Physics 115

Electronics and Instrumentation

Laboratory Manual

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Introduction

Electronics are a part of every modern laboratory. Physics, chemistry, biology, and geology all utilize electronic devices to measure and record various phenomena. Whether you need to measure temperature, light intensity, magnetic fields, humidity, charged particles, time, or strain, all can be measured using readily available transducers.

The goal of this course is not to turn you into an electronics whiz. Rather, it is a survey course that will introduce you to the broad range of electronic devices and techniques that are commonly used in laboratories today. While we will spend some time on historical and fundamental devices, such as transistors and A/D chips, we will focus most of our attention on practical and useful devices: op amps, computer-integrated data acquisition cards, and specialized integrated circuits (ICs). Our goal is to instill in you a degree of comfort and familiarity with electronics that will be useful in designing experiments, building simple circuits, and understanding the behavior of complex circuits. By the end of the semester you should be comfortable in developing computer-controlled data systems where you have conditioned the signal of interest using your newfound electronic skills and collect the data on the computer using the LabVIEW software package.

I have chosen not to include much theory in this manual. First of all, all of the information would be repetitious because the same information will be in your textbook and/or lecture notes. Second of all, I've tried to prevent this manual from being a self-contained cookbook. Forcing you to use your notes and textbook will, in the end, make you more self-reliant.

Some experiments will take a single session, others will take two. They are, however, all equally weighted.

Because the LabVIEW software package is commonly encountered in research and industrial laboratories, there is a recommended text in the bookstore that teaches the details of it. We also have a couple of copies of the LabVIEW text in the lab to use.

This manual will also likely serve as a reference for future classwork, particularly in Physics 116, Advanced Electronics and Instrumentation. I suggest that if you are planning on taking this course, you hold onto this book.

This is the sixth edition of this manual; it is mainly for correcting some errors and restructuring some experiments. It is only available electronically; it is not for sale in the bookstore.

Safety

In general, the electronics that one encounters in this class are no more dangerous than those one may encounter upon replacing a 9-V battery in a household electronic device; most electronics textbooks do not even discuss safety hazards. In fact, the biggest risk to ones health in this class is mechanical rather than electrical: dropping an instrument or computer on your foot.

However, one must still be careful to avoid exceeding tolerances on all devices. Over-powered resistors can get very hot very fast and can leave a blister on one's fingers if touched. Transistors are famous for "popping" when improperly wired. The shrapnel from one could scratch the cornea of your eye; an experience that your contact lens wearing friends will assure you does not feel good. While we don't normally solder in this class, if you find that you need to, make sure you use a pair of safety glasses Soldering flux or molten solder would be very unpleasant in an eye (as Dr. DeGraffenreid can attest to).

However, one should not take a cavalier attitude towards electronics. There are many cases one will encounter in the laboratory where high voltages are a part of the experiment. Care needs to be taken in such a case; a current of a few milliamperes through your heart can cause severe problems. If you find yourself working on high voltages, it is a good practice to have your arm grounded so that if you touch the high voltage with your hand, the current won't cross through your body.

In fact, it is a good practice to use grounding straps at all times when working with electronics. This is not necessary for your own safety, but rather for the safety of the devices you are working with; static discharge can be deadly for many semiconductor devices. Unfortunately, we don't have grounding straps to go around. Luckily, we use generally inexpensive components. If you find yourself using high-end components in your final project, please ask about borrowing a grounding strip to use.

Measurement Instruments

<u>Multimeters</u>

We will normally use benchtop digital multimeters (DMM) in this course, although we do have some analog and handheld digital multimeters available if needed. The theory behind multimeters, particularly analog meters is very interesting but, unfortunately, we don't have time to cover it in this course. If you are interested in finding out more information regarding them, refer to your textbook. There are two models of benchtop Keithley multimeters that we will commonly use in the lab: the Model 2000 and the Model 179(A). The Keithley Model 2000 will be our primary instrument, but for measurements we will also need to use the 179(A). The Tektronix Model #2236 Oscilloscope also has a built in multimeter that we might occasionally use for DC voltage measurements.

The specifications of the primary meters are listed below:

		Model 2000	Model 179A
	Digits	6 ½	4 ½
RANGE	DCV	0.1 μV – 1 kV	10 μV – 1.2 kV
	ACV	0.1 μV – 750 V	10 μV – 1.0 kV
	DCA	10 nA – 3 A	10 nA – 20 A
	ACA	1 μA – 3 A	10 nA – 20 A
	Ω	100 μΩ – 120 MΩ	100 mΩ – 20 MΩ
	Frequency	3 Hz – 500 kHz	– NA –
Input Impedance	DC	10 GΩ	1 MΩ
	AC	1 MΩ	1 MΩ

Clearly the Model 2000 is a more precise instrument. It can also be computer interfaced via GPIB if desired. Its main drawback is its complexity. For most purposes 6 ½ digits is overkill and just slows down the refresh rate. From the front panel you can decrease the number of digits displayed. The Model 2000 can only measure currents up to 3 amperes, whereas the Model 179A can go up to 20 amperes. This isn't usually a concern in this course where we usually work with currents less than 1 ampere. Several copies of the Model 2000 user's manual are available for review and it is also available in pdf format on the Electronics Laboratory Resource Page.

Our analog multimeters are the Triplett 630-NS. The Tripplett meters can be used to measure AC and DC voltages and DC currents. While the controls for the Tripplett meters indicate resistance can be measured, we no longer keep batteries in these meters that are required to power the resistance measurements. When you make connections, you should use the V·Ω·A and "common" inputs (unless you are measuring currents higher than 1.2 A, in which case you use the 12A input and the common).

Oscilloscope

The most widely used instrument in the lab is probably the oscilloscope. In this lab, we will be using the Tektronix Model 2236. This is a fairly advanced analog "scope" with a number of useful features, including a built in period/frequency readout. We also have a classroom set of Tektronix Model TDS1002 scopes and two "high end" scopes: the TDS 3044B and the DPO 4054. These will only be used sporadically in 115; while the digital scopes are have somewhat more power and flexibility, they can also be misleading if you are not familiar with the basics of making measurements with an analog scope. User manuals for all digital scopes are available on the Electronics Laboratory Resource Page.

While the exact operation of oscilloscopes varies widely, the most important elements of the front end are basically unchanged. While your textbook has a brief section describing the operation and use of oscilloscopes, I would also like to refer you to "The XYZ's of Oscilloscopes," published by Tektronix (one of the leading oscilloscope manufacturers). There are several copies of this available for use in the classroom and is also available in pdf format on the Electronics Laboratory Resource Page. I suggest that you read this manual before using the oscilloscope.

Workstations

ELVIS Lives! The most common tool in 115 is the National Instruments ELVIS workstation. These workstations integrate a breadboard (prototyping board), power supplies, waveform generators, and computer interface into a single package. These features can be controlled via the workstation's front panel or by software on the computers; we will generally use the front panel. See the Electronics Laboratory Resource Page for the ELVIS User's Guide.

Breadboards

The most convenient way to design and troubleshoot a new circuit is to first design it on a "breadboard". Breadboards can be of the stand-alone variety, have built in power supplies (we have a large collection of these that might be useful for your projects), or may be bundled with additional stuff for easy access (like our ELVIS stations and the Protoboards that preceded them). All are handy because circuits can be wired up without the use of soldering irons, or wire wrapping tools. Be careful not to use wires that are too thick for the board. Forcing oversized wire into the board may permanently bend the spring contacts: leading to poor connections, no connections, or even possible short circuits to other rows.

We will discuss how to use the board in class.

Power Supplies

We will generally use the built-in power supplies that are on the ELVIS workstation or on the powered breadboards. So far, these supplies have proven to be rather stable sources of DC power. The ELVIS workstations have five supplies built into it: +5 V, +15 V, -15 V, and variable positive and negative voltages. The powered breadboards have +5 V, +15 V, and -15 V sources. Additionally we have other fixed and variable sources available if needed.

Function Generators

We will use Tektronix AFG3022 Arbitrary Waveform Generators to produce the AC signals that we will use in this course. These generators will be shared between adjacent groups, as they have dual outputs that can be independently controlled. It can produce sinusoidal, square, triangle, and many other signals with frequencies up to 25 MHz. It can be programmed to produce a certain signal without turning the signal on. It has the capability of producing user-defined waveforms also.

We have a couple of high performance Agilent 33120 waveform generators that can produce signals up to 15 MHz. These instruments can do the traditional sinusoidal, square, and triangle-waves, but can also do sawtooth, cardiac, exponential decay, and user defined waveforms.

The ELVIS also has a built in function generator, that is useful for "low frequency" applications. It is limited to less than 30 kHz signals and should not be used as a primary source.

We also have a classroom set of WaveTek function generators. The WaveTek produces frequencies from < 1 Hz to 2 MHz. DC offset voltages may be applied to all of the previously listed waveforms. The square-wave also has a variable duty cycle. The WaveTek also has a TTL output jack for digital timing purposes.

Lab I: Basic DC Circuits

Introduction

This set of experiments will introduce you to some basic DC circuits and give the chance to get some experience using the meters and the breadboards.

Procedure

1. Measure the internal resistance R_m of an analog ammeter.

    a. Build the following circuit:
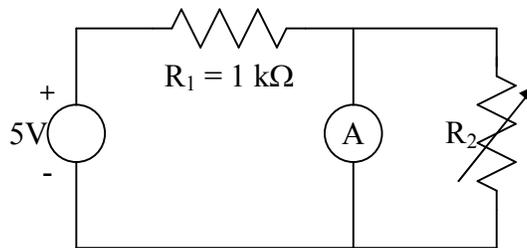
       R_2 is a "decade resistance box"; select one that has a resolution of $0.1\ \Omega$ or less. Set the initial resistance of the box to its largest value.

    b. Measure the ammeter current.

    c. Reduce R_2 until the ammeter current drops to one half the initial value. The ammeter resistance now equals R_m.

    d. In the write up, indicate the internal resistance R_m and prove why this method works.

