EEAP 243

CIRCUITS LABORATORY

LABORATORY HANDBOOK

SPRING 1988

PROFESSOR F. MERAT
GLENNAN 515
368-4572

EEAP 243

F. Merat
Glennan 515
368-4572

secretary: Donna Buggs, Glennan 517

Course philosophy

- support 241/242 lecture material
- real as opposed to ideal circuit operation
- basic skills (schematics, soldering, etc.)

rules & regulations

- lab assignments
  try to do one per week (probably 13-14 total)
  will be available Friday unless a screw-up.
- partners
  usually groups of 2
  work at your assigned stations
- data will be collected on data sheets and handed in with lab
- grading
- equipment.
  - tool boxes (sign out)
  - parts kits yours.

EEAP 243 COURSE GRADING POLICY

1. Each lab will be worth a maximum of four points.
   - A≥3.5
   - B≥2.5
   - C≥1.5
   - D≥1
   - F<1
2. All late labs will receive a maximum grade of 1 point.
3. There will be no final.
4. All grades will be based upon points accumulated in the course through graded labs.
5. The final course grade will be (12 labs) based upon the following point distribution:
   - A≥52.5 ... 42.
   - B≥37.5 30.
   - C≥22.5 18.
   - D≥15 12.
   - F<15 12.

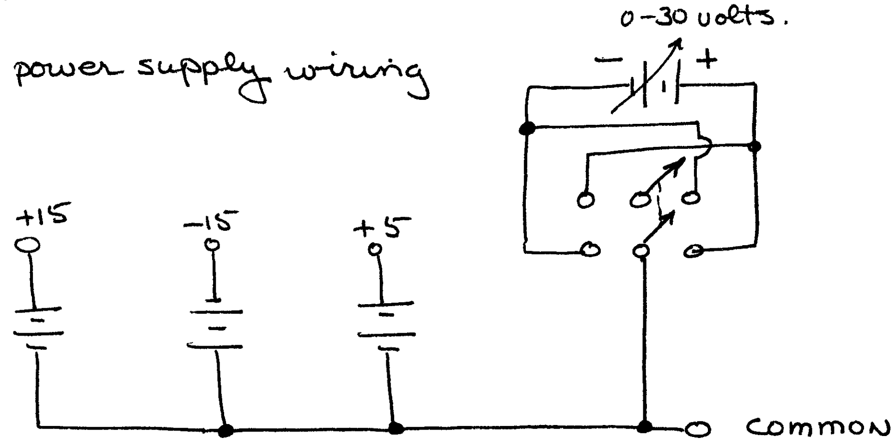
   assuming that 15 labs will be assigned. If 15 labs are not assigned the grade cutoff points will be reduced accordingly.
6. Any lab not handed in will count -3 points toward your final grade.

p	Your grade will be based upon a strict interpretation of this point distribution and the above rules. There will be no exceptions without notes from the Dean's Office.

No student who has not passed EEAP 241 (or its equivalent) and is not concurrently enrolled in EEAP 242 will be allowed to take EEAP 243. The only exception will be students who have already taken EEAP 242 or its equivalent.

station lay-out

simplified power supply wiring



DMM is electrically separate from common

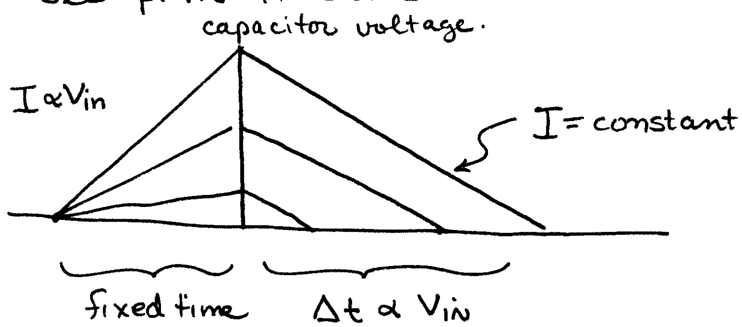
three modes of measurement.

- single ended
- differential
- current

frequency limited performance.

uses low frequency, very accurate dual slope integration

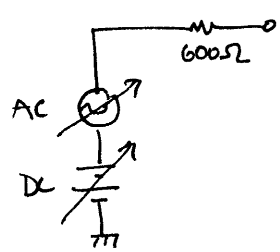
see p. 418 Horowitz



use digital counter to time this period

Signal generator

2 - outputs.



EEAP 243 Lecture #2.

Lab #1 done this week

lab partners posted tonite if not assigned

Labs due tuesday next week. (where ?)

announce in next class

→ Office hours Thursday 10 – 3

Lab questions assigned : 1, 4, 7 MUST BE TYPED

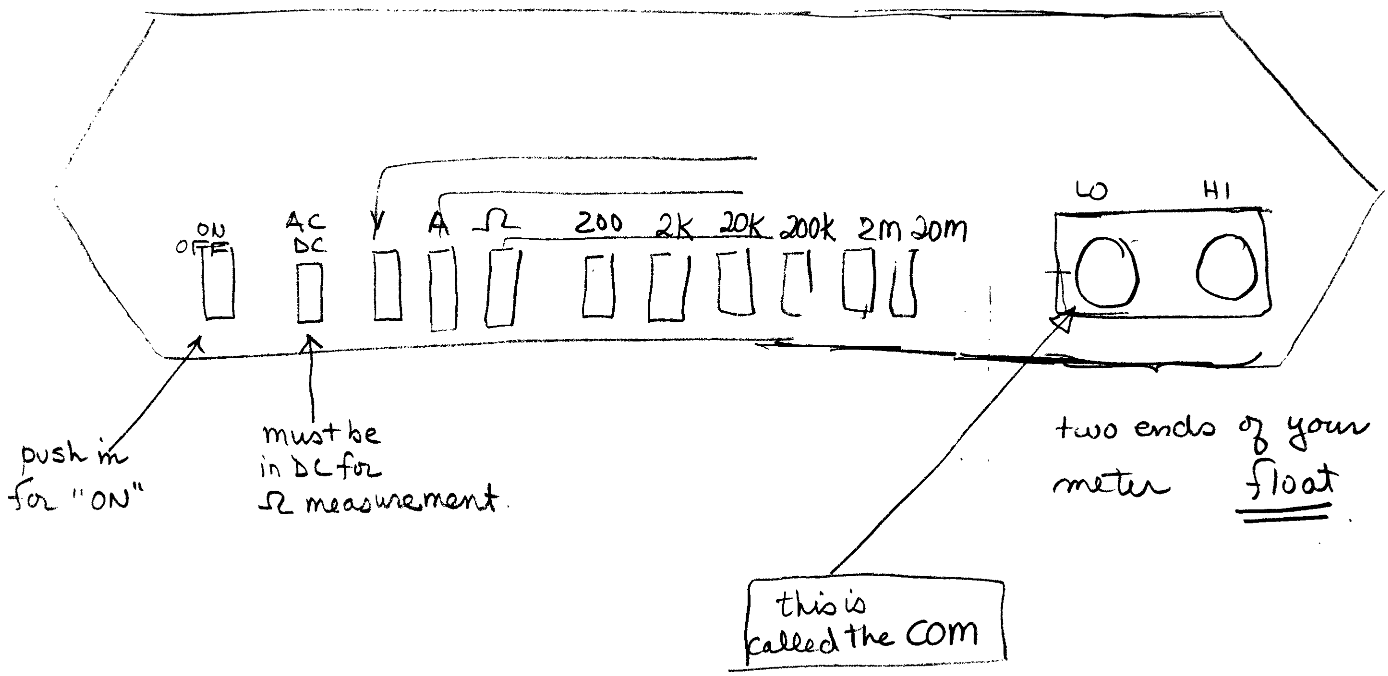
INCLUDE DATA LOG SHEET
(will be returned)

T.A. must initial data sheet (and date it)

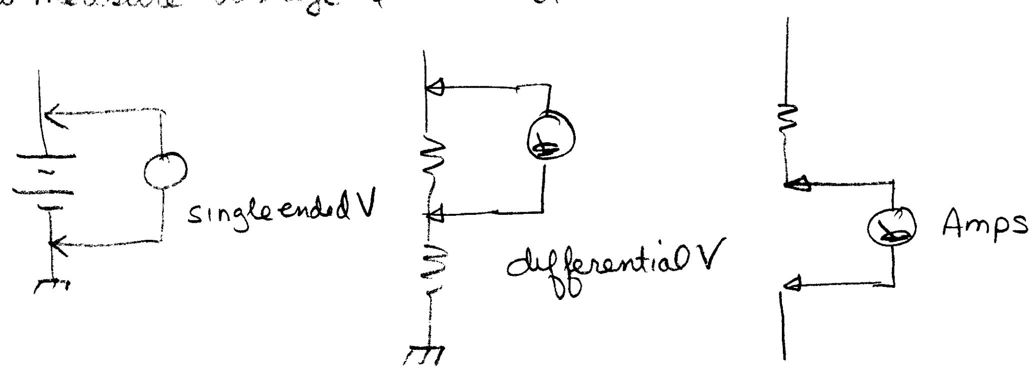
make up labs MONDAY
TUESDAY } evening 7-9 pm.

Dmm

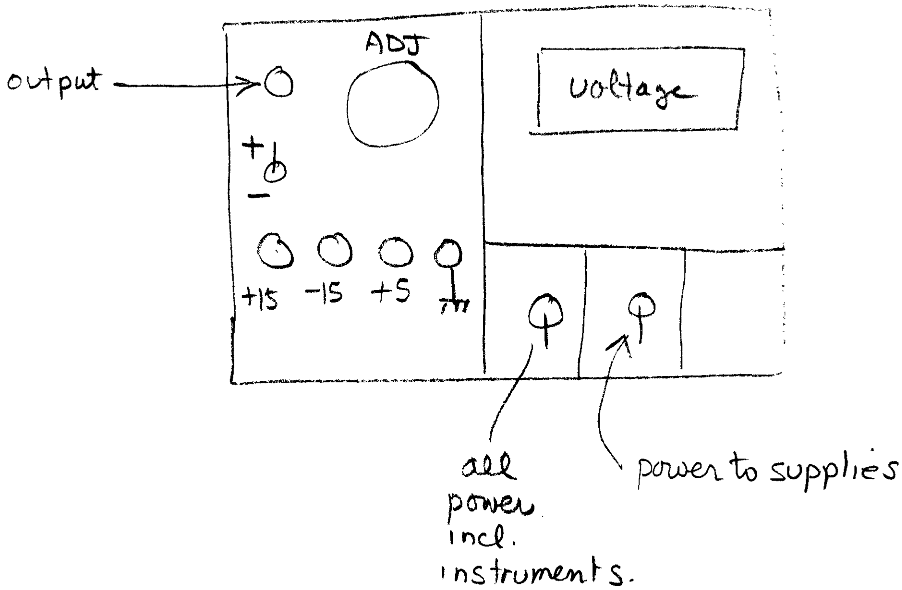
we don't have Keithley's
we have Flukes.

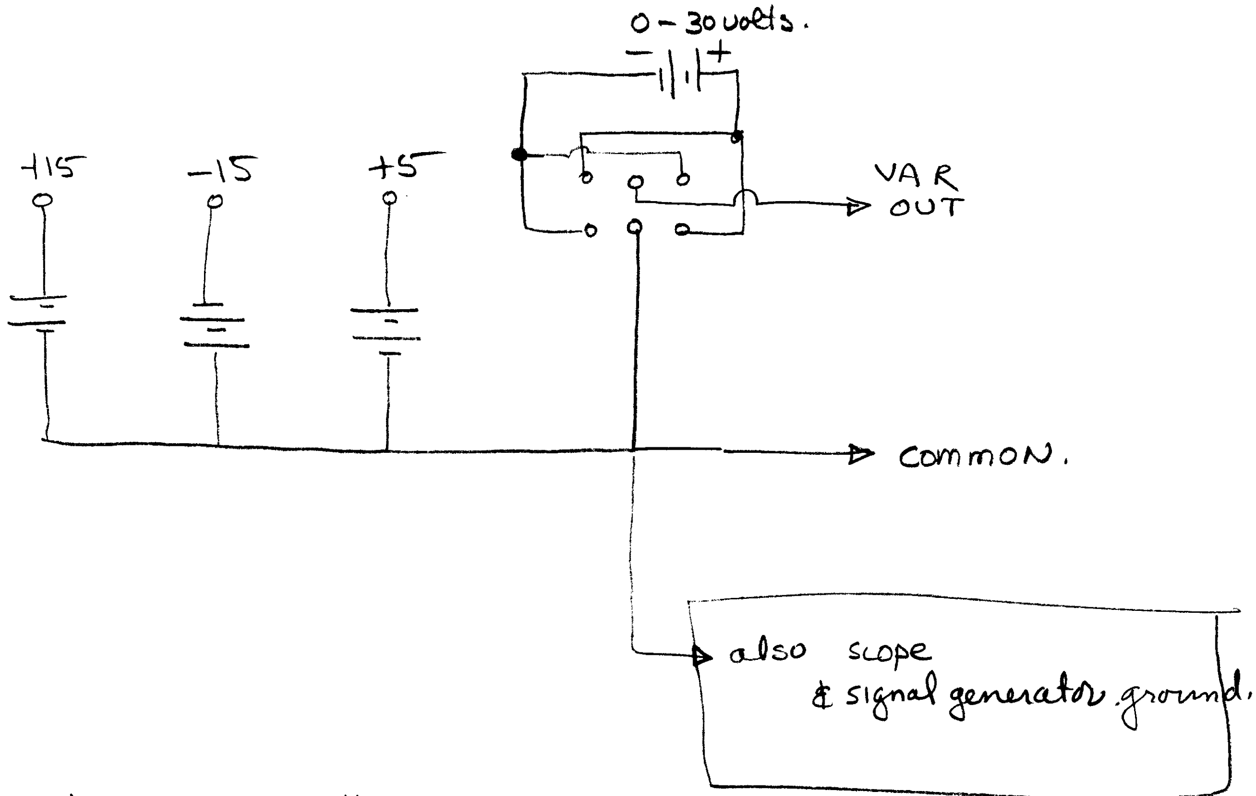


How to measure voltage & current



Power supplies :



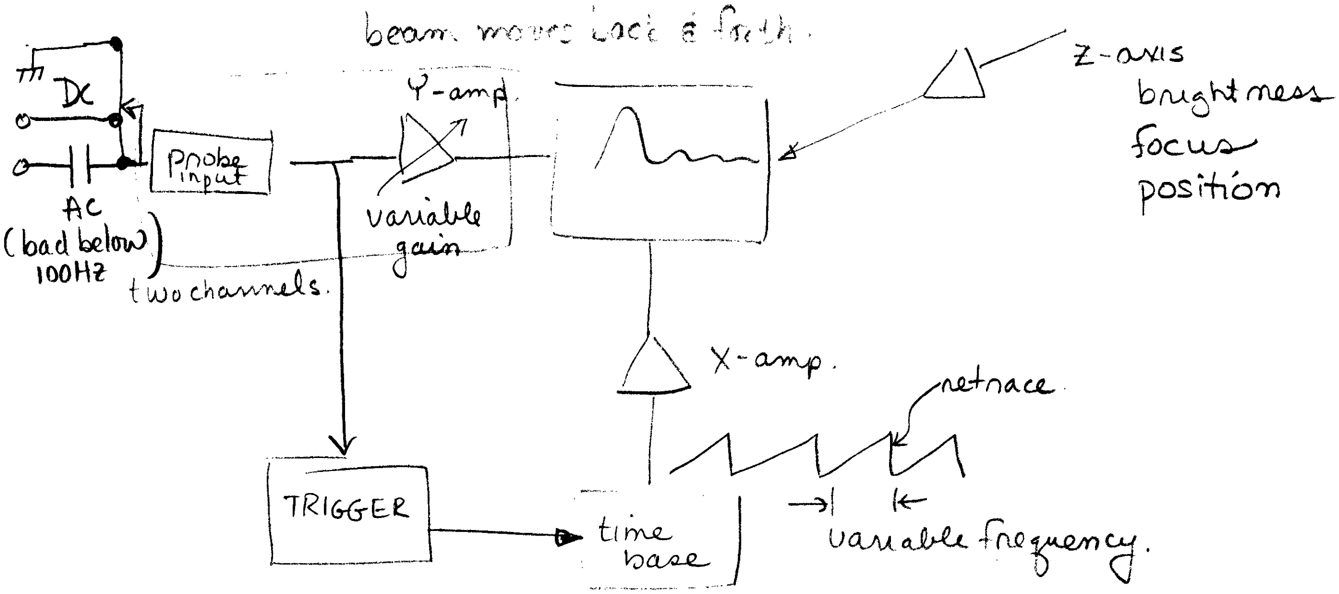


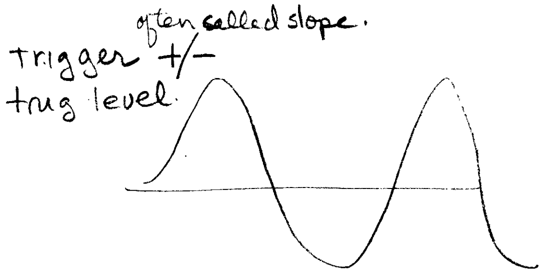
You will measure these voltages. <u>Use DC power switch</u>

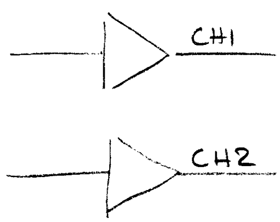
No reading if com not connected!

Scope

basic background





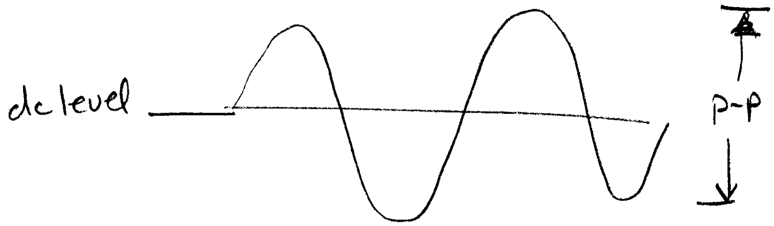


CH1 } single channel.
CH2 }
DUAL } most used.
ADD }
X-Y

POINT OUT VARIABLE SENSITIVITY, multiples sensitivity i.e. reduces it

TURN CLOCKWISE

MAGNIFY - don't push IN.



adjust to coupling you want.

adjust gnd to some screen marking.

trigger slope +/− } synchronizes oscillator with
level } input voltage level.

Bright Line should always be out.
Is a special automatic sweep.
if NO signal keeps screen display!

lab write-ups due by start of next lab – typically Tuesday.

resistors

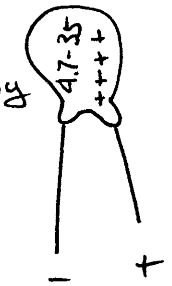
(transparancy)

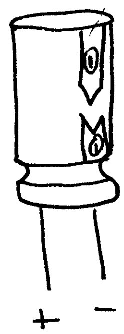
capacitors

electrolytics

tantalum

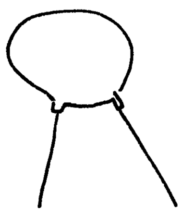
round & lumpy





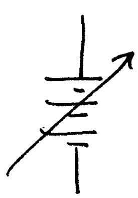
can explode if you reverse polarity

disk ceramics

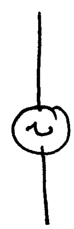


flat.

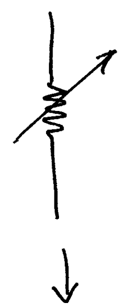
symbols used



variable power supply



signal generator



RSB or pot.

go to rsb.

EEAP 243

CIRCUITS LABORATORY

LABORATORY HANDBOOK

SPRING 1988

PROFESSOR F. MERAT
GLENNAN 515
368-4572

EEAP 243 COURSE GRADING POLICY

1. Each lab will be worth a maximum of four points.
   - $A \geq 3.5$
   - $B \geq 2.5$
   - $C \geq 1.5$
   - $D \geq 1$
   - $F < 1$
2. Late labs will be deducted 1 point per day late to a maximum of three points to be deducted–any lab not handed in will count -3 points toward your final grade.
3. There will be no final.
4. All grades will be based upon points accumulated in the course through graded labs.
5. The final course grade will be based upon the following point distribution:
   - $A \geq 52.5$
   - $B \geq 37.5$
   - $C \geq 22.5$
   - $D \geq 15$
   - $F < 15$

   assuming that 15 labs will be assigned. If 15 labs are not assigned (very likely) the grade cutoff points will be reduced proportionately.

7. Lab writeups will consist of the data collected by the lab group PLUS the answers to assigned questions. The proper collection of the lab data will be worth one point; the answers to the lab questions will be worth three points.

> ☞ Your grade will be based upon a strict interpretation of this point distribution and the above rules. There will be no exceptions without notes from the Dean's Office.

No student who has not passed EEAP 241 (or its equivalent) and is not concurrently enrolled in EEAP 242 will be allowed to take EEAP 243. The only exception will be students who have already taken EEAP 242 or its equivalent.

EEAP 243 | Lab Work:
Lab 0 | Questions Due:

SPECIAL PARTS:

This course uses the following parts:

Qty	Description
1	1500:500 Ω audio transformer
1	100 mH inductor
1	1.2-30 pF trimmer capacitor
1	1K potentiometer
1	10K potentiometer
1	100K potentiometer
2	100pF disk capacitor
2	1000pF disk capacitor
2	0.01µF disk capacitor
1	0.022µF disk capacitor
6	0.05µF disk capacitor
2	0.1µF disk capacitor
1	4.7µF disk capacitor
5	47µF disk capacitor
1	100µF disk capacitor
1	1000µF disk capacitor
1	15Ω 5 watt resistor
1	680Ω 5 watt resistor
*	resistors
6	1N4002 rectifier diode
1	1N4735 6.2 volt, 1 watt zener diode
*	MPS4124 NPN transistor
*	MPS4126 PNP transistor
*	2N2222 transistor
3	2N5951 N-channel FET
4	LM741 op amp
4	LF357 op amp

* These will be available from the instrument room as we have very large stocks of these components.

EEAP 243
Lab 1

Lab Work:
Questions Due:

TEST INSTRUMENT FUNDAMENTALS

Reading Assignment: Horowitz, pgs. 1-8, 638-642, 645-649

Abstract:
This laboratory introduces the test equipment and measurement procedures used in the electronic circuits lab. It also describes some of the common problems you will encounter.

> One common problem is the failure to recognize and report faulty equipment. If you ever suspect that an instrument is faulty, call a teaching assistant to check it out. Remember that the clip board which hangs next to the lab bulletin board is used to report faulty test equipment. Always report faulty equipment immediately so that it can be repaired promptly.

This assignment contains both background material and instructions for work to be done in the lab. For this lab only, instructions are started with the symbol "[ ]" so that you can check off your progress.

Part 1 - The Lab Station, Front Panel, and Tool Box

Each lab station contains the following test equipment: an oscilloscope (scope), a signal generator, a digital multimeter (DMM), and four DC power supplies. The test station is pictured in Fig. 1.1.

The main power switch (Fig. 1.1D-1) on the front panel controls the power for the whole station.

[ ] Turn the main power switch on at the beginning of your lab session and leave it on for the entire period. You will usually want to turn on the lab equipment every time you start a lab session.

Your tool box contains the following items: one screwdriver, one pair of pliers, one wire cutter, one wire stripper, one resistor board, ten test leads, ten alligator clips, and one solderless "breadboard". The breadboard consists of a plastic frame with an array of holes and metal clip assemblies under the holes. A wire or component inserted in a hole will be held by the clip and electrically connected to other components inserted in the same row or column. Figure 1.2 shows the protoboard and how the holes in the board are electrically connected.

Part 2 - The RSB and Ohmmeter

The Resistor Substitution Board (RSB) is a printed circuit board containing seven strings of resistors connected to a common point. You can generate almost any resistor value you might need using the RSB. Its schematic is shown in Fig. 1.3. With a little practice, using this board will simplify lab procedures and reduce the number of resistors you will need from the instrument room.

NEVER SOLDER TO THE RSB

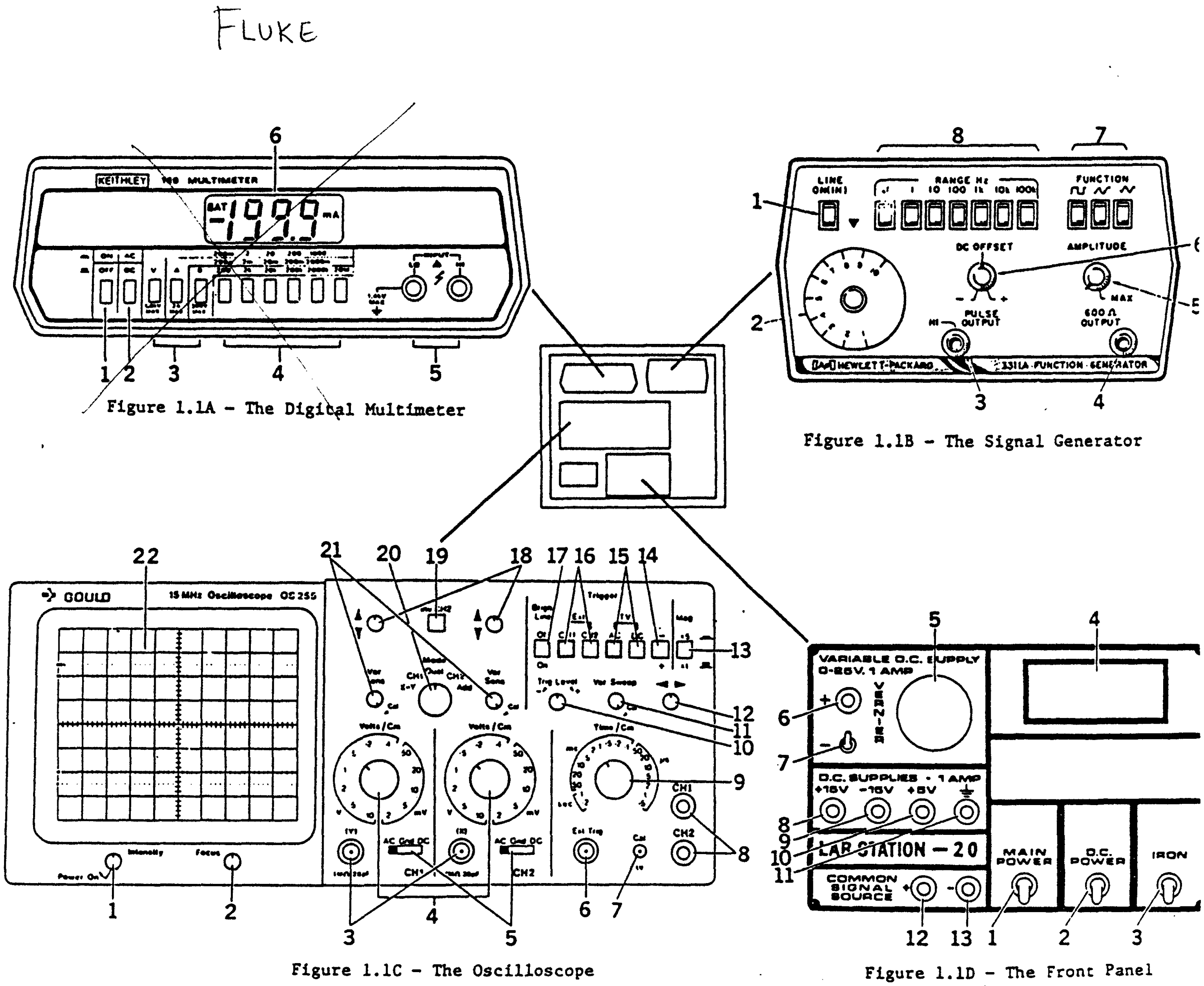


Figure 1.1A - The Digital Multimeter

Figure 1.1B - The Signal Generator

Figure 1.1C - The Oscilloscope

Figure 1.1D - The Front Panel

Figure 1.1 - Lab station

Make it a point to use 22 gauge wire. !
larger wire will damage board !

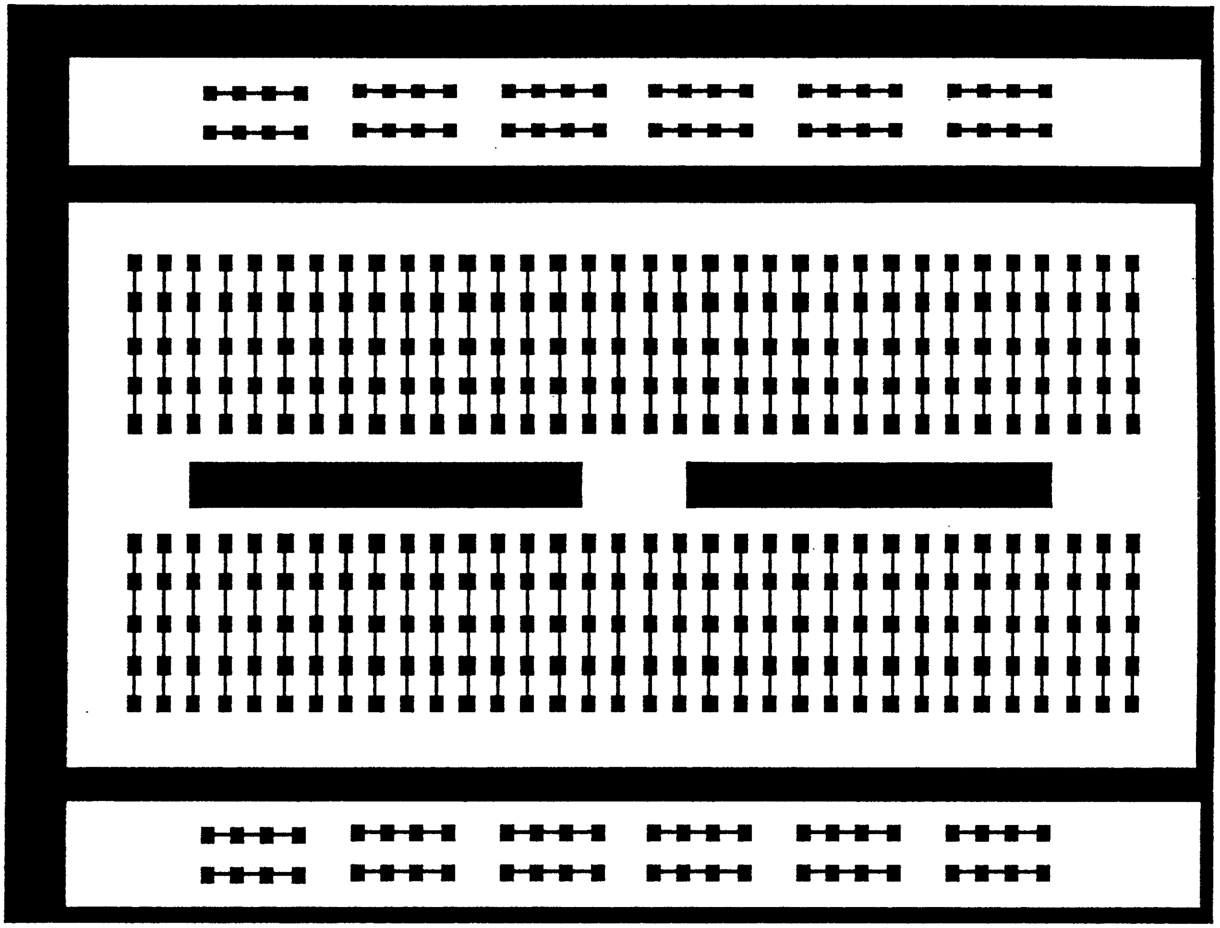


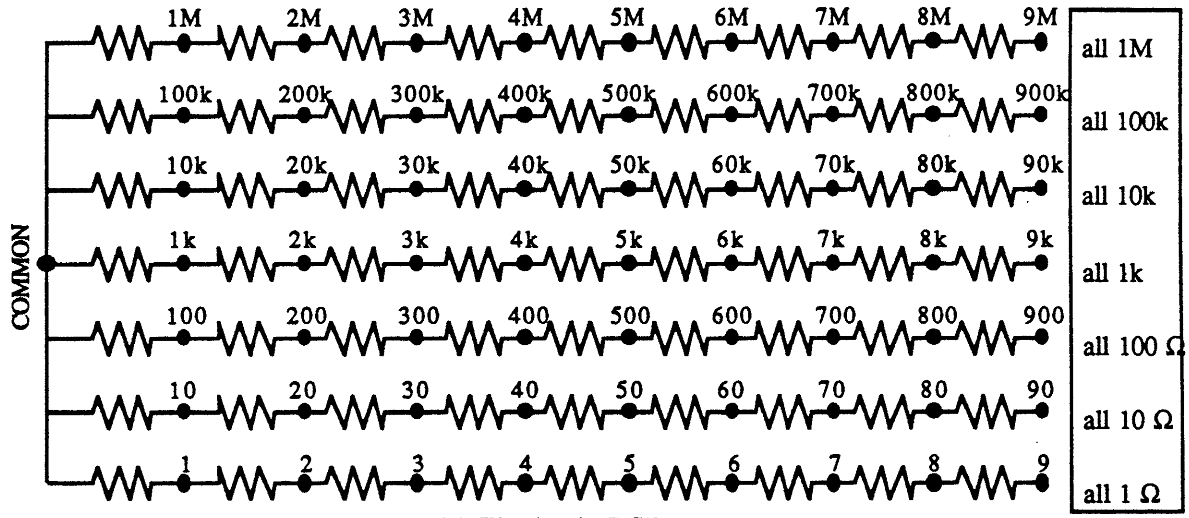
Figure 1.2 - Solderless breadboard

Always connect to the RSB by using test leads and/or alligator clips–do NOT solder to the RSB. Clipping test leads to resistor junctions in adjacent rows allows you to obtain any two digit resistor value. The resistance between the clips is simply the sum of the values printed at the resistor junctions. For example, to get a 470 ohm resistance you would clip to 400 and 70. These connections are shown in Fig. 1.3(b). In another example, connecting to 6M and 300K would give you a 6.3 M resistance. The left end of each resistor string is connected to a common point. To get a 50 K resistance, you would connect to 50K and one of the "common" junctions. You will not normally make more than two connections to the RSB–it can only be used for one resistance in a circuit.

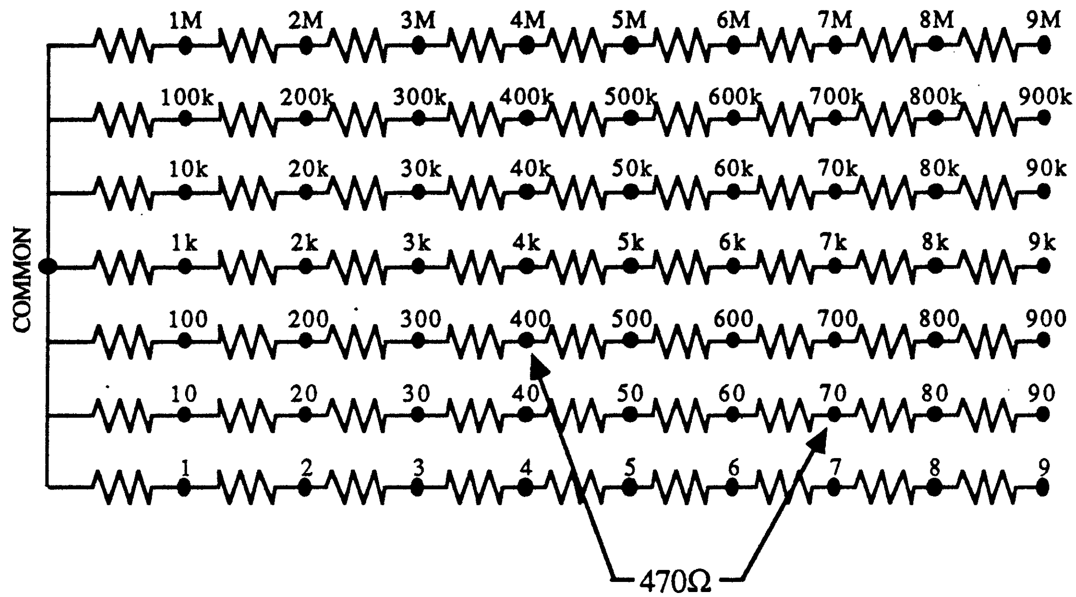
Your DMM can measure AC and DC volts, AC and DC amps, and ohms. The three function buttons (A-3)* are used to select the measurement of volts, amps, or ohms. The separate button which selects AC or DC (A-2) should be in the DC position for measuring ohms. <u>NEVER SELECT THE OHMS FUNCTION WHILE THE DMM IS CONNECTED TO A CIRCUIT TO WHICH POWER IS APPLIED.</u> Otherwise, you may damage the circuit or your DMM.

---

* Labels in parentheses refer to Figure 1.1. For example, A-5 refers to Figure 1A, the switch labeled 5.



(a) The basic RSB



(b) Connections to achieve 470 ohm resistance

Figure 1.3 - Resistance Substitution Board

Each of the five functions is broken down into 5 or 6 ranges which are selected by the range buttons (A-4). For example, the ohms function has ranges of 0-200 ohms, 0-2 K ohms (or just 0-2 K), 0-20 K, 0-200 K, 0-2000 K (0-2 M), and 0-20 M.

When using the DMM, you must be careful to use the proper range. For example, consider the measurement of a 1.234 K resistor. Selecting the 0-200 ohm range would cause an "out of range" condition, indicated by a "1" followed by blanks on the display (A-6). Selecting the 0-20 K range would produce a display of " 1.23 K" which doesn't fully use the instrument's accuracy. The most appropriate range for this measurement is the 0-2 K range, which would display "1.234 K". When measuring widely varying quantities, you should switch the DMM range to get the most accurate reading for each quantity being measured.

The DMM is a sensitive instrument. NEVER TOUCH THE METAL PARTS OF THE TEST LEADS CONNECTED TO THE DMM INPUTS mA, COM, AND VKS (All at A-5) WHILE MAKING MEASUREMENTS. If you do, the DMM may measure noise and resistance from your hands instead of from your circuit.

[ ] Turn on the DMM (A-1) and set it to ohms. Plug a test lead into the VKS input (A-5), another into the common (A-5), and put alligator clips on the free ends of the leads. Connect one clip to 40 on the RSB and the other to 7. Starting with the 200 ohm range button, press each range button in its turn and record the resulting display. (Some readings will display an out of range condition and others will not use all available significant digits.) Do the same for connections to 100 and 50, 1K and 800, 2K and 200, 50K and "common", 900K and 10K, and 5M and 500K. Record your readings below.

Part 3 - DC Power Supplies and DC Voltmeter

There are four DC power supplies in each lab station: +15 V (D-8), -15 V (D-9), +5 Volts (D-10), and a variable voltage source (D-6). The meter (D-4) monitors the voltage of the variable supply and the vernier (D-5) allows you to adjust the voltage from zero to 25 V. The polarity switch (D-7) makes the variable supply positive (up) or negative (down) with respect to the lab station ground.

The DC POWER switch (D-2) turns the DC power supplies on and off. You will usually want to turn the DC power off before making modifications to a circuit. This will prevent you from accidentally destroying sensitive components.

[ ] In this lab you should turn the DC power supplies on and leave them on. These power supplies are fairly rugged, but they can be damaged if you let their outputs short circuit to one another or to ground.

Two wires, a signal wire and a ground wire (or source and return), are needed to complete the circuit between two instruments. THE OSCILLOSCOPE, SIGNAL GENERATOR, AND POWER SUPPLIES ARE ALL CONNECTED TO A COMMON EARTH GROUND. This ground point (D-11) is included with the power supply outputs.

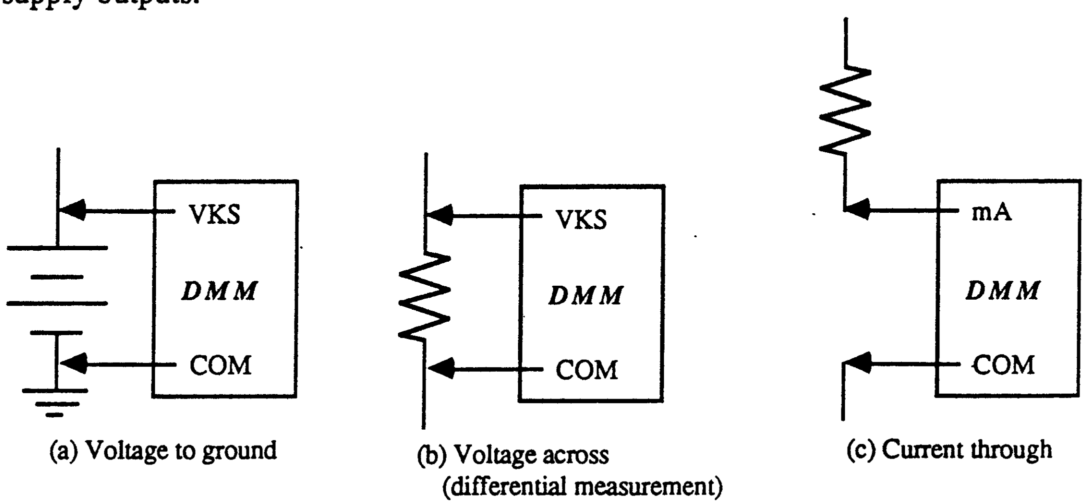


Figure 1.4 - How to measure voltage and current

THE DMM IS NOT CONNECTED TO GROUND LIKE THE REST OF YOUR INSTRUMENTS. Therefore, when measuring the voltage from a point to ground, you must connect VKS (A-5) to the point to be measured and COM (A-5) to ground (See Figure 1.4). When measuring the voltage across a component, VKS (A-5) is connected to one end of the component and COM (A-5) is connected to the other end. When measuring the current through a component, disconnect one end of the component and use mA (A-5) and COM (A-5) to bridge the broken connection. This procedure is illustrated in Fig. 1.4.

[ ] To prove that the DMM is not grounded, you will attempt to make some measurements using just one wire. Remove the test leads from the DMM, make sure that the AC/DC button is out, and select the volt function and the 20 volt range. Set the variable supply to +10 V. Plug one end of a test lead into VKS (A-5) and record the display values when the other end is plugged into the power supply outputs +variable (D-6), +15 (D-8), -15 (D-9), +5 (D-10), and COM (D-11).

[ ] A ground reference must be established between a source and the DMM to make meaningful measurements. Use a second test lead to connect COM (A-5) to D-11. Set the DMM to the 200 mV scale, connect VKS (A-5) to +5 (D-10), and record the measured voltage as each of the range buttons is pressed in its turn. (Some readings will indicate an out of range condition and others will not make use of all of the significant digits.) Make the same measurements with VKS (A-5) connected to -15 (D-9), +15 (D-8), +variable (D-6) with positive polarity, and [redacted] with negative polarity. -variable (D-6)

Part 4 - The Oscilloscope

Your scope displays a graph of input voltage versus time and provides far more information than your DMM. The functional blocks of the scope are illustrated in Fig. 1.5. The display system contains the cathode-ray tube (CRT) where the graph is drawn. An electron gun at the back of the tube fires a beam of electrons at the screen (C-22). The screen, which is covered with a phosphor coating, glows when it is hit by the electron beam producing the display. The vertical system deflects the beam vertically and controls the amplitude axis of the display. The horizontal system deflects the beam horizontally and controls the time axis of the display. The trigger system turns the beam on and off and synchronizes the display to the input signal.

[ ] Set the scope and signal generator according to the settings shown in Table 1.4. Connect the signal generator output (B-4) to the scope channel 1 input (C-8). If you do not see a straight line and a stationary sine wave on the screen within one minute, call a teaching assistant.

The intensity knob (C-1) controls the scope's power and display brightness. It turns clockwise, with some difficulty and an audible click, to turn on the scope. If the knob is set to its midpoint and the display remains blank after 15 seconds, one of the other knobs or switches is set wrong. The focus of the display is better at lower intensity levels, so the intensity should be set as low as possible for comfortable viewing. Do not set the intensity so low that the display is difficult to see. The focus knob (C-2) should be adjusted after you have selected the proper intensity.

[ ] Adjust the scope intensity and focus at this time.

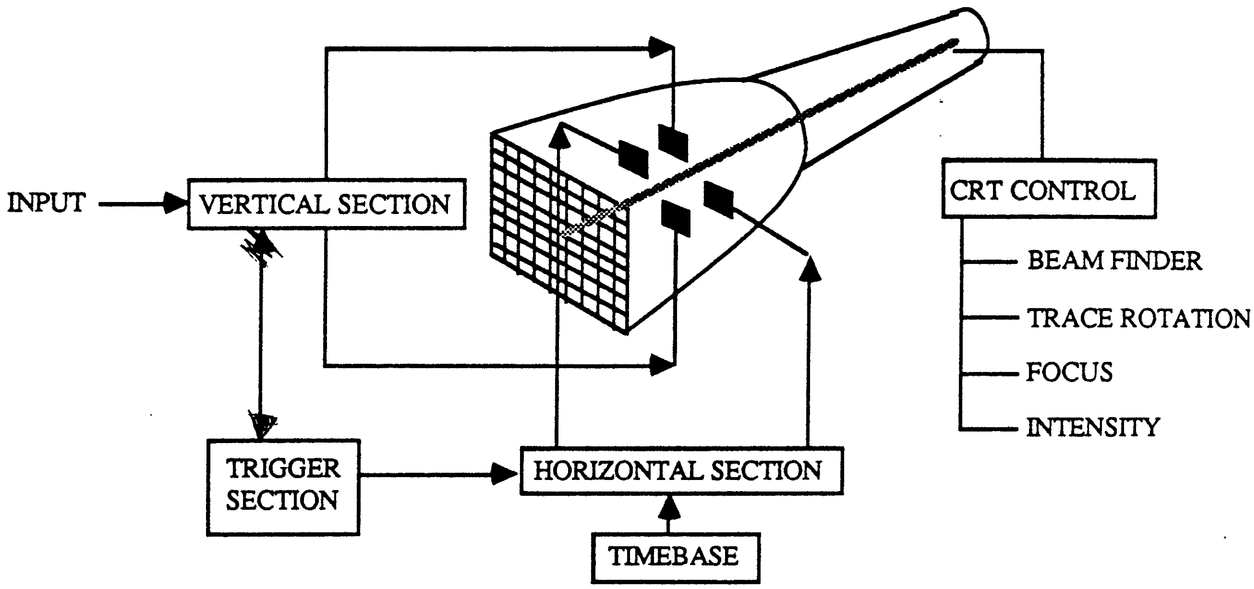


Figure 1.5 - Functional diagram of oscilloscope

OSCILLOSCOPE		GENERATOR	
INTENSITY	midpoint	LINE	in
FOCUS	midpoint	VERNIER	1
		AMPLITUDE	midpoint
VERTICAL POSITION (2)	midpoint	DC OFFSET	fully clockwise
VAR SENS (2)	fully clockwise	FUNCTION	sine
VOLTS/CM (2)	0.5 V	RANGE	1K
AC GND DC (2)	AC		
MODE	dual		
INV CH2	out		
HORIZONTAL POSITION	midpoint		
VAR SWEEP	fully clockwise		
TIME/CM	1 mS		
MAG X5/X1	out		
TRIG LEVEL	midpoint		
BRIGHT LINE	out		
CH1	in		
CH2	out		
AC	in		
DC	out		
+/-	out		

Table 1.4 - Initial Equipment Settings

The vertical system supplies the Y axis, or vertical, information for the graph on the CRT screen. It produces the voltages which deflect the electron beam and provides internal signals for the trigger circuit. Your scope has two input channels, with a set of vertical controls for each, and can display both channels simultaneously.

You will use CH1 (C-8) and CH2 (C-8) as the inputs to your scope. The two BNC connectors (C-3) are also connected to the inputs and are used with special probes which are not needed for this lab.

Both input signals should be visible if the vertical position knobs (C-18) are set to their midpoints.

[ ] Observe what happens as you turn both vertical position knobs. Position the sine wave at the center of the screen.

Five different ways of displaying the two input channels can be selected using the mode switch (C-20). You can select channel 1 alone (CH1), channel 2 alone (CH2), both channels displayed simultaneously (DUAL), both channels algebraically summed (ADD), or a mode in which channel 1 controls the vertical movement of the electron beam and channel 2 controls its horizontal movement (X-Y). If the mode switch is on ADD and you invert channel 2 (C-19), the scope will display the algebraic difference of the two channels.

[ ] Set the mode switch to CH1. The remainder of these instructions apply only to channel 1.

The vertical sensitivity switch (C-4) changes the vertical scale factor (the voltage value) of the major divisions (centimeters) on the screen from 10 volts/cm to 2 millivolts/cm. With a setting of 0.5 V, each of the eight vertical major divisions represents 0.5 volts and the entire screen can show 4 volts from bottom to top.

[ ] Record the peak-to-peak height (the distance in centimeters from the highest to the lowest point on the waveform) of the sine wave in Table 1.5 for the following vertical sensitivity settings: 10 V, 5 V, 2 V, 1 V, 0.5 V, 0.2 V and 0.1 V. Reset the vertical sensitivity to 0.5 V after you take your data.

The variable sensitivity knob (C-21) multiplies the vertical scale factor by up to 2.5. This allows a maximum vertical scale factor of 25 V/cm. The measurements you will be making in this lab call for an absolute measurement of voltage. <u>YOU MUST KEEP THE VARIABLE SENSITIVITY KNOBS TURNED TO THEIR CALIBRATED (CLOCKWISE) POSITIONS UNLESS TOLD OTHERWISE!</u> Since these knobs are a major source of problems in this lab, you must check that they are calibrated at the beginning of each lab session.

[ ] Observe what happens when you turn the variable sensitivity knob and turn it back to its calibrated position.

The input coupling switch (C-5) lets you control how the input signal is connected. DC input coupling lets you see all of the components of the input signal. AC coupling blocks any constant signal component and permits only the alternating portion to be displayed. For frequencies below 100 Hz it is necessary to use DC coupling at all times so that the signals are not distorted.

The middle position of the coupling switch is marked GND for ground. Choosing this position disconnects the input signal and displays the scope's ground reference level. With this switch in the GND position, the ground reference can be moved to a convenient point on the screen with the vertical position knob. Any display in AC or DC mode can then be interpreted with respect to this ground position.

[ ] Set the input coupling to GND and move the line so that there are seven major divisions above it. Change the input coupling to DC and measure the AC and DC

parts of the signal for the following vertical sensitivity settings: 10 V, 5 V, 2 V, and 1 V. The AC part of the signal is measured from the highest point on the waveform to the lowest point. This is called a peak-to-peak measurement. The DC part of the signal is measured from the ground reference point (you set it to 1 cm. from the bottom of the screen) to the center of the waveform (for symmetric waveforms such as sine waves).

[ ] Set the sensitivity back to 0.5 V, set the coupling back to AC, and position the waveform in the center of the screen.

To draw a graph, the scope needs horizontal as well as vertical data. The horizontal system of your scope supplies this data by providing the voltage which moves (or sweeps) the electron beam horizontally at a constant speed. Because the speed is calibrated with time, the horizontal system is often called the time base.

Like the vertical position knobs, there is a horizontal position knob (C-12). This single knob changes the horizontal position of both the input channels.

[ ] Observe what happens as you turn the horizontal position knob. Position the sine wave so that you can see its starting point at the left side of the screen.

The sweep speed switch (C-9) lets you select the speed at which the beam sweeps across the screen (from 0.2 seconds/cm to 0.5 microseconds/cm). It allows you to look at longer or shorter time intervals of the input signal. Like the vertical sensitivity switch, its markings refer to the screen's horizontal scale factor. If the sweep speed is set to 1 mS, each horizontal major division equals one millisecond and the total screen displays a 10 mS time interval.

[ ] Record the period (in centimeters) of the sine wave for the following sweep speed settings: 0.1 mS, 0.2 mS, 0.5 mS, 1 mS, 2 mS, 5 mS, and 10 mS. Set the sweep speed back to 1 mS.

The variable sweep knob (C-11) multiplies the horizontal scale factor by up to 2.5. This makes the slowest possible sweep 0.5 S/cm. The measurements you will be making in this lab call for an absolute measurement of time. <u>YOU MUST KEEP THE VARIABLE SWEEP KNOB TURNED TO ITS CALIBRATED (CLOCKWISE) POSITION UNLESS TOLD OTHERWISE!</u> Since this knob is a major source of problems in this lab, you must check that it is calibrated at the beginning of each lab session.

[ ] Observe what happens when you turn the variable sweep knob and return it to its calibrated position.

Your scope can horizontally magnify the display and stretch the waveforms far beyond the displayable limits of the CRT. The magnify switch (C-13) produces a sweep five times faster than the sweep speed setting. For example, using the 50 µS setting with magnification will give you 10 µS/cm. This magnification provides greater precision when measuring fast voltage changes and allows a maximum sweep rate of 100 nanoseconds per centimeter. YOU MUST KEEP THE MAGNIFICATION OFF UNLESS TOLD OTHERWISE.

[ ] Press the magnify switch, observe what happens, and return it to the out position.

The phosphor on the inside of the CRT glows for only a few milliseconds after the electron beam hits it. The display looks constant because the scope repeats the sweep across the screen at a rate faster than the eye can detect. The display would be a hopeless jumble of lines if each sweep did not start at exactly the same point on the waveform. The trigger system insures that the start of each sweep is synchronized to the waveform being displayed. Fig. 1.6 shows 3 consecutive displays of a waveform.

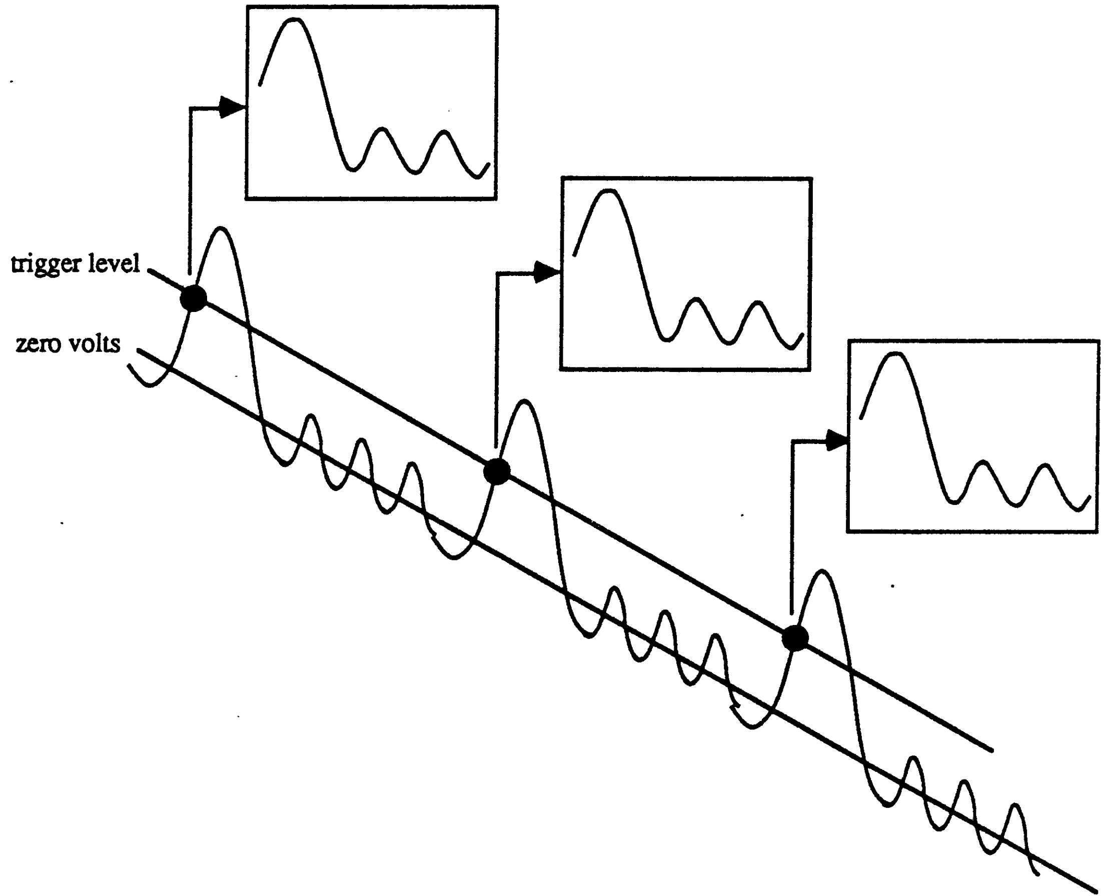


Figure 1.6 - Oscilloscope waveform display

The trigger point, the point at which a sweep is started, is defined by the level knob (C-10) and slope switch (C-14). The slope switch determines whether the trigger point is found on the rising (+) or falling (-) slope of the signal. The level knob sets the voltage of the trigger point.

[ ] Press the trigger slope button, observe what happens to the display, and return it to the out position. Observe what happens as you slowly turn the trigger level knob. Set the trigger level so that the displayed sine wave starts at the center of the waveform.

The trigger source switches (C-16) select CH1 or CH2 as the input to the trigger system. The scope will trigger from an external source (C-6) if both buttons are pressed. The trigger system must be connected to an active signal which continuously provides trigger points. Otherwise, the scope's display will be meaningless. Be careful not to have the display mode set to CH1 with a CH2 trigger source or vice versa.

[ ] Push the CH2 switch and observe what happens.

The trigger's coupling switches (C-15) work the same way as those for the vertical channels. By using the AC or DC buttons you can trigger from the alternating portion of the signal or from the total signal. These buttons have no effect if the trigger source is taken from an AC coupled input channel.

The trigger mode switch (C-17) selects one of two display modes. With "Bright Line Off" (switch in), a sweep will not be started unless there is a trigger signal present. Otherwise, the screen will be blank. With "Bright Line On" (switch out) there should always be a display on the screen because a timer starts running at the end of each sweep. If another trigger isn't found before the timer runs out, a trigger is generated anyway causing whatever is on the input channel to be displayed. Having the trigger mode switch out lets you observe signals with changing amplitudes without completely losing the display. However, if the trigger frequency is below 50 Hz, the scope will automatically trigger before the next trigger comes from the input. This will make the display unstable. YOU MUST KEEP THE TRIGGER MODE SWITCH OUT UNLESS TOLD OTHERWISE.

[ ] With the triggering still set to CH2, press the trigger mode switch several times and observe what happens. Return the trigger mode switch to the out position and set the trigger source back to CH1.

Part 5 - The Signal Generator

Your signal generator can produce signals from 0.1 Hz to 1 MHz. The signal amplitude is adjustable up to 20 volts peak-to-peak (20 Vp-p) with an adjustable DC offset of up to 10 V positive or negative. The generator has a 600 ohm output impedance (see Figure 1.7) which will affect your selection of resistor values in several experiments.

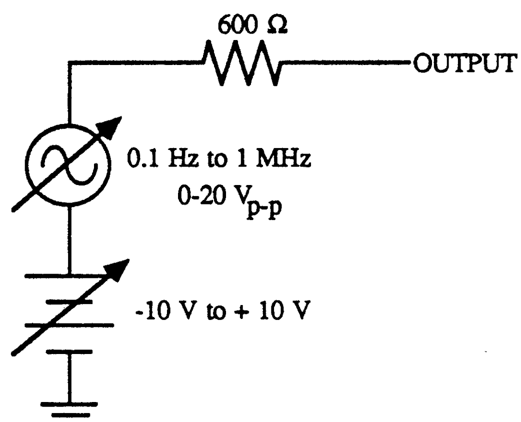


Figure 1.7 - Functional circuit of signal generator

With the three function switches (B-7) you can choose a sine, square, or triangle wave as the output signal.

[ ] Observe what happens as you push each of the function buttons (B-7) and set the function back to a sine wave. The range switches (B-8) allow you to choose base frequencies of 0.1 Hz to 100 KHz.

[ ] Observe what happens as you push each of the range switches and set the range back to 1 KHz. The vernier (B-2) acts as a multiplier on the selected range and allows an order of magnitude increase over the base frequency.

[ ] Observe what happens as you slowly turn the vernier from 1 to 10 and set it back to 1.

The generator also has two knobs which control the amplitude (B-5) and DC offset (B-6) of the signal. You can think of the signal as having an AC (time varying) component and a DC (constant) component, both of which are individually controlled. The amplitude knob controls the top to bottom height of a waveform while the DC offset controls the constant displacement of the center of the waveform from ground. See Fig. 1.8 for an illustration.

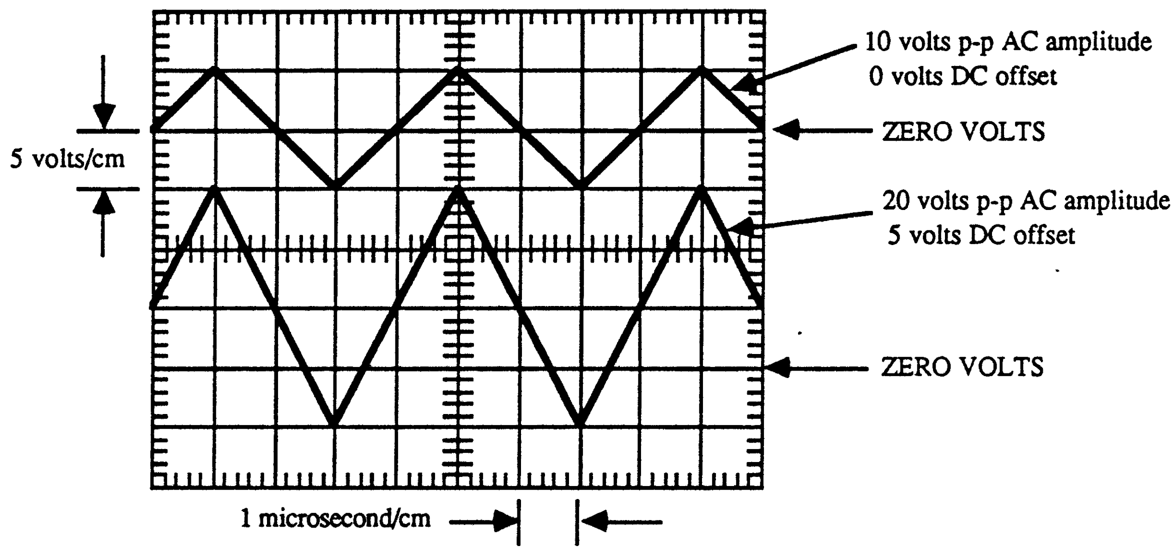


Figure 1.8 - Signal generator output with offset

[ ] Use the scope's input coupling switch and vertical position knob to set ground at the center of the screen. Set the coupling to DC and the sensitivity to 5 V/cm.
(1) Observe what happens as you turn the DC offset knob. Leave it at its midpoint.
(2) Observe what happens as you turn the amplitude knob. Leave it at its midpoint.
(3) Repeat (1) and (2) again with the scope AC coupled.

The signal generator has two output terminals. The pulse output (B-3) provides a pulse that is synchronized with the waveform and can be used to synchronize the scope display with the beginning of each generator waveform. You will normally use the waveform output (B-4) when using the signal generator.

[ ] Move the test lead from the waveform to the pulse output, observe the pulse signal, and return the test lead to the waveform output.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE LEAVING.

Questions

Instructions:

The answers to the lab questions need be no more than a few sentences each with the exception of question 7. If you refer to data, indicate which table, etc. you are referring to. Points will be deducted for poorly written answers.

1. List the RSB connections you would make to get the following resistances: 500 ohms, 8.2 M, 44 K, 7 ohms, 250 K, 180 ohms, 59 ohms, 60 ohms, 300 K, 4 M, 10 K, 4.7 K, 6 K.
2. When you performed the DMM measurements of resistance, what was your most accurate measurement for each resistance and on what range was it made? What should have been the value of each resistance? By what percentage was each resistance less or greater than what it should have been?
3. Why was the DMM reading wrong when only one test lead was used?
4. What was the most accurate voltage measurement you made of the four power supply jacks and on what range was it made? By what percentage was each of the power supply voltages different from what it should be?
5. What was the effect of turning the variable sensitivity knob on your oscilloscope? What happened as the vertical sensitivity was increased with AC coupling? With DC coupling?
6. What was the effect of turning the oscilloscope's variable sweep knob? What was the effect of turning on the magnification? Make a table of the actual period (centimeters times setting) you measured for each of the horizontal sweep settings.
7. Explain how the trigger circuitry of an oscilloscope works. Specifically answer what happens when you change the oscilloscope's trigger slope and trigger level? Explain what happened when you selected CH2 and changed the trigger mode in the lab?

EEAP 243 LAB 1 EVALUATION

NAME (print)______________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

My partner's name is ____.

I am in the Tuesday/Wednesday/Thursday section at 12:30/2:45/3:30/7:00.

Question #2

What is the frequency _______________, AC amplitude _______________, and DC offset _______________ of the pictured signal?

EEAP 243

NAMES: ______________________________

Lab 1 Data

DMM range	200	2k	20k	200k	2M	20M
40 and 7						
100 and 50						
1K and 800						
2K and 200						
50K and "common"						
900K and 10K						
5M and 500K						

Table 1.1 - RSB measurements

+variable	
+15	
-15	
+5	
COM	

Table 1.2 - Ungrounded DMM measurements

DMM range	200mV	2	20	200	2000
+15					
-15					
+variable					
-variable					
+5					

Table 1.3 - DMM power supply measurements

sensitivity setting (volts/cm)	peak-peak voltage (cm)
10	
5	
2	
1	
0.5	
0.2	
0.1	

should all be the same. Will not be

Table 1.5 - Vertical sensitivity measurements

sensitivity setting (volts/cm)	AC part (volts p-p)	DC part (volts)
10		
5		
2		
1		
0.5		
0.2		
0.1		

Table 1.6 - DC coupled measurements

sweep setting (mS/cm)	period (cm)
10	
5	
2	
1	
0.5	
0.2	
0.1	

Table 1.7 - DC coupled measurements

Library of Congress Cataloging-in-Publication Data

Smith, Ralph Judson.
Electronics: circuits and devices.

Includes index.
1. Electronics. I. Title.

TK7816.S6 1987 621.381 86-28910
ISBN 0-471-84446-2

Printed in the United States of America

10 9 8 7 6 5 4 3 2

CHAPTER **4**

Cathode-Ray Tubes

Electron Motion

Cathode-Ray Tubes

Oscilloscopes

The discovery of cathode rays a century ago marked the beginning of the electronic era, and the invention of the multielectrode vacuum tube brought electronics into our daily living. As we learned to build efficient devices for generating and controlling streams of electrons, these electron tubes were applied in communication, entertainment, industrial control, and instrumentation. In many of these applications, the tube has been replaced by the semiconductor devices emphasized in the remainder of this book. However, sophisticated versions of the basic cathode-ray tube are widely used in oscilloscopes, data display devices, television cameras and receivers, and radar scanners.

In this chapter we study some of the physical principles that underlie the operation of electronic devices. First we examine the behavior of electrons in a vacuum and derive the equations for motion in electric and magnetic fields. Then we consider electron emission, acceleration, and deflection in a cathode-ray tube. Finally, we see how cathode-ray oscilloscopes can be used for precise observations over a wide range of conditions.

ELECTRON MOTION

The model of the electron as a negatively charged particle of finite mass but negligible size is satisfactory for many purposes. Based on many careful measurements, the accepted values for charge and mass of the electron are

$$e = 1.602 \times 10^{-19}\ \text{C} \cong 1.6 \times 10^{-19}\ \text{C}$$

$$m = 9.109 \times 10^{-31}\ \text{kg} \cong 9.1 \times 10^{-31}\ \text{kg}$$

In contrast, the hydrogen ion, which carries a positive charge of the same magnitude, has a mass approximately 1836 times as great. If the mass, charge, and initial velocity are known, the motion of individual electrons and ions in electric and magnetic fields can be predicted using Newton's laws of mechanics.

Motion in a Uniform Electric Field

A uniform electric field of strength $\mathcal{E}$ is established between the parallel conducting plates of Fig. 4.1a by applying a potential difference or voltage. By definition (Eq. 1-5)

$$\mathcal{E} = -\frac{dv}{dl} = -\frac{V_b - V_a}{L}\ \text{volts/meter} \qquad (4\text{-}1)$$

if the spacing is small compared to the dimensions of the plates.

By definition (Eq. 1-4), the electric field strength is the force per unit positive charge. Therefore, the force in newtons on a charge q in coulombs is

$$\mathbf{f} = q\mathcal{E} \qquad (4\text{-}2)$$

In Fig. 4.1b, $V_b > V_a$, $V_b - V_a$ is a positive quantity, and the electric field is negative (directed in the $-x$ direction). Considering the energy dw gained by a charge q moving a distance dl against the force of the electric field (Eq. 1-3), the voltage of point b with respect to point a is

$$V_{ba} = \frac{1}{q}\int_a^b dw = \frac{1}{q}\int_a^b f\,dl = \frac{1}{q}\int_a^b q(-\mathcal{E})\,dl = -\int_a^b \mathcal{E}\,dl \qquad (4\text{-}3)$$

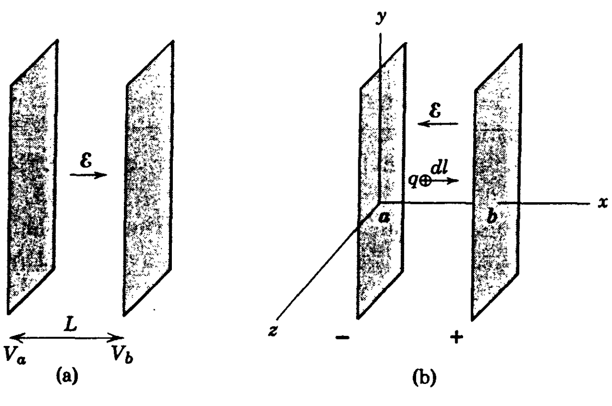


Figure 4.1 An electric charge in a uniform electric field.

In words, the voltage between any two points in an electric field is the line integral of the electric field strength. Equation 4-3 is the corollary of Eq. 4-1.

In general, an electron of charge $-e$ in an electric field $\mathcal{E}$ experiences a force

$$f = (-e)(\mathcal{E}) = -e\,\mathcal{E} = ma$$

and an acceleration

$$a = \frac{f}{m} = -\frac{e\mathcal{E}}{m} \tag{4-4}$$

We see that an electron in a uniform electric field moves with a constant acceleration. We expect the resulting motion to be similar to that of a freely falling mass in the earth's gravitational field. Where u is velocity and x is displacement, the equations of motion in a field $\mathcal{E}_x$ are

$$u_x = \int_0^t a_x\,dt = a_x t + U_O = -\frac{e\,\mathcal{E}_x}{m}t + U_O \tag{4-5}$$

$$x = \int_0^t u_x\,dt = \frac{a_x t^2}{2} + U_O t + X_O = -\frac{e\,\mathcal{E}_x}{2m}t^2 + U_O t + X_O \tag{4-6}$$

Application of these equations is illustrated in Example 1.

EXAMPLE 1

A voltage V_D is applied to an electron deflector consisting of two horizontal plates of length L separated a distance d, as in Fig. 4.2. An electron with initial velocity U_O in the positive x direction is introduced at the origin. Determine the path of the electron and the vertical displacement at the time it leaves the region between the plates.

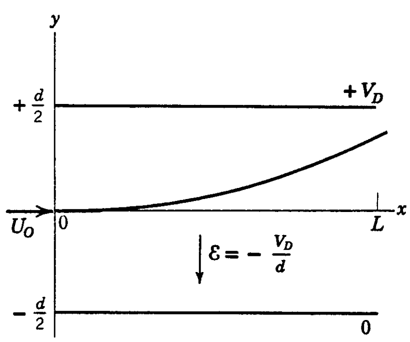


Figure 4.2 Calculation of electron deflection in a uniform electric field.

Assuming no electric field in the x direction and a uniform electric field $\mathcal{E}_y = -V_D/d$, the accelerations are

$$a_x = 0 \qquad \text{and} \qquad a_y = -\frac{e\,\mathcal{E}_y}{m} = \frac{eV_D}{md}$$

There is no acceleration in the x direction and the electron moves with constant velocity to the right. There is a constant upward acceleration and the electron gains a vertical component of velocity. The path is determined (Eq. 4-6) by

$$x = U_O t \qquad \text{and} \qquad y = -\frac{e\,\mathcal{E}_y}{2m}t^2 = \frac{eV_D}{2md}t^2$$

Eliminating t,

$$y = \frac{eV_D}{2mdU_O^2}x^2 \tag{4-7}$$

or the electron follows a parabolic path.

At the edge of the field, $x = L$ and the vertical displacement is

$$y_L = \frac{eV_D}{2mdU_O^2}L^2$$

If V_D exceeds a certain value, displacement y exceeds $d/2$ and the electron strikes the upper plate.

Energy Gained by an Accelerated Electron

When an electron is accelerated by an electric field it gains kinetic energy at the expense of potential energy, just as does a freely falling mass. Since voltage is energy per unit charge, the potential energy "lost" by an electron in "falling" from point a to point b is, in joules,

$$\text{PE} = W = q(V_a - V_b) = -e(V_a - V_b) = eV_{ba} \tag{4-8}$$

where V_{ba} is the potential of b with respect to a.

The kinetic energy gained, evidenced by an increase in velocity, is just equal to the potential energy lost, or

$$\text{KE} = \tfrac{1}{2}mu_b^2 - \tfrac{1}{2}mu_a^2 = \text{PE} = eV_{ba} \tag{4-9}$$

This important equation indicates that the kinetic energy gained by an electron in an electric field is determined only by the voltage difference between the initial and final points; it is independent of the path followed and the electric field configuration. (We assume that the field does not change with *time*.)

Frequently we are interested in the behavior resulting from a change in the energy of a single electron. Expressed in joules, these energies are very small; a more convenient unit is suggested by Eq. 4-8. An *electron volt* is the potential energy lost by 1 electron falling through a potential difference of 1 volt. By Eq. 4-8,

$$1 \text{ eV} = (1.6 \times 10^{-19} \text{ C})(1 \text{ V}) = 1.6 \times 10^{-19} \text{ J} \tag{4-10}$$

For example, the energy required to remove an electron from a hydrogen atom is about 13.6 eV. The energy imparted to an electron in a linear accelerator may be as high as 24 BeV (24 billion electron volts).

For the special case of an electron starting from rest ($u_a = 0$) and accelerated through a voltage V, Eq. 4-9 can be solved for $u_b = u$ to yield

$$u = \sqrt{2(e/m)V} = 5.93 \times 10^5 \sqrt{V} \text{ m/s} \tag{4-11}$$

In deriving Eq. 4-11 we assume that mass m is a constant; this is true only if the velocity is small compared to the velocity of light, $c \cong 3 \times 10^8$ m/s.

EXAMPLE 2

Find the velocity reached by an electron accelerated through a voltage of 3600 V.

Assuming that the resulting velocity u is small compared to the velocity of light c, Eq. 4-11 applies and

$$u = 5.93 \times 10^5\sqrt{3600} = 3.56 \times 10^7 \text{ m/s}$$

In this case,

$$\frac{u}{c} = \frac{3.56 \times 10^7}{3 \times 10^8} \cong 0.12$$

At the velocity of Example 2 the increase in mass is appreciable, and the actual velocity reached is about 0.5% lower than that predicted. For voltages above 4 or 5 kV, a more precise expression should be used. (See Problem 1.)

Motion in a Uniform Magnetic Field

One way of defining the strength of a magnetic field (Eq. 1-6) is in terms of the force exerted on a unit charge moving with unit velocity normal to the field. In general, the force in newtons is

$$\mathbf{f} = q\mathbf{u} \times \mathbf{B} \tag{4-12}$$

where q is charge in coulombs and $\mathbf{B}$ is magnetic flux density in teslas (or webers/meter^2). The vector cross product is defined by the right-hand screw rule illustrated in Fig. 4.3. Rotation from the direction of $\mathbf{u}$ to the direction of $\mathbf{B}$ advances

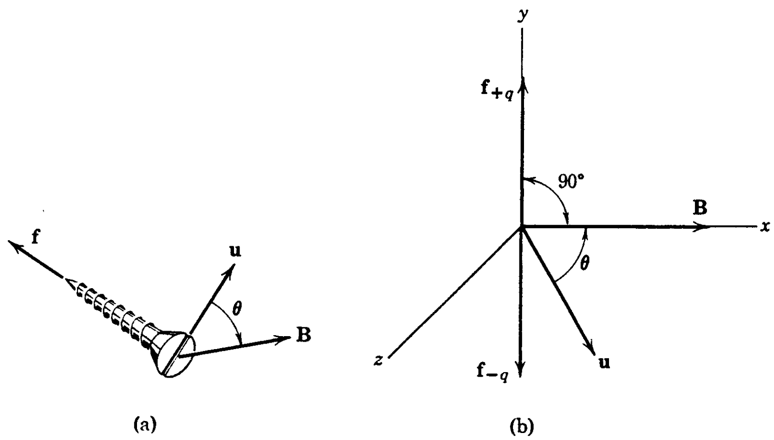


Figure 4.3 The right-hand screw rule defining the vector cross product.

the screw in the direction of $\mathbf{f}$. The magnitude of the force is $quB \sin \theta$ and the direction is always normal to the plane of $\mathbf{u}$ and $\mathbf{B}$.

Equation 4-12 is consistent with three observable facts:

1. A charged particle at rest in a magnetic field experiences no force ($u = 0$).
2. A charged particle moving parallel with the magnetic flux experiences no force ($\theta = 0$).
3. A charged particle moving with a component of velocity normal to the magnetic flux experiences a force that is normal to u and therefore the magnitude of velocity (or speed) is unchanged.

From the third statement we conclude that no work is done by a magnetic field on a charged particle and its kinetic energy is unchanged.

