Brock University Physics Department

St. Catharines, Ontario, Canada L2S 3A1

Phys 3P92: Experimental Physics II (Electronics)

E. Sternin

Abstract

This is a senior undergraduate laboratory course, 13 weeks in duration, four hours per week. Seven experiments, running one or two weeks each, are completed:

1. **Breadboard techniques and simple circuits**
   — errors introduced by instruments, low–pass filtering, measuring phase shift
2. **Operational amplifiers: basic concepts**
   — operational characteristics, offset voltages and currents, gain, simple op-amp circuits
3. **Building circuits with operational amplifiers**
   — current–to–voltage converter, math operations, op-amp operational characteristics
4. **Advanced op-amp designs**
   — op-amps integrator and differentiator, difference amplifier, instrumentation amplifier, logarithmic amplifier, analog multiplier
5. **Active filters and tuned amplifiers**
   — active filters, notch filter, lock-in amplifier
6. **Microcomputers in a Physics Laboratory**
   — basics of microcomputer design, IBM PC registers and I/O, introduction machine-language programming, controlling PC LAB interface board
7. **Building and using a digital thermometer**
   — A/D and D/A conversion, mixed-language programming

Each experiment requires a written lab report. In addition, a term project requiring at least three weeks of independent work by the student is completed and a final report written.

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Contents

Introduction

In this course you will learn to build, understand, and debug working electronic circuits; you will develop a basic understanding of the way modern laboratory instruments interface with microcomputers; and you will perform physical measurements using microcomputer–controlled electronic devices built in the course of the lab. To quote Brock Calendar, the course covers "operational amplifiers, converters, switches, microcomputers and their application to physical measurements."

General Remarks

Electronics is a tool. Physics, like everything else in everyday life, is greatly influenced by the continuous explosive developments in electronics, and one's success in physics, like everywhere else, often depends on mastering this tool. That is why we study electronics as part of the physics curriculum. The hope is that by understanding how our instruments work and what their limitations are we can use them to do better science.

One cannot learn electronics all at once. Like in any complex subject, gaining a reasonable level of electronic skills requires going back over the material several times. Repetition and review are crucial in any learning situation. This course will provide you with a small opening into a much larger world; you will have to expand your knowledge and enhance your expertise in electronics on your own.

Get your hands dirty! This is a laboratory course, and you will need to get actively involved. You will be given few instructions on how to proceed, and sometimes these instructions will be deliberately vague. The results you get and the time you spend on experimental work will depend strongly on your ingenuity.

Use the best tools for the job. For example, you will be given access to personal computers; you are encouraged to use them to plot and analyze your data and to prepare lab reports. Often, only the raw data needs to be filled in the tables in your lab book, and all calculations can be done inside the computer program on the entire data set at once.

Safety is a state of mind. Take this trite slogan to heart. Be alert, look out for possible dangers, check your circuits and *think* before turning the power on. Acquire and maintain good working habits around your workbench, keep your work area tidy and free of loose wires and components. Turn the power off before leaving.

Conducting an experiment

- Begin by reading through the entire description of the experiment. Make sure you understand the goals of the experiment *before* you begin. Make note of and attempt to resolve all questions that may arise during preparation, by consulting the references and/or the instructor. Do not perform experimental steps whose purpose you do not understand!

- Aim to complete each experiment in the scheduled time. Keep clear and complete records; write down answers to the questions asked *as well as* your own observatons without waiting to be prompted. Remember to describe the problems you encounter and how you solved them. You might run into the same difficulty a few weeks later.

- Make a preliminary measurement before you start to acquire your final results. This way, you will:
  - understand the operation of the equipment;
  - ensure that the equipment is working correctly;
  - establish the range of values, so that you can choose the optimal settings on all your instruments;
  - find out what takes the most time, and budget accordingly.

- Graph the experimental curves and staple or glue them into the lab book.

  Remember the importance of proper captions, axes' labels, specification of units, and definition of symbols. These must be done *as you go along*, do not wait until later as you will lose track of the settings once you change them in the course of an experiment.

- Analyze your measurements and estimate the errors.

- Keep your reports *brief*, with an absolute maximum length of ten pages. Reference your work, do not copy text from manuals and books. However, make sure your reports are *complete.* Always include properly annotated diagrams of your circuits, make sure pinouts, meter settings, and other "trivial" details are clearly marked. Pay attention to these details: what may seem obvious at the moment will be forgotten soon after you complete the experiment. Your lab book should contain all of the information necessary to reproduce your experiments later, and to write your lab reports away from your lab station.

  You will be required to submit seven lab reports over the course of the first ten weeks of labs (experiments #4, #5, and #6 take two weeks each). Each report is due one week after the lab date. All of these lab reports together will account for 70% of your final mark.

  Attempt to write your lab reports as if they were scientific papers. To find out what format you are expected to follow see, for example, *Canadian Journal of Physics.* Generally speaking, you should address the following points clearly and explicitly:

  Title The name of the experiment performed.

  Abstract A brief summary of the most important factors in the experiment including the statement of the final result and conclusions.

  Introduction Describe the motivation for doing the experiment, the physical principles involved, how the technique used differs from other techniques, *etc.*

  Procedure A carefully labelled diagram of the apparatus, with a description of its features; a careful account of how the measurements were done including the precautions taken to eliminate systematic errors. In simple cases, it may be sufficient to simply state that the procedure as described in the Manual was followed exactly. All changes in the procedure, modifications of the circuit or of the component values, *etc.* must be clearly noted.

  Results A tabulation of the experimental data, graph(s) where appropriate, derivation of the desired result, plus an estimate of the random and systematic errors as well as numerical fit of theoretical curves to the experimental data points where appropriate. If a computer program or a macro is used to analyze the data, its listing should be attached as an Appendix to your report.

Discussion A discussion of the precision of the result, how the experiment can be improved and its ultimate limitations, possibly a comparison with other methods of obtaining the same result.

Conclusions As appropriate.

References All texts, publications, and other references used to assist in the experiment should be listed.

Handwritten reports will **not** be accepted. You are encouraged to use TeX/LaTeX to write your reports. A skeleton report is available for you to copy into your own filespace and to edit as appropriate. Several different programs capable of data analysis and plotting are available on the PC's in the lab and on the University Unix servers, including `physica/edgr`, `gnuplot`, `maple`, `xmgrace`, and `SigmaPlot`. All of these are capable of generating PostScript output which can then be included in your lab report. Consult your instructor for details.

- The last three weeks of the course are reserved for your term project, although you are encouraged to select one and start preliminary work on it as early as possible. A list of available projects should be posted in the lab early in the semester. Unlike the step–by–step experiments in this lab manual, you will be given a task, and a minimum of instructions on how to proceed.

  In lieu of a final exam, you will be required to present your project and demonstrate its operation, as well as to submit a written report on your work. Several Faculty members and representatives from the Electronics Shop usually attend these final presentations.

  Your project report may take the form of a lab report, or that of a User's Manual for your particular device. Under certain circumstances, the report may be replaced by an interactive Help facility built into the software that you have written to support your device.

  The term project (including the report) is worth 30% of the final mark.

Please refer to this outline, and to this introductory chapter throughout the course of the experiments. The marking scheme used to evaluate your work is implicitly contained here.

Conventions used in this manual

(!) Whenever you see a paragraph marked off with this symbol, it indicates an experimental step. You are expected to perform one or several operations and write down your results and observations in the lab book.

$\boxed{?}$ When you encounter this symbol, it indicates a question or a problem. You are expected to perform the necessary calculation and to provide a written answer and, possibly, a brief explanation in your lab book *before* you proceed to the next stage of the experiment.

