applied to the decoder/driver. A two-post connector at dp select controls the dp segment.

NEW TERMS AND WORDS

7-segment LED display - an IC that can be configured to display numbers 0 through 9 and hexadecimal values A through F.

luminous intensity - specifies the light energy generated by a segment for a given test current.

common cathode - a 7-segment display with all of the cathode elements connected together.

common anode - a 7-segment display with all of the anode elements connected together.

decoder/driver - an IC that can decode a BCD input code and provide the drive current required for a 7-segment display.

BCD-to-7-segment decoder/driver - an IC designed to control an individual segment display.

sink current - the current that flows into an output pin of a driver; usually considered with a low-level TTL output.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit

Multimeter

Oscilloscope, dual trace

DIGITAL CIRCUIT FUNDAMENTALS 2 circuit board

UNIT 6 – PARITY GENERATOR/CHECKER

UNIT OBJECTIVE

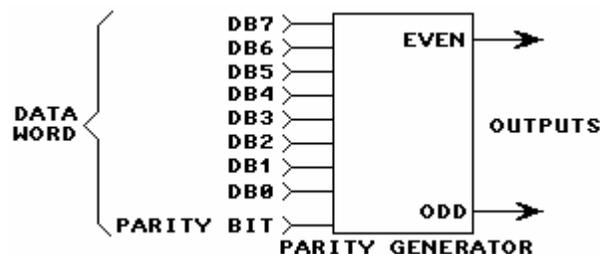
At the completion of this unit, you will be able to establish the parity of an 8-bit word by using a parity generator and checker.

UNIT FUNDAMENTALS

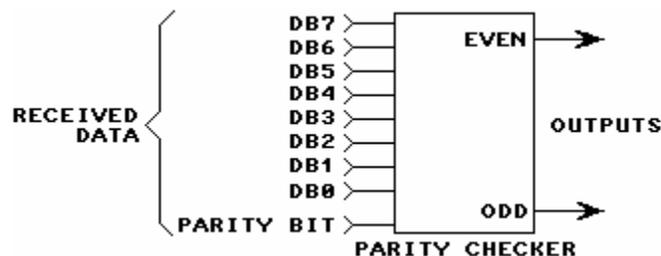
Parity refers to error detection. Computers use parity to ensure that the bit pattern of a word is not corrupted during the data transfer process. Generally, a ninth bit, called the **parity bit**, is set or reset to ensure that the correct parity of a system is maintained; therefore, an 8-bit system has a 9-bit data bus. Parity is associated with the number of **ones** present in the data word.

PARITY BIT	8-BIT DATA WORD	SYSTEM PARITY
OFF <LOW>	[0] 1010 1010	EVEN
ON <HIGH>	[1] 1010 1000	EVEN
ON <HIGH>	[1] 1010 1010	ODD
OFF <LOW>	[0] 1010 1000	ODD

Even parity systems require an even number of ones in the data word, which includes the parity bit. **Odd parity** systems require an odd number of ones in the data word, which includes the parity bit. Because the data word, \$AA for example, determines the 8 bits of the word, the parity bit is set high or low to ensure that the data word matches the **system parity**.



In this parity generator and for an even parity system, the parity bit input is set or reset to ensure that the even output is high (odd output low). For an odd parity system, the parity bit input is set or reset to ensure that the odd output is high (even output low).



In this parity checker, the even output is high if an even number of ones is present in the received data. The odd output is high if an odd number of ones is present in the received data.

APPENDIX A – SAFETY

Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