Figure 4.4 shows an electron entering a finite region of uniform flux density. For an electron ($q = -e$) moving in the plane of the paper ($\theta = 90°$), the force is in the direction shown with a magnitude

$$f = eU_O B \tag{4-13}$$

Applying the right-hand rule, we see that the initial force is downward and, therefore, the acceleration is downward and the path is deflected as shown. A particle

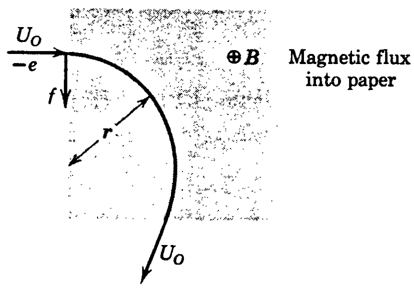


Figure 4.4 Electron motion in a uniform magnetic field.

moving with constant speed and constant normal acceleration follows a circular path. The centrifugal force due to circular motion must be just equal to the centripetal force due to the magnetic field, or

$$m\frac{U_O^2}{r} = eU_OB$$

and the radius of the circular path is

$$r = \frac{mU_O}{eB} \tag{4-14}$$

The dependence of radius on the mass of the charged particle is the principle underlying the *mass spectrograph* for analyzing unknown substances.

Motion in Combined $\mathcal{E}$ and B Fields

In the general case, both electric and magnetic fields are present and exert forces on a moving charge. The total force is

$$\mathbf{f} = q(\mathcal{E} + \mathbf{u} \times \mathbf{B}) \tag{4-15}$$

The special cases previously described can be derived from this general relation. If both $\mathcal{E}$ and B are present, the resulting motion depends on the relative orientation of $\mathcal{E}$ and B, and also on the initial velocities. An interesting case is that in which an electron starts from rest in a region where $\mathcal{E}$ and B are mutually perpendicular. The electron is accelerated in the direction of $-\mathcal{E}$, but as soon as it is in motion there is a reaction with B and the path starts to curve. Curving around, the electron is soon traveling in the $+\mathcal{E}$ direction and experiences a decelerating force that brings it to rest. Once the electron is at rest, the cycle starts over; the resulting path is called a *cycloid* and resembles the path of a point on a wheel as it rolls along a line.

If the fields are not uniform, mathematical analysis is usually quite difficult. A case of practical importance is the "electron lens" used in electron microscopes and for electric-field focusing of the electron beam in the cathode-ray tube.

CATHODE-RAY TUBES

The television picture tube and the precision electron display tube used in oscilloscopes are modern versions of the evacuated tubes used by Crookes and Thomson to study cathode rays. The electrons constituting a "cathode ray" have little mass or inertia, and therefore they can follow rapid variations; their ratio of charge to mass is high, so they are easily deflected and controlled. The energy of high-velocity electrons is readily converted into visible light; therefore, their motion is easily observed. For these reasons, the C-R tube or CRT is a unique information processing device; from our standpoint, it is also an ingenious application of the principles of electron motion and electron emission.

Electron Emission

The Bohr model of the atom is satisfactory for describing how free electrons can be obtained in space. As you may recall, starting with the hydrogen atom consisting of a single proton and a single orbital electron, models of more complex atoms are built up by adding protons and neutrons to the nucleus and electrons in orbital groups or shells. In a systematic way, shells are filled and new shells started. The chemical properties of an element are determined by the *valence* electrons in the outer shell. Good electrical conductors like copper and silver have one highly mobile electron in the outer shell.

Only certain orbits are allowed, and atoms are stable only when the orbital electrons have certain discrete energy levels. Transfer of an electron from an orbit corresponding to energy W_1 to an orbit corresponding to a lower energy W_2 results in the radiation of a *quantum* of electromagnetic energy of frequency f given by

$$W_1 - W_2 = hf \tag{4-16}$$

where h is Planck's constant $= 6.626 \times 10^{-34}\ \text{J}\cdot\text{s}$.

The energy possessed by an orbital electron consists of the kinetic energy of motion in the orbit and the potential energy of position with respect to the positive ion representing all the rest of the neutral atom. If other atoms are close (as in a solid), the energy of an electron is affected by the charge distribution of the neighboring atoms. In a crystalline solid, there is an orderly arrangement of atoms and the permissible electron energies are grouped into *energy bands*. Between the permissible bands there may be ranges of energy called *forbidden bands*.

For an electron to exist in space it must possess the energy corresponding to motion from its normal orbit out to an infinite distance; the energy required to move an electron against the attractive force of the net positive charge left behind is the *surface barrier energy* W_B. Within a metal at absolute zero termperature, electrons possess energies varying from zero to a maximum value W_M. The minimum amount of work that must be done on an electron before it is able to escape from the surface of a metal is the *work function* W_W where

$$W_W = W_B - W_M \tag{4-17}$$

For copper, $W_W = 4.1$ eV, while for cesium $W_W = 1.8$ eV.

The energy required for electron emission may be obtained in various ways. The beta rays given off spontaneously by *radioactive* materials (along with alpha and gamma rays) are emitted electrons. In *photoelectric* emission, the energy of a quantum of electromagnetic energy is absorbed by an electron. In *high-field* emission, the potential energy of an intense electric field causes emission. In *secondary* emission, a fast-moving electron transfers its kinetic energy to one or more electrons in a solid surface. All these processes have possible applications, but the most widely used process is *thermionic* emission in which thermal energy is added by heating a solid conductor.

The temperature of an object is a measure of the kinetic energy stored in the motion of the constituent molecules, atoms, and electrons. The energies of the individual constituents vary widely, but an average energy corresponding to temperature T can be expressed as kT, where $k = 8.62 \times 10^{-5}$ eV/K is the Boltzmann constant. At a temperature above absolute zero, the distribution of electron energy in a metal is modified and some electrons possess energies appreciably above W_M. Statistical analysis shows that the probability of an electron receiving sufficient energy to be emitted is proportional to $e^{-W_W/kT}$. At high temperatures, many electrons possess energies greater than W_B and emission current densities of the order of 1 A/cm^2 are practical. Commercial cathodes make use of special materials that combine low work function with high melting point.

CRT Components

The essential components of a CRT are shown in Fig. 4.5; an *electron gun* produces a focused beam of electrons, a *deflection system* determines the direction of the beam, and a *fluorescent screen* converts the energy of the beam into visible light.

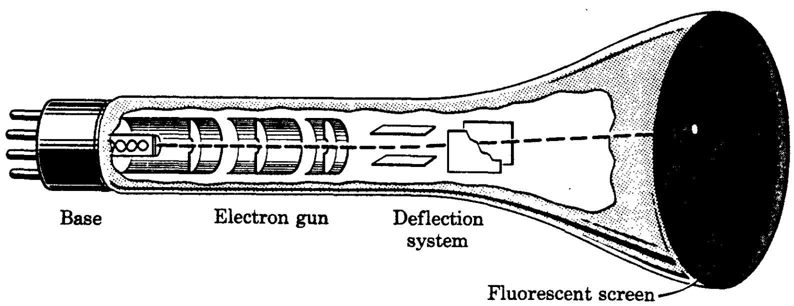


Figure 4.5 The essential components of a cathode-ray tube.

Electron Gun. Electrons are emitted from the hot cathode (Fig. 4.6a) and pass through a small hole in the cylindrical control electrode; a negative voltage (with respect to the cathode) on this electrode tends to repel the electrons and, therefore, the voltage applied controls the intensity of the beam. Electrons passing the control electrode experience an accelerating force due to the electric field established by the positive voltages V_F and V_A on the focusing and accelerating anodes. The space between these anodes constitutes an electron lens (Fig. 4.6b); the electric flux lines and equipotential lines resulting from the voltage difference $V_A - V_F$ provide a precise focusing effect. A diverging electron is accelerated forward by the field, and at the same time it receives an inward component of velocity that brings it back to the axis of the beam at the screen.

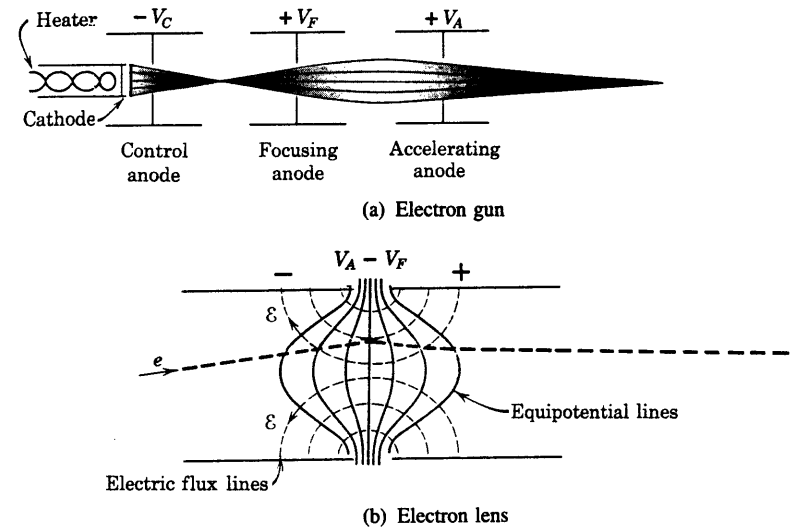


Figure 4.6 An elementary electron gun with electric-field focusing.

Deflection System. In a television picture tube, the beam is moved across the screen 15,750 times per second, creating a picture consisting of 525 horizontal lines of varying intensity. The deflection of the beam may be achieved by a magnetic field or an electric field. Figure 4.7 shows the beam produced in the electron gun entering the vertical deflection plates of an electric-field system.

We can calculate the beam deflection at the screen by using our knowledge of electron motion. For the coordinate system of Fig. 4.7, Eq. 4-11 gives an axial velocity

$$U_z = \sqrt{2eV_A/m} \tag{4-18}$$

where V_A is the total accelerating potential. Within the deflecting field, the parabolic path (Eq. 4-7) is defined by

$$y = \frac{eV_D}{2mdU_z^2}z^2 = kz^2 \tag{4-19}$$

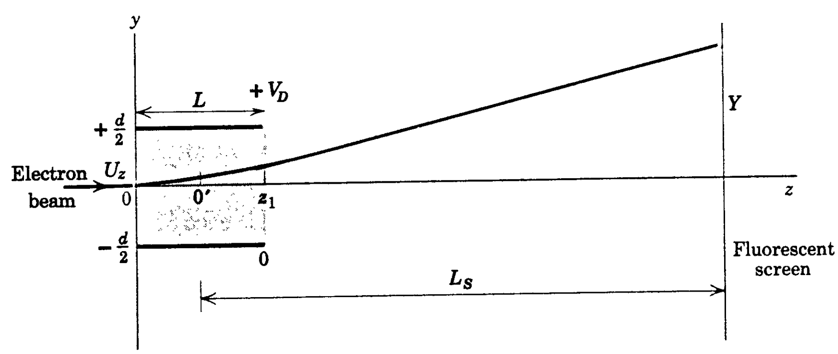


Figure 4.7 An electric-field vertical deflection system.

The slope of the beam emerging from the deflecting field at $z = z_1 = L$ is

$$\frac{dy}{dz} = 2kz = 2kL \tag{4-20}$$

The equation of the straight-line path followed by the beam to the screen is

$$y - y_1 = \frac{dy}{dz}(z - z_1) = 2kL(z - z_1)$$

where $z_1 = L$ and $y_1 = kz_1^2 = kL^2$. Substituting these values and solving,

$$y = 2kL(z - L) + kL^2 = 2kL\left(z - \frac{L}{2}\right) \tag{4-21}$$

Since for $y = 0$, $z = L/2$, Eq. 4-21 leads to the conclusion that the electron beam appears to follow a straight-line path from a virtual source at 0′. At the screen, $z = L_S + L/2$ and (by Eqs. 4-19 and 4-18) the deflection is

$$Y = 2kLL_S = \frac{eV_D LL_S}{mdU_z^2} = \frac{eV_D LL_S}{md} \cdot \frac{m}{2eV_A} = \frac{LL_S}{2dV_A} V_D \tag{4-22}$$

or the vertical deflection at the screen is directly proportional to V_D, the voltage applied to the vertical deflecting plates. A second set of plates provides horizontal deflection.

EXAMPLE 3

Determine the *deflection sensitivity* in centimeters of deflection per volt of signal for a CRT in which $L = 2$ cm, $L_S = 30$ cm, $d = 0.5$ cm, and the total accelerating voltage is 2 kV.

From Eq. 4-22, the deflection sensitivity is

$$\frac{Y}{V_D} = \frac{LL_S}{2dV_A} = \frac{0.02 \times 0.3}{2 \times 0.005 \times 2000}$$

$$= 0.0003 \text{ mV} = 0.03 \text{ cm/V}$$

To obtain a reasonable deflection, say 3 cm, a voltage of 100 V would be necessary. In a practical CRO, amplifiers are provided to obtain reasonable deflections with input signals of less than 0.1 V.

Fluorescent Screen. Part of the kinetic energy of the electron beam is converted into luminous energy at the screen. Absorption of kinetic energy results in an immediate *fluorescence* and a subsequent *phosphorescence*. The choice of screen material depends on the application. For laboratory oscilloscopes, a medium persistence phosphor with output concentrated in the green region is desirable; the eye is sensitive to green and the persistence provides a steady image of a repeated pattern. For color television tubes, short persistence phosphors that emit radiation at various wavelengths are available. For radar screens, a very long persistence is desirable.

OSCILLOSCOPES

The CRT provides a controlled spot of light whose x and y deflections are directly proportional to the voltages on the horizontal and vertical deflecting plates. The cathode-ray oscilloscope (CRO), consisting of the tube and appropriate auxiliary apparatus, enables us to "see" the complex waveforms that are critical in the performance of electronic circuits.

The block diagram of Fig. 4.8 indicates the essential components of a CRO. A signal applied to the "Vert" terminal causes a proportional vertical deflection of the spot; the calibration of the *vertical amplifier* can be checked against an internal calibrating signal. The *attenuator* precisely divides large input voltages. An external *intensity control* varies the accelerating potentials in the electron gun, and a *focus control* determines the potentials on the focusing electrodes.

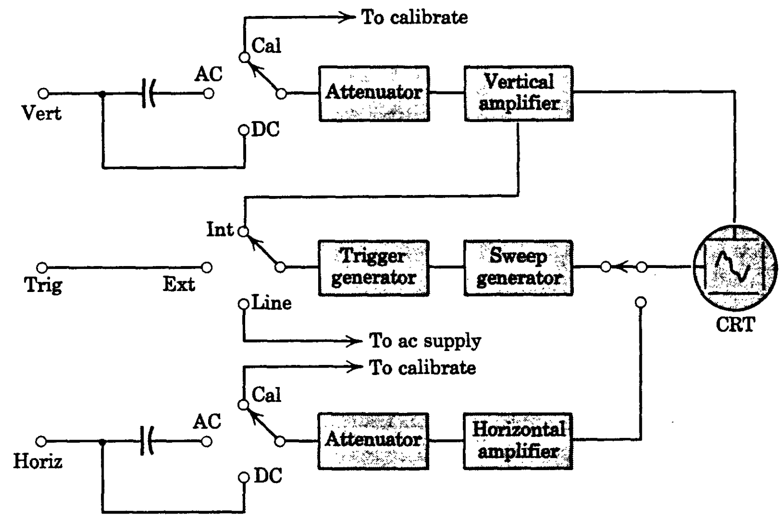


Figure 4.8 Basic components of a cathode-ray oscilloscope.

The *sweep generator* causes a horizontal deflection of the spot proportional to time; it is *triggered* to start at the left of the screen at a particular instant on the internal vertical signal ("Int"), an external signal ("Ext"), or the ac supply ("Line"). Instead of the sweep generator, the *horizontal amplifier* can be used to cause a deflection proportional to a signal at the "Horiz" terminal.

The particular point on the triggering waveform that initiates the sawtooth sweep is determined by setting the *slope* and *level* controls. In Fig. 4.9, the input to the vertical amplifier provides the triggering waveform. The level control determines the instantaneous voltage level at which a trigger pulse is produced by the trigger generator. With the slope switch in the "+" position, triggering occurs only on a positive slope portion of the triggering waveform. By proper adjustment of these two controls, it is possible to initiate the sweep consistently at almost any point in the triggering waveform. For example, if slope is set to "−" and level is set to "0," the sweep will begin when the triggering signal goes down through zero.

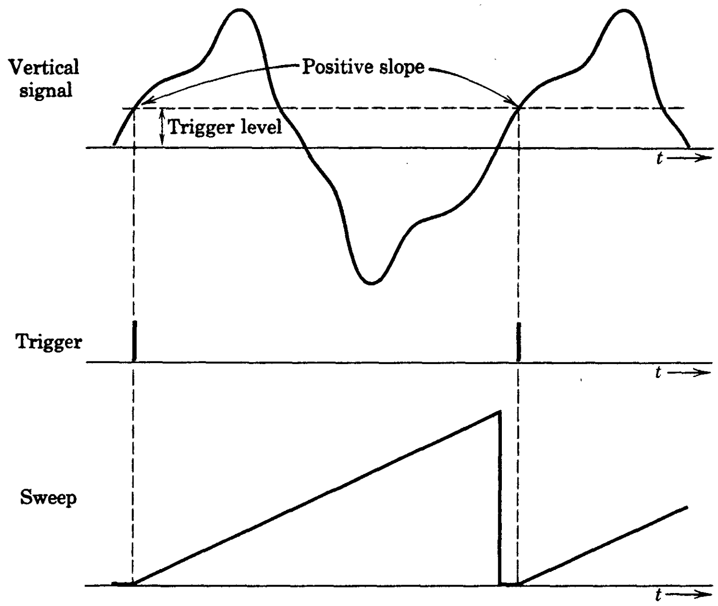


Figure 4.9 Trigger operation.

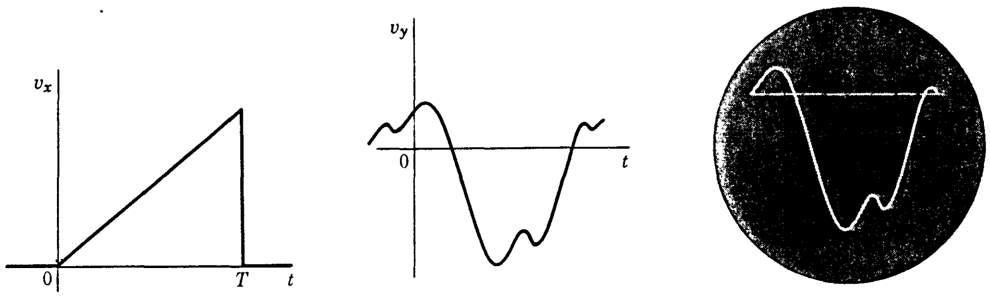
CRO Applications

In its practical form, with controls conveniently arranged for precise measurements over a wide range of test conditions, the CRO is the most versatile laboratory instrument.

Voltage Measurement. An illuminated scale dividing the screen into 1-cm divisions permits use of the CRO as a voltmeter. With the vertical amplifier sensitivity set at 0.1 V/cm, say, a displacement of 2.5 cm indicates a voltage of 0.25 V. Currents can be determined by measuring the voltage across a known resistance.

Time Measurement. A calibrated sweep generator permits time measurement. With the sweep generator set at 5 ms/cm, two events separated on the screen by 2 cm are separated in time by 10 ms or 0.01 s. By measuring the period of a wave, the frequency can be determined by calculation.

Waveform Display. A special property of the CRO is its ability to display high-frequency or short-duration waveforms. If voltages varying with time are applied to vertical (y) and horizontal (x) input terminals, a pattern is traced out on the screen; if the voltages are periodic and one period is an exact multiple of the other, a stationary pattern can be obtained. A sawtooth wave from the sweep generator (Fig. 4.10a) applied to the x-deflection plates provides an x-axis deflection directly proportional to time. If a signal voltage wave is applied to the vertical-deflection plates, the projection of the beam on the y-axis is directly proportional to the amplitude of this signal. If both voltages are applied simultaneously, the pattern displayed on the screen is the signal as a function of time (Fig. 4.10c). A *blanking circuit* turns off the electron beam at the end of the sweep so the return trace is not visible. Nonrepetitive voltages are made



(a) Sawtooth sweep (b) Signal waveform (c) Oscilloscope pattern

Figure 4.10 Display of a repeated waveform on an oscilloscope.

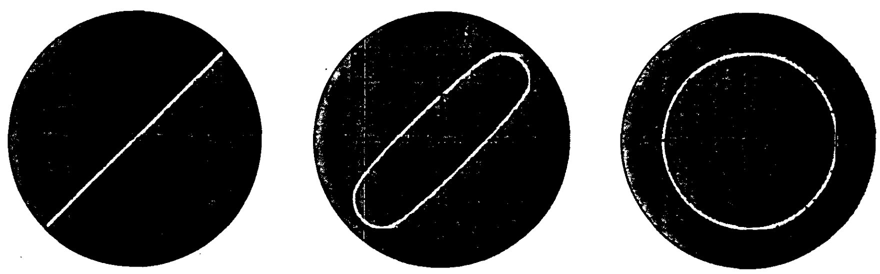
more visible by using a long persistence fluorescent material, or a high-speed camera can be used for a permanent record. New CROs provide digital waveform storage.

***X-Y* Plotting.** The relation between two periodic variables can be displayed by applying a voltage proportional to x to the horizontal amplifier and one proportional to y to the vertical amplifier. The characteristics of diodes or transistors are quickly displayed in this way. The hysteresis loop of a magnetic material can be displayed by connecting the induced voltage (proportional to B) to the vertical amplifier and an iR drop (proportional to H) to the horizontal amplifier. Since the two amplifiers usually have a common internal ground, some care is necessary in arranging the circuits.

Phase-Difference Measurement. If two sinusoids of the same frequency are connected to the X and Y terminals, the phase difference is revealed by the resulting pattern (Fig. 4.11). For applied voltages $v_x = V_x \cos \omega t$ and $v_y = V_y \cos(\omega t + \theta)$, it can be shown that the phase difference is

$$\theta = \sin^{-1}\frac{A}{B} \tag{4-23}$$

where A is the y deflection when the x deflection is zero and B is the maximum y deflection. The parameters of the circuit are useful in determining whether the angle is leading or lagging.



(a) 0° (b) 30° (c) 90°

Figure 4.11 Phase difference as revealed by CRO patterns.

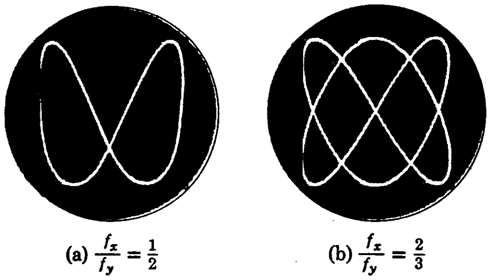


Figure 4.12 Lissajous figures for comparing the frequencies of two sinusoids.

Frequency Comparison. When the frequency of the sinusoid applied to one input is an exact multiple of the frequency of the other input, a stationary pattern is obtained. For a 1:1 ratio, the so-called Lissajous patterns are similar to those in Fig. 4.11. For the 1:2 and 2:3 ratios, the Lissajous figures might be as shown in Fig. 4.12. For a stationary pattern, the ratio of the frequencies is exactly equal to the ratio of the numbers of tangencies to the enclosing rectangle. Patterns can be predicted by plotting x and y deflections from the two signals at corresponding instants of time.

Square-Wave Testing. The unique convenience of a CRO is illustrated in the measurement technique called *square-wave testing*. Any periodic wave can be represented by a Fourier series of sinusoids. As indicated in Fig. 4.13b, the sum of the first three odd harmonics (with appropriate amplitude and phase) begins to approximate a square wave; additional higher harmonics would increase the slope of the leading edge and smooth off the top. If a square-wave input to a device under test results in an output resembling Fig. 4.13c, it can be shown that low-frequency components have been attenuated and shifted forward in phase. If the output resembles Fig. 4.13d, it can be shown that high-frequency components have been attenuated and shifted backward in phase. The frequency response of an amplifier, for example, can be quickly determined by varying the frequency of the square-wave input until these distortions appear; the useful range of the amplifier is bounded by the frequencies at which low-frequency and high-frequency defects appear. As another example, two devices giving similar responses to a square-wave input can be expected to respond similarly to other waveforms.

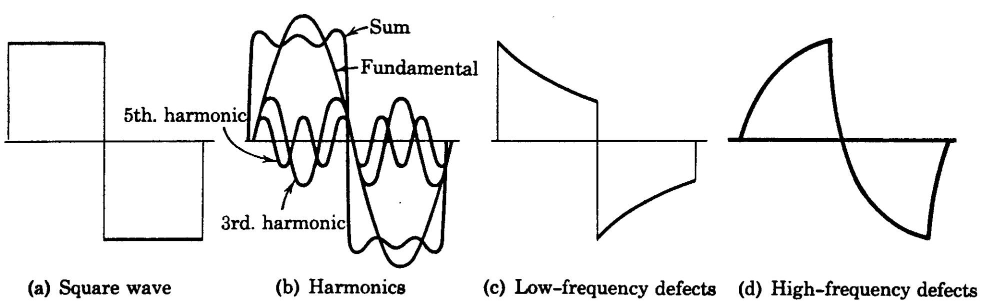


Figure 4.13 Square-wave testing with a CRO.

CRO Features

Every year sees new advances in CRO design as the instrument manufacturers strive to meet new needs of the laboratory and the field by taking advantage of newly developed devices and techniques. Among the features offered by modern CROs are:

Differential Inputs. Each amplifier channel has two terminals in addition to the ground terminal. By amplifying only the difference between two signals, any common signal such as hum is rejected. (See p. 439.)

Optional Probes. To improve the input characteristics of a CRO or to expand its functions, the input stage can be built into a small unit (connected to the CRO by a shielded cable) that can be placed at the point of measurement. *Voltage probes* insert impedances in series with the CRO input to increase the effective input impedance. *Current probes* use transformer action or the Hall effect to convert a current into a proportional voltage for measurement or display.

Dual Channels. The waveforms of two different signals can be displayed simultaneously by connecting the signals alternately to the vertical deflection system. The more expensive *dual beam* feature requires separate electron guns and deflection systems but permits greater display flexibility.

Delayed and Expanded Sweep. An auxiliary delayed sweep with a faster sweep speed displays a magnified version of a selected small portion of a waveform.

Storage. If the input signal is a single, nonrepetitive event, the image can be *stored* by using a long persistence phosphor. By placing a storage mesh directly behind the phosphor and controlling the rate at which the charge pattern leaks off the mesh, a *variable persistence* is obtained.

Sampling. To display signals at frequencies beyond the limits of the CRO components, very short *sample* readings are taken on successive recurrences of the waveform. Each amplitude sample is taken at a slightly later instant on the waveform and the resulting dots appear as a continuous display. With this sampling technique, 18-GHz signals can be displayed.

Digital Readout. The addition of a built-in *microprocessor* provides direct digital readout of time interval, frequency, or voltage in addition to the conventional CRO display. The operator sets two markers to indicate a horizontal or vertical displacement on the waveform; the microprocessor, a computer-on-a-chip, interrogates the function switches and the scale switches, calculates the desired variable, and converts it to digital form for display by light-emitting diodes.

Programmability. The oscilloscope is preeminent in displaying information; the digital computer is preeminent in processing information. The new digitizing oscilloscope is an open-ended instrument that accepts either preprogrammed or user-programmable instructions and into which the user enters his or her choice of parameters, functions, frequency ranges, data reduction operations, and display characteristics by means of a single keyboard just as we enter numbers in a hand-held calculator. It can store, display, measure, and analyze complex signal waveforms.

SUMMARY

- Individual charged particles in electric and magnetic fields obey Newton's laws. For electrons (of primary interest here),

$$\mathbf{f} = -e(\mathcal{E} + \mathbf{u} \times \mathbf{B})$$

- In any electric field, KE gained = PE lost = $W_{ab} = eV_{ab}$.
For an electron starting from rest (and for $V < 4$ kV),

$$u = \sqrt{2(e/m)V} = 5.93 \times 10^5\sqrt{V} \text{ m/s}$$

In a uniform electric field where $\mathcal{E}_x = \mathcal{E}$, $f_x = -e\mathcal{E}$, and

$$a_x = -\frac{e\mathcal{E}}{m} \qquad u_x = -\frac{e\mathcal{E}}{m}t + U_O \qquad x = -\frac{e\mathcal{E}}{2m}t^2 + U_Ot + X_O$$

- In any magnetic field, **f** is normal to **u** and no work is done.
In a uniform magnetic field, the path is circular with $r = mU_O/eB$.
- Electron emission from a solid requires the addition of energy equal to the work function; this energy can be obtained in various ways.
The probability of an electron possessing energy eV_T varies as $e^{-eV_T/kT}$.
- A cathode-ray tube consists of an electron gun producing a focused beam, a magnetic or electric deflection system, and a fluorescent screen for visual display.
For deflecting voltage V_D, the deflection is

$$Y = \frac{LL_s}{2dV_A}V_D$$

- A cathode-ray oscilloscope includes display tube, intensity and focus controls, amplifiers and attenuators, sweep generator, and triggering circuit.
A cathode-ray oscilloscope measures voltage and time, displays waveforms, and compares phase and frequency.

REVIEW QUESTIONS

1. What quantities are analogous in the equations of motion of a mass in a gravitational field and motion of an electron in an electric field?
2. Define the following terms: electron-volt, electron gun, vector cross product, work function, and virtual cathode.
3. Justify the statement that "no work is done on a charged particle by a steady magnetic field."
4. Describe the motion of an electron starting from rest in a region of parallel electric and magnetic fields.
5. Sketch the pattern expected on a CRT screen when the deflection voltages are $v_x = V \sin \omega t$ and $v_y = V \cos 2\omega t$.
6. What is the effect on a TV picture of varying the voltage on the control anode (Fig. 4.6)? On the accelerating anode?
7. Sketch a magnetic deflection system for a CRT.
8. Explain qualitatively the process of thermionic emission.
9. How can a CRO be used to measure voltage? Frequency? Phase?
10. Explain the operation of CRO sweep, trigger, and blanking circuits.

EXERCISES

1. An electron is accelerated from rest by a potential of 200 V applied across a 5-cm distance under vacuum. Calculate the final velocity and the time required for transit. Repeat for a hydrogen ion. Express the energy gained by each particle in electron-volts.
2. In Fig. 4.14, an electron is introduced at point P in an evacuated space. It is accelerated from rest toward anode 1 at voltage V_1 and passes through a small hole at point b. In terms of the given quantities and the properties of an electron:
   (a) What is the acceleration at point a?
   (b) What is the velocity at point b?
   (c) What voltage V_2 would just bring the electron to rest at point c?

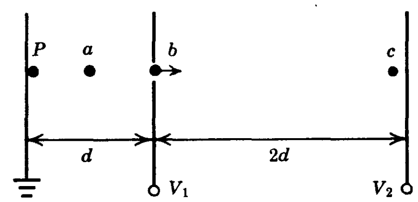


Figure 4.14

3. In a region where $\mathcal{E}$ = 200 V/m, an electron is accelerated from rest. Predict the velocity, kinetic energy gained, displacement, and potential energy lost after 2 ns. Compare the PE lost ($e\Delta V$) and the KE gained ($\frac{1}{2}mu^2$).
4. An electron is to be accelerated from rest to a velocity $u = 12 \times 10^6$ m/s after traveling a distance of 5 cm.
   (a) Specify the electric field required and estimate the time required.
   (b) Repeat part (a) for a hydrogen ion.
   (c) Express the energy gained by each particle in joules.
5. For the electron of Exercise 3, derive expressions for velocity as a function of time and as a function of distance.
6. An electron with an energy of 200 eV is projected at an angle of 45° into the region between two parallel plates carrying a voltage V and separated a distance d = 5 cm. (See Fig. 4.15.)
   (a) If $V = -200$ V, determine where the electron will strike.
   (b) Determine the voltage V at which the electron will just graze the upper plate.

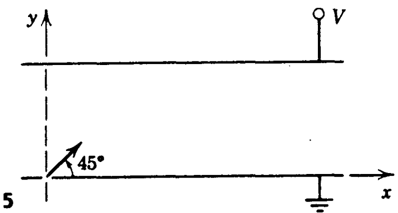


Figure 4.15

7. If the polarity of the upper plate in Fig. 4.15 is reversed so that $V = +200$ V, determine where the electron will strike.
8. Two electrons, e_1 traveling at velocity u and e_2 traveling at velocity $2u$, enter an intense magnetic field directed out of the paper (Fig. 4.16). Sketch the paths of the electrons.

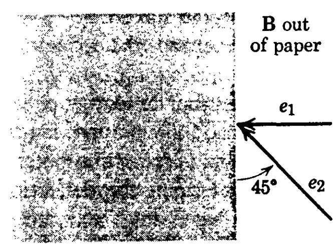


Figure 4.16

9. An electron with a velocity of 30 km/s is injected at right angles to a uniform magnetic field where B = 0.02 T into the paper.
   (a) Sketch the path of the electron.
   (b) Predict the radius of the path and the time required to traverse a semicircle.
10. In a *mass spectrograph*, isotopes of charge e and unknown mass are accelerated through voltage V and injected into a transverse magnetic field B. Derive an expression for the mass m in terms of the radius r of the circle described by the particle.
11. In a cyclotron (see any physics book), hydrogen ions are accelerated by an electric field, curved around by a magnetic field, and accelerated again. If B is limited to 2 T, what cyclotron diameter is required for a velocity half that of light?
12. An electron moves in an electric field $\mathcal{E}$ = 100 V/m with a velocity of 10^6 m/s normal to the earth's magnetic field ($B = 5 \times 10^{-5}$ T). Compare the electric and magnetic forces with that due to the earth's gravitational field. Is it justifiable to neglect gravitational forces in practical problems?

13. The work function of copper is 4.1 eV and the melting point is 1356 K. Thorium has a work function of 3.5 eV and melts at 2120 K. Compare the factor of $e^{-W_W/kT}$ for these two metals at 90% of their respective melting points and decide which is more likely to be used as a cathode.

14. The Richardson-Dushman equation indicates that cathode emission current is proportional to $T^2 e^{-W_W/kT}$. For a special cathode coating with a work function of 1 eV, the emission current density at 1100 K is 200 mA/cm^2. Estimate the emission current densities at 800 and 1200 K.

15. In the CRT deflection system of Fig. 4.7, the accelerating voltage is 1000 V, the deflecting plates are 2.5 cm long and 1 cm apart, and the distance to the screen is 40 cm.
(a) Determine the velocity of the electrons striking the screen.
(b) Determine the deflecting voltage required for a deflection of 4 cm.

16. The vertical deflecting plates of a CRT are 2 cm long and 0.5 cm apart; length L_S in Fig. 4.7 is 50 cm. The acceleration potential is 5 kV.
(a) Determine the deflection sensitivity.
(b) What is the maximum allowable deflection voltage?
(c) For a brighter picture, the acceleration potential is increased to 10 kV. What is the new deflection sensitivity?

17. A CRO with a 10 × 10-cm display has vertical amplifier settings of 0.1, 0.2, and 0.5 V/cm and horizontal sweep settings of 1, 2, and 5 ms/cm. Assuming the sweep starts at $t = 0$, select appropriate settings and sketch the pattern observed when a voltage $v = 2 \sin 60\pi t$ V is applied to the vertical input.

18. Repeat Exercise 17 for an applied voltage $v = 0.5 \cos 1000t$ V.

19. On the CRO of Exercise 17, determine the frequency of a square-wave signal that occupies:
(a) 2.5 cm per cycle at a sweep setting of 5 ms/cm.
(b) 4.0 cm for 10 cycles at a sweep setting of 1 ms/cm.

20. On a CRO vertical and horizontal amplifiers are set at 1 V/cm. Sketch the pattern observed when the voltages applied to the vertical and horizontal inputs are:
(a) $v_v = 5 \cos 400t$ and
$v_h = 5 \cos 100t$ V.
(b) $v_v = 5 \cos 200t$ and
$v_h = 5 \cos (700t - \pi/2)$ V.

21. Design a circuit for displaying the v-i characteristic of a diode on a CRO. Assume that the horizontal and vertical amplifiers have a common internal ground.

22. The CRO of Exercise 21 has an 8 × 8-cm screen. Anticipating an I-V characteristic similar to that shown in Fig. 5.8, specify the significant CRO settings.

PROBLEMS

1. As Einstein pointed out, the actual mass m of a moving particle is $m = m_O/\sqrt{1 - u^2/c^2}$ where m_O is the rest mass, u is velocity, and c is the velocity of light. Since energy and mass are equivalent, the potential energy lost in falling through a voltage V must correspond to an increase in mass $m - m_O$.
(a) Equate the potential energy lost to the equivalent energy gained and calculate the voltage required to accelerate an electron to 99% of the speed of light.
(b) Calculate the electron velocity for $V =$ 24 kV, a typical value in a television picture tube, and determine the percentage of error in Eq. 4-11.

2. The magnetic deflecting *yoke* of a TV picture tube provides a field $B = 0.002$ T over an axial length $l = 2$ cm. The *gun* provides electrons with a velocity $U_Z = 10^8$ m/s. Determine:
(a) The radius of curvature of the electron path in the magnetic field.
(b) The approximate angle at which electrons leave the deflecting field.
(c) The distance from yoke to screen for a 3-cm *positive* deflection.
(d) A general expression for deflection Y in terms of acceleration potential V_a and compare with Eq. 4-22. (Assume small angular deflections where $Y/L = \tan \alpha \cong \alpha$.)

3. How long is an electron in the deflecting region of the CRT of Exercise 16? If the deflecting voltage should not change more than 10% while deflection is taking place, approximately what frequency limit is placed on this deflection system?

4. The useful range of an amplifier is bounded by frequencies f_1 and f_2 at which low-frequency and high-frequency defects occur.

(a) In a certain amplifier, signals at $3f_1$ are amplified linearly, but at f_1 sinusoidal components are reduced to 70% of their relative value and shifted forward 45° in phase. For a square-wave input of frequency f_1, draw the fundamental and third harmonic components in the output and compare their sum to Fig. 4.13c.

(b) In the same amplifier, signals at $f_2/3$ are amplified linearly, but at f_2 sinusoidal components are reduced to 70% of their relative value and shifted backward 45° in phase. For a square-wave input at frequency $f_2/3$, repeat part (a) and compare to Fig. 4.13d.

EEAP 243
Lab 2

Lab Work:
Questions Due:

MEASUREMENT OF VOLTAGE, CURRENT, AND IMPEDANCE

READING ASSIGNMENT: Horowitz, pgs. 8-20

Abstract:
This lab will demonstrate advanced use of the test instruments and some of their shortcomings. Linear resistances and non-linear resistances such as diodes will be characterized using the test equipment. Simple networks which demonstrate Kirchoff's Laws, Ohm's Law, impedance and superposition will be examined.

You should always review these assignments before coming to the lab and make calculations to predict your experimental data. If you review the lab assignment including the assigned reading you will know what your data should look like, you will be able to catch your mistakes, and you will spend less time in the lab. For this lab, calculate the resistor voltages and currents in part 4 before coming to the lab.

NOTE: This assignment requires the use of two DMM's and will consequently require two lab groups to work together. Each lab group should work with the group immediately across from them so that test leads can be kept short.

Part 1 - DC Measurements

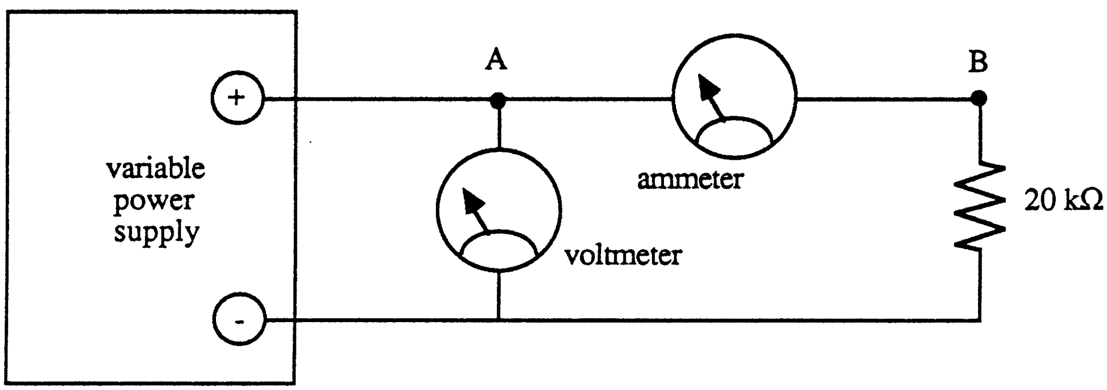


Figure 2.1

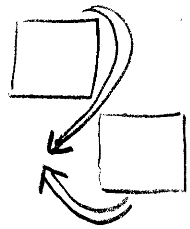
Construct the circuit shown above. Measure V and I with two DMM's as mentioned in the note above. Record your results for five different voltages of your choice between 1 and 15 volts.

Remove the voltmeter's positive terminal from point A and reconnect it at point B. Again record V and I for five different values of V.

Construct the circuit shown below using your breadboard. The diode is shown in the forward-biased mode.

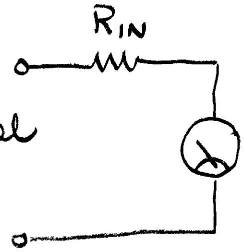
LAB #2 (Assign questions 2, 4, 6, 7)

Lab requires two meters — work across

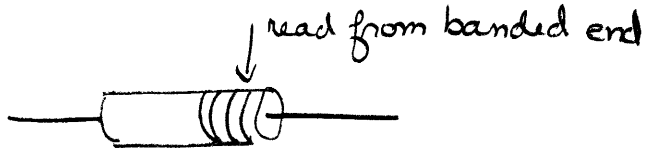


models of most instruments include internal resistances

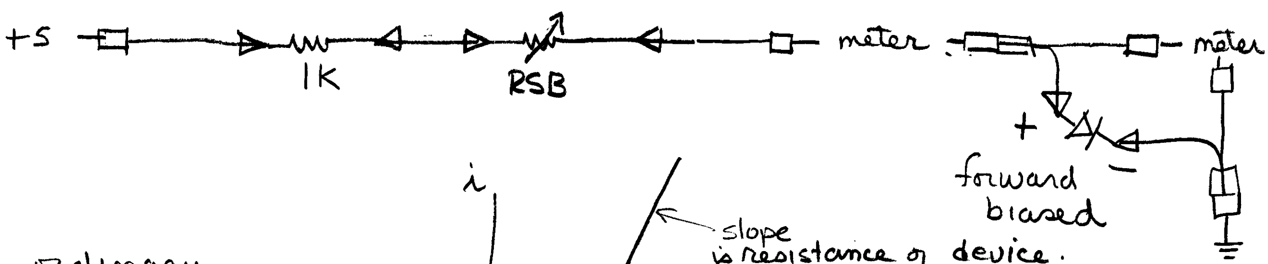
typical meter model

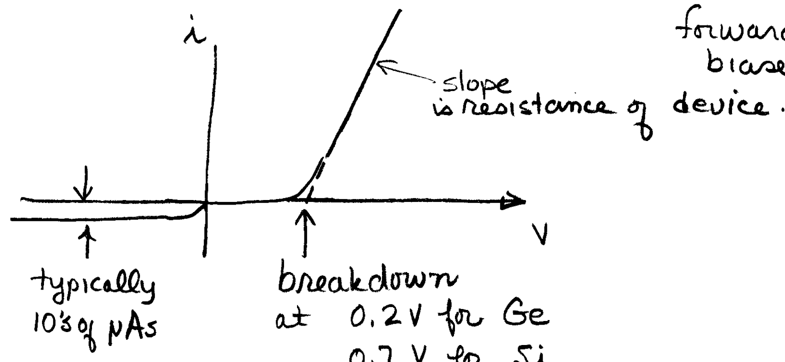


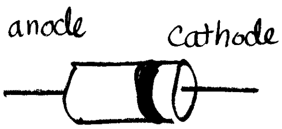
resistors



connect circuit on your proto board or just use clips.

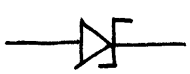




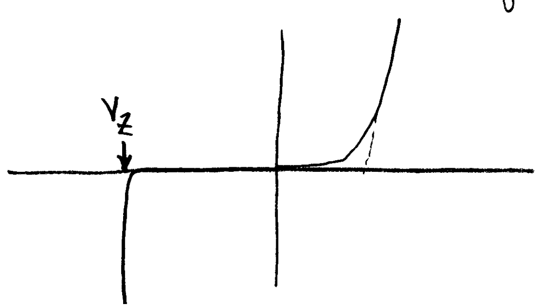


ordinary diode

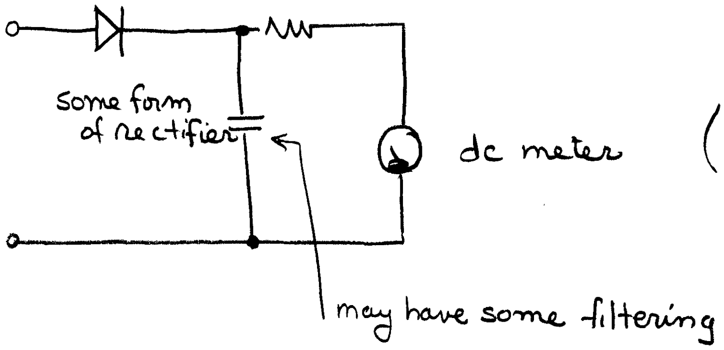
Boylestad and Nashelsky have a good ·lanation



zener diode



AC measurements:



(will measure ac AND DC present)

could be confusing

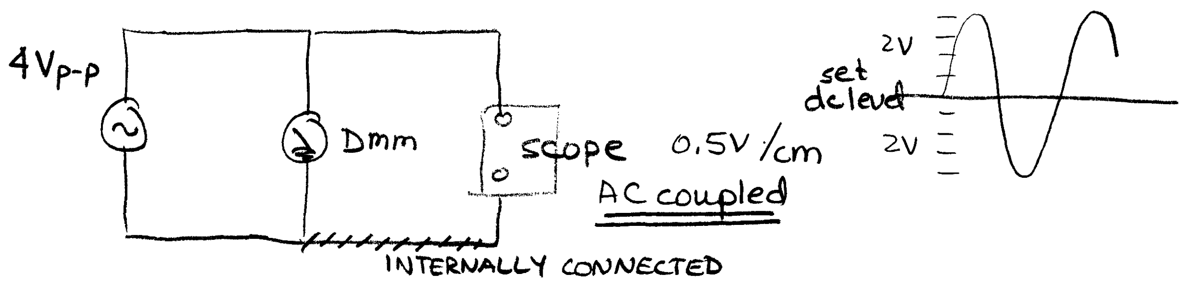


table 2-5

	vernier signal generat	range	time	scope	meter (set to AC volts)
frequency ↓			[this is NOT critical]	(Volts Not cm)	

RMS Measurements

general

$$V_{RMS} = \sqrt{(AC)^2 + (DC)^2}$$

more technically:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T V^2(t)\,dt}$$

For sinusoidal signals the above formula reduces to

if $V(t) = V_m \cos \omega t$

$$V_{RMS} = \frac{V_m}{\sqrt{2}}$$

For signals of different frequencies

$$V_{RMS} = \sqrt{V^2_{f1,rms} + V^2_{f2,rms} + \ldots + V^2_{fn,rms}}$$

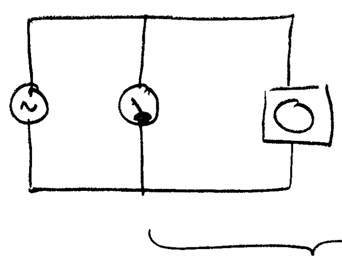
↑ one of these can be dc

Note that the rms value of a dc voltage is the dc voltage.

For triangle $V_{RMS} = \frac{V_m}{\sqrt{3}}$

for this lab

4 $V_{p\text{-}p}$
+1 V DC offset



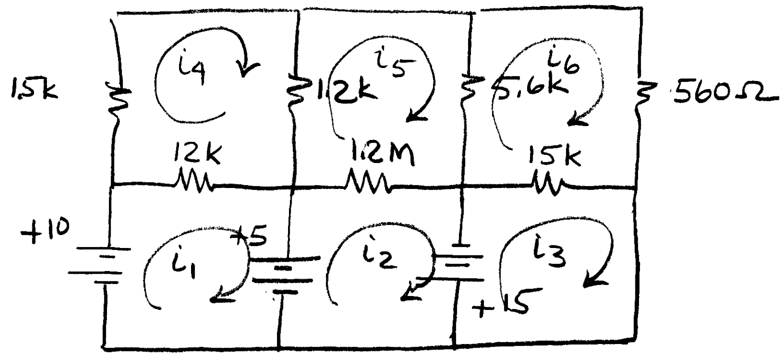
DC coupled

do for
- sine
- square
- triangle
- pulse

measure AC & DC components.

pulse is a little misleading

Part 4 KCL



LAY THIS OUT BEFORE YOU COME TO CLASS

Record tolerances of your resistors

use superposition
loop equations, etc.

$$-10 + 12k(i_1 - i_4) + 5 = 0$$

$$-5 + 1.2M(i_2 - i_5) - 15 = 0$$

$$+15 + 15k(i_3 - i_6) = 0$$

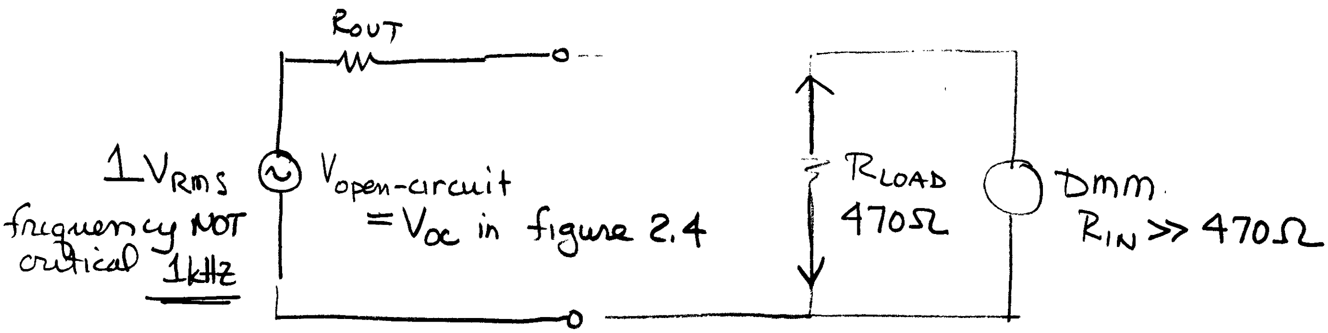
$$15k(i_4) + 12k(i_4 - i_1) + 1.2k(i_4 - i_5) = 0$$

$$1.2k(i_5 - i_4) + 1.2M(i_5 - i_2) + 5.6k(i_5 - i_6) = 0$$

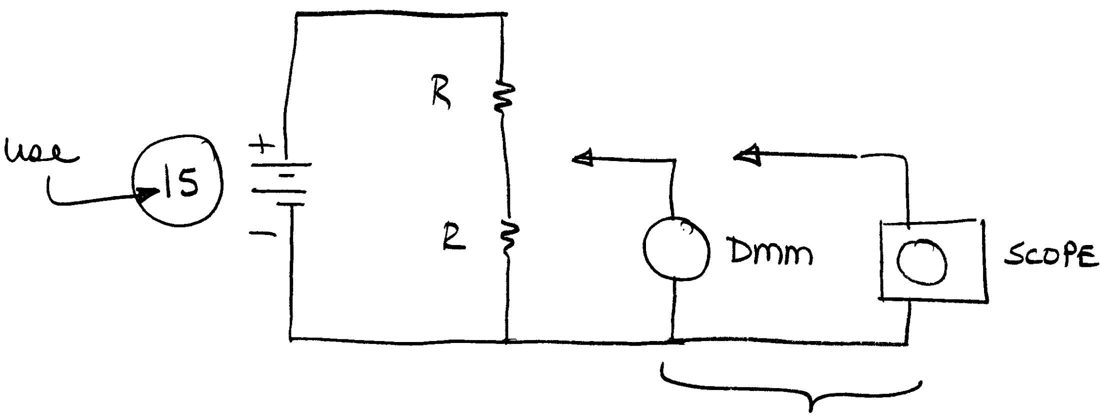
$$5.6k(i_6 - i_5) + 15k(i_6 - i_3) + 560\, i_6 = 0$$

6 equations in 6 unknowns.

Part 5 - Z of test equipment



VOLTAGE DIVIDER



R initially = 10 kΩ.

probably won't detect any differences until R = 1M or 10M

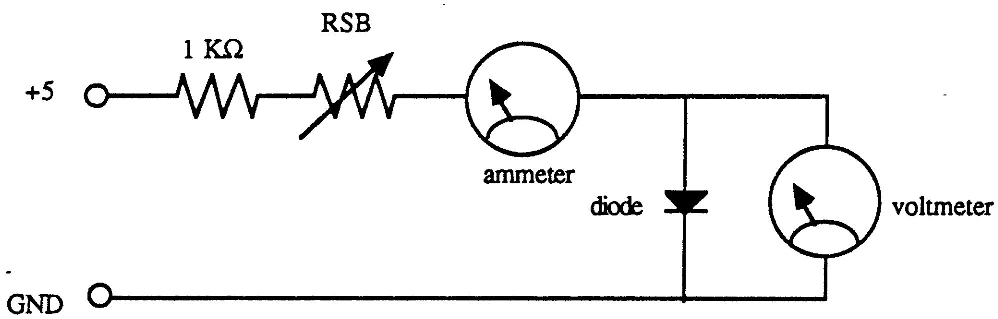


Figure 2.2 (a)

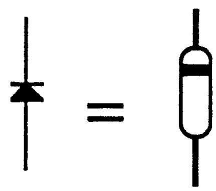


Figure 2.2 (b)

Record the values of I and V in Table 2.3 as you set the resistance of the RSB to 10K, 20K, 30K, 40K and 50K. Then, reverse the diode in your circuit and repeat the measurements. Record your results in Table 2.3.

A zener diode is a special diode used in voltage regulators and voltage protection circuits. Replace the diode you used above with the zener diode in your part kit. Record the values of I and V in Table 2.4 as you set the resistance of the RSB to 10K, 20K, 30K, 40K and 50K. Then, reverse the diode in your circuit and repeat the measurements. Record your results in Table 2.4. — zener diode

Part 2 - AC Measurements

Your DMM reads AC by first converting the AC signal to a DC voltage and then measuring the DC. It is not capable of making accurate measurements at all frequencies. We will measure the frequency response of the DMM by comparing oscilloscope and DMM readings over a wide range of frequencies.

Connect the DMM input VKS (A-5) to the signal generator output (B-4) and to the oscilloscope's channel 1 input CH1 (C-8). Connect the DMM's common input COM (A-5) to the station ground (D-11). Set the oscilloscope to 0.5 V/cm, bright line off, and AC coupling. Set the output of the signal generator to 4 volts peak-to-peak. Do this by adjusting the generator's amplitude knob so that the entire signal spans eight major divisions on the oscilloscope. This establishes a reference amplitude of 4 volts peak-peak at 1 KHz. Set the DMM to read AC volts on the 2 volt scale. — Ø volts dc offset; confusing

Complete Table 2.5. Be sure that, for each line on the table, you have made the corresponding signal generator vernier, signal generator range, and oscilloscope sweep speed settings. To read peak-to-peak voltage (Vp-p) on the oscilloscope, set the vertical position so that the bottom of the waveform is on a major division, measure the height of the waveform in major divisions, and multiply by the vertical sensitivity. The DMM reads root-mean-square voltage (V_{rms}) automatically.

Part 3 - RMS Voltage Measurement

Since the oscilloscope displays information graphically, it can display any waveform so long as the signal does not change faster than the oscilloscope can move the electron beam. The DMM does not give wave shape information and cannot directly measure the total RMS voltage of a combined AC and DC signal. However, the total RMS voltage of a combined signal can be calculated using the following equation.

$$\text{Total RMS voltage} = \sqrt{(\text{AC voltage})^2 + (\text{DC voltage})^2} \qquad (2.1)$$

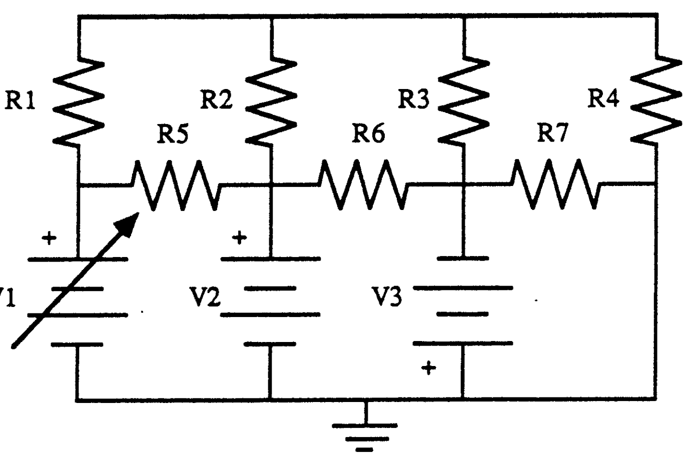
Connect the DMM and oscilloscope directly to the generator's 600 ohm output and set the oscilloscope to DC coupling. Select a 1 KHz sine wave and, using the oscilloscope, set the generator to produce a 4 Vpp signal with +1 V DC offset. Measure both the AC and DC components of the signal using the DMM and the oscilloscope. Repeat the measurements for the triangle and square waves.

Move the test lead to the generator's pulse output. Using the oscilloscope, measure ~~and record the duty cycle (high time vs. low time) of the pulse, its peak-to-peak amplitude, and its vertical position relative to the zero volt reference.~~ its AC and DC components. Measure both the AC and DC components of the pulse using the DMM.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE CONTINUING.

Part 4 - Kirchoff's Laws

Build the circuit shown in Fig. 2.3 using your protoboard. Use the RSB for the one resistance which is not a standard value. Use the DMM to measure all of the voltages (including the sources) and all of the currents. Record your measurements in Table 2.7. IF YOU MEASURE ANY CURRENT ABOVE 10 mA YOU ARE DOING SOMETHING WRONG! The meter must be put in series with the resistors (or sources) to measure current. To do this you must disconnect one end of a resistor (or source) from the rest of the circuit and use the meter to bridge the broken connection. Remember to use the "VKS" input for measuring voltage and the "mA" input for measuring current.



R1 - 1.5k	R2 - 1.2k	~~R3 - 5.1k~~ 5.6K
~~R4 - 520Ω~~ 560Ω	R5 - 12k	R6 - 1.2M R7 - 15k
V1 - 10 volts	V2 - 5 volts	V3 - 15 volts

Figure 2.3 Resistive network

Part 5 - Impedance of the test equipment

Your signal generator has an equivalent circuit such as shown in Figure 2.5 with an internal impedance R_{OUT}.

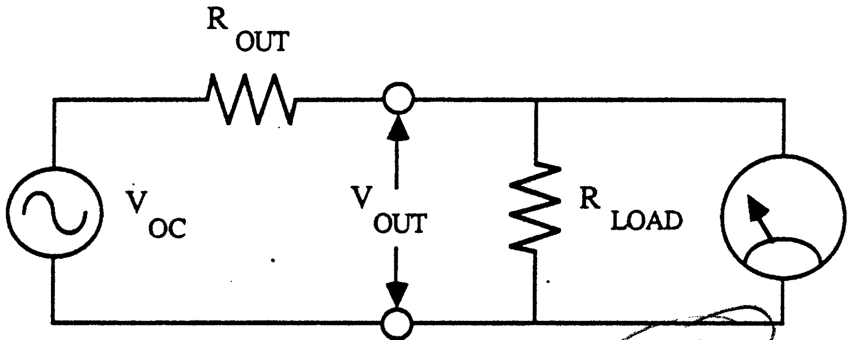


Figure 2.4

Set your ac signal generator output to 1 volt rms at 1kHz using your DMM — zero volts offset. Now connect a 470Ω resistor (R_{LOAD} as shown above) between the output of the signal generator and ground. DO NOT change the signal generator settings. Record the new generator rms output voltage. In Table 2.8.

Construct the circuit shown in Figure 2.5 using 10K resistors for R.

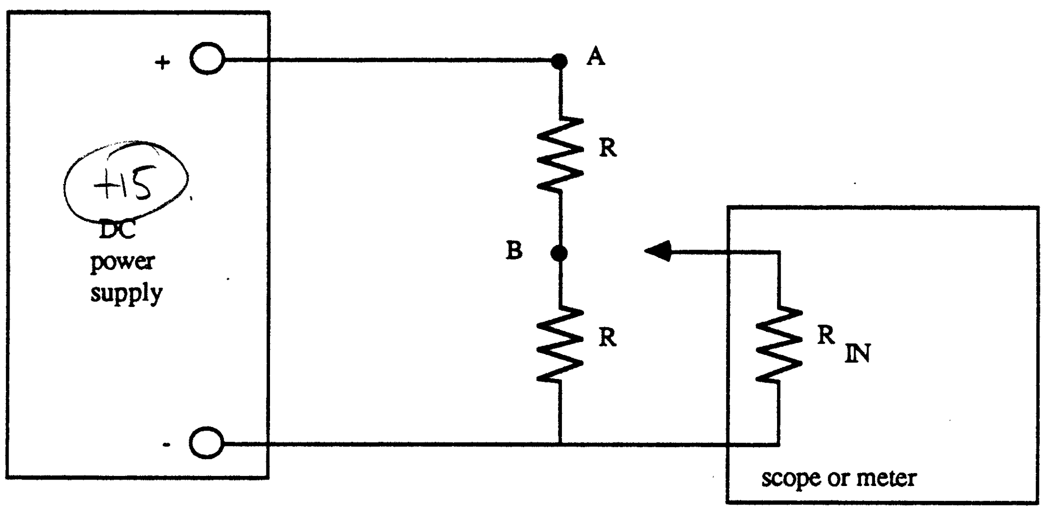


Figure 2.5

Measure the voltages at points A and B using the DMM. Record your results in Table 2.9. Use the voltage range setting which gives you maximum accuracy. Now repeat your measurements using the oscilloscope. Again use the range setting which allows for maximum accuracy. Do not at any time connect the oscilloscope and DMM inputs together. Repeat your measurements changing R to 100K, 1M and 10M.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE LEAVING.

Questions:

1. Plot your results from Table 2.1 and 2.2 on the same graph. What is the significance of the slope of the best fitting line through each set of data? Explain any difference between your results for points A and B in the circuit.
2. Using your data from Tables 2.3 and 2.4 plot V versus $\log_{10} I$ on the same graph for the forward and reverse biased diode and zener diode.
3. Using your results from question 2, what might have happened if you had connected the +5 volt supply directly to the diode you measured? DON'T ACTUALLY TRY IT!
4. (a) Make a graph of your data from Table 2.5 plotting the oscilloscope amplitude on the vertical axis and the log of the frequency on the horizontal axis. Multiply each DMM reading by 2.828 and plot the DMM amplitude on the same graph. frequency response
   (b) Why are the DMM measurements multiplied by 2.828 before plotting?
   (c) Assuming that the oscilloscope measurements are correct, at what frequency does the DMM give a 5% error?
   (d) Should the DMM be trusted when measuring AC signals over 10 KHz?
5. (a) What are the general RMS voltage equations, in terms of the peak voltage times a constant, for the sine, triangle, square and pulse waveforms?
   (b) Calculate the RMS voltages of the four signals using the oscilloscope measurements.
   (c) Calculate the RMS voltages of the four signals using the DMM measurements.
6. (a) Starting from the source voltages and resistance values, calculate the voltage across and current through each resistor in Figure 2.3. Do not use any of your experimental data. Show your work.
   (b) Compare your actual measurements from Table 2.7 to the values you calculated in (a). Why aren't they exactly the same?
   (c) Assuming the voltages and currents you measured were accurate, calculate the actual value of each resistor by using the voltages and currents measured. Were the resistors within their stated tolerances?
7. Using your data from Tables 2.8 and 2.9, calculate R_{OUT} for the signal generator and R_{IN} for the DMM and oscilloscope?

EEAP 243 LAB 2 EVALUATION

NAME (print)___________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

sine wave RMS = __________ $\times V_{peak}$

triangle wave RMS = __________ $\times V_{peak}$

square wave RMS = __________ $\times V_{peak}$

Question #2

What will happen to the voltage at point A in Fig.2.1 if we increase/decrease the value of $R_1/R_2/R_3/R_4$?

The voltage will increase / decrease / stay the same.

EEAP 243

NAMES: ____

Lab 2 Data

V	I
________	________
________	________
________	________
________	________
________	________

Table 2.1 V-I characteristics of 20K resistor

V	I
________	________
________	________
________	________
________	________
________	________

Table 2.2 V-I characteristics of 20K resistor

	--- forward biased ---		--- reverse biased ---	
RSB	V	I	V	I
10K	________	________	________	________
20K	________	________	________	________
30K	________	________	________	________
40K	________	________	________	________
50K	________	________	________	________

Table 2.3 V-I characteristics of diode

RSB	forward biased V	forward biased I	reverse biased V	reverse biased I
10K				
20K				
30K				
40K				
50K				

Table 2.4 V-I characteristics of zener diode

VERNIER	RANGE	TIME/CM	SCOPE (V_{pp})	DMM (V_{rms})
1	10 Hz	20 mS		
2	10 Hz	10 mS		
5	10 Hz	5 mS		
1	100 Hz	2 mS		
2	100 Hz	1 mS		
5	100 Hz	0.5 mS		
1	1 KHz	0.2 mS		
2	1 KHz	0.1 mS		
5	1 KHz	50 µS		
1	10 KHz	20 µS		
2	10 KHz	10 µS		
5	10 KHz	5 µS		
1	100 KHz	2 µS		
2	100 KHz	1 µS		
5	100 KHz	0.5 µS		
10	100 KHz	0.5 µS		

Table 2.5 - DMM Frequency Response Data

waveform	DMM (DC)	DMM(AC)	Oscilloscope (AC)	Oscilloscope (DC)
sine				
triangle				
square				

Table 2.6 RMS voltages for various waveforms

RESISTOR	VOLTAGE	CURRENT
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Table 2.7 Measured Voltages/Currents in Resistor Mesh Circuit

V_{out}	R_{LOAD}
1.0	∞
	470Ω

Table 2.8 Loaded generator output

R	$V_{A,oscilloscope}$	$V_{B,oscilloscope}$	$V_{A,DMM}$	$V_{B,DMM}$
10K				
100K				
1M				
10M				

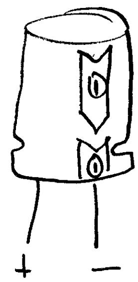
Table 2.9 DMM and oscilloscope loading

capacitors

marked with value in microfarads
or scientific notation in picofarads $\quad$ ## $\times 10^{\#}$

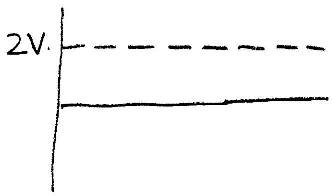
$\therefore 333 = 33{,}000\text{ pf} = .033\text{ pf}.$

very important which way electrolytics go in a circuit

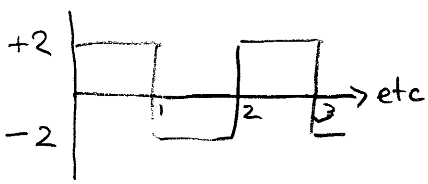


capacitors can explode if polarity is reversed

rms voltages $\quad V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)\,dt}$



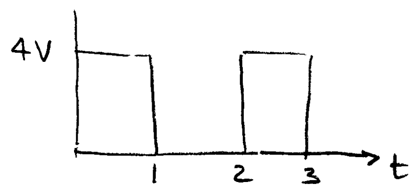
$V_{rms} = 2V.$ $\quad$ since $\sqrt{\frac{1}{T}\int_0^T 2^2\,dt} = \sqrt{\frac{1}{T}4t\Big|_0^T} = 2$



$$V_{rms} = \sqrt{\frac{1}{2}\left[\int_0^1 (2)^2 dt + \int_1^2 (-2)^2\right] dt}$$

$$= \sqrt{\frac{1}{2}4 + \frac{1}{2}\cdot 4} = \sqrt{4} = 2$$

Add two together



$$V_{rms} = \sqrt{\frac{1}{2}\int_0^1 (4)^2 dt} = \sqrt{\frac{1}{2}\cdot 16} = 2\sqrt{2} \text{ volts.}$$

this is the basis for the formula

$$V_{rms} = \sqrt{V_{AC,rms}^2 + V_{dc}^2}$$

$$= \sqrt{4+4} = 2\sqrt{2}$$

EEAP 243
Lab 3

Lab Work:
Questions Due:

TIME RESPONSE

READING ASSIGNMENT: Horowitz, pgs. 20-25, Millman and Taub, p.50-54.

Abstract:
This lab demonstrates and measures the time response of RC networks and oscilloscope probes.

Part I - RC circuits
In Circuits I you analyzed the time response of the circuit shown in Figure 3.1 assuming that the switch S was closed at time t=0. We will experimentally verify your analysis except, instead of using a switch, we will use the signal generator. A square wave signal generator output which goes from 0 to some positive voltage V will simulate the opening and closing of the switch S connected to a battery of voltage V as shown in Figure 3.1.

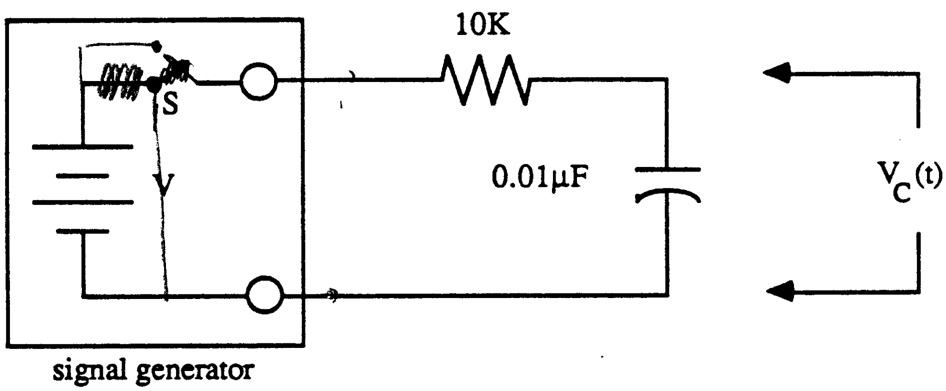


Figure 3.1 - Time response of RC circuit

change to 0-1 volt

To begin this lab construct the circuit shown in Figure 3.1. Adjust your signal generator output to produce a 0 to 10 volt, 500 Hz square wave. Note that this may require adjusting both the output amplitude and DC offset of the generator output. Connect the output of the signal generator to your circuit. Measure the voltage across the capacitor with your oscilloscope. Plot the time dependent voltage waveform you see on the scope on the graph in Table 3.1.

Change your generator output to a 100 kHz square wave. Measure the amplitude of $V_C(t)$ with the oscilloscope. You may need to turn the generator output all the way up to get a measurable output. Plot your results in Table 3.2.

This circuit now functions as an integrator, i.e. a low-pass filter. Verify this by changing your generator output from a square wave to a triangle waveform. Plot your results in Table 3.3.

compare to a sine wave

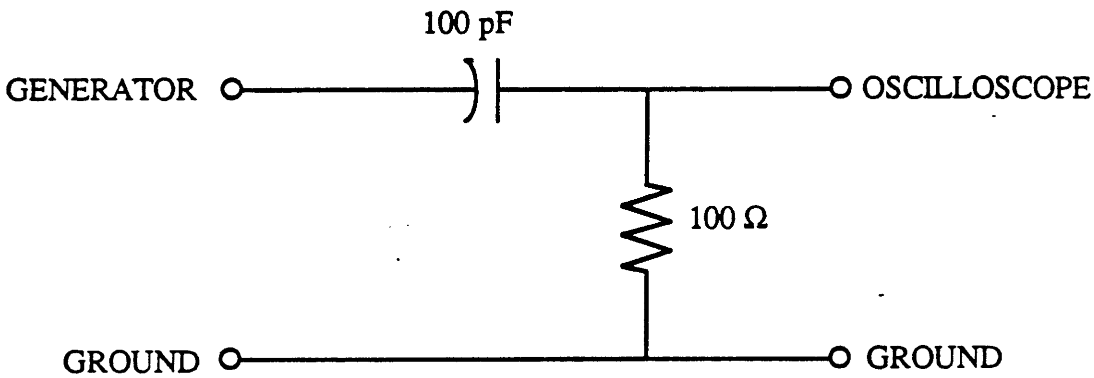


Figure 3.2 - RC Network

Build the RC circuit shown in Figure 3.2. Adjust the generator output to a 0-1 volt, 100 kHz square wave. Connect the circuit of Figure 3.2 to the output of the signal generator. Measure the voltage across the 100Ω resistor with the oscilloscope. Plot your results in Table 3.4. This circuit functions as a differentiator, i.e. a high-pass filter. Verify its performance by switching the generator output to a triangle waveform and measuring the voltage across the resistor. Plot your results in Table 3.5.

Part II - Oscilloscope probes

Unshielded wires connected to a scope often act like antennas and introduce unwanted random signals (noise). These signals often originate from the 60 Hz power lines or from nearby unconnected signal sources. To see if you can actually see any noise from the 60 Hz power lines: probably will not see 60 H.

(1) Set your scope to AC coupling and disconnect any wires from its input jacks.
(2) Observe what happens to the straight line displayed as you switch to each scale factor setting from 10 V/cm to 2 mV/cm. can oscillate (Sweep = 1 msec/cm)
(3) Plug a test lead into the scope input and let the free end lie on the lab bench.
(4) Repeat step 2.

Coaxial cables are often used to reduce unwanted noise.

(5) Repeat steps 3 and 4 using a coaxial cable and the BNC scope input instead. The connector/clip assembly should be removed from the cable while making this observation.

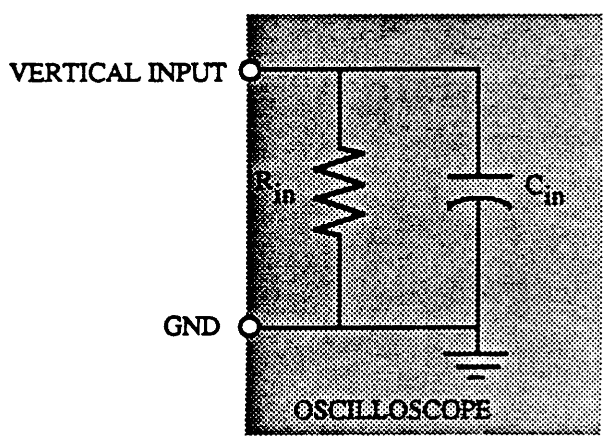


Figure 3.3 - Equivalent input circuit of oscilloscope

As shown in Fig. 3.3, the input of the oscilloscope appears as a parallel resistance and capacitance to ground. Unfortunately, the use of a coaxial cable adds additional capacitance to the scope input. You will learn in fields that a coaxial cable is a cylindrical capacitor and, consequently, has a certain capacitance per unit length. (This capacitance may be as high as 20-30 pF per foot.) The combined input capacitance of the scope and coax, coupled with the high resistances in the circuit to be measured, can introduce errors in measuring waveforms.

(6) Use your coaxial cable assembly to observe the generator output.
(7) Set the generator to produce a maximum amplitude 10 kHz square wave with zero DC offset.
(8) Record the voltage waveform you see in Table 3.6.

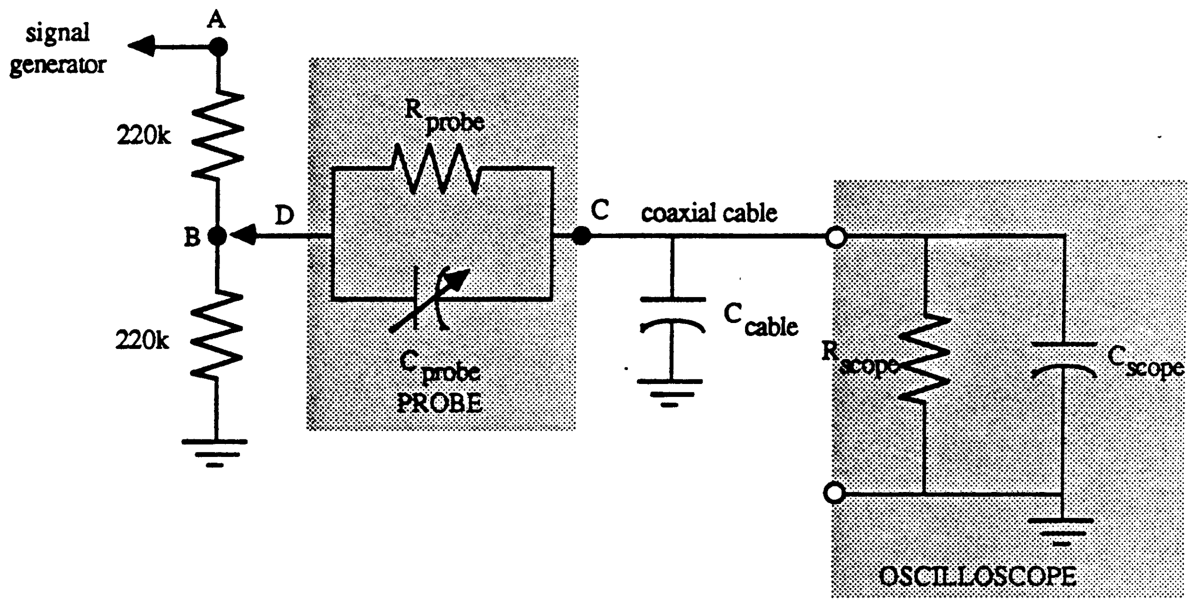


Figure 3.4 - Compensated scope probe circuit

A resistor and variable capacitor, as shown in Fig. 3.4, can be used to form what is called a compensated probe which can eliminate cable capacitance effects. Basically, the circuit is a capacitative voltage divider in parallel with a resistive voltage divider.

(1) Set the generator to a 10 KHz square wave at maximum amplitude and zero DC offset. Connect the signal generator to a divider composed of two 220k resistors as shown in Figure 4. These resistors can be on your protoboard.
(2) Use the coaxial cable to directly look at the output of the generator at point A in Figure 3.4.
(3) Connect a 10 M resistor (R_{probe}) and a 1.2-30 pF variable capacitor (C_{probe}) to the coax as shown in Fig. 3.4. This circuit should be soldered to the end of your coaxial cable to eliminate any capacitance you might pick up from constructing it on your protoboard. NOTE: If soldering is not possible, construct the compensated probe on your protoboard using the layout shown in Figure 3.5.