References

Numerous excellent introductory electronics books exist, and you are encouraged to refer to them often. Some selected titles are listed below, with Brock Library calling numbers shown where appropriate.

Other references such as manufacturers' data books and the equipment manuals should be consulted as needed. Photocopies of selected parts of some of the references are available in the lab, and other reference material can be obtained from the University Technical Services (see your instructor if you require access). You are encouraged to consult journals such as *American Journal of Physics*, *Electronics*, and *Reviews of Scientific Instruments* for further reading.

1. H. Austerlitz, *Data Acquisition Techniques Using Personal Computers.* Academic Press, 1991.
2. D. Barnaal, *Analog and Digital Electronics for Scientific Applications.* Waveland Press, 1982. TK7816 B34.
3. J. J. Brophy, *Basic Electronics for Scientists.* McGraw–Hill, 1990. TK7815 B74.
4. M. M. Cirovic, *Basic Electronics: Devices, Circuits, and Systems.* 1974. TK7815 C53.
   A.J. Diefenderfer and B.E. Holton, *Principles of Electronic Instrumentation*, 3rd ed.[1] Saunders, 1994.
5. W. L. Faissler, *An Introduction to Modern Electronics.* J. Wiley & Sons, 1991.
6. B. Grob, *Basic Electronics.* 1989. TK7816 G75.
7. P. Horowitz and W. Hill, *The Art of Electronics.* Cambridge University Press, New York, 1989. TK7815 H67.
8. H. V. Malmstadt, C. G. Enke, and S. R. Crouch, *Electronics and Instrumentation for Scientists.* Benjamin/Cummings Publishing Co., 1981.
9. J. O'Malley, *Theory and Problems of Basic Circuit Analysis.* Schaum's Outline Series, McGraw–Hill, 1992. TK454 O46.
10. M. Plonus, *Electronics and communications for scientists and engineers.* Harcourt/Academic Press, San Diego, 2001.
11. R. E. Simpson, *Introductory Electronics for Scientists and Engineers*, 2nd ed. Prentice Hall, 1987.
12. W. F. Stubbins, *Essential Electronics.* John Wiley and Sons, New York, 1986.
13. J. C. Sprott, *Introduction to Modern Electronics.* John Wiley and Sons, New York, 1981.
14. B. G. Thomson and A. F. Kuckes, *IBM–PC in the Laboratory.* Cambridge University Press, 1989. QC52 T46.

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[1] This is the required text for PHYS 2P31/32.

Experiment 1

Breadboard techniques and simple circuits.

1.1 Introduction to the workbench.

Spend some time getting acquainted with the tools available at your workstation. Make sure you understand their markings, controls, and limitations. A few minutes spent now on learning your way through the oscilloscope's knobs and dials will quickly pay off.

(!) Become familiar with the breadboard socket connections

(!) Investigate the power-supply controls and the output voltages provided

(!) Practice the techniques of connecting between devices on the breadboard, and to devices not on it.

(!) Measure variable voltages on the "job board" over their full range, ±1 V and ±10 V. Use both the scope and the DMM.

1.2 Errors introduced by the instruments

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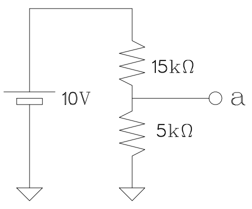
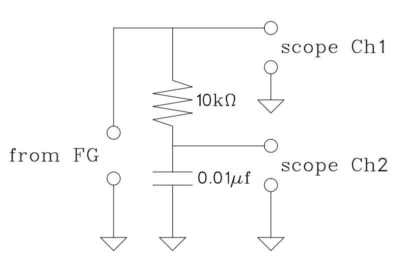


For the circuit diagram shown, what is the voltage between the point a and the ground?
What will be measured at point a with a voltmeter set to the 5 V range if the meter has a sensitivity of $10,000\,\Omega/\mathrm{V}$? It may help to re-draw the circuit diagram including the Thévenin equivalent representation of this voltmeter.

(!) Using one or two resistors and the +5 V power supply of the breadboard system, estimate the internal resistance of the DMM when used as a DC voltmeter. Compare your result with the posted specs of the DMM.

1.3 Low-pass filter

In this part of the experiment we compare the relative importance of various sources of error: systematic errors due to differences between nominal and actual component values, instrumental errors, random scatter, etc.

(!) 

Wire the circuit shown. The FG and scope should be connected to the circuit using BNC or banana plug connectors on the frame. Be sure all common connections are made, especially if using the banana connectors (with BNC connectors, the connection to common is automatically made).

(!) Measure the input and output amplitudes as a function of frequency, [at least] for the frequencies shown in the table below. An easy way to do this is to set the scope time base so that dozens of cycles appear on the screen. The signals then appear as horizontal bands whose height is a measure of the signal amplitude. The FG output can be adjusted if necessary, to keep the Ch1 amplitude constant. Use an FG amplitude of 5 to 10 V. Express the gain $G = V_{\text{out}}/V_{\text{in}}$ in decibels (dB).[1]

Frequency, ν	$\log_{10}(\nu)$	V_{in}, V	V_{out}, V	$\lvert V_{\text{out}}/V_{\text{in}}\rvert$, dB
10 Hz				
30 Hz				
100 Hz				
300 Hz				
1000 Hz				
3000 Hz				
10 kHz				
30 kHz				
100 kHz				

If you are using a computer program to do your calculations, fill only the two middle columns of the above data table.

[?] Plot the absolute value of the gain, $|G|$, in dB *vs.* log frequency. Determine the cutoff frequency and the attenuation slope (in dB/decade) at high frequencies.

[?] Review Simpson, Sec. 2.10. Using the nominal (marked on the component) values of C and R, calculate and add to your plot the line representing the expected frequency response of this low–pass filter.

Treat $\tau = RC$ as a parameter and, starting with the initial value given by the nominal component values, fit a theoretical curve to your data. Add this curve to the same plot. Explain any differences observed.

1.4 Observing phase shift with Lissajous patterns

(!) With the FG at 100 kHz, set the scope time base to observe 1–5 cycles. Note that signal across the capacitor lags the signal across the function generator. This phase shift can be measured as the fraction of a cycle delayed times 360°. What is the phase shift at 100 kHz?

(!) Now measure the phase shift by means of Lissajous figures. Switch the scope display to *xy*–mode to observe the Lissajous pattern as shown in figure below. Consult the manual for your

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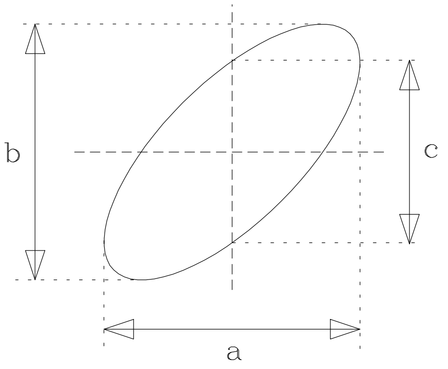
[1] see Simpson, p. 81, for the definition of decibel.

scope to find how to select the xy–mode. Be sure to note the sensitivity setting of each input in your measurement. The amplitude values should be recorded in volts rather than divisions. Set the sensitivities so that the major axis of the ellipse is at an angle of about 45° and several divisions in length. The pattern should be centered on the screen so that the central chord of the ellipse c, can be measured with the vertical centerline of the scope graticule.