2. Measure the series resistance R_S of a 9-V battery.

    a. Build the following circuit, using the same decade box as above:
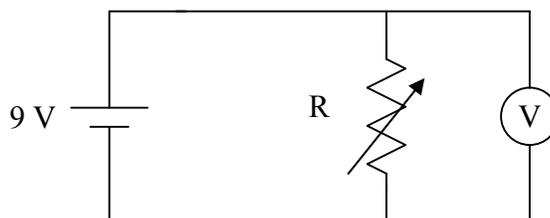
b. Start with the decade box at "near infinite" resistance. Measure the voltage on the DMM.

c. Decrease resistance until the DMM reading falls by one half. The value of the resistance at this level is R_S.

d. Report the battery's internal resistance and prove why this method works.


3. Measure resistance of a lamp.

a. Measure the resistance of a lamp directly using the DMM.

b. Build the circuit below to measure the resistance of a lamp, using ELVIS's positive variable supply as the voltage source.
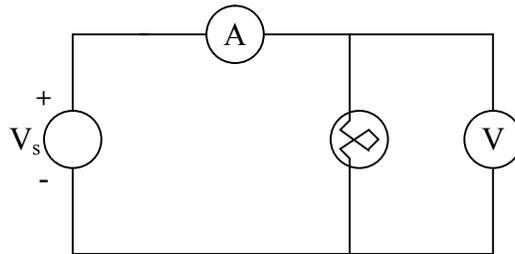
c. Measure the V-I characteristics of the lamp. Do not exceed 12 V on the lamp. The lamp should not be left on at voltages above 6 V for an extended time.

d. Will a lamp work as a resistor in a pinch? Plot the I-V characteristics and compare to an ideal resistor. Discuss your thoughts of the behavior in the write up.

4. Voltage Dividers

a. **_Design_** a circuit with the following form.
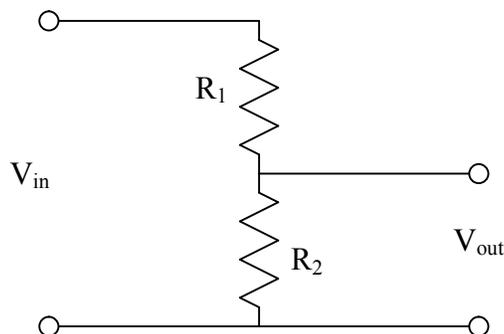
Select R_1 and R_2 so that they add to ~5 kΩ (within 10%) and the gain of the circuit is 0.33 (also within 10%). You may have to combine resistors to get a system that meets these requirements.

b. Build your design. Does it work as you expect?

c. Design and build a variable –5 to +5 V supply using two 9-V batteries and a 1 kΩ potentiometer. Hint: Other components may be required.

d. Show me your working circuit.

Lab II: Basic AC Circuits

Introduction

The purpose of this experiment is to introduce you to some simple AC circuits. These circuits are commonly used to condition electronic signals. Examples of conditioning include integrating, differentiating, and filtering signals.

Procedure

1. Comparison of Amplitudes

   a. Connect a 100 kΩ resistor across the waveform generator's (Tektronix or Agilent) output.

   b. Using the oscilloscope to measure the output waveform, set the generator to a ~1 kHz sine-wave (with no DC Offset), with a peak-to-peak voltage of 1 V.

   c. Measure the rms voltage with the DMM. Does this value make sense? Why or why not?

   d. Repeat with triangle- and square-waves. Do these values of the V_{rms} make sense? Why or why not?

   e. Replace the Tektronix generator with a WaveTek. Examine the waveforms again. How do the generators compare to each other? Which would you prefer to use in class and why?

2. Charging of a capacitor.

   a. Build the following circuit, using your Tektronix or Agilent generator:
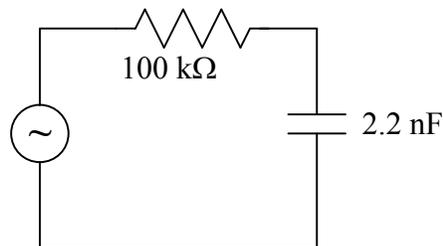
   b. Set the generator to a ~ 400 Hz square-wave and adjust the amplitude and DC offset so that the output varies from 0 V to 1.5 V.

c. Measure the voltage across the capacitor C using the oscilloscope. Setup the oscilloscope to display both the input and output waveforms "simultaneously."

d. Using only the waveforms, determine the time constant τ (the time it takes for the voltage to drop to 1/e the initial value) for the circuit. How does this compare the theoretical value for the given circuit elements?

3. Integrator Circuit

   a. Build the following circuit with a square-wave driving signal.
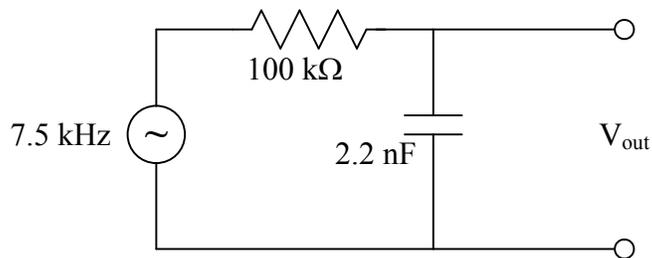
   100 kΩ

   7.5 kHz

   2.2 nF

   V_{out}

   b. Record (i.e. sketch in your notebook) the input and output waveforms. Does the output make sense? Does it vary from the expected value?

   c. Instead of a square-wave, try using sine- and triangle-waves. Does this circuit "integrate" properly? (Note: you may have to get clever with the oscilloscope to do this.)

4. Differentiator Circuit

   a. Build the following circuit with a square-wave driving signal.
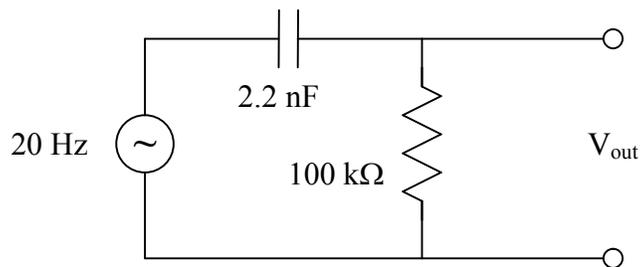
   2.2 nF

   20 Hz

   100 kΩ

   V_{out}

b. Record (i.e. sketch in your notebook) the input and output waveforms. Does the output make sense? Does this vary at all from the expected value?

c. Instead of a square-wave, try using sine- and triangle-waves. Does this circuit "differentiate" properly?

5. Build the following three circuits. Build the circuits so that the cutoff point is in the neighborhood of 75 kHz. For each circuit, measure the gain over the range 50 Hz – 2 MHz. Choose your steps carefully: fine enough to show details, but coarse enough that you finish in reasonable time. In the write-up, do a detailed comparison of the gain curve that you measured to theory. Note the general trend of any phase shifts that you observe.

a. High Pass:

V_{in}

V_{out}

b. Low Pass:

V_{in}

V_{out}
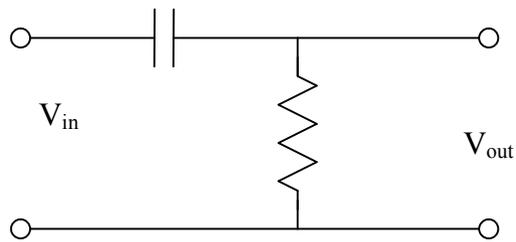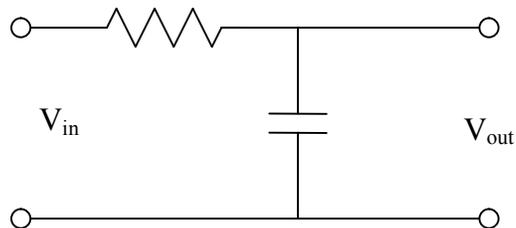
c. High Emphasize (use same values of C and R as in above):

V_{in}

V_{out}
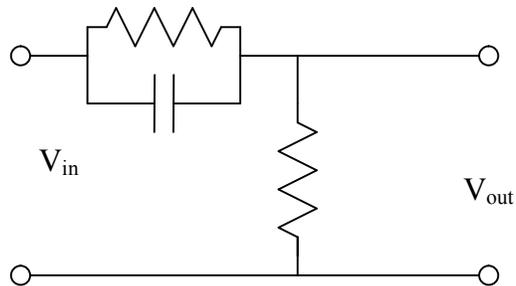
6. Build the LRC circuit below. Measure the transfer function of this filter. What is the FWHM bandwidth of the transfer function?

V_{in}
270 Ω
1 µF
0.1 mH
V_{out}
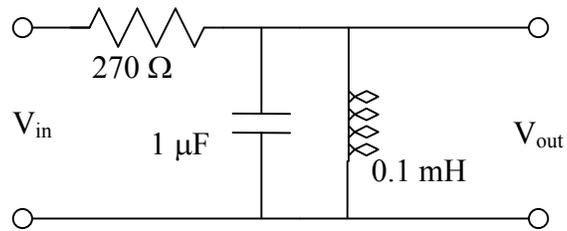
7. For the circuit in part 6 replace the resistor with one that is an order of magnitude higher. Measure the characteristic curve. How does the response (i.e. central frequency, bandwidth, transmission maximum) change?

8. The following circuit is called a notch filter. Measure its characteristics. In your write-up describe a situation where this might be useful.

V_{in}
56 Ω
0.1 µF
0.1 mH
V_{out}
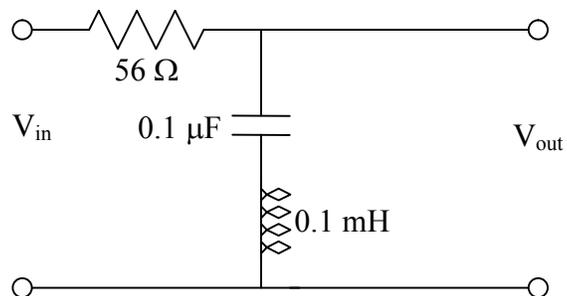
Lab III: Diodes

Introduction

In this lab, you will characterize several varieties of diodes and build some basic and useful diode circuits.