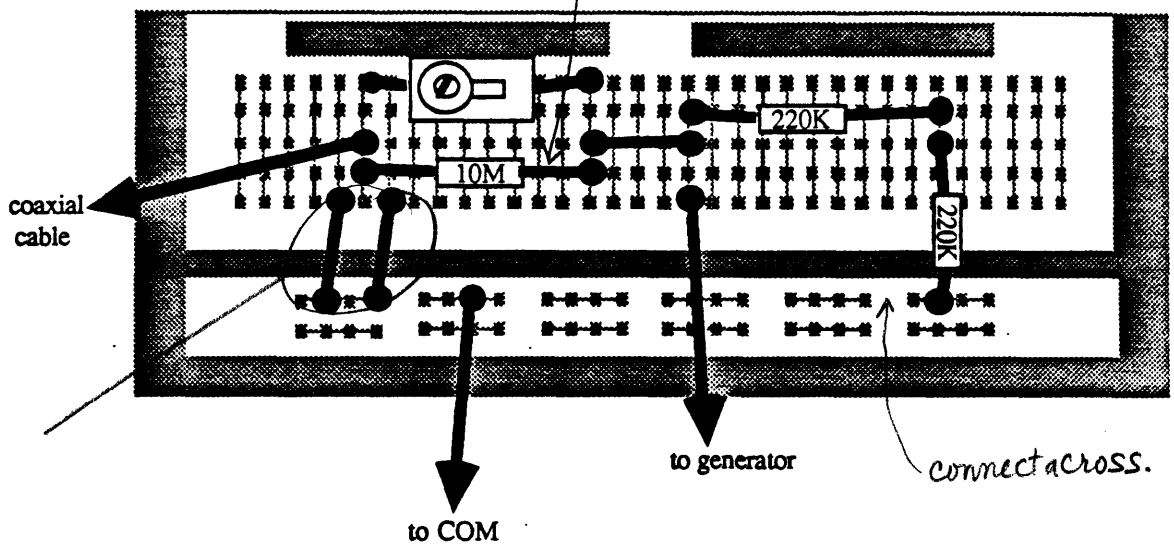


Figure 5 - Recommended protoboard construction of compensated probe

(4) Connect the input to your probe (point D) to point A.
(5) Observe what happens as you turn the variable capacitor a full 360 degrees. —— works well
(6) Adjust the capacitor so that the tops and bottoms of the square wave are perfectly flat and horizontal.(Note that this is how you would adjust any commercial compensated probe. A terminal (C-7) on your scope provides a square wave source for adjusting compensated probes.)
(7) ~~Now connect your probe (point D) to point B.~~ Compare to uncompensated probe, i.e. cable
(8) Record the displayed voltage waveform in Table 3.7.

We studied the compensated probe from a viewpoint of a RC filter in this lab; we will consider its frequency response characteristics in Lab #4.

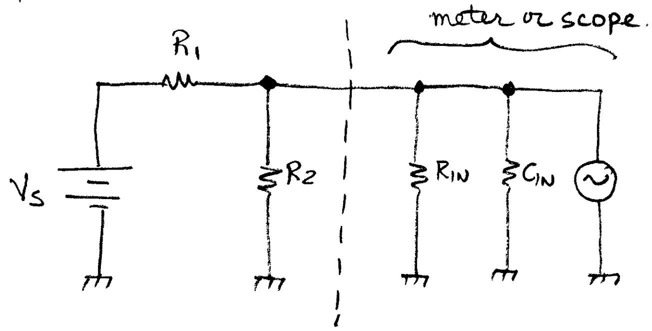
PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE YOU LEAVE.

Questions:

1. What was the measured time constant of your circuit? ~~Did it~~ agree with the calculated value? 5.2cm × 20msec/cm (Figure 3.1)
2. Under what conditions does a RC circuit function as a differentiator? As an integrator?
3. Calculate the combined input capacitance of the cable and oscilloscope from your data. ← not enough info, didn't record figure
4. By what factor did the compensated probe circuit divide the input signal? ~1000
5. The compensated scope probe was alluded to as a voltage divider in parallel with a resistive voltage divider. Analyze the circuit of Figure 3.4 with this viewpoint. What are the required time constants for compensation? HINT: See Millman and Taub, <u>Pulse, Digital and Switching Waveforms</u>, p.50-54.

no data to answer #3

Input impedance and time response.



for dc.

$$V_{o,\,ideal} = V_s \frac{R_2}{R_1+R_2}$$

$$V_{o,\,real} \quad V_s \cdot \frac{R_2 \parallel R_{IN}}{R_1 + R_2 \parallel R_{IN}}$$

if $R_1 = R_2 = R$ for $R_{IN} \gg R$ $V_o \cong \frac{1}{2} V_s$

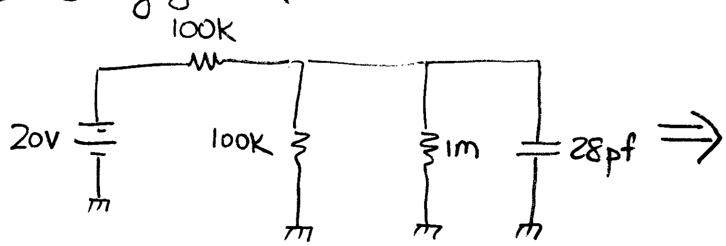
for $R_{IN} \ll R$ $V_o \to 0$

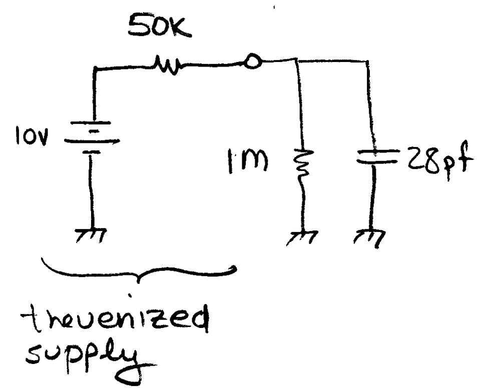
to calculate R_{IN}, you want $R_{IN} \cong R$

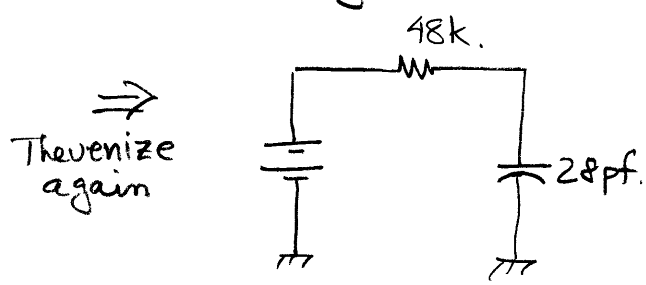
R_{IN} meter $\cong$ 10M

R_{IN} scope $\cong$ 1M $C_{IN,\,scope} = 28\,pf$

Is C negligible?



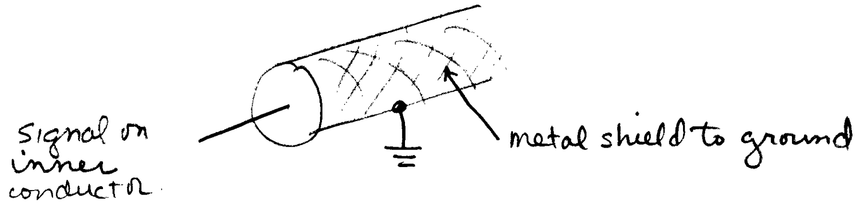




$$f_{cutoff} = \frac{1}{2\pi RC} = \frac{1}{2\pi(48\times10^{3})(28\times10^{-12})} \cong$$

bare wires pick up a lot of noise because they act as antennas

coax is used to reduce noise

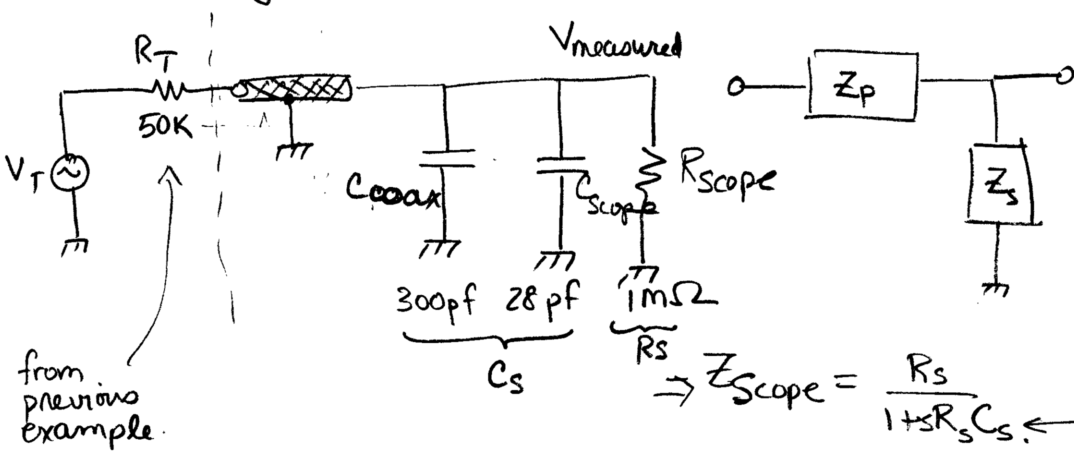


shield adds a lot of capacitance, possibly 50pf/foot.

a 6 foot length of cable is now 300 pf + 28 pf of scope.

$$f_{cutoff} = \frac{1}{2\pi(48\times10^3)(328\,pf)} \approx 10\,kHz,$$ not very useful.

improve by compensating probe.



$$Z = R \parallel \frac{1}{sC} = \frac{R}{1+sRC}$$

$$\Rightarrow Z_{scope} = \frac{R_s}{1+sR_sC_s}$$ ← this includes the coax.

$$\frac{V_{measured}}{V_T} = \frac{Z_{scope}}{R_T + Z_{scope}}.$$

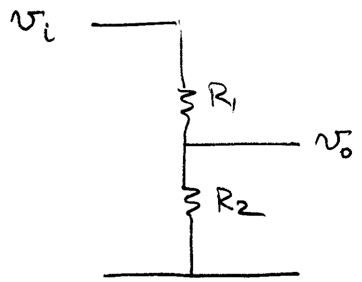
for the above conditions

$$\frac{V_{measured}}{V_T} \approx 0.95$$ at low frequencies

$$f_{cutoff} = \frac{1}{2\pi RC} = \frac{1}{2\pi(1M \parallel 50K)(300+28\,pf)}$$

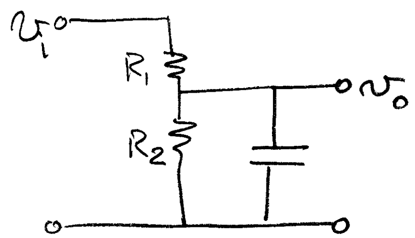
$$\cong 10.1\,kHz$$

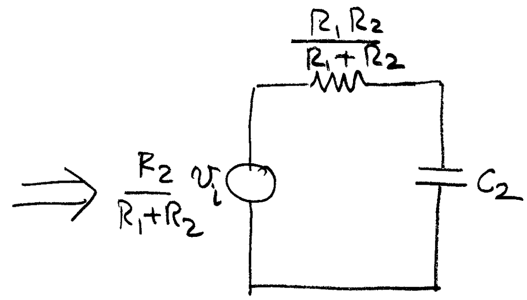
time domain analysis – Consider a simple attenuator



independent of f.

in reality we have.

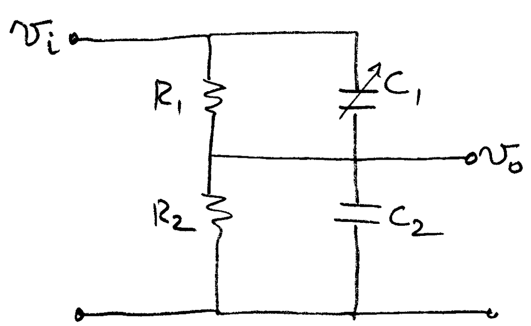




If $R_1 = R_2 = 1\,M$ and $C_2 = 15\,pF$.

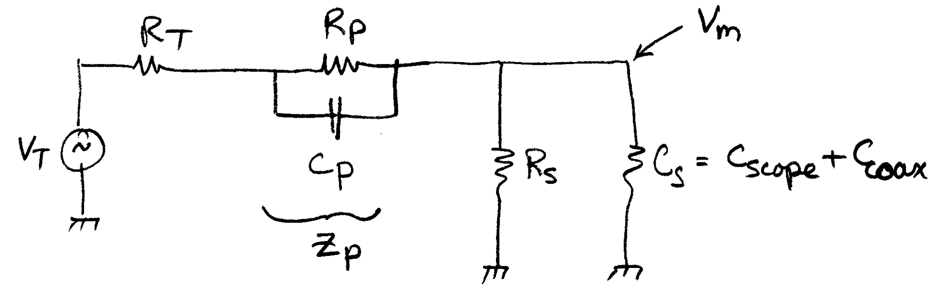
$$f_{cutoff} = \frac{1}{2\pi(500\times10^3)(15\times10^{-12})}$$

The way to extend the frequency response is to <u>compensate</u> the probe by bypassing it with a capacitance C_1



if $RC_1 = RC_2$ the bridge will be balanced independent of frequency.

Now, what happens with probe



$$\frac{V_m}{V_T} = \frac{Z_s}{R_T + Z_s + Z_p} \quad \text{where} \quad Z_s = \frac{R_s}{1 + sR_sC_s} \quad Z_p = \frac{R_p}{1+sR_pC_p}$$

$$= \frac{\dfrac{R_s}{1+sR_sC_s}}{R_T + \dfrac{R_p}{1+sR_pC_p} + \dfrac{R_s}{1+sR_sC_s}} \quad \text{multiply through by } \frac{1+sR_sC_s}{1+sR_sC_s}$$

$$= \frac{R_s}{R_T(1+sR_sC_s) + R_p\left(\dfrac{1+sR_sC_s}{1+sR_pC_p}\right) + R_s}$$

Now, consider what happens if $R_pC_p = R_sC_s$

$$\Rightarrow \frac{R_s}{R_T(1+sR_pC_p) + R_p + R_s}$$

$$= \frac{R_s}{R_s + R_p} \; \frac{R_s + R_p}{R_T(1+sR_pC_p) + R_p + R_s}$$

voltage divider with no frequency dependence.

define $R_{eq} = R_s + R_p$

$$\frac{R_{eq}}{R_T(1+sR_pC_p) + R_{eq}}$$

but $R_pC_p = R_pC_p \dfrac{C_s + C_p}{C_s+C_p} = \dfrac{R_pC_sC_p + R_pC_pC_p}{C_s + C_p} = \dfrac{R_pC_sC_p + R_sC_sC_p}{C_s+C_p}$ ($R_pC_p = R_sC_s$)

$$= (R_s + R_p)\left(\frac{C_pC_s}{C_p+C_s}\right)$$

↑ C_{eq}

$$\therefore \frac{V_{measured}}{V_T} = \underbrace{\frac{R_S}{R_S + R_P}}_{\text{division factor.}} \underbrace{\frac{R_{eq}}{R_T(1 + sR_{eq}C_{eq}) + R_{eq}}}_{H(s) \text{ frequency response factor}}$$

Suppose we set $R_p = 99\,M\Omega$

then $C_p = \frac{R_S C_S}{R_p} = \frac{1m(328\,pf)}{99m} = 3.31\,pf$

$$\therefore \frac{V_{measured}}{V_{in}} = \frac{1}{1+99} = \frac{1}{100}$$

$R_{eq} = R_S + R_P = 1m + 99m$

$C_{eq} = \frac{C_S C_P}{C_S + C_P} = \frac{(328)(3.31)}{328 + 3.31}$

$= 3.28\,pf.$

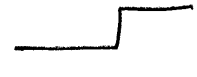
$$H(s) = \frac{R_{eq}}{R_T + sR_TR_{eq}C_{eq} + R_{eq}} = \frac{R_{eq}}{R_T + R_{eq} + sR_TR_{eq}C_{eq}}.$$

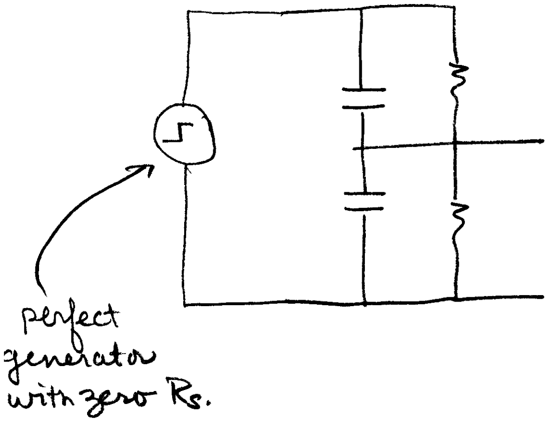
$$= \frac{R_{eq}/R_T + R_{eq}}{1 + s\left(\frac{R_TR_{eq}}{R_T + R_{eq}}\right)C_{eq}}$$

$$H(0) \rightarrow \frac{R_{eq}}{R_T + R_{eq}} = \frac{100m}{48K + 100m} \cong .9995$$

$$f_{cutoff} = \frac{1}{2\pi\left(\frac{R_TR_{eq}}{R_T + R_{eq}}\right)C_{eq}} \cong \frac{1}{2\pi(48K)(3.28pf)} \approx 970\,kHz.$$

which is actually better than scope with no coax.

Consider the response to a unit step in voltage, 



by Kirchoff's Law $V = \frac{q}{C_1} + \frac{q}{C_2} = \frac{C_1 + C_2}{C_1 C_2} q.$

at $t = 0^+$

$$v_o(0^+) = \frac{q}{C_2} = \frac{\frac{C_1 C_2}{C_1 + C_2} V}{C_2} = \frac{C_1}{C_1 + C_2} V$$

∴ the initial output voltage is determined by the capacitors.

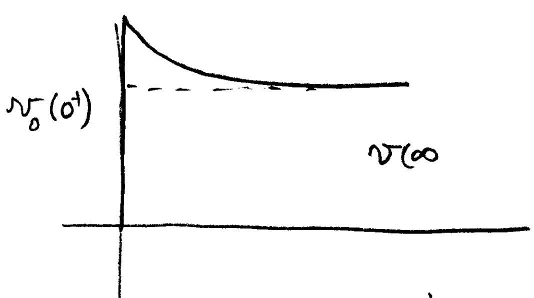
the final output voltage will be determined by the resistors

$$v_o(\infty) = \frac{R_2}{R_1 + R_2} V$$

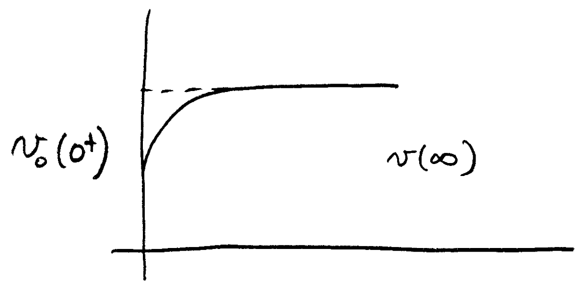
For the circuit to be compensated $v_o(0^+) = v(\infty)$ or any other time in between. Then

$$\frac{C_1}{C_1 + C_2} V = \frac{R_2}{R_1 + R_2} V \quad \text{or} \quad C_1 R_1 + C_1 R_2 = C_1 R_2 + C_2 R_2$$

$$\text{or} \quad R_1 C_1 = R_2 C_2 .$$

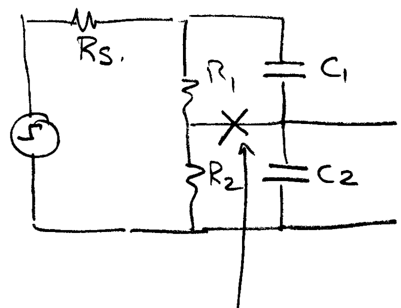


overcompensation

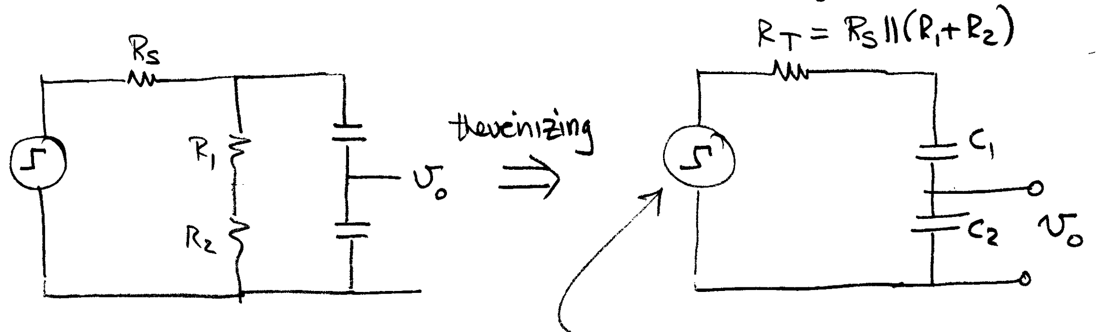


undercompensation

If we include the source impedance R_s we get.



break this connection for the moment since the capacitors alone determine $v_o(0^+)$ and the resistors alone determine $v_o(\infty)$



$$v_T = \frac{R_1 + R_2}{R_1 + R_2 + R_s}$$

If $R_s \ll (R_1 + R_2)$ <u>usually true</u> then the input waveform will have a time constant $\tau \cong R_s C'$ where $C' = \dfrac{C_1 C_2}{C_1 + C_2}$.

If the input were directly connected to the output, i.e. the input of the scope the time constant would be

$$\tau' \cong R_s C_2 \quad \text{connected straight through.}$$

so, the improvement in rise-time is

$$\frac{\tau'\ (\text{direct})}{\tau\ (\text{probe})} = \frac{R_s C_2}{R_s C'} = \frac{C_2 (C_1 + C_2)}{C_1 C_2} = \frac{C_1 + C_2}{C_1} > 1$$

∴ probe decreases timeconstant

However, this is at the expense of signal level since

$$\frac{v'(\infty)}{v(\infty)} = \frac{\dfrac{R_2}{R_s + R_2}}{\dfrac{R_2}{R_1 + R_2 + R_s}} = \frac{R_1 + R_2 + R_s}{R_2 + R_s} \approx \frac{R_1 + R_2}{R_2}$$

∴ probe decreases signal by $\dfrac{R_2}{R_1 + R_2}$.

EEAP 243 LAB 3 EVALUATION

NAME (print)______________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

The value of C_{coax} is proportional to the length of coaxial cable used. Suppose that you have a compensated probe. How would you re-compensate it if you made its cable (longer/shorter) ?

I would (increase/decrease) the value of R_{probe} / C_{probe} / R_{scope} / C_{scope}.

Question #2

What will happen to the (amplitude/frequency) of the resonance, i.e. the peak in the Bode plot, of Fig. 3.7 if we (increase/decrease) the value of the resistance/inductance/capacitance ?

It will increase / decrease / stay the same.

EEAP 243

NAMES: ____

Lab 3 Data   STATION 12

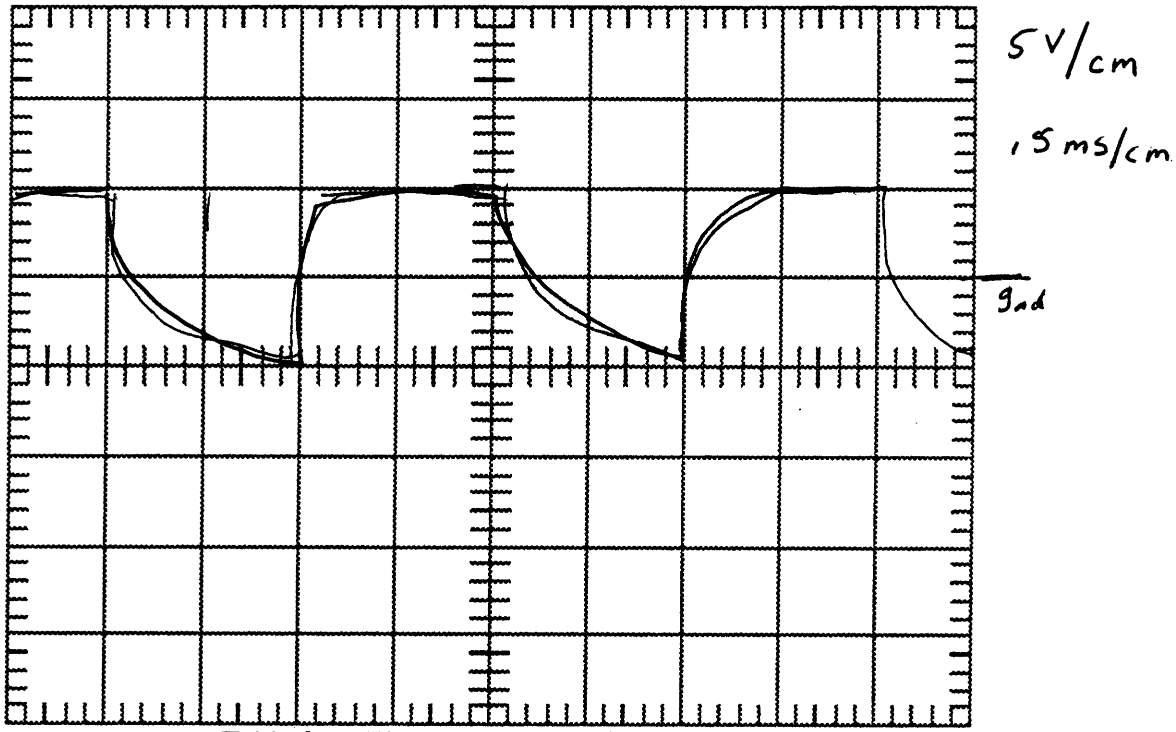


Table 3.1 - Time dependent RC waveform

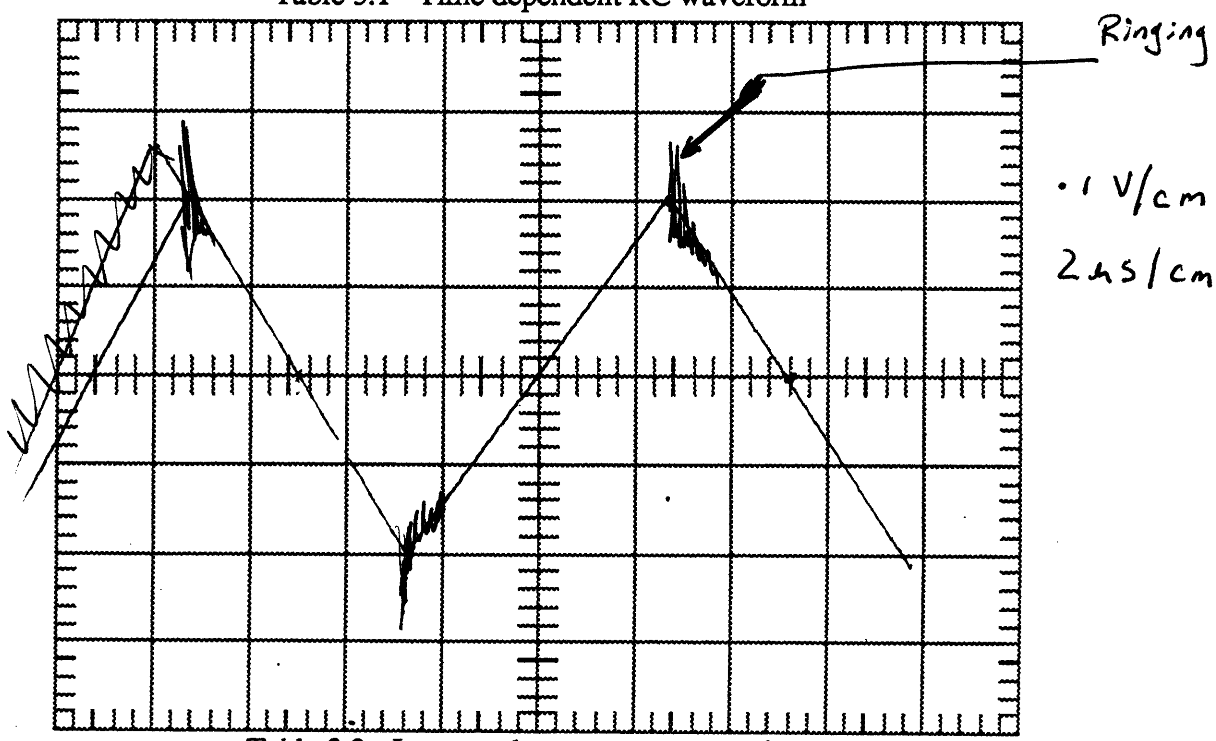


Table 3.2 - Integrated square wave waveform

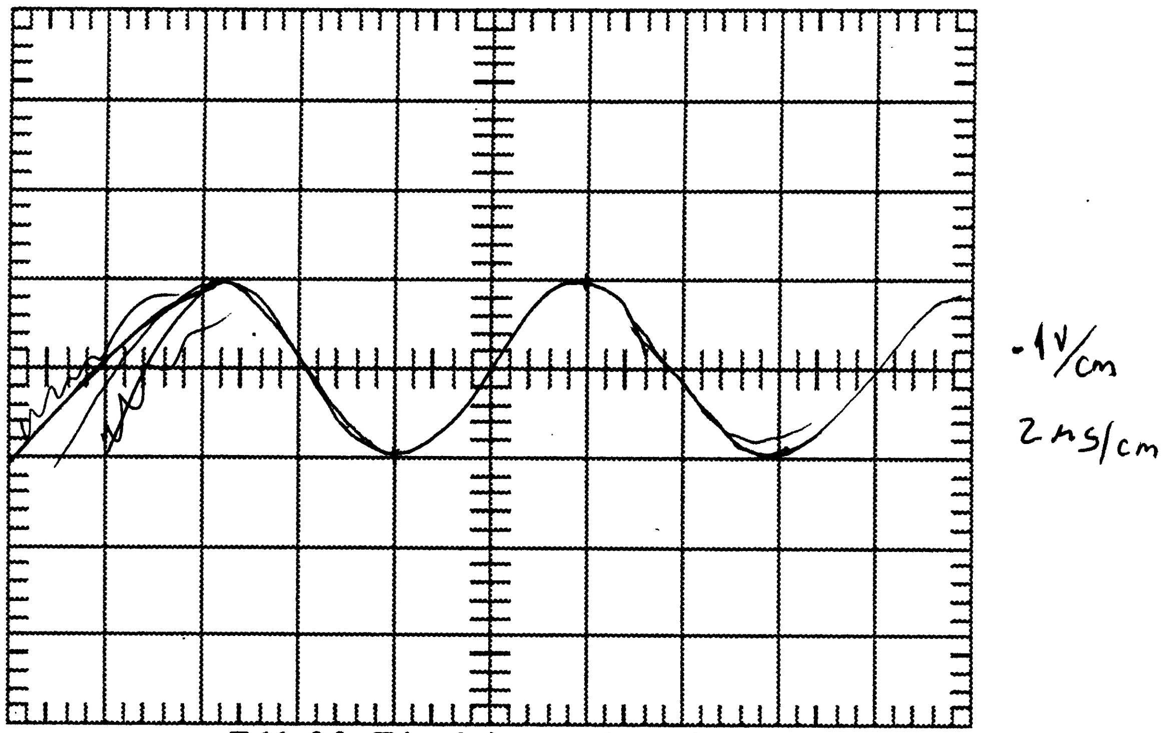


Table 3.3 - Triangle integrated waveform

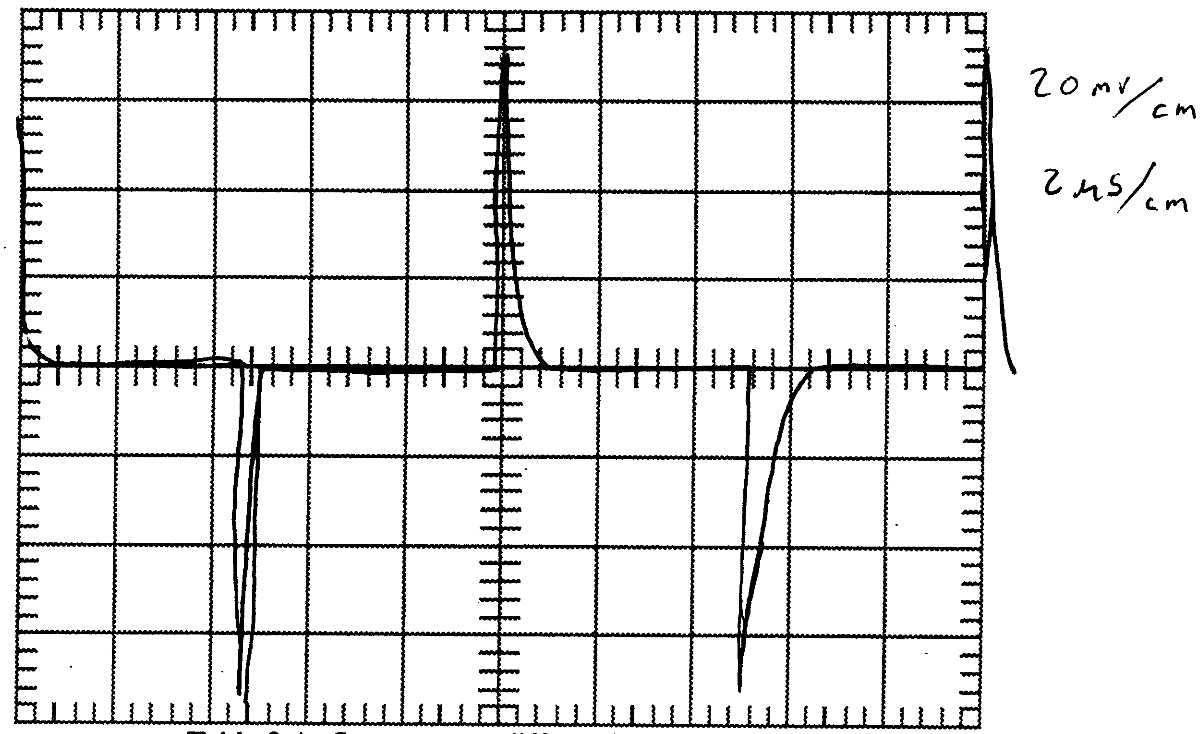


Table 3.4 - Square wave differentiator waveform

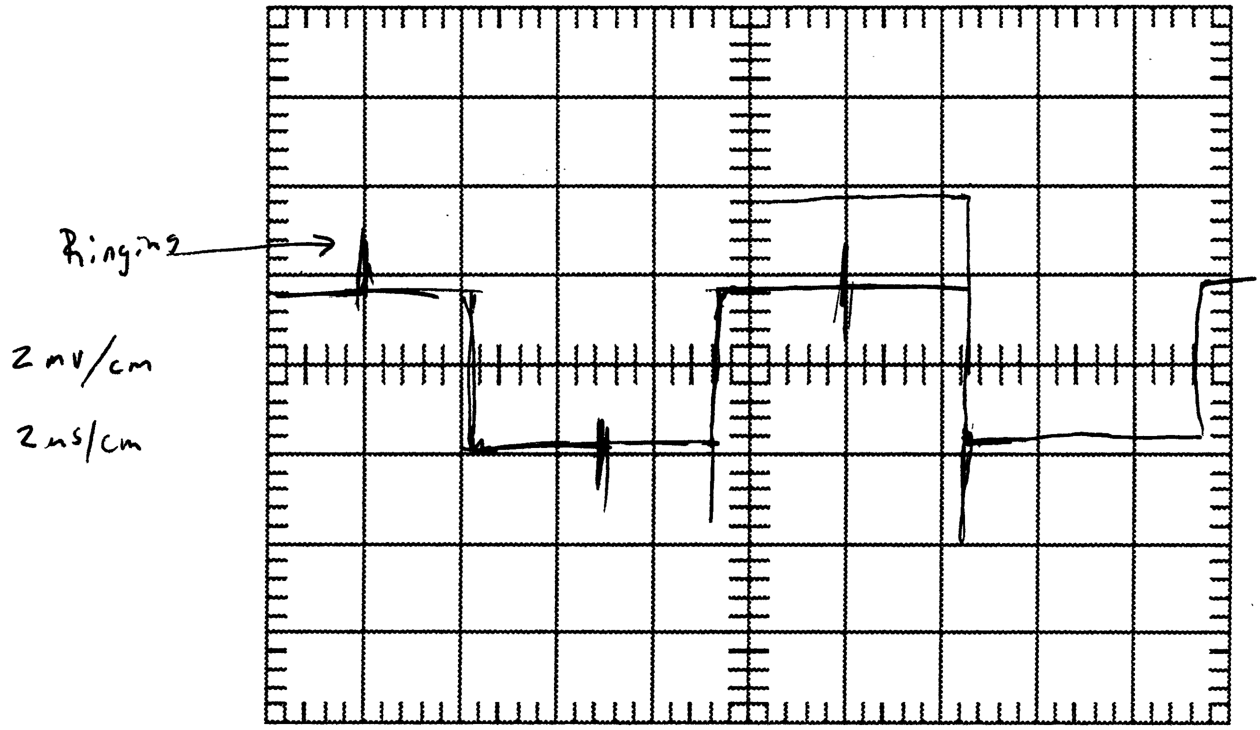


Table 3.5 - Triangle wave differentiator waveform

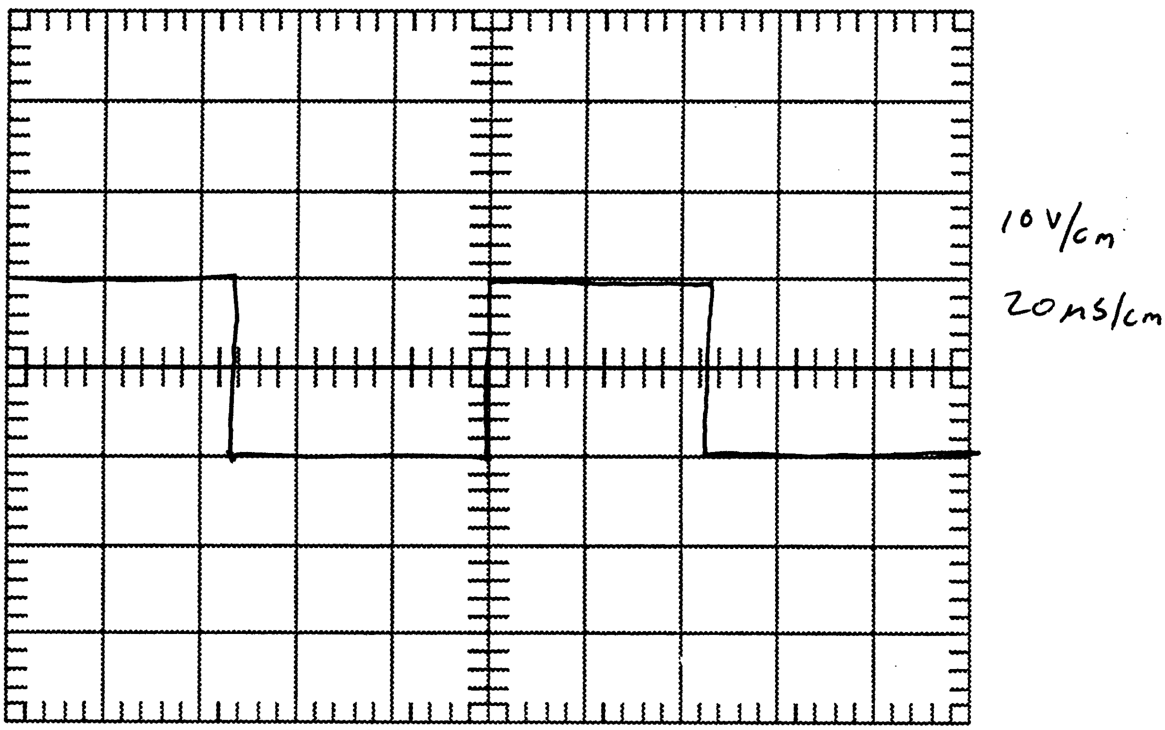


Table 3.6 - Probe measurements

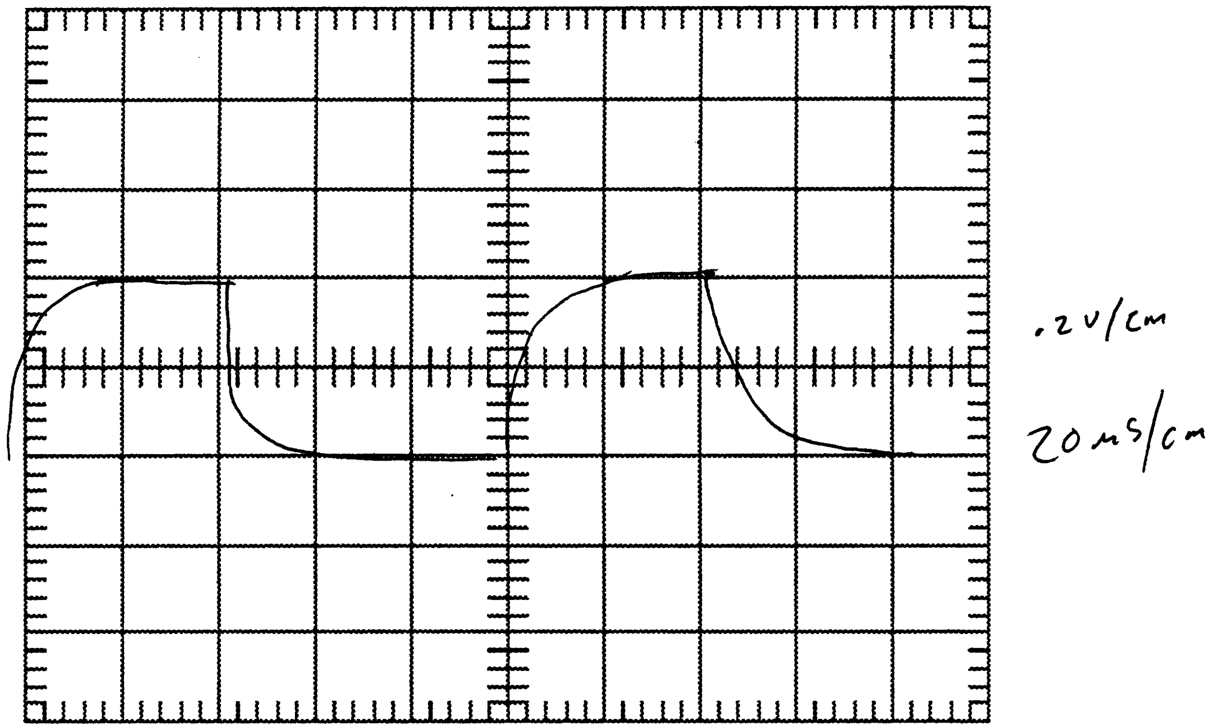
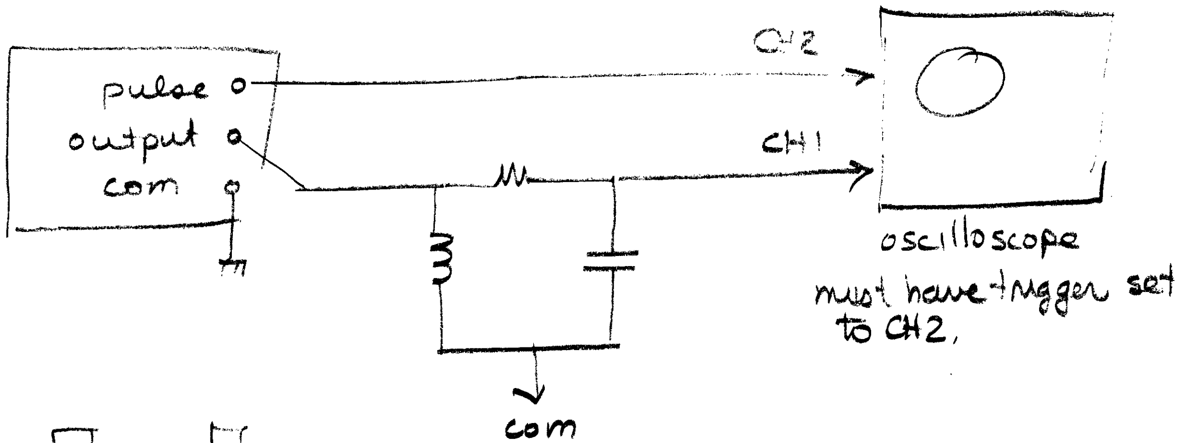


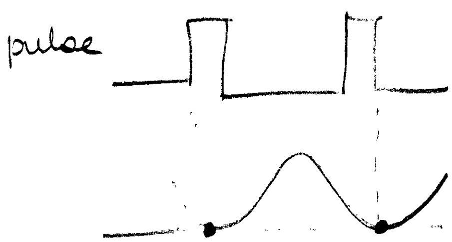
Table 3.7 - Compensated probe measurement

Boylestad & Nashelsky – Electronic Design & Circuit Theory

diodes	74
power diodes	92
zener diodes	74-82

Figure 4.1



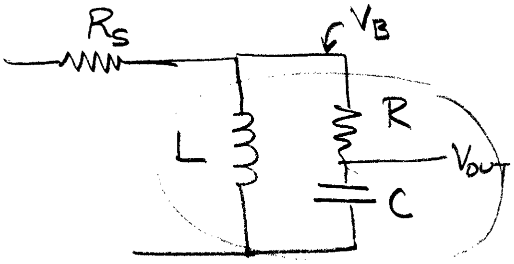


can set your scope to get 8 divisions across using variable adjust on time base

$$\frac{360}{8} = 45^\circ/\text{div.}$$

use DMM to measure series L of inductor !

<u>don't do part 2.</u>



$$Z_{11} = j\omega L \,\|\, \left(R + \frac{1}{j\omega C}\right) = \frac{(j\omega L)\left(R + \frac{1}{j\omega C}\right)}{R + j\omega L + \frac{1}{j\omega C}}$$

$$\frac{V_B}{V_S} = \frac{Z_{11}}{Z_{11} + R_S} = \frac{(j\omega L)\left(R + \frac{1}{j\omega C}\right)\frac{1}{R + j\omega L + \frac{1}{j\omega C}}}{(j\omega L)\left(R + \frac{1}{j\omega C}\right)\frac{1}{R + j\omega L + \frac{1}{j\omega C}} + R_S}$$

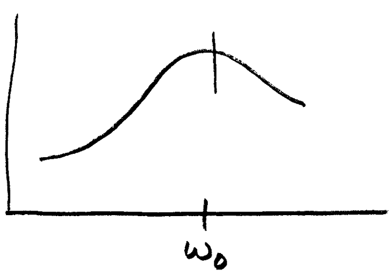
$$= \frac{(j\omega L)\left(R + \frac{1}{j\omega C}\right)}{(j\omega L)\left(R + \frac{1}{j\omega C}\right) + R_S\left(R + j\omega L + \frac{1}{j\omega C}\right)}$$

$$\frac{V_{OUT}}{V_S} = \frac{(j\omega L)\left(R + \frac{1}{j\omega C}\right)}{(j\omega L)\left(R + \frac{1}{j\omega C}\right) + R_S\left(R + j\omega L + \frac{1}{j\omega C}\right)} \left(\frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C} + R}\right)$$

$$= \frac{\frac{\omega L}{\omega C}}{R_S R + \frac{j\omega L}{j\omega C} + Rj\omega L + R_S j\omega L + \frac{R_S}{j\omega C}}$$

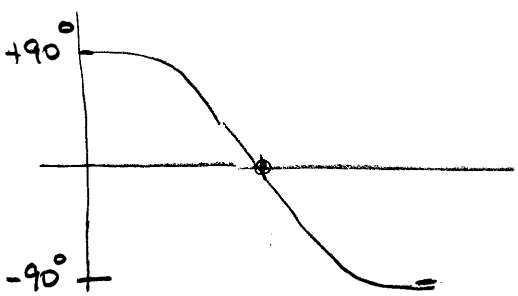
$$= \frac{L/C}{R_S R + \frac{L}{C} + j\left(R\omega L + R_S\omega L - \frac{R_S}{\omega C}\right)}$$

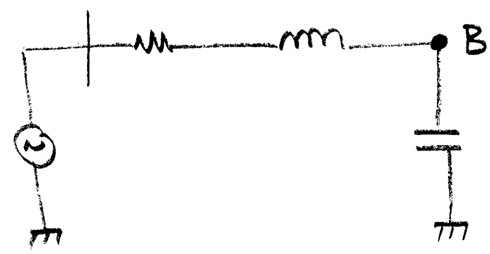
$\left|\frac{V_{OUT}}{V_S}\right|$



$\angle \frac{V_{OUT}}{V_S}$

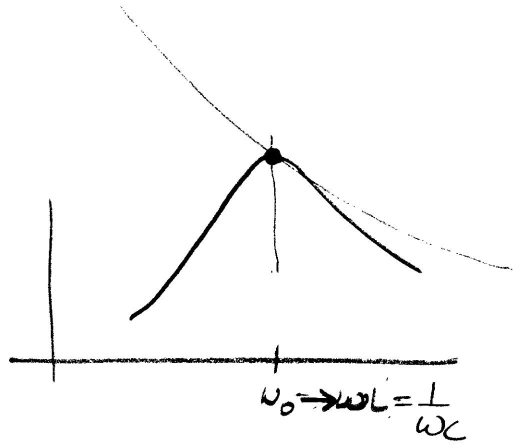
$\angle 0 - \angle +90$





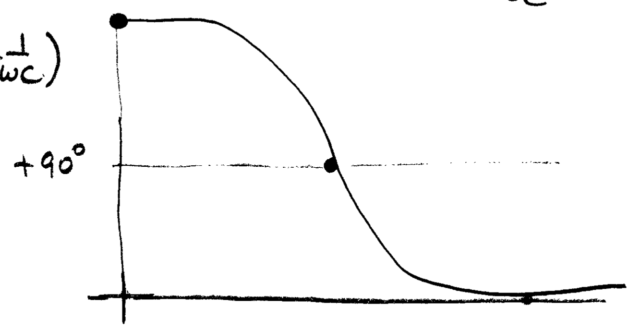
$$\frac{V_B}{V_S} = \frac{\frac{1}{j\omega C}}{R_S + j\omega L + \frac{1}{j\omega C}}$$

$$\left|\frac{V_B}{V_S}\right| = \frac{\left|\frac{1}{j\omega C}\right|}{\left|R_S + j\left(\omega L - \frac{1}{\omega C}\right)\right|}$$



$$\angle \frac{V_B}{V_S} = \angle \frac{1}{j\omega C} - \angle R_S + j\left(\omega L - \frac{1}{\omega C}\right)$$

$+90^\circ$



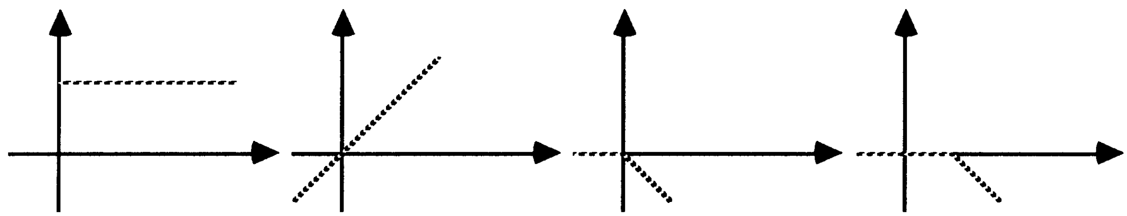
Given that

$$H(s) = \frac{10s}{(1+s)(1+\frac{s}{10})}$$

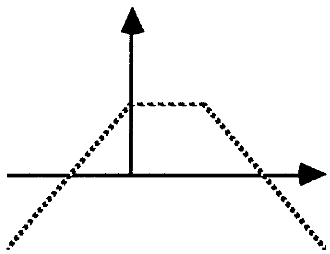
plot $|H(j\omega)|$ and $\angle H(j\omega)$

Solution:

$$20\log_{10}|H(j\omega)| = 20\log_{10}(10) + 20\log_{10}|\omega| - 20\log_{10}|1+j\omega| - 20\log_{10}|1+\frac{j\omega}{10}|$$



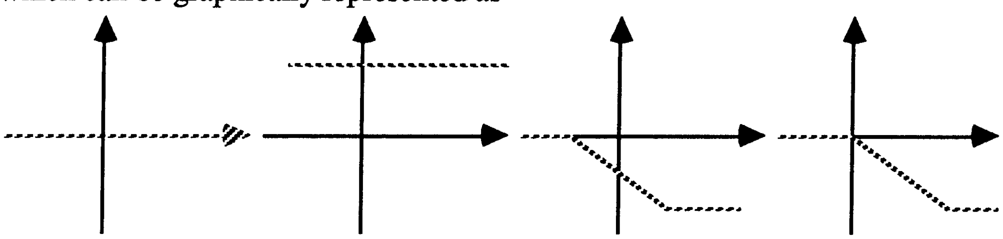
which sum up to



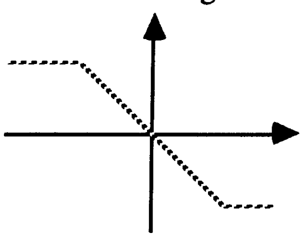
Similarily, the phases are

$$\angle H(j\omega) = \angle 10 + \angle j\omega - \angle(1+j\omega) - \angle(1+\frac{j\omega}{10})$$

which can be graphically represented as

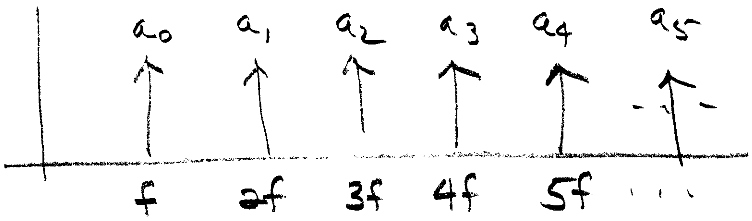


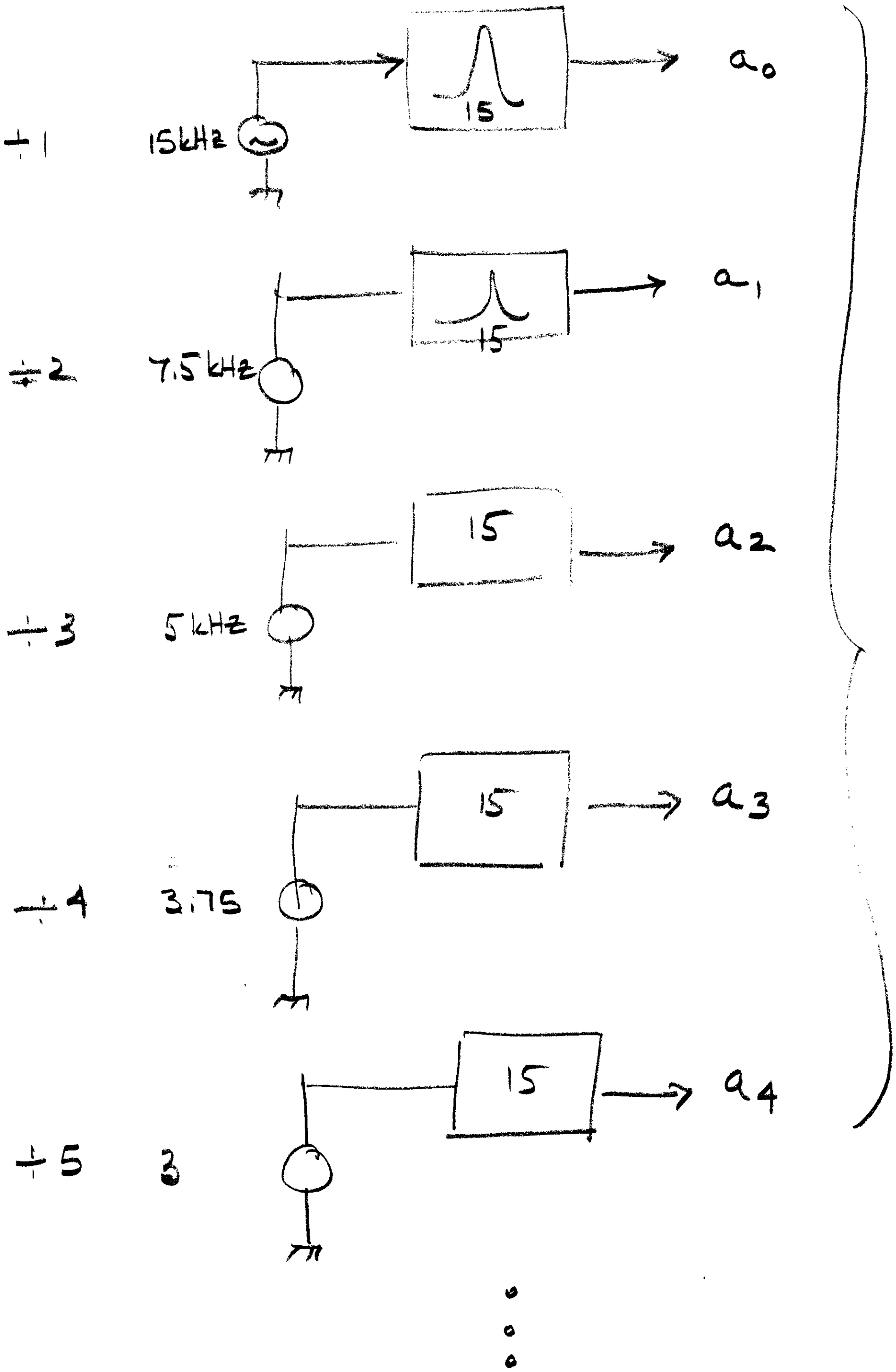
and summed to give



Fourier Analysis

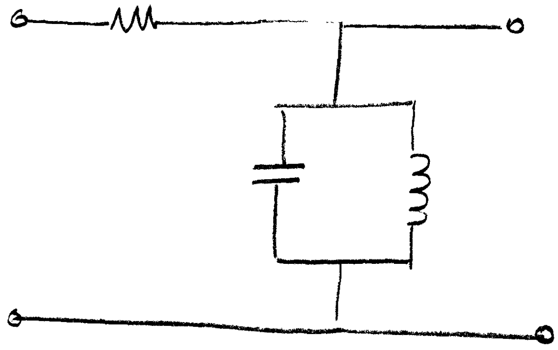
periodic signals





doesn't give phase
just magnitude

Part 3 resonance.

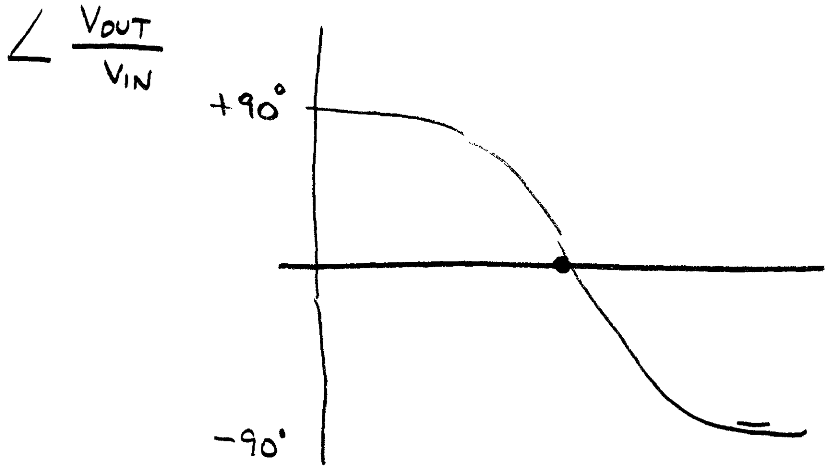


$$Z_{11} = \frac{1}{j\omega C} \,\Big\|\, j\omega L = \frac{j\omega C \cdot \frac{1}{j\omega L}}{\frac{1}{j\omega C} + j\omega L}$$

$$= \frac{C/L}{j\left(\omega L - \frac{1}{\omega C}\right)}$$

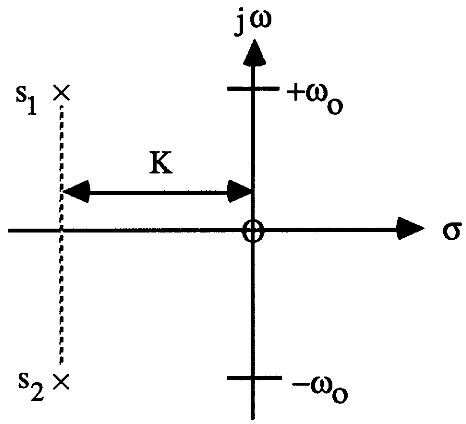
$$\frac{V_{OUT}}{V_{IN}} = \frac{Z_{11}}{Z_{11} + R} = \frac{C/L \; \frac{1}{j\left(\omega L - \frac{1}{\omega C}\right)}}{C/L \; \frac{1}{j\left(\omega L - \frac{1}{\omega C}\right)} + R}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{C/L}{C/L + Rj\left(\omega L - \frac{1}{\omega C}\right)} = \frac{C/LR}{C/LR + j\left(\omega L - \frac{1}{\omega C}\right)}$$



measure L, RC using digital <u>LRC meter</u>

A system has the pole-zero diagram shown below.



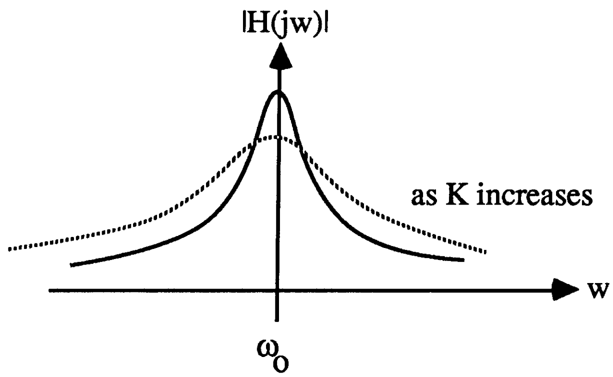
(a) Sketch the magnitude of the system frequency response for K very small, i.e. near the jω axis.

(b) Indicate what happens to your answer for (a) as K becomes larger, i.e. the poles move away from the jω axis.

Solution:

(a)

$$H(j\omega) \approx K\frac{j\omega-0}{(j\omega-s_1)(j\omega-s_2)} \rightarrow K\frac{\omega}{(\omega_o+\omega)(\omega_o-\omega)} = K\frac{\omega}{\omega_o^2-\omega^2}$$



(b) as K increases the peak diminishes and broadens

EEAP 243
Lab 4

Lab Work:
Questions Due:

FREQUENCY RESPONSE

READING ASSIGNMENT: Horowitz, pgs. 25-35

Abstract:
This lab demonstrates the frequency response of RC and RLC networks. Frequency response is shown to be an alternative to differential equations and time constants for analyzing the time response of RC circuits, specifically a compensated scope probe. A resonant circuit is studied and used to examine the spectral content of a square wave.

Part 1 - Phase and Frequency Response Measurement
Networks which include inductors and capacitors affect both the amplitude and the phase of periodic signals. To measure phase shift, connect your circuit to the scope's channel 1 input (CH1) and connect the pulse output of the signal generator to channel 2 (CH2). Set the display mode knob to DUAL, press the CH2 trigger source button to trigger on the pulse, and make sure that the INV CH2 button is not pressed. Under these conditions, the positive going step of the pulse signal is always synchronized with the negative peak of the generator's waveform output. See Fig. 4.1.

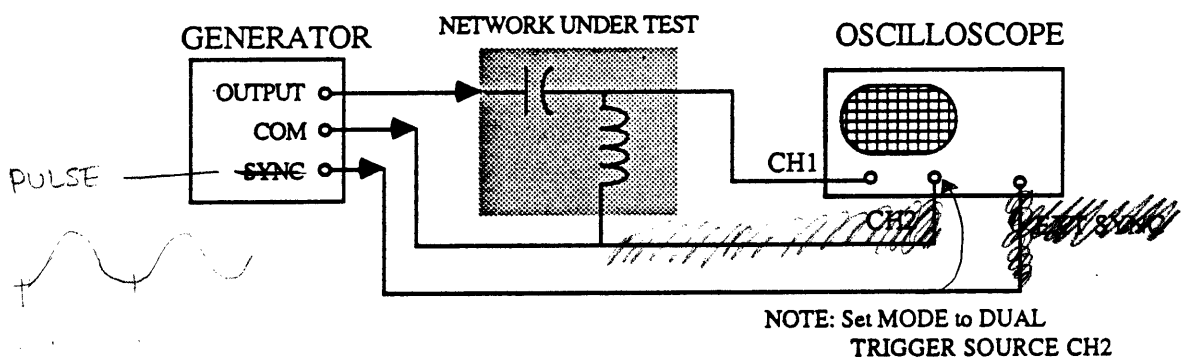


Figure 4.1 - Oscilloscope synchronization to generator output

A convenient way to measure phase shift is to set the scope's VAR SWEEP control at each of your test frequencies so that the distance between rising steps on the pulse signal is eight centimeters. If you do this, each centimeter of displacement between the negative peak at point B and the rising step of the pulse will correspond to a 45 degree phase shift. This phase shift is illustrated in Fig. 4.2.

(1) Using the scope, set the signal generator to produce a 10 V_{p-p} sine wave at 1 KHz with zero DC offset. Do not change the amplitude setting for the rest of this part. You can assume that the generator will produce a constant 10 V_{p-p} for all of the frequencies used in this part of the lab.
(2) Build the circuit shown in Fig. 4.3. R_s is the internal output resistance of the generator.

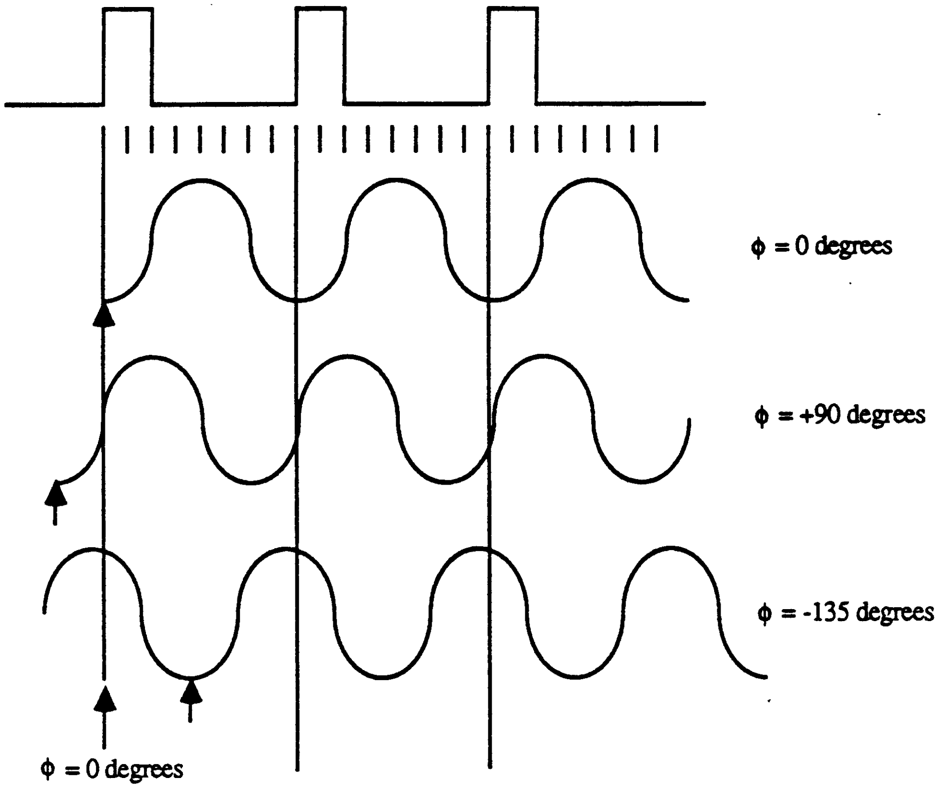


Figure 4.2 - Oscilloscope phase measurements

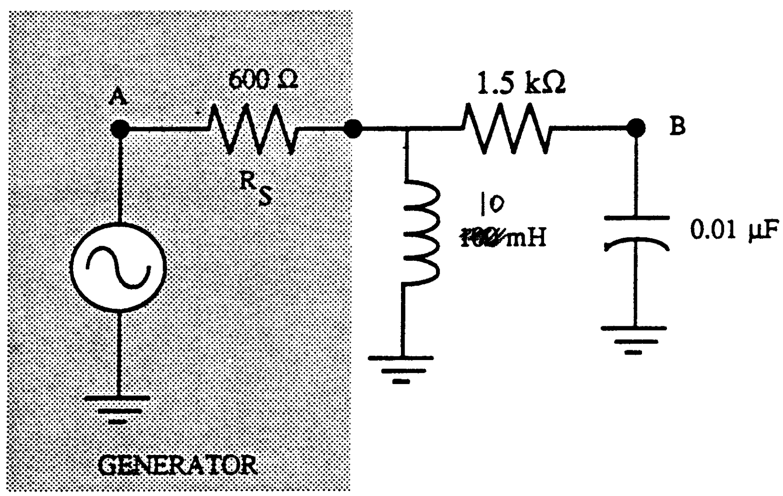


Figure 4.3 - Network for frequency response measurements

(3) Using the scope, record the amplitude and phase shift for the frequencies from 10 Hz to 100 KHz listed in Table 4.1. Adjust the vertical sensitivity as necessary to make accurate amplitude measurements and try to measure the phase shift to within 9 degrees (one minor division). You should use BRIGHT LINE OFF for your low frequency measurements or else the scope display will not be stable.

(4) Repeat steps 2 and 3 for the circuit of Fig. 4.4. You may start your measurements at 100 Hz. Record your results in Table 4.2.

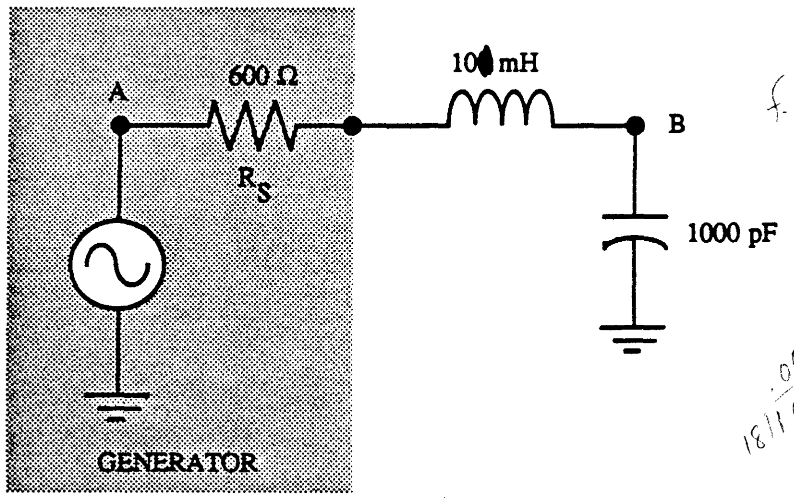


Figure 4.4 - Second frequency response network

(5) Find the frequency at which the amplitude reaches its peak (probably [redacted] KHz) and measure the amplitude and phase shift at that frequency.

(6) Use the DMM to measure the series resistance of the inductor. Record your result in Table 4.3.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA

Part II - Compensated oscilloscope probe

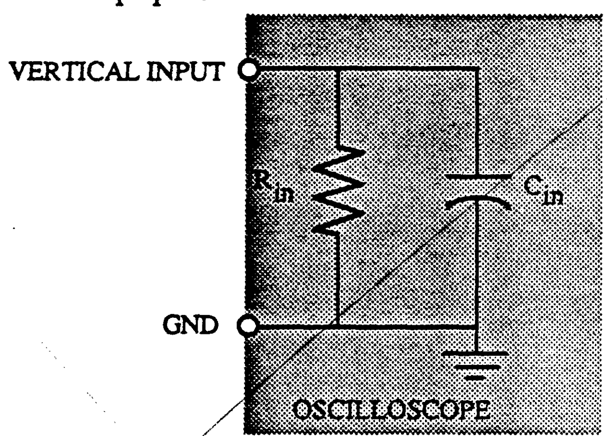


Figure 4.5 - Equivalent input circuit of oscilloscope

As shown in Fig. 4.5 and discussed in Lab #3, the input of the oscilloscope appears as a parallel resistance and capacitance to ground. We compensated for the cable capacitance in Lab #3 using a voltage divider analysis. The same analysis can be done more formally using frequency domain analysis.

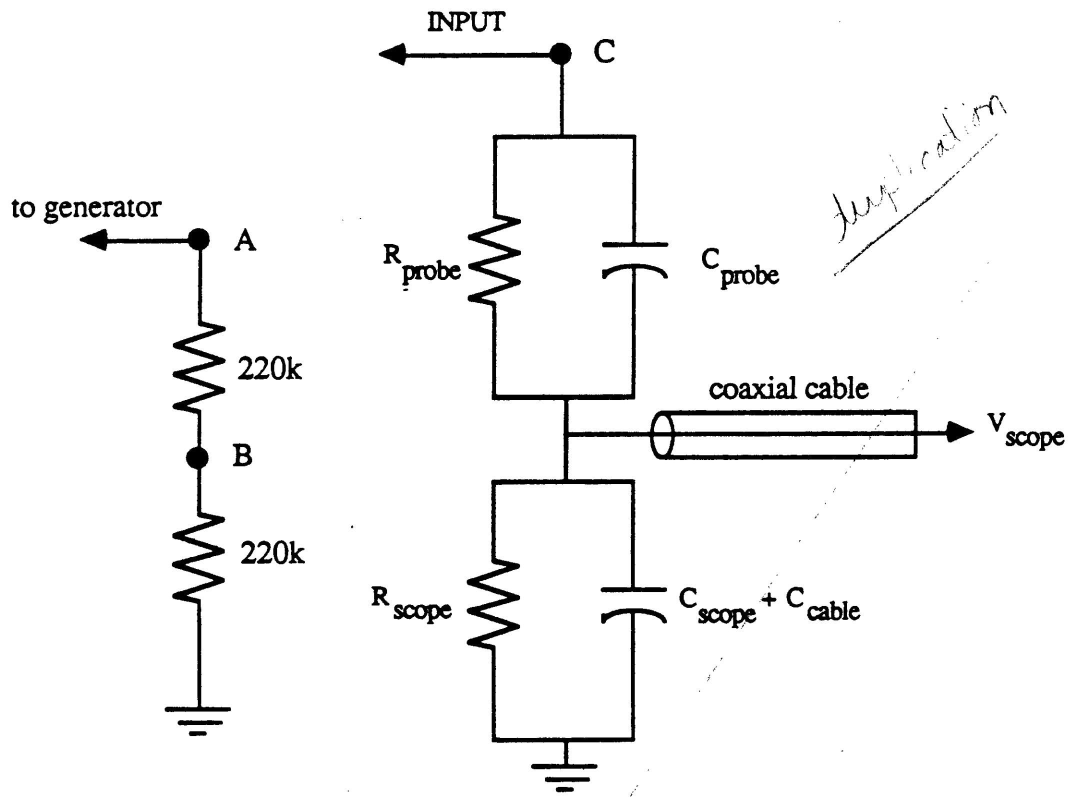


Figure 4.6 - Compensated scope probe circuit

(6) Set the generator to maximum amplitude with zero DC offset.
(7) Use the coaxial cable to measure the peak-peak AC voltage at points A and B with the generator set to a sine wave output at the frequencies shown in Table 4.4.

If we define "compensation" as adjusting the probe circuit to produce a waveform equivalent to a resistive voltage divider, we can "compensate" the probe circuit by adjusting the capacitor. When the probe is adjusted to satisify Eqn.(1), the scope will display amplitude according to Eqn. 4.2.

$$R_{probe} \times C_{probe} = R_{scope} \times (C_{scope} + C_{coax}) \quad (4.1)$$

$$\text{displayed V} = \text{actual V} \times \frac{R_{scope}}{R_{scope} + R_{probe}} \quad (4.2)$$

(1) Construct the circuit shown in Figure 4.3 where R_{probe}=10M and C_{probe} is a 1.2-30 pF variable capacitor. This is the same circuit you built in Lab #3.
(2) Set the generator to a 1 KHz square wave at maximum amplitude and zero DC offset.
(3) Connect the probe input (point C) to point A. Observe what happens as you turn the variable capacitor a full 360 degrees.
(4) Adjust the capacitor so that the tops and bottoms of the square wave are perfectly flat and horizontal.(Note that this is how you would adjust any compensated probe. Terminal C-7 on your scope is a square wave source provided for compensating probes.)
(5) Remove the wire between points A and C and connect points B and C.

(6) Record the displayed voltages with the generator set to a sine wave for the frequencies shown in Table 4.5.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE CONTINUING.

Part 3 - Resonance

Construct the circuit shown in Figure 4.7. Adjust your signal generator for a 15 kHz sine wave output and connect it to the input of your circuit. Measure the peak-peak input and output voltage with an oscilloscope for the frequencies shown below.

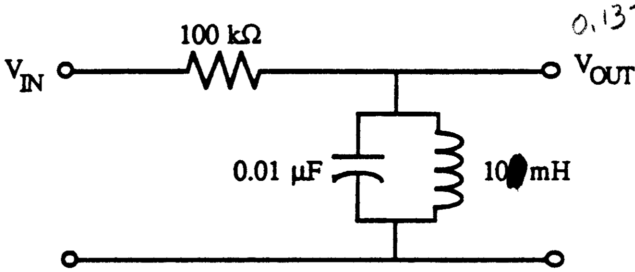


Figure 4.7 - Resonant network

Measure your component values (i.e. L, R and C) using the digital LCR meter in the instrument room.

Part 4 - Fourier analysis

All signals can be modeled as sums of sinusoids according to the following Fourier series expansion

$$v(t) = \sum_{i=1}^{\infty} \{ a_i \cos(\omega_i t) + b_i \sin(\omega_i t) \} \qquad (4.3)$$

where $\omega_i = 2\pi/T$. The signal must repeat every T seconds where T is known as the period of the signal. This is a very important relationship as it allows us to solve problems in the frequency domain. This is especially useful for filters and resonance problems. We will not attempt to prove this relationship or really do anything with it. However, we can establish that it really works by doing a crude experiment. The resonant circuit of Figure 4.7 has a very narrow resonance which means that only a small band of frequencies can pass through it. For example, if the network was resonant at 15 kHz then it would pass only a small band of frequencies near 15 kHz. If we could vary the filter's resonant frequency then we could look at the frequency components of a signal. Unfortunately, we do not have the components to vary the resonant frequency of our network nor to build enough filters with different resonant frequencies to check the spectrum of any real signal. However, we can vary our signal frequency and then scale the results. This sounds more complicated that it really is. Measure the output voltage of your resonant network for a square wave signal at the resonant frequency. Record this voltage and frequency in Table 4.7. Now slowly decrease the generator frequency until you see another output signal from the filter. Find and record at least three more signals. HINT: all signals will be at odd multiples of your resonant frequency, i.e. 1, 3, 5, etc.