An easy way to perform the measurement is as follows:



1. Ground the vertical amplifier input (with the input switch) and align the trace with the horizontal center line.
2. Switch the vertical amplifier to DC and ground the horizontal amplifier input. Center the trace horizontally. Measure the length of that trace which is the quantity b.
3. Switch the horizontal amplifier to DC and measure c. Repeat for the same frequencies as before (you may simply add columns to the table from the previous Section.).

Frequency, ν	$\log_{10}(\nu)$	b, V	c, V	$\phi = \arcsin(c/b)$
10 Hz				
⋮	⋮	⋮	⋮	⋮
100 kHz				

? Plot the phase angle, ϕ, *vs.* log frequency. Again, if you are using a computer program to plot the data, you only need to fill out the columns for b and c.

On your plot, add the line $\phi = -\arctan(\omega\tau)$, where again $\tau = RC$, using the nominal component values. Does it agree with the data?

? As before, treat τ as a parameter and fit the theoretical curve to your data. Compare the two curves, and the data. Are the results of this fit in agreement with the ones from Section 1.3? Explain the differences, if any.

1.5 Shielding and induced signals

! Disconnect all signal inputs and outputs from the breadboard frame. Connect a shielded cable to the scope input, but leave the other end of the cable unconnected. Observe the display and record the amplitude of any open circuit signal present. Connect the cable to the breadboard frame and again measure the signal amplitude. Now insert a job board and again measure the signal amplitude. Also determine the signal frequency. The signal can be further increased by connecting a wire to a job board contact to the scope connector and touching the other end of the wire. The amplitude of the signal is also affected by whether you are touching the frame (or other ground) or not.

? What is the source of the signal observed and why is it affected by the amount of unshielded conductor exposed?

(!) Connect the FG signal output to a frame connector. Connect the FG output to the Ch1 scope input through the contacts on a job board. Set the FG for a 1 kHz, 10 V sine wave. Connect the Ch2 scope input to another frame connector, but do not make any connections to the corresponding job board contact. Record the magnitude of the signal observed on Ch2 at the frequencies in the table below. Keep the Ch1 amplitude constant at 10 V. Now connect a 10 kΩ resistor between the Ch2 input contact on the job board and common. Repeat for a resistor of 1 kΩ.

Frequency	Ch2 amplitude, V		
	no load	10 kΩ	1 kΩ
10 Hz			
100 Hz			
1000 Hz			
10 kHz			
100 kHz			
1 MHz			

NB: What you have observed is called *cross–talk*. It occurs when a signal in one conductor can induce a signal by capacitive, inductive or electromagnetic coupling in another conductor. The small currents induced in the “receiving” conductor produce voltages across the impedance between the conductor and common. The larger the impedance, the larger the voltage as your data shows. When high impedance signal lines must be used, they should be shielded. Examples of shielded lines used in high–impedance voltage measurements are BNC cables and oscilloscope probes.[2]

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[2] See Faissler, p. 137, or the scope manual for a discussion of scope probes.

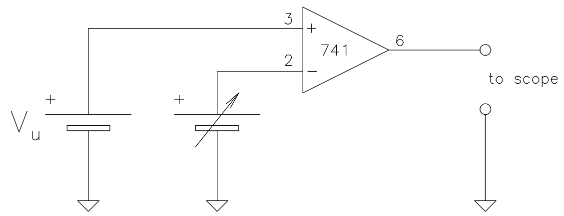
Experiment 2

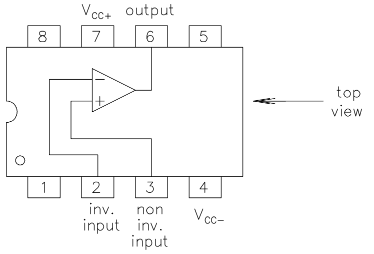
Operational Amplifiers: Basic Concepts

The purpose of this experiment is to introduce op-amp, a key element of analog electronics circuits. Several configurations of a voltage follower will be built, introducing the key characteristics of op-amps.

2.1 Null voltage measurement

(!) Wire up the following circuit using a 741 op-amp.





> **! Care should be taken to ensure that all integrated circuits (IC's) are powered with both $V_{\mathrm{CC}+}$ and $V_{\mathrm{CC}-}$ whenever an input signal is supplied! Failure to do this will destroy IC's**.

Use ±10V output from the job board as V_u (unknown); set it to any value between $+0.95\,\mathrm{V}$ and $-0.95\,\mathrm{V}$. Connect ±1 V output of the job board to the inverting input of the op-amp. Use $V_{\mathrm{CC}+} = +15\,\mathrm{V}$ and $V_{\mathrm{CC}-} = -15\,\mathrm{V}$.

(!) Use the scope to monitor the output and adjust the ±1 V supply until a transition from one output voltage limit to the other occurs. Measure and record the positive and the negative voltage limits of the op-amp output.

(!) In the same circuit, connect the DMM to the ±1 V supply. Adjust the potentiometer (carefully) to the value where the op-amp output just begins to decrease from its positive limit (as observed on the scope), where it is as close to zero output as you can set it, and where it is not quite at the negative limit. Record these three values. They may be very close to each other; in this case estimate the upper limit on the change of the input voltage(s) that causes the output to jump from one limit to another. Repeat these observations several times.

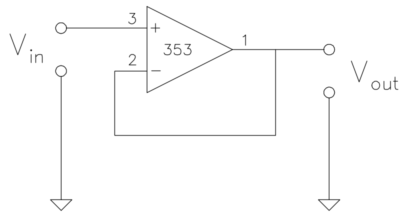
(!) Without changing any settings, use DMM to measure V_u.

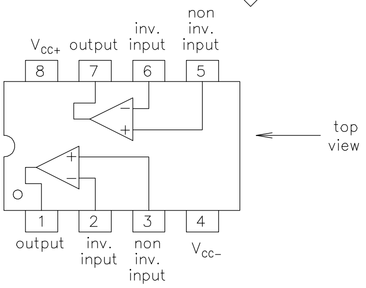
$\boxed{?}$ Estimate the **open loop gain**, A, of the op-amp and its input offset voltage from the above measurements. Compare with the nominal value, 103 dB for 741.

Note: $V_{\text{output}} = A \times (V_+ - V_-)$, see Simpson, pp. 367–369 or Faissler p. 247–248.

2.2 Voltage follower

(!)

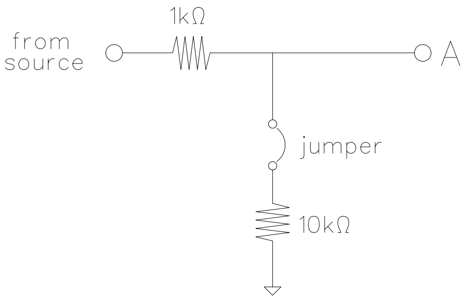




Connect one of the 353 op-amps as a voltage follower.
Use the ±10 V as V_{in} and the DMM to measure V_{out} and V_{in} for five or more settings in the range +10 to −10 V. Calculate the gain.

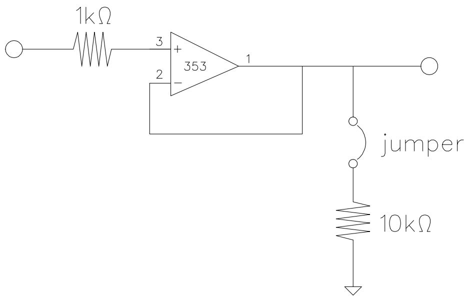
V_{in}	V_{out}	Gain

(!)