Procedure

1. Measure the I-V characteristics of a 1N914 diode. Use the following circuit to measure the voltage. Pick a resistor of high power tolerance so that it does not burn up. You should be able to use ELVIS's positive variable power supply for the source voltage.
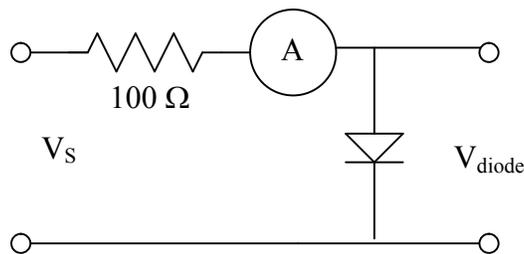

   For the negative bias case, use the ELVIS's negative variable voltage as the source. Keep "an eye" on the resistor to make sure that you don't overload it. Plot your results for your write-up (I as a function of V). Prepare a second plot focusing on the region where the curve changes the most. What is the diode voltage drop in the forward direction? Estimate the forward and reverse resistances from this plot.

2. Build a half-wave rectifier. In the write-up show me the circuit layout. Sketch the input and output on the same graph. Hint: looking at input and output on the scope at the same time will help this. Add a capacitor to the rectifier output. How does the output voltage change? Again, plot the input and output

3. Build a full-wave rectifier. In the write-up show me the circuit layout. Sketch the input and output on the same graph. See the note at the end of this paragraph regarding how to measure the output voltage. Add a capacitor to the output and observe how the output changes. Sketch what you see.

   WARNING: You cannot observe the input and outputs simultaneously with this circuit because neither end of the output is at ground. To properly measure the output voltage, we'll need to take what is called a differential measurement. Use channels A

and B on the scope to measure the voltages on either side of the load resistor with respect to ground. Use the Add and Invert functions on the oscilloscope to display the difference in voltage between the two ends of the load resistor. I can bring over our fancy 4 channel scope to really show the entire behavior: input and differential output at the same time.

4. Build a voltage clamp, as we discussed in class, with a variable voltage. Systematically study its behavior and report what you find in the write-up.

5. Measure and plot the **reverse** bias characteristic curve for a Zener diode (use one with a $V_Z < 5$ V) as done in part 1. Note the type (#, and V_z) of the diode.

6. Build a clipper with two Zener diodes and observe its behavior as you vary the amplitude of the input. Where might this be useful?

$100 \ \Omega$

V_S
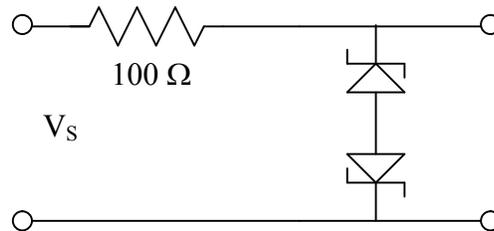
Bonus experiment (if time permits)

Use the same circuit above to measure the forward biased characteristic curves of at least two different colored LEDs: red and green. Discuss the difference. Does the light output reflect the I-V characteristics?

Lab IV: Transistors and Voltage Regulators

Introduction

In this lab, we will be using the 2N4124 general-purpose npn bipolar junction transistor. We build several useful circuits. We will also observe the performance of an integrated circuit voltage regulator and the effect of feedback on an amplifier.

Procedure

1. Build the following BJT switch:
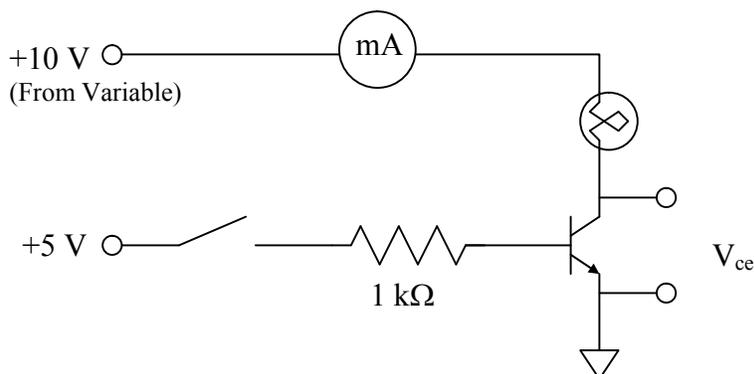
   The switch is simply a wire that you can insert or remove one end of to make or break the connection between the +5 V source and the 1 kΩ resistor. Take note of the values of I_c and V_{ce} for the two cases (on/off). Do these values make sense given what we know about the switch circuit? Why?

2. In lecture, we learned about voltage dividers and the drop in the output voltage that occurs when a "low" impedance load is connected to it. Build a voltage divider with $R_1 =$ 1 kΩ and $R_2 = 10$ kΩ and measure the output voltage. Now put a "load resistor" R_L (~ 8 kΩ) in parallel to R_2 and measure the output voltage.

   Now build the "buffer" circuit to the right with the base connection going to the output of the voltage divider. Measure the voltage across the load resistor. Does this voltage agree with theory?

   Note: such a circuit becomes very useful when interfacing with computers as the data boards generally have low output impedances compared to standalone power supplies.
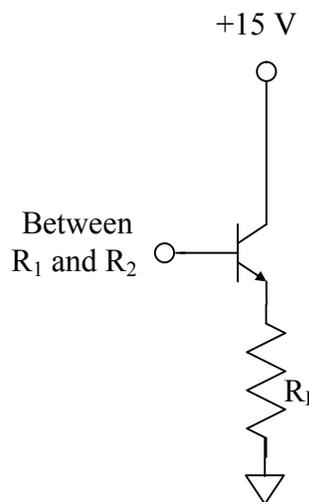
3. Constant current source. This circuit produces a nearly constant current through a load resistor connected to the collector. The collector current I_c is controlled by the base current in this circuit. Measure the current as you vary the load resistance from 0 to 2.5 kΩ. Use a decade resistance box for the variable resistor.
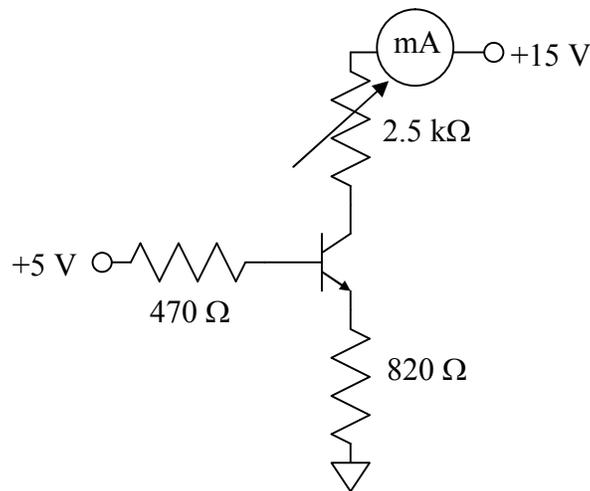
4. Integrated circuit voltage regulators. There are many families of chips used to regulate voltages. We will be using the LM340 family. These are high accuracy fixed voltage, three-terminal regulators very closely related to the LM78XX series discussed in the textbook. Connect the LM342P5.0 (5.0 regulate voltage output) as shown below.

Pin 1. Input
     2. Ground
     3. Output
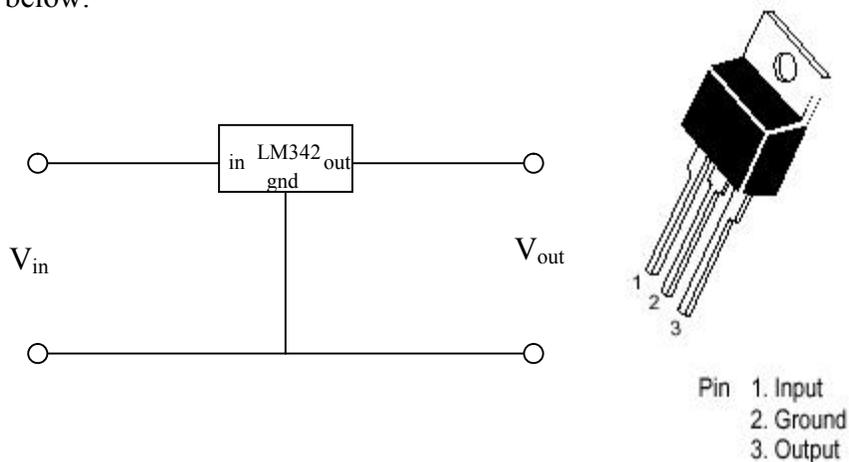
Use the function generator for the input voltage source; you will need to vary the offset voltage. For the LM342 to work, the average voltage must be ~ 2 V above the regulation value, so make sure that the DC offset is set high enough for the regulator

to work. Observe the input and output on the oscilloscope for different DC offsets, sinusoidal and triangular ripple, and with varying ripple magnitude. What happens if a portion of the input waveform drops below the $V_{out} + 2V$ threshold? It makes things easier to observe if V_{in} and V_{out} are displayed on the oscilloscope simultaneously.