Questions:

1. Make Bode plots of the phase and magnitude response of the circuits of Figures 4.3 and 4.4 using your data from Tables 1 and 2. Using a different color pen or pencil, add straight line approximations to each of the four graphs. Please draw all of your plots on graph paper.
2. (a) What is the transfer function of the circuit shown in Figure 4.4?
   (b) Without using your experimental data, calculate the frequency and amplitude of the peak output voltage. (Hint: at what frequency is the slope of the amplitude zero?)
   (c) What peak amplitude and frequency are indicated by your Bode plots?
3. Re-draw circuit 4.4 modelling the inductor as an ideal inductor in series with the resistance you measured. Re-calculate the poles and zeros.
4. The frequency dependent terms in the combined probe/scope input circuit transfer function (V_o/V_s) drop out when Eqn. 4.1 is satisfied. Find the transfer function of the circuit in Figure 4.6 and prove that it is frequency independent when Eqn. 4.1 is satisfied.
5. Calculate the resonant frequency of Figure 4.7 and compare it with your measured value. Explain any discrepancies.
6. Plot $\log_{10}(V_{OUT}/V_{IN}@f_{res})$ from Table 4.5 on the vertical axis of versus frequency on the horizontal axis. The resulting graph is a realization of the Fourier series equation, Eqn. 4.3, and is called the frequency spectrum of the generator output signal.

BONUS
Write a computer program to sum sine (or cosine) signals at f, 2f, 3f up to 10f together according to Eqn. (4.1). Your data ($V_{OUT}/V_{IN}@f_{res}$) from Table 4.1 represents the b_i coefficients in Equation 4.1. Assume that the a_i coefficients are zero. Plot your results for a single sine wave of amplitude 1 at frequency f. Then, add the sine wave of amplitude $V_{OUT}/V_{IN}@f_{res}$ at frequency 3f. Plot your results. Repeat this process for as many frequency coefficients you measured (up to 10). Discuss your results. What would have happened if you had used your results for the a_i coefficients rather than for the b_i coefficients?

Explain the Fourier series!

EEAP 243 LAB 4 EVALUATION

NAME (print)__________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1-3

Assume that $F_x = 0.9$, $V_f = 1.0$, and that the transformer's nominal ratings are correct. What load resistance would be necessary in each of the three rectifier circuits to to establish a DC load current of 50 mA ?

__________ half wave rectifier

__________ full wave bridge rectifier

__________ full wave center tap rectifier

EEAP 243

NAMES: ____

Lab 4 Data

frequency	Amplitude, V_{P-P}	Phase, degrees
10 Hz	________	________
20 Hz	________	________
50 Hz	________	________
100 Hz	________	________
200 Hz	________	________
500 Hz	________	________
1 KHz	________	________
2 KHz	________	________
5 KHz	________	________
10 KHz	________	________
20 KHz	________	________
50 KHz	________	________
100 KHz	________	________

Table 4.1 Frequency response of Figure 4.3 circuit

frequency	Amplitude, V_{P-P}	Phase, degrees
100 Hz	________	________
200 Hz	________	________
500 Hz	________	________
1 KHz	________	________
2 KHz	________	________
5 KHz	________	________
10 KHz	________	________
20 KHz	________	________
50 KHz	________	________
100 KHz	________	________

Table 4.2 Frequency response of RC circuit

DC series resistance of inductor: ________________ohms.

Table 4.3

frequency	$V_{A,P-P}$	$V_{B,P-P}$
1 KHz	________	________
2 KHz	________	________
5 KHz	________	________
10 KHz	________	________
20 KHz	________	________
50 KHz	________	________
100 KHz	________	________
200 KHz	________	________
500 KHz	________	________
1 MHz.	________	________

Table 4.4 Frequency response measurements of uncompensated scope cable

frequency	V_{P-P}
1 KHz	________
2 KHz	________
5 KHz	________
10 KHZ	________
20 KHz	________
50 KHZ	________
100 KHz	________
200 KHz	________
500 KHz	________
1 MHz.	________

Table 4.5 Frequency response measurements of compensated scope cable

change

frequency	V_{IN}	V_{OUT}
15 kHz		
16 kHz		
17 kHz		
18 kHz		
19 kHz		
20 kHz		
21 kHz		
22 kHz		
23 kHz		
24 kHz		
25 kHz		

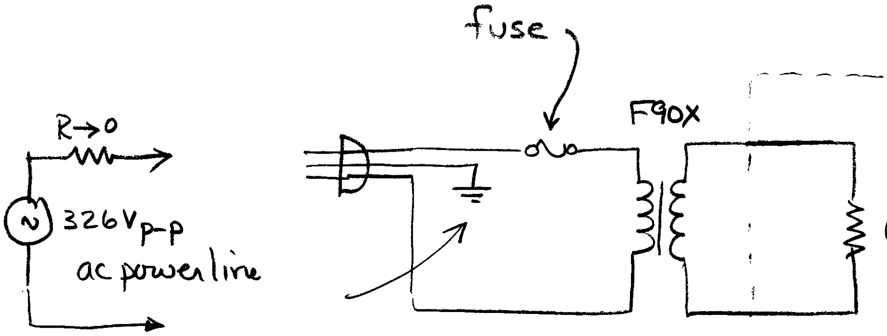
Table 4.6 - Frequency response measurements of resonant circuit

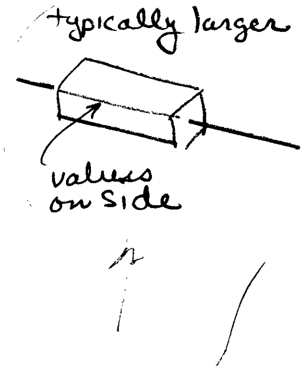
frequency	multiple of f_{res}	VIN	V_{OUT}	$V_{OUT}/(V_{IN}@f_{res})$
	1			

Table 4.7 Frequency Analysis of a Square Wave

1

real transformers





can deliver hundreds of amperes

Triad F90X
Secondary 10-20CT-40CT@100mA

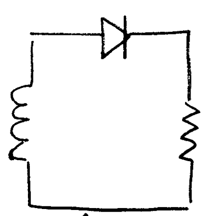
dc voltage — half-wave — bridge

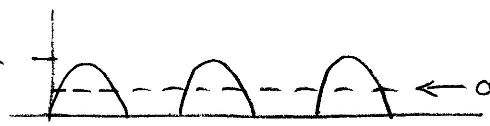
typically only specified as rms ac voltage for a given secondary current.

⟶ what is color code?
- RED
- YELLOW (CT)
- GREEN
-
-

half-wave rectifier

suppose transformer is 12.6 vac.





← average value $= \frac{1}{T}\int_0^T \sin t \, dt$ over one halfcycle $= \frac{1}{\pi}$

peak secondary voltage is $\sqrt{2}\ 12.6 = 17.8$ volts

$\therefore V_{dc} = \frac{\sqrt{2}}{\pi} 12.6$

≈ 5.66 volts

diode characteristics

max. current diode can handle

I_{dc} = average load current $= \frac{V_{DC}}{R_L}$ (usually listed as I_o on datasheets)

1N4001 has an I_o of 1A.

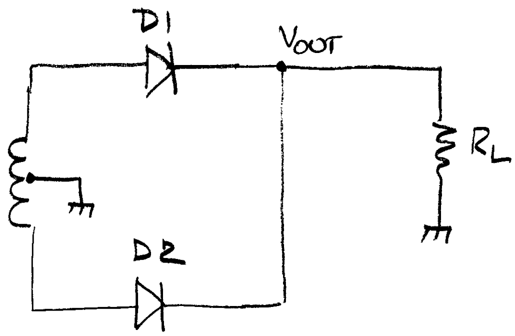
If $R_L = 10\Omega$ in above bridge rectifier, $I_{dc} = \frac{5.66}{10\Omega} \approx 0.56A$ which is ok

Sections 1.25 – 1.28 in Horowitz

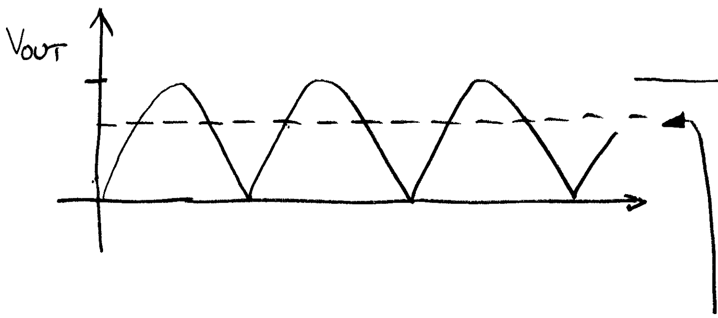
on negative half cycle diode is off and <u>must</u> withstand the peak voltage without conducting current.

maximum reverse voltage is called PIV or PRV.

<u>Full-wave rectifier</u>



When D1 is on, D2 is off and vice verse.



$= \frac{1}{2} V_{peak}$ (due to center tap)

$\frac{\sqrt{2}}{2}(12.6) \approx 8.91$ volts.

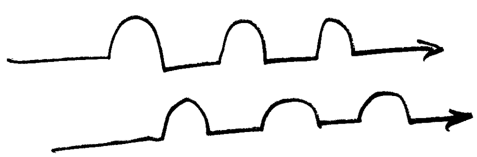
dc is now $\frac{2}{\pi} V_{peak}$ since twice as much dc to average.

$\frac{2}{\pi}\left(\frac{\sqrt{2} \cdot 12.6}{2}\right) = 5.67$ volts.

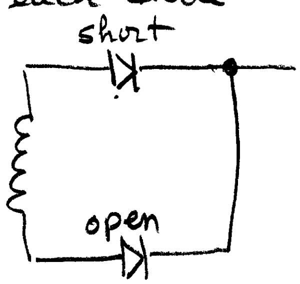
(peak across each diode is only $\frac{1}{2}$ as much)

if $R_L = 10\Omega$ as before $I_{dc} = \frac{5.67}{10\Omega} = 0.567A$

but each diode need only be $\frac{1}{2}$ this since each diode's current looks like



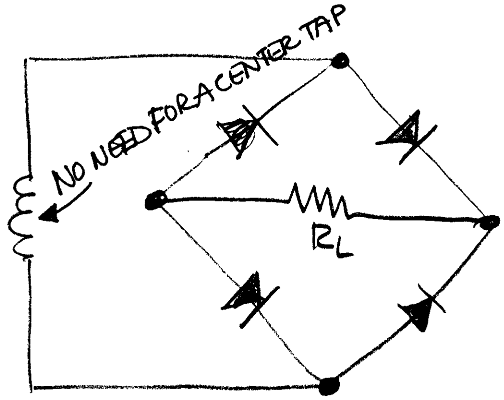
how about PIV of each diode $PIV = \sqrt{2}\,(12.6)$

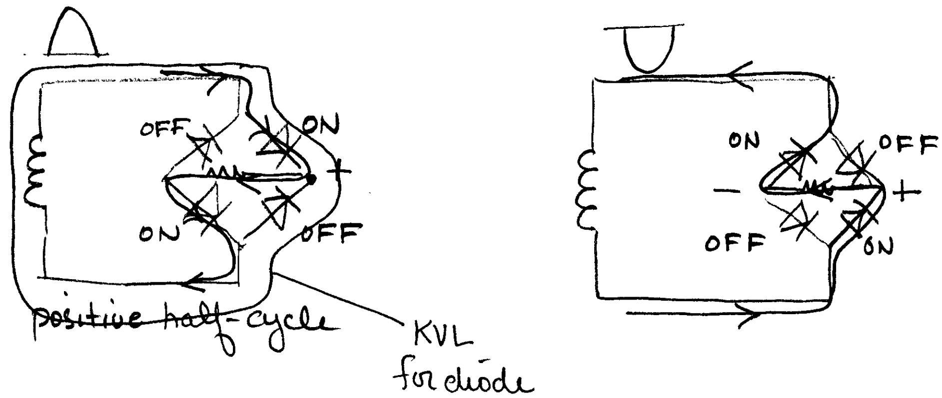


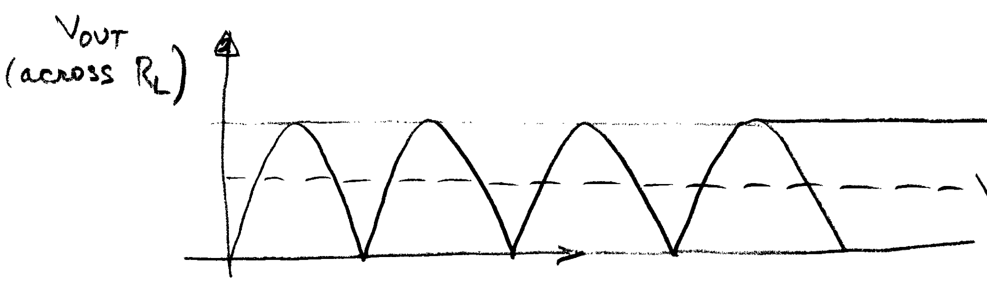
apply KVL around this loop!

most popular rectifier circuit — bridge rectifier

full peak voltage of half-wave rectifier
higher average value of full wave







$V_{peak} = \sqrt{2}(12.6) \approx 17.8 \text{ v.}$

$V_{dc} = \frac{2}{\pi} V_{peak} \cong 11.3$ volts.

If $R_L = 10\Omega$ $\quad I_{dc} = \frac{11.3 \text{ volts}}{10\,\Omega} = 1.13$ A.

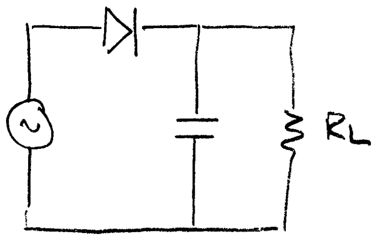
but each diode only conducts $\frac{1}{2}$ cycle so its ratings drop to $\frac{1.13}{2}$ A.

use KVL around loop shown above

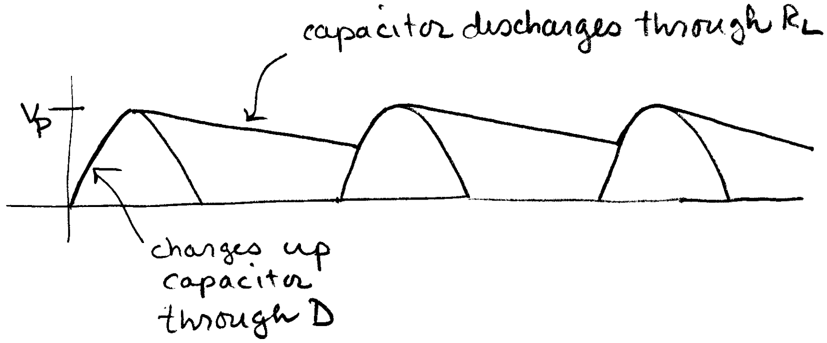
$$V_{peak} - PIV - 0 = 0$$

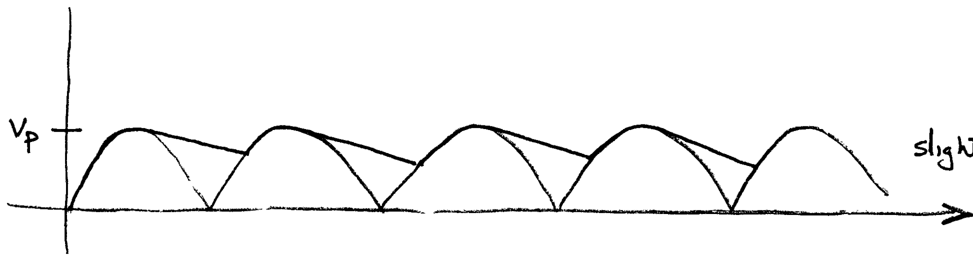
$$\therefore \quad PIV = V_{peak}.$$

capacitor input filter

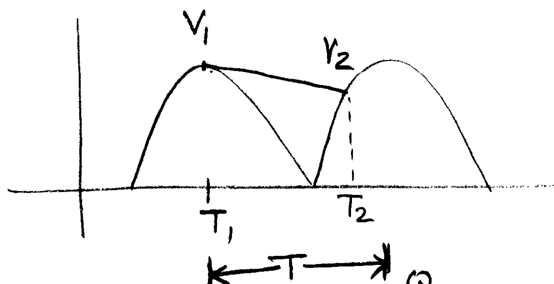


half-wave





slightly higher average dc.



for a capacitor $C = \frac{Q}{V}$ or $V = \frac{Q}{C}$.

from the graph $V_{ripple} = V_1 - V_2 = \underbrace{\frac{Q_1}{C} - \frac{Q_2}{C}}_{\text{C does not change}} = \frac{Q_1 - Q_2}{C}$

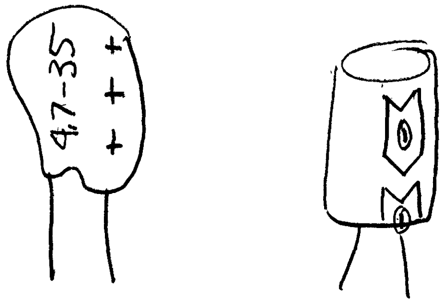
Now: $$\frac{V_1 - V_2}{T_1 - T_2} = \frac{1}{C} \frac{Q_1 - Q_2}{T_1 - T_2}$$

if $R_L C$ is very large $T_1 - T_2 \approx T$, the period of the ripple.

$$\frac{V_1 - V_2}{T} = \frac{1}{C} \frac{Q_1 - Q_2}{T} = \frac{1}{C} I$$

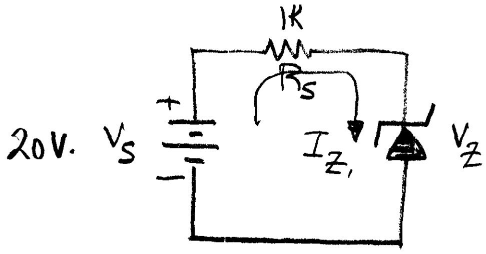
$$\therefore V_{ripple} = V_1 - V_2 \cong \frac{T}{C} I = \frac{I}{fC}$$

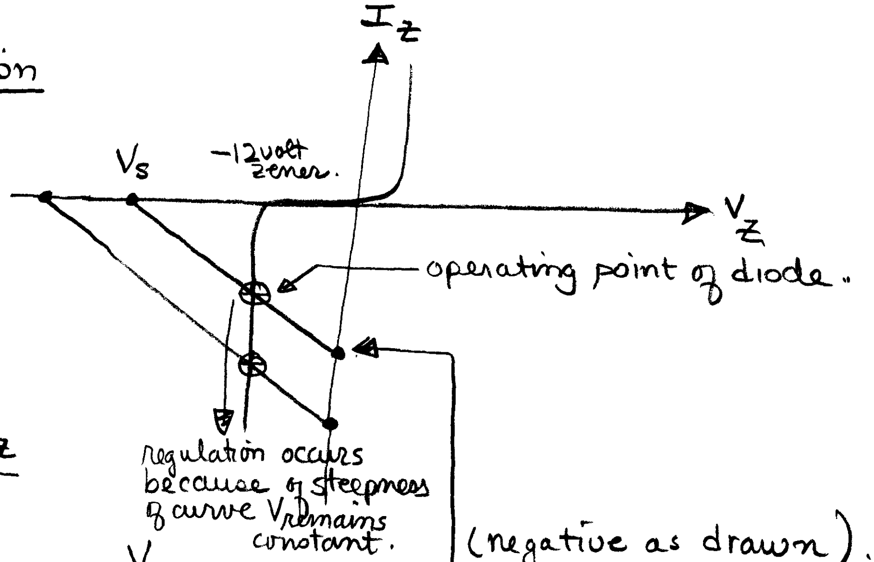
capacitors



capacitors **can** **explode** if polarity is reversed!

zener diode regulation



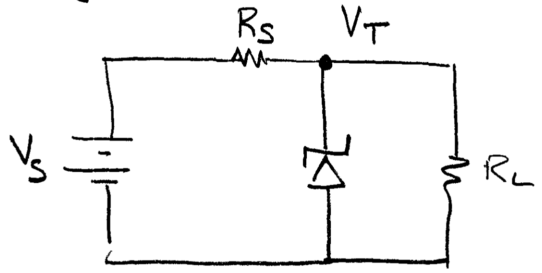


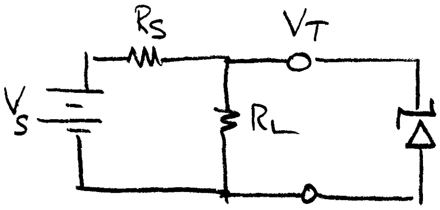
(equals I_Z) $I_S = \dfrac{V_S - V_Z}{R_S}$

if $V_Z = 0 \quad I = \dfrac{V_S}{R_S}$

if $I_Z = 0 \quad V_Z = V_S$

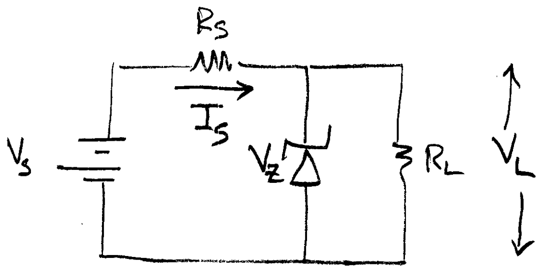
zener regulator.





$V_T = \dfrac{R_L}{R_S + R_L} V_S$

$R_T = R_S \parallel R_L$.



assume diode is working.
(broken down)

<u>R_S is for current limiting</u>

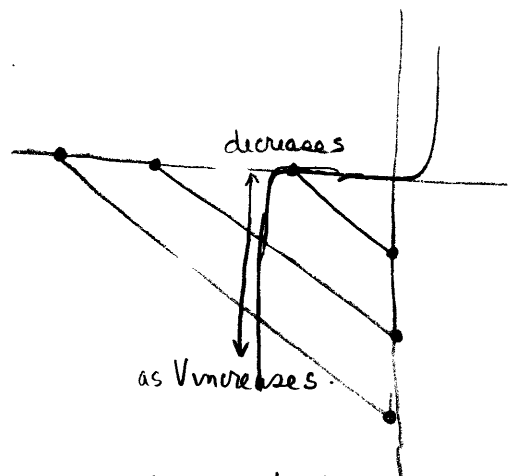
$$I_S = \frac{V_S - V_Z}{R_S}$$

$$I_L \approx \frac{V_Z}{R_L}.$$

$$\therefore \quad I_Z = I_S - I_L$$

<u>zener dropout point</u>

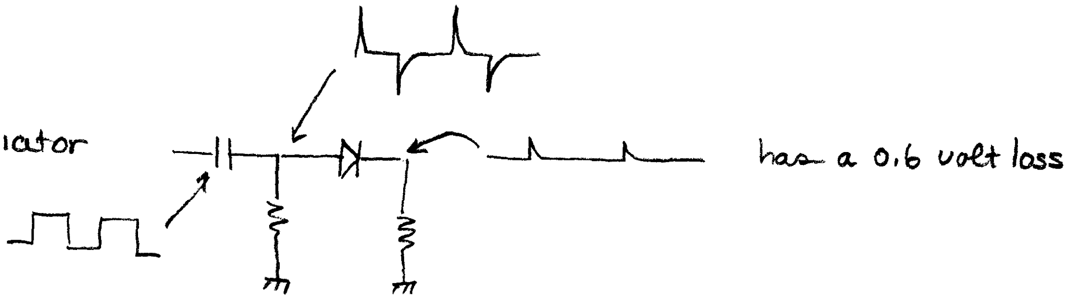
(see section 2.04 of Horowitz).



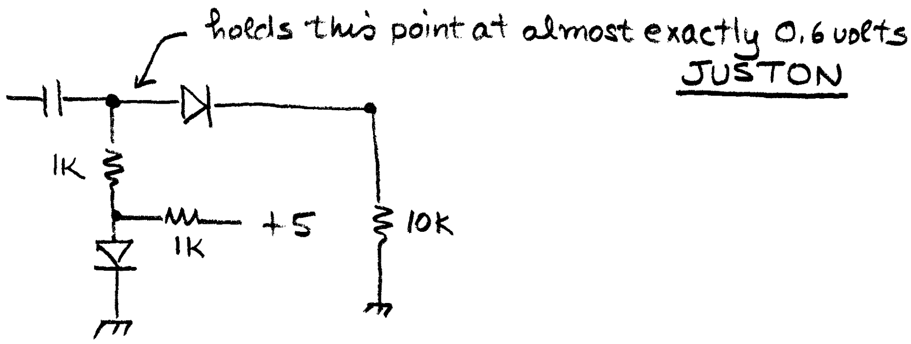
whenever $I_Z \rightarrow 0$ regulation is lost.

1.30 diode clamps

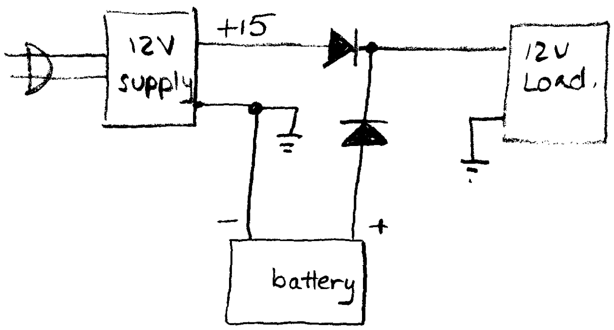
rectifying differentiator



bias diode

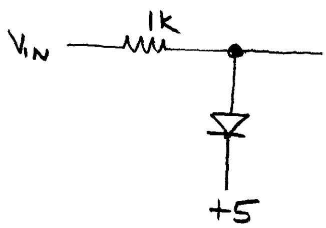


diode switching.

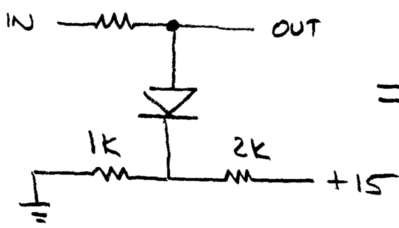


diode clamps.

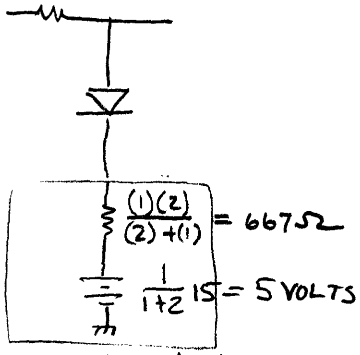
standard for all CMOS circuits



if $V_{IN} > 5.0 + 0.7$ volts output saturates at 5.7 volts.



⟹



Thevenized

Harris
Should have students look at output of diodes with scope. to ~~[illegible]~~ - however, it seems this is done by measuring A→C.

EEAP 243 | Lab Work:
Lab 5 | Questions Due:

DIODE CIRCUITS

READING ASSIGNMENT: Horowitz, pgs. 35-43, 187-194.

Abstract:
This laboratory will examine the application of diodes to practical power supply, clamping and switching circuits.

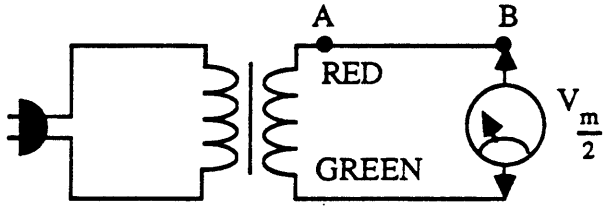
Part 1: Power supply circuits (do one only)

The fundamental component of a power supply is the transformer. We will measure the open and loaded output voltage of a transformer.

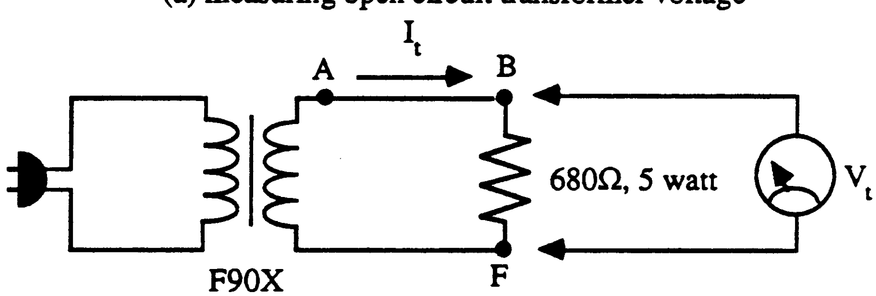
(1) Set the DMM to the 200 V AC scale, connect it to the transformer as shown in Fig.5.1 (a), and record $V_{m/2}$, the no load transformer voltage. Note that the color coding of the transformer secondary, shown explicitly in Figure 5.1 (a), indicates the transformer output voltage and is used to denote different connections such as a center tap.

(2) Connect the resistor as shown in Fig.5.1 (b) and measure V_t across the load.

(3) Remove the short circuit between A and B, connect the mA input of the DMM to A, connect the DMM COM input to B, set the meter to the 200 mA AC, and record I_t through the load.



(a) measuring open circuit transformer voltage



(b) measuring loaded transformer voltage and current

Figure 5.1 Measuring transformer characteristics

A single diode can be used to rectify the output from your transformer to create a simple power supply. Unfortunately, the output voltage is a pulsating dc. A capacitor will serve to remove most of this pulsation. From a time dependent viewpoint, the function of the capacitor is to store electrons when the diode output voltage is large and release electrons when the diode output voltage is low. The result is a reduction of the ac component, called ripple, of the output voltage. From the frequency domain viewpoint the capacitor (acting with the forward resistance of the diode and other circuit resistances) acts as a low-pass filter. By choosing the capacitor value to attenuate 60Hz and above a relatively constant dc output voltage can be produced.

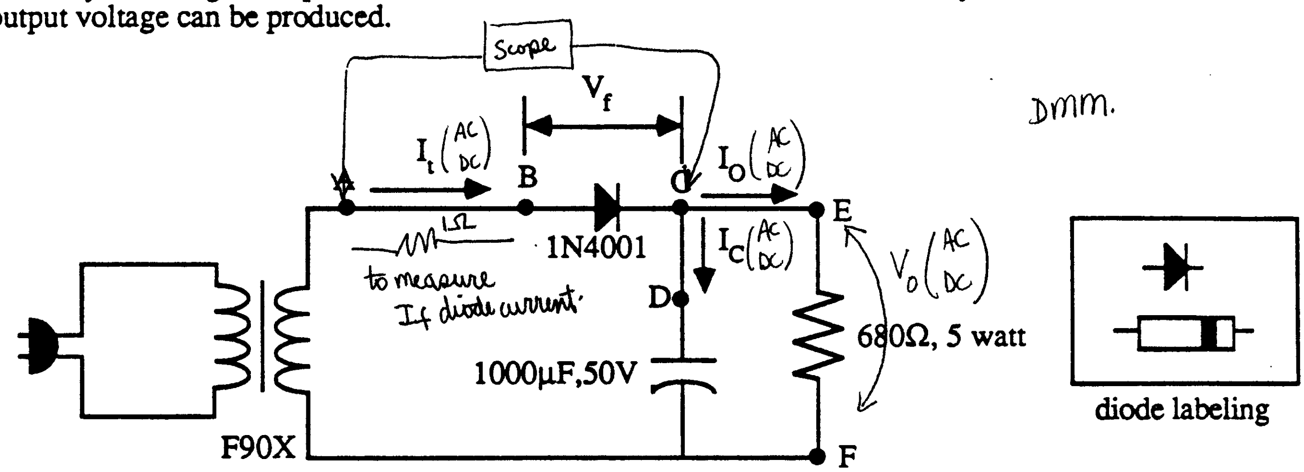


Figure 5.2 Half-Wave Diode Rectifier Power Supply

(1) Build the circuit shown in Fig. 5.2, being careful of the polarity of the capacitor and diode. See the insert for the diode polarity.

WARNING: AN ELECTROLYTIC CAPACITOR CAN ONLY WITHSTAND VOLTAGE IN ONE DIRECTION. REVERSING YOUR CAPACITOR OR DIODE CAN CAUSE THE CAPACITOR TO EXPLODE! MAKE SURE THAT YOUR CIRCUIT IS CONNECTED PROPERLY BEFORE CONNECTING YOUR TRANSFORMER.

(2) Remove the short between A and B. Connect the mA input of the DMM to point A and the COM to point B. Set the DMM to the 200 mA AC scale, and record I_t AC through the transformer.

(3) Set the meter to DC, record I_t DC through the transformer, remove the meter, and short A to B.

(4) Remove the short between C and D. Connect the mA input of the DMM to point C and the COM to point D, set the meter to the 200 mA AC scale, and record I_c AC through the capacitor.

(5) Set the meter to DC, record I_cDC through the capacitor, remove the meter, and short C to D.

(6) Remove the short between C and E. Connect the mA input of the DMM to point C and the COM to point E, set the meter to the 200 mA AC scale, and record I_O AC through the load.

(7) Set the meter to DC, record I_O DC through the load, remove the meter, and short C to E.

(8) Set the meter to the 200 V AC scale, connect the DMM (VKS) to E and (COM) F, and record V_O AC across the load.

(9) Set the meter to DC, record V_O DC across the load, and remove the meter.

(10) Set the scope to 0.2 V/cm and DC coupling, connect the scope GND to A, connect CH1 input to C (instead of point C use point G for the circuits of Figures 5.3 and 5.4), and record the peak forward voltage V_f across the diode.

(11) Replace the short circuit between A and B with a 1 ohm resistor, connect the CH1 scope input to B, set the scope to 0.1 V/cm, record the peak voltage across the resistor (this is proportional to the forward current I_f through the diode), and remove the scope connections.

do one only Figure 5.2 5.3 or 5.4

(12) Repeat steps 2 through 11 using the circuit shown in Fig. 5.3. Record your data in Table 5.2 using the full-wave bridge column.

(13) Repeat steps 2 through 11 using the circuit shown in Fig. 5.4. Record your data in Table 5.2 using the full-wave column.

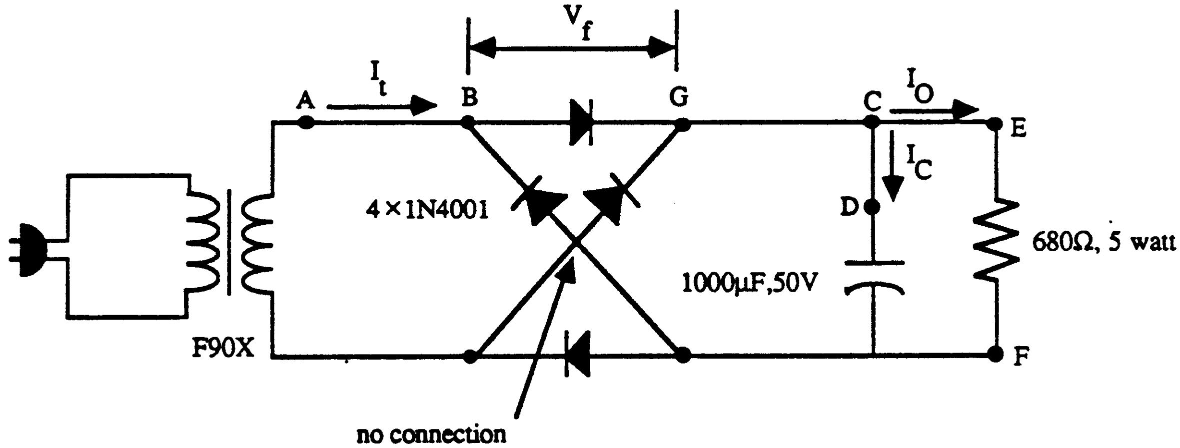


Figure 5.3 Full-wave Bridge Rectifier power supply

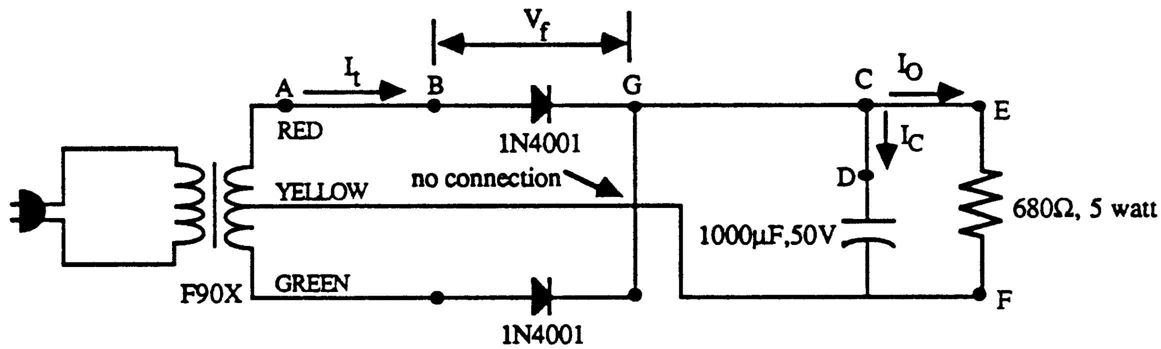


Figure 5.4 Full-wave rectifier power supply

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE LEAVING

Part 2: Zener diode regulated power supply

A simple DC power supply is composed of 5 elements: the transformer, rectifier, filter and/or regulator, and load. You have just measured the characteristics of power supply transformers and commonly used rectifier and filter circuits. A load is normally just a resistance. In this section you will study the characteristics of filters and regulators. A power supply filter is often nothing more than a capacitor which stores electrons when the rectifier output voltage is high and releases them when the rectifier output voltage is low. This storing and releasing, or charging and discharging, increases the DC component of the signal going to the regulator and decreases its AC component. The AC component of the filter's output is called the "ripple" voltage and is often measured as a peak-to-peak quantity. It is usually small compared to the DC component of the filter's output, which is called the "unregulated" dc voltage. This unregulated voltage is measured from ground to the center of the ripple voltage and can change depending on the power supply's load current.

A voltage regulator produces a "regulated" DC voltage, one that is constant with a very small AC component. The regulator's output voltage is should be independent of the load current so long as the load current is less than the regulator's specified maximum. If the maximum current is exceeded, the DC output voltage will drop and the AC component of the output will increase. When this occurs, regulation is "lost".

You should keep five things in mind when working with these power supply circuits.
(1) The oscilloscope allows peak-to-peak measurements while the DMM reads in RMS volts.
(2) Always disconnect one of the transformer wires before attempting to modify your circuits. This will prevent you from accidentally damaging components.
(3) Your load resistors may get quite hot, so be careful.
(4) Transformer output voltages can vary by several percent over short periods of time because of line voltage fluctuations.
(5) Your filter capacitor can explode if you connect it, or your diodes, backwards.

It is sometimes possible to use an unregulated power supply circuit for your applications.
(1) Build the circuit shown in Fig.5.2 replacing the 680 ohm resistor by your RSB. Remove the CE jumper. Connect the scope GND and DMM COM to point F.
(2) Connect the DMM VKS input to point C. Measure and record in Table 5.3 the so-called no-load DC and AC (RMS) voltages at point C.

(3) Set the RSB to 6K and connect points C and E.
(4) Connect the scope CH1 input to point C. Record the AC waveform at point C in Figure 5.4.
(5) With the DMM still connected to point C, measure the DC and AC (RMS) voltages at point C. Record your results in Table 5.5.
(6) Repeat step 5 with RSB values of 3 K, 2 K, 1.5 K, 1.2 K, 800 ohms, and 600 ohms recording your results in Table 5.5.

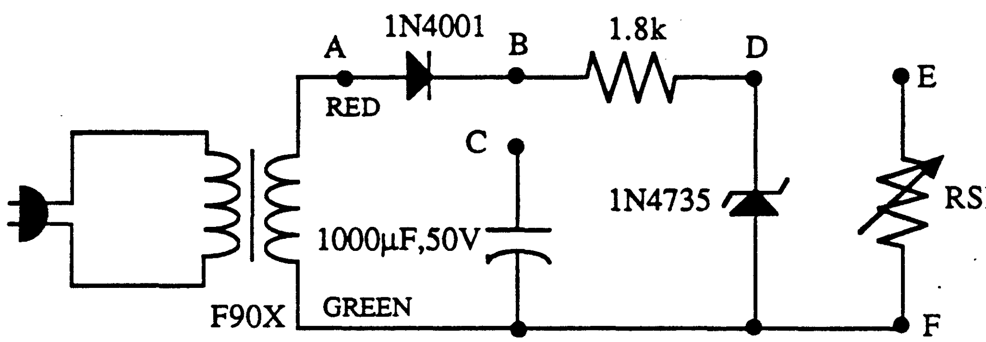


Figure 5.5 Zener diode regulated power supply

A zener diode and a current limiting resistor can be used as a simple voltage regulator.
(7) Build the circuit shown in Fig.5.5.
(8) Connect your scope CH1 input to point B. Connect your scope COM to point F. Measure the waveform at point B and record your results in Table 5.6. Connect your scope CH1 input to point D, measure the waveform at point D and record your results in Table 5.7.
(9) Connect points B and C.
(10) Connect your DMM (VKS) input to point B. Connect your DMM COM to point F. Record the DC and AC (RMS) voltages in Table 5.8. Connect your DMM (VKS) input to point D. Record the DC and AC (RMS) voltages in Table 5.8.
(11) Connect your scope CH1 input to point B. Measure and record the AC voltage at point B in Table 5.9.
(13) Set the RSB to 3.2k. Connect points D and E.

(14) Connect your DMM (VKS) input to point D. Connect your DMM COM to point F. Record the DC and AC (RMS) voltages in Table 5.10.
(15) Repeat step 14 with RSB values of 1.6 K, 1.1 K, 800, 700, 500, 300, and 100 ohms.

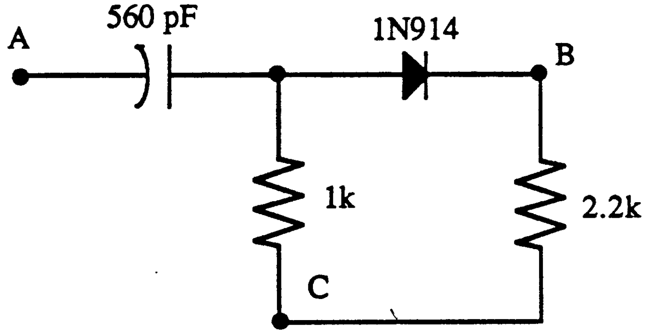


Figure 5.6 - Rectifying differentiator

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE CONTINUING

Part 3 - Specialized diode circuits   Explained in Section 1.30 of Horowitz (about p. 41)

Build the rectifying differentiator shown in Figure 5.6.

(1) Set your signal generator to 10 Vp-p, 0 volts dc offset at 10 kHz.
(2) Connect your generator OUT to point A. The generator common is connected to point C.
(3) Connect your oscilloscope CH1 input to point B. Record the waveform you see at point B in Table 5.11.
(4) Remove the 2.2k resistor. Record the waveform you see at point B in Table 5.12.

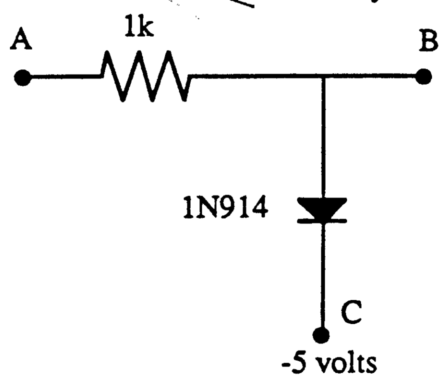


Figure 5.7 - ~~Rectifying differentiator~~ Voltage clamp.

(1) Build the circuit shown in Figure 5.7.
(2) Change the generator output to a $20V_{p\text{-}p}$ sine wave. You will use this setting for the rest of this part of the lab. Connect your generator output to point A. Note that the generator common is connected through the power supply to your circuit.
(3) Connect your scope's CH1 input to point B and record the waveform you see in Table 5.13.
(4) Modify the circuit to that shown in Figure 5.8.

Resistor Values

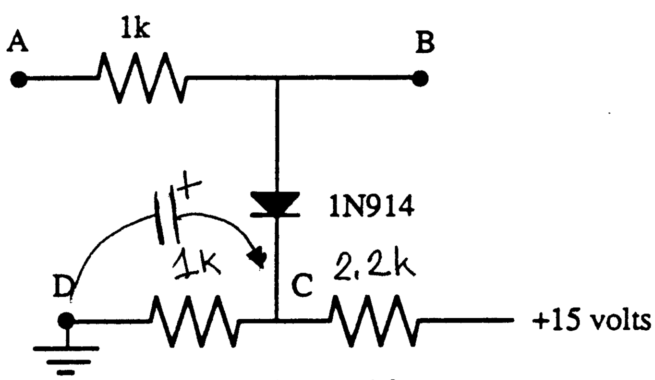


Figure 5.8

(5) With your scope's CH1 input still connected to point B and your generator still connected to point A record the waveform you see in Table 5.14.
(6) Connect a 10μF capacitor between points C and D. Be sure to connect the positive side of the capacitor to point C. Repeat step (5) recording your results in Table 5.15.

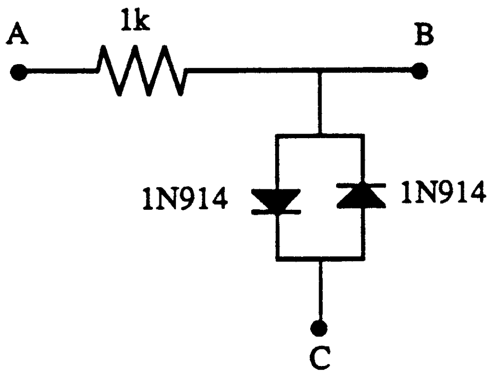


Figure 5.9

The final circuit we will examine is the diode limiter of Figure 5.9.

(1) Build the circuit shown in Figure 5.9.
(2) Adjust your signal generator to 0.5 volts p-p output (0 volts DC) at 1 kHz. Connect your signal generator output to point A. Connect the COM to point C.
(3) Connect your scope CH1 input to point B. Record the waveform you see at point B in Table 5.16
(3) Repeat step (3) for generator output voltages of 1.0,1.5,2.0 and 2.5 volts. Record your results in Table 5.16.

EEAP 243 LAB 5 EVALUATION

NAME (print)______________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

What will happen to the current through the zener diode in Fig. 5.2 if we connect B to C, connect D to E, and increase/decrease the resistance of the 1.8K/RSB?

It will increase / decrease / stay the same.

Question #2

What will happen to the ripple voltage across the filter capacitor in Fig. 5.3 if we connect C to D to E and increase/decrease the resistance of the potentiometer/120 ohm/15 ohm ?

It will increase / decrease / stay the same.

Questions:

1. Why is the loaded transformer voltage different than the unloaded voltage?
2. For the half-wave, full-wave and full-wave bridge rectifiers compare your measured values of V_O AC, I_O AC, and I_C DC to V_O DC, I_O DC, and I_C AC. Which rectifier circuit might be better and why?
3. What is the equivalent RMS voltage of your Table 5.4 waveform? What is the significance of this measurement?
4. For your results of Table 5.5
   (a) Make a graph of the DC voltage across the load (RSB) versus the DC current through the load.
   (b) Make a graph of the RMS AC voltage across the load versus the DC current through the load.
   (c) Do power supplies exhibit output impedance? If so, what is the output impedance of your power supply?
5. (a) What is the breakdown voltage of the zener diode you used?
   (b) Using the waveforms you recorded in Table 5.6 and Table 5.7, sketch the waveform across the 1.8 K resistor.
   (c) Calculate the DC current flowing through the 1.8 K resistor from your part (b) results.
   (d) Using these results, calculate the expected ripple voltage.
6. (a) Make a graph of the DC voltage across the load (RSB) versus the DC current through the load.
   (b) Make a graph of the RMS AC voltage across the load versus the DC current through the load.
   (c) What is the current through the zener diode?
   (d) At what load current do your graphs indicate that regulation is "lost"?
   (e) What is the current through the zener diode at this load current?

5.8
5.9

7. What is the role of the [redacted]k resistor in Figure 5.7? Explain the circuit operation. 1k
8. (a) Explain the waveform you recorded in Table 5.13.
   (b) Explain the waveform you recorded in Table 5.14.
   (c) Explain the waveform you recorded in Table 5.15.
   (d) What are the necessary characteristics for the capacitor to behave as it did to achieve the results of Table 5.15?
9. Explain why the circuit of Figure 5.9 resulted in the performance you recorded in Table 5.16.

EEAP 243

NAMES: ____

Lab 5 Data

$V_{m/2}$	____________
V_t	____________
I_t	____________

Table 5.1 Basic transformer characteristics

	half-wave	full-wave bridge	full-wave
$I_{t,AC}$	________	________	________
$I_{t,DC}$	________	________	________
$I_{C,AC}$	________	________	________
$I_{C,DC}$	________	________	________
$I_{O,AC}$	________	________	________
$I_{O,DC}$	________	________	________
$V_{O,AC}$	________	________	________
$V_{O,DC}$	________	________	________
$V_{f,peak}$	________	________	________
$I_{f,peak}$	________	________	________

Table 5.2 - Rectifier circuit characteristics

AC no-load voltage	________
DC no-load voltage	________

Table 5.3

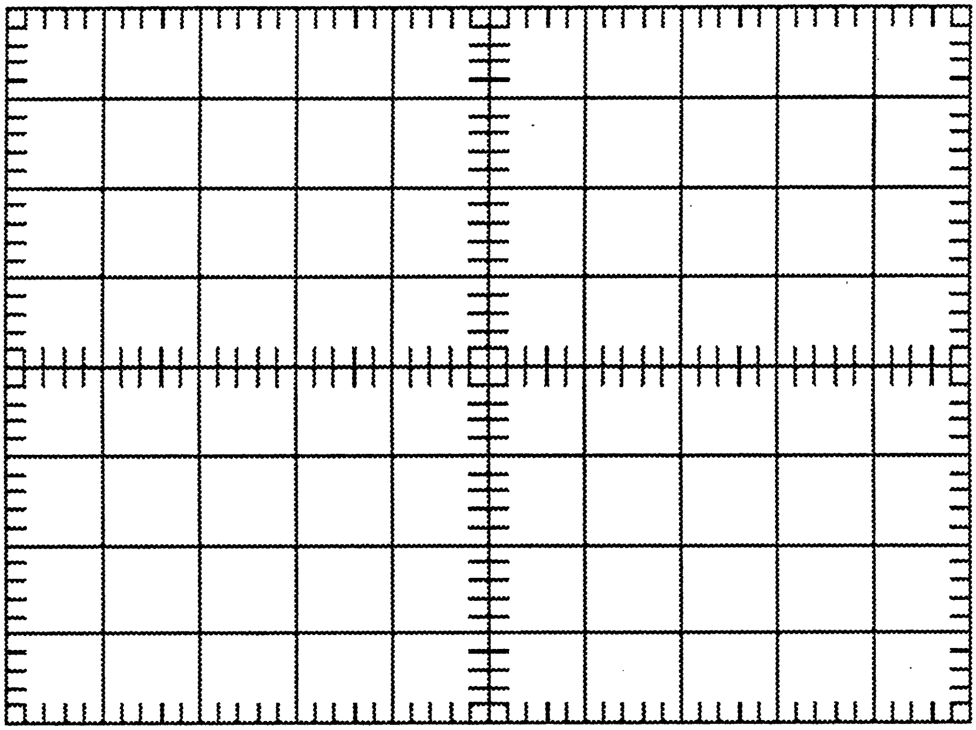


Table 5.4

Load resistance	DC voltage	AC(rms) voltage
6K		
3K		
2K		
1.5K		
1.2K		
800		
600		

Table 5.5

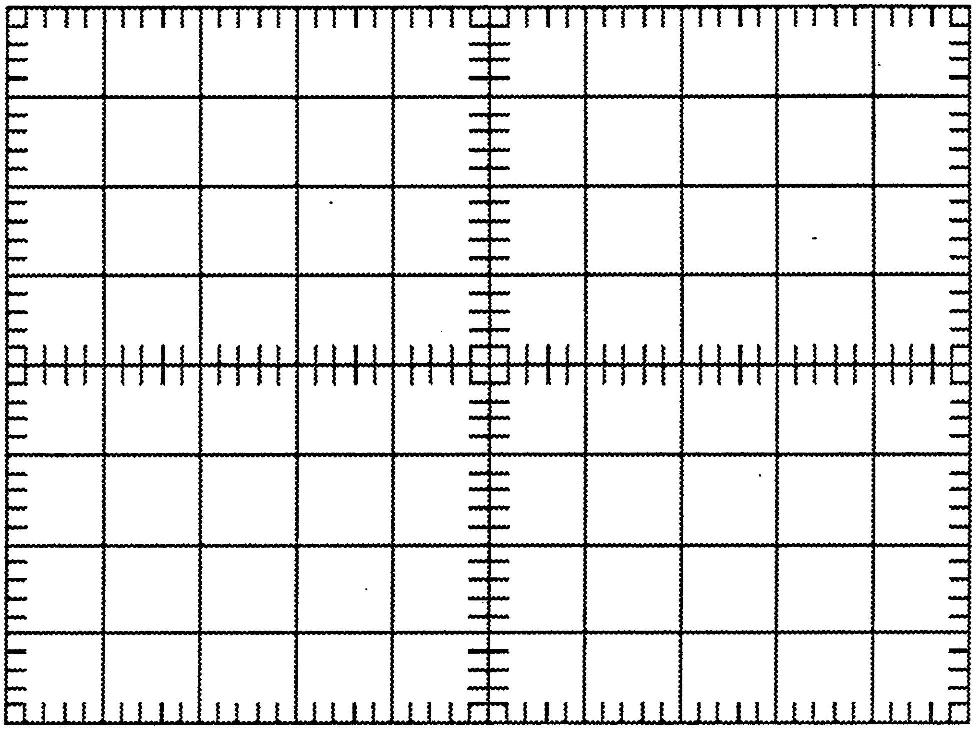


Table 5.6

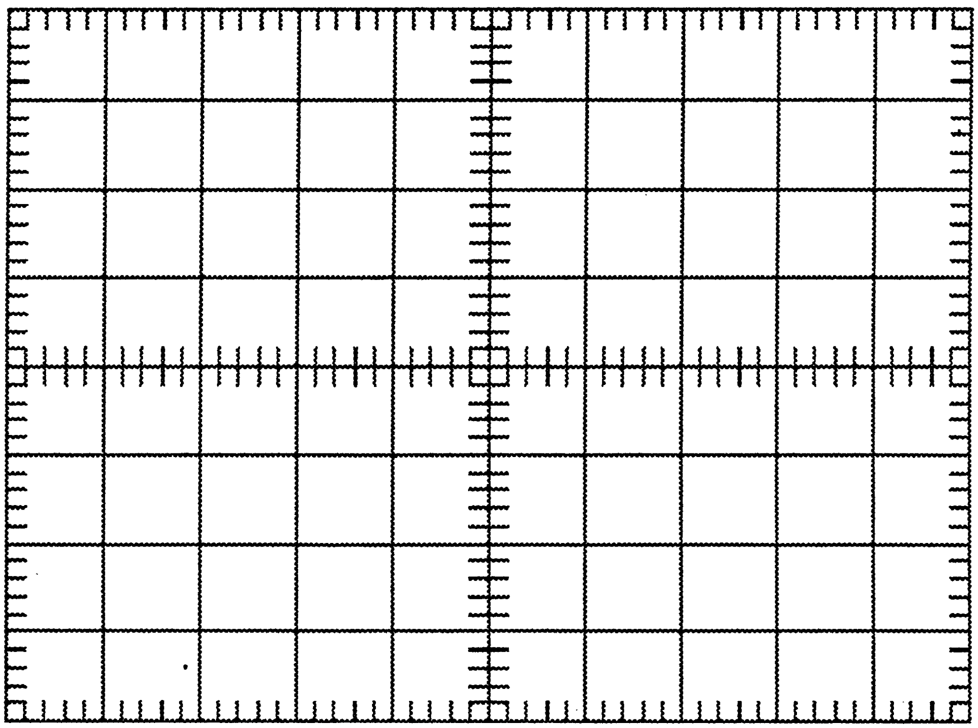


Table 5.7

AC no-load voltage ____________

DC no-load voltage ____________

Table 5.8

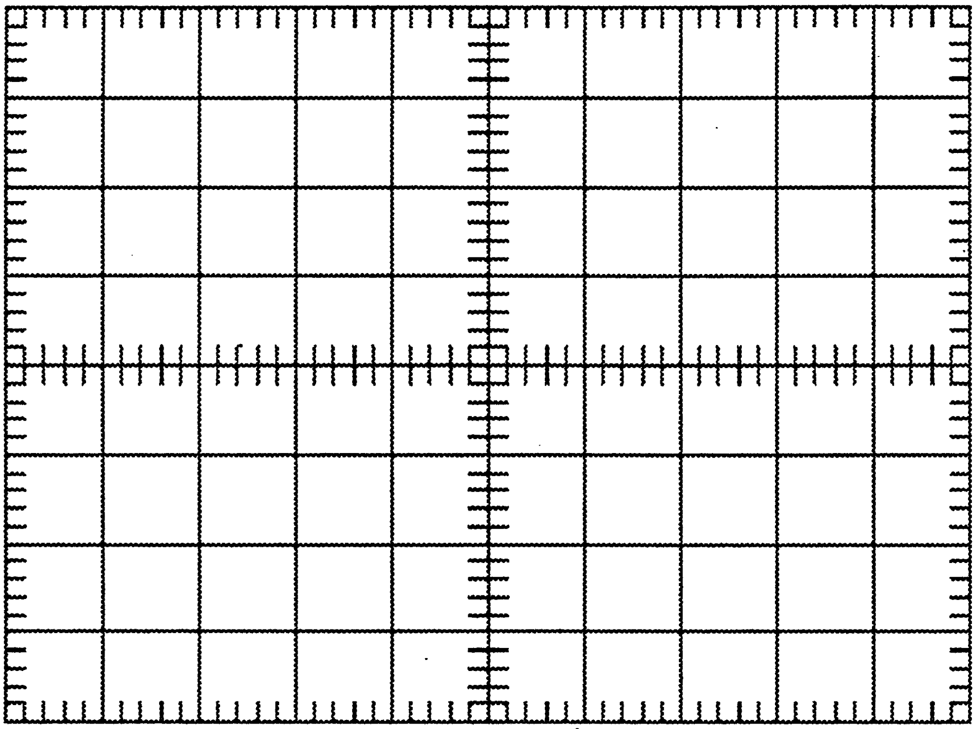


Table 5.9

Load resistance	DC voltage	AC(rms) voltage
3.2K		
1.6K		
1.1K		
800		
700		
500		
300		
100		

Table 5.10

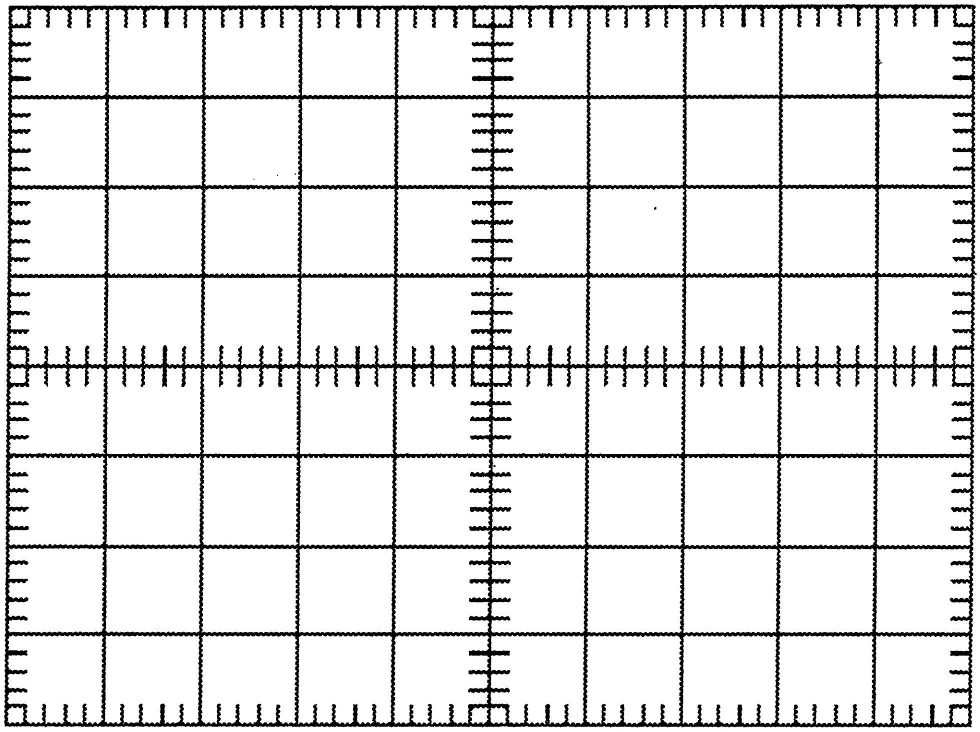


Table 5.11

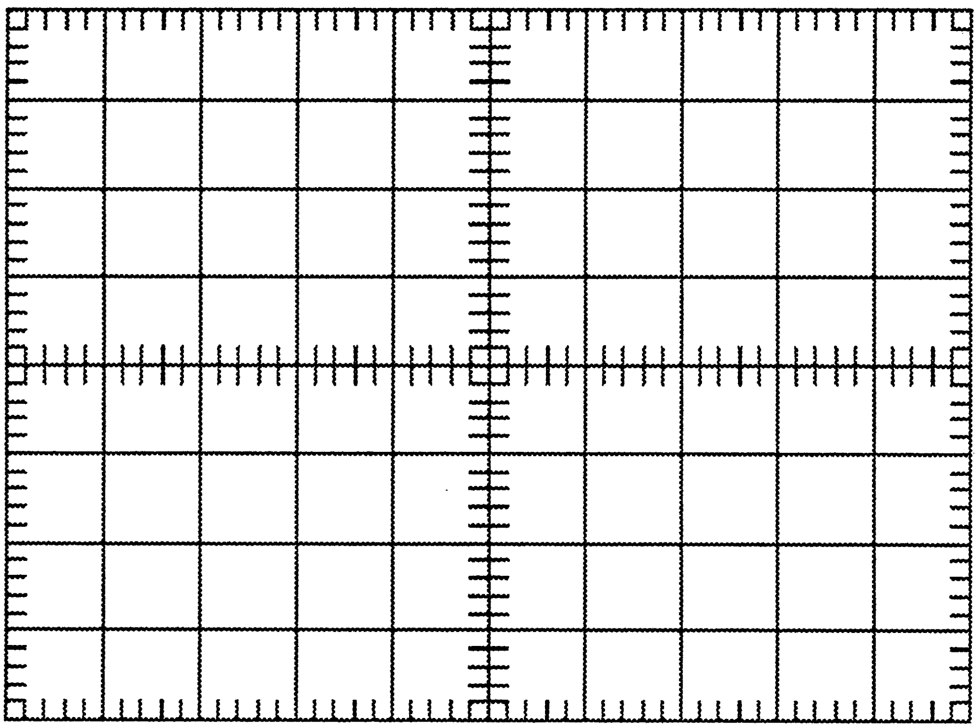


Table 5.12

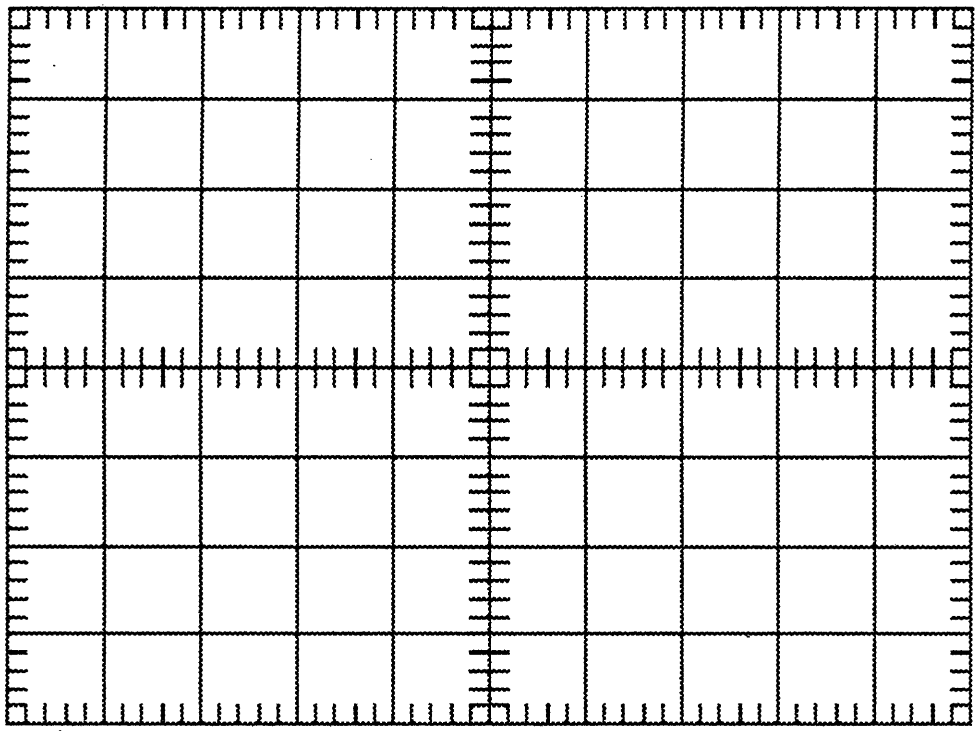


Table 5.13

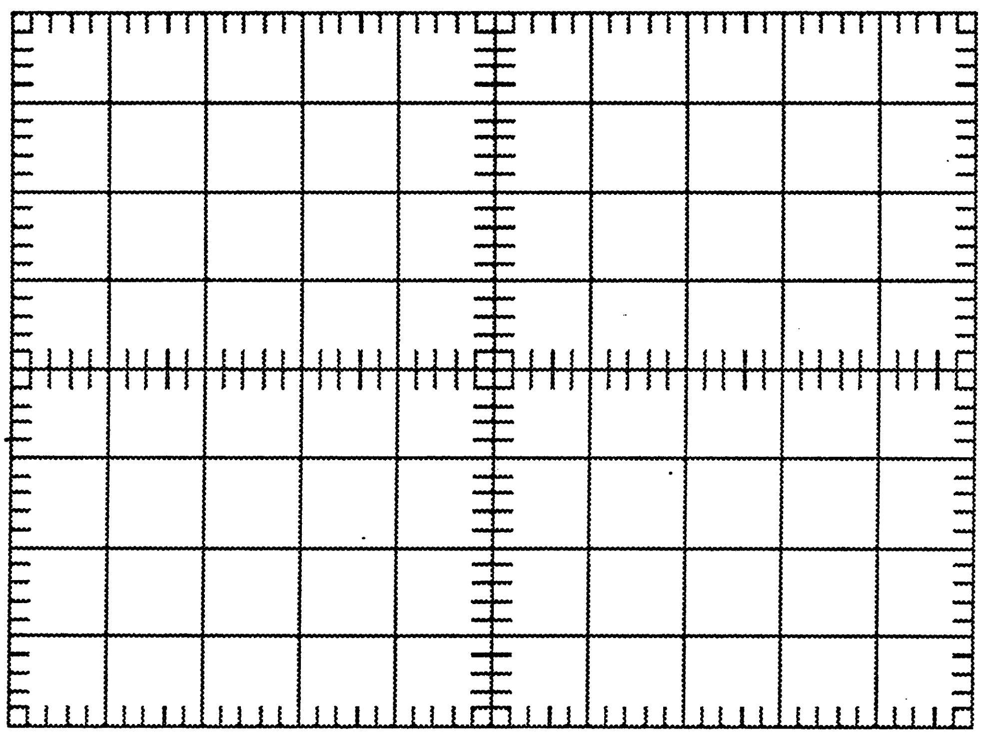


Table 5.14

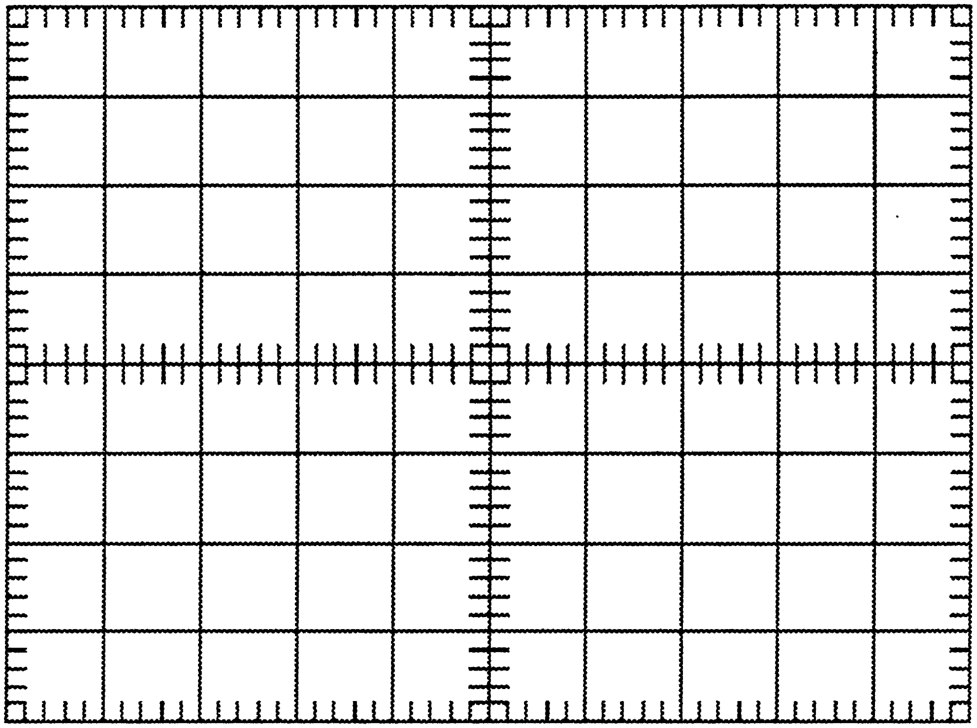


Table 5.15

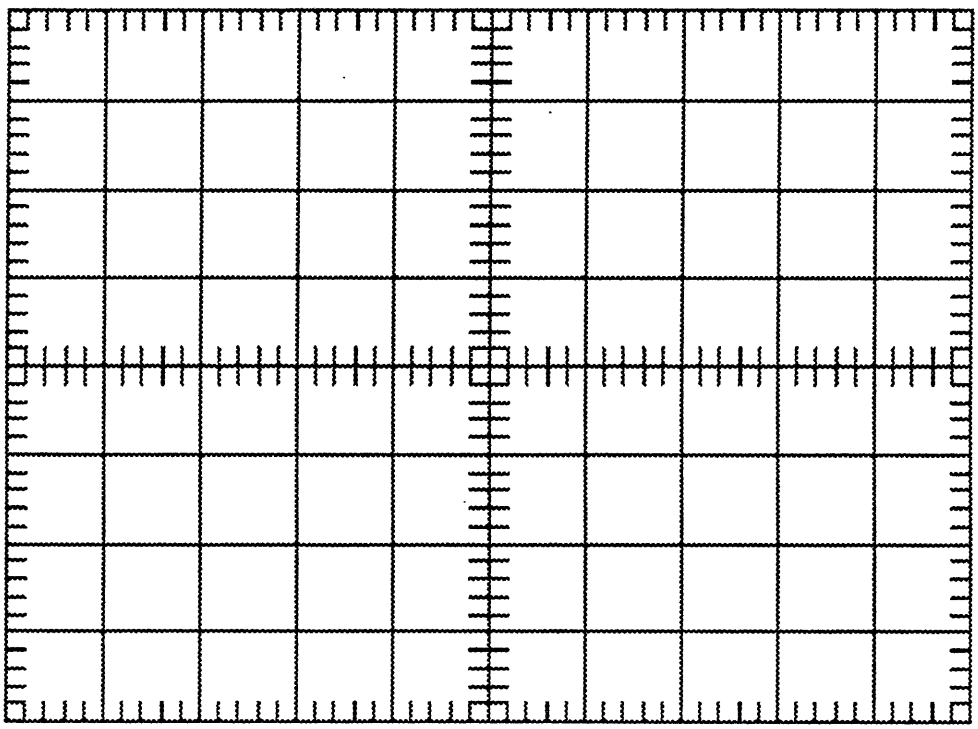
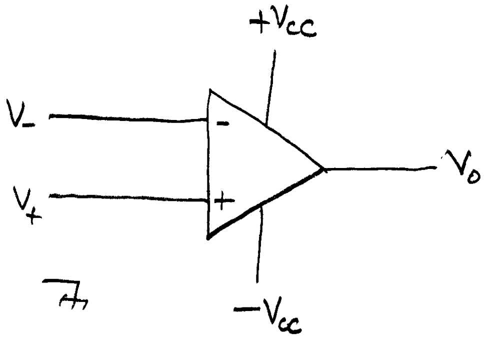


Table 5.16



most op-amps require + and − power supplies

$$V_{OUT} = A(V_+ - V_-)$$

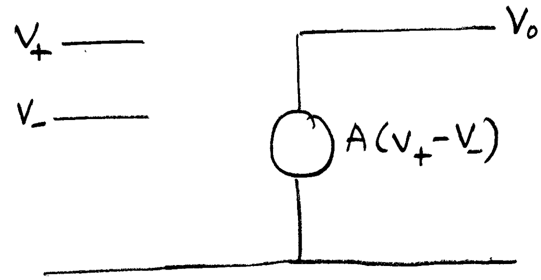
or $$\frac{V_o}{A} = V_+ - V_-$$

normal assumptions $A \to \infty$

$I_{os} \to 0$

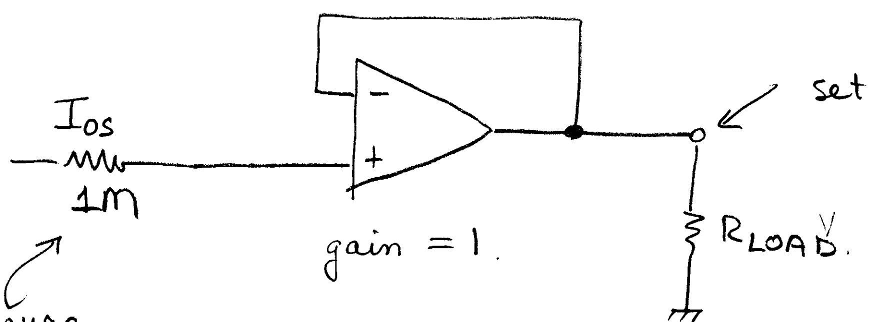
$V_{os} \to 0$

these are related to Horowitz's golden rules.



Analyzed in 3.04 Horowitz with unity feedback

unity gain voltage follower



measure dc drop across 1m resistor

if $I_L = \frac{V_o}{R_L}$ is not large

the output voltage $= V_+$

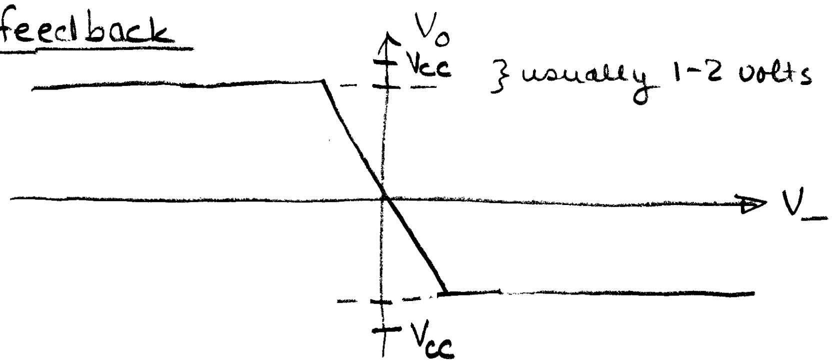
$$V_{OUT} = A(V_+ - V_-) \quad \text{but } V_- = V_{OUT}$$

$$V_{OUT} = A(V_+ - V_{OUT})$$

$$V_{OUT} + A\,V_{OUT} = A\,V_+$$

$$\frac{V_{OUT}}{V_+} = \frac{1+A}{A} \approx 1 \quad \text{if } A \text{ is large.}$$

without feedback

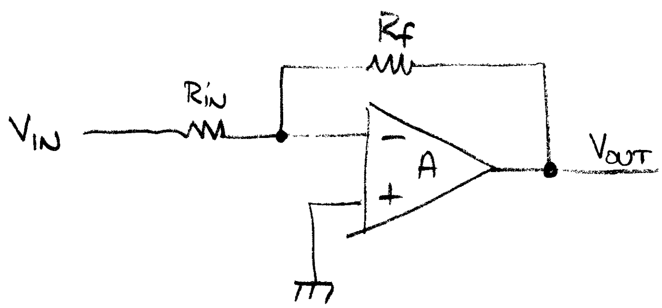


ΔV_{IN} linear region may be only a few millivolts.