A 1 kΩ resistor will be used in series with the ±10V output to simulate a voltage source with a 1 kΩ internal resistance. A 10 kΩ resistor will be used to simulate the input resistance of the readout device used to measure the source voltage.
Wire the circuit on the left, set the source voltage to a value between 1 V and 2 V, and measure the voltage at point A with and without the 10 kΩ load connected.

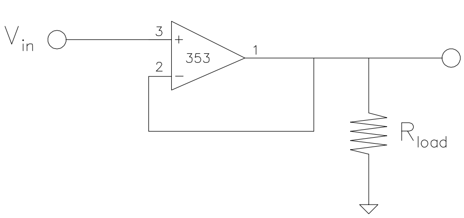
(!)



Now connect an op-amp voltage follower (353) to buffer the voltage source from the load resistance. Measure the follower output voltage with and without the 10 kΩ load resistor connected.

[?] A transducer has an output resistance of 80 kΩ. Describe how a follower could be used to decrease the loading error if the transducer output voltage is to be measured with a 1 MΩ input resistance oscilloscope and indicate the percent error avoided.

(!)



Fix the input voltage at +10 V. Connect a 1 kΩ load resistor (R_{load}) to the follower output as shown and measure the output voltage with the DMM. Remove R_{load} and measure the no-load voltage.

Repeat using the 100 Ω and 47 Ω load resistors. Calculate the output current for each case.

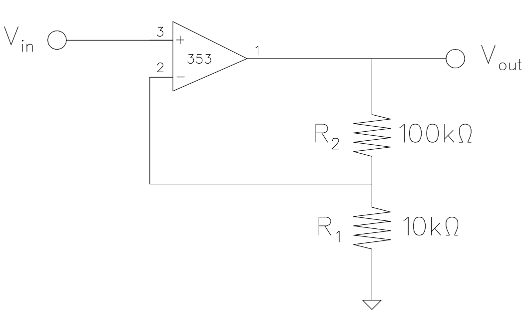
R_{load}	V_{out}, with load	V_{out}, without load	I_{out}, with load

The small output voltage change observed with the 1 kΩ load indicates the very low output resistance of the voltage follower. At lower load resistance, it is possible to exceed the maximum output current capability of the op-amp. A significant loading of the output voltage occurs in such a case.

? On the basis of the change in output voltage with a 1 kΩ load, estimate the output resistance of the voltage follower, or if no change was observed, place an upper limit on the output resistance, *i.e.* calculate the value the output resistance would have if the smallest observable change had been measured. It may help to draw an equivalent circuit for the op-amp (see Simpson, Fig.9.21 or Faissler, Chapters 29 and 31).

Calculate the maximum output current the op-amp can supply, based on your observations with the 100 Ω and 47 Ω loads.

2.3 Follower with gain

! 

Use a 353 op-amp to wire the follower with gain amplifier circuit as shown. You may find it convenient to use the precision resistor arrays for R_1 and R_2.
Use the ±10 V supply as V_{in} and vary the input voltage in the range of ±5 V. For each value, accurately measure both V_{in} and V_{out}, and calculate the observed gain.

Plot V_{out} *vs.* V_{in}, determine the region of linearity, and fit that part of the data to a straight line to determine gain. Note that you must allow for a non–zero intercept, thus use a two–parameter fit. Compare the gain you obtain with the values calculated at each data point, and with the value you would expect for this circuit from the nominal resistor values.

? Explain what limits the gain for large values of V_{in}.

! Use the ±1 V supply as input, set at slightly below 10 mV. Vary the gain of the circuit by using different values of R_2: 100 kΩ, 1 MΩ, and 10 MΩ.

Compare the measured gains to those expected and explain any deviations.

? Can a gain of less than 1 be obtained with this circuit? Explain why or why not.

! In the above plot, the x–intercept of the straight line corresponds to the input offset voltage, V_{offset}. It may be more clearly observed at low input voltages and high gains. Examine this effect by connecting the follower input to common and measuring V_{out}, for the same R_2 values as above. **Be sure to disconnect the voltage source from the follower input before grounding the latter!**

R_2	Gain	V_{out}	V_{offset}
100 kΩ			
1 MΩ			
10 MΩ			

$\boxed{?}$ Compare your V_{offset} value to the x–intercept above and comment on differences, if any.

$\boxed{?}$ What causes a greater % deviation from nominal gain, V_{offset} or the resistor inaccuracy?

$\boxed{?}$ *Optional*: Repeat the straight–line fit to the data, but this time force the intercept to be zero (*i.e.*, a one–parameter fit). This assumes $V_{\text{offset}} = 0$. Calculate and comment on % error caused by this assumption.

Experiment 3

Building circuits with op-amps

The purpose of this experiment is to build several realistic op-amp circuits. We learn how to use op-amps for signal conditioning in various measurements.

3.1 Current–to–voltage converter

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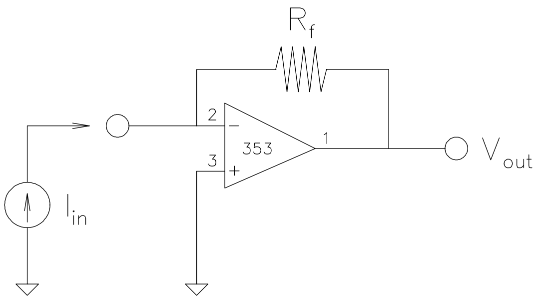


Wire up the current-to-voltage converter circuit (note that this corresponds to simply interchanging the input and ground connections in the circuit of Section 2.3). Here we emphasize the fact that the input is explicitly a current, while the output is a voltage:

$$V_{\text{out}} = -R_f I_{\text{in}}$$

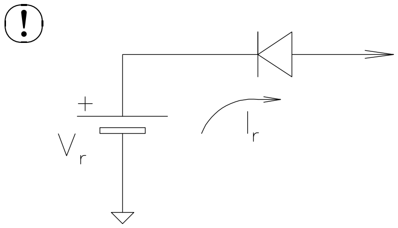
Use a feedback resistor of 10 kΩ.

Use a 10 MΩ precision resistor in series with a variable voltage supply as the current source: $I_{\text{in}} = V_{\text{in}} \times 10^{-7}$, for several (five or more) input currents in the nanoamperes-to-microamperes range. Measure V_{out} with the DMM.

I_{in}	Calculated V_{out}	Measured V_{out}	% error

? Will the input offset voltage affect the measurement of small currents more (a) when the current source is a small voltage and a small resistance, or (b) when it is a large voltage and a large resistance?

(!)



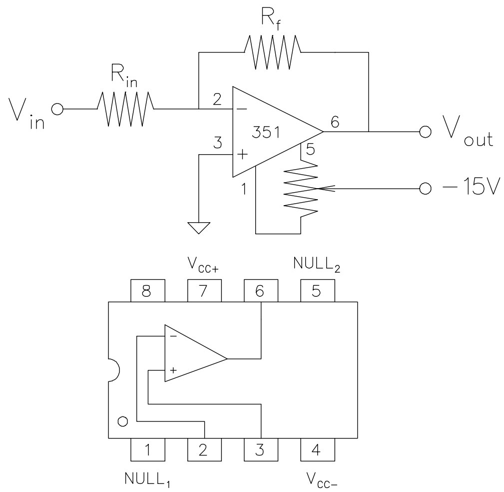
Using a signal diode 1N914, wire the following input circuit to measure the reverse bias current of the diode. Select the value of R_f necessary to give a reasonable V_{out}. Use reverse bias voltages $V_r = 1$, 2, and 5V.

V_r	V_{out}	R_f	I_r
1 V			
2 V			
5 V			

3.2 Inverting amplifier

As seen in Section 3.1, the input offset voltage of op-amps can introduce significant output errors. Many op-amps (351, 741) have additional pins for adjusting the offset to zero.