5. Build the following transistor amplifier; don't worry too much about the actual design of the circuit – just note that with an ideal BJT it has a gain of 100 (in actuality, it will be closer to 50) without the feedback. Use the largest valued capacitors you can find ($\geq 1\ \mu F$). Measure the gain as a function of frequency with a sine-wave. Make sure the amplitude to the input signal is small enough that the output isn't clipped due to the circuit's high gain! Also observe the output when driven by a triangle-wave. Note the frequency when the output triangle is distorted.
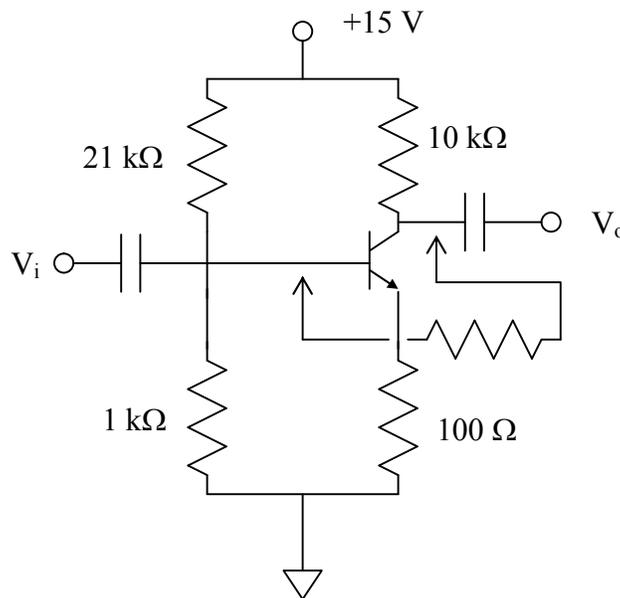
Add the feedback network (a 1 kΩ resistor). Measure the gain as a function of frequency. Again observe the output when driven by a triangle-wave. At what frequency is the triangle wave distorted?

Lab V: Operational Amplifiers

Introduction

In this experiment, we will be building many different circuits that will demonstrate the usefulness and simplicity of using operational amplifiers.

Procedure

For the first several parts of any of the amplifiers will work. It is not until parts 4 and 5 that you will need to be careful of the type of op-amp you will be using. Because of the high gains of these circuits, you need not provide a very large input voltage.

1. Amplifiers

   a. Build an inverting amplifier with a theoretical gain of –20.

   b. Build a non-inverting amplifier with a theoretical gain of +20.

   c. Measure the gain of these circuits using both AC and DC inputs. At what frequency does the gain begin to significantly deviate from theory?

2. Mathematical Functions

   a. Build a dual input voltage adder with the following behavior:

$$V_{Out} = -(V_1 + V_2/2)$$

   Use two different DC voltages to verify the behavior of this circuit. Also try adding an AC signal to a DC signal.

   b. Build the following difference amplifier and verify its behavior:

$$V_{out} = (V_2 - V_1)(R_f/R_1)$$
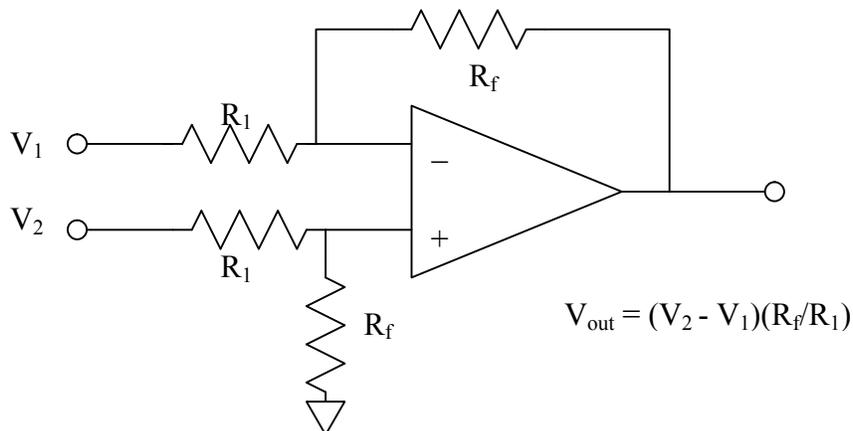
c. Build the differentiator circuit:
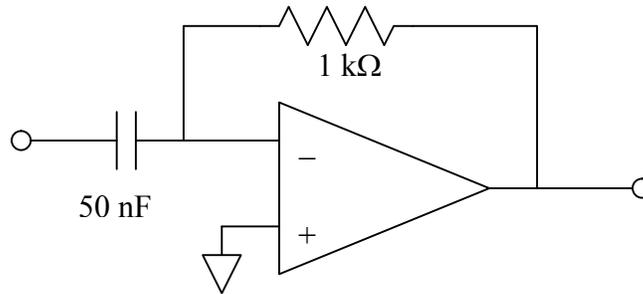
Observe the input and output with 1 kHz sine, triangle, and square-waves. Do your measured values make sense given what you know about the differentiator circuit?

d. Build the integrator circuit:
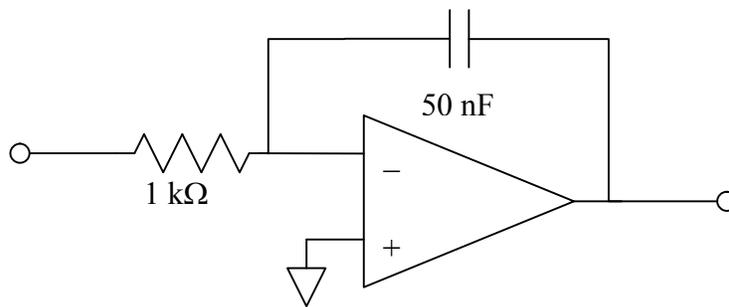
Observe the input and output with 1 kHz sine, triangle, and square-waves. Do your measured values make sense given what you know about the integrator circuit?

3. Filters

a. Build the following low pass filter and measure the gain as a function of frequency.
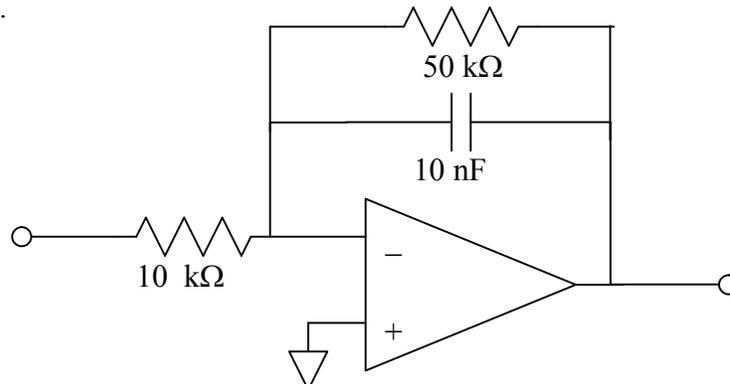
What is the approximate cutoff frequency? How does the gain compare to theory?

b. Build the following bandpass filter:
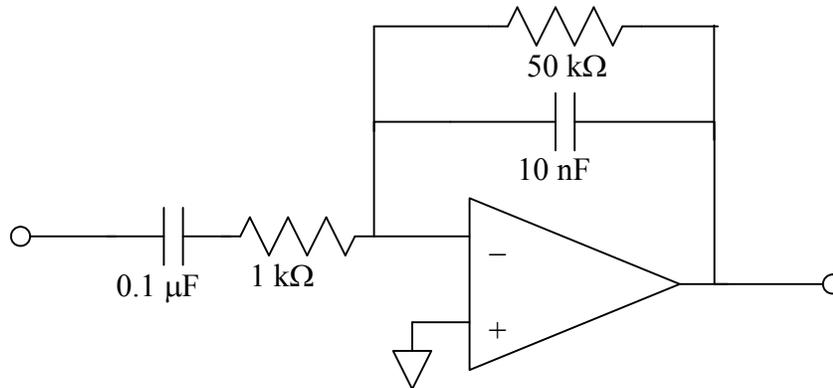
Measure the gain as a function of frequency. In your write-up, determine the theoretical transfer function and compare it to what you observed.

4. Peak detector circuit

a. Build the circuit shown on the next page. The output of this circuit is held at the maximum value of the input. The output is reset by closing the switch to short the first feedback loop to ground through the 1 kΩ resistor. In this circuit, you may want to use the 353 amplifier because it contains two independent amplifiers (2 x 351) on a single chip. NOTE: the 353 amplifier does not have the same pin-outs as the other amplifiers!
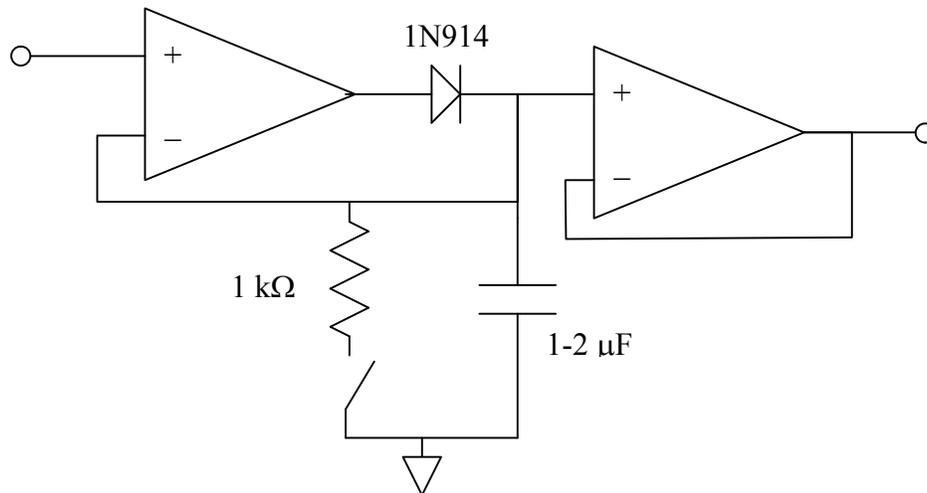
By varying the input voltage, verify the operation of this circuit. This circuit is best observed by watching the trace of the input and output signals on the oscilloscope using a 0.5 s/div timebase.

5. "Ideal" Diode

   a. Using the sample circuit diagram in your textbook, build an "ideal diode half-wave rectifier" and test its behavior.