If $A = 10^5$ and $V_{OUT} = 30$ VOLTS

then $\Delta V_{IN} = \dfrac{30}{100 \times 10^3} = 0.3$ mV (and usually less)

with feedback



in this circuit

$$V_{OUT} = A(V_+ - V_-)$$

using superposition

$$V_- = \frac{R_{IN}}{R_{IN}+R_f} V_{OUT} + \frac{R_f}{R_{IN}+R_f} V_{IN}$$

$$\therefore \quad V_- = \frac{R_{IN} V_{OUT} + R_f V_{IN}}{R_{IN} + R_f}$$

but $V_{OUT} = A(V_+ - V_-) = -AV_-$ since $V_+ = 0$

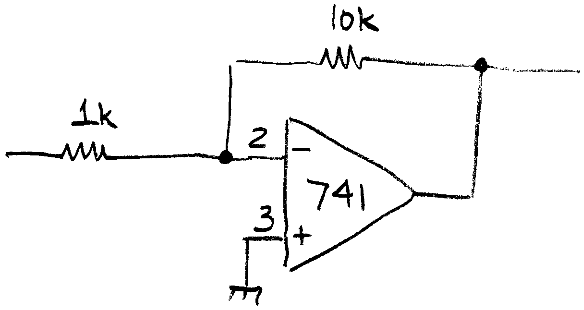
$$\frac{V_{OUT}}{-A} = \frac{R_{IN}}{R_{IN}+R_f} V_{OUT} + \frac{R_f V_{IN}}{R_{IN}+R_f}.$$

$$\therefore \quad V_{OUT}\left(-\frac{1}{A} - \frac{R_{IN}}{R_{IN}+R_f}\right) = \frac{R_f}{R_{IN}+R_f} V_{IN}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{-AR_f}{(R_{IN}+R_f) + R_{IN}A} \longrightarrow -\frac{R_f}{R_{IN}}$$

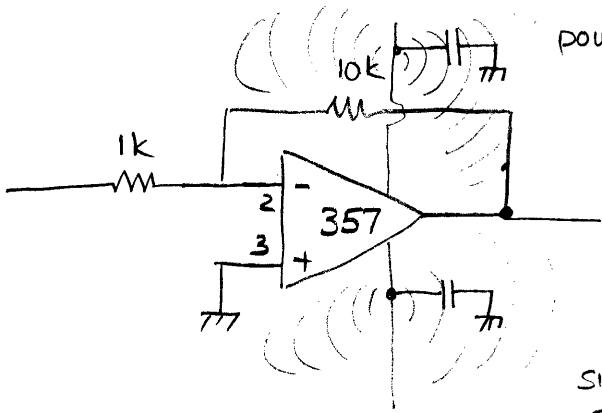
Figure 2:

AC: 2Vp-p
DC: 0



AC: 20 V_{p-p}
DC: 0 (supposedly).

Figure 3:



power lines radiate

unstable w/o decoupling capacitors. for LF357 due to large input impedance

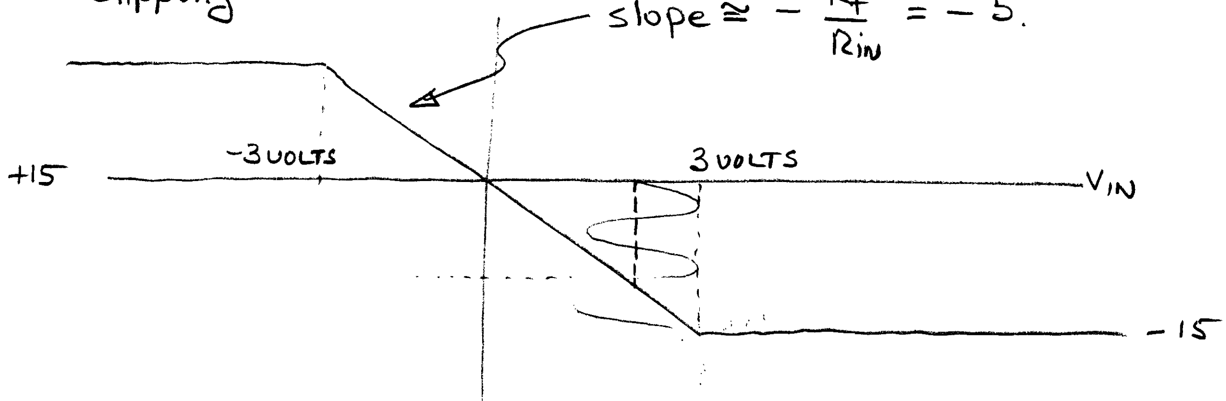
---

simply want an ac short to ground.

3.08 precautions with op-amps

clipping

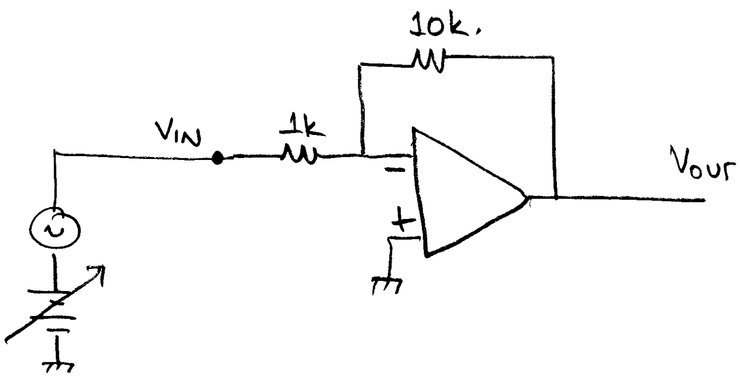
slope $\cong -\frac{R_f}{R_{in}} = -5.$



if $V_{IN} = +10$ $V_{OUT} = -15$, etc.

suppose $V_{IN} = 2V\,DC + 1V \cos\omega t$. OK

but if either ac or dc component increases clipping occurs.



① Vary V_{DC} to see V_{OUT}

② set $V_{DC} = 0$ increase V_{AC} to see what happens.

③ record for $V_{IN} = 5V$ p-p.

problems with real op-amps

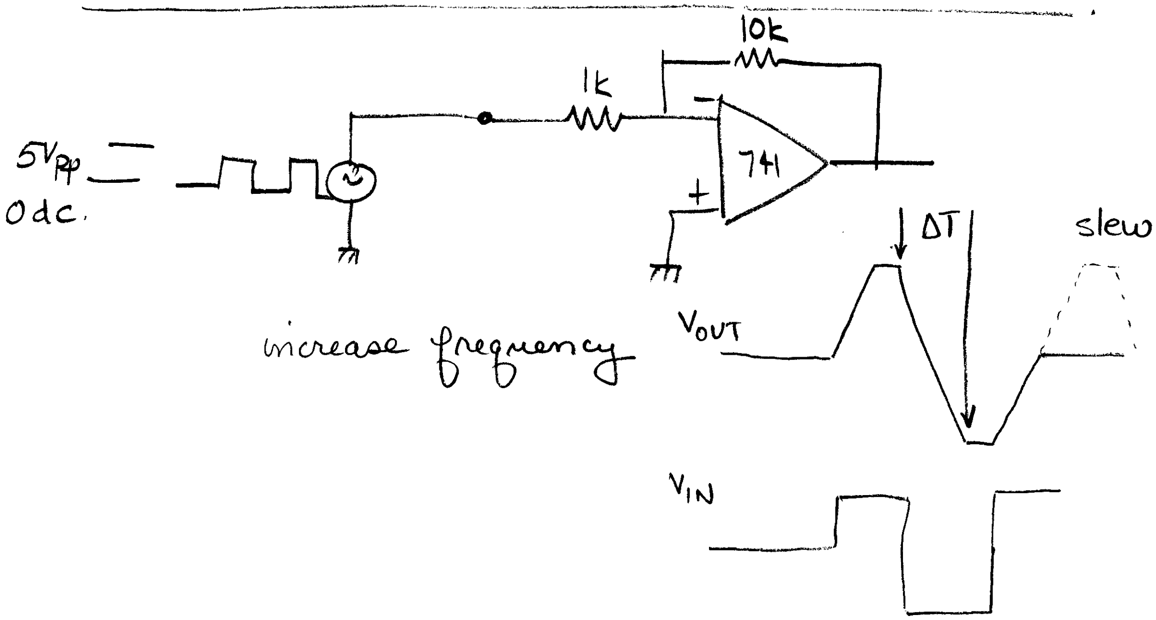
p.113 1. $I_{os} \neq 0$ already saw this

p.107 2. finite slew rate $\left|\frac{dV}{dt}\right| <$ constant

p.107 3. finite GBW

p.112. 4. $V_{os} \neq 0$

slew rate p. 107.



slew rate $= \frac{\Delta V}{\Delta t}$. record both.

increase frequency

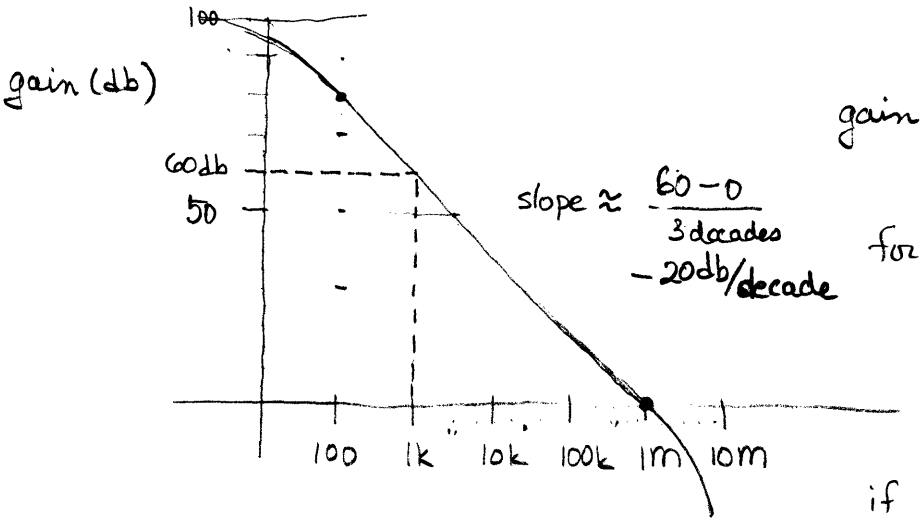
Interesting problems with real op-amps

1. $V_{os} \neq 0$
2. $I_{os} \neq 0$ ← already saw this.
3. finite GBW
4. finite slew rate

finite GBW

p. 107

MC1741 data sheet.



$$\text{gain}_{db} = 20 \log_{10}\left(\frac{V_{OUT}}{V_{IN}}\right)$$

for example. ×1000 gain

$G. = 20 \log_{10}(10^3) = 60$ db.

→ about 1kHz BW.

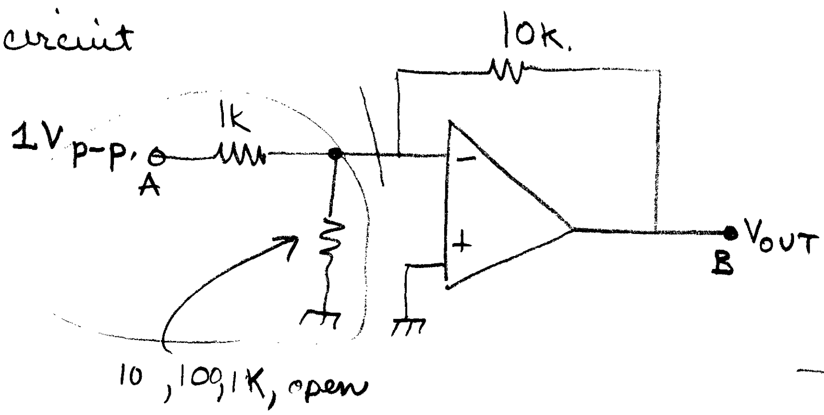
if $G = 40$ db (×100 gain)

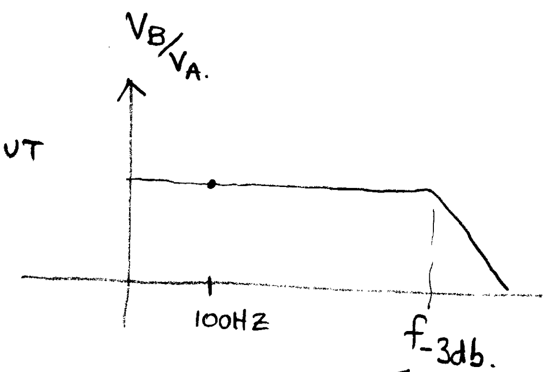
→ about 10kHz BW

$G = 20$ db (×10)

→ about 100kHz BW.

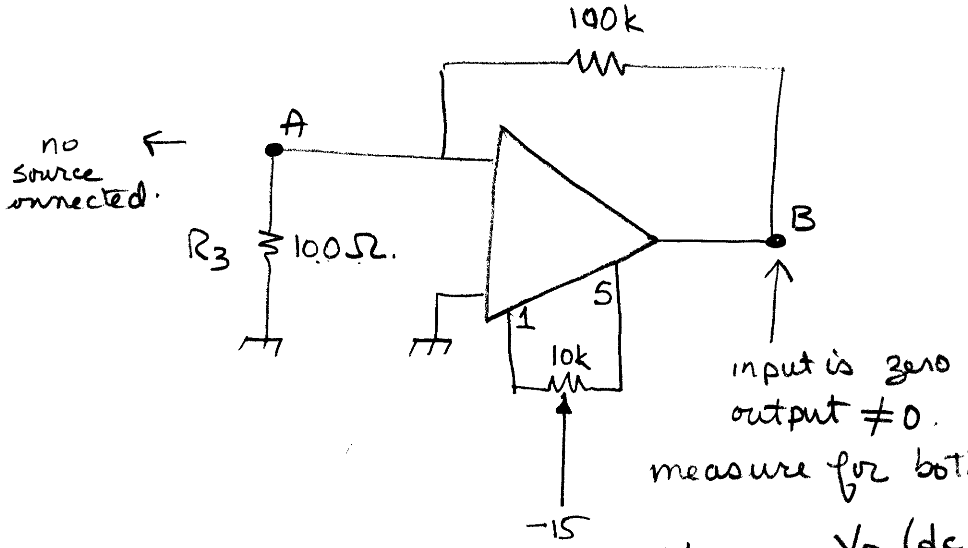
circuit





find this for 10, 100, 1k, open for LM741 and LF357

Thevenize input:



gain $= \frac{100\,k}{0.1\,k} = 1000$

measure for both. LM741 and LF357

$$V_{os} \cong \frac{V_B\,(dc)}{1000}$$

trim to zero using special circuit

---

read history of op-amp on p. 115.

Some general suggestions: layout circuit before coming to Lab.
* use colored wire
use Radio Shack alligator clips

EEAP 243 Lab Work:
Lab 6 Questions Due:

INTRODUCTION TO REAL-OPERATIONAL AMPLIFIERS

READING: Horowitz, pgs. 92-98 (skip Section 3.08), 103-116, 127-130, 132, 136-143.

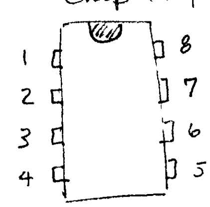
Abstract:
In this laboratory, you will investigate practical operational amplifiers. Your Circuits I course presented ideal operational amplifiers. In this lab, we will examine the limitations of real operational amplifiers such as slew rate and clipping and examine the basic inverting amplifier topology.

Part I: Basic Operational Amplifiers

The operational amplifiers used in this experiment are integrated circuits (ICs) housed in 8-pin dual in-line packages (DIPs). Please be careful when inserting and removing your op-amps from your protoboard. You may need to straighten the two rows of pins before plugging the op-amp into your breadboard. To remove the op-amp from your breadboard, pry it out with your screwdriver. Please try not to bend the pins of your op-amps. Bent pins often break, leaving an otherwise good IC useless.

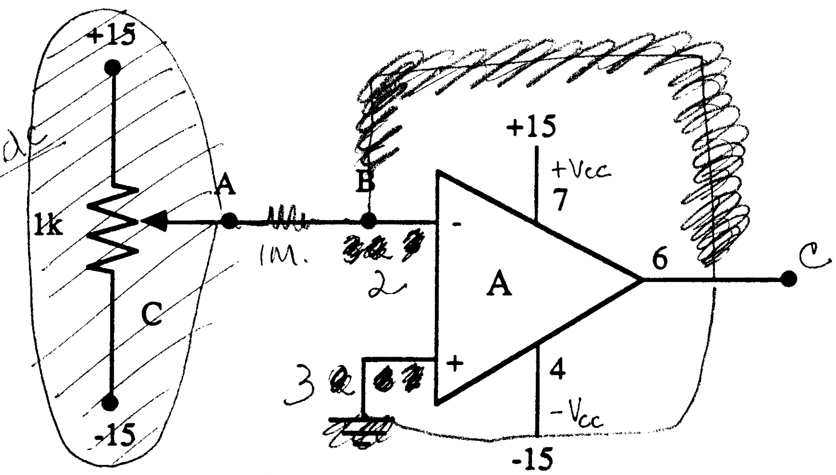
You will make five connections to the op-amp: the positive power supply ($+V_{CC}$), the negative power supply ($-V_{CC}$), the non-inverting input (+), the inverting input (-), and the output. Please refer to the data sheets for the IC's pin assignments. The power supply connections for your op-amps are $+V_{CC}$ = +15 V and $-V_{CC}$ = -15 V. Connections can be made using your breadboard, test leads, alligator clips, and short pieces of solid wire. Pin #1 of the integrated circuit is usually marked with a dot.

chip (top view)



section 3.02

use signal generator instead ±10 volts dc



Remove pin 2 from ground or connect pin 2 to pin 6

Figure 1 - Basic open loop high-gain op amp

(1) Build the simple circuit shown in Figure 1 using an LM741. Attempt to measure the dc input voltage at point A and the dc output voltage at point C with your DMM. Record any results you get in Table 6.1. ← Adjust your dc input to result in a dc output at C of 5 volts

(2) Replace the short between A and B with a 1M resistor. Measure the dc voltage drop across this resistor with your DMM. Record your results in Table 6.2.

dependent upon voltage drop ?

(3) Replace your 741 op-amp with a LF357. The pin outs are identical. Repeat step 2.

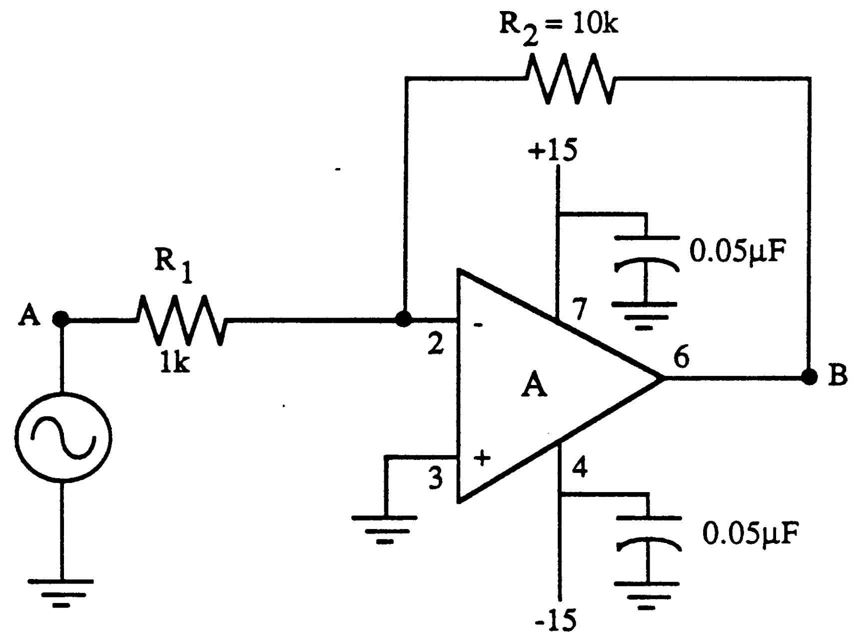


Figure 2 - Basic Inverting Amplifier Configuration

An inverting amplifier is probably the most common operational amplifier circuit and will be used to illustrate some basic concepts.

(1) Set the signal generator to deliver a 2 V_{p-p} sine wave with zero DC offset at 1 KHz before connecting it to the circuit. (The displayed waveform will not jump when the coupling is switched from AC to DC if the DC offset is zero.)

(2) Build the circuit of Fig. 2 using an LM741. Do NOT put the 0.05 μF capacitors in your circuit yet.

(3) Display point A on channel 1 (CH1) with 1 V/cm, display point B on channel B (CH2) with 5 V/cm, and DC couple both channels.

(4) Record the waveforms at points A and B in Table 6.3. Make special note of the phase difference between the two signals.

Instability is often a problem when using high frequency op-amps. One common source of instability in op-amp circuits is coupling between the amplifier's output and its power supply connections. The inductance and capacitance of the power supply wires can provide a path for positive feedback to the op-amp input which can make it oscillate at a very high frequency. A "decoupling" capacitor is usually connected from each power supply connection to ground. These capacitors provide an effective short circuit for any high frequency signals which may appear at the power supply connections, thus eliminating the feedback and consequent oscillation.

(5) Replace the LM741 with an LF357 op-amp. The scope display should become unintelligible.

(6) NOW connect a 0.05 μF decoupling capacitor from $+V_{cc}$ to ground and from $-V_{cc}$ to ground as shown in Figure 2. The circuit should now operate as it did in step 4.

(7) Record the signal (peak-peak) amplitudes at points A and B in Table 6.4 and make special note of the phase difference between them.

"Clipping" occurs when an amplifier tries to amplify a signal to voltages beyond the range of its power supplies. For example, consider an amplifier with +15 V and -15 V power supplies, a gain of ⊕5, and an input signal of +10 V DC. The output voltage of the amplifier ought to be ⊕50 V but it will "saturate" somewhere around ⊕15 V since the amplifier cannot produce voltages beyond its power supply. When an AC input signal causes the output to lie partially inside and partially outside the range of voltages which the op amp can produce, the output will be faithfully reproduced for the in range portion and will remain fixed at the saturation voltage for the out of range portion. Thus the output, when viewed on an oscilloscope, will appear as though a portion has been clipped off.

(1) Put the LM741 back into the circuit and set ground at the center of the screen for both scope channels.
(2) Starting with the generator's DC offset knob fully counterclockwise, slowly turn it fully clockwise and make note of what happens.
(3) Record the highest positive and lowest negative voltages produced at the op-amp's output in Table 6.5.
(4) Set the generator's DC offset to zero and slowly increase the amplitude of the generator, making note of what happens at point B.
(5) Record the waveform at B in Table 6.6 for 5 V_{p-p} at point A, making special note of the DC voltages at which the signal flattens.
(6) Repeat steps 2 to 5 using the LF357 in the circuit.

Slew rate is one parameter which determines the quality of an amplifier. The slew rate of an op-amp is the maximum rate at which the output voltage can change and is usually expressed in volts per microsecond. A high quality op-amp usually has a very high slew rate.

(1) With the generator still on 5 V_{p-p}, change the signal to a square wave and put the LM741 back in the circuit.
(2) Increase the frequency until the waveform at point B looks like a slightly flattened triangle wave. Record this waveform in Table 6.7. Be sure to measure the time it takes for point B to ramp from the positive saturation voltage to the negative saturation voltage.
(3) Repeat steps 2 and 3 using the LF357 in the circuit.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE CONTINUING

Fig. 2 in the LM741 data sheet shows the open loop frequency response (gain versus frequency) of the device. An op-amp has its greatest gain when there is no feedback (open loop). However, this maximum possible gain decreases as the frequency to be amplified increases. As a matter of fact, the product of the frequency times the maximum gain at that frequency (the gain bandwidth product) is a constant from 100 Hz to 1 MHz.

It is a simple matter to predict the frequency response of an amplifier circuit with feedback. Simply draw a horizontal line across the open loop graph at the appropriate gain up to the point where it intersects the open loop line and follow the open loop line from that point on. For example, the frequency response for an amplifier with a gain of 1000 would be a horizontal line along the +60 db line up to 1 KHz, at which point it would start to decrease at a rate of 20 db per decade.

(1) Build the circuit shown in Fig.3, making R_3=10Ω.
(2) Set the signal generator to a 1 $V_{p\text{-}p}$ sine wave at 100 Hz.
(3) Measure the signal amplitudes (peak-peak) at points A and B.
(4) Increase the signal generator frequency and record in Table 6.8 the frequency for which the signal amplitude at B falls to 0.7 $V_{p\text{-}p}$. i.e −3db compared to the voltage at B at 1kHz.
(5) Repeat steps 2 to 4 for R_3 equal to 100Ω, 1K, and an open circuit.

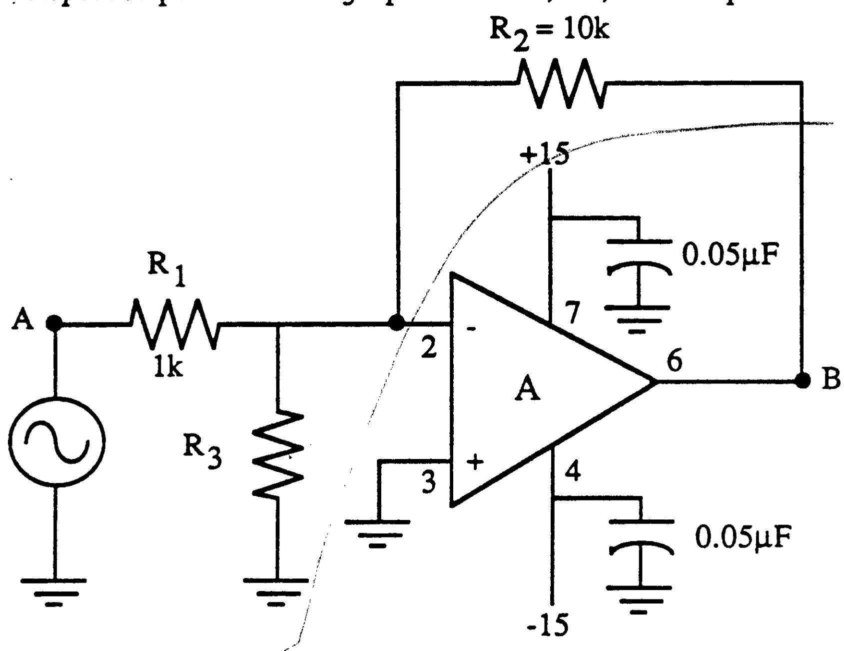


Figure 3 - Inverting Amplifier

The LF357 has a much higher bandwidth than the LM741 and can effectively amplify much higher frequencies.

(6) Repeat steps 2 to 4 above using the LF357 op-amp with R_3 resistances of 10Ω, 100Ω, and 1K. Record your results in Table 6.8.

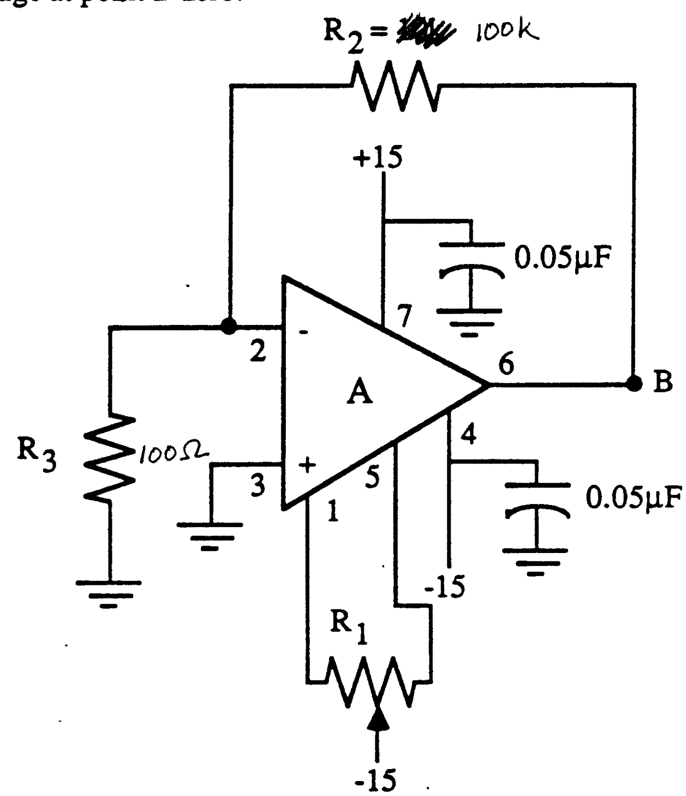
Real op-amps do not have a zero output voltage for zero input voltage. As you will learn later this is due to mismatches between transistors in the input stage of the op-amp. This non-zero output voltage is modeled as a dc voltage source called the input offset voltage connected between the op-amp inputs. This offset voltage is not a real problem in most applications but can be significant when you are attempting to amplify very weak signals or are using several dc coupled amplifiers.

(1) Replace the LM741 in your circuit of Figure 3. To measure the input offset voltage V_{OS} disconnect the signal generator from your previous circuit.You may also remove R1. Change R_2 to 100k and R_3 to 100Ω. This results in a very high gain (×1000) amplifier which will allow us to see the input offset voltage.
(2) Measure the dc output voltage (at point B) with your DMM and record your results in Table 6.9. Even though the input voltage to the op-amp is zero your

output is non-zero. The input offset voltage is simply the voltage you measured at B divided by the gain of the amplifier.

(3) Replace the LM741 with the LF357. Repeat step 2.

(4) Op-amps can be "trimmed" so that their output voltage IS zero for zero input signal and chip manufacturers provide special "trimming" circuits to adjust the amplifier output to zero by applying a variable potential between two pins of the chip. The 741 can be trimmed by connecting a 10k (R1 in Figure 4) potentiometer between pins 1 and 5. Build the circuit of Figure 4. Be sure that the wiper of your potentiometer is connected to the -15 volt power supply. While measuring the voltage at point B with the DMM, adjust the potentiometer to make the DC voltage at point B zero.



Stop here! too long!

Figure 4 - Input offset voltage trimming circuit

The penalty for using op-amps with high slew rate and bandwidth is instability. You already corrected one instability problem by using decoupling capacitors. However, certain configurations such as the unity gain configuration are particularly prone to instability.

(1) Set the generator to 1 KHz. Build the circuit of Figure 5 without R_3 and C_3. Connect point A to your generator output.

(2) Examine point B with the CH1 input of your scope. Your circuit should be oscillating at a very high frequency.

(3) Connect R_3 and C_3 as shown in Fig.5. Use values of C_3=100pF and R_3=1k. These components increase the effective gain at high frequencies and eliminate the oscillation you saw in step (2).

(4) Measure the amplitudes at point B for frequencies of 1 KHz, 10 KHz, 100 KHz, and 1 MHz. Record your results in Table 6.10

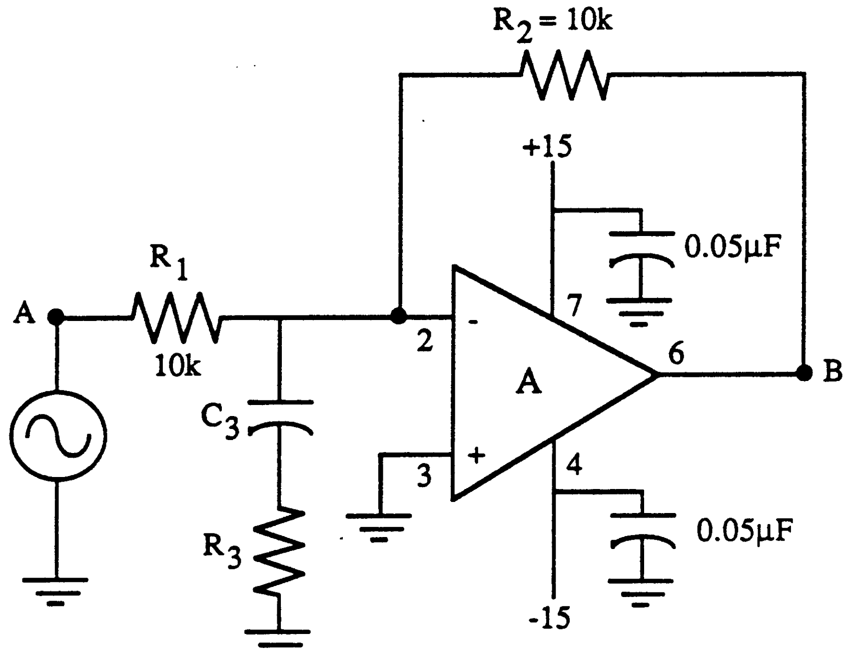


Figure 5 - Unity Gain Amplifier

Built with LF357
Try it with a 741 - no oscillations

Questions:

1. (a) Can you estimate the gain from your data of Table 6.1? If so, what was it?
   (b) The 741 is supposed to have a gain of approximately 200,000? Does this agree with your data?
   (c) What is the input resistance of the amplifier circuit (the resistance looking to the right of point A)?
2. (a) Using your data of Table 6.3 what is the input current of the LM741 and LF357?
   (b) This current is specified on the manufacturer's data sheet as I_{bias}. The manufacturer's values are 80 nA (typical) for the 741 and 0.03 nA (typical) for the 357. Is this data consistent with your results?
3. (a) What is the overall gain (B/A) of the circuit of Figure 2? Use your data of Table 6.3.
   (b) Did the signal generator output voltage (point A) change when you connected it to the circuit?
   (c) What is the input resistance of the amplifier circuit (the resistance looking to the right of point A)?
4. (a) At what voltages does the LM741 saturate?
   (b) At what voltages does the LF357 saturate?
   (c) What would you have expected from an ideal amplifier?
   (d) Which is the better op-amp when it comes to saturation voltage?
5. (a) Calculate the slew rate of the LM741 using your data of Table 6.7.
   (b) Calculate the slew rate of the LF357.
   (c) How do your measured values of slew rate compare with the data sheet values?
   (d) Which is the better op-amp when it comes to slew rate?
6. (a) Prove that for any value of R_3, the THEORETICAL overall gain (B/A) of the circuit shown in Figure 3 is [illegible]
   (b) For each value of R_3, transform the signal generator, R_1, and R_3 into a single Thevenin voltage source (V_{thev}) and resistance (R_{thev}).
   (c) Calculate the THEORETICAL Thevenized gain of the circuit (B/V_{thev}) for each value of R_3.
   (d) Reproduce Fig.2 from the LM741 data sheet on a sheet of graph paper, add lines for each of the gains calculated in part (c), and find the frequency at which each line intersects the open loop curve.
   (e) How do these frequencies compare with the 3-db frequencies recorded in Table 6.9?
7. (a) Reproduce the open loop frequency response curve from the LF357 data sheet on a sheet of graph paper, add lines for each of the theoretical thevenized gains, and find the frequency at which each line intersects the open loop curve.
   (b) How do these frequencies compare with the 3-db frequencies recorded in table 6.9?
   (c) Just how much better than the LM741 is the LF357.
8. Did the resistor and capacitor adversely affect the gain up to 1 MHz in your amplifier of Figure 4?
9. (a) What is the overall gain (B/A) of the circuit of Figure 5?
   (b) Did the signal generator output voltage (point A) change when you connected it to the circuit?
   (c) What is the input resistance of the amplifier circuit (the resistance looking to the right of point A)?
   (d) What is the purpose of the 47 μF capacitor?
   (e) Why is R_3 needed?

EEAP 243 LAB 6 EVALUATION

NAME (print)____________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

Assume that A is disconnected from B and that H is connected to I in Fig. 6.2. What will happen to the DC voltage at point D if we increase/decrease the resistance of the $R_S/R_{B1}/R_{B2}/R_C/R_{E1}/R_{E2}/R_L$?

It will increase / decrease / stay the same.

Question #2

Assume that A is disconnected from B and that H is connected to I in Fig. 6.2. What will happen to the AC voltage at point H if we increase/decrease the resistance of the $R_S/R_{B1}/R_{B2}/R_C/R_{E1}/R_{E2}/R_L$?

It will increase / decrease / stay the same.

EEAP 243

NAMES: ______________________________

Lab 6 Data

input voltage (DC)	output voltage (DC)

Table 6.1

	LM741	LF357
voltage drop		

Table 6.2

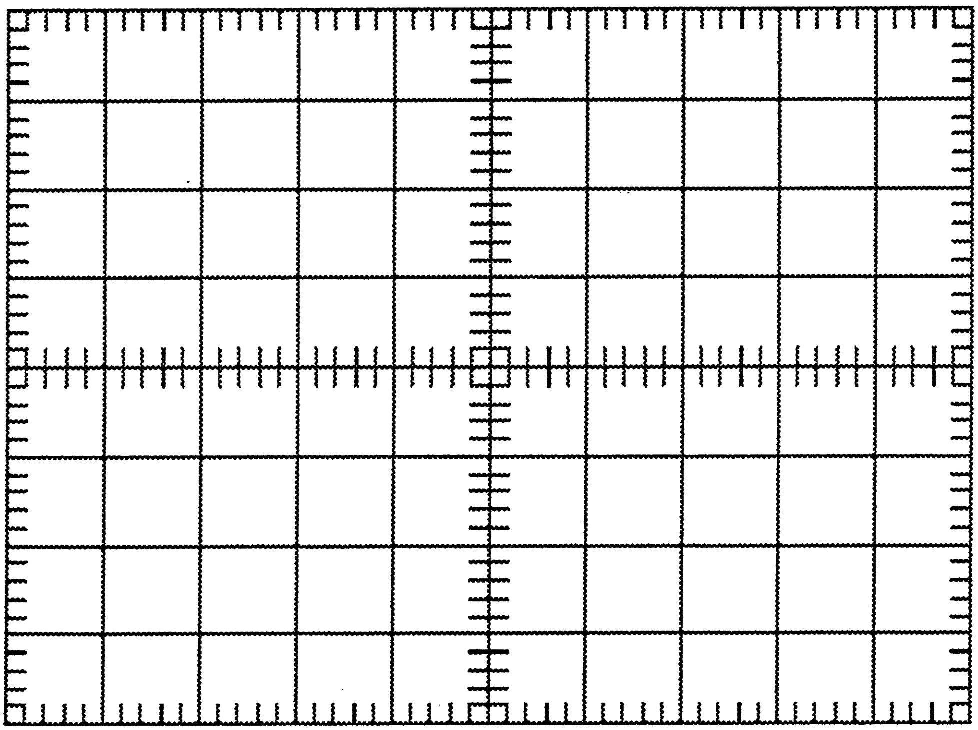


Table 6.3

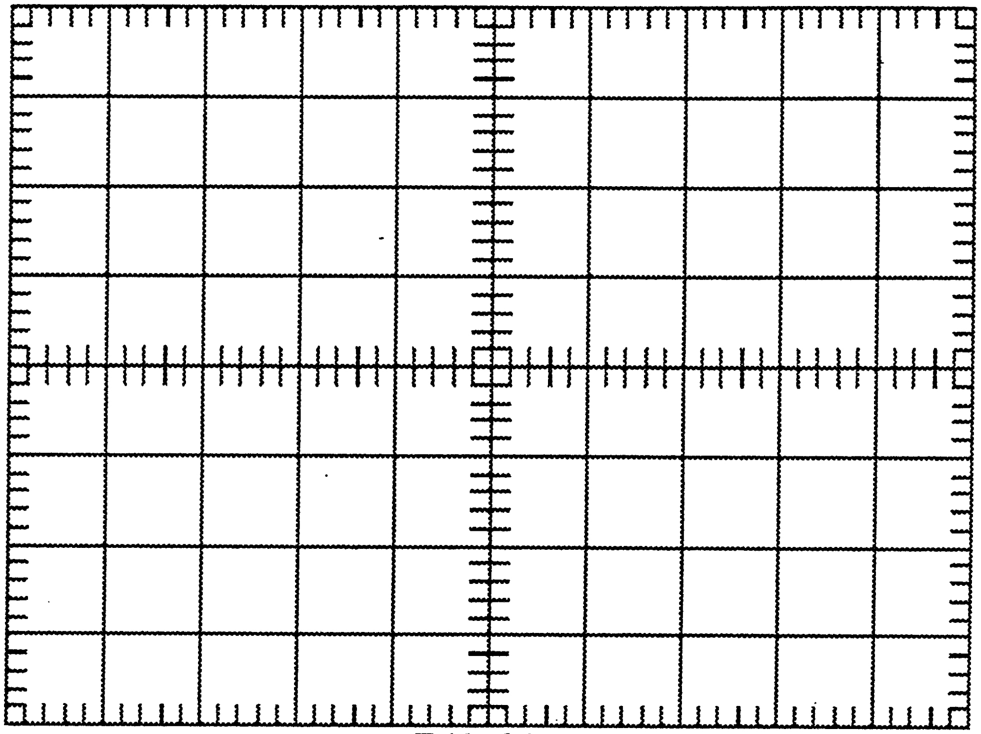


Table 6.4

	maximum + voltage	maximum - voltage
LM741		
LF357		

Table 6.5

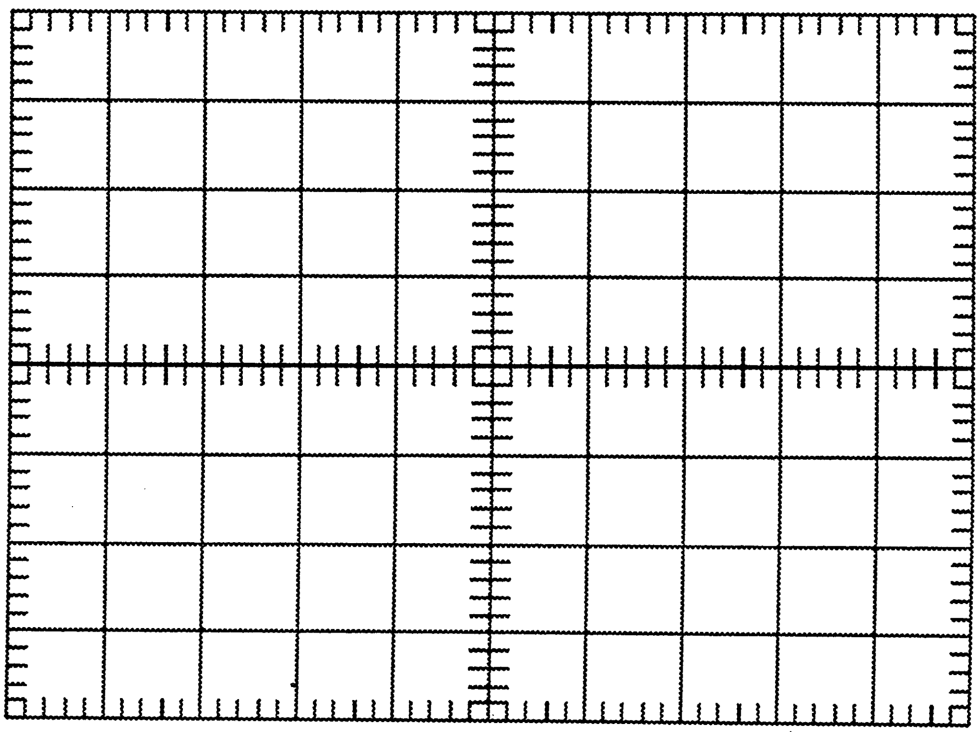


Table 6.6

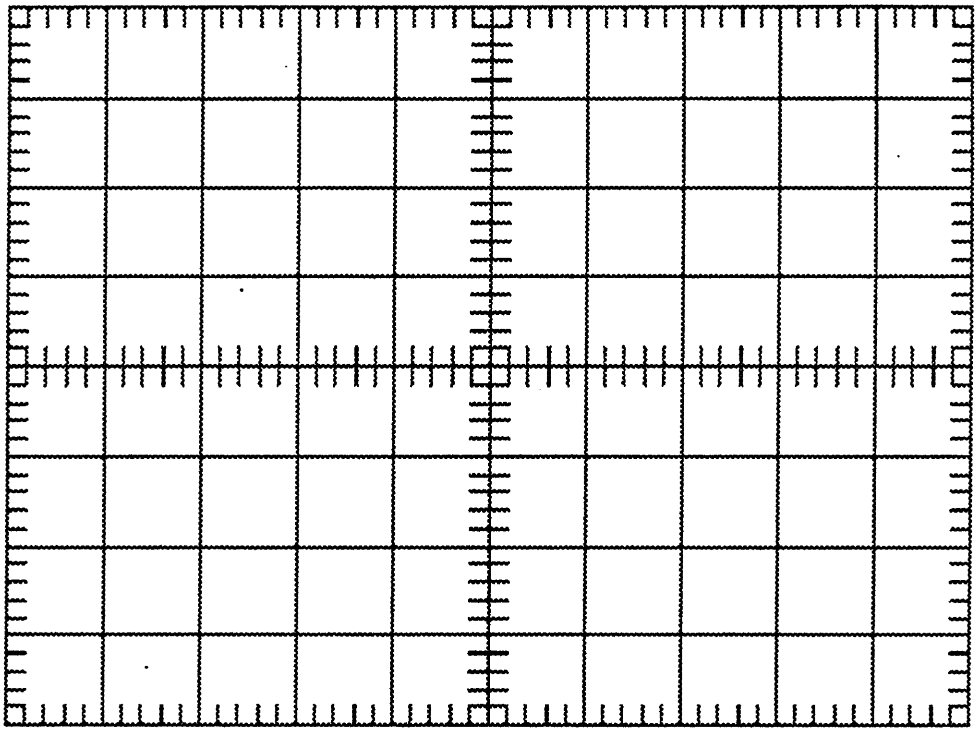


Table 6.7

	LM741	LF357
10		
100		
1000		
open-circuit		

Table 6.8 High frequency roll-off frequencies.

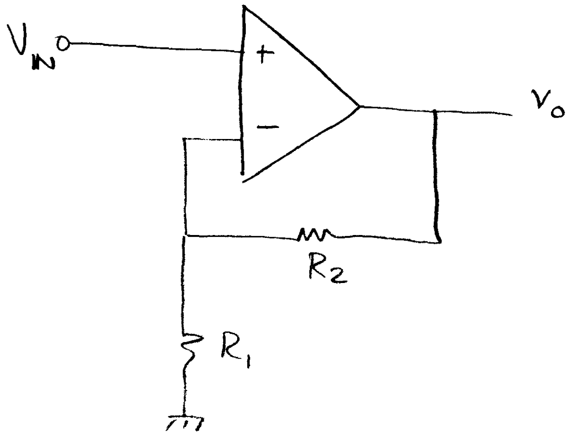
	LM741	LF357
V_{OS}		

Table 6.9 Input Offset Voltage

frequency	$V_{p\text{-}p}$
1 kHz	
10 kHz	
100 kHz	
1 MHz	

Table 6.10 High frequency cutoff characteristics.

non-inverting amplifier



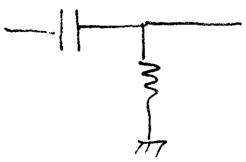
$$V_o = A(V_+ - V_-) = A\left(V_{in} - \frac{R_1}{R_1+R_2} V_o\right).$$

$$V_o\left(1 + \frac{AR_1}{R_1+R_2}\right) = A\,V_{in}$$

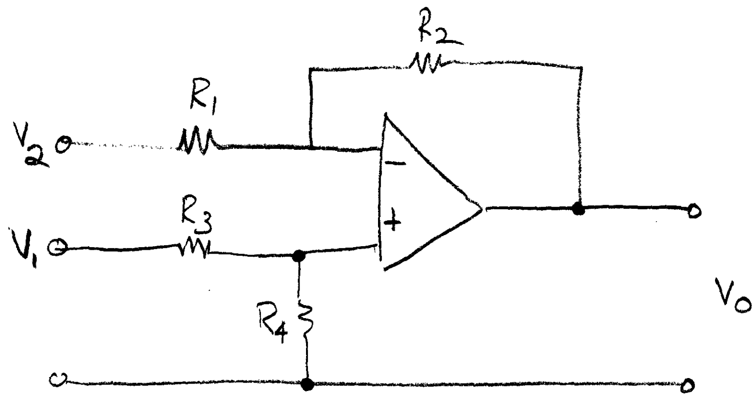
$$\frac{V_o}{V_{in}} = \frac{A}{1 + \frac{AR_1}{R_1+R_2}} \rightarrow \frac{R_1+R_2}{R_1} \quad \text{as} \quad A \rightarrow \infty$$

$$\cong 1 + \frac{R_2}{R_1}$$

see p.95 Horowitz



if source is ac coupled you <u>must</u> provide a resistance to ground for I_{os}, otherwise the amp will not work.



We can use superposition to analyze this circuit

If $V_1 = 0$ then we have an ordinary inverting op-amp given by

$$V_o = -\frac{R_2}{R_1} V_2$$

The analysis for $V_2 = 0$ is a little more complex.

If $V_2 = 0$, then $V_- = \frac{R_1}{R_1 + R_2} V_o$

$$V_+ = \frac{R_4}{R_4 + R_3} V_1$$

$$V_o = A\,(V_+ - V_-)$$

$$V_o = A\left(\frac{R_4}{R_4 + R_3} V_1 - \frac{R_1}{R_1 + R_2}\right) V_o$$

$$V_o + \frac{A R_1}{R_1 + R_2} V_o = \frac{A\, R_4}{R_3 + R_4} V_1$$

$$\left(\frac{R_1 + R_2 + A R_1}{R_1 + R_2}\right) V_o = \left(\frac{A R_4}{R_3 + R_4}\right) V_1$$

$$V_o = \frac{A R_1 + A R_2}{A R_1 + R_1 + R_2} \; \frac{R_4}{R_3 + R_4} V_1$$

and as $A \to \infty$

$$V_o = \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) V_1$$

by superposition

$$V_o = \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) V_1 - \frac{R_2}{R_1} V_2$$

$$V_0 = \frac{R_2}{R_1}\left[\frac{\cancel{R_1}}{R_2}\left(\frac{R_1+R_2}{\cancel{R_1}}\right)\frac{R_4}{R_3+R_4}V_1 - V_2\right]$$

$$V_0 = \frac{R_2}{R_1}\left[\left(\frac{R_1+R_2}{R_2}\right)\left(\frac{R_4}{R_3+R_4}\right)V_1 - V_2\right].$$

Now, if the coefficient of V_1 is 1

$$V_0 = \frac{R_2}{R_1}\left[V_1 - V_2\right]$$

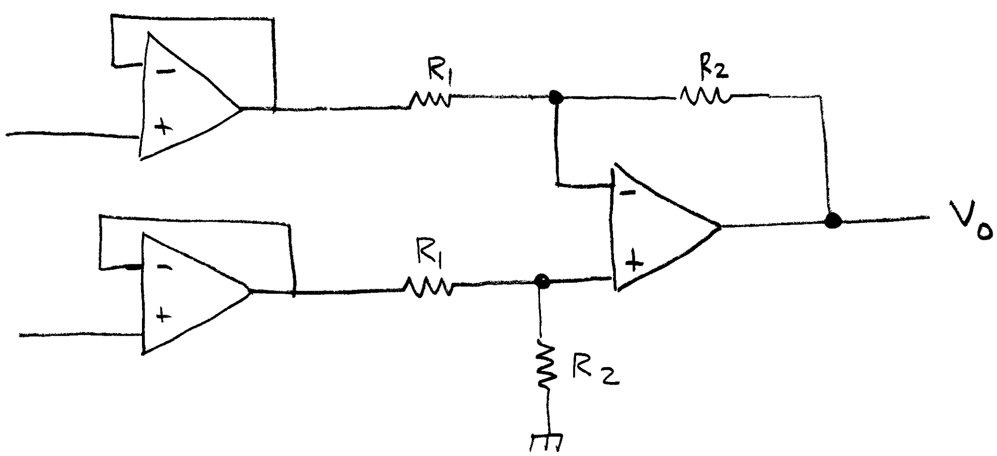
this is a differential amplifier whose output depends upon the difference between the inputs. For $\frac{R_1+R_2}{R_2}\,\frac{R_4}{R_3+R_4} = 1$

we get $\frac{R_1+R_2}{R_2} = \frac{R_3+R_4}{R_4}$

or $\frac{R_1}{R_2} + 1 = \frac{R_3}{R_4} + 1$

The requirement is that $\frac{R_1}{R_2} = \frac{R_3}{R_4}$

The input current at the non-inverting input depends upon R_3 and R_4. (Assuming I_{os} is very small). On the other hand the input current at the inverting input is dependent upon R_1 and V_1. This is undesirable in high-performance systems where we want R_{IN} to be always very large. Consequently we will usually preced each input by a non-inverting amplifier.



Experimental procedures

ideal amplifier only responds to $(V_2 - V_1)$

real amplifiers also have a small dependence on the individual input voltages

A_{cm} common-mode

A_{DM} difference-mode

$V_{icm} \triangleq$ average of the two inputs $= \frac{V_1 + V_2}{2}$

$V_{idm} =$ difference of the inputs $= V_1 - V_2$

An amplifiers output is thus given by

$$V_o = A_{cm} V_{icm} + A_{dm} V_{idm}$$

$$= A_{cm} \frac{V_1 + V_2}{2} + A_{dm} (V_1 - V_2)$$

$$= \left(\frac{A_{cm}}{2} + A_{dm}\right) V_1 + \left(\frac{A_{cm}}{2} - A_{dm}\right) V_2$$

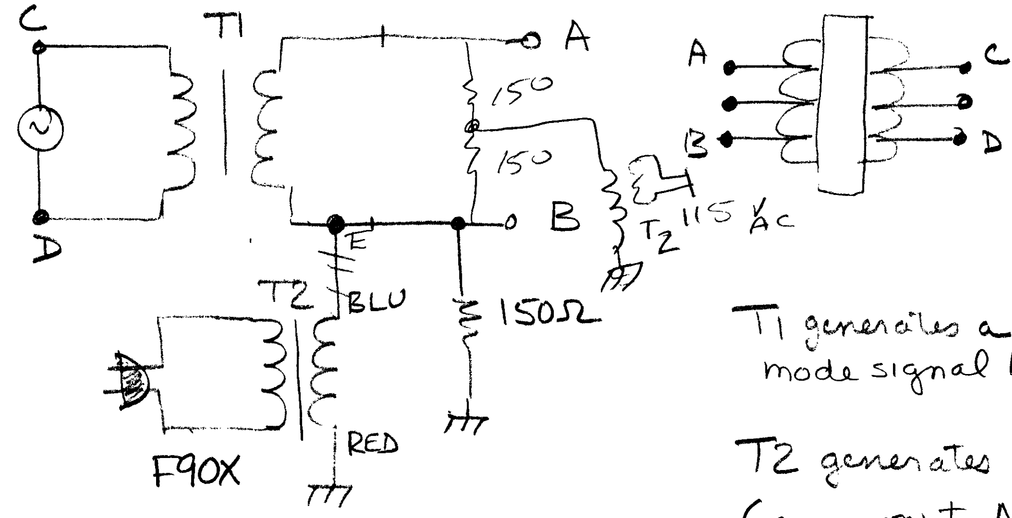
with two constants we can represent any two coefficients

In a real-application we want A_{cm} to be as small as possible

$$CMRR = \left| \frac{A_{dm}}{A_{cm}} \right|$$

A very good amp will have CMRRs greater than 100db.

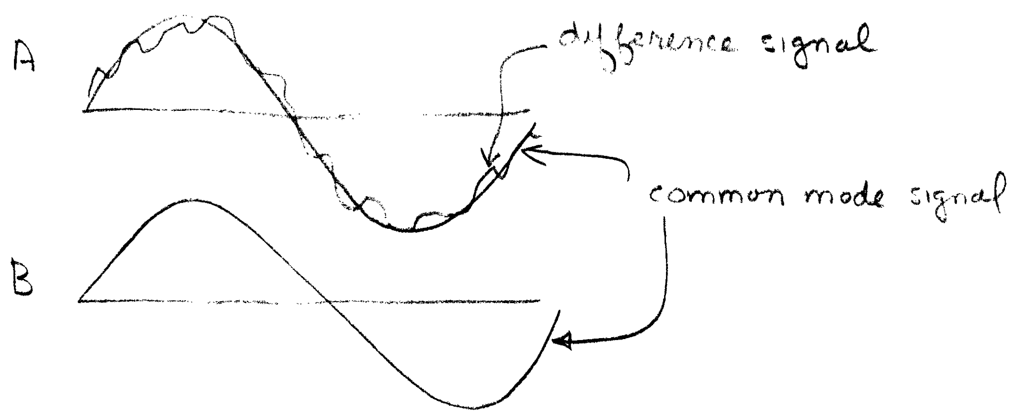
how to generate differential and common mode signals.



T1 generates a differential mode signal **between** A and B.

T2 generates a common mode (common to A and B) = voltage **at** A and B; The 150Ω resistor provides a ground path for T2.

technically



EEAP 243 Lab Work:
Lab 7 Questions Due:

MORE REAL OPERATIONAL AMPLIFIERS

READING ASSIGNMENT: Horowitz, pgs. 80, 95, 99-100, 279-286.

Abstract:
The performance of non-inverting and instrumentation amplifiers will be examined.

Part I: Non-inverting amplifier

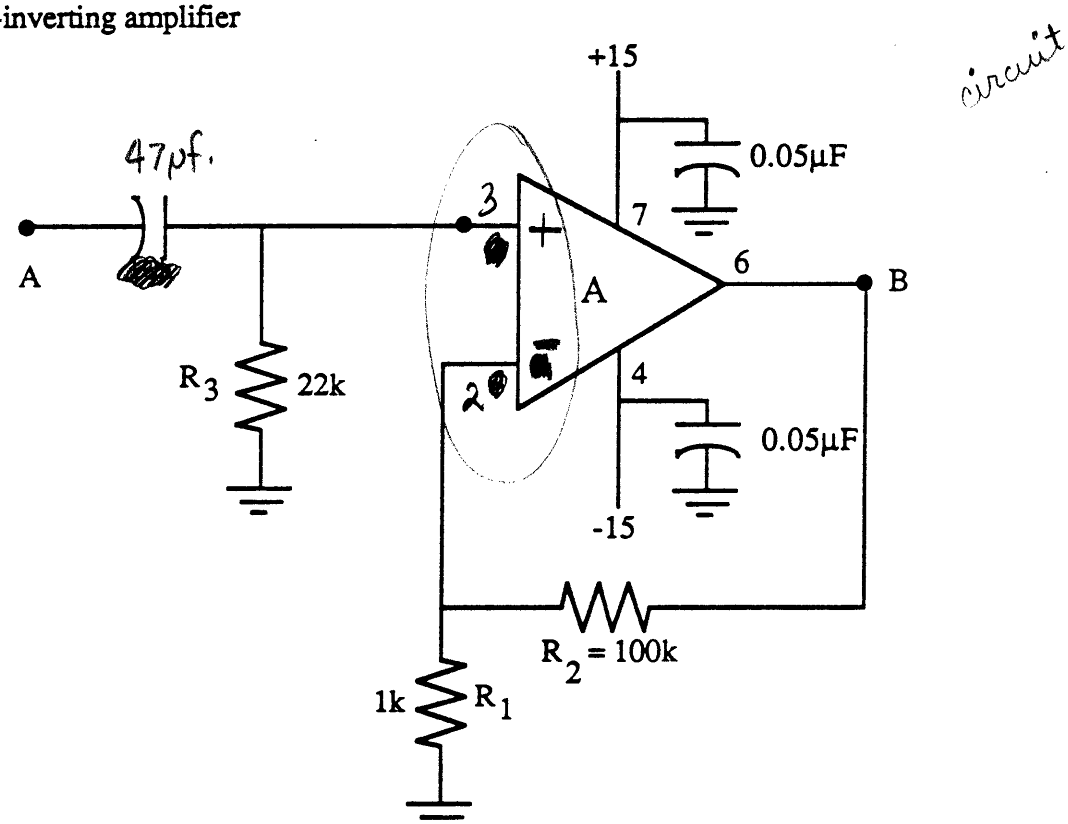


Figure 1

Up to this point, you have only built inverting amplifiers. The non-inverting amplifier configuration is also often useful.

(1) Set the generator to produce a 0.2 V_{p-p} sine wave at 1 KHz with +1 V DC offset.
(2) Build the circuit of Fig. 1 connecting the signal generator to point A.
(3) Record the waveforms at points A and B in Table 7.1 and make note of the phase difference between them.
(4) Vary the generator's DC offset and observe what happens.
(5) Remove resistor R_3, vary the DC offset, and observe what happens.

Part II: Instrumentation amplifier

One of the most useful amplifiers configurations in the real world is the instrumentation amplifier. Imagine that you are using a sensor to, for example, measure temperature or blood pressure. This sensor will typically have two output leads which you will run for some distance to a high gain amplifier to get the signal you need for analysis, control, etc. The problem is that long wires and single-ended inputs are very susceptible to picking up noise from external electromagnetic fields. Consider what you say when you connected a test probe to your scope and simply placed it on the table top. Any real-world circuit must deal with similar noise problems.

To understand the basic principle of an instrument amplifier consider the circuit of Figure 2. The basic requirement of an instrument amplifier is to amplify the signal voltage (E_S) while rejecting the common mode noise voltage (E_{CM}). In actual applications, E_S is often on the order of millivolts while E_{CM} can be on the order of volts. The gain of the circuit shown above is given by

$$E_{OUT} = (E_A - E_B)\frac{R_3}{R_1}$$

provided that $R_1=R_2$ and $R_3=R_4$. In fact, it is very critical that $R_1=R_2$ and $R_3=R$, otherwise, the amplifier will not reject E_{CM}. R_{S1} and R_{S2} are simply the output impedance of E_S.

Practical instrumentation amplifiers use circuits similar to Figure 3. The amplifiers A_1 and A_2 increase the input impedance. Basically, A_1 and A_2 are connected as voltage followers, i.e. ×1 voltage amplifiers.

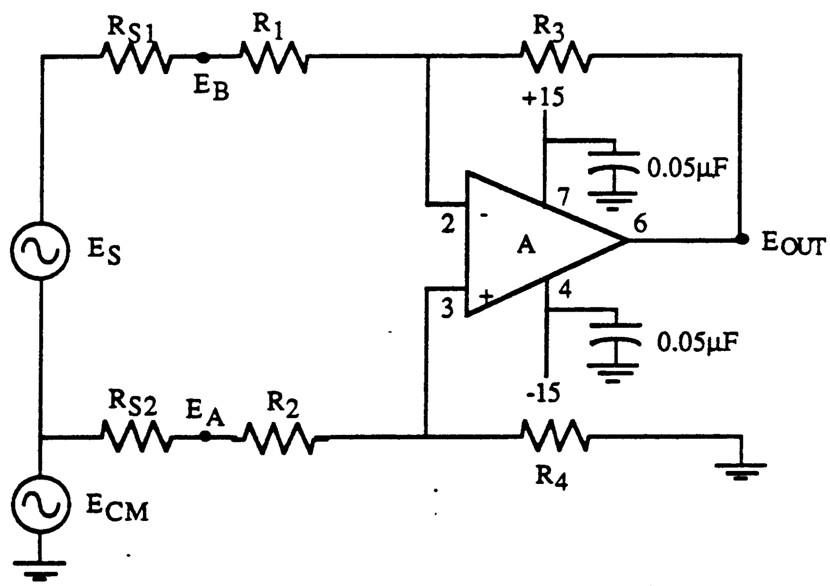


Figure 2 - Basic Instrumentation Amplifier

(1) Build the circuit of Fig.3. Use 1k resistors for R_1 and R_2, a 100k resistor for R_3, and 2.2k resistors for R_5 and R_6. R_7 is a 10k pot. R4 is a 100k pot. Use LM741's for A_1 and A_2. Use a LF357 for A_3. All capacitors unless otherwise shown are 0.05 µF bypass capacitors.

(2) Measure R_1, R_2 and R_3 with your DMM. Record the values in Table 7.2. Calculate

$$R_2 \times \frac{R_3}{R_1}$$

Connect your DMM between the wiper and one of the resistance connections of R_4 and adjust R_4 to equal the value you calculated above as accurately as you can. Connect R_4 into your circuit–DO NOT EVER CHANGE THE VALUE OF R4 unless specifically told to do so. Be careful that you connect R_4 so that the resistance the circuit sees is the same resistance you measured with the DMM.

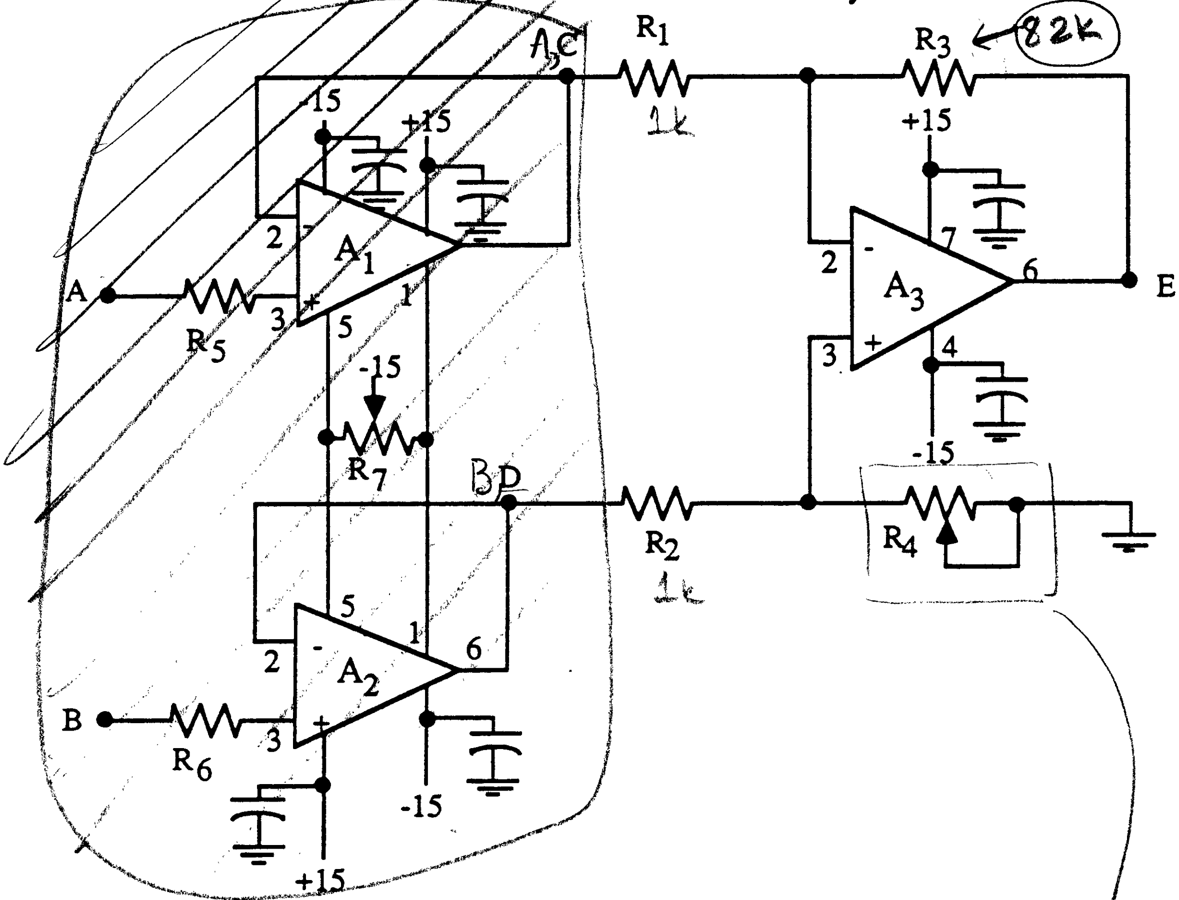
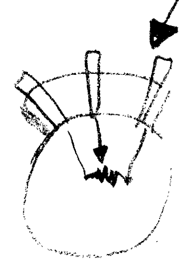
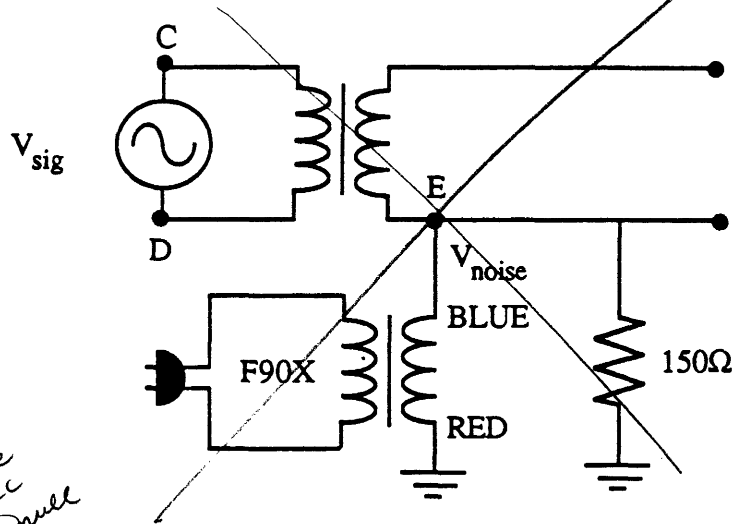


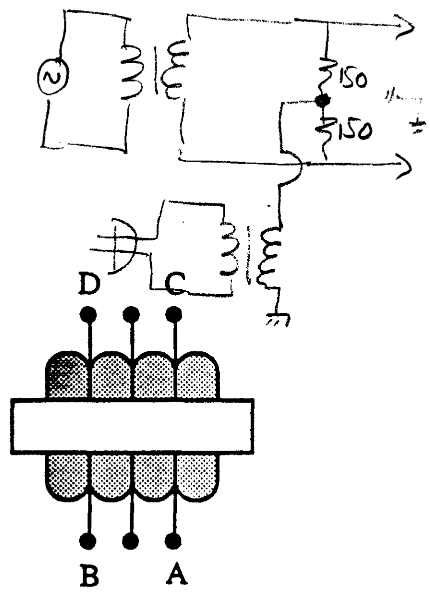
Figure 3 - Practical Instrumentation Amplifier

diagram of potentiometer



replace





Top view of audio transformer

Figure 4 - Differential and Common Mode signal circuit.

instead use common ac waveform to null amplifier

(3) Connect your DMM to point E. Connect points A and B with a jumper. Adjust R_7 until your output voltage is exactly zero. Your amplifier is now ready to test.

(4) Build the signal producing circuit shown in Figure 4 on your protoboard. The points labeled A and B will connect to the correspondingly labeled points of your instrumentation amplifier. Do NOT disassemble your instrumentation amplifier circuit. The upper transformer is your audio transformer. The second transformer is your familiar power transformer. The function of the audio transformer is to allow the signal generator output to be added in series to the output of the power transformer. Do NOT plug the power transformer in yet.

(5) Connect the signal generator output to point C. The other side of the transformer primary should be connected to your station COM. Adjust the signal generator output to $0.2V_{p\text{-}p}$, 0 volts DC at 1 KHz. Connect point A of your signal circuit to point A of your instrumentation amplifier. Connect point B of your signal circuit to point B of your instrumentation amplifier.

(6) Connect your scope CH1 input to point A, connect the scope CH2 input to point B and record the waveform you see in Table 7.3. The signals will look almost identical. Set your scope mode to ADD and the INV CH2 switch out. *IN* You should now see the signal corresponding to "A-B", the differential signal which the amplifier will see. Vary the generator output–your signal on the scope should follow the change in generator output.Measure and record in Table 7.4 the peak-peak voltage of the "differential" signal you see between points A and B. This is the input signal to your amplifier.

(7) Disconnect the output of your signal generator from point C. Plug in the power transformer. You are now inserting a signal in series with points A and B–a common mode signal. ~~Record the value of any 60Hz signal you see between A and B.~~ *record these in Table 7.4*

What signal? confusing

(8) Unplug the power transformer. Reconnect the signal generator to point A.

(9) Remove the CH1 probe from point A. Reconnect it to point E. Change the mode switch to CH1. You are now looking at the amplifier output. Record the peak-peak ac voltage in Table 7.5.

(10) Disconnect the signal generator from point C. Plug in the power transformer. Record any 60Hz output voltage (peak-peak) you see at point E in Table 7.5.

Questions:

1. (a) What is the overall gain (B/A) of the circuit of Figure 1?
   (b) Did the signal generator output voltage (point A) change when you connected it to the circuit?
   (c) What is the input resistance of the amplifier circuit (the resistance looking to the right of point A)?
   (d) What is the purpose of the 47 μF capacitor?
   (e) Why is R_3 needed?
2. (a) What is the differential gain of your instrumentation amplifier?
   (b) What is the common mode (60Hz) gain?
   (c) The common mode rejection ratio (CMRR) is defined to be

$$\text{CMRR} = \frac{A}{-A_{CM}}$$

   where A_{CM} is the common mode gain and A is the differential gain. Calculate the CMRR for your instrumentation amplifier.
   (d) Explain the function of the two transformers in the signal circuit of Figure 4.
3. Show that the CMRR of the instrumentation amplifier is dependent upon how well matched the RATIO's R3/R1 and R4/R2 are.

EEAP 243 LAB 7 EVALUATION

NAME (print)__________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

Assume that A is connected to B, E is connected to F, G is connected to H, and that J is connected to L in Fig. 7.1. What will happen to the DC voltage at point I if we increase/decrease the resistance of $R_S/R_B/R_E/R_{L3}$?

It will increase / decrease / stay the same.

Question #2

Assume that A is connected to B, E is connected to F, G is connected to H, and that J is connected to L in Fig. 7.1. What will happen to the AC voltage at point J if we increase/decrease the resistance of $R_S/R_B/R_E/R_{L3}$?

It will increase / decrease / stay the same.

EEAP 243

NAMES: ____

Lab 7 Data

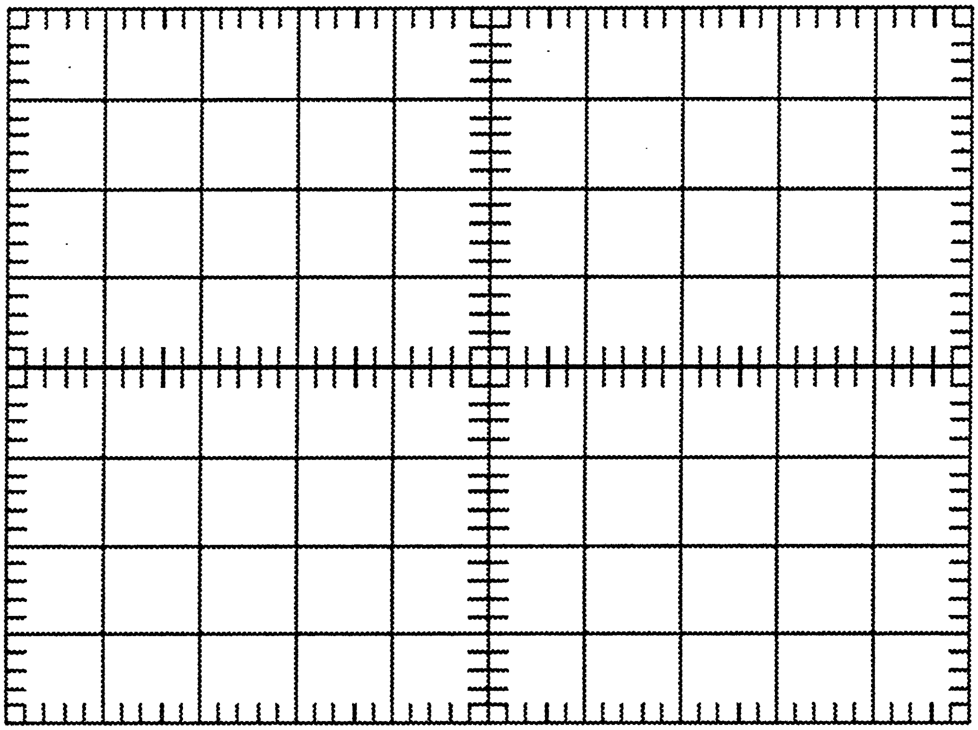


Table 7.1

R_1	____________
R_2	____________
R_3	____________

Table 7.2 instrumentation amp gain resistor measurements

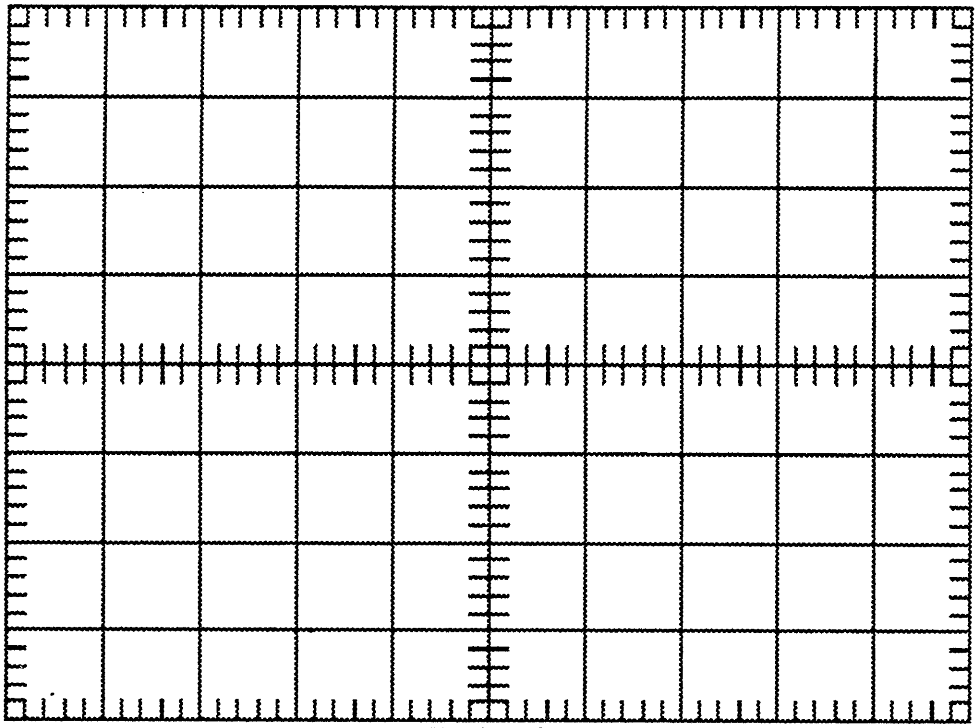


Table 7.3

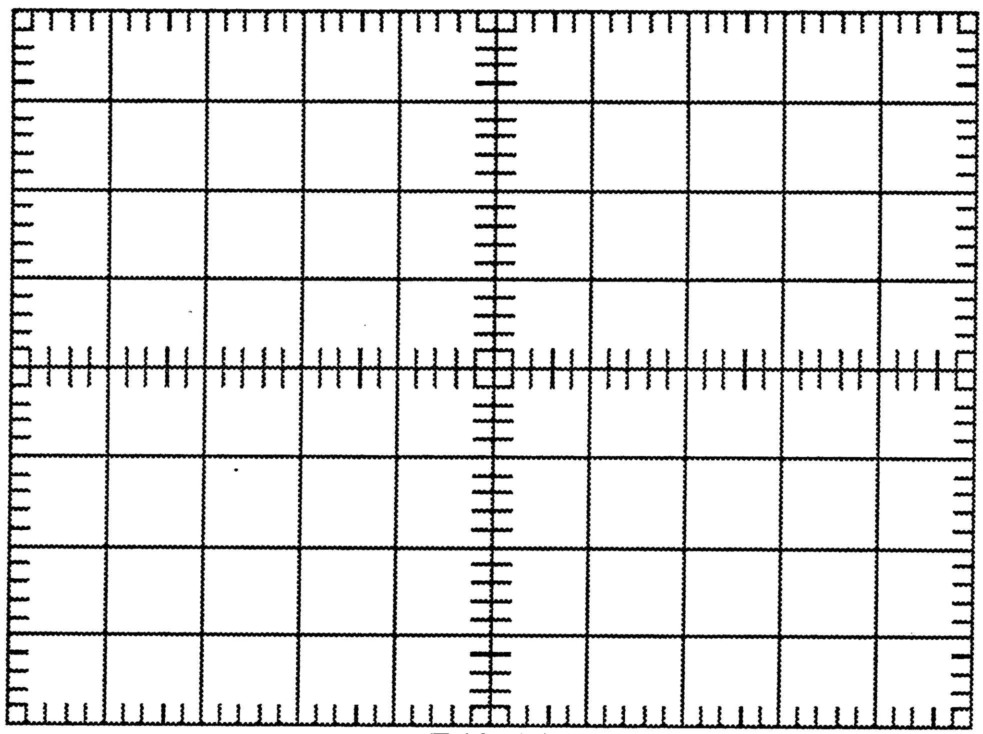


Table 7.4

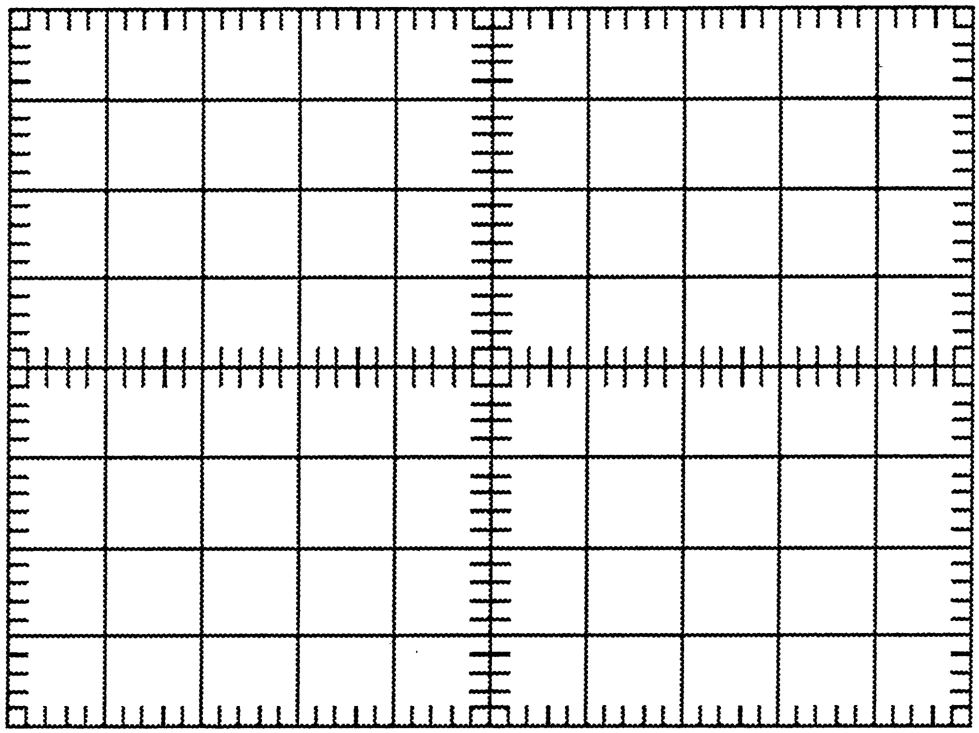
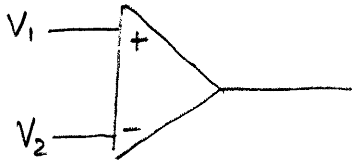


Table 7.5

comparator – determine which or two signals is larger
– know when a signal exceeds a given threshold.