(!)



Wire the circuit shown with $R_f = 100$ kΩ and $R_{\text{in}} = 10$ kΩ (gain $\simeq 10$); connect input to common, and adjust the balance potentiometer until the op-amp output is nearly zero ($\leq$ 1mV). Set DMM to an appropriate scale.

Prior to every other experiment in this lab, check in the same manner whether the op-amp remains balanced (it should!)

Use a ±1V supply as V_{in} (disconnect the wire to common first!). Measure V_{out} for five or more values of V_{in}, in the range ±0.7V.

I_{in}	Calculated V_{out}	Measured V_{out}	% error

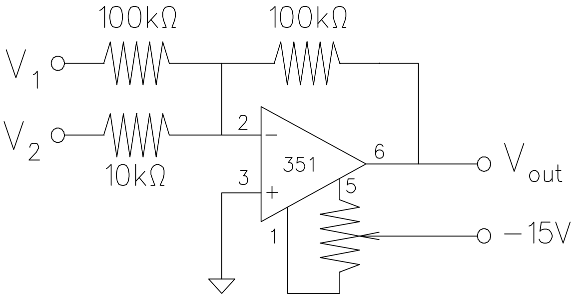
(!) Use the FG set at 1 kHz as V_{in}. Use the two channels of the scope to monitor the inverting input of the op-amp and V_{out}. Slowly increase the amplitude of the input signal, starting near zero. Observe what happens at the inverting input as the amplifier saturates. Is the assumption of virtual ground still valid?

(!) Keeping the amplitude of the input low and constant, vary its frequency. Can you estimate the maximum slew rate of the 351?

3.3 Summing amplifier

Inverting amplifier configuration may be used to perform several mathematical operations. The summing amplifier provides an output related to the algebraic sum of two or more signals.

(!)



Wire up a summing amplifier, as shown. Use the ±10V supply as V_1 and the ±1V supply as V_2. Measure V_{out} for six or more combinations of input voltage values. Keep one value constant for at least three values of the other and *vice versa.*

V_1	V_2	V_{out}
. . .		

[?] Plot V_{out} *vs.* V_2 for constant V_1, and V_{out} *vs.* V_1 for constant V_2. Explain the values of the slopes and intercepts.

Disconnect the summing network from the 351; leave the balance pot and power connections in place for later use.

[?] Design a circuit whose output represents $3V_1 - 4V_2$.

[?] Design and describe an inverting amplifier with a thermistor as one resistor such that the output voltage becomes more positive as the temperature inreases. The thermistor resistance is 10.5 kΩ at 28°C and 9.5 kΩ at 23°C. Choose the component values so that V_{out} changes 10 mV per °C near room temperature. Also include an offset circuit so that $V_{\text{out}} = 250$ mV at 25°C. Assume that the thermistor resistance changes linearly with T^{-1}.

3.4 Op-amp characteristics

It is important to recognize the limitations of op-amps so that measurement errors may be avoided in instrumental applications. We will explore two important characteristics of several different common integrated circuit op-amps.

(!) To measure the input offset voltage V_{offset}, connect the op-amp as a voltage follower and connect the non-inverting input to common. The output voltage equals V_{offset}. Perform this measurement for the three different types of op-amps and include the data in the table. Repeat for both of the LF353 dual op-amps. Note that the pinout of the 741 op-amp is identical to that of the LF351.

(!) To measure the input bias current, I_{bias}, a 10 MΩ resistor should be connected between the non-inverting input of the voltage follower and common. The IR drop across the resistor results from the bias current. The output voltage V_{out} is the sum of the offset voltage, V_{offset}, and the IR drop across the resistor. $I_{\text{bias}} = (V_{\text{out}} - V_{\text{offset}})/R$. Carry out this determination for each of the op-amps under investigation, tabulate, and comment on the results.

Op–Amp	$V_{\text{offset}} = V_{\text{out}}$, for $R_{\text{in}} = 0$	V_{out}, for $R_{\text{in}} = 10\text{M}\Omega$	I_{bias}, nA
LF353-1			
LF353-2			
LF351			
μA741			

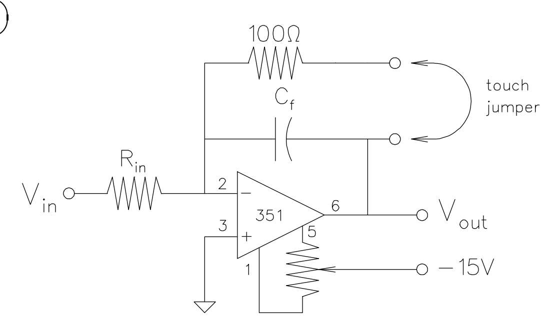
Experiment 4

Advanced op-amp designs

4.1 Op-amp integrator

The purpose of this section is to wire up and analyze an analog integrator, using a carefully balanced op-amp and a low-leakage quality capacitor. We will observe the circuit response to both dc input signals and to the ac waveforms generated by the FG.

(!)



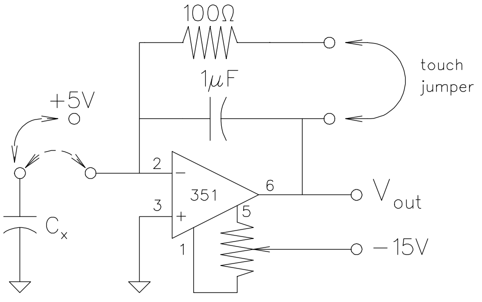
Using a capacitor as the feedback element in the inverting amplifier circuit, wire up the op-amp integrator.
Use a 1 μF low–leakage capacitor (10% tolerance or better), $R_{\rm in}$ = 1 MΩ, and set $V_{\rm in}$ = 100 mV.

(!) Measure the times required for the output to change by 1V, 3V, 5V, and 8V. Begin the timing when the touch jumper is removed. Use the jumper to discharge the integrating capacitor, *i.e.* to restart the integrator. Repeat 1V measurement at least 3 times, estimate the precision of your measurements (standard deviation).

The above measurements require that the op-amp be well-balanced. To test, restart the integrator, and quickly remove $V_{\rm in}$ when $V_{\rm out} \simeq$ 1V. Does $V_{\rm out}$ remain constant after that? If not, re-balance the op-amp.

(!) Connect the input to ground, reset the integrator, and observe $V_{\rm out}$ on the most sensitive DMM scale. Record your observations.

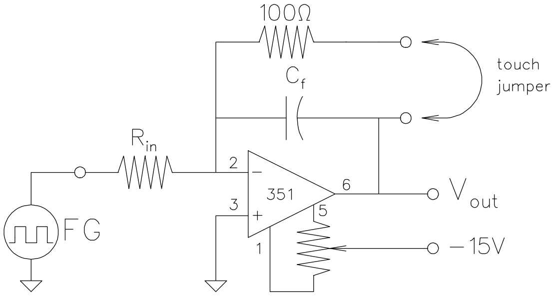
(!)



Modify the circuit as shown, turning it into a charge–to–voltage converter. The circuit will be used to measure the capacitance of another capacitor, C_x.
Discharge C_f (1 μF), disconnect the touch jumper, then carefully move the input jumper from +5V to the negative input of the op-amp, and observe changes in $V_{\rm out}$. Repeat several times.

? Compare the measured value of the ratio C_f/C_x with that obtained by a direct reading of the capacitance meter.

!