6. Offset voltage compensation

   a. Build an inverting amplifier with nominal gains of −50 using either a 741 or 411 amplifier. By applying a carefully measured voltage of ~.1 V to the input, determine the actual gain of the circuit by measuring the output.

   b. Now set the input voltage of the amplifier from part a) to ground. Measure the output voltage. Given the gain from a), estimate the offset voltage (V_{os}) of the op amp. How do the values you measure compare to the data sheets?

   c. Using the manufacturer's instructions, modify your circuit so the offset voltage can be cancelled out.

Lab VI: Instrumentation Amplifiers and Transducers

Introduction

In this lab you will use "instrumentation amplifiers" to amplify the input of different kinds of transducers. We will be using pairs of each because instrumentation amplifiers are best suited for measuring the difference between two quantities. The transducer data sheets are located on the electronics resources website.

Procedure

1. In the last experiment, we built a difference amplifier. This amplifier, while it was simple, suffered from low input impedance ($Z_{in} = R_1$), essentially eliminating one of the best features of op amps. A better approach is the "three-amp" difference amplifier. The input impedance of this circuit is very high, because of the buffers on the inputs, but, as in the single-amp difference amplifier, to get the desired gain, care must be taken to ensure that the resistors are carefully matched. Build this circuit with a gain of ~10. Test the circuit by applying "known" voltages to V_1 and V_2. Don't break apart your circuit; you will need it for part 3.

If $R_2 = 2R_1$
$V_{out} = (V_2 - V_1)(2R_4/R_3)$
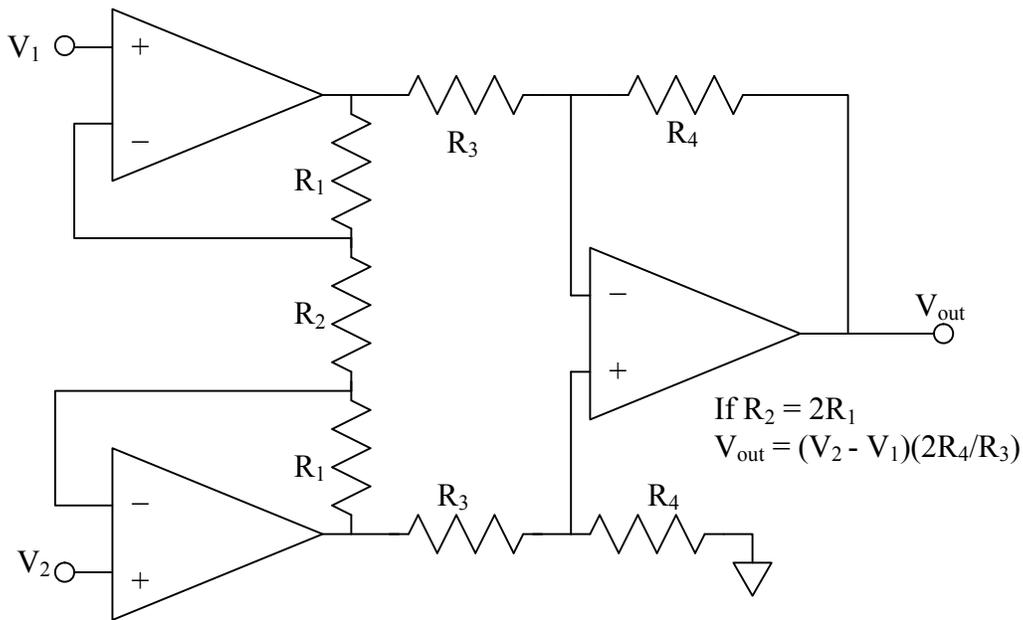
2. Build an instrumentation amplifier using the AD524 or the INA101. These chips have the desired high input impedance and the AD524 has several built in gain settings (it doesn't come cheap). Hook up your chip according to the data sheet instructions for a gain of 10. READ THE DATA SHEET CAREFULLY! Verify the gain with known input voltages.

3. Build each of the transducer systems below. Get a "feel" for how instrumentation amplifiers can work to cancel background signals and to make differential measurements. We have laser pointers, flashlights, and magnets to use in this experiment.

Transducers

Hall Sensors

We have several versions of Hall Sensors available; the sensors provide a voltage proportional to the magnetic field normal to the face of the sensor. At B = 0, $V_{OUT} \approx V_{CC}/2$. The sensitivities are listed on the appropriate datasheet.

We will use two sensors next to each other, front-to-back. Such an arrangement will allow us to measure the $\Delta B/\Delta x$, i.e. the rate of change of the magnetic field. The circuit will be as follows:
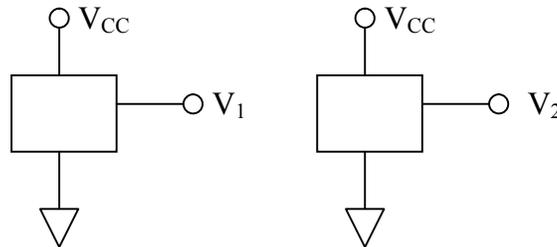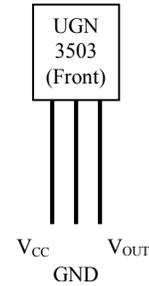
Use the ELVIS +5 V supply to power the Hall sensors.

Move a bar magnet around the pair of sensors and see if the field gradients you observe make sense given what you know about magnetic fields.

Phototransistors

The absorption of light at the base drives a base current in the transistor that is proportional to the intensity of light on the active surface. Similar to a traditional BJT, when the phototransistor is properly biased, the collector current is proportional to the base current. The result is the phototransistor has internal gain, making it more sensitive (albeit at a cost of response speed) than photodiodes, as we will investigate shortly.

The circuit is shown below. Use the +5 V to power the phototransistor. Build two of these circuits and measure the signal as you modify the relative intensity of the light on them and see if your circuit behaves as you expect. Use a laser pointer on one of the phototransistors to drive it into saturation (i.e. the base current deviates from

linear response). What happens? If you were trying to measure the intensity of the light accurately, how would you work around this problem? Is there an electronic solution? Keep one of your phototransistor circuits built, we will use it in the next section.
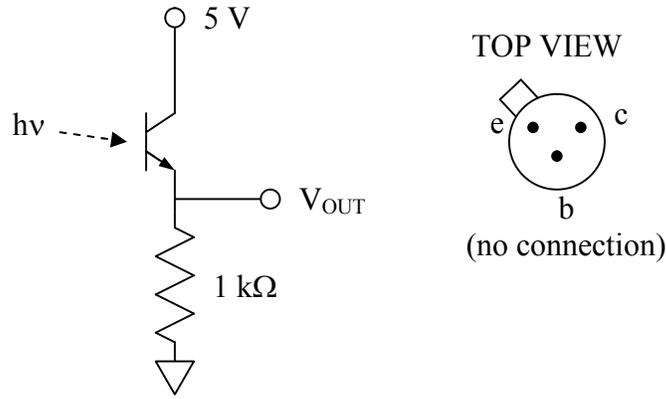
Photodiode

Use a photodiode as a current source for an op amp in a current-voltage configuration and observe the response of a flashing LED on your oscilloscope (use a ~500 Ω resistor in series with the LED and drive them with a 0 – 5 V signal). Compare the response speed of the photodiode to that of the phototransistor.   What is the maximum frequency of a square wave that you have confidence in measuring for both systems?

Solid State Temperature / Thermistor

Use an instrumentation amplifier to compare the differences in responses of a solid state temperature sensor (LM355) and a thermistor near room temperature.

Lab VII: Introduction to Digital

Introduction

In this lab, you will be building some very basic circuits to familiarize yourself with the behavior of digital electronics. You will also be using the 555 oscillator in both the astable (oscillator) and monostable (one-shot) mode.

Procedure

1. Logic probes are used to test the logic (high/low, 1/0, T/F) at points within a digital circuit. We have logic probes available for our use, but building a very simple one ourselves proves to be a nice exercise in understanding digital circuits. The circuit below is a simple and moderately useful probe:
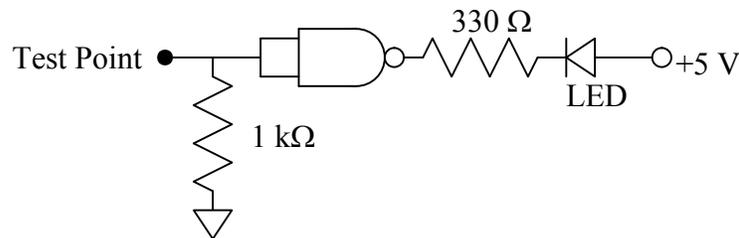
What is the purpose of the 1 kΩ resistor connected to the test point? What would happen if it were removed? In your write-up describe to me why this circuit works.

2. Use a logic probe (I'd suggest one of the real ones) to produce truth tables (i.e. verify that they do what they are supposed to do) of a NOT gate (inverter), a NOR gate, a NAND gate, and one "complex gate" of your own design.

3. Throwing switches can cause problems in digital circuits. Because you want to make sure that a) there is no "noisy" turn on and b) you _must_ avoid undefined states while the switch is being thrown. The bounceless switch shown below resolves these problems.
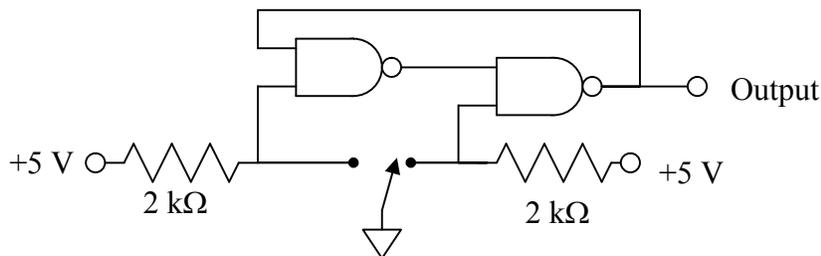
Use a wire as the switch. Describe the action of this switch, using your logic probe to test the output. Use what you've learned about digital logic to explain to me in your

report why this circuit works the way it does. You may want to keep a version of the bounceless switch on your bread board for the next few weeks as there are several opportunities to use it.