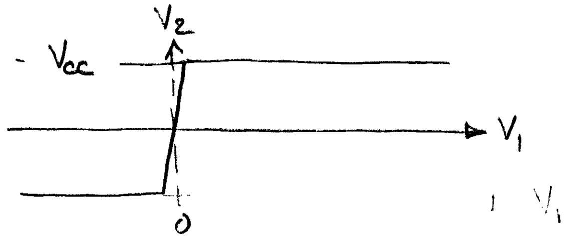
simplest comparator – high gain differential amplifier



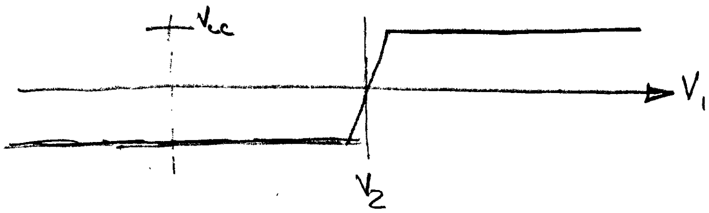
$V_{out} = A(V_1 - V_2)$

$V_1 - 5$

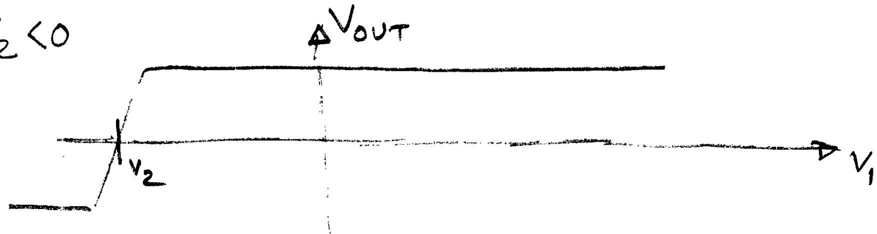
if $V_2 = 0$



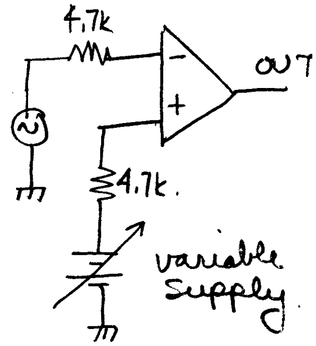
$V_2 \neq 0$, $V_2 > 0$



$V_2 < 0$



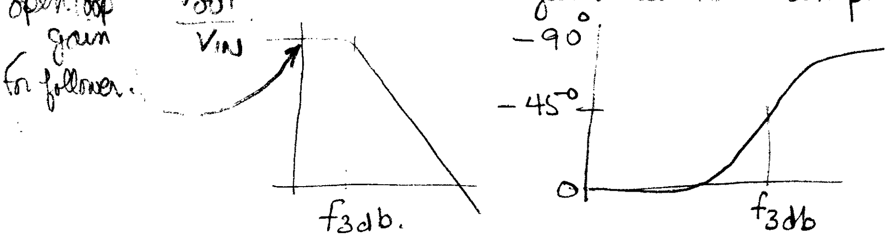
lab circuit

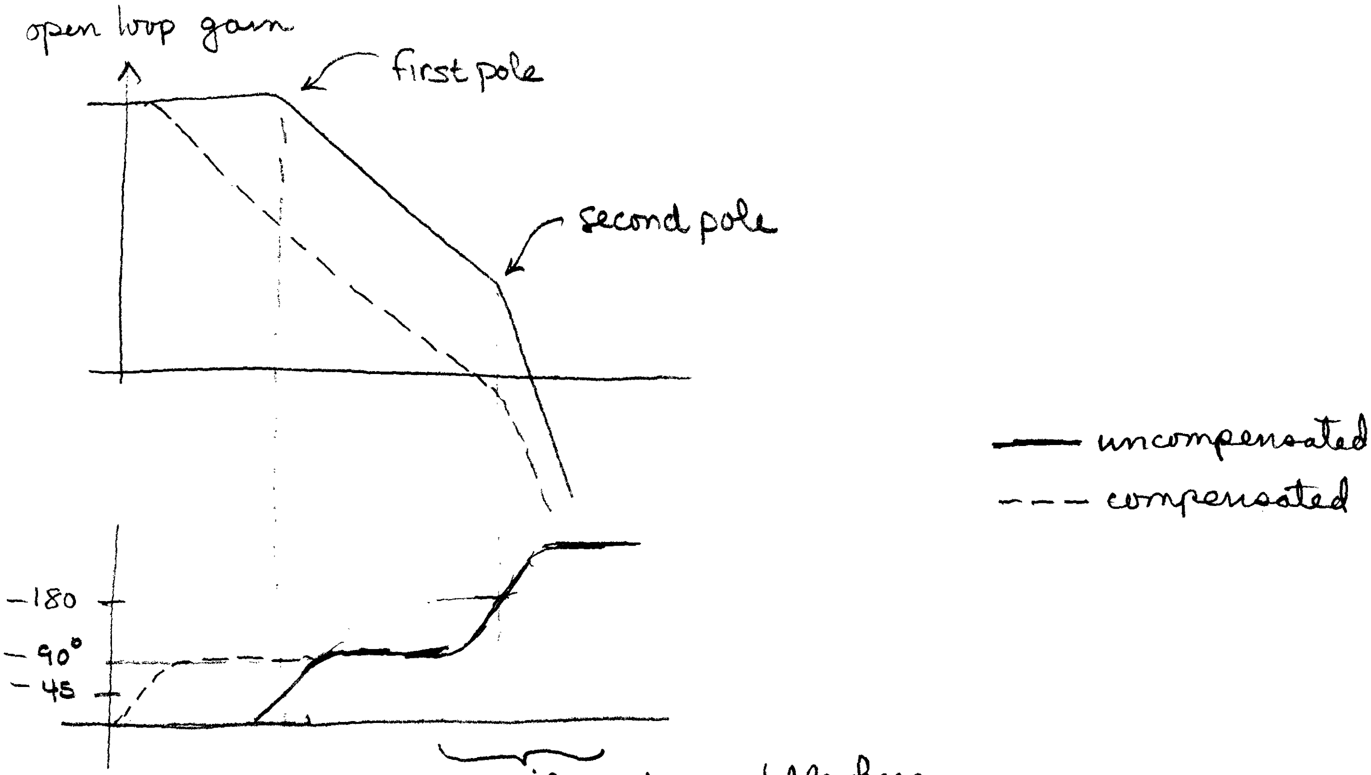


excellent for alarms!

op-amps are usually not good – use specialized IC chips instead
i.e. LM311
with better output circuits

Never use negative feedback – unstable with negative feedback.
need high gain for comparator
lower gain reduces comparator action,

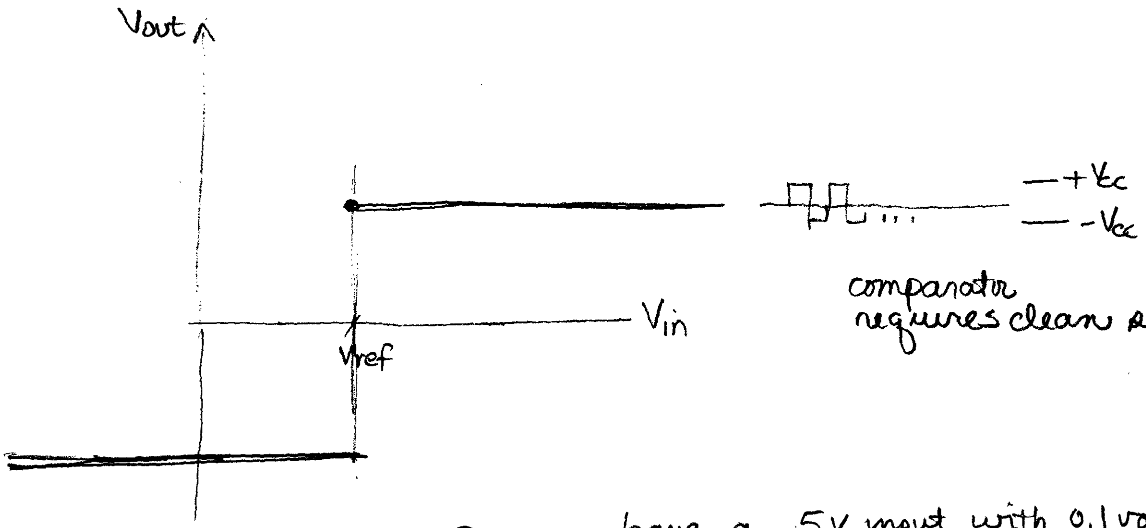




amplifier gets unstable here
since 180° feedback point has <u>positive</u> gain

compensate to reduce gain

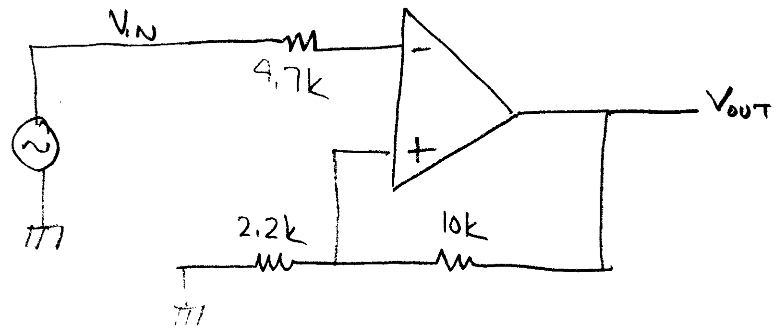
problems with noise:



comparator requires clean signal

say you have a 5V input with 0.1 volt noise

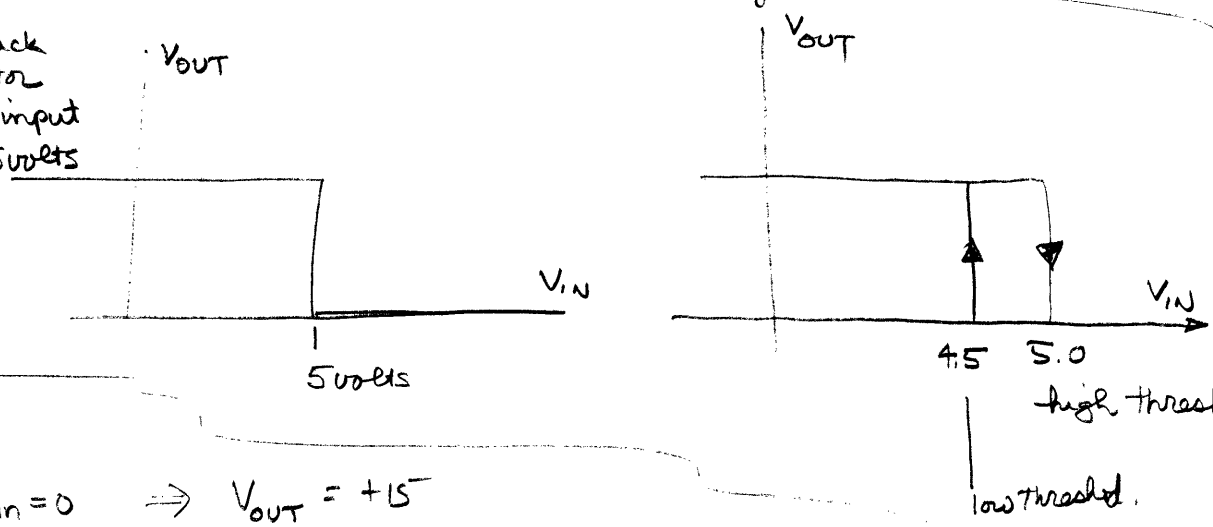
How to elimate noise – feedback to get hysteresis



POSITIVE FEEDBACK!

Figures 3.54, 3.55, 3.56 are very good.
not for above diagram

no feed back comparator
signal to neg. input
set V_{ref} to 5 volts

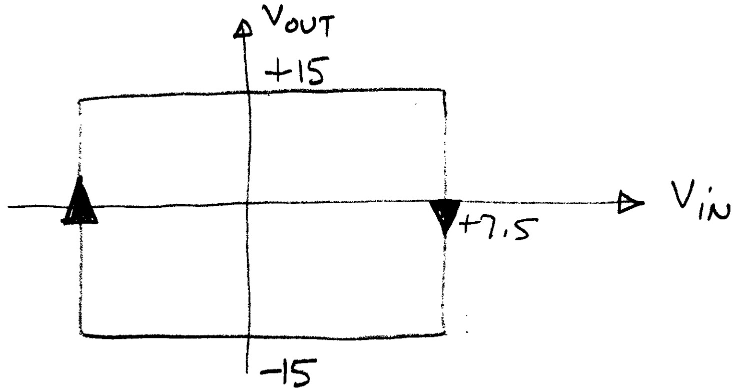


Example:
For Schmitt trigger

$V_{in} = 0 \Rightarrow V_{OUT} = +15$

Suppose $R_2 = R_3$ then $V_+ = 7.5$ volts,
forcing $V_{OUT} = +15$

If the input voltage rises to +7.5 no change in V_{OUT}
When input rises to +7.50015 output switches to −15V
and V_+ changes to −7.5 volts, voltage must drop
to below −7.5 volts, i.e. −7.50015 before the
output switches.

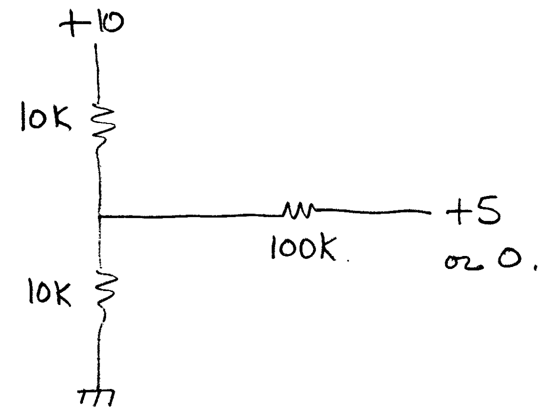


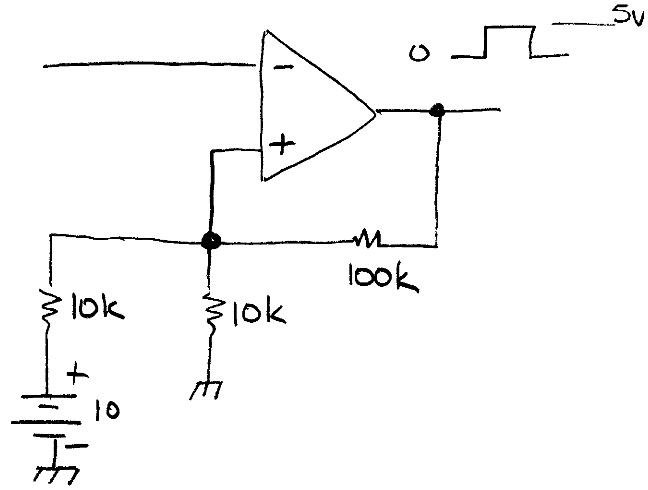
what are the upper and lower trigger points set by?

$$\left(\frac{2.2}{10+2.2}\right)15 = \frac{2.2}{12.2}\,15$$

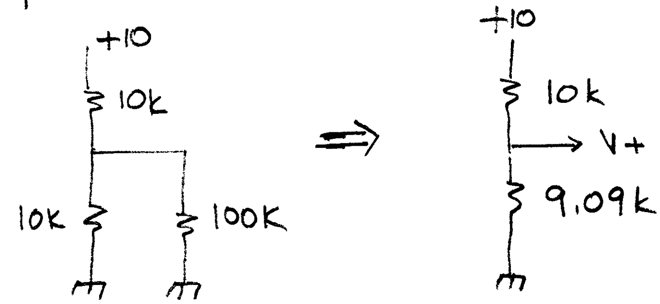
≈ 2.7 volts.

Sample calculation

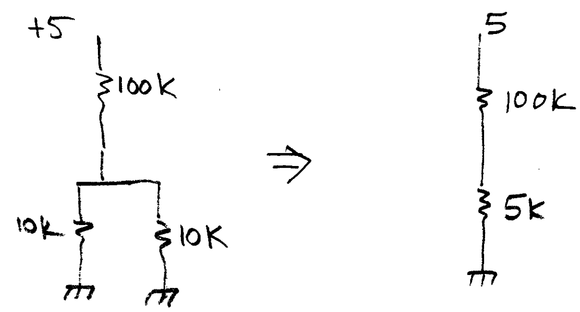




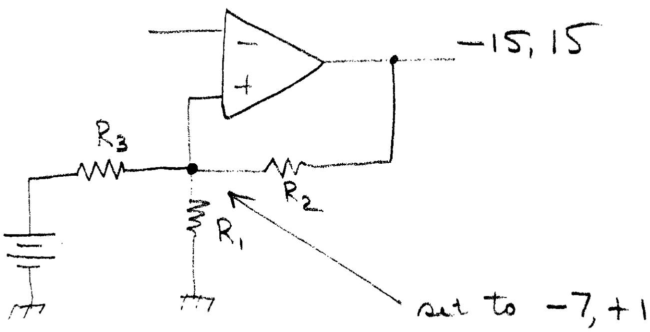
use superposition

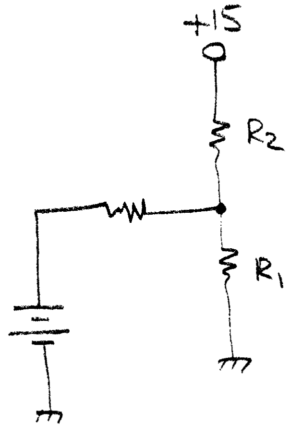


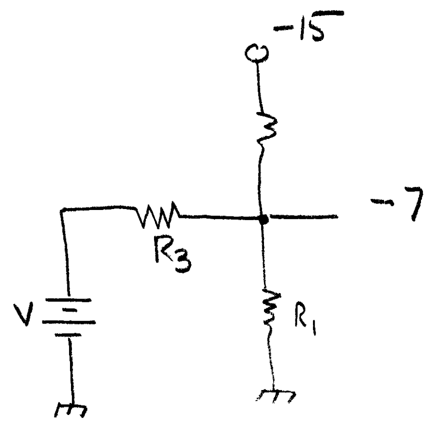
$$V_+ = \frac{9.09}{10+9.09}(10) = 4.76$$



$$V_+ = \frac{5}{100+5}(5) = \frac{5}{105}(5) = 0.24V.$$







pick $R_1 = 6.8K$

Then $\left(\frac{6.8}{6.8 + R_2}\right) 15 = 7$

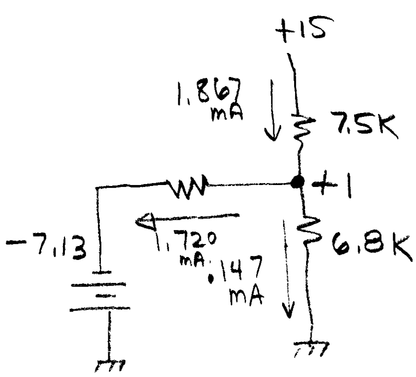
$$R_2 = \frac{(6.8)(15)}{7} - 6.8 = 14.57 - 6.8 = 7.7k$$

$\Rightarrow$ pick $R_1 = 6.8K$

$R_2 = 7.5K$

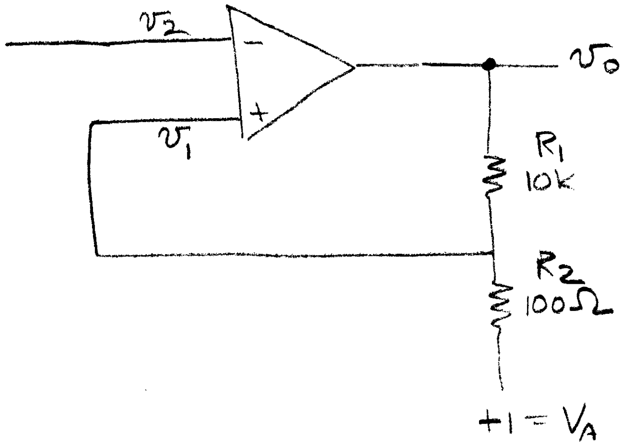
This gives $\frac{6.8}{6.8 + 7.5} 15 = 7.13$ volts.

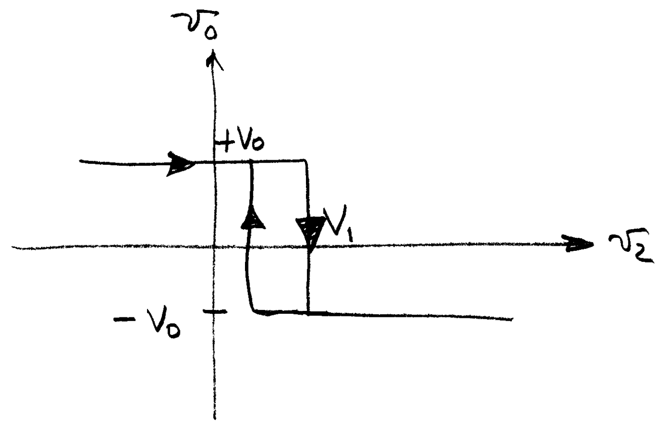
Set $V = -7.13$ volts



$$R_3 = \frac{+1 - (-7.13)}{1.720 \text{ mA}}$$

$$= \frac{8.13}{1.720 \text{ mA}} = 4.73k$$





$$v_o = A v_i$$

feedback gain $\quad T = -\dfrac{R_2 A v}{R_1 + R_2}$

---

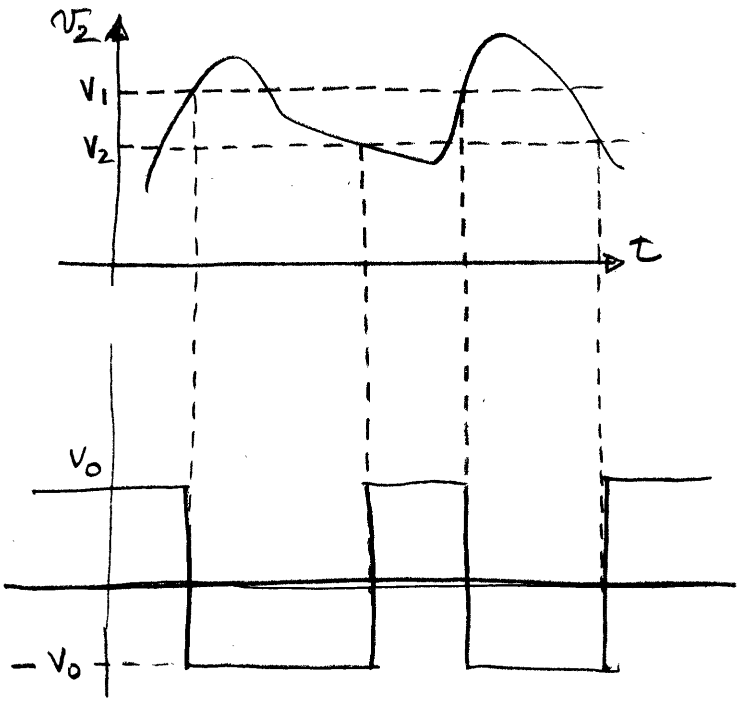
let $\quad v_o = +V_o$

$$v_1 = V_A + \frac{R_2}{R_1 + R_2}(V_o - V_A) \equiv V_1$$

notice that if v_2 is increased v_o remains constant at V_o and $v_1 = V_1$ until $v_2 = V_1$.
At this threshold, the output switches to $v_o = -V_o$

$$v_1 = V_A - \frac{R_2}{R_1 + R_2}(V_o + V_A) \equiv V_2 < V_1$$

difference between V_2 and V_1 is the hysteresis:



EEAP 243
Lab 8

Lab Work:
Questions Due:

NON-LINEAR OP-AMP CIRCUITS

READING ASSIGNMENT: Horowitz, pgs. 124-127., read section 9.07, p. 390 – 393 also.

Abstract:
This laboratory will examine the principles and operation of non-linear op-amp circuits. The Schmitt trigger exhibits hysteresis and is often used to "square up" analog signals. The comparator is often used to monitor the presence or absence of analog signals. Effectively, these circuits convert analog signals into 0's or 1's. The performance of these circuits in the presence of simulated "noise" will be examined.

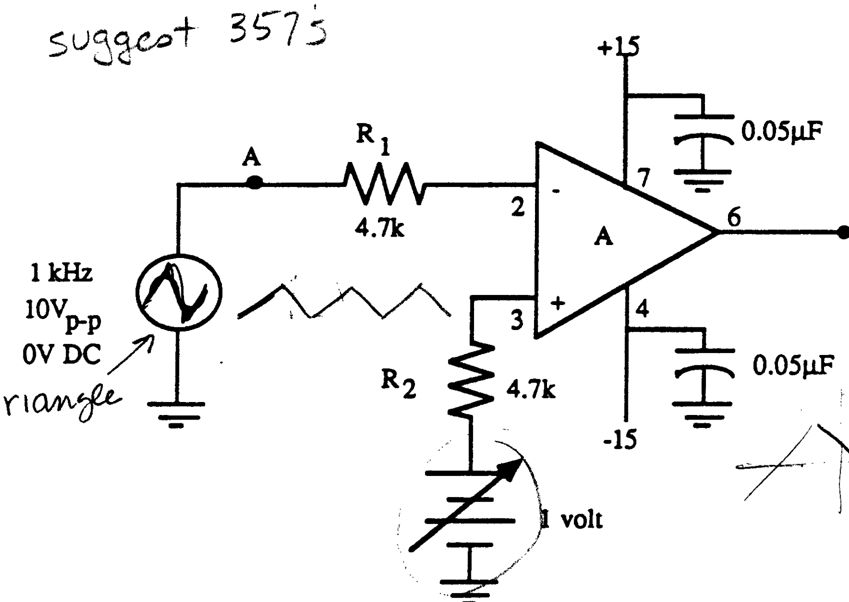
As a pre-lab exercise, you should determine the switching points and output voltages for the comparator and Schmitt trigger circuits and the voltage and resistor values needed to modify the Schmitt trigger. Remember to connect $+V_{cc}$ to +15 V and $-V_{cc}$ to -15 V.

Part 1 - The Comparator and Noise

When an op-amp is used without feedback, it is said to be "open-loop". Under these conditions the gain of the amplifier is $A(IN^+ - IN^-)$ where A is on the order of 100,000. For $(IN^+ - IN^-) > +150\ \mu V$, the theoretical output is higher than $+V_{cc}$ and the output will saturate at +15 V. For $(IN^+ - IN^-) < -150\ \mu V$, the theoretical output is lower than $-V_{cc}$ and the output will saturate at -15 V. The region of linear operation is very small and, for the most part, the amplifier's output will saturate at either +15 V or -15 V, depending on which of its inputs is greater. This type of circuit is known as a "comparator" because it compares the two input voltages to see which is greater and produces an output which is one of two states (+15 V or -15 V), depending on the result of the comparison. The circuits used in this part compare the input voltage at the inverting input to a "reference" voltage at the non-inverting input. Other configurations are possible; the reference may be on the inverting input and both the reference and input voltages may be any voltage between $+V_{cc}$ and $-V_{cc}$.

suggest 357's

Use the 741's
357



switching point

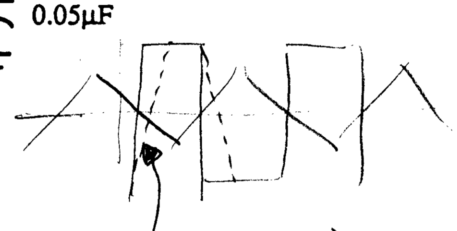


Figure 1 - Comparator circuit

slew rate distortion causes misrepresentation of where switching points

(1) Build the comparator circuit of Fig.1.
(2) Display points A and B simultaneously on the oscilloscope and record each waveform in Table 8.1.
(3) Carefully note the phase difference between A and B and note the two switching points.
(4) Set the DC offset to +3 V. To do this, set the scope channel connected to point A to 2 V/cm. A +3 V DC offset will make the triangle wave jump up 1.5 cm when the mode is switched from AC to DC.
(5) Record the waveforms in Table 8.2 and make note of the phase difference between A and B.
(6) Repeat step 5 for a DC offset of -3 V.

A "noisy" signal can be thought of as the sum of a desired signal and other, unwanted signals. The result is a signal which generally follows the desired one, but which deviates from it. If a noisy signal is fed into a comparator, the noise will cause unwanted changes of state at the output as the desired signal crosses zero volts.

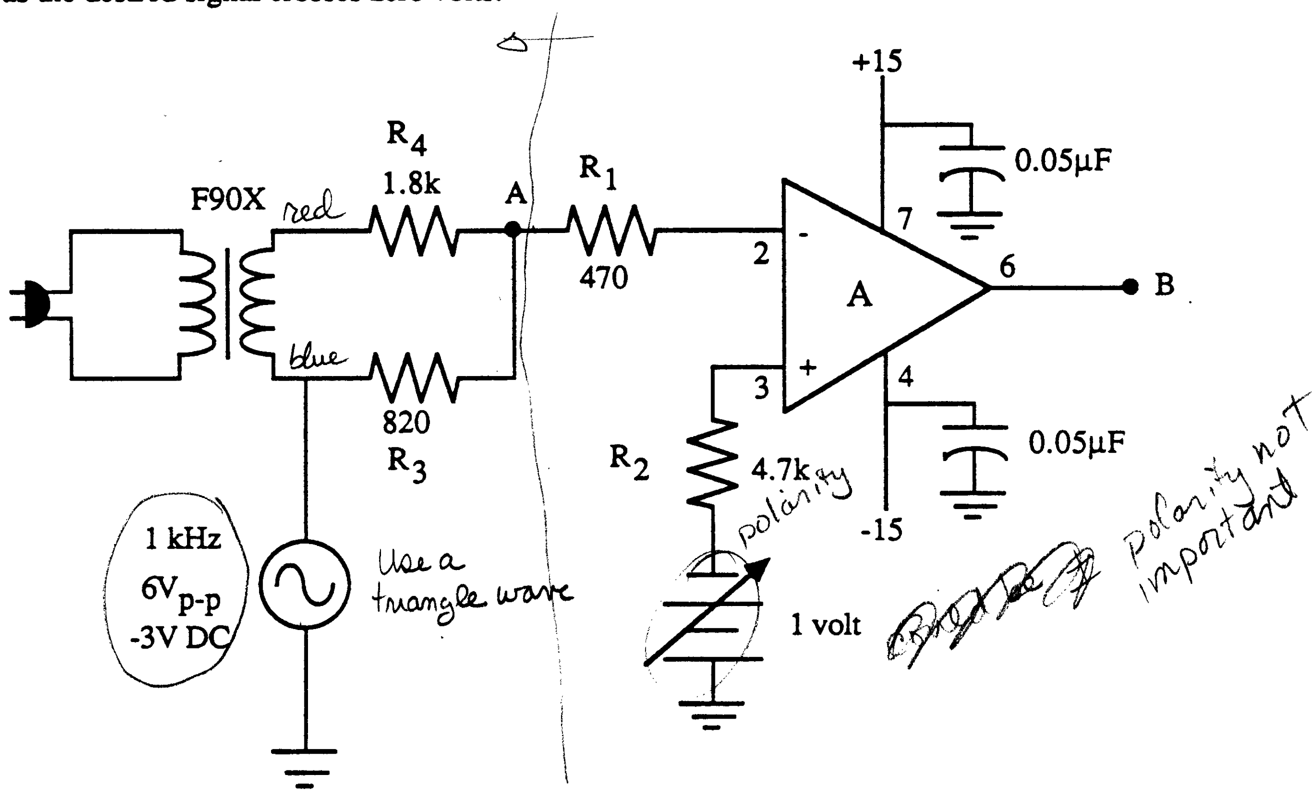


Figure 2 - Signal + "Noise" generator

(1) Disconnect the signal generator from your circuit and adjust its output to that shown in Fig.2.
(2) Build the circuit shown in Fig.2. Plug in the transformer. The transformer produces a sine wave at 60 Hz, which is added to the 1 KHz from the signal generator.
(3) If the composite signal at A is not around 14 $V_{p\text{-}p}$ you have not connected the circuit properly.
(4) Display the waveforms at A and B and record them in Table 8.3 making special note of the phase difference between them. It will not be possible to get an absolutely stable trace on the oscilloscope.
(5) Make note of exactly what takes place when the waveform at B changes state.

Part 2 - The Schmitt Trigger and Noise

The amplifiers you built in Lab 6 and 7 used negative feedback - a resistor feeding the output signal back to the inverting input. By using positive feedback - a resistor feeding the output back to the non-inverting input - the two switching points can be moved further apart. Consider the circuit of Fig.3 and assume that the input is zero, that the output is +15 V, and that $R_2 = R_3$. R_2 and R_3 set the voltage at the non-inverting input to +7.5 V, $(IN^{+}-IN^{-}) > 0$, and the output is indeed forced to +15 V. If we raise the input to +7.50015 V, then $A(IN^{+}-IN^{-}) = -15$ V and the output switches to -15 V. This changes the voltage at the non-inverting input to -7.5 V which makes $(IN^{+}-IN^{-})$ very negative, maintaining the output at -15 V. The output will stay at -15 V until the input drops to 7.50015 V which will make $A(IN^{+}-IN^{-}) = +15$ V, setting the output to +15 V, setting the non-inverting input to +7.5 V. This makes $(IN^{+}-IN^{-})$ very positive, maintaining the output at +15 V. We can summarize the operation of the circuit by saying that, when the input goes above the upper switching point, the output will go negative and stay negative until the input goes below the lower switching point. This characteristic is called "hysteresis" and this type of circuit is called a "Schmitt trigger".

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE CONTINUING.

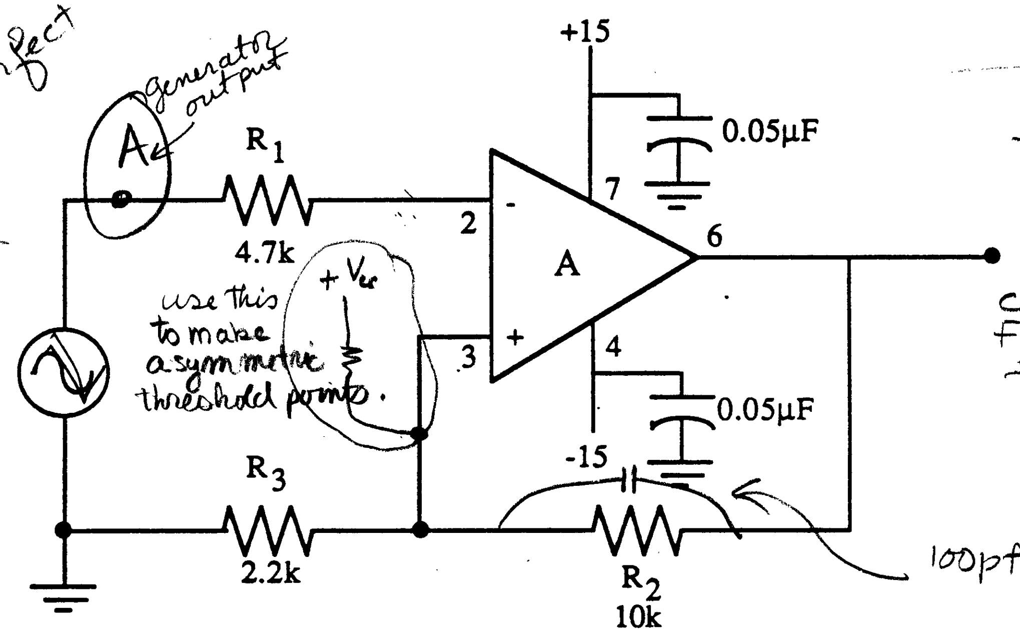
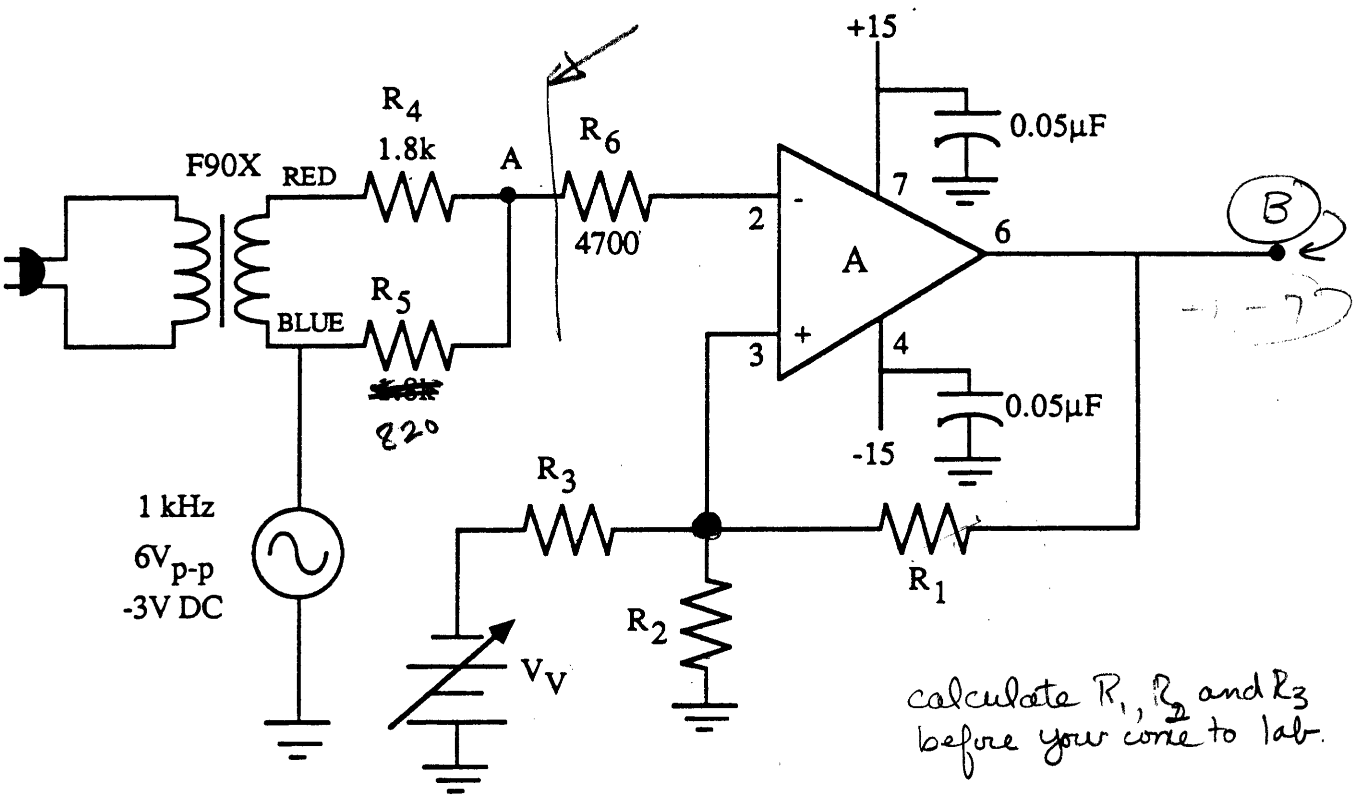


Figure 3 - Schmitt trigger

(1) Build the Schmitt trigger circuit of Fig. 3 with R_2 = 10K and R_3 = 2.2K.
(2) Display points A and B simultaneously on the oscilloscope and record each waveform in Table 8.4.
(3) Carefully note their phase difference and the two switching points.
(4) Slowly vary the DC offset between +3 V and -3 V and observe what happens at point B.



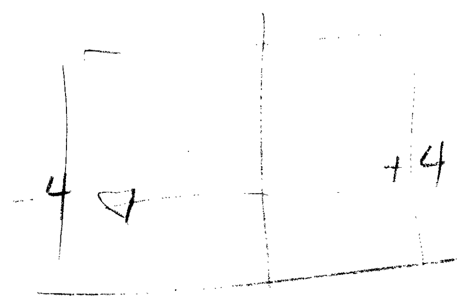
calculate R_1, R_2 and R_3 before you come to lab.

Figure 4

The Schmitt trigger can be used to eliminate signal noise.

(1) Disconnect the signal generator from your circuit and set it as shown in Fig. 4.
(2) Build the circuit shown in Fig. 4 and plug in the transformer. Select a variable supply voltage and standard values for R_1, R_2, and R_3 so that the switching points are +1 V and -7 V.
(3) If the composite signal at A is not around 14 V_{p-p} you have not connected the circuit properly.
(4) Display the waveforms at A and B and record them in Table 8.5 making special note of their phase difference. It will not be possible to get an absolutely stable trace on the oscilloscope.
(5) Make note of exactly what takes place when the waveform at B changes state.

at point A



Use DC coupling for everything in lab

Questions:

1. (a) What are the two switching points for the circuit of Figure 2 ?
   (b) Describe what point B does as the triangle wave goes from its lowest to highest and back to its lowest voltage.
   (c) Explain why the relative phase acts as it does when you change the DC offset.

2. (a) Describe the input waveform at point A in Figure 2.
   (b) Describe why point B changes state several times before stabilizing.
   (c) Why does ~~this sort of~~ comparator have problems with a "noisy" signal? (in the circuit of Figure 2

3. (a) Calculate the switching points for the circuit of Figure 3 without using your experimental data.
   (b) What switching points are indicated by the scope?
   (c) Why aren't they the same as your calculated values?
   (d) Explain why the signal at point B acts as it does when you change the DC offset.

4. (a) Show your calculations for R_1, R_2, R_3, and V_{in} in Figure 4.
   (b) How is the output different from that seen in [redacted] the circuit of Figure 3?
   (c) Why is a Schmitt trigger better at handling signals which contain undesirable noise?
   (d) Are both R_2 and R_3 really needed?

EEAP 243

LAB 8 EVALUATION

NAME (print)____________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

What will happen to the DC voltage at point D in Fig. 8.3 if we increase/decrease the resistance of $R_1/R_2/R_3/R_4/R_5$?

It will increase / decrease / stay the same.

Question #2

What will happen to the AC voltage at point D in Fig. 8.3 if we increase/decrease the resistance of $R_1/R_2/R_3/R_4/R_5$?

It will increase / decrease / stay the same.

EEAP 243

NAMES: ____

Lab 8 Data

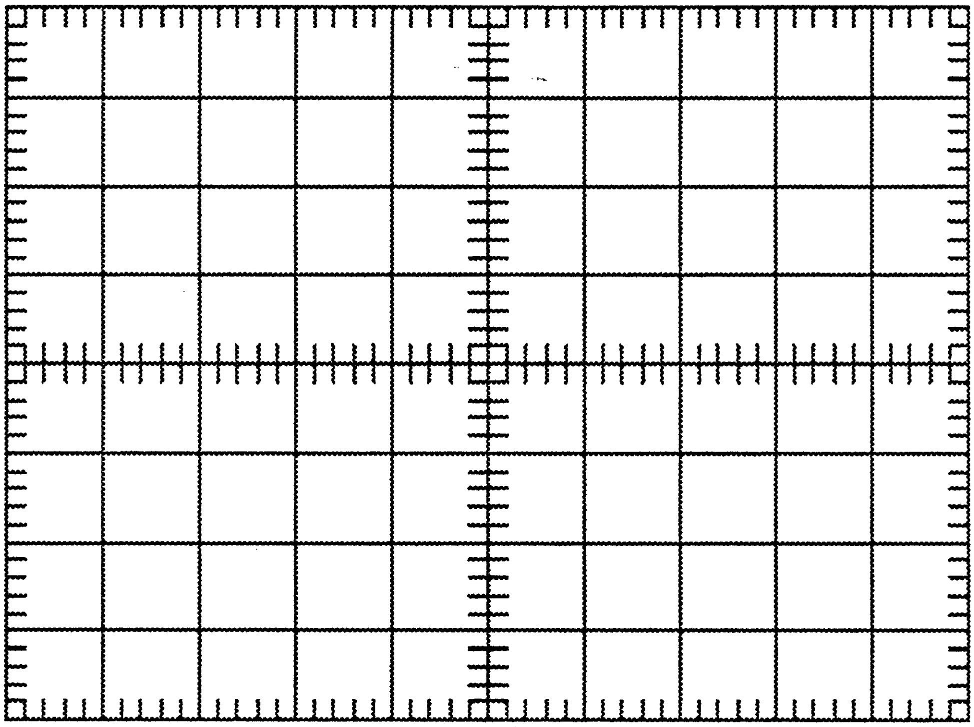


Table 8.1

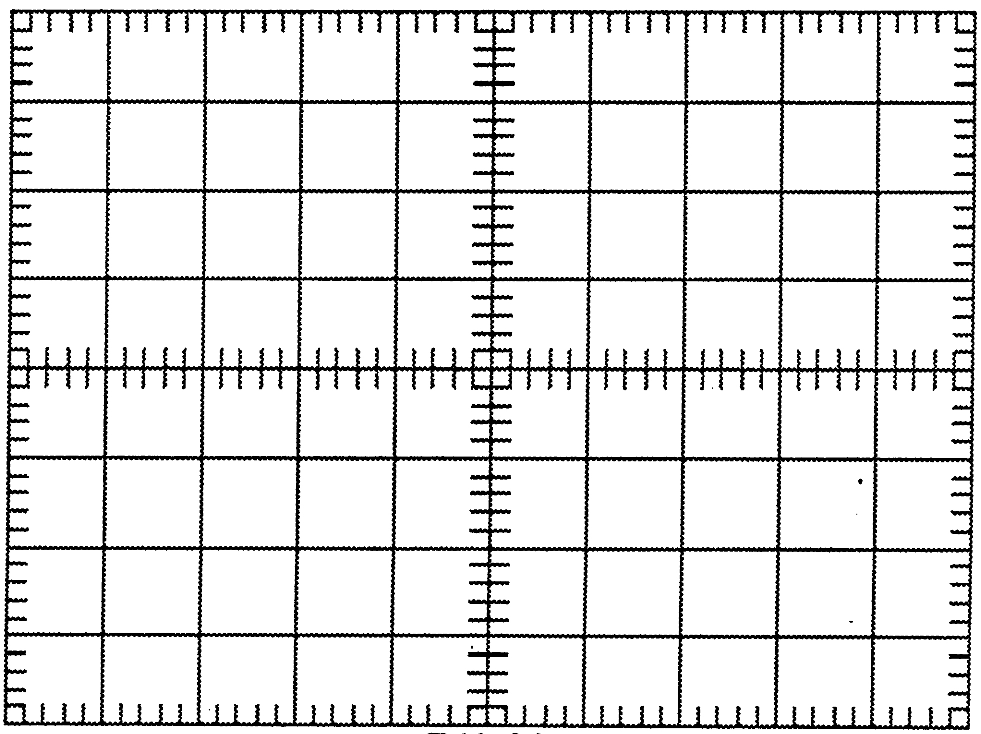


Table 8.2

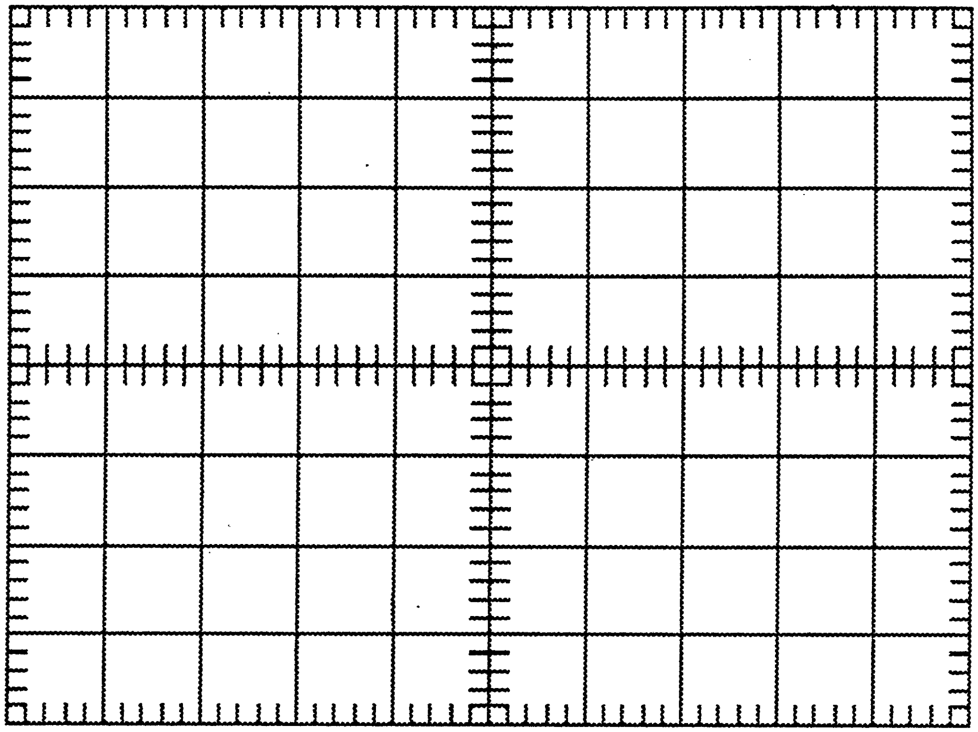


Table 8.3

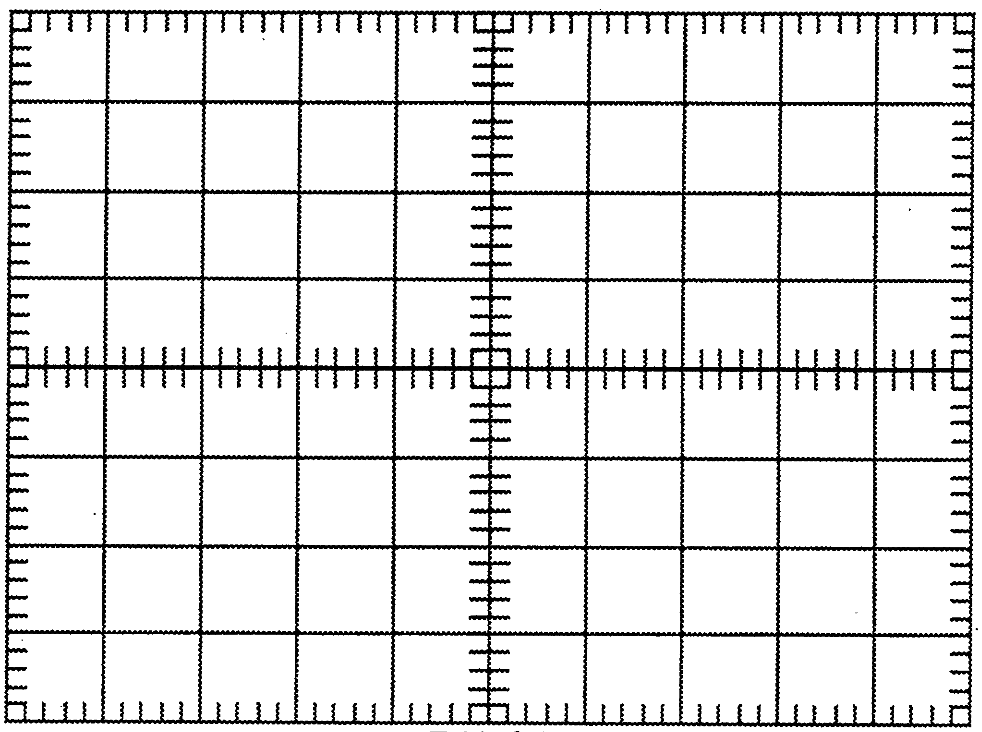


Table 8.4

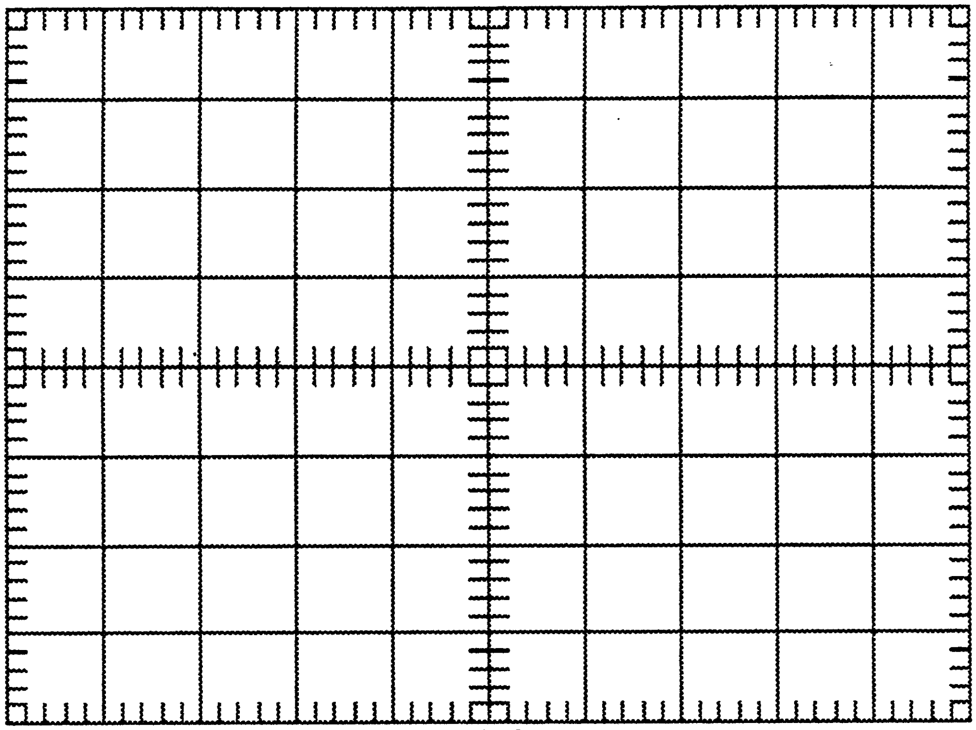
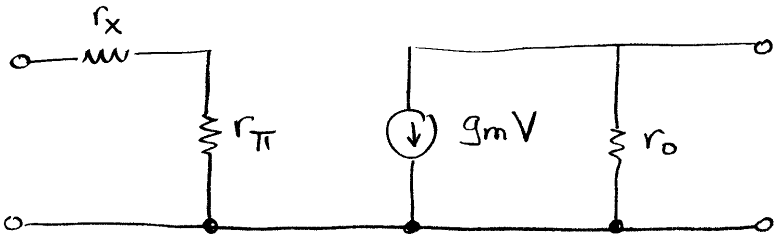


Table 8.5

Hybrid-π transistor model.



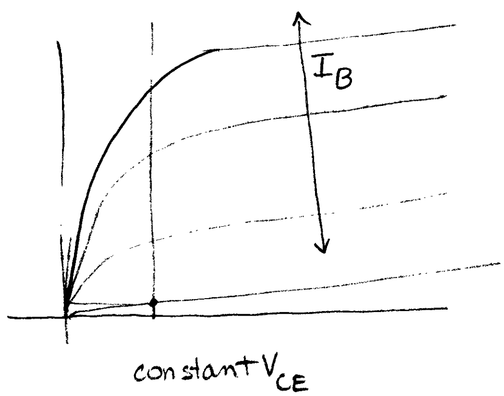
β_{dc} dc beta

β_o ac beta

r_π input resistance

$$g_m = \frac{|I_c|}{25\,mV}$$

$\beta \approx$ independent of I_c.

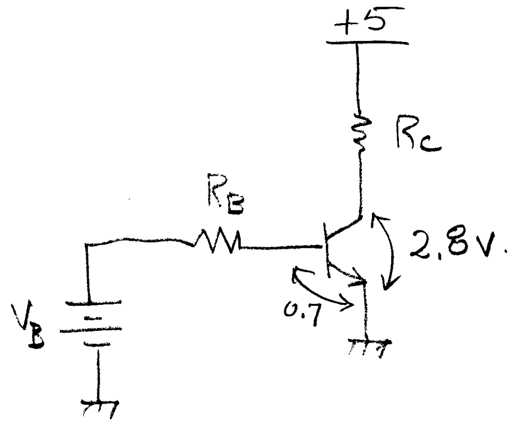


$$\beta_{dc} = \frac{I_c}{I_B}.$$

depends upon where Q-point is located.

$$\beta_o = \beta_{Ac} = \frac{\Delta I_c}{\Delta I_B}$$

DC analysis

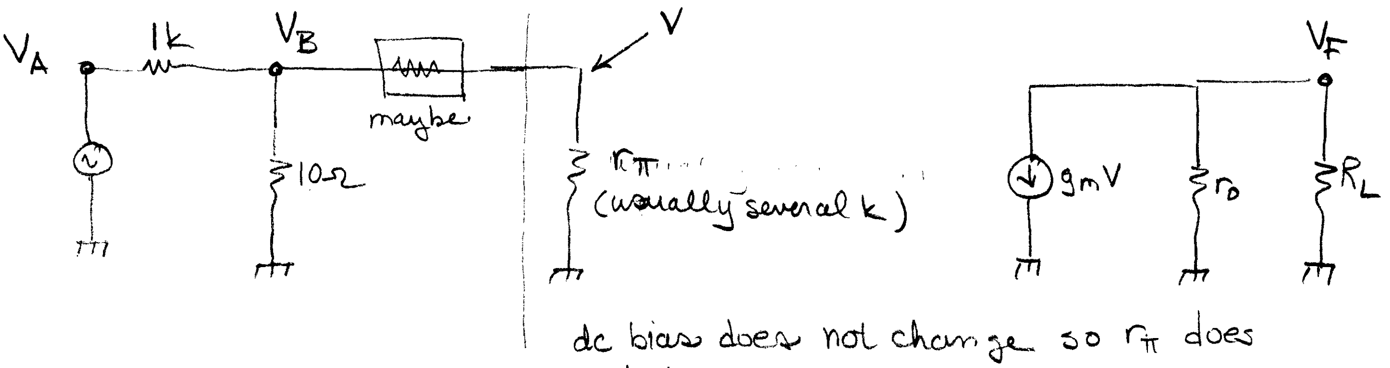


$I_c = 1\,mA$ or $I_c = 100\,mA$.

$$I_B = \frac{V_B - 0.7}{R_B}$$

$$\therefore \beta_{DC} = \frac{I_c}{I_B} = \frac{I_c R_B}{V_B - 0.7}$$

AC analysis:



dc bias does not change so r_π does not change.

dc bias circuit not shown.

$$V_B \approx \frac{10}{1010} V_A$$ irregardless of R_S or R_B or r_π since 10Ω is so small.

$$V_B = \frac{V_A}{101}$$

if $R_S = 0$

$$V = V_B$$

$$V_F = -(g_m V)(r_o \| R_L)$$

$\approx R_L$ since $r_o >> R_L$

$$V_F \approx -g_m \frac{V_A}{101} R_L = -g_m r_\pi \left(\frac{V_A}{101}\right) \frac{R_L}{r_\pi} = -\beta_{AC}\left(\frac{V_A}{101}\right)\frac{R_L}{r_\pi}$$

if $R_S = 4.7K$.

$$V = V_B \frac{r_\pi}{r_\pi + 4.7K}$$

$$V_F \approx -(g_m)\frac{V_A}{101}\left(\frac{r_\pi}{r_\pi + 4.7k}\right) R_L = -\beta_{AC}\left(\frac{V_A}{101}\right)\frac{R_L}{r_\pi + 4.7k}$$

$$\therefore \boxed{\frac{V_F}{V_A} = -\frac{\beta_{AC}}{101}\,\frac{R_L}{r_\pi + R_S}}$$

unknowns are β and r_π.

$$-\underbrace{\frac{101}{R_L}\frac{V_F}{V_A}}_{\text{call this } K} = \frac{\beta_{AC}}{r_\pi + R_s}$$

$$K_1 = \frac{\beta_{AC}}{r_\pi}$$

$$K_2 = \frac{\beta_{AC}}{r_\pi + 4.7K}.$$

solve for β_{AC} $\quad r_\pi K_1 = \beta_{AC} = K_2 (r_\pi + 4.7K)$

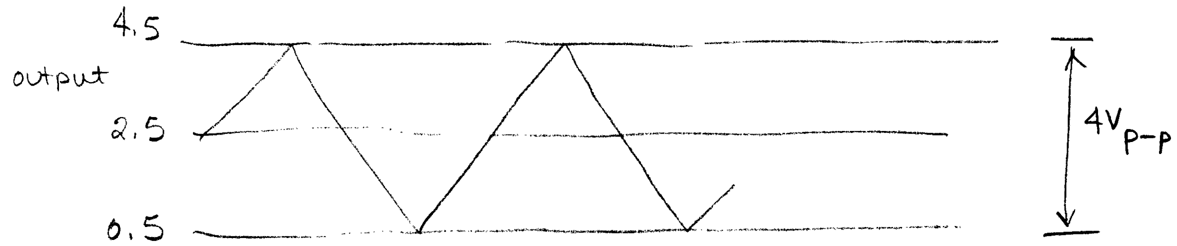
$$r_\pi K_1 = r_\pi K_2 + (4.7K) K_2 ,$$

$$r_\pi (K_1 - K_2) = (4.7K) K_2$$

$$r_\pi = \frac{(4.7K) K_2}{K_1 - K_2}.$$

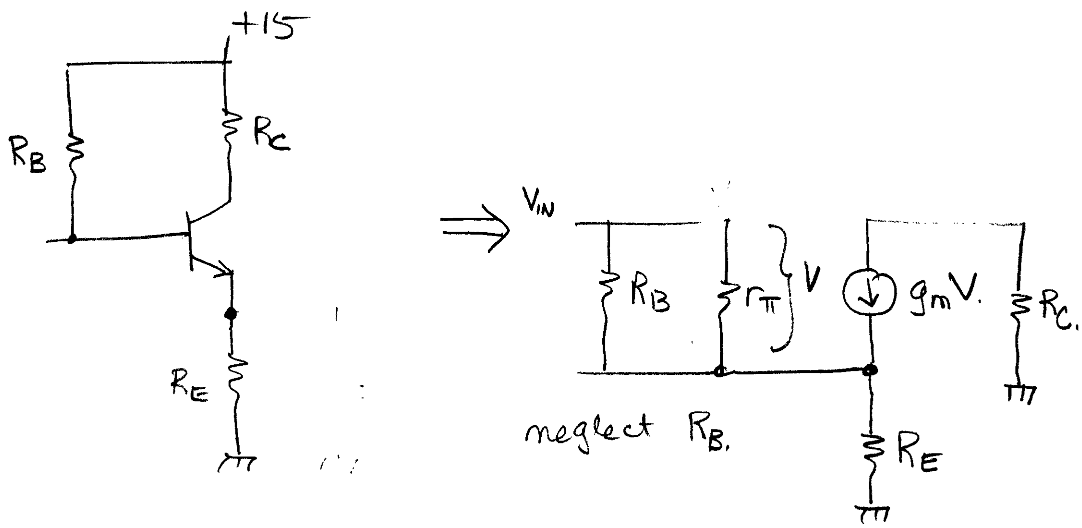
Part 2.

distortion , adjust V_{Gen} to get V_F shown below



adjust the scale factor and variable sensitivity so that both waveforms have identical amplitudes subtract the waveforms and record.

Part 3



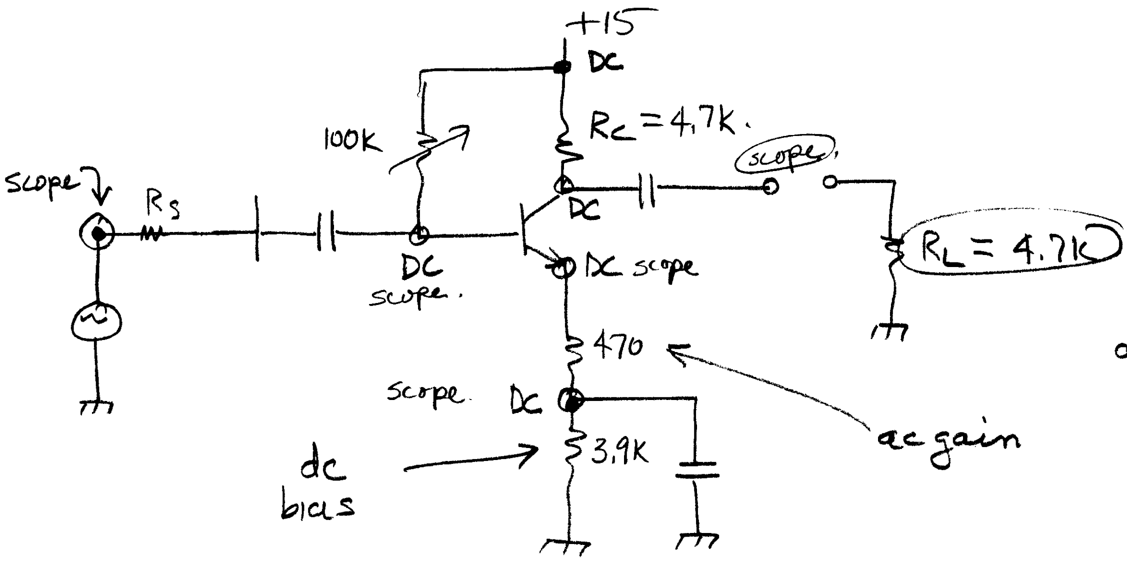
neglect R_B.

simple ac analysis

$$V = V_{IN} \frac{r_\pi}{(\beta+1)R_E + r_\pi}$$

$$V_{OUT} = (g_m V)R_c = g_m \frac{V_{IN}\, r_\pi}{(\beta+1)R_E + r_\pi} \cdot R_c = \frac{\beta R_c}{(\beta+1)R_E + r_\pi} V_{IN}$$

$$\boxed{\frac{V_{OUT}}{V_{IN}} = \frac{\beta R_c}{(\beta+1)R_E + r_\pi} \approx \frac{R_c}{R_E}}$$



Then add a 4.7K, and record new output

1. do dc measurements, no ac } $R_S = 0$
2. do ac measurements } $R_L = \infty$
3. now $R_L \to 4.7k$ measure ac out.
4. $R_L \to \infty$, $R_S \to 27k$ measure at point H
5. measure $\frac{V_{OUT}}{V_{IN}}$ for $V_{IN} = 1, 2, 3, 4\ V_{p\text{-}p}$.

---

cutoff & saturation

EEAP 243
Lab 9

Lab Work:
Questions Due:

COMMON EMITTER AMPLIFIERS

READING ASSIGNMENT: Horowitz, pgs.50-53, 62-63, 65-71.

Abstract:
In this lab you will study two different transistor amplifier configurations and demonstrate the variability of the parameters β_{dc}, β_o, and r_π for commercial transistors.

NOTE: All of this lab must be done using the same transistor so that your test data will be consistent. You can avoid burning out your transistor by disconnecting both power supplies while making changes to the circuit. Disconnecting the supplies is more effective than turning off the DC POWER switch.

Part 1 - Common Emitter Measurement of β_{dc}, β_o, and r_π

The transistor parameters β_{dc}, β_o, and r_π vary widely with temperature, with collector current, and from component to component. This variation can easily be observed using a common emitter amplifier without an emitter resistor. In this configuration DC biasing is determined by β_{dc} and AC gain is determined by β_o and r_π. Because this configuration has a very high gain, you will be using a voltage divider to reduce the output of your signal generator by a known factor. You will be using relatively low V_{cc} and V_{ce} voltages to reduce the power dissipated by your transistor. More power dissipation would cause a rise in temperature, which would change its characteristics. You will use capacitors to "decouple" the power supplies on your breadboard to reduce the possibility of oscillation.

We NEED to teach students
how to TEST transistors and diodes!

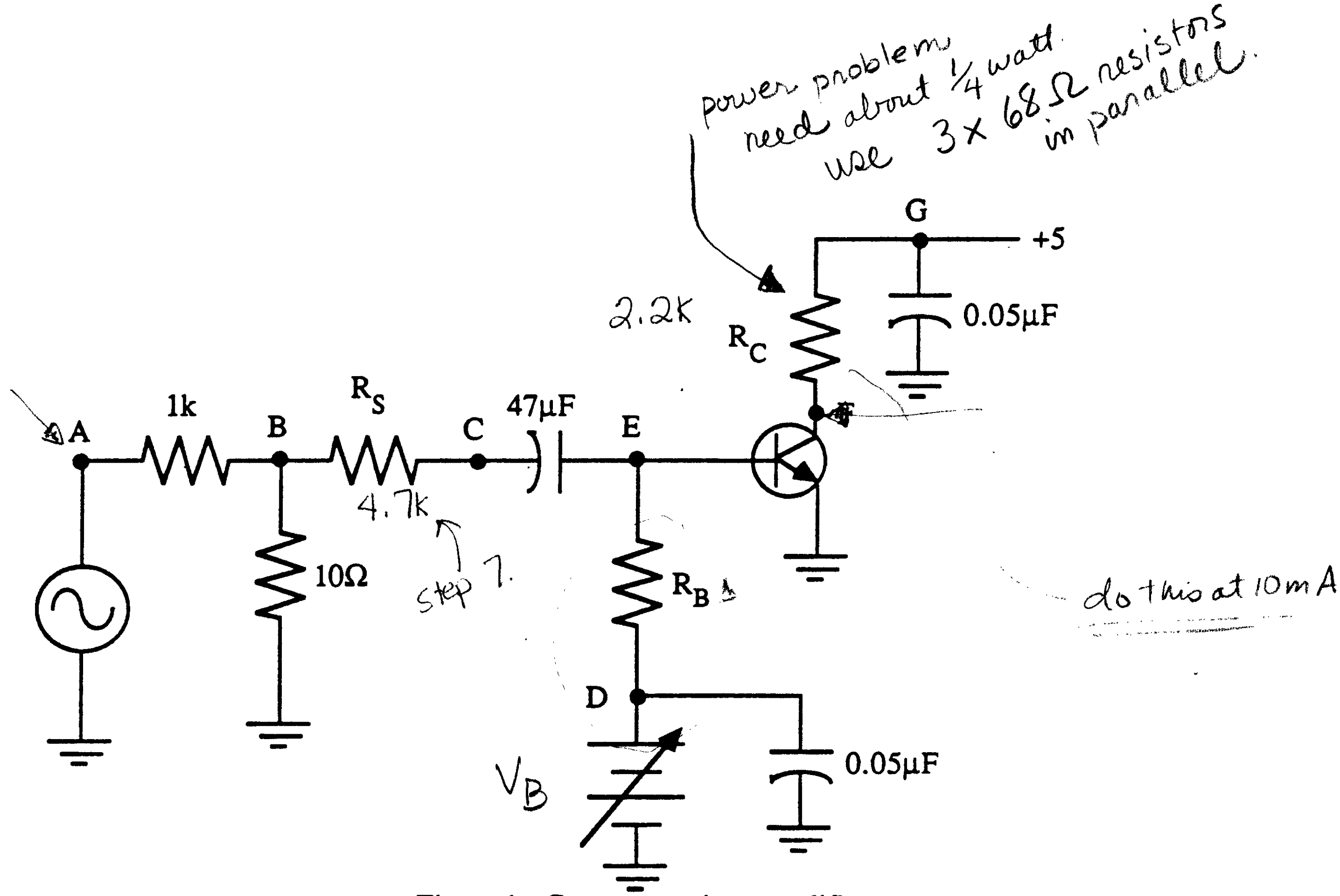


Figure 1 - Common emitter amplifier

(1) Build the circuit shown in Fig.1 using R_B = 100 K, R_S = 4.7 K, and R_C = 2.2 K. Points B and C should be shorted together. Connect your scope CH1 input to point A and CH2 to point F. Set the signal generator to a 10 KHz sine wave.
(2) Set the generator's AC amplitude to zero and adjust ~~the variable power supply~~ V_B so that the DC voltage at point F is approximately 2.80 V.
(3) Use the DMM to measure the exact DC voltages at points D, E, F, and G and record your results in Table 9.1.
(4) Increase the generator's AC amplitude so that the AC signal at point F is approximately 200 $mV_{p\text{-}p}$.
(5) Using your scope measure the exact AC peak-to-peak voltages at points A (C) and F. Record your results in Table 9.1 Circuit 1
(6) Remove the short circuit between points B and C.
(7) Measure the new peak-to-peak voltage at point F.
(8) Perform steps 1 through 7 for a second time with R_B = 10 K, R_S = 47 ohms, and R_C = 22 ohms. Record your results in Table 9.2 — circuit 2.

Part 2 - Common Emitter Amplifier Distortion

You saw in part 1 that the parameter β_o depends on the transistor's ~~DC collector current~~ actually its operating point. The instantaneous value of βo also depends on the transistor's instantaneous collector current. If the collector current varies over too wide a range in amplifying a signal, it is possible to get nonlinear amplification (distortion) due to the changing value of βo.

(1) Rebuild the circuit shown in Fig.1 using R_B = 100 K and R_C = 2.2 K. Points B and C should be short circuited together. Connect scope CH1 to point A and CH2 to point F. Set the signal generator to a 10 KHz triangle wave. Adjust V_B so that the potential at point F is 2.5 VDC.