Use FG to provide a square–wave input to the integrator. Use $R_{\text{in}} = 1\ \text{M}\Omega$ and set the frequency to about 1 kHz. Choose the C_f value appropriate for this frequency. Monitor both the input and the output with the scope. Make sure you adjust FG to have a zero DC offset. Alternatively, you may want to use a small capacitor ($\simeq 1\,\mu$F) in series with FG, to remove the dc component from the input.

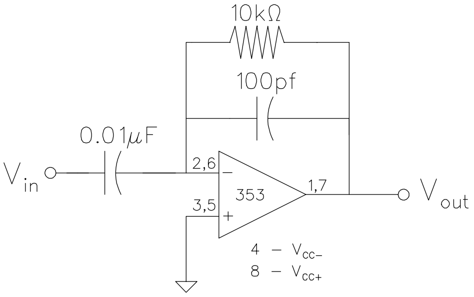
! Sketch and explain the observed waveforms.

4.2 Op-amp differentiator

By interchanging the resistor and capacitor of the op-amp integrator, we obtain an op-amp differentiator. We will analyze its response to various waveforms of the FG.

Do not remove the circuit of the previous section; you may want to re-use it in Section 4.3.

!



Wire up an op-amp differentiator as shown. In a dual-353 package you may choose either of the two op-amps (pins 2,3,1 or 6,5,7). The 100 pF capacitor is included to provide noise stability. For this circuit,

$$V_{\text{out}} = -RC\frac{dV_{\text{in}}}{dt}$$

Set the FG to 5V peak–to–peak 1 kHz triangular wave and connect it as V_{in}.

! Sketch the input and output waveforms, including the proper scales. Make sure your scope is on a calibrated setting.

Calculate and record the slope of the input triangular wave. Also, record the amplitude of the square wave at the output.

? Calculate the expected theoretical value for the differentiator output and compare it to the experimental value.

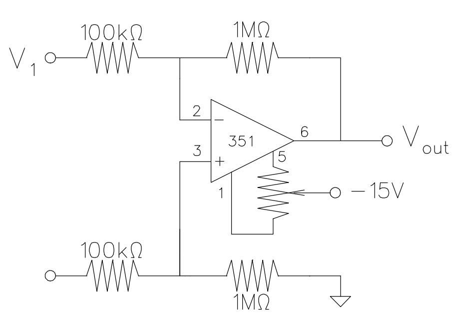
! Change the FG to square wave setting. Sketch the observed waveforms.

4.3 Difference amplifier

The purpose of this section is to introduce precision amplifiers and to learn to distinguish differential and common mode signals.

Ref: Simpson, Ch. 9–10, esp. Sec. 9.8.7, 10.4; Faissler, Ch. 31 (review); Malmstadt *et al.*, Ch. 8.1.

(!)



Wire up the difference amplifier as shown: Balance the op-amp by connecting both V_1 and V_2 to ground and adjusting the offset potentiometer until $V_{\text{out}} = 0$.
Leaving V_2 grounded, vary V_1 (several values between +1V and −1V) and measure V_{out}.

⍰ Calculate the average gain of the amplifier. In this measurement, which components determine the gain of the amplifier? How does the measured value compare with the theoretical one?

(!) Connect V_2 to a constant +1V source and repeat the above two steps.

(!) Connect *both* V_1 and V_2 to the same variable voltage source; measure V_{out} for several values of $V_1 = V_2$ between +1V and −1V.

⍰ Plot V_{out} *vs.* V_1 and determine the value of the **common mode gain** from the plot.

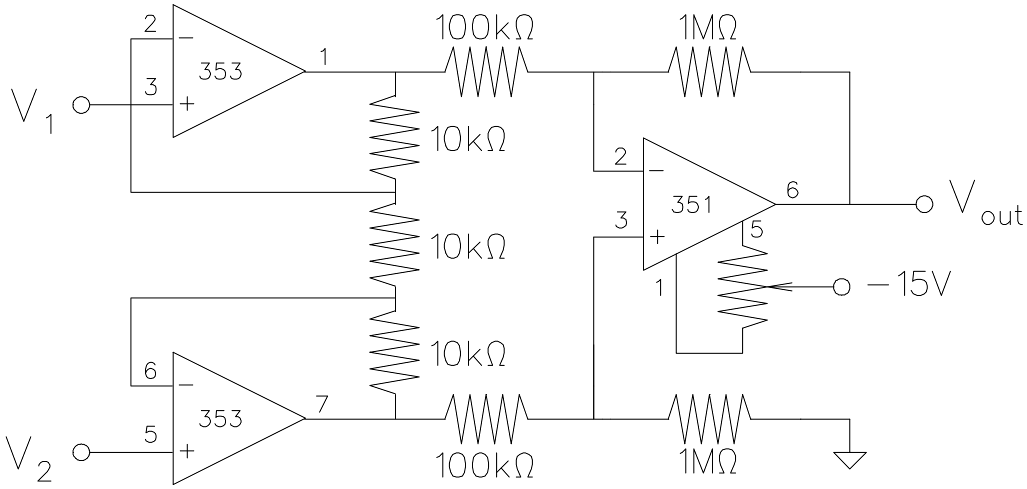
⍰ Interpret your data in terms of the imbalance of the resistance ratios of the two pairs of resistors determining the gain, for the inverting and for the non-inverting input. Which pair has the higher gain and by how much? How could this common mode gain be reduced?

⍰ Calculate the **common-mode rejection ratio** (CMRR) for your difference amplifier. Calculate the maximum common-mode signal the amplifier can accept if a 100 mV signal is to be amplified with an error of less than 0.1%.

4.4 Instrumentation amplifier

The purpose of this section is to combine the advantages of a difference input with the high input resistance of the voltage follower in a complete instrumentation amplifier.

(!) Wire up the instrumentation amplifier as shown (add the input voltage followers to the existing circuit).



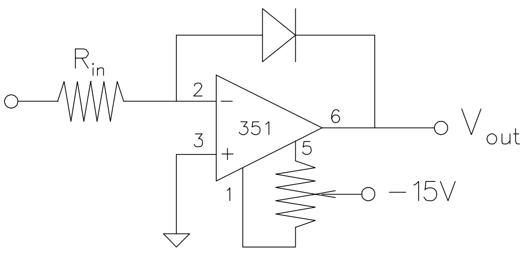
Check the offset of the instrumentation amplifier and adjust the difference amplifier offset potentiometer if needed. Measure V_{out} for various values of V_1 and V_2 so that you will be able to determine the difference gain and the common mode rejection ratio of the instrumentation amplifier. Be sure you have taken sufficient data to perform your calculations.

[?] Describe the reasoning you used in selecting the values for V_1 and V_2. From these data, determine the gain and the CMRR. Explain your interpretation of the data. Compare your results with the expected values.

4.5 Logarithmic amplifier

Using a non-linear feedback element with an op-amp (e.g. a pn–junction diode) produces startlingly different transfer functions. Logarithmic amplifiers serve as the basis for circuits such as analog multipliers studied in Section 4.6.

(!)



Carefully balance a 351 op-amp. Then wire the logarithmic amplifier (log amp), using a signal diode as the feedback element.

(!) Measure V_{out} as a function of V_{in} and R_{in}:

V_{in}	R_{in}	I_{in}	V_{out}
10.0mV	1MΩ		
10.0mV	100kΩ		
100.0mV	100kΩ		
1.0V	100kΩ		
10.0V	100kΩ		
10.0V	10kΩ		

$\boxed{?}$ Plot $\log I_{\text{in}}$ *vs.* V_{out}.