4. Use the 555 timer (data sheet online) in its astable mode to build an oscillator operating at 10 kHz with a duty cycle of about 30%. Observe the output waveform on the oscilloscope. When you've got it working, hook the output up to a speaker and frustrate your laboratory neighbors.

    Note: for reasons not clear to ANYBODY, the duty cycle of the 555 is in terms of the percentage of time off. Usually, duty cycle refers to percentage of time on.

5. Use the 555 in the monostable mode and build a one-shot with a 2 second long period. Trigger the one-shot with your bounceless switch (see, I told you to keep it!). Use a logic probe and oscilloscope to observe the behavior. For the one-shot to work properly, the trigger must go back to HI logic prior to the end of the one-shot pulse, so move that wire quickly!

Lab VIII: Digital Circuits

Introduction

In this lab, you will be building some fairly simple circuits to familiarize yourself with digital circuits. Static circuits you will be using are encoders, decoders, BCD-seven segment LED decoders. You will be building some fairly simple dynamic digital circuits as well, including build delay flip-flops (DFF), toggle flip-flops (TFF), and a divide-by-16 counter from J-K flip-flops (JKFF).

Procedure

1. Build a 4-2 encoder. That is, build a circuit that will put out a specific 2-bit code depending on which of the four possible inputs is selected. The truth table and the circuit are shown below. Test the circuit to make sure that behaves properly:

Input				Output	
1	2	3	4	A	B
On	-	-	-	0	0
-	On	-	-	1	0
-	-	On	-	0	1
-	-	-	On	1	1
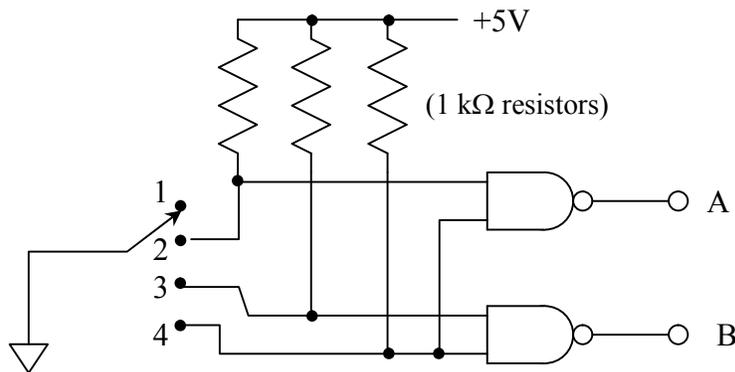
Use a wire as the four-way switch. Does this circuit behave as you expect? Do not disassemble your circuit; you will use it in part 3.

2. Build a 2-4 decoder that will take 2-bit inputs and drive one of 4 lines. The truth table and circuit are shown below.

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Input		Output			
A	B	1	2	3	4
0	0	1	0	0	0
1	0	0	1	0	0
0	1	0	0	1	0
1	1	0	0	0	1
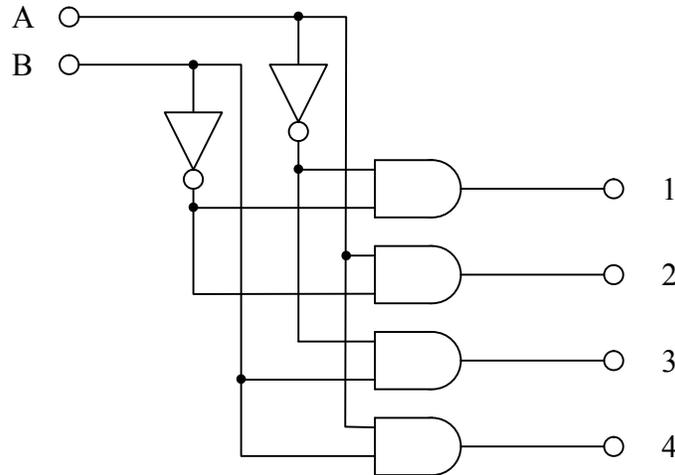
Wire the inputs to the logic switches to the +5 and GND lines on the ELVIS to select the states of A and B. Wire outputs 1-4 to LEDs (with resistors) as logic indicators or use the build in LED's on your ELVIS.

3. Now, connect the encoder and the decoder and see if the data properly sent. Connect the A/B outputs on the encoder to the A/B inputs on the decoder. Does your action with the switch drive the correct LEDs on the logic indicators? Why would two circuits like this be useful? Why not just run four wires directly? Think about this in terms of needing to send more than four possible signals.

4. We will now use one of the more useful chips available: the 7447, a BCD to 7 segment LED decoder. This is used to drive a 7 segment LED used to indicate numbers on a panel. Notes on the BCD numbering system are at the end of the procedure.

We will be using a MAN-72 (or compatible) display. It is a common device used to display numbers on a panel. It is made up of 7 segments that light up to form numbers that a reader can understand. Below is a sketch of what the pins and the LEDs look like:

```
Cathode a  ──1                              14──  +5 V
                         a
Cathode f  ──2                              13──  Cathode b
                   ┌─────────┐
   +5 V    ──3     │ f     b │              12──  (no pin)
                   │    g    │
 (no pin)  ──4     ├─────────┤              11──  Cathode g
                   │ e     c │
 (no pin)  ──5     │         │              10──  Cathode c
                   └─────────┘
Cathode l.h.d.p. ──6       d                 9──  Cathode r.h.d.p.

Cathode e  ──7   ■              ■            8──  Cathode d
```
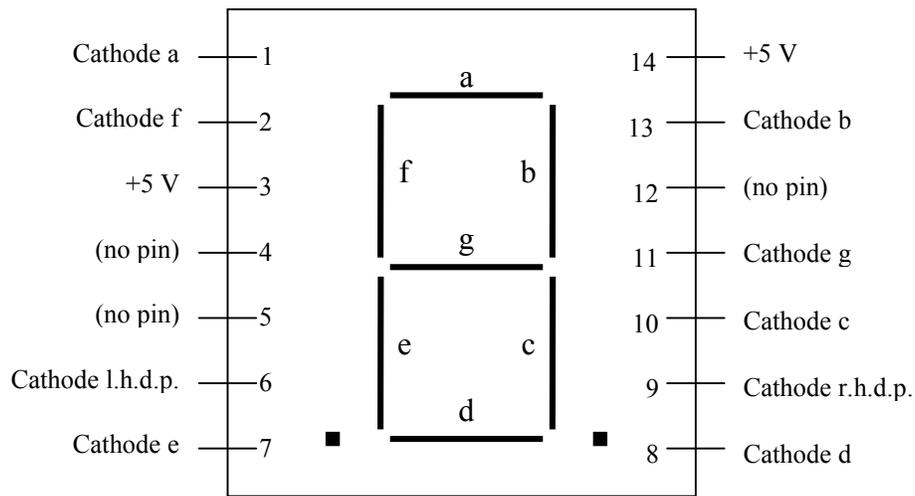
The lettering of the individual LEDs is industry standard and allows fairly easy interchange of components. The MAN-72 does not have any internal resistance in series with the LEDs so you **_MUST_** have a small series resistor each cathode and the decoder output. Resistors of value 400 – 700 Ω will suffice. This prevents the forward bias current from getting to high and burning out the LEDs.

Connect the 7447 decoder according to the datasheet and connect to the MAN-72. Set the logic state of the inputs for the 7447 by wiring them to ground and +5 V. Can you count from 0 (0000) to 9 (1001) in binary? What happens if you put binary values that are larger than 1001? Don't break this down, you'll need it in a later part of this experiment.

Note that the MAN-72 is a "common anode" type display. That means that the LED elements will light when the cathode goes to LO logic. If you want to see this in action, use a logic probe to test the logic going into the MAN-72. This implies that you need to have a decoder specifically for common anode displays when using a MAN-72 or related display. Common cathode displays require decoders intended for them also.

Can you figure out a way to get the 7447 to blink on and off?

5. Build a Delay Flip-Flop (DFF) from a JK Flip-Flop. Verify the truth table for the DFF. The data sheet for the JKFF in the Appendix.

6. Build a Toggle Flip-Flop (TFF) from a JK Flip-Flop. Verify that the TFF toggles the output as the clock triggers it using one of the logic switches to drive the clock

manually. Then drive the clock with a 1 kHz TTL signal from your function generator. What happens if J = K = 0?

7. Build a "divide-by-16" counter using JKFFs. Wire the Q_A, Q_B, Q_C, and Q_D to the logic indicators on the Protoboard. Use a bounceless logic switch to drive the counter. Are you counting properly as you keep throwing the switch? Drive the input with a 0.5 Hz TTL signal from the function generator and observe the logic display. Does the circuit behave differently when using the TTL signal? Any ideas why?

Increase the TTL input to 10 kHz and simultaneously observe the input and Q_C on the oscilloscope. Sketch the waveforms that you see and explain what you are seeing.

8. Wire up a BCD-7 segment decoder (7447) with a MAN-72 display, if you didn't leave it on your board. Connect the output of the divide-by-16 to the inputs on the 7447 and see if you can "count" in decimal numbers.

BCD Numbering System

As you are aware, it is often difficult to handle large numbers in binary code. A system has been developed that simplifies the notation used for large numbers, Binary Coded Decimal (or BCD). In this code, we use 4 bit words to describe a digital equivalent. Each decimal "order" is independently coded in binary and is offset from the other orders by a space. As in decimal notation, leading 0's are usually not written. The numbering systems is as follows:

Decimal	BCD Equivalent
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	0001 0000
11	0001 0001
12	0001 0010
43	0100 0011
287	0010 1000 0111

Lab Aside: Intro to LabVIEW

LabVIEW is a software package designed for data collection, data analysis, and process control. It has been around since 1986; it is made by National Instruments (known in the business as NI). It has become an industry standard – serving companies, universities, and national research laboratories around the world. One could study the details of LabVIEW for years and still not be an expert at all of the features that it has. My goal is to make you proficient in using existing LabVIEW programs and to develop your own simple programs for data analysis and data acquisition.