(2) Adjust the variable power supply and the generator's AC amplitude in combination so that you have a 4 Vp-p signal at point F which goes between 0.5 V and 4.5 V.
(3) Measure the peak-to-peak voltage at point A. Record the waveform at point F in Table 9.3.
(4) Adjust the scale factor and sensitivity of CH1 so that both waveforms have the same amplitude on the oscilloscope screen.
(5) Change the display mode to ADD and record the resulting waveform in Table 9.4. Set the mode back to DUAL and set CH1's sensitivity back to its calibrated position.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE CONTINUING

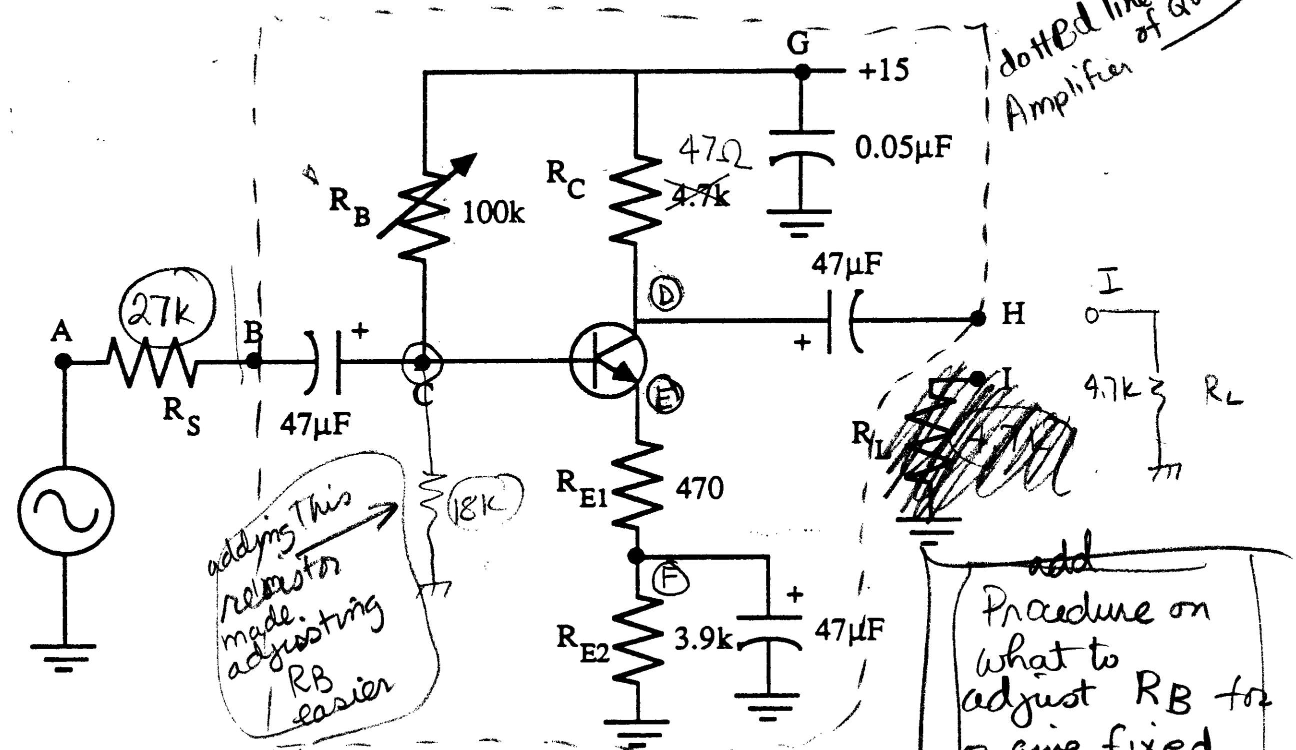


Figure 2 - Common emitter amplifier with split emitter resistor

Part 3 - Common Emitter Amplifier with Split Emitter Resistor

The effects of β_{dc}, β_o, and r_π can be largely eliminated by including a resistor from the emitter to ground. By using a capacitor to bypass part of this resistance to ground, an amplifier can be built which has a very stable gain and operating point.

(1) Build the circuit shown in Fig.2. Points A and B should be shorted together and points H and I should not be connected to anything. Connect the scope CH1 input to point A.
~~(2) Adjust the signal generator for a 0.5 V_{p-p} 10 KHz triangle wave with zero DC offset.~~
(3) Use the DMM to measure the exact DC voltages at points C, D, E, F, and G. Record your measurements in Table 9.5.
(4) Increase the generator's AC amplitude so that signal at point A is approximately 0.5 Vp-p.
(5) Measure the exact rms and peak-to-peak voltages at points A, C, E, F, and H. Record your results in Table 9.5.

(6) Connect points H and I together and measure the new rms and peak-to-peak voltage at point H.
(7) Remove the short circuits between points A and B and points H and I.
(8) Measure the new RMS and peak-to-peak voltages at point H.
(9) Record the maximum and minimum voltages at point D (the waveform peaks) for signals at point A of 1 V_{p-p}, 2 V_{p-p}, 3 V_{p-p}, and 4 V_{p-p}. Record these waveforms in Table 9.6-9.8.
9.6 9.7 9.8 9.9

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE LEAVING.

Vin	Rs	RL	A	C	D	E	F	H	Comments
			~~AC/DC~~	~~AC/DC~~	~~AC/DC~~	~~AC/DC~~	~~AC/DC~~	~~AC/DC~~	
0	0	∞			X				DC meas ~~AC meas~~
500mVpp	0	∞			X				rms/p-p AC measure
500mV	0	4.7K			X				rms/p-p
500mV	27K	∞			X				rms/p-p
~~500mV~~	~~27K~~								
1			X	X		X	X	X	waveform peaks.
2			X	X		X	X	X	
3			X	X		X	X	X	
4			X	X		X	X	X	

Most students did not have background to understand questions.

Questions:

1. Calculate the following parameters for ~~both circuits:~~ the circuit of Figure 1. for both $R_S = 0$ and $R_S = 4.7K$. $g_m = \frac{I_c}{25mA}$
   (a) A_V (F/B) in step 5,
   (b) A_V (F/B) in step 7,
   (c) β_{DC},
   (d) β_{AC}, (use $\frac{\Delta I_c}{\Delta I_b}$ from measurements)
   (e) r_π, and
   (f) the theoretical r_π (.026/I_B) (i.e. I_B in amps. where does this come from $\beta = g_m r_\pi$)

2. (a) Calculate the expected voltage at point F based on your measured voltage at point A and your values for β_0 and r_π from ~~part 1.~~ Question #1.
   (b) How does the expected value compare with what you measured?
   (c) Why is the output waveform distorted? (see Part 2)
   (d) What was displayed when you added the waveforms?

3. Your "amplifier" is defined by the dotted line in Fig.2. part 3
   (a) Use your results from ~~part 1~~ Question #1 (not your data from ~~this part~~) to calculate what A_V, I_C, Z_i, and Z_O should be. i.e. use r_π, β_{AC}, etc.
   (b) Calculate A_V, I_C, Z_i, and Z_O using your data from ~~this part.~~ part #3.
   (c) Explain any differences between (a) and (b).
   (d) Suppose that β_{dc} and β_O were to increase by a factor of 4 and that r_π were to become zero. Calculate the percent change in A_V, I_C, Z_i, and Z_O that would occur.
   (e) Calculate the overall voltage gain that would result if two of these amplifiers were cascaded. question is not clear what cascading means.

4. (a) Sketch the waveform at D (4 V_{p-p} input) and indicate the periods of saturation and cutoff.
   (b) What was the DC voltage from collector to ground during cutoff?
   (c) Can the collector voltage be greater than V_{cc}?
   (d) What was the DC voltage from collector to ground during saturation?
   (e) Can the collector voltage be less than the emitter voltage?

too long — these questions need to be explained better.

too long.

$\frac{V_{OUT}}{V_{IN}} =$

generate the equations and get values for vout) $A_V = \left(-\frac{R_L}{R_{E1}}\right)$

This homework was TOO Long.

EEAP 243 LAB 9 EVALUATION

NAME (print)_____________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

What will happen to the collector current of Q3 in Fig. 9.2 if we increase/decrease the resistance of $R_8/R_9/R_{10}$?

It will increase / decrease / stay the same.

Question #2

What will happen to the gain from point D to point G in Fig. 9.3 if we increase/decrease the resistance of $R_4/R_5/R_6/R_7/R_{18}$?

It will increase / decrease / stay the same.

EEAP 243

NAMES: ______________________________

Lab 9 Data

	------- R_S=0 -------		------- R_S=4.7k -------	
	DC voltage	AC voltage (p-p)	DC voltage	AC voltage (p-p)
D	____		____	____
E	____	____	____	____
F	____	____	____	____
G	____		____	____

Table 9.1

	------- R_S=0 -------		------- R_S=4.7k -------	
	DC voltage	AC voltage (p-p)	DC voltage	AC voltage (p-p)
D	____		____	____
E	____	____	____	____
F	____	____	____	____
G	____		____	____

Table 9.2

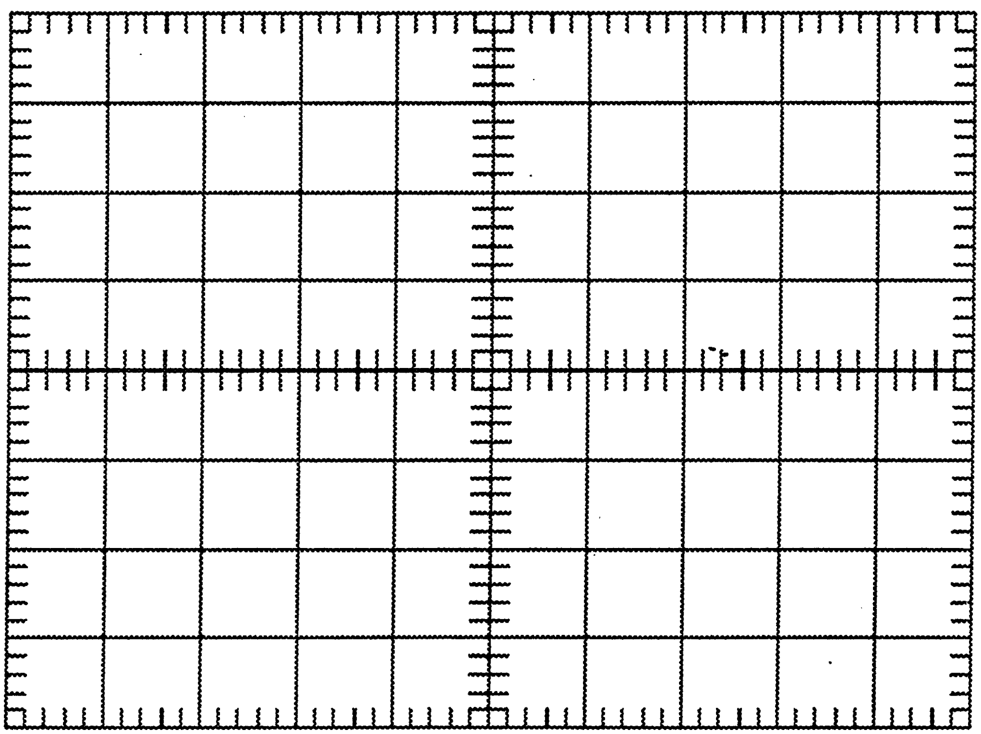


Table 9.3

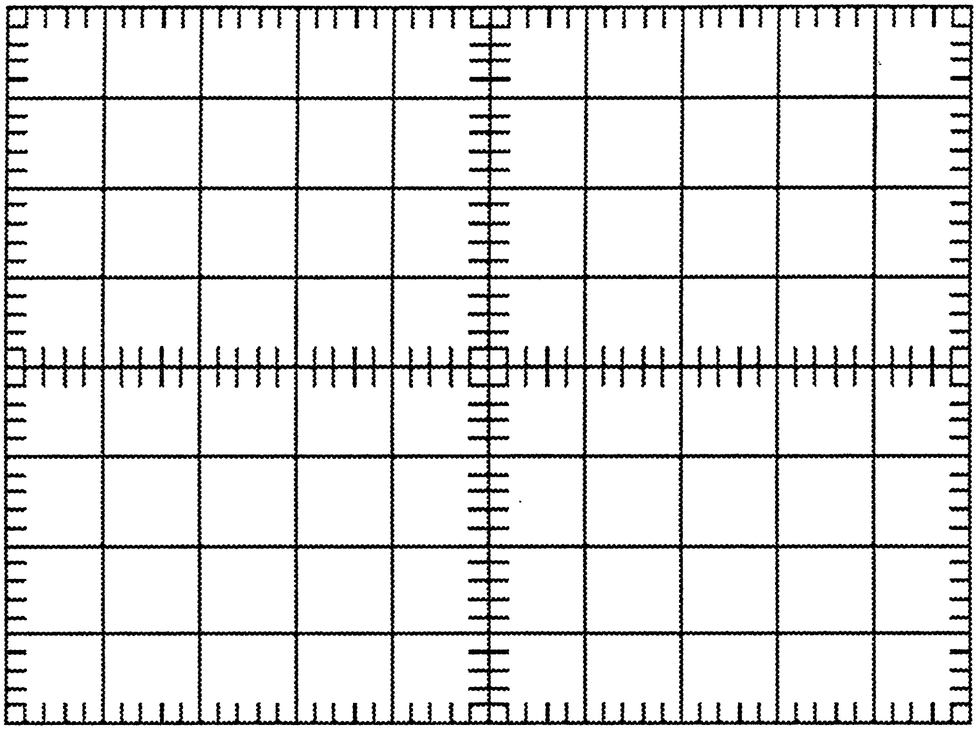


Table 9.4

	--------------------R_S=4.7k	--------------------	
	DC voltage	AC voltage (p-p)	AC voltage
(rms)			
A		____________	____________
C	____________	____________	____________
D	____________		
E	____________	____________	____________
F	____________	____________	____________
G	____________		
H (HI open & AB shorted)	____________	____________	
H (HI & AB shorted)	____________	____________	
H (HI & AB open)	____________	____________	

Table 9.5

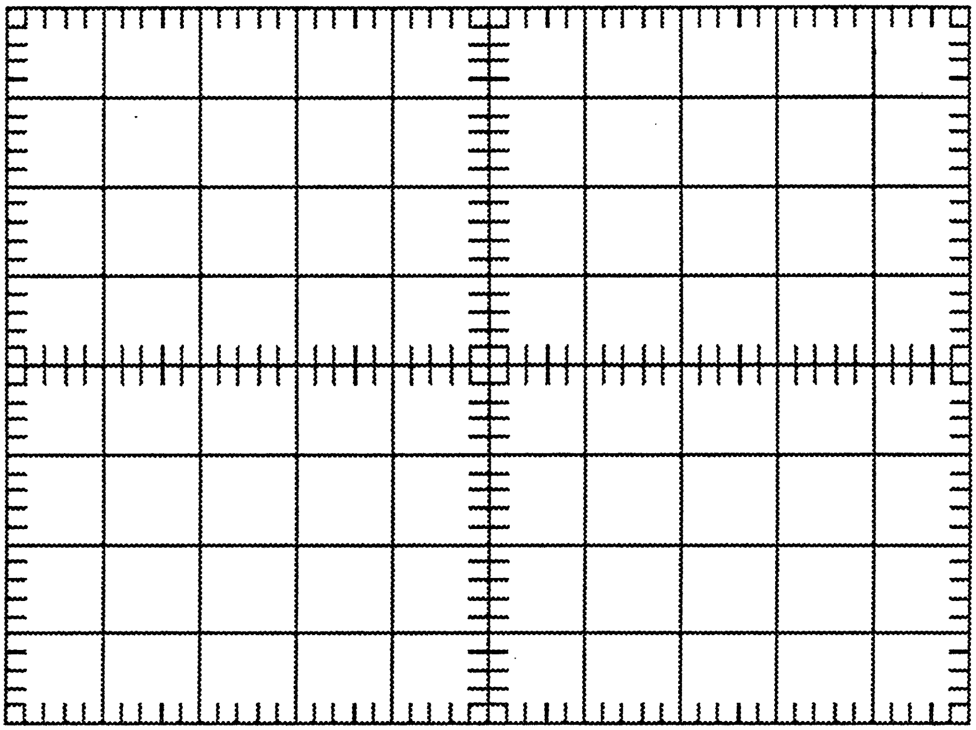


Table 9.6

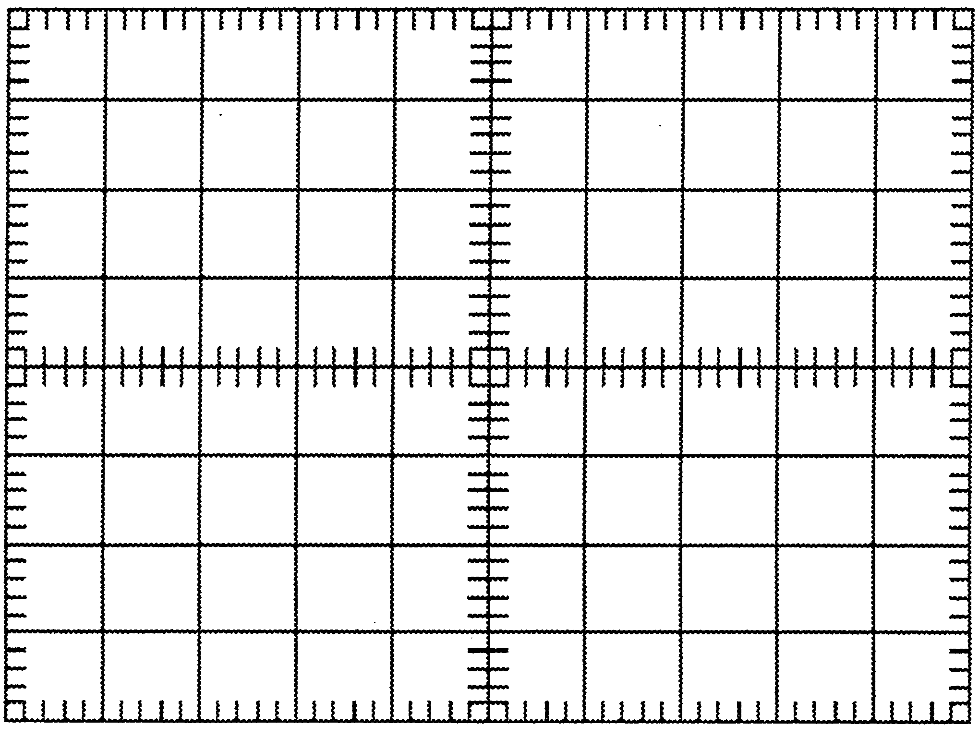


Table 9.7

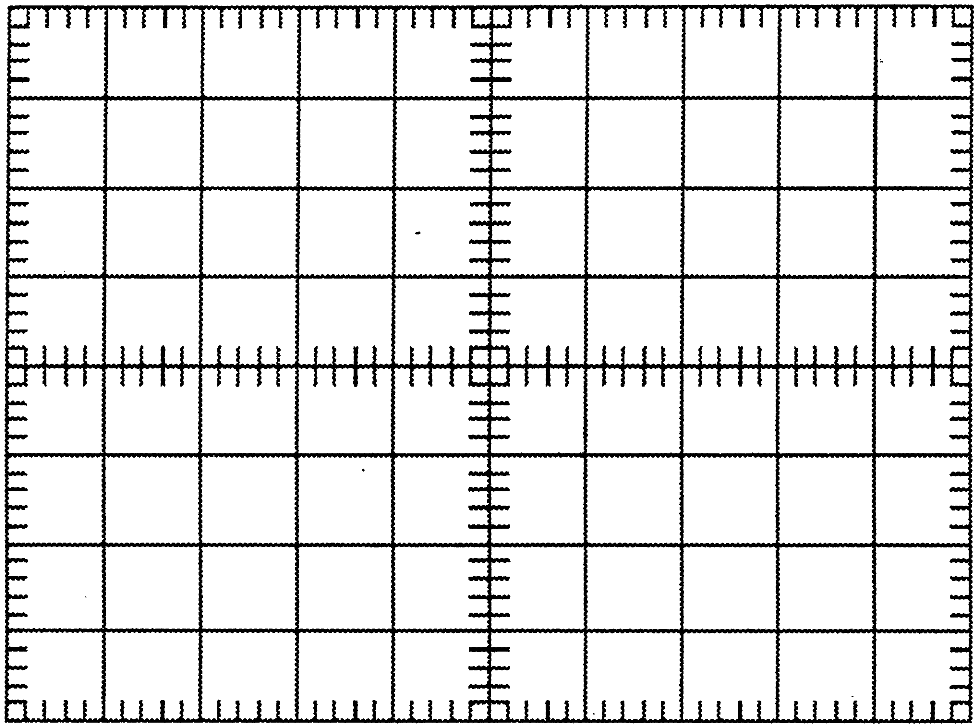
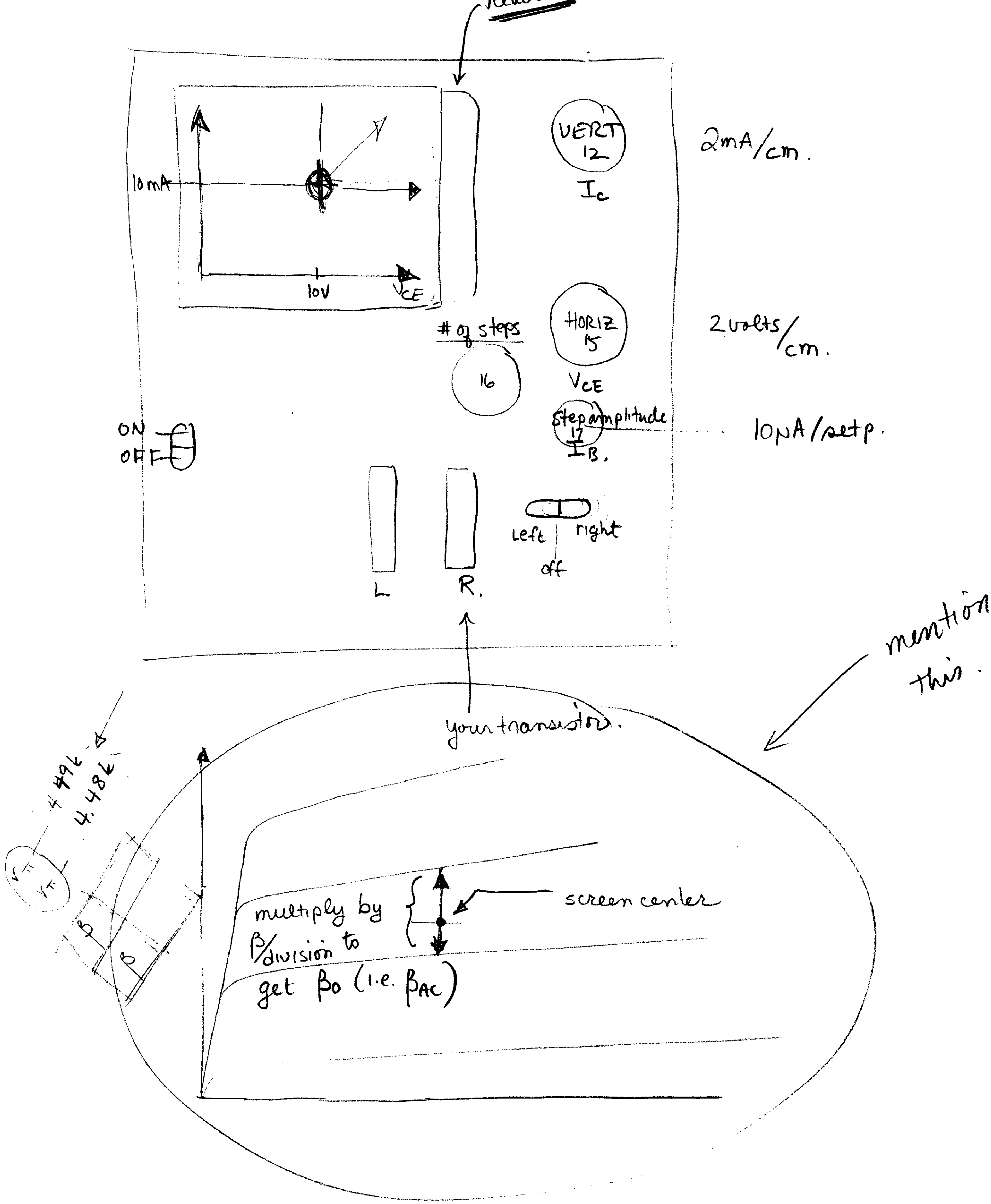
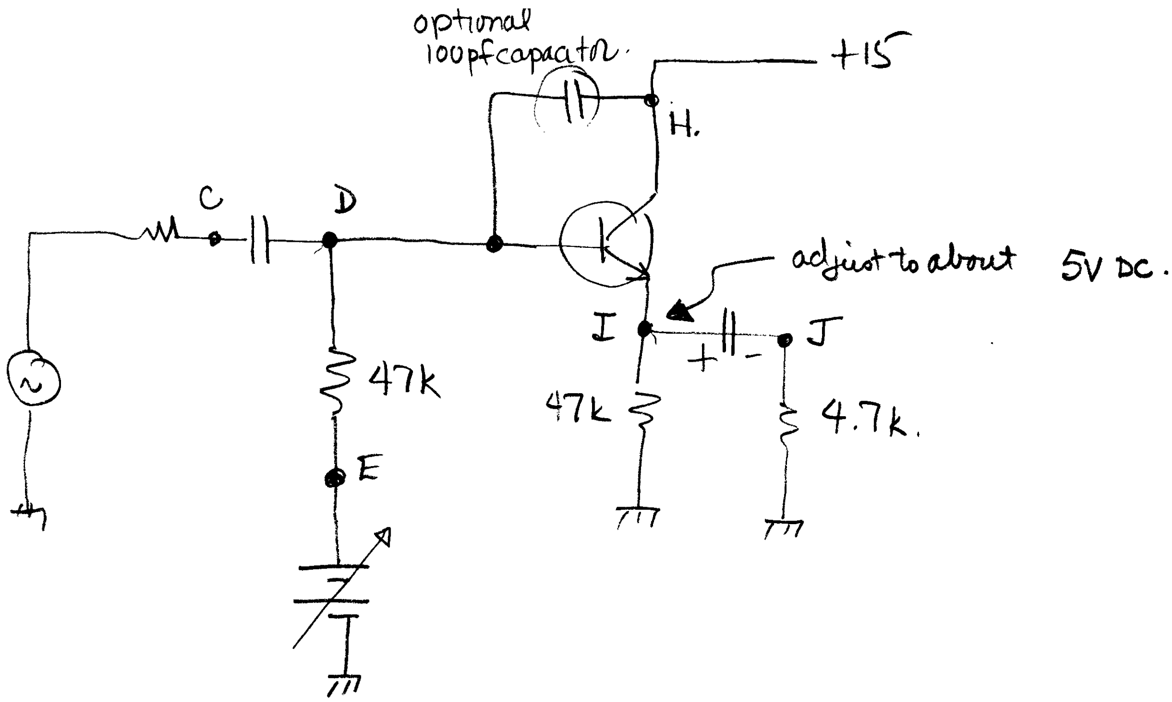


Table 9.8

curve tracer.





FIRST bad method

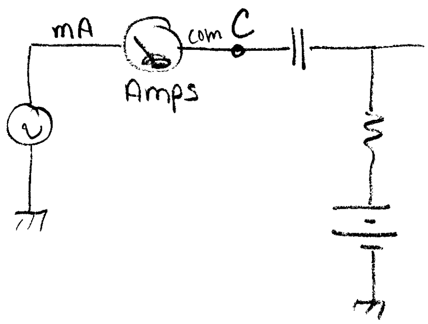
dc characteristics — measure C, D, I, J. resistance to ground — BAD, pick up power supply voltages.

disconnect power supplies and ground H and E — re measure.

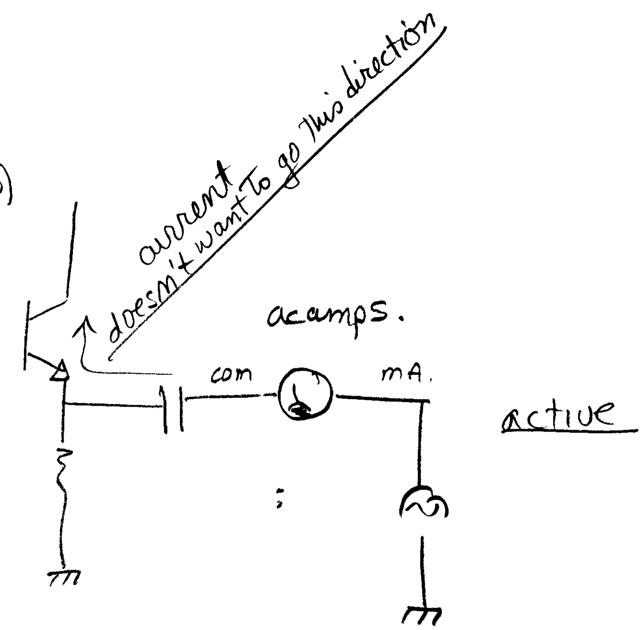
racteristics

SECOND bad method

(a) TOO SMALL To measure ac current

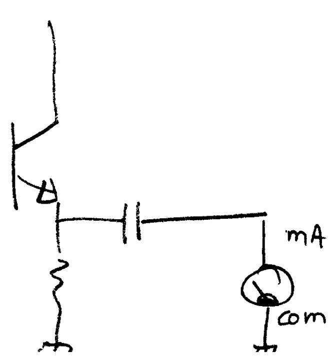


(b)

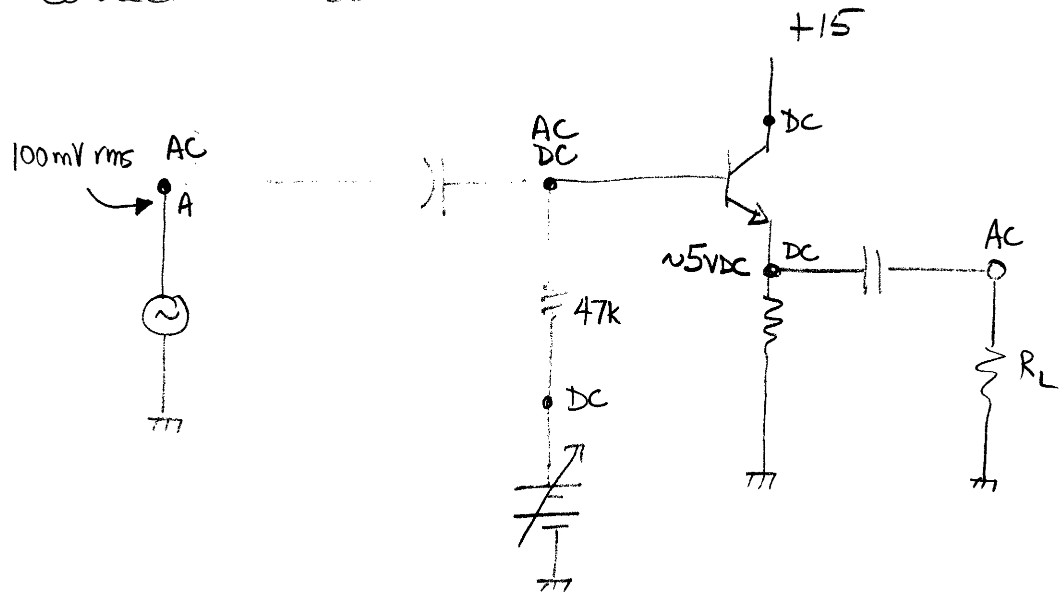


active

THIRD bad method (passive)



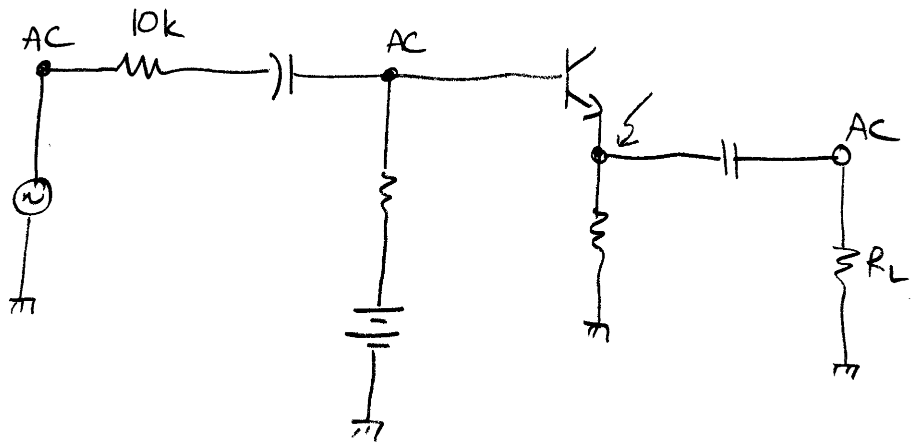
correct method.



measure dc values once

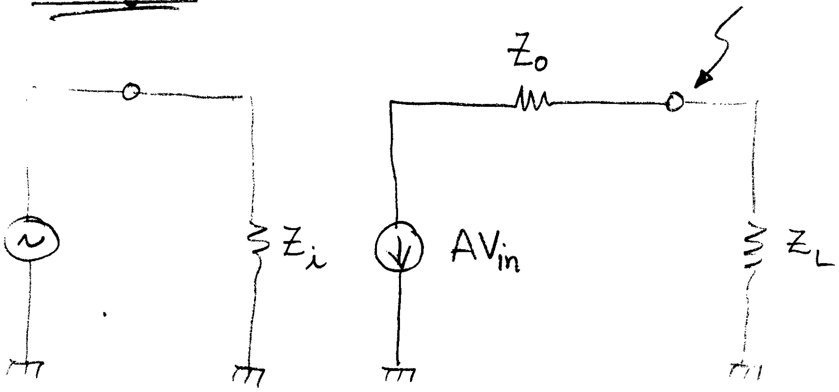
measure ac values for R_L = ∞
4.7k
470
47

now add a 10k input resistance and repeat. all ac procedures.



R_L = ∞
4.7k
470
47.

analysis



works best when $Z_L > Z_o$

for output.

measure

V_{oc}

$V_{4.7k}$

V_{470}

V_{47}

$$V_{OUT} = \frac{Z_L}{Z_L + Z_o} AV_{in}.$$

if $Z_L = \infty$ $\quad V_{OUT} = AV_{IN} = V_{oc}$

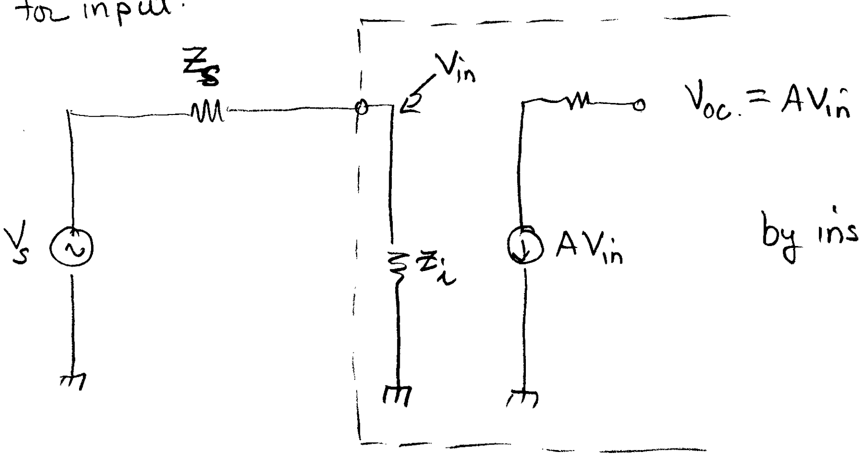
$Z_L = 4.7k \quad V_{OUT} = \frac{4.7k}{4.7k + Z_o} V_{oc}.$

$Z_L = 470 \quad V_{OUT} = \frac{470}{470 + Z_o} V_{oc}$

$Z_L = 47 \quad V_{OUT} = \frac{47}{47 + Z_o} V_{oc}.$

test to see how consistent these are.

for input.



by inspection if $Z_s = 0 \quad V_{oc} = AV_s$

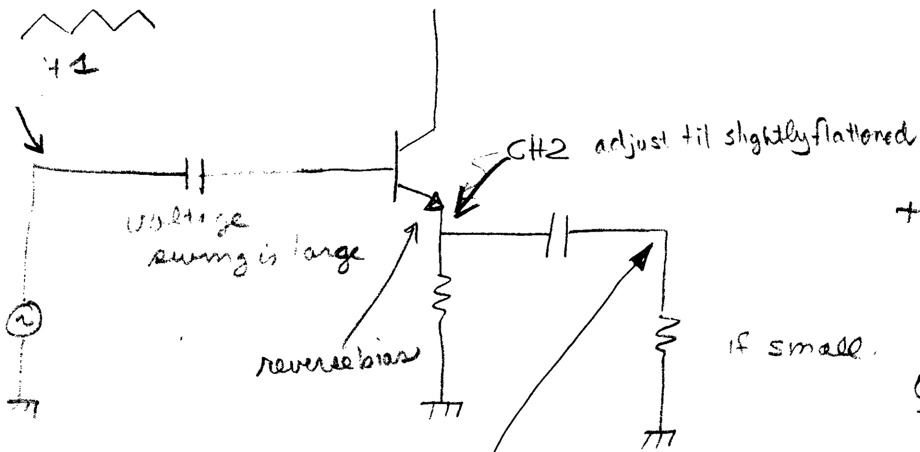
if $Z_s \neq 0 \quad V_{in} = \frac{Z_i}{Z_i + Z_s} V_s$

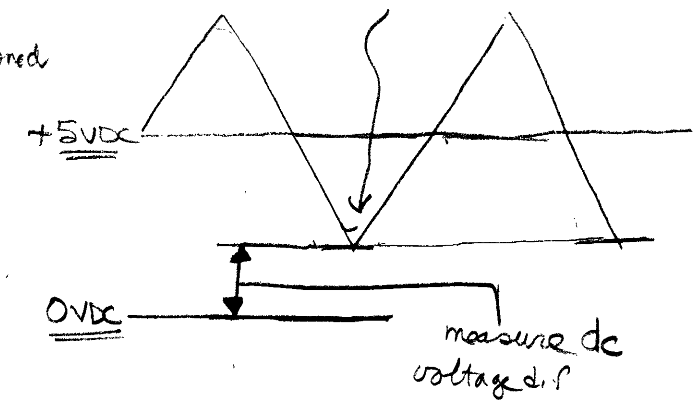
$V_{OUT} = AV_{IN} = \frac{AZ_i}{Z_i + Z_s} V_s.$

$$\therefore \frac{V_{OUT,\, Z_s = 0}}{V_{OUT,\, Z_s}} = \frac{Z_i}{Z_i + Z_s}$$

and solve for Z_i

part 3





measure dc voltage differential between ground and flattened part of waveform here.

EEAP 243
Lab 10

Lab Work:
Questions Due:

EMITTER FOLLOWER AMPLIFIERS

READING ASSIGNMENT: Horowitz, pgs.53-58.

Abstract:

In this experiment you will study the emitter follower amplifier, its input impedance, its output impedance, and its ability to drive a load. You will also learn how to operate the lab's curve tracer which allows you to display a transistor's output characteristics.

NOTE: You will need to use the same transistor for the whole experiment, so be careful with your alligator clips and test leads. Accidental short circuits can easily destroy your transistor.

The input and output impedances of an "active" circuit must be measured under "active" conditions. For example, you do not measure DC parameters with the DC power supplies turned on and the signal generator tuned off, nor do you measure AC parameters with the DC power supplies turned off and the signal generator turned on. In part 2 you will try several flawed methods for measuring input and output impedance. These flawed methods will produce erroneous or inconclusive results. This is done to

(a) demonstrate that the methods are invalid and
(b) to emphasize the right way of doing things. All of your measurements in part 2 will be made with the DMM. Use several DMM ranges when making the flawed measurements.

Part 1 - Transistor Characterization

The transistor curve tracer can be used to quickly and accurately measure your transistor's β_o. This can be done any time during the lab period, so don't waste time by standing in line. The instrument room attendant can help you if you have any problems.

(1) Set the transistor curve tracer to the default positions listed in Figure 1.
(2) Move switch 24 to the left to display the reference transistor's characteristics in order to verify that everything is set properly.
(3) Move switch 24 to the right to display your transistor's characteristics.
(4) The exact center of the display corresponds to I_c = 10 mA and V_{ce} = 10 V which is approximately the operating point for your circuits.
(5) You can adjust switch 17 to change the base current per step to change the spacing between the displayed curves. Changing switch 12 (I_c per vertical cm) or switch 15 (V_{ce} per horizontal cm) will change the position of the operating point on the display.
(6) Measure the vertical distance between the curves above and below the display's center, and multiply by the β per division (lowest readout) to get β_o in the vicinity of your operating point.

add a Figure to record characteristics make it 10X10

explain in class.

also can calculate based upon $\frac{I_C}{I_B}$

CONTROL	DEFAULT SETTING	DESCRIPTION
2	on	main power
7	5 o'clock	graticule (grid) illumination
8	3 o'clock	readout illumination
10	1 o'clock	display intensity
11	1 o'clock	display focus
19	in (steps)	continuous curves
22	in (rep)	draw curves repetitively
21	in (norm)	normal curve repetition rate
4	norm	normal display mode
14	out	display not inverted
13	*	- set so display starts at point labeled 9
5	NPN	transistor type
23	step generator base term	test configuration
24	center	disconnect both transistors
		right to test your transistor
		left to display reference transistor
3	140 (black arrow)	collector resistance
6	15 (white arrow)	maximum collector voltage
1	100	percent of maximum collector voltage
12	2 mA	I_C - collector current per vertical cm.
15	2 ~~collector~~ volts	V_{CE} - collector voltage per horiz. cm.
16	10	number of base current steps
20	out	base current polarity not inverted
18	in (zero)	no base current offset
17	10μA	I_B - base current increment per step

NOTE: Any unlabeled switches are in the OUT position.

Figure 1(a) Default settings for testing an NPN transistor

TEST SET-UP CHART TYPE 576

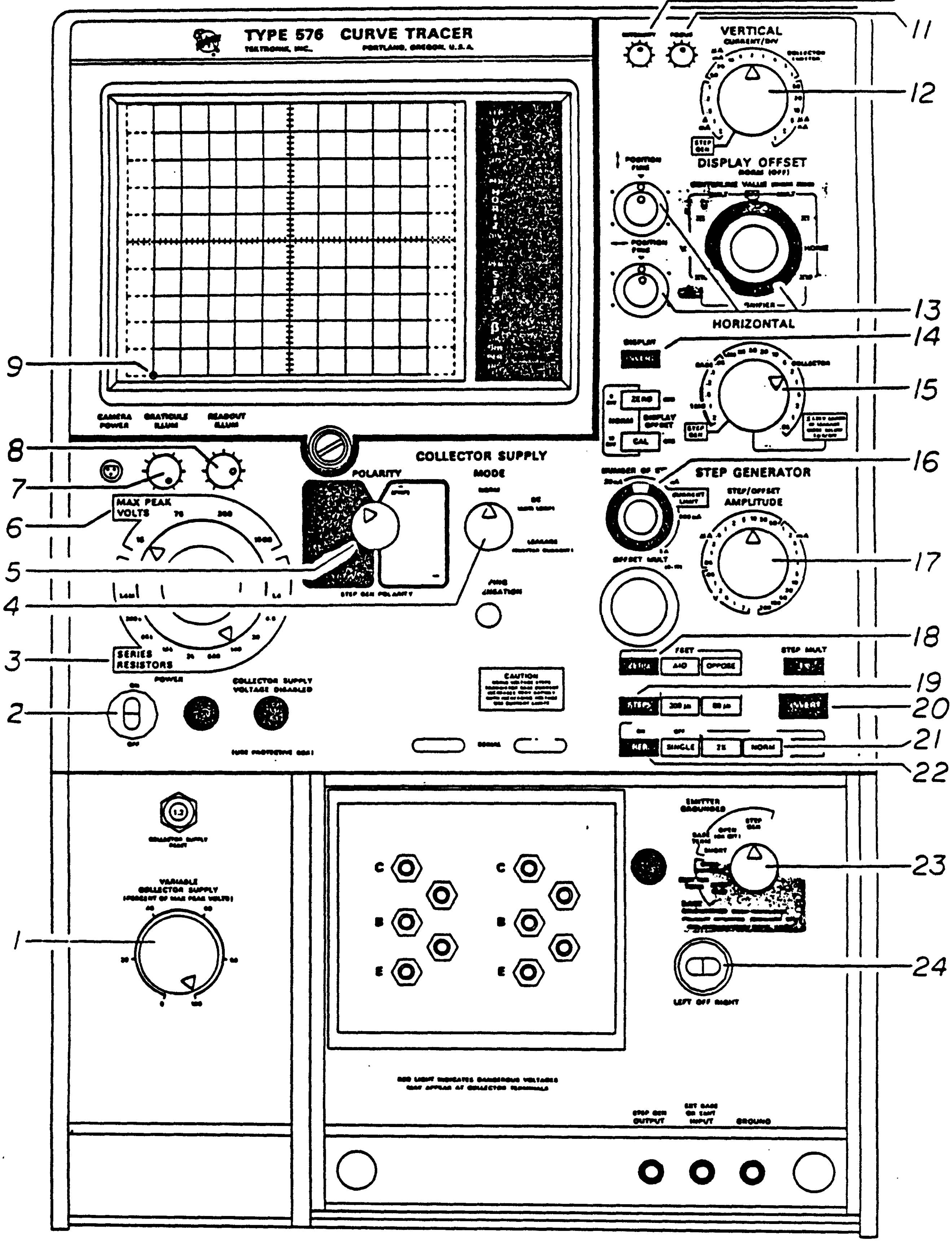


Figure 1(b) - Front Panel of Curve Tracer

Part 2 - Input and Output Impedance

Before you can try to measure input and output impedances, you must first build the circuit and bias it correctly.

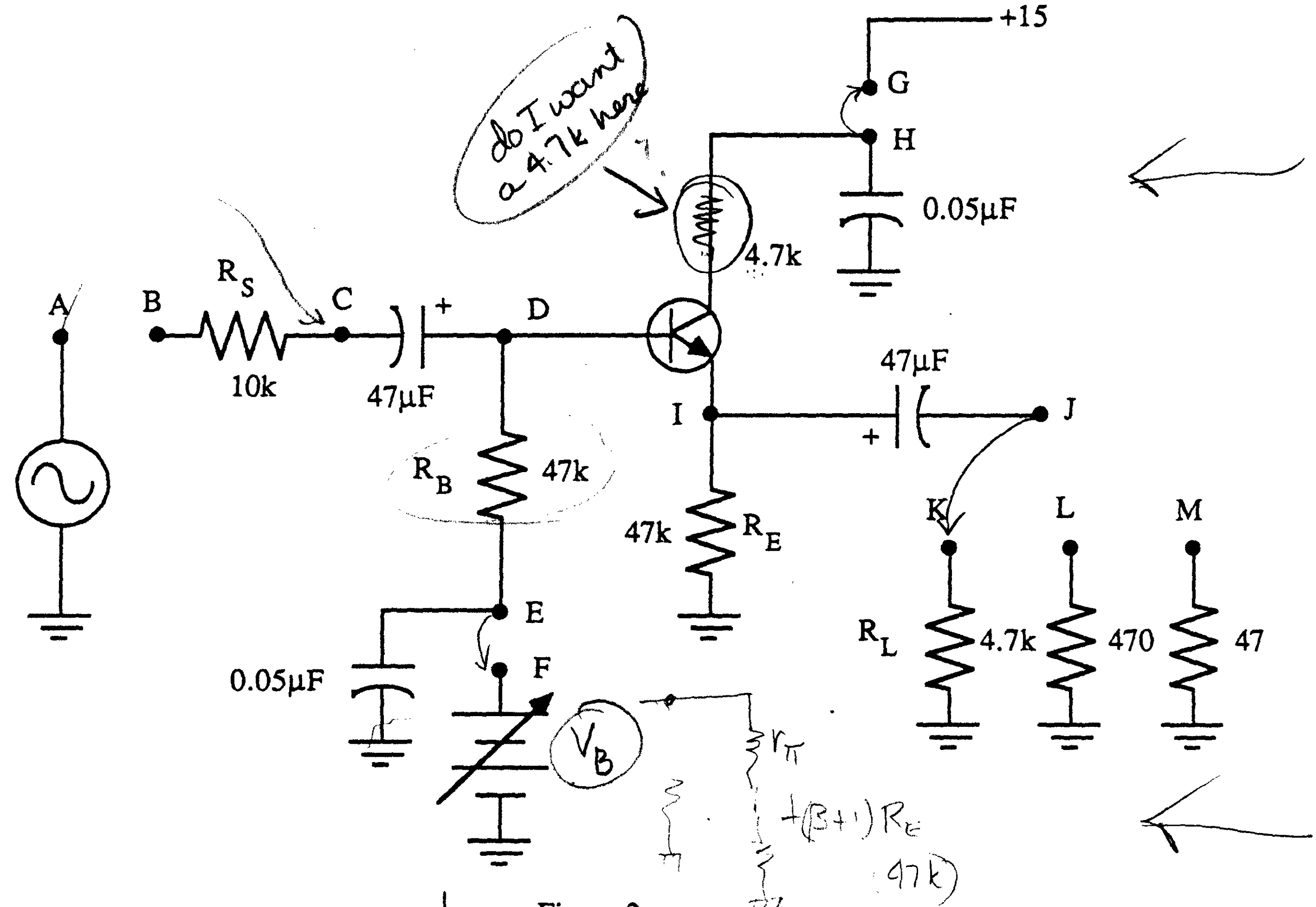


Figure 2

(1) Build the circuit of Fig.2 exactly as it is shown. Connect the scope CH1 input to point A and CH2 input to point F. (You will keep these connections for this ENTIRE part.)
(2) Set the signal at point A to a 2 KHz sine wave at approximately 100 mV RMS with zero DC offset. Set the voltage at point F to approximately 7 V DC.
(3) Connect A to C, E to F, G to H, and J to K. If you observe high frequency oscillation, connect a 100 pF capacitor from D to H. (If you need this capacitor, it must stay in place for the ENTIRE lab.)
(4) Adjust the variable supply so that point I is at approximately 5 V DC.

The first flawed method of measuring Z_i and Z_o that you will try is that of simply using the DMM. Your meter measures resistance by using the unknown resistance in a voltage divider with a known resistance and a known DC voltage. This method is clearly useless when trying to measure AC impedances in an active circuit.

(5) Set the DMM to OHMS and (try to) measure the resistance to ground at points C, D, I, and J. Record your results (if any) in Table 10.2.
(6) Disconnect E from F and G from H so that you don't short circuit your power supplies. Connect E and H to ground.
(7) Repeat step 5.

The second flawed method of measuring Z_i and Z_o that you will try is that of applying a known AC voltage source at the input and the output and measuring the current that flows. This doesn't work for Z_i because the current is too small to be accurately measured. It doesn't work for Z_o because the transistor does not appreciate trying to force current into its output. The resistances of the ammeter and signal generator don't help, either.

(8) Restore the circuit to that of Fig.2. Connect E to F, G to H, and J to K.
(9) Set the DMM to AC AMPS, connect its mA input to A, and connect its COM input to C.
(10) Measure (or try to) the AC current flowing into the amplifier's input. Record any results in Table 10.3.
(11) Restore the circuit to that of Fig.2. Connect E to F and G to H.
(12) Set the DMM to AC AMPS, connect its mA input to A, and connect its COM input to J.
(13) Measure (or try to) the AC current flowing through the amplifier's output. Record any results in Table 10.3.

The third flawed method of measuring Z_o that you will try is that of measuring the AC short circuit current at the output. This doesn't work because the transistor becomes nonlinear with small load resistances and because the ammeter does not provide a true short circuit.

(14) Restore the circuit to that of Fig.2. Connect A to C, E to F, and G to H.
(15) Set the DMM to AC AMPS, connect its mA input to J, and connect its COM input to ground.
(16) Measure (or try to) the AC short circuit current at the output. Observe the signal at J on your scope. RECORD ANY RESULTS IN TABLE 10.4.

The proper way to measure Z_i is to use a voltage divider with a series source resistance. This method works best when Z_i and the series resistance are comparable. The resultant loss in input voltage can be used to calculate Z_i. If the input voltage is small, the resultant loss in output voltage can be used instead. The correct way to measure Z_o is to use it in a voltage divider with a load resistance. This method works best when the load is larger than Z_o because amplifiers often become nonlinear when small load resistances are used. Again, the resultant loss in output voltage can be usedto calculate Zo.

(17) Restore the circuit to that of Fig.2. Connect A to C, E to F, and G to H.
(18) Adjust the generator so that point A is at approximately 100 mV RMS. Adjust the variable supply so that point I is at approximately 5 V DC.
(19) Measure the exact DC voltages at D, E, H, and I. Record your measurements in Table 10.5.
(20) Measure the exact AC RMS voltages at A, D, and J. Record your measurements in Table 10.5.
(21) Repeat step 20 for J connected to K, J connected to L, and J connected to M.
(22) Disconnect J from M to remove the load. Disconnect A from C and connect A to B.
(23) Repeat steps 20 and 21.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE CONTINUING.

Part 3 - Emitter Follower Cutoff

The emitter follower amplifier is often capacitively coupled to its load. If the load resistance is too small and the signal's voltage swing is too large, it is possible to reverse bias the transistor's base-emitter junction. This results in clipping of the lower portion of the output waveform.

(1) Restore the circuit to that of Fig.2. Connect A to C, E to F, and G to H.
(2) Connect the scope CH2 input to point I. DC couple both scope channels.
(3) Set the signal generator to a triangle wave and set its amplitude so that the lower peaks of the waveform at I are SLIGHTLY flattened.
(4) Record the DC voltage difference between ground and the flattened portion of the waveform at I.
(5) Connect the scope CH2 input to point J and record the DC voltage difference between ground and the flattened portion of the waveform at J.
(6) Repeat steps 2 to 5 for J connected to K, J connected to L, and J connected to M.

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE LEAVING.

Questions:

1. Consider the circuit of Fig.[redacted] and assume connections from A to C, E to F, and G to H. Use your measured b_o, I_c = 10.6 mA and $r_\pi = .026 b_o/I_c$ (not your data from subsequent parts) in the following calculations.

   Calculate Z_i looking to the RIGHT from point C for
   (a) no load,
   (b) the 4.7 K load,
   (c) the 470 ohm load, and
   (d) the 47 ohm load.
   (e) Calculate Z_o looking to the LEFT from point J.

   Calculate the gain (J/C) for
   (f) no load,
   (g) the 4.7 K load,
   (h) the 470 ohm load, and
   (i) the 47 ohm load.

2. In the following calculations, use the experimental data which will yield the "best" calculations.

   Calculate Z_i looking to the RIGHT of point C for
   (a) no load,
   (b) the 4.7 K load,
   (c) the 470 ohm load, and
   (d) the 47 ohm load.

   (e) Calculate Z_o looking to the LEFT of point J.

   Calculate the gain (J/C) for
   (f) no load,
   (g) the 4.7 K load,
   (h) the 470 ohm load, and
   (i) the 47 ohm load.

   Calculate
   (j) r_π and
   (k) b_o.

3. (a) Compare your r_p and b_o values from Questions 1 and 2. Which do you feel is the most accurate?
   (b) Did you need to use the 100 pF capacitor?
   (c) Do any of the [redacted] methods yield Z_i [redacted] values close to those found in Ques.[redacted]?

4. For each of the four cases tested, calculate the instantaneous current through the emitter, emitter resistor, and load resistor during the flattened portion of the waveform.

5. Write an equation which defines the maximum undistorted AC output voltage in terms of the operating point, emitter resistance, and load resistance.

EEAP 243 LAB 10 EVALUATION

NAME (print)____________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

In Fig. 10.1 assume connections from F to J and from E to N. What will happen to the gain from point D to point L if we increase/decrease the resistance of $R_4/R_6/R_8/R_9/R_{10}/R_{11}/R_{12}$?

It will increase / decrease / stay the same.

Question #2

In Fig. 10.1 assume connections from F to J and from E to N. What will happen to the gain from point D to point L if we increase/decrease the resistance of R_{13}/R_5 ?

It will increase / decrease / stay the same.

EEAP 243

NAMES: ______________________________

Lab 10 Data

E/H grounded.

C	________	________
D	________	________
I	________	________
J	________	________

Table 10.2 Measuring Z with an ohmmeter

AC INPUT CURRENT: ________

AC OUTPUT CURRENT: ________

Table 10.3 Measuring Z using source current

AC OUTPUT CURRENT: ________

Table 10.4 Measuring Z using short circuit current

	----- V DC -----	---------- V AC (rms) ----------			
		no load	4.7k	470	47
A		________	________	________	________
D	________	________	________	________	________
E	________				
H	________				
I	________				
J		________	________	________	________

Table 10.5 DC and AC Measurments of emitter follower

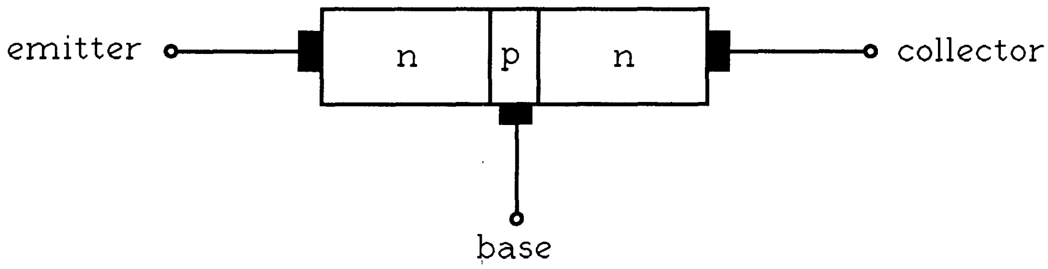
6

	point I	point J
DC VOLTAGE DIFFERENCE (J open):	________	________
DC VOLTAGE DIFFERENCE (J-K):	________	________
DC VOLTAGE DIFFERENCE (J-L):	________	________
DC VOLTAGE DIFFERENCE (J-M):	________	________

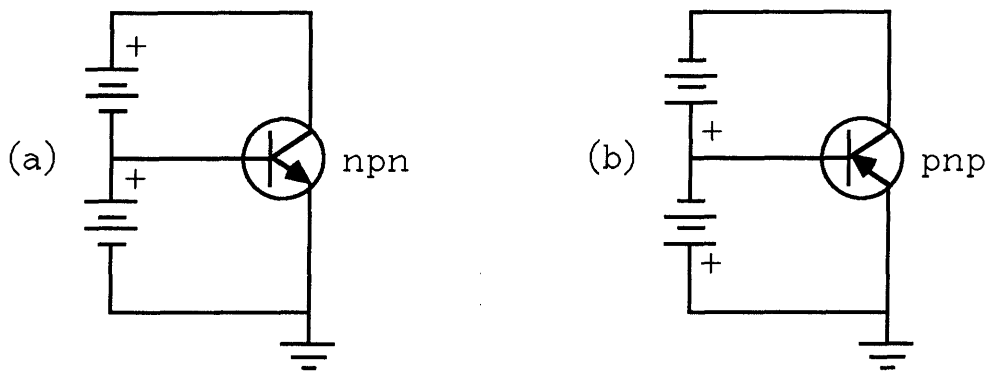
Table 10.6 - Emitter follower cutoff

DC CHARACTERISTICS OF BJTs AND FETs

Before we can understand how to design circuits usings BJTs and FETs we must review their basic properties. These basic properties are functions of the operational mechanisms of these devices, i.e. the solid state physics which is covered in other courses. The bipolar transistor, or BJT, comes in two types: npn and pnp referring to the physical construction of the device. The npn transistor is a thin slice of p-type material sandwiched between two slabs of n-type material as shown below.

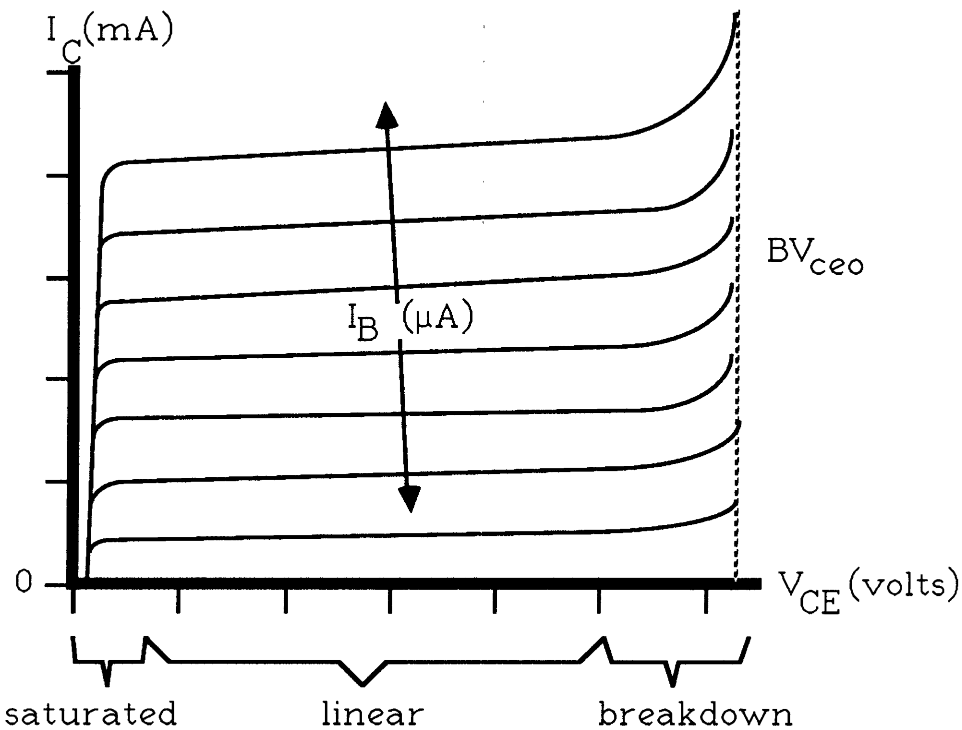


The middle layer is called the base; the substrate (or base upon which the entire structure is fabricated) is called the collector; and the top layer is called the emitter. The net result of this construction is that two diode junctions are formed: one between the collector and base and the other between the base and emitter. In practice, both transistor junctions (the diodes referred to above) are forward biased. Proper bias for npn and pnp transistors are shown below.



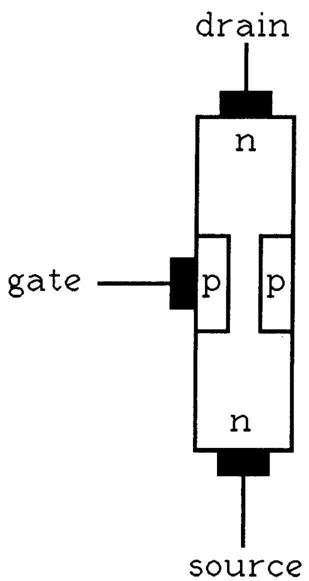
The net result of this bias is that current continuously flows through the junctions of the transistor; however, it is the relative magnitudes of these currents and the relationships between these currents that make the transistor an amplifier. For an npn transistor we can regard current as entering the transistor at both the base and collector and exiting at the emitter. This makes the emitter current the sum of the collector and base currents. The base current is quite small, however, and controls the collector current. The ratio of collector current to base current is the dc beta of the transistor and is denoted by β_{DC}. This ability to amplify current is what makes the bipolar transistor so useful, and even though the primary mode of operation of the BJT is current based, it can usefully function as a voltage and power amplifier when placed in a proper circuit.

The operation of the BJT can be summarized in the relationship between the base current I_B, the collector current I_C and the collector-emitter voltage V_{CE}. The exact relationship can be derived only after a fair digression into physical electronics. Suffice it to say that all bipolar junction transistors have characteristics similar to those shown in the graph below.

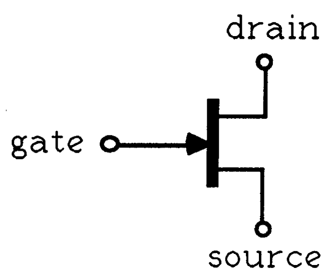


For amplifier operation the BJT is used in the "linear" region where the slope of the I_C-V_{CE} curve is almost constant. This linear region makes possible an amplifier with very little distortion as will be discussed later. One wants to avoid operation, for amplifiers, in the saturated region characterized by small V_{CE} (typically 0.2 volts or less). Similarly, one wants to avoid operation in the region to the far right of the graph. This is the region in which large electric field strengths from the large V_{CE} can destroy the transistor junction.

Field effect transistors, or FETs, are voltage-biased rather than current biased like BJTs. The basic structure of the FET is a thin connection between two terminals of similar semiconducting material. For example, the p-type material is used to connect two pieces of n-type material through a narrow n-type gate region as shown below. The two pieces of n-type material are known as the drain and source with current flow from the drain to the source for the FET shown below. The p-type/n-type connecting region is known as the channel region and the p-type material is called the gate.



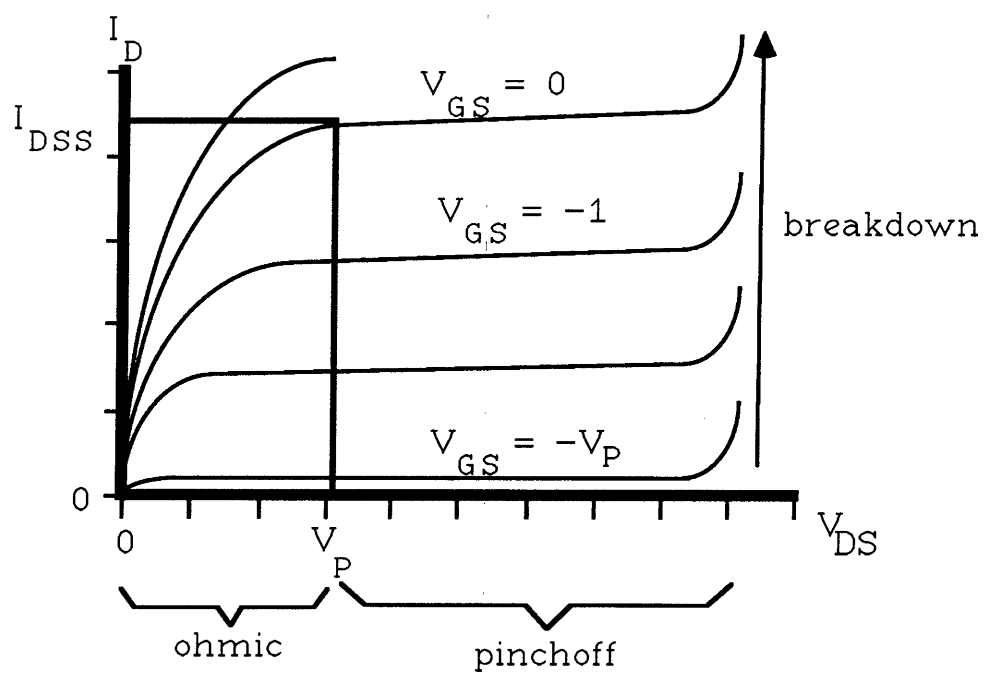
n-channel JFET



The drain current is at its maximum value I_{DSS} when the gate-source voltage is zero. The precise definition of I_{DSS} is that it is the short circuit drain current, i.e. the drain current that flows when the gate is shorted to the source. For operation of the FET as a control device the gate-source voltage must be negative. This creates a reverse biased diode and produces a depletion region in the neighborhood of the gate. This depletion region reduces the amount of free carriers and consequently reduces the current flow between the source and drain. As the gate-source potential becomes more negative it eventually reaches a point called the pinchoff voltage V_P where the gate depletion regions close together and the source-drain current becomes essentially zero. The exact relationship between the drain current and V_{GS} is an exact square-law relationship:

$$I_D = I_{DSS}\left(1 - \frac{|V_{GS}|}{V_P}\right)^2$$

The pinchoff voltage (actually $-V_P$) is also the drain-source voltage which marks the boundary between the ohmic and pinch-off regions of operation of the FET. Essentially, the FET behaves like a variable (but non-linear) resistance in the ohmic region and then remains essentially constant for $V_{DS} > V_P$. For amplifiers it is this linear or pinch-off region that is of interest. In the pinch-off region the drain current is almost linearly proportional to the V_{GS} and independent of V_{DS} (see graph below).



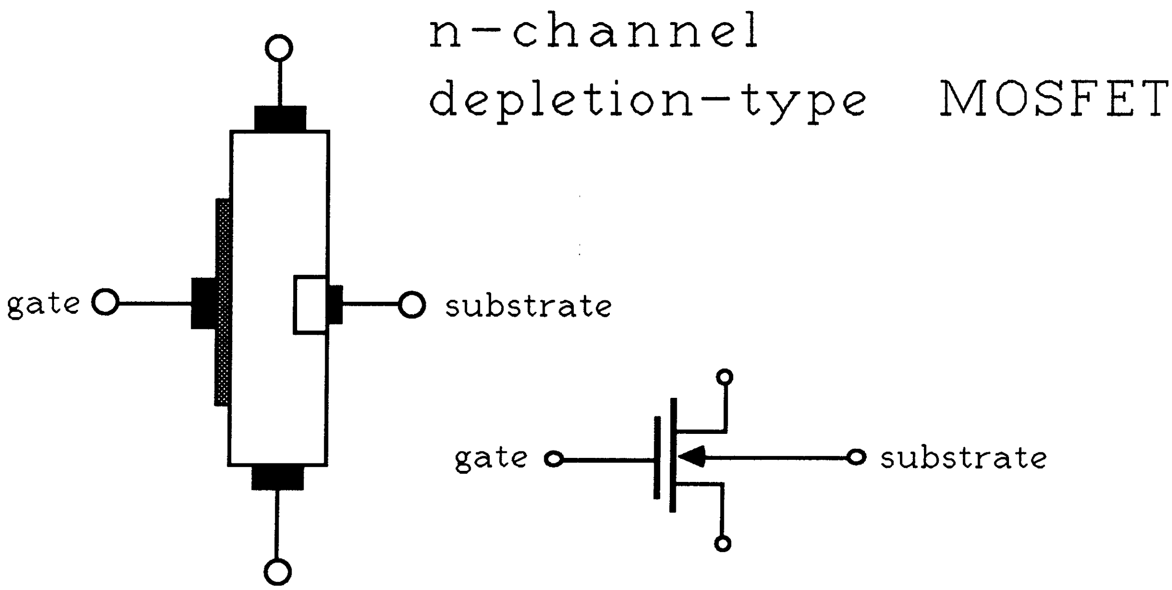
The ratio of change in I_D to the corresponding change in V_{GS} is known as the device transconductance g_m and is of fundamental concern when using the FET as an amplifier. The transconductance when the gate-source voltage is zero is denoted by g_{mo} and is often specified by the transistor manufacturer. The transconductance g_{mo}, the drain saturation current I_{DSS} and the pinch-off voltage V_P are all related by the relationship

$$g_{mo} = \frac{2I_{DSS}}{|V_P|}$$

where $|V_P|$ is the absolute value of the pinch-off voltage.

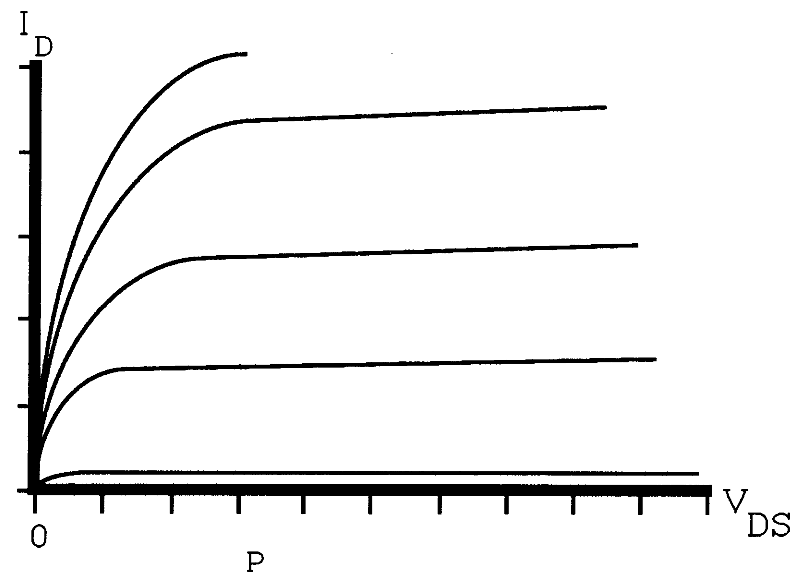
The above discussion was for a n-channel junction FET, or JFET for short. The same device with the semiconductor materials reversed is known as a p-channel JFET.

There is a special version of the JFET known as the MOSFET which is of particular interest in this course. The MOSFET or Insulated Gate FET, is a FET in which a silicon dioxide layer electrically insulates the gate electrode from the rest of the transistor. The internal structure of a MOSFET is shown below.



Since the FET operates by the electrode field created between the gate and the drain and source regions the insulated gate FET also functions in the same manner as an ordinary FET. However, the insulated gate now shifts the gate-source voltages and effectively reduces any already small gate currents to effectively zero.

MOSFETs are characterized as enhancement or enhance/depletion mode devices depending upon the properties of the channel. In enhancement mode MOSFETs the drain current increases as V_{GS} increases; however, the channel only exists when V_{GS} is greater than a certain threshold voltage V_T. In enhancement/depletion mode MOSFETs the drain current increases as V_{GS} increases and the FET will continue to operate for $V_{GS} > 0$. Note that enhancement mode MOSFETs are the only type of FET which can operate with a forward biased gate. It must be pointed out that the polarity of V_{GS} is determined by the type of the bulk semiconducting material. Characteristic curves for n-type (not n-channel) enhancement and enhancement/depletion MOSFETs are shown below.

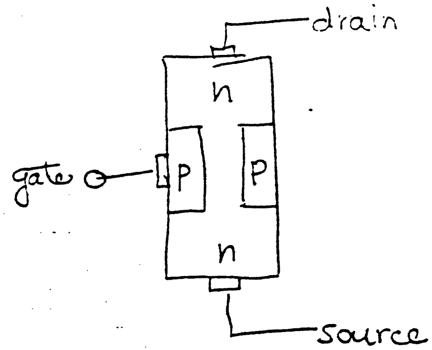


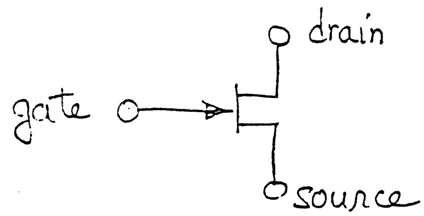
V_{GS}

enhancement	enhancement /depletion
+5	+2
+4	+1
+3	0
+2	−1
+1	−2
0	

The structure of the MOSFET is such that multiple gates can be fabricated for a common drain-source geometry. This allows the MOSFET to be used for logic circuits and active devices such as mixers where it is important to keep the device inputs electrically isolated from each other.

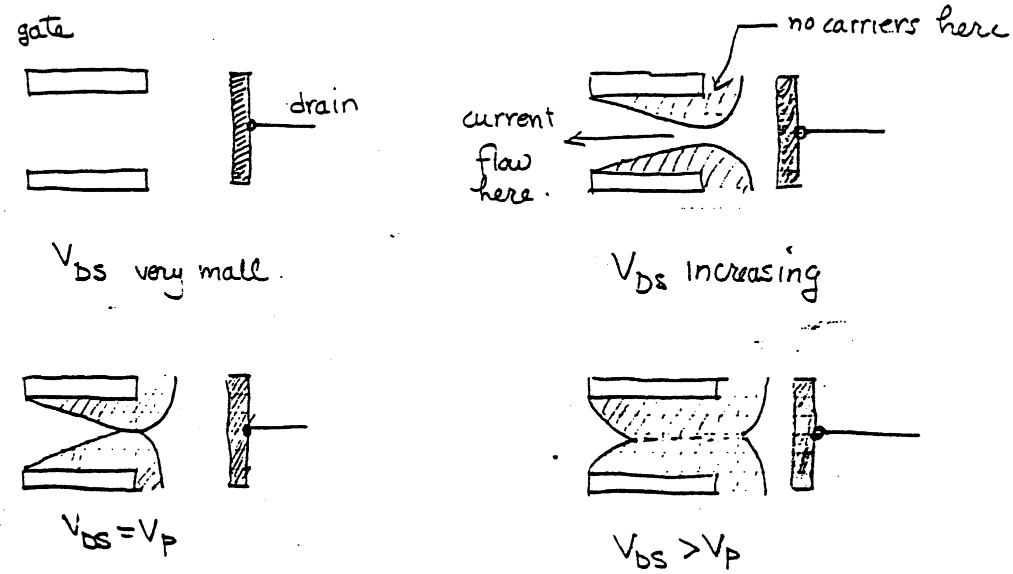
Field effect transistors — voltage amplifiers

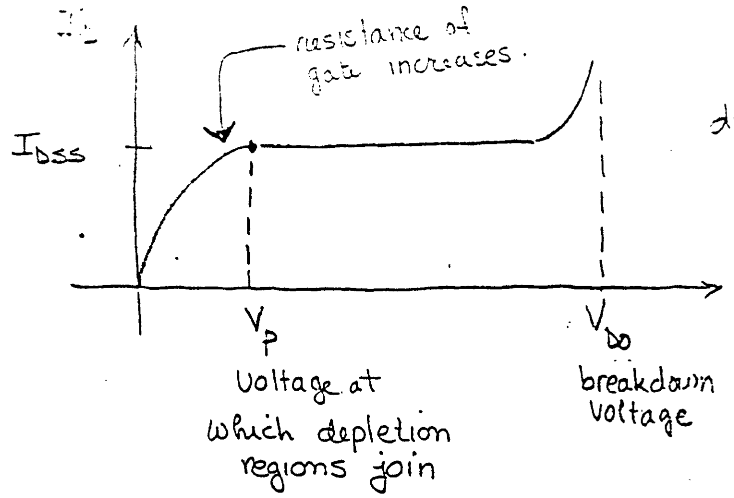




the drain current is at a maximum when $V_{GS} = 0$
we call this maximum current I_{DSS}
specifically I_{DSS} is the drain current when the gate is short circuited to the source.