For all but very small forward bias voltages, the current through a diode varies exponentially with the applied voltage:

$$I \simeq I_i e^{eV/\eta kT}$$

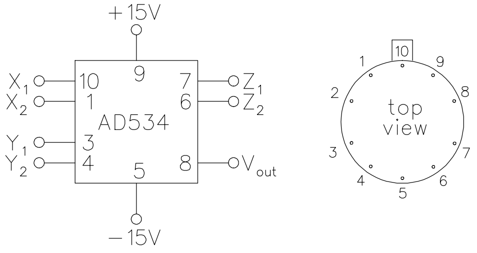
where η is an empirical parameter (~ 2 for Si, 1 for Ge diodes), and I_i is the intrinsic current at zero bias.

Apply circuit analysis (Simpson, Sec. 9.7) to your logarithmic amplifier and verify that the same relationship holds for the measured I_{in} and V_{out}.

Fit your data to the above equation and determine the parameters η and I_i for your diode. Can you tell if this is a Si or a Ge diode?

4.6 Analog multiplier

Combining log amps with adding amps allows one to build analog multipliers and other components of analog computers (for a review, see Faissler, Ch. 30). Here we examine the transfer functions of one such commercial device, AD534.



AD534 is internally trimmed and does not require external trimmer potentiometers. Its pinout is shown on the left.

(!) For multiplication, use the fixed +10V supply from the job board as the X_1 input and use several fixed voltages from the reference job board as the Y_1 input (+10V, −10V, −1V, +1V). Connect the Z_1 input to the output. Connect the X_2, Y_2, and Z_2 inputs to common. Test the multiplier in all four quadrants by applying voltages of both polarities in the range of ±10V. The multiplier transfer function should be $V_{\text{out}} = (V_x \times V_y)/10$. Include in your data set (X_1, Y_1) values of $(+10, 0)$, $(0, 0)$, and $(0, +10)$.

$\boxed{?}$ Offsets modify the multiplier equation:

$$V_{\text{out}} = V_{\text{out}}{}^{(0)} + 0.1 \times \left[V_x - V_x^{(0)}\right] \times \left[V_y - V_y^{(0)}\right]$$

where $V_x^{(0)}$, $V_y^{(0)}$, and $V_{\text{out}}{}^{(0)}$ are the X, Y, and output offsets, respectively. Use your data to evaluate each of the offsets. Explain how magnitude of offset–induced errors changes with X and Y input levels.

(!) To obtain an output voltage proportional to the square of an input voltage, connect both X_1 and Y_1 inputs to the same voltage source and the X_2 and Y_2 inputs to common. The Z_1 input remains connected to the output. Test the circuit over a ±10V range of voltages and compare to the expected $V_{\text{out}} = 0.1 \times {V_{\text{in}}}^2$.

(!) The "squared voltage"output can be plotted against the input with the xy–mode of the oscilloscope. Substitute the output of the FG set in the sine wave mode as the source in the squaring circuit wired above. Connect the multiplier output to the vertical scope input and the FG output to the horizontal. Use a 10 Hz sine wave signal. Sketch the resulting display.

(!) Now use the dual-trace mode to observe the waveforms of the input and output signals. Sketch a representative display and indicate the position of OV for each waveform.

⍰ Explain the relationship of the frequencies and the DC components of the input and output waveforms.

Optional: analog division

(!) To obtain division, connect the multiplier output to the Y_2 input. Now Z_1 is no longer connected to the output, and Z_2 is no longer grounded. In this configuration:

$$V_{\text{out}} = 10 \times \frac{V(Z_2) - V(Z_1)}{V(X_1) - V(X_2)} + V(Y_1)$$

Measure V_{out} for several values of $V(Z_2) - V(Z_1)$ and $V(X_1) - V(X_2)$. For simplicity, you may want to ground Z_1, X_2, and Y_1. Make sure you keep $V(X_1) - V(X_2)$ positive (see the spec sheets of AD534).

⍰ The output limits of AD534 are ±11 V. Calculate and plot the minimum value for $V(X_1) - V(X_2)$ as a function of $V(Z_2) - V(Z_1)$ over the $V(Z)$ range of ±10 V.

Experiment 5

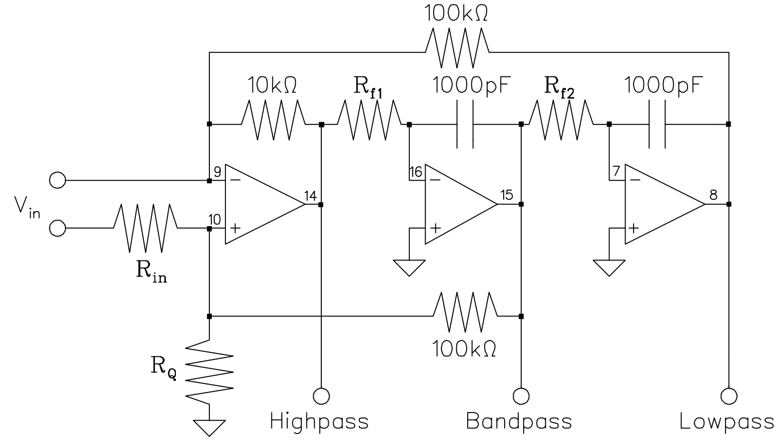
Active filters and tuned amplifiers

5.1 Active filter

Weak signals require special attention. The techniques of separating signal from noise vary depending on the nature of the signal and of noise. There are no general easy prescriptions.

When the frequencies of the signal and of the noise differ, one way to increase the signal–to–noise (S/N) ratio is to restrict the bandwidth of the amplifier in such a way that only the signal frequencies are transmitted. This principle is illustrated using an active filter device.

The AF100 universal active filter is a versatile active filter device. It has high–pass (HP), low–pass (LP), and band–pass (BP) outputs simultaneously available and an uncommitted summing amplifier for making notch filters. The centre frequency is tunable from 200 Hz to 10 kHz with two resistors. The quality factor (Q) is variable from 0.01 to 500 by changing two additonal resistors. The AF100 can be used in either an inverting or a non–inverting configuration.

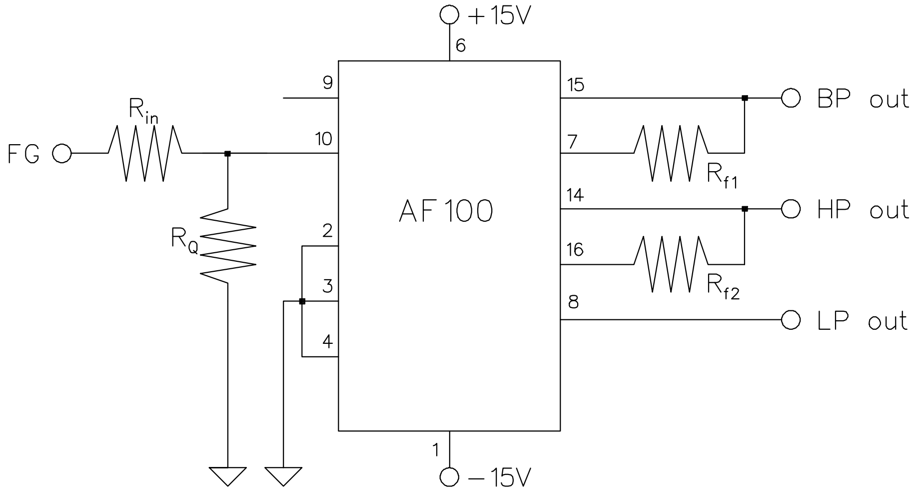


The pinout and the schematic diagram of an AF100 are as shown. R_{in}, R_{Q}, R_{f1}, and R_{f2} must be supplied externally to AF100 (see below). All other components are internal.