Most semesters we'll try to schedule a campus tutorial for the most recent version of LabVIEW. Included in the LabVIEW program is a document called "Getting Started with LabVIEW" that can be found on its start screen. On the Electronics Resources Website, there is a PowerPoint presentation produced by NI called "LabVIEW in Three Hours" that covers many of the basics of LabVIEW. It is written for Version 8, but the basics of the program haven't changed. Other items for students can be found at NI's Academic Website (www.ni.com/academic/students/).

Many of you have experience in programming computers so I will not spend time discussing data types in class. I will spend only a little bit of time discussing the different kinds of structures that you will encounter. If you have any questions about them, please see me or find resources on National Instruments website or elsewhere. If you don't understand the different kinds of data you encounter in programming, you will never get a very good handle on what the programs are supposed to do.

The main idea behind LabVIEW is to create measuring and analysis instruments on your computer, rather than to purchase individual instruments for these purposes. These virtual instruments (VI for short) are a flexible and powerful way of processing your data. Data is typically loaded into the VIs via a data acquisition (DAQ) card or via another device (such as the Keithley 2000 multimeter) connected to the computer. Once the data is loaded, the various analysis tools built into LabVIEW can be used to process and display the results to the user on the monitor.

LabVIEW VIs are organized in two windows. The first is called the front panel. It is the user interface. Two kinds of graphical elements are placed on the panel. "Controls" are used to input data and "flip" switches, while "indicators" display results from the program. The second window is called the diagram. It is the working part of the program. Once you have a program working well, you may never open up the diagram. It is in the diagram that all of the processes that your program does are defined. It is organized very much like a flow chart. Data moves between different operations along "wires." The operations can include simple things, like adding two numbers together, or more complex, like finding the frequency components of an arbitrary signal.

There are several types of data that LabVIEW can handle; most are common to all programming languages: *floating point* number (numbers with a decimal point), *integer*

number (no decimal), *string* (i.e. character), *Boolean* (True/False), and *array* (a set of any of the other types of data). The *waveform* is a rather unique format – it is an array of data with timing information included. A couple of other unusual data types you will come across are *clusters* (it is essentially a grouping of several pieces of data to simplify your code – it is used when you need to send several different things to the same place), *dynamic* data type (this is a fairly new type – it is essentially a specialized type of cluster that is used by the Express VIs that were introduced in version 7.1), and *path* (a special string data type that is used for identifying file paths for accessing data files on your computer).

As you go through the activities, feel free to play around with the VI's you build. Add extra features, make changes to the output, have some fun. HOWEVER, for the sake of the students following you, please DO NOT WRITE OVER any sample VI's that come with LabVIEW. In fact, be careful and make sure that you save all your own VI's a unique folder (i.e. D:/LabVIEW/bobandsarah_f09/)

In the experiments that follow, you will be given several projects to build. The instructions are to guide you, but you are responsible for developing your own code. You should submit your VI's to me via e-mail after completion, along with any other information that is asked for (data files, comments, etc.).

Lab IX: LabVIEW Projects

Introduction

   You will be performing the following exercises using LabVIEW. Make sure that everyone in the group understands the program. Your write-up for this week's experiment will be the VIs themselves and the output files that I have asked you to prepare using LabVIEW. Send these all to me in a single email. You will be graded on whether you completed the asked tasks, your program's organization and usability. To this end, make sure that your VIs are labeled and the default values of controls are reasonable.
   The best way to learn a program is to use it. Feel free to come in and play with it. We will be using LabVIEW more in the future when we start using computer data acquisition (DAQ).

Projects

1. Build a VI that generates and displays a sinusoidal wave using simple mathematical tools (not using the waveform generator that comes with the program). You should use the "get time in seconds" VI to get the time. This VI outputs the time in a time stamp data type. It can't be directly used in mathematics, it has to be converted into a floating point number; use the conversion tools in the numeric palate to do this. Put the calculations into a while loop that will allow this data to be generated until a "stop" button is depressed on the front panel. You will want to have a delay inside the while loop so that you don't generate data at a ridiculous rate. Consider the options for doing the timing carefully – one choice is much better than the others. The VI should have controls on the front panel for amplitude, frequency, and DC offset. Is there a difference between placing these controls inside or outside of the while loop? Name this project1.vi.

2. Modify the VI in project one by giving the user the option of adding random noise to the sinusoidal signal. This should involve the random number generator. You will want to use a case structure to control whether noise gets added or not. The noise should cause deviation from the sine wave in either direction and its amplitude should be variable from zero to no more than the amplitude of the sine wave itself. Your chart should be modified to display both the noisy signal and the noise. Name this project2.vi.

3. Create a VI that reads in the 1D spreadsheet file named testfile1.txt that is available for download on my website. You can use either the express VI or the read from spreadsheet VI on this; however, the express VI requires a correct file path. The advantage for the read from spreadsheet is that if a path isn't given, it allows you to browse for the desired file. Once the data is loaded, display it using an array indicator and graphically. Identify and display the following items: the number of elements in

the array, the maximum of the array, the average of the array, and the standard deviation of the array. Also square the individual elements of the array and take the tangent of each element (assume the values in the array are in units of degrees). Build a 2D array that has three columns, the first containing the original data, the second the squares, and the final the tangent values. Export this 2D array to a spreadsheet file and also using the express VI for writing data. Both can be opened in Excel or notepad – the express VI has a lot more information, but can be a bit more challenging to figure out. *Project3.vi*.

4. In this VI, you will be creating another waveform, but this time, you will be using a For loop (instead of the while we used earlier) and you will also get the chance to use the formula node. The formula node is used to perform more complex mathematical operations without cluttering the diagram with wires and functions. It essentially uses a box of text based code to do the math. Build a VI that calculates the following function:

$$y = \left[\sin\left(\frac{x}{3}\right) + 0.5\cos(2x) \right] e^{-\frac{x}{75}}$$

Do this for x = 1, 2 … 100. I would like you to perform the calculations using the formula node AND with the graphical wiring of functions. Plot the results of each method. Calculate the difference between the two values for each value of x and display the average and standard deviation of them. Name it, yes you guessed it: *project4.vi*.

5. Build the VI described in the document *peakdetect.pdf* on my website. Actually, you will only be graded on the content thru the end of page 7. Adding the markers on the graph is strictly optional. Some of the icons have changed since this document was first put together, so read them carefully. Data files are available on my website: *spectra1.txt*, *spectra2.txt*, *hydrogen.txt*.

Lab X: LabVIEW DAQ Projects

Introduction

      We will be building several projects using DAQ cards and LabVIEW. We will be using LabVIEW to input and output data in several ways: single point, waveform (N-samples), and continuous. We will be using the DAQ Assistant to configure the channels. The DAQ Assistant is an Express VI that asks what type of data to collect (or output), on which channel, and the kind of collection (or output). After the options are configured, the VI compiles the appropriate code to handle what you've requested, but it keeps this stuff hidden from you. It simplifies things, but also takes away some flexibility when trying to optimize performance. Fortunately, for the kinds of things we're interested in, it won't be an issue.

Projects

1. Build a selectable voltmeter VI. On the front panel, create a knob that will allow you to select from one of four possible channels (0-3) to "sample" the voltage at the channel (just a single measurement) and display it. You will want to use a **case** structure for selecting the channel; each case will have a different DAQ Assistant VI in it. Have the selected output display on the front panel (but only the selected one), along with the channel number, and the time that the data was collected.   Save your VI as DAQ1_*name*.vi.

2. Starting with the VI from project 1, use a **sequence structure** and a "waiting while loop" to the VI so that when you run the VI, no recording is made until you depress a button that you also add called "Sample". To do this, the while loop should run and hold until you press the "sample" button, which then forces the VI to move to the next step in the sequence, the data recording. Save your VI as DAQ2_*name*.vi.

3. The problem with single point acquisition is that the software controls the data collection. This can limit the speed of the data collection. If the DAQ Assistant is configured to collect a waveform, or N-samples, the system is configured to collect the data at a specific rate for a specific number of samples and collect the data using the built in memory on the DAQ Card, the buffer, so that you don't have to shuttle configuration information back and forth between the software and the card.

    Build a VI that will collect waveforms on two channels. The waveforms should have a sample rate of 50 kS/s and collect for three seconds. Use the Signal Manipulation Palette to convert the data from the DDT data type to a 2D array of scalars, with each column representing a channel. Plot the channels using the Waveform Chart.

    On your prototyping board, build a low pass filter with a capacitor and resistor with a cutoff frequency of about 100 Hz. Using the built in function generator, power the

circuit with a sine wave. Use your new VI to record the input and output simultaneously for several different frequencies.   Save your VI as DAQ3_*name*.vi.

4. Build a VI that acts like a strip chart recorder by using the continuous collection option. A strip chart recorder is a device that was once very common in laboratories. A piece of paper rolled under a pen that moved as the input voltage changed. This allowed researchers to record voltage changes as a function of time. Put a waveform chart inside of the while loop that the DAQ Assistant creates for you to display the data as it is collected. As you configure the DAQ, the number of samples field indicates that number of samples that will be sent to the software from the buffer at one time. The bigger this number, the "blockier" the data comes out. Have the DDT data converted to a 1D array. Save the entire set of data by appending (concatenating) the most recent output data to the past data by using a shift register and the build array feature. See figure below. Save your VI as DAQ4_*name*.vi.
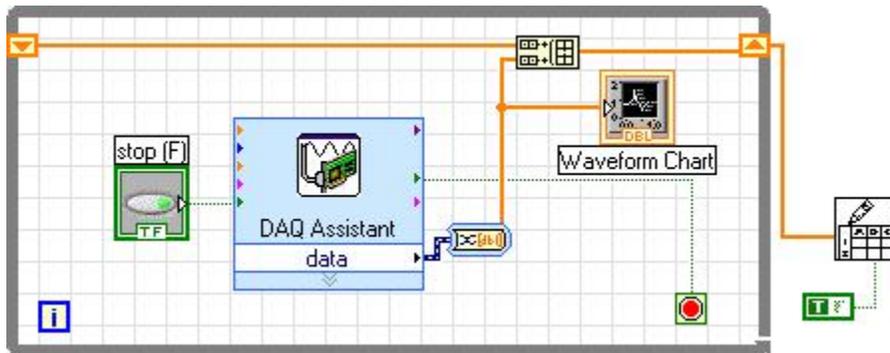

5. Design a system that will interface a transducer with a VI. I'll leave it to you to design what sort of system you want (i.e. changing lighting, temperature, or magnetic fields), but the VI should display the information gathered in a clean (and relatively calibrated) way. Think what an end user would want the display to show. Save your VI as DAQ5_*name*.vi.