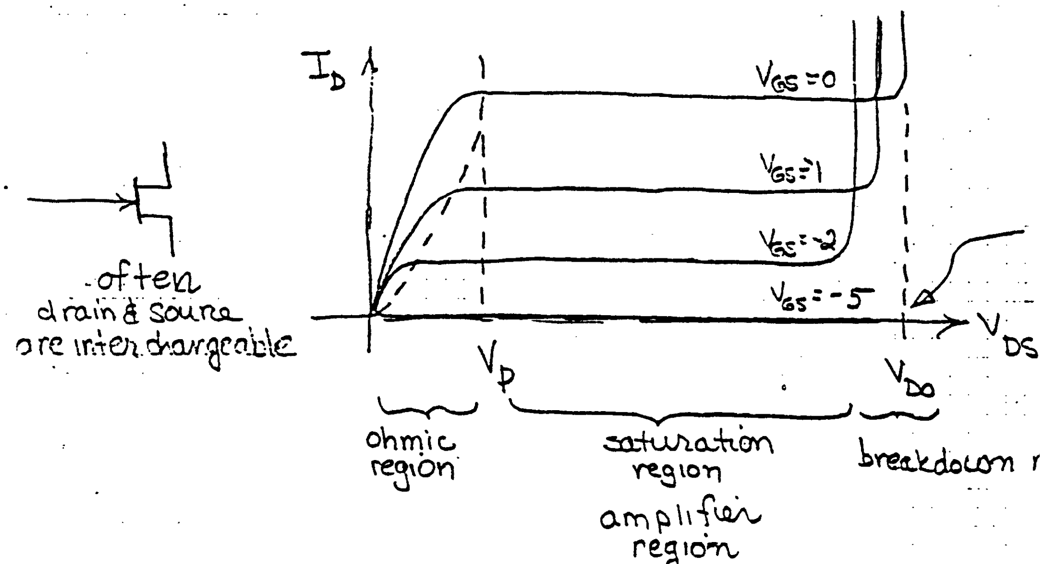
Without going into a lot of detail a FET operates like a voltage controlled resistor. Suppose $V_{GS} = 0$. For small values of V_{DS} we have a typical resistor's linear i-v relationship. As V_{DS} increases the gate-drain junction becomes more reverse biased and a larger depletion region, i.e. an area with few mobile charges appears. As V_{DS} increases the depletion region increases increasing the resistance of the junction and lowering the slope (conductance) of the i-v curve.





drawn for $V_{GS} = 0$

As we vary V_{DS} we can generate a family of device curves



If $V_{GS}>0$ junction is not reverse biased so transistor will not work

for a constant V_{DS} as V_{GS} becomes more negative it eventually cutsoff the FET.

at cutoff (or pinchoff) for a constant V_{DS} (V_p decreases as V_{GS} decreases)

$$V_{DS}(\text{pinchoff}) \approx V_{po} + V_{GS} = V_p$$

V_{po}: pinchoff for zero V_{GS}; V_p: pinchoff voltage

The operation of the junction FET can be mathematically summarized as

1. ohmic region

$$I_D = I_{DSS}\left[2\left(1+\frac{V_{GS}}{V_{po}}\right)\frac{V_{DS}}{V_{po}} - \left(\frac{V_{DS}}{V_{po}}\right)^2\right]$$

for V_{DS} small $\quad I_D \approx \frac{2 I_{DSS}}{V_{po}}\left(1+\frac{V_{GS}}{V_{po}}\right)V_{DS}$

looks like a resistor with

$$\frac{1}{r_{DS}} \approx \frac{2 I_{DSS}}{V_{po}}\left(1+\frac{V_{GS}}{V_{po}}\right)$$

2. saturation region

$$I_D = I_{DSS}\left(1 + \frac{V_{GS}}{V_{po}}\right)^2$$

note: $V_{GS} < 0$
$V_{po} > 0$

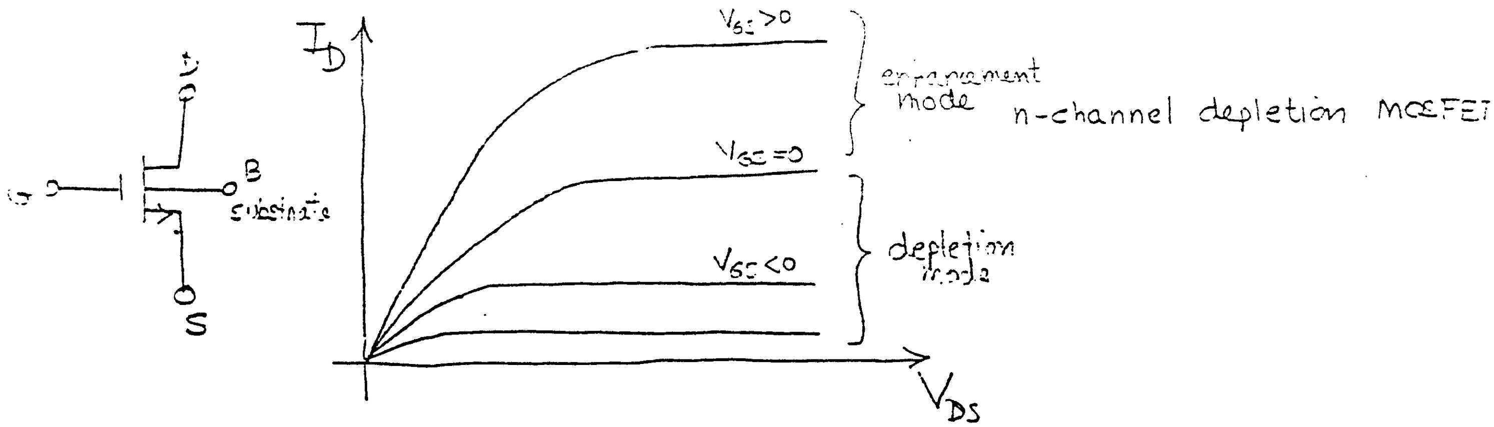
3. cutoff region $\quad I_D = 0$

A transistor manufacturer will often specify the transconductance g_{mo} defined by

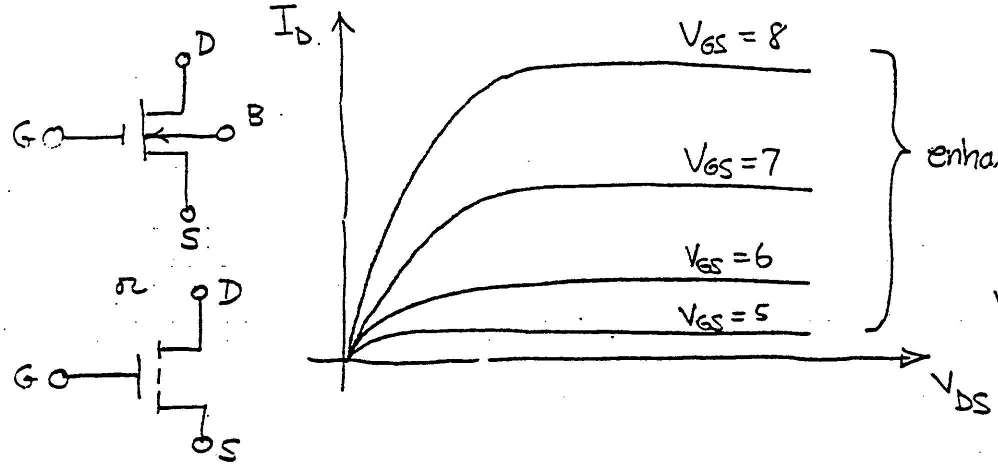
$$g_{mo} = \frac{2 I_{DSS}}{|V_{po}|}$$

MOSFET

The MOSFET is a special version of the JFET in which a silicon dioxide layer electrically insulates the gate electrode from the rest of the transistor. Basically the MOSFET behaves identically to a JFET. As V_{GS} becomes more negative the minority carriers become depleted and the MOSFET behaves exactly like a JFET. However, because the gate is insulated from the rest of the transistor no p-n junction is formed at the gate and even if V_{GS} becomes positive no gate current can flow. If V_{GS} becomes positive negative charges are induced in the channel creating an "effective" larger majority carrier concentration. This increases the conductivity of the channel and increases I_D. When $V_{GS} > 0$ the MOSFET is operating in the enhancement mode.

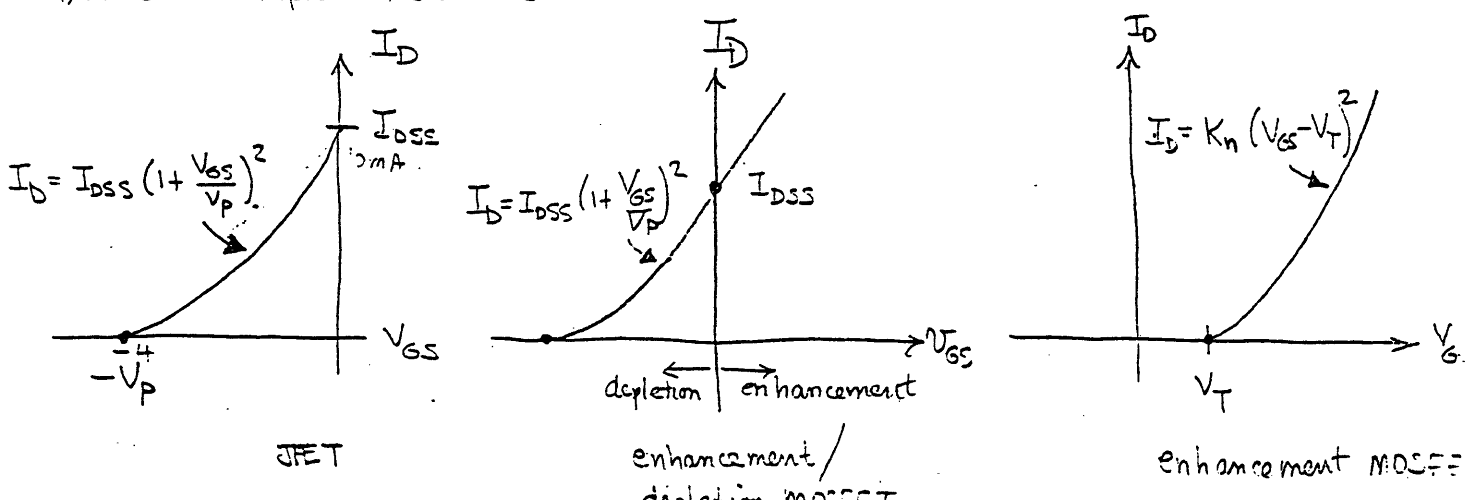


certain MOSFET's can only operate in the enhancement mode. This is because a channel is formed by the applied field (adding majority carriers) and does not exist when $V_{GS} \leq 0$.



V_{GS} at which the channel form is called V_T, the thresho voltage.

A very common way of displaying FET characteristics is the transfer characteristic curve which plots I_D as a function of V_{GS}, i.e. the output versus the input for a FET.



JFET

enhancement/depletion MOSFET

enhancement MOSFET

V_T is the threshold voltage

all are n-channel.

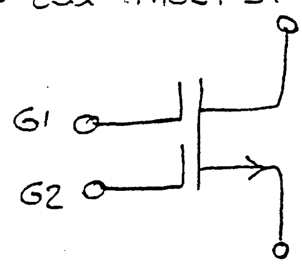
Why use FET's? <u>their transfer characteristics</u>

A square-law relationship is good for mixers, amplifiers and gain-controlled stages.

$$g_m \triangleq \frac{\Delta I_D}{\Delta V_{GS}}$$ so this is the parameter that will be important.

g_{mo} is also the slope of the transfer characteristic.

Specialized MOSFET – dual gate

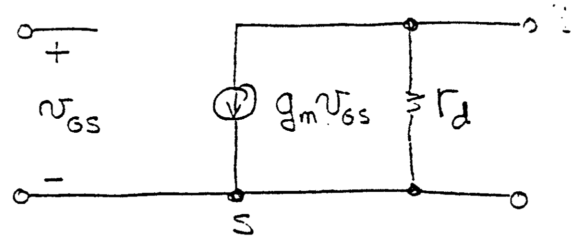


common substrate

very useful for mixers:

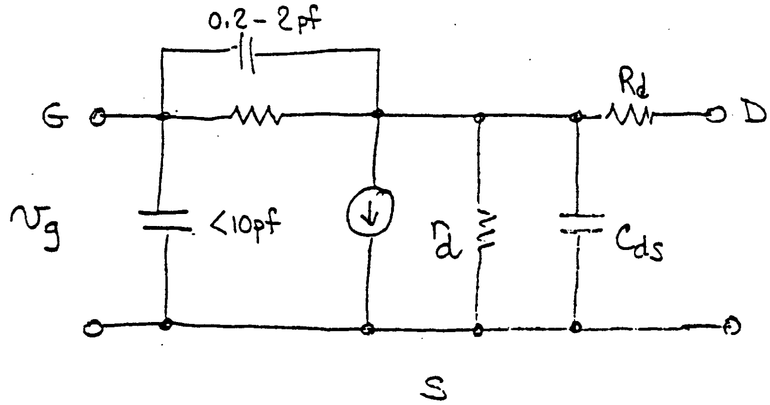
FET small signal model

circuits II (midband) model:

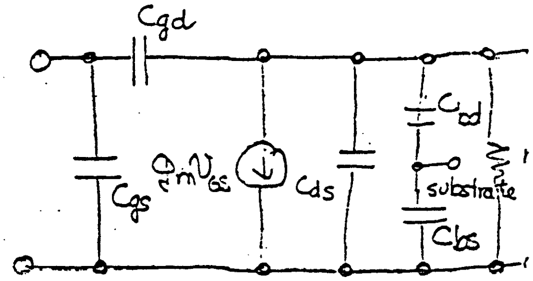


high frequency models;

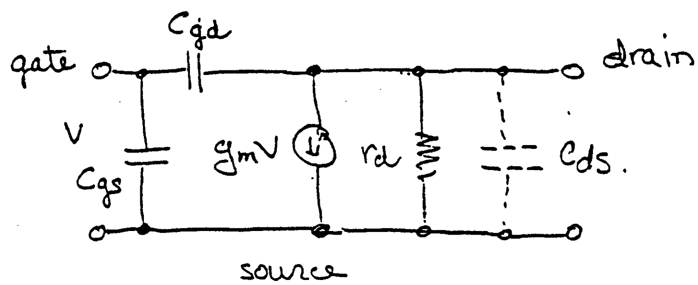
JFET



MOSFET



simplified high frequency π model



C_{gd} feedback capacitance
0.05 − 5 pf

C_{gs} input capacitance
0.1 − 10 pf

r_d effective channel resistance
500 − 5000 Ω

C_{ds} is usually small enough to be neglected.

In general, a FET is <u>NOT</u> better than a BJT at high frequencies

① The input impedance drops rapidly with frequency and quickly becomes reactive for a FET. (Even though the FET still has a somewhat higher impedance this can be made up for by a matching circuit for a B

② A BJT usually has a better power gain.

③ The BJT has a larger gain bandwidth product.

FET data sheets

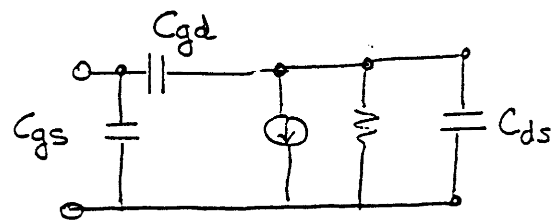
transconductance $g_{mo} = \frac{2 I_{DSS}}{|V_p|}$

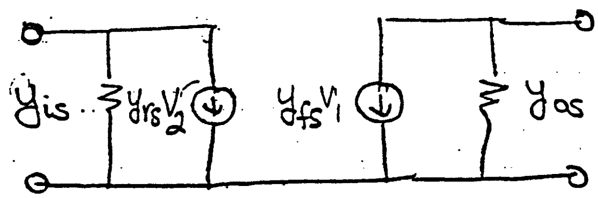
C_{iss} common source short-circuit input capacitance

C_{rss} reverse transfer capacitance

C_{ds} output capacitance

use π-model



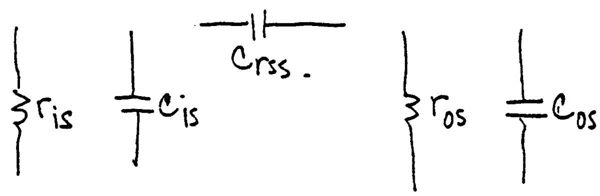


$C_{gd} \approx C_{rss}$ corresponds to C_p.

$C_{gs} \approx C_{iss} - C_{rss}$ input ∥ feedback

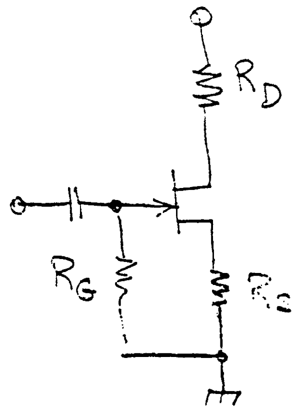
$C_{ds} \approx C_{oss} - C_{rss}$ output ∥ feedback.

i.e.



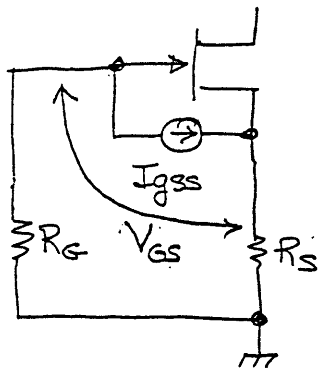
Biasing FET's (p. 93)

simple self-bias circuit



Why does this work?

Leakage current I_{gss} thru gate.



use KVL on gate bias circuit.

$$0 = I_{gss} R_G + V_{GS} + (I_{gss} + I_D) R_S$$

usually $I_{gss} \ll I_D$

$$V_{GS} = -\left(I_{gss} R_G + R_S I_D\right)$$

differentiate with respect to I_{gss}

$$\frac{\partial V_{GS}}{\partial I_{GSS}} = -R_G - R_S \frac{\partial I_D}{\partial I_{GSS}}$$

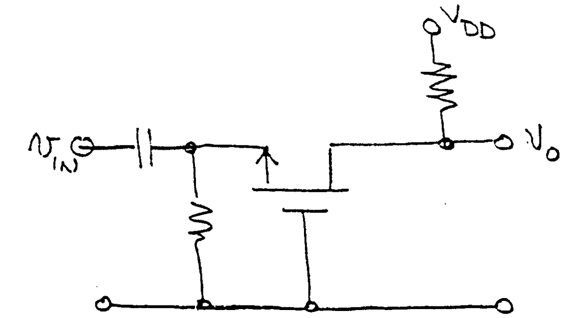
equivalent to stability criteria except for FET's.

$$\text{pick } R_G \leq -R_S \left.\frac{\partial I_D}{\partial I_{gss}}\right|_{max} + \left.\frac{\partial V_{GS}}{\partial I_{DSS}}\right|_{min}$$

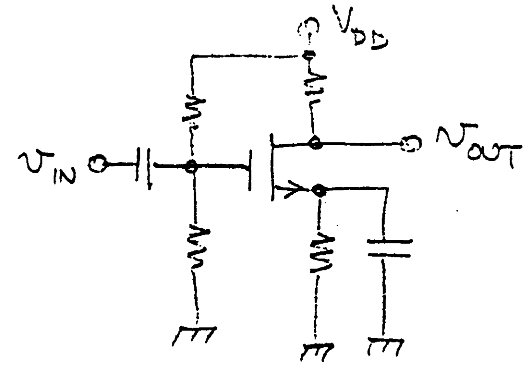
usually $R_G \sim 1 - 1.5 M\Omega$

FET amplifier topologies

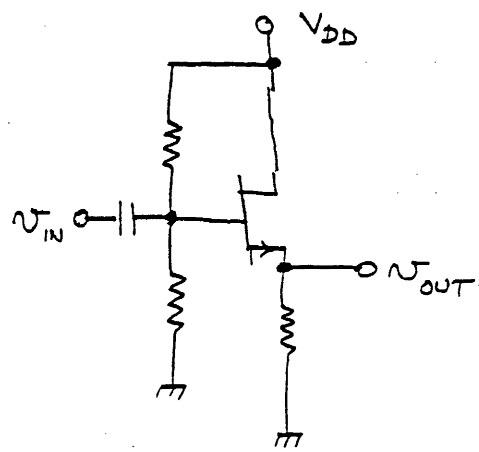
common gate



common source



common drain (source follower)

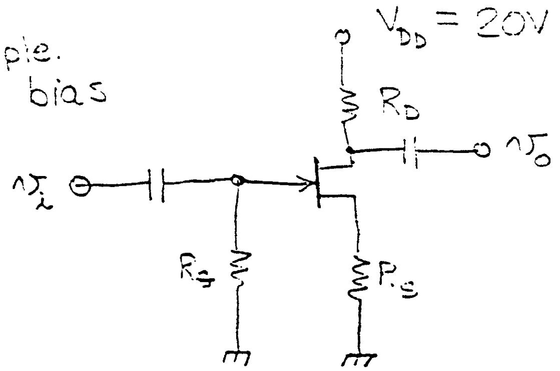


properties of a FET amplifier

	common gate	common source	common drain
R_{IN}	500Ω	∞	∞
R_{OUT}	∞	20kΩ	500Ω
A_v	4	−4	0.80

($g_m = 2\times10^{-3}$ ℧, $r_d = 20k$, $r_L = 2k\Omega$)

Example.
JFET bias



For the JFET shown
$I_{DSS} = 8\,mA$
$V_P = -6V$

Bias at $I_D = 2.0\,mA$, $V_{DS} = 10V$

① Find V_{GS} from transfer characteristic

$$I_D = I_{DSS}\left(1 + \frac{V_{GS}}{V_P}\right)^2$$

$$2 = 8\left(1 + \frac{V_{GS}}{+6}\right)^2$$

$$\frac{1}{4} = \left(1 + \frac{V_{GS}}{6}\right)^2$$

$$\pm\frac{1}{2} = 1 + \frac{V_{GS}}{6}$$

$$\frac{1}{6}V_{GS} = -1 + \frac{1}{2}, -1 - \frac{1}{2} = -\frac{1}{2}, -\frac{3}{2}$$

$$V_{GS} = -3, -9$$

↖ beyond Pinchoff

$\Rightarrow V_{GS} = -3$ volts

② Pick $R_G \approx 0.5\,M\Omega$

③ Use KVL at input

$$V_{GS} = -I_G R_G - I_D R_S \approx -I_D R_S$$

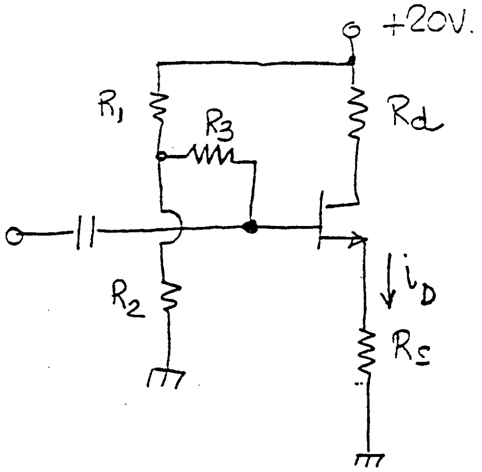
$$R_S \approx \frac{-V_{GS}}{I_D} = \frac{+3}{2\,mA} = 1.5K$$

④ use KVL at output

$$V_{DD} = I_D R_D + V_{DS} + I_S R_S$$

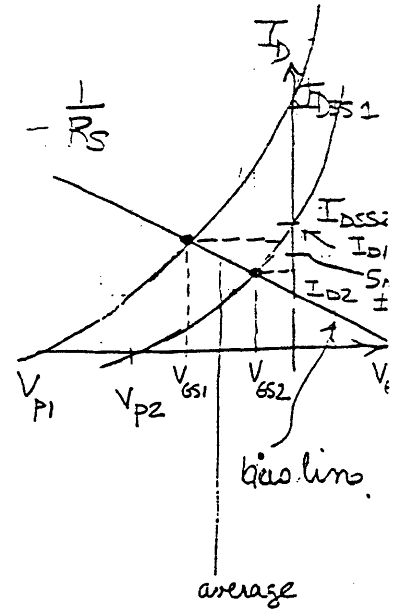
$$R_D = \frac{V_{DD} - V_{DS} - I_S R_S}{I_D} = \frac{20 - 10 - 1.5(2mA)}{2mA} = 3.5K$$

Example: depletion type MOSFET



$4 < V_p < 6$ volts

$8 < I_{DSS} < 10mA$



bias at $I_D = 5mA$, $V_{DS} = 8V$ with ±10% variation in I_D

① use transfer characteristic to get V_{gs}

$$I_D = I_{DSS}\left(1 + \frac{V_{GS}}{V_P}\right)^2$$

$$\pm\left(1 + \frac{V_{GS}}{V_P}\right) = \sqrt{\frac{I_D}{I_{DSS}}}$$

$$V_{GS} = V_P\left(\mp\sqrt{\frac{I_D}{I_{SSS}}} - 1\right)$$

V_{GS} will be a maximum when V_P is a maximum, I_D is a maximum

$$V_{GS} = 6\left(\mp\sqrt{\frac{5.5}{10}} - 1\right) = 6(\mp .74 - 1) = \begin{cases} -1.56 \\ -10.44 \leftarrow \text{belo pinc} \end{cases}$$

use 10% variation in I_D.

V_{GS} will be a minimum when V_P is a minimum, I_D is a minimum

$$V_{GS} = 4\left(\mp\sqrt{\frac{4.5}{8}} - 1\right) = 4(\mp .75 - 1) = \begin{cases} -1.0 \\ -7.0 \leftarrow \text{below pinc} \end{cases}$$

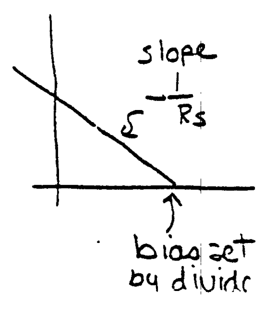
?? ~~[illegible]~~ volts due to parameter variation

② small signal analysis

$$-V_{GS} = V_G - R_S I_D$$

$$I_D = \frac{V_G}{R_S} - \frac{1}{R_S} V_{GS}$$

↖ slope.



$$\therefore \quad R_S = \frac{\Delta V_{GS}}{\Delta I_D} = -\frac{1.55 + 1.0}{5.5mA - 4.5mA} = \frac{-0.55}{1mA} = 550\Omega$$

③ find V_G

$$V_G = V_{GS} + I_D R_S$$

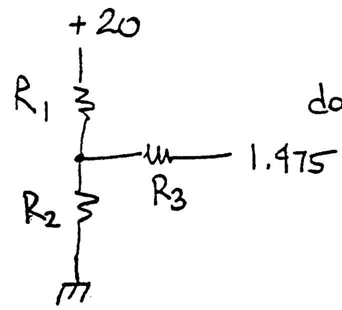
use average $V_{GS} = -\frac{1.55 - 1.0}{2} = -1.275$

$$V_G = -1.275 + (5\times10^{-3})(550) = +1.475$$

nominal value

④ pick simple voltage divider

pick $R_3 = 500K$ for leakage current



doesn't really matter

pick $R_1 = 100K$

$$\frac{R_2}{R_1+R_2} 20 = 1.475$$

$$20R_2 = 1.475R_1 + 1.475R_2$$

$$R_2 = \frac{1.475R_1}{18.525} = .0796\,(100K)$$

$$= 7.9K$$

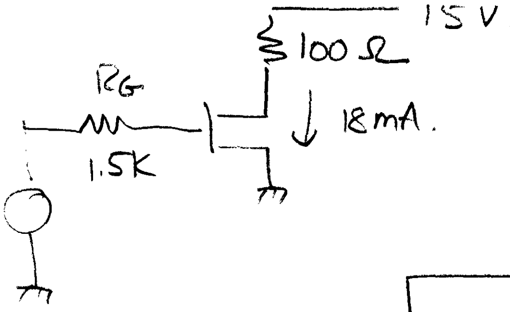
⑤ use KVL at output

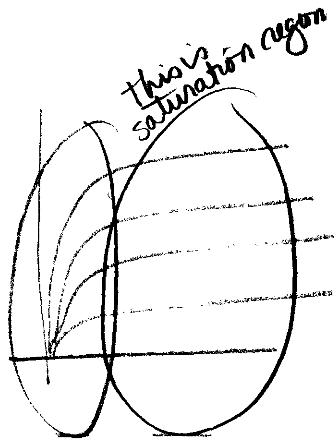
$$V_{DD} = I_D R_D + V_{DS} + I_S R_S$$

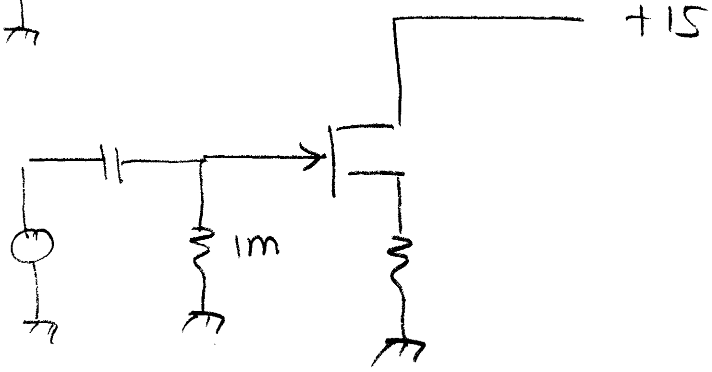
$$20 = (5)R_D + 8V + (5)(550)$$

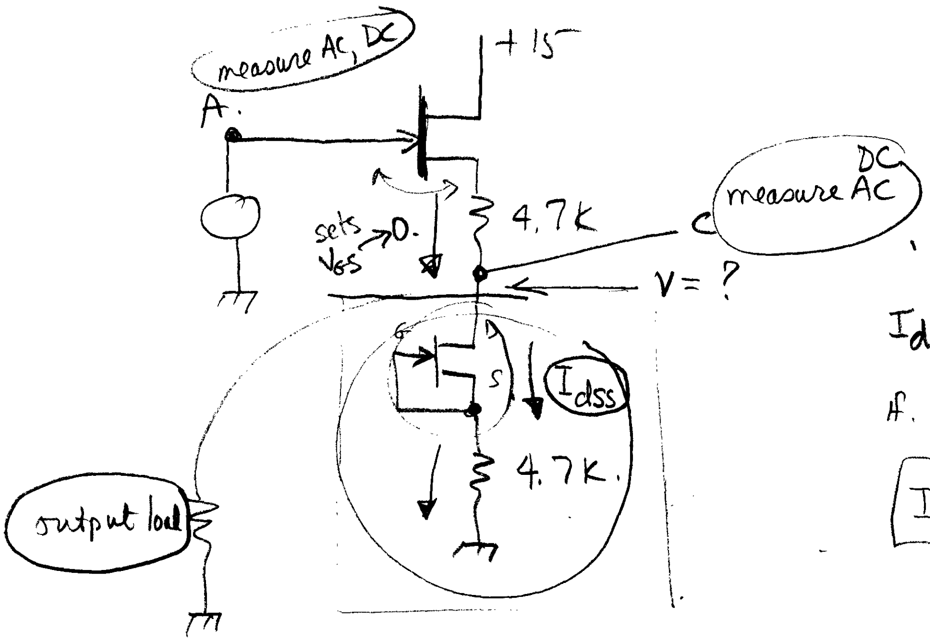
$$R_D = \frac{20-8}{5mA} - 550\Omega = 1850\Omega.$$

part 1.







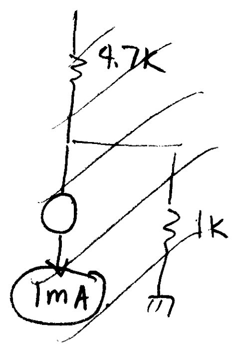


$I_d = I_{dss}\left(1 - \frac{V_{GS}}{V_p}\right)^2$.

if. $V_{GS} \to 0$.

$I_d = I_{dss}$.

if the transistors are identical



if $I_d = I_{dss}$

then. $V_{GS} \Rightarrow 0$

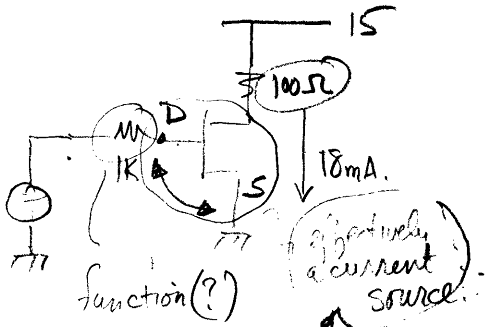
as I_d increases above I_{dss}.

then

$I_{dss}\left(1 - \frac{V_{GS}}{V_p}\right)^2 = I_d > I_{dss}$

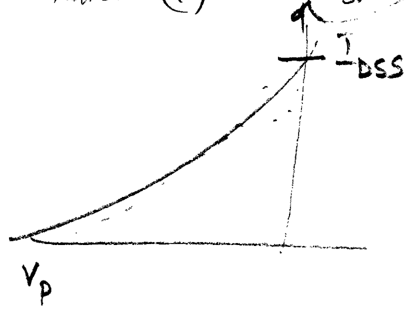
Then $\left(1 - \frac{V_{GS}}{V_p}\right)^2 > 1$

$1 - \frac{V_{GS}}{V_p} > 1$ $\therefore$ $V_{GS} > |V_p|$.



$$I_d = I_{dss}\left(1 - \frac{V_{GS}}{V_p}\right)^2$$

$$\boxed{I_{dss} = 12 - 18\ mA.}$$



g_{fs} = CS forward transfer conductance.

1 - 6.5 m ℧

$P_d = (.1k)(15) = 1.5$ watts.

$$I_D = I_{DSS}\left(1 - \frac{I_D R_S}{V_p}\right)^2$$

$$\frac{I_D}{I_{DSS}} = \left(1 - \frac{I_D R_S}{V_p}\right)^2$$

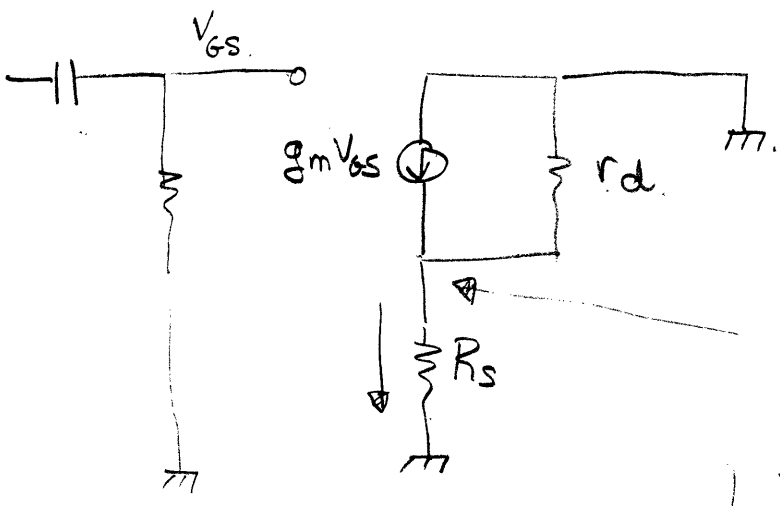
$$\frac{I_D}{I_{DSS}} = 1 - 2\frac{I_D R_S}{V_p} + \frac{I_D^2 R_S^2}{V_p^2}$$

$$I_D^2\left(\frac{R_S}{V_p}\right)^2 - 2\frac{I_D R_S}{V_p} - \frac{I_D}{I_{DSS}} + 1 = 0.$$

$$\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$I_D = \frac{\left(\frac{2R_S}{V_p} + \frac{1}{I_{DSS}}\right) \pm \sqrt{\left(\frac{2R_S}{V_p} + \frac{1}{I_{DSS}}\right)^2 - 4\left(\frac{R_S}{V_p}\right)^2}}{2\left(\frac{R_S}{V_p}\right)^2}$$

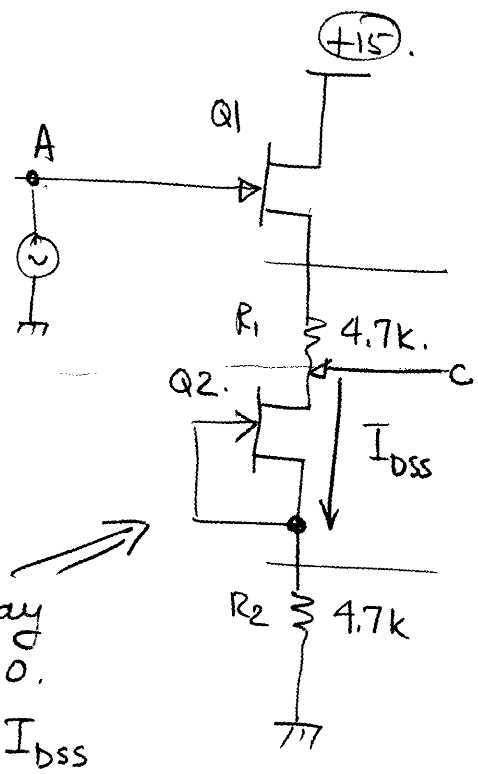
know R_S, V_p and I_{DSS} from transistor characteristics otherwise measure I_D and solve for I_{DSS} or V_p.



$Z_{OUT} \approx R_S$

$Z_{IN} \approx \infty$

$V_{OUT} \approx +\, g_m R_S$

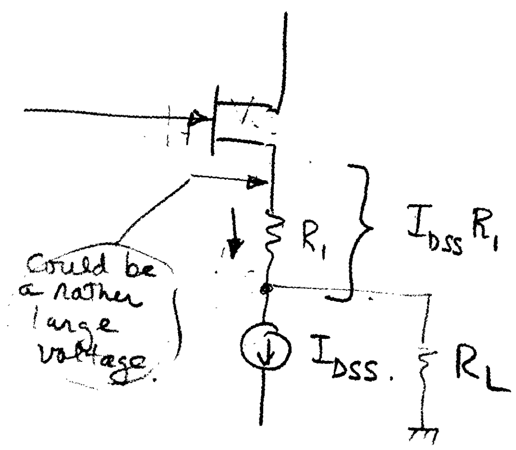


dead give away

$V_{GS} = 0.$

$\therefore\ I_D = I_{DSS}$

$$I_D = I_{DSS}\left(1 + \frac{V_{GS}}{V_p}\right)^2$$



As I add a load resistor

$I_D > I_{DSS}$. for Q2

V_{GS} changes

EEAP 243
Lab 11

Lab Work:
Questions Due:

FET CHARACTERISTICS, AMPLIFIERS, AND APPLICATIONS

READING ASSIGNMENT: Horowitz, pgs.223-231, 232-234, 240-241.

Abstract:
In this lab you will compare methods for measuring the dc characteristics of an N-channel JFET. The performance of a FET current source will be examined. The common source and common drain amplifiers will be studied.

Part 1 - DC Characterization

In this part, you will use determine your transistor's I_{DSS} and V_P by using the curve tracer and by direct measurement. You can use the curve tracer any time during your lab period, so don't waste time standing in line.

(1) Set the curve tracer to the default drain characteristic settings listed in ~~Figure~~ Table 1.

CONTROL	DEFAULT SETTING	DESCRIPTION
13	*	- set so display starts at point labeled 9
12	2 mA	I_D - drain current per vertical cm.
15	2 collector	V_{DS} - drain voltage per horiz. cm.
20	in	gate voltage polarity inverted
17	0.5 V	V_{GS} - gate voltage increment per step
all others	NPN default positions	

~~Figure~~ Table 1 Curve tracer settings for characterizing FETs

(2) Test the reference transistor to make sure you have the settings right.
(3) Display your transistor's drain characteristics and adjust the controls as needed to get a nice display. ACCURATELY record the characteristics in Table 11.1. Pay particular attention to the slopes of the curves in the resistive and saturation regions.
(4) Set the curve tracer to the default transfer characteristic settings listed in ~~Figure~~ Table 2.

CONTROL	DEFAULT SETTING	DESCRIPTION
13	*	- set so display starts at point labeled 9
12	2 mA	I_D - drain current per vertical cm.
15	steo gen	V_{DS} - drain voltage per horiz. cm.
20	in	gate voltage polarity inverted
17	0.5 V	V_{GS} - gate voltage increment per step
all others	NPN default positions	

~~Figure~~ Table 2 Curve tracer settings for measuring the transfer characteristics of FETs

(5) Test the reference transistor to make sure you have the settings right.

SAVE A XEROX OF YOUR DATA FOR LAB #12

(6) Display your transistor's transfer characteristics and adjust the controls as needed to get a nice display. ACCURATELY record the characteristics in Table 11.2. The curve will be a set of points rather than a continuous curve. Pay particular attention to the horizontal (V_P) and vertical (I_{DSS}) axis intercepts.

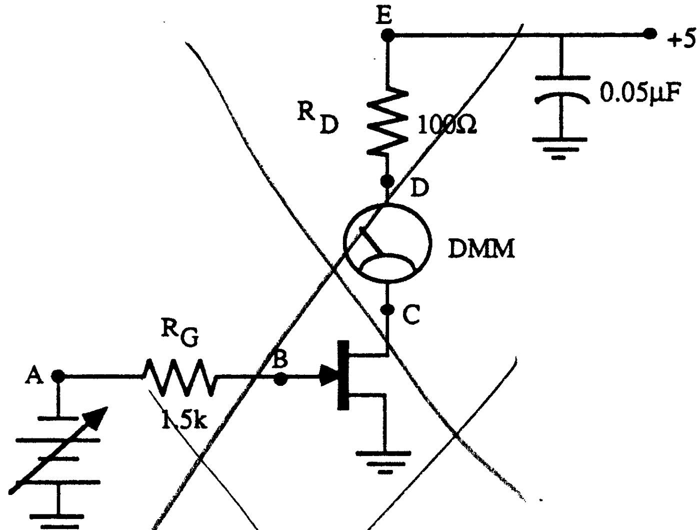


Figure 1 - Circuit for characterizing FETs

(7) Build the circuit shown in Fig.1.
(8) Adjust the variable supply so that the DMM reads approximately 1 μA.
(9) Remove the DMM and use it to measure V_{GS}, which is very nearly V_P. Record your results in Table 11.3
(10) Put back the ammeter (DMM), remove the variable supply, and ground point A.
(11) Record I_D, which is I_{DSS}. The current may slowly decrease due to heating of the transistor, so take your reading quickly. Record your results in Table 11.3.

FETs are commonly used as current sources for circuits found on IC's. Consider the FET current source shown in Figure 2.

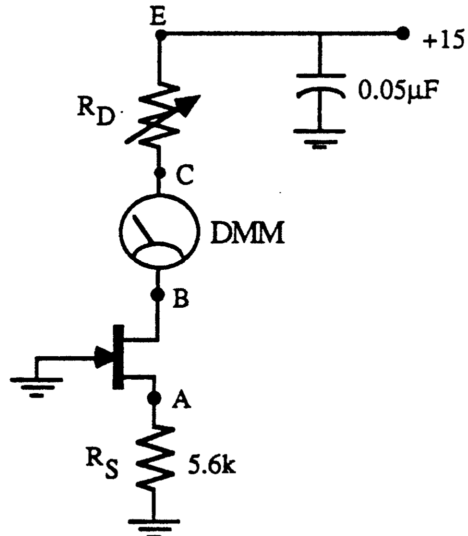


Figure 2A. FET current source

(1) Build the circuit of Figure 2A. Use your RSB for R_D.
(2) Measure I_D for R_D values of 10k, 20k, 30k, 40k and 50k. Record your measurements in Table 11.4.
(3) The constant current should break down when V_{DS} is near $-V_P$. Take additional data near this breakdown point. Record your data in Table 11.4.

Part 2 - AC Characteristics

The value of g_m for the FET is much more variable than β_o was for the BJT. The gain of an FET amplifier is very dependent on its operating point. Follow these steps to characterize the AC operation of your transistor. You should notice if the CH2 waveform ever becomes distorted.

(1) Build the circuit shown in Fig.2B. Connect scope CH1 to point A and CH2 to point C. Adjust the generator to produce a 100 mV_{p-p} 1 kHz triangle wave at point A.
(2) Adjust the generator's DC offset so that point A is at approximately +1.0 V DC.
(3) Use the scope to measure the AC_{p-p} voltage at point C. Record your data in Table 11.5.
(4) Repeat steps 2 and 3 using +0.5 V, 0.0 V, -0.5 V, -1.0 V, -1.5 V, etc. in step 2 until you reach your transistor's V_P.
(5) Set the generator's DC offset so that point A is at +1.0 V DC. Use the DMM to measure the DC voltage at point B. Record your result in Table 11.5.

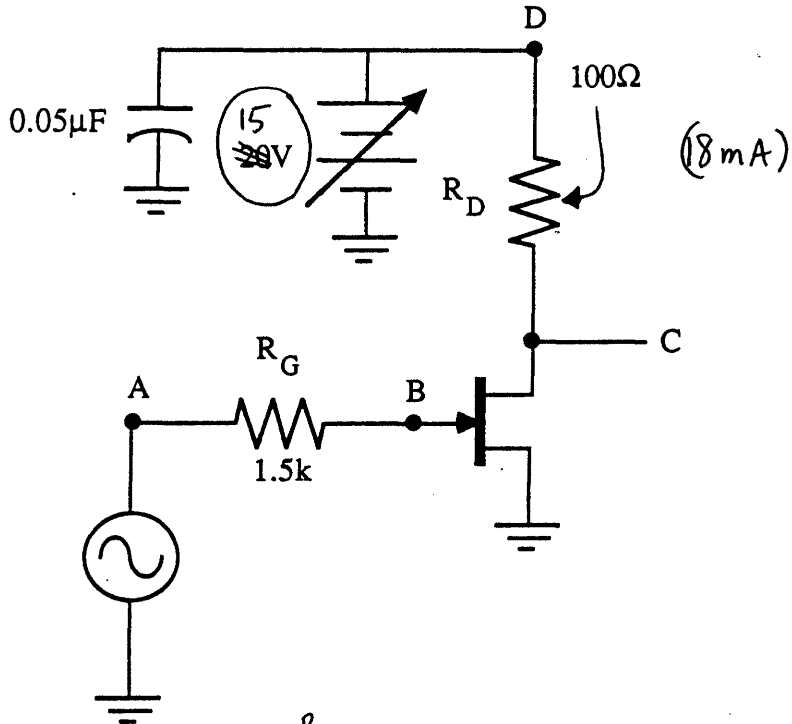


Figure 2 - FET amplifier

The FET can be used in the common gate, common source mode, or common drain just as a BJT can operate in the common base, common emitter or common collector modes. The common source amplifier configuration of Figure 2 is usually used for voltage amplifiers; however, when impedance matching or high output power is a consideration the source follower (also called the common drain) configuration is usually employed.

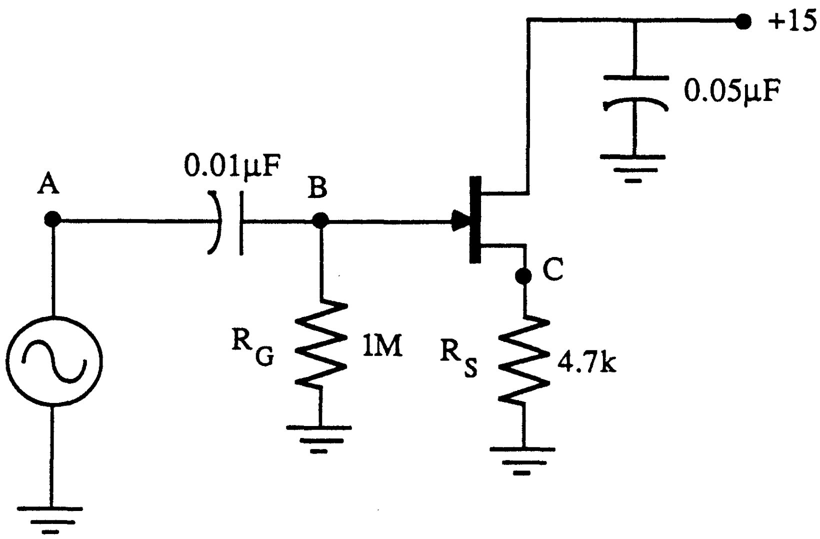


Figure 3 - Source follower

(1) Build the circuit shown in Fig.3. Connect the scope CH1 input to point A and CH2 input to point C. Use your DMM to measure the DC potentials at points A and C. Record these values in Table 11.6.

(2) Adjust the generator to produce a 100 mV_{p-p} 1 kHz triangle wave at point A.

(3) Use the scope to measure the AC_{p-p} voltage at point C. Record your data in Table 11.6.

(4) Repeat steps 2 and 3 using 200mV, 400 mV, etc. in step 2 until your signal begins to distort.

(5) Connect a 1000 ohm resistor between point C and ground. Repeat steps (2) and (3).

The performance of many FET amplifiers can be improved by using current biasing. Modify your circuit to that of Figure 4 which is a source follower with a current source load.

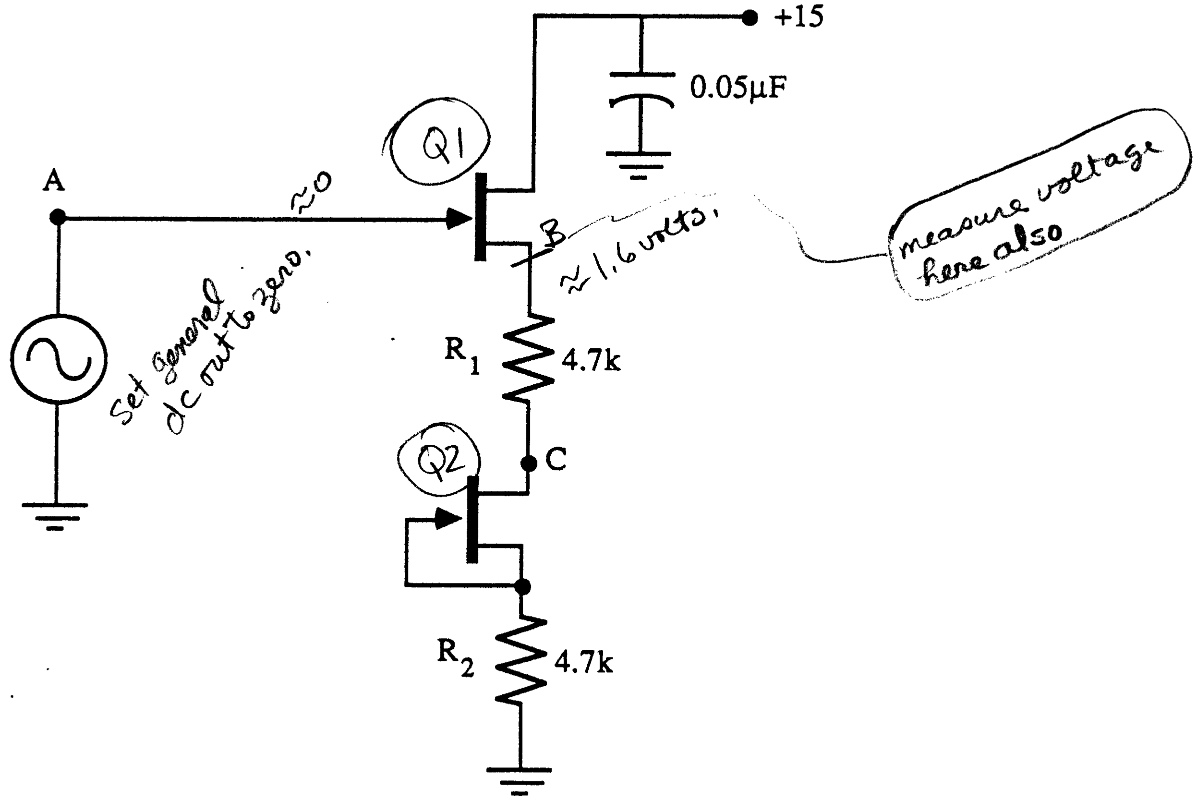


Figure 4 - Source follower with common source load

(1) Build the circuit shown in Fig.4. Connect the scope CH1 input to point A and CH2 input to point C. Measure the DC voltages at points A and C. Record your measurements in Table 11.7.

(2) Interchange your FETs. Remeasure the DC voltages at points A and C. Record your results in Table 11.7.

(3) Adjust the generator to produce a 100 mV_{p-p} 1 kHz triangle wave at point A.

(4) Use the scope to measure the AC_{p-p} voltage at point C. Record your data in Table 11.7.

(5) Repeat steps 2 and 3 using 1V, 1.5V, etc. in step 2 until your signal distorts.

(6) Connect a 1000 ohm resistor between point C and ground. Repeat steps (2) and (3).

PLEASE CALL A TEACHING ASSISTANT TO CHECK YOUR DATA BEFORE CONTINUING.

Questions:

1. (a) What values of I_{DSS} and V_P were indicated by the curve tracer?
   (b) [redacted]
   (c) What are the values for I_{DSS} and V_P on the data sheet?
   (d) What is your most accurate estimate of each parameter? Why?

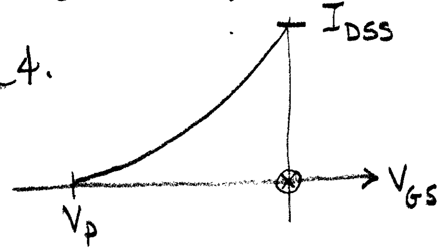
2. You recorded your transistor's drain characteristics using the curve tracer. The slopes of these characteristics in the saturation region are not zero, indicating the presence of an FET parameter called g_d.
   (a) Use your knowledge of the BJT model to draw a FET small signal model which includes g_d. Write an equation for g_d.
   (b) Calculate the value of g_d for each of your curves.
   (c) Compare g_d at $V_{GS} = 0$ to the data sheet value of g_{os}.

$\frac{1}{g_d} = \frac{\Delta I_D}{\Delta V_{GS}}$ using a linear approximation

3. (a) Use your data of Table 11.5 to make a graph of g_m vs V_{GS}.
   (b) Use your drain characteristics from Part 1 to make a similar graph of g_m vs V_{GS}.
   (c) Compare g_m at $V_{GS} = 0$ to the data sheet value of g_{fs}.
   (d) What was unusual about the voltage at B when you used +1.0 V? Why?

~~4. No question about Figure 4.~~

$g_m = \frac{\Delta I_D}{\Delta V_{GS}}$



~125μ℧

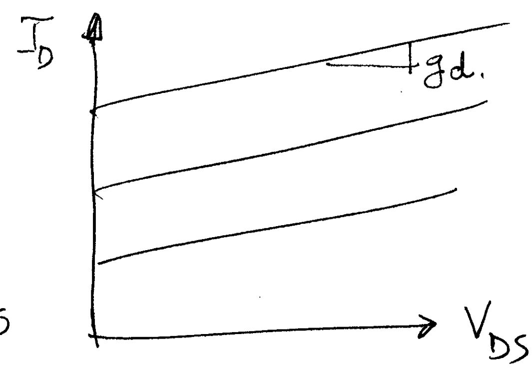
≈ 8kΩ

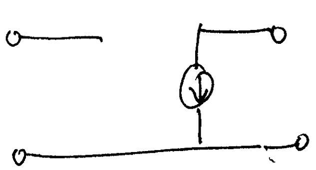
Hint: what was your relationship with V_p?

$g_{fs} \triangleq \frac{\Delta I_D}{\Delta V_{GS}}$ ← small-signal transconductance with common source amp.

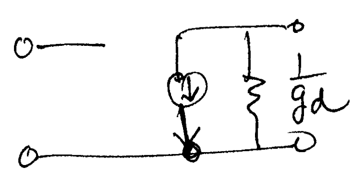
$g_{fso} = g_{fs}|_{V_{GS}=0}$.

4. Need question about Figure 4.

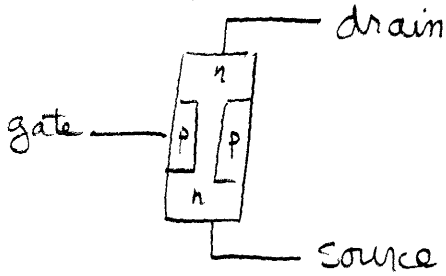


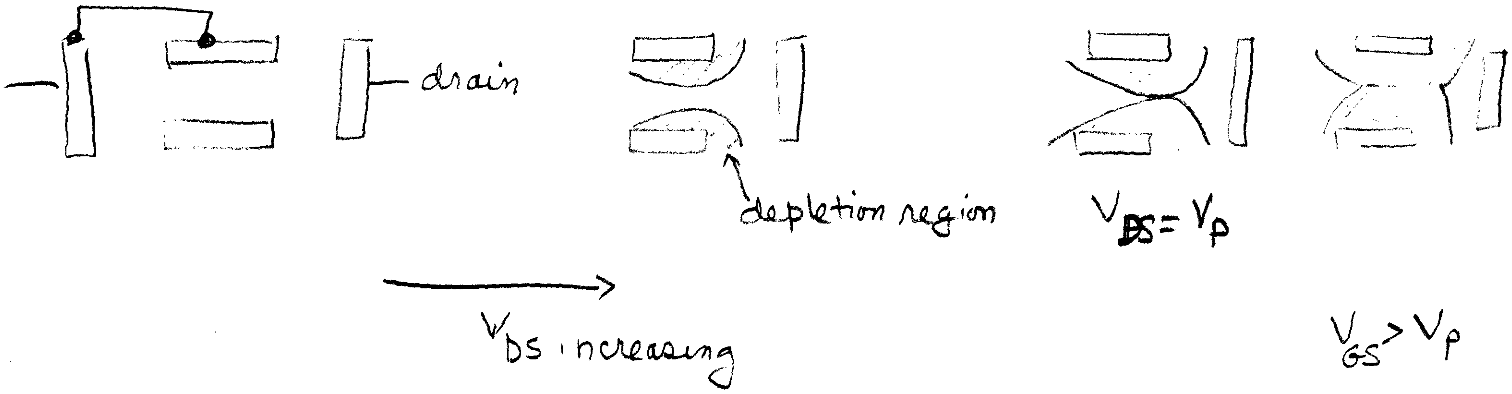


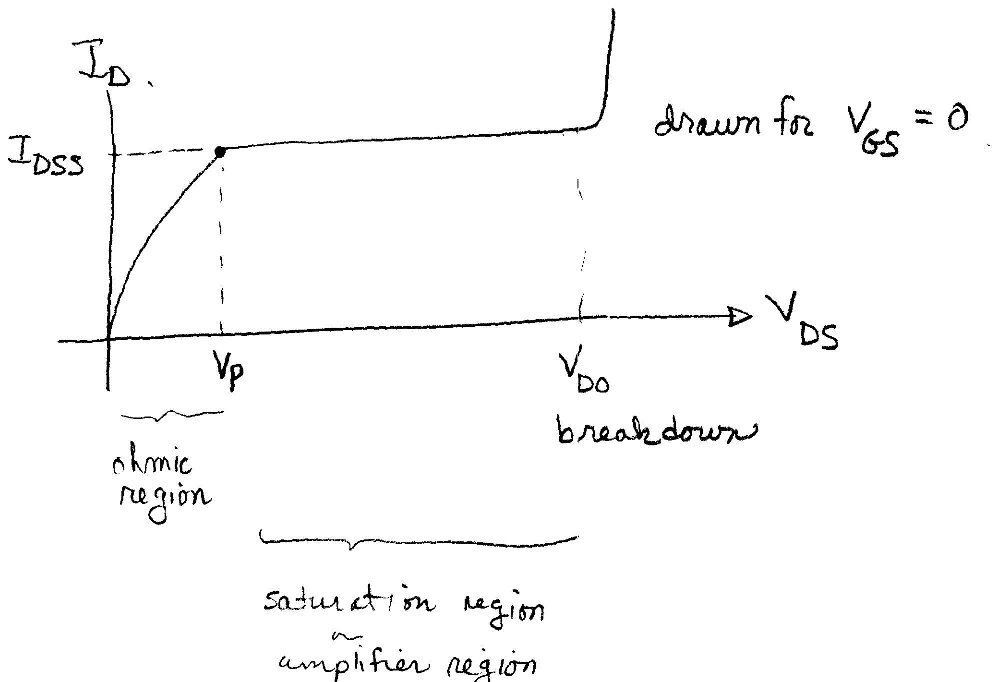
$\frac{1}{r_d} = \text{slope} = \frac{\Delta I_D}{\Delta V_{DS}}$



basic FET characteristic







$$I_D = I_{DSS}\left(1 + \frac{V_{GS}}{V_p}\right)^2$$

$$g_m = \frac{2 I_{DSS}}{V_p}$$

V_p & g_{mo} measured at $V_{GS} = 0$.

small signal model.

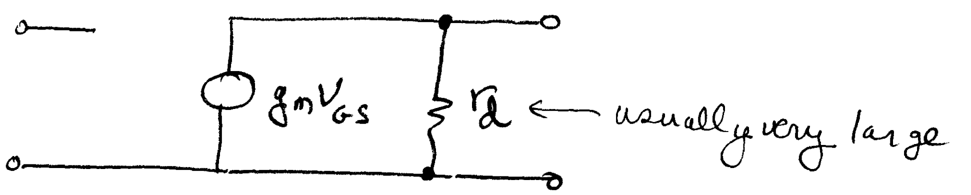
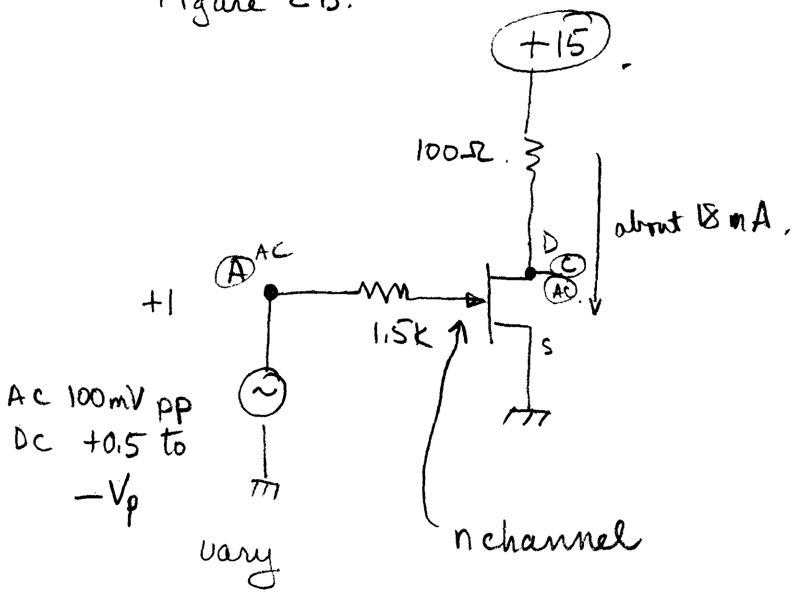
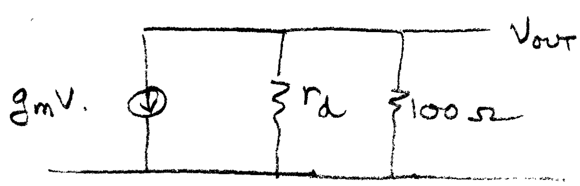


Figure 2B.

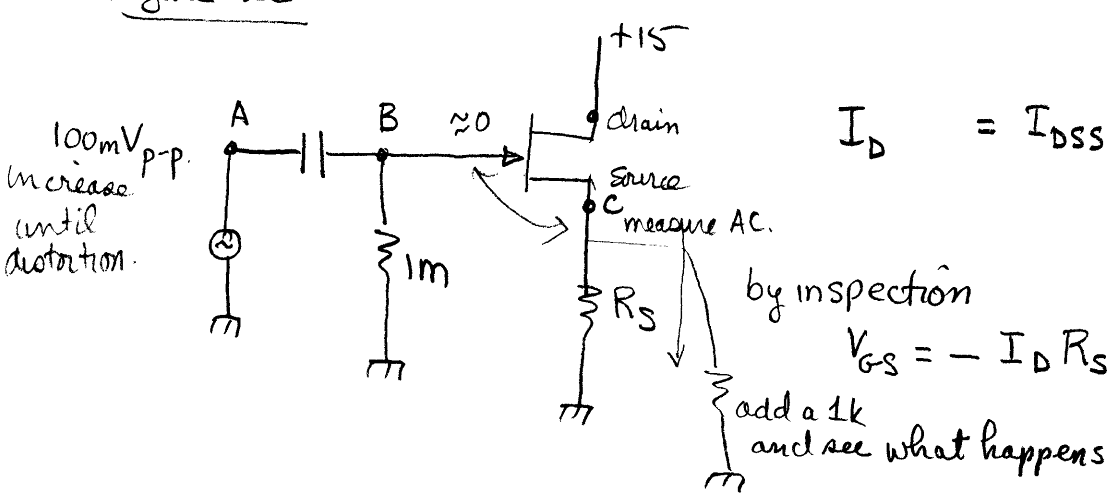




$$V_{out} = -(g_m V_{GS})(100\Omega)$$

$$\frac{V_{out}}{V_{in}} = -g_m R_L$$

Figure 2c



$$I_D = I_{DSS}\left(1 + \frac{V_{GS}}{V_P}\right)^2$$

by inspection

$$V_{GS} = -I_D R_S$$

EEAP 243 LAB 11 EVALUATION

NAME (print)____________________________ CHECKPOINT #1 ___ DATE _____
GRADE _____/_____ CHECKPOINT #2 ___ DATE _____

With respect to the course material, this lab was: (pick one)
___ highly relevant ___ relevant ___ not relevant ___ completely irrelevant

This lab was: (pick one)
___ too long ___ long ___ just right ___ short ___ too short

This lab was: (pick one)
___ too hard ___ hard ___ just right ___ easy ___ too easy

The background material in the lab assignment was: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

The step by step procedures in the lab assignment were: (pick one)
___ too detailed ___ just right ___ sufficient ___ insufficient ___ totally inadequate

Describe any mistakes made in the lab assignment.

Describe anything that just didn't work right.

Describe how this lab could be made better.

QUIZ

NOTE: THE TEACHING ASSISTANT IS TO SELECT BOTH QUESTIONS FROM THE UNDERLINED OPTIONS AT THE SECOND CHECKPOINT

Question #1

What will be the gain (don't forget the sign) from point A to point B in Fig. 11.2 if we halve/double the resistance of $R_1/R_2/R_3$?

The gain will be __________.

Question #2

What will be the gain (don't forget the sign) from point A to point B in Fig. 11.4 if we halve/double the resistance of $R_1/R_2/R_3$?

The gain will be __________.

EEAP 243

NAMES: ____

Lab 11 Data

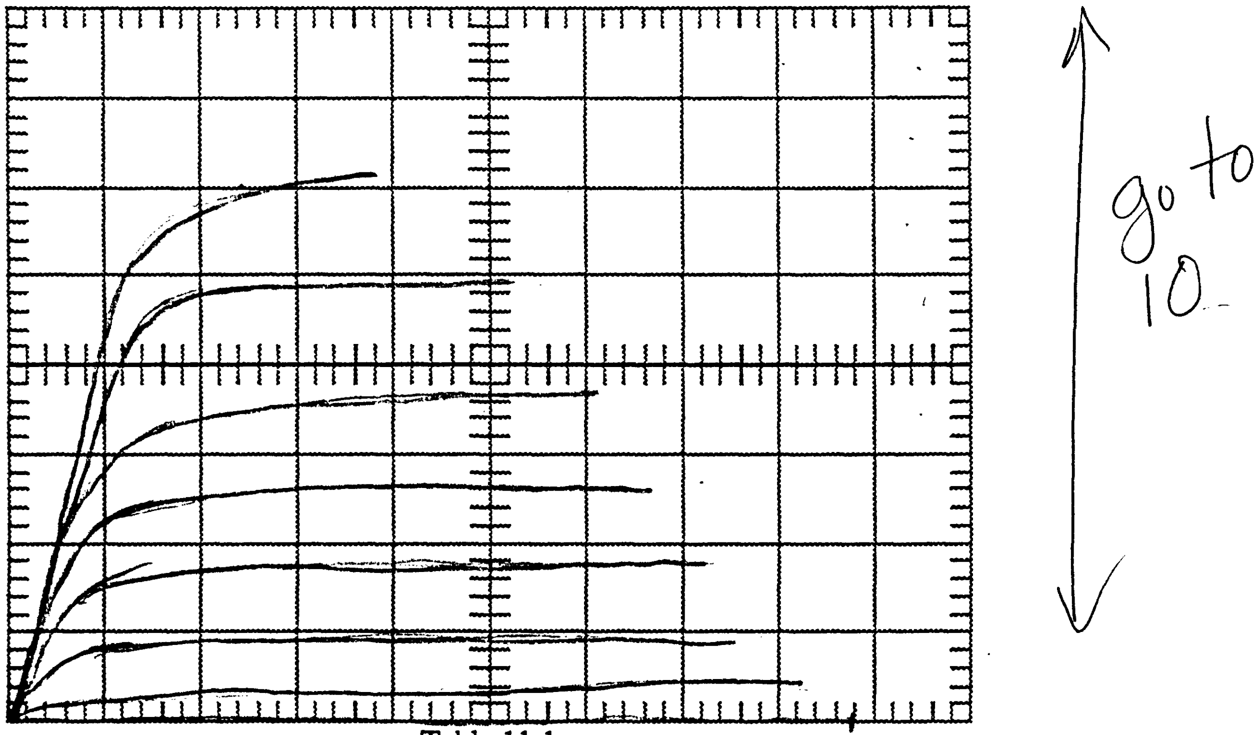


Table 11.1

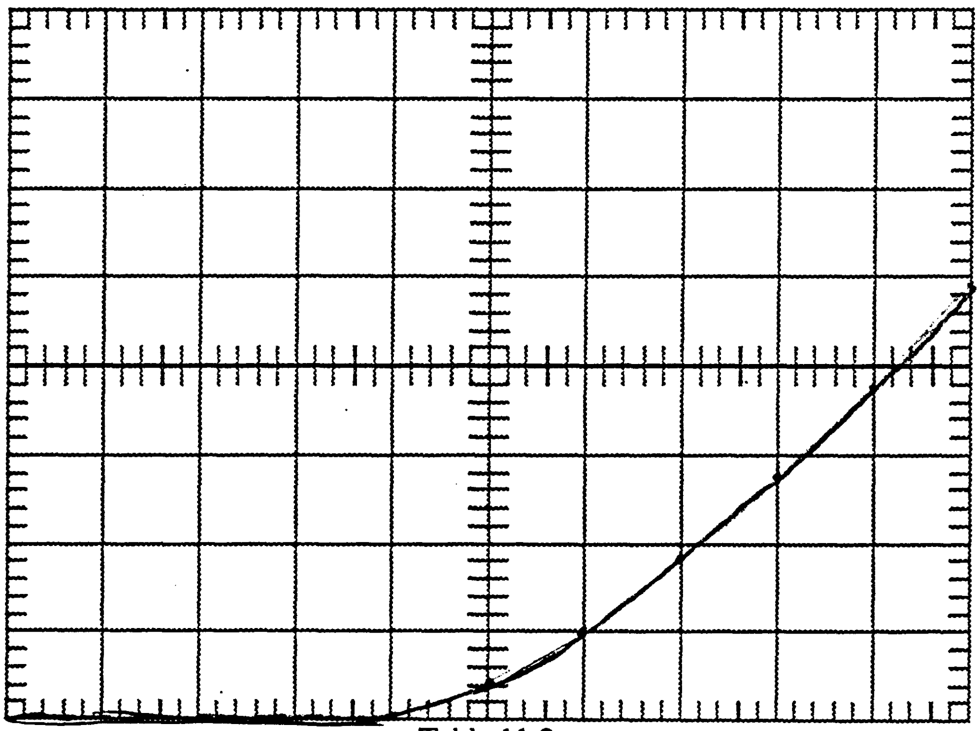


Table 11.2

Difficult to keep at 1μA

V_{GS}: -3.55 v I_D: -1.0 μA

Table 11.3 DC FET characteristics

I_{DSS} = -11.11 mA.

R_D	I_D mA	
10k	~~[illegible]~~	0.529
20k	~~[illegible]~~	0.513
30k	~~[illegible]~~	0.415
40k	~~[illegible]~~	0.332
50k	~~[illegible]~~	0.267
9k		0.530
60k		0.272
70k		0.249
+1.0	1.4x50 mV	→ $V_B = 0.696$ v

Table 11.4 FET current source characteristics

V @ A	Output Voltage (p-p)
+0.5	1.3x50 mV
+0.0	1.0x50 mV
-0.5	1.0x50 mV
-1.0	0.9
-1.5	0.8
-2.0	0.7
-2.5	0.6
-3.0	0.44
-3.5	1.1x5 mV
-4.0	~~~~
-4.5	~~~~
-5.0	~~~~
DC V_{GS}:	~~~~

Table 11.5 AC FET characteristics

V_{GATE}: 0.0 V.

V_{SOURCE}: 2.99 V (≈3.0 V)

$V_{input,p-p}$	$R_L=\infty$ $V_{output,p-p}$	$R_L=1k$ $V_{output,p-p}$
100mV	100 mV	1.45×20
200mV	200 mV	145 mV
400mV	360	300 mV
800mV	3.8×0.2	500 mV
1.2V	2.1×0.5	
1.4V	≥1.35	
1.6V	≥1.35	
1.8V	1.7	
2.0V	~1.8	

Table 11.6 Source Follower characteristics

o/p flatten at bottom after 8V

o/p distort after 3.6×2=7.2 V

	Original	Reversed
V_{GATE}:	6.9mV	6.9 mV
V_{SOURCE}:	1.621 v	1.523 v

$V_{input,p-p}$	$R_L=\infty$ $V_{output,p-p}$	$R_L=1k$ $V_{output,p-p}$
100mV	50 mV	0.3×50mV
1.0V	0.5 V	0.3×0.5
1.5V	0.75	0.3×0.5
2.0V	1.0	0.3 v
2.5V	1.25	0.3×
3.0V	1.5	0.3×

Table 11.7 Source Follower characteristics

signal distorts after 7.0V

o/p. distortion after 7.2 V

EEAP 243

NAMES: ____

Lab 11 Data

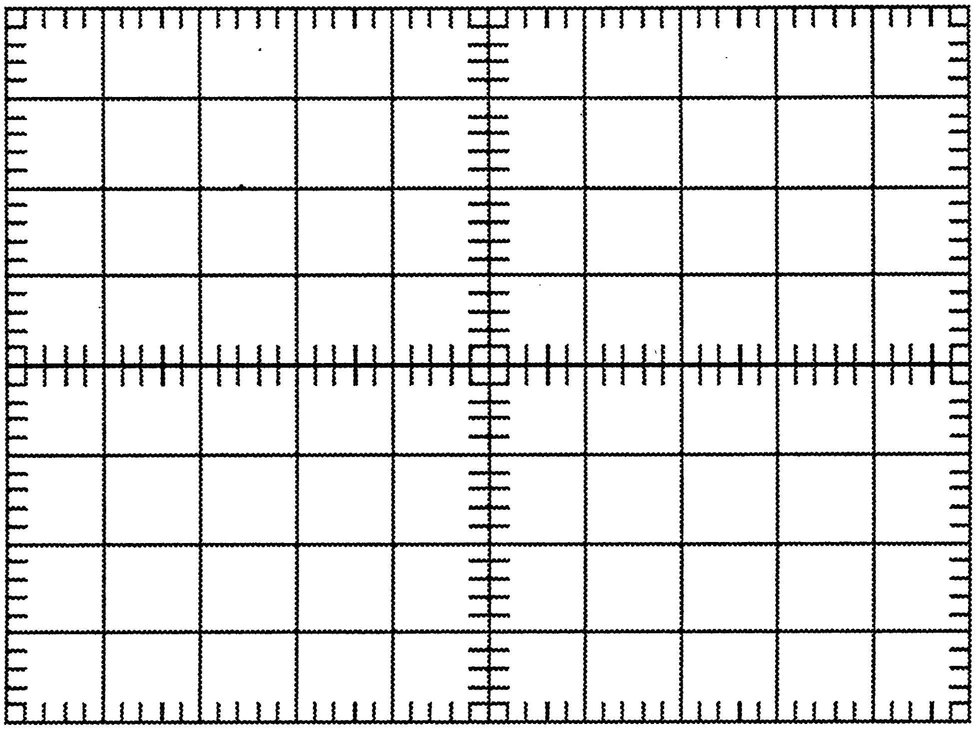


Table 11.1

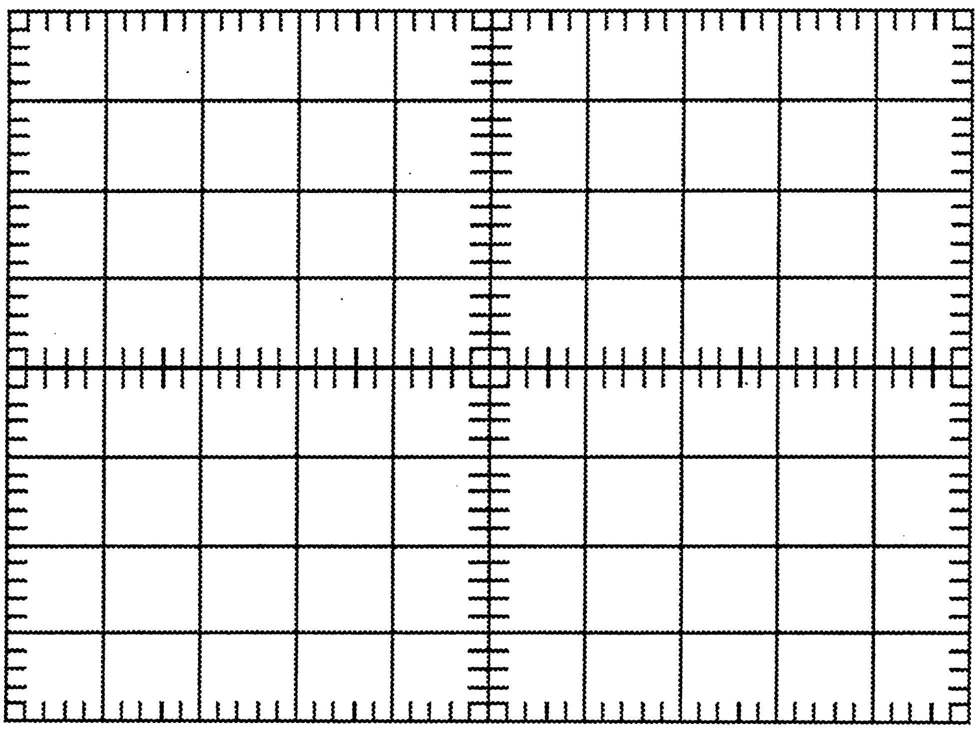


Table 11.2

V_{GS}: ____________ I_D: ____________

Table 11.3 DC FET characteristics

R_D	I_D
10k	____________
20k	____________
30k	____________
40k	____________
50k	____________
_______	____________
_______	____________
_______	____________
_______	____________
_______	____________

Table 11.4 FET current source characteristics

V @ A	Output Voltage (p-p)
+0.5	____________
+0.0	____________
-0.5	____________
-1.0	____________
-1.5	____________
-2.0	____________
-2.5	____________
-3.0	____________
-3.5	____________
-4.0	____________
-4.5	____________
-5.0	____________
DC V_{GS}:	____________

Table 11.5 AC FET characteristics

V_{GATE}: ________

V_{SOURCE}: ________

$V_{input,p-p}$	$R_L=\infty$ $V_{output,p-p}$	$R_L=1k$ $V_{output,p-p}$
100mV	________	________
200mV	________	________
400mV	________	________
800mV	________	________
1.2V	________	________
1.4V	________	________
1.6V	________	________
1.8V	________	________
2.0V	________	________

Table 11.6 Source Follower characteristics

	Original	Reversed
V_{GATE}:	________	________
V_{SOURCE}:	________	________

$V_{input,p-p}$	$R_L=\infty$ $V_{output,p-p}$	$R_L=1k$ $V_{output,p-p}$
100mV	________	________
1.0V	________	________
1.5V	________	________
2.0V	________	________
2.5V	________	________
3.0V	________	________

Table 11.7 Source Follower characteristics