6. Design a VI that will write out a voltage of the following form, using the output feature of the DAQ Assistant:

$$V_{out}(t) = 2 + 3\sin(0.5\,Hz \cdot 2\pi t) - 0.5\cos(10\,Hz \cdot 2\pi t)$$

Observe the output on your oscilloscope. Save the VI as DAQ6_*name*.vi.

7. Design a VI that will allow you to power and monitor a light bulb. Use a phototransistor located about 2" from the light bulb to monitor the light intensity coming off of the bulb as your VI steps up the light bulb voltage in 0.25 V steps from 0 to 8 V. Save the VI as DAQ4_*name*.vi. Use the phototransistor circuit below:
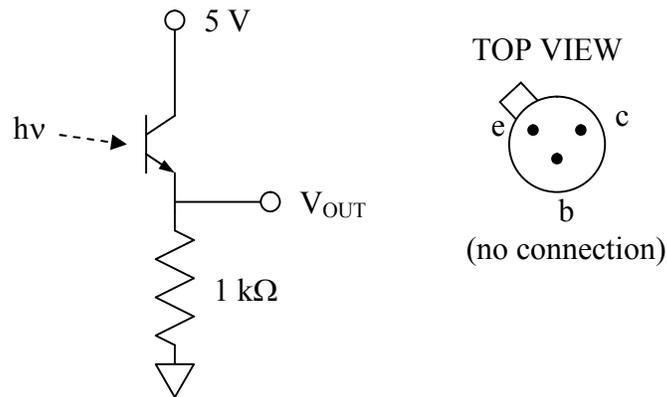
The DAQ card will not provide enough current to power the lightbulb so you will have to use a BJT as a power/current amplifier.
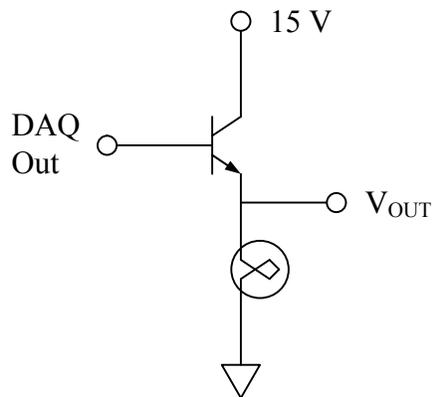
Because of the voltage drop across the BJT, also record the voltage across the lamp with your VI so that an accurate intensity versus voltage curve can be obtained. Plot the intensity as a function of the voltage in an x-y graph (use the XY Graph Express VI) in your VI. Write the XY Data file out to a file. Save this project as DAQ7_*name*.vi.

Appendices

Appendix A: Parts List

Discrete Passive Components
        Assorted Resistors
        Decade Boxes
        Assorted Potentiometers
        Assorted Capacitors
        0.1 mH Inductors

Discrete Active Components
        1N914 – Small Signal Diode
        1N4001 – Small Voltage Rectifier
        2N4124 – Small Signal NPN Transistor
        2N4126 – Small Signal PNP Transistor (complimentary to 2N4124)
        2N3904 – General Purpose NPN
        2N3906 - General Purpose PNP (complimentary to 2N3906)
        Assorted Zener Diodes

Operational Amplifiers
        741 – General Purpose Bipolar
        411 – General Purpose JFET
        351 – General Purpose JFET
        353 – Dual 351
        356 – General Purpose JFET
        AD547 – Precision Op Amp
        OP177 – Top Shelf Precision Op Amp

Instrumentation Amplifiers
        AD524 – Precision Variable/Internal Gain Instrumentation Amplifier
        INA101 – Precision Variable Gain Instrumentation Amplifier

Comparators
        311 – General Purpose Comparator
        339 – Dual GP Comparator
        711 – Quad GP Comparator

Timers/Oscillators
        555 – Single Timer
        556 – Dual Timer

TTL and TTL-compatible CMOS Logic
7400 / 74LS00 / 74HCT00 – Quad 2-Input NAND
7402 / 74LS02 / 74HCT02 – Quad 2-Input NOR
7404 / 74LS04 / 74HCT04 – Hex NOT
7408 / 74LS08 / 74HCT08 – Quad 2-Input AND
7410 / 74LS10 / 74HCT10 – Triple 3-Input AND
7427 / 74LS27 / 74HCT27 – Triple 3-Input NOR
7486 / 74LS86 / 74HCT86 – Quad 2-Input XOR
7447 / 74LS47 / 74HCT47 – BCD to 7-Segment Decoder
7474 / 74LS74 / 74HCT74 – Dual Positive Edge JKFF

Optoelectronics
Phototransistors
Photodiodes
Photoresistors
Assorted visible and IR LEDs
7 Segment LED Displays (MAN-72 and compatibles)
Photoswitches (Reflective and Transmissive)
4N31, 4N32 Optocoupler
4N37 Optoisolator

Transducers
AD590 Temperature Sensors
LM355 Temperature Sensors
UGN3503 Hall Sensors
EMD-4000 Humidity Sensors

Color	Figure	Multiplier	Tolerance
Black	0	1	-
Brown	1	10	-
Red	2	100	-
Orange	3	1000	-
Yellow	4	10^4	-
Green	5	10^5	-
Blue	6	10^6	-
Violet	7	-	-
Grey	8	-	-
White	9	-	-
Gold	-	10^{-1}	5%
Silver	-	10^{-2}	10%

Appendix C: Operational Amplifiers

We have several kinds of operational amplifiers available to us in this course. Additionally, there are many different kinds of specialized amplifiers, instrumentation amplifiers, audio amplifiers, low power, high speed, ... the list goes on an on. Many of the amplifiers are "generic." By generic, I mean that several manufacturers make their own version of the chips, but a common number identifies them. A summary of the specifications of several common, general purpose, generic op amps is shown in the table below. Detailed sheets are in Appendix D.

Op Amp	Type	Gain	Slew Rate (V/μs)	V_{os} (typ.) (mV)	Comment
741	Bipolar	2×10^4	0.5	6	An Old Classic
351	JFET	2.5×10^4	13	5	
411	JFET	2.5×10^4	15	0.8	Very good general purpose
353	JFET	2.5×10^4	13	5	Dual 351
356	JFET	5.0×10^4	12	3	Higher Gain

Additionally, we have some higher gain and precision amplifiers available. We will probably not use these until project time, if at all.

Op Amp	Type	Gain	Slew Rate (V/μs)	V_{os} (typ.) (mV)	Comment
AD547	JFET	2.5×10^5	3	< 0.25	Precision amp.
OP177	Bipolar	1.2×10^7	0.3	< 0.025	Top shelf precision amp.

The "pin-out" diagrams for the single unit amplifiers are all basically the same (for DIP-8 packages). The main differences between the pin-outs are the method used to compensate for the offset voltages (using the remaining pins 1, 5, and 8). Detailed pin-outs and data sheets are available for you to use.

Typically V- and V+ (the supply voltages) are ± 15 V, but the op amp will usually operate over a much wider range of voltages than this. Keep in mind that the input and output voltages cannot go outside of the range defined by V- and V+. Also keep in mind that in circuit diagrams, the connections for V± are rarely shown.
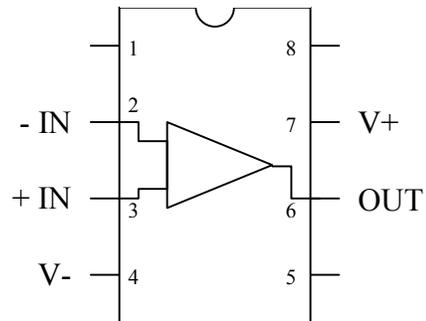
Note that the pins are numbered from the upper left corner (as indicated by the notch or a dot at the end).

Appendix D: Common Data Sheets

The following data sheets are for your use in this course. They are fairly generic data sheets and may not be for the exact manufacturer that we have in stock. In fact, most of the ICs in stock will be a mixture of brands. For more detailed information regarding each chip, you may want to visit the manufacturer's web site and download pdf files of the datasheets yourself.

In this version of this manual, the following data sheets are included:

Device	Manufacturer	Document Date
2N4124	Vishay Semiconductors	5/2002
2N4126	Vishay Semiconductors	5/2002
2N3958	Vishay Semiconductors	6/2001
LM741	National Semiconductor	7/2000
LF411	National Semiconductor	7/2000
LF351	National Semiconductor	12/1995
LF353	National Semiconductor	7/2000
OP177	Analog Devices	2002
AD524	Analog Devices	1999
INA101	Burr-Brown	1998
LM111/LM211/LM311	National Semiconductor	1/2001
LM555	National Semiconductor	2/2000
DM74LS00	Fairchild Semiconductor	7/1986
DM74LS02	Fairchild Semiconductor	5/1986
DM74LS04	Fairchild Semiconductor	3/2000
DM74LS47	Fairchild Semiconductor	10/1988
DM74LS74A	Fairchild Semiconductor	7/1986
AD590	Analog Devices	1997
UGN3503	Allegro Microsystems	