The gain and Q value of the filter are determined by R_{in} and R_{Q}. The centre frequency of the filter is determined by identical resistors, R_{f1} and R_{f2}, according to

$$f_0 = \frac{50.33 \times 10^6}{R_{\mathrm{f}}}, \qquad \text{in Hz}$$

(!)



Wire up the non–inverting mode filter using external resistors of $R_{f1} = R_{f2} = 100\text{k}\Omega$ and $R_{in} = R_Q = 100\text{k}\Omega$. Use precision resistors if possible.

(!) These external resistor values should give a centre frequency of $\sim$ 500Hz and a Q of slightly greater than unity. Connect the FG output to R_{in} and use the scope in the two–channel mode to observe both the FG output and the bandpass output of the filter. Connect the FG TTL output to the digital counter for a readout of frequency. Set the FG for a 1V peak–to–peak sine wave. Observe the bandpass output as the FG frequency is varied through the centre frequency, f_0.

[?] What happens to the bandpass output at f_0?

(!) To measure f_0 accurately, switch the scope to produce an xy–plot (Lissajous figure) of filter output *vs.* filter input. At the centre frequency the bandpass output should be exactly 180° out of phase with the input signal. Use the Lissajous figure to adjust the FG exactly to the centre frequency (see Experiment 1, and/or *Malmstadt* p.43 or *Brophy* p.63, for a discussion of Lissajous figures).

(!) Now switch the scope back to the dual trace mode and measure the peak–to–peak output voltage of the bandpass filter as a function of FG frequency over a range of 20 Hz to 20 kHz. Record 10–15 values in this range including several near f_0.

(!) Calculate and plot the filter gain in dB *vs.* log frequency.

[?] From the graph, determine the rolloff rate of the filter in dB/decade, on both sides of f_0.[1] Comment on the values you obtain.

(!) Now connect the scope to the low–pass filter output. Convince yourself that the device acts as a low–pass filter. Accurately measure and record the 3 dB frequency where gain $G = 0.707 \times G(\text{lowfrequency})$, and the phase shift at the 3 dB frequency.

(!) Repeat for the high–pass filter output.

(!) To get a filter with a higher Q, use $R_{in} = 20\,\text{k}\Omega$ and $R_Q = 1\,\text{k}\Omega$. Set the FG to give a sine wave with $V_{p-p} \simeq 0.5\text{V}$. Observe the bandpass output.

(!) Measure and plot the gain in dB *vs.* log frequency for the high–Q bandpass filter.

---

[1] A useful `physica` trick: `fit G=(a*f+b)*(f<=480)` will only fit $G(f)$ for values of $f = 480$ and below.

? Estimate the Q of the two bandpass filters you have investigated. Q can be measured as the ratio of the centre frequency f_0 of the bandpass output to the bandwidth (the difference in frequency between the upper and the lower 3 dB points).

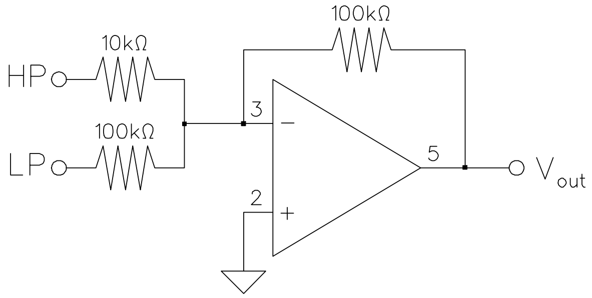
! Return the AF100 to the low–Q state, ($R_{\text{in}} = 100\text{k}\Omega$, $R_{\text{Q}} = 100\text{k}\Omega$). Vary the feedback resistors and measure the centre frequency of the bandpass output.

$R_{\text{f1}} = R_{\text{f2}}$	f_0, predicted	f_0, measured	% error
10kΩ			
50kΩ			
200kΩ			

5.2 Notch filter

A special form of active filtering can be thought of as the reverse of bandpass filtering. In analyzing a notch filter *we concentrate on the noise rather than the signal.*

!



AF100 has one additional, uncommitted, summing op–amp. It can be used to construct a notch filter by summing the low and high–pass outputs, as shown. Wire up the above circuit. **Make sure you disconnect the grounding wire from pin 3!** Set the AF100 to $f_0 = 500\text{Hz}$.

! Measure the frequency response of the notch filter. Choose the frequencies of the FG wisely: take a sufficient number of measurements to resolve the shape of the filter's transfer function.

! Plot the gain *vs.* log frequency.

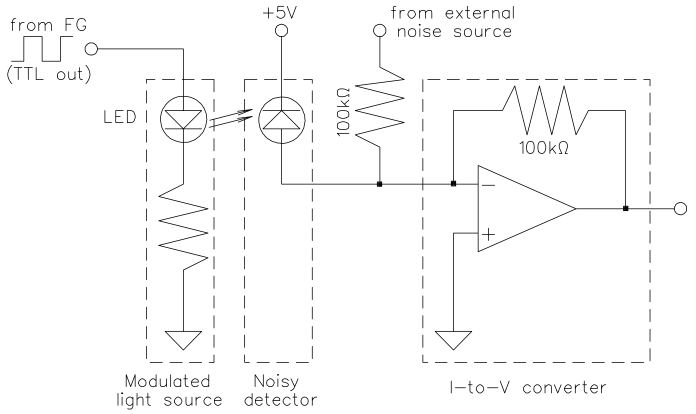
? What type of noise could be reduced using the notch filter?

? Determine f_0 from your plot. How does it compare with the expected value?

5.3 Lock–in amplifier

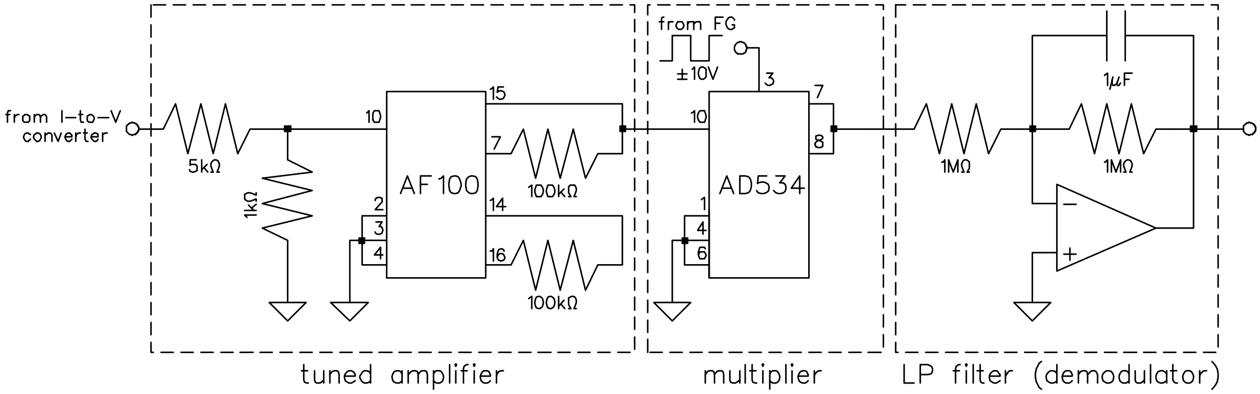
One of the best ways to dicriminate against noise is to use a lock–in amplifier. It combines the techniques of signal modulation at the source, band–pass limitation, and phase–lock demodulation to provide ability to distinguish weak signals "buried" in the noise. Because they actively modulate the source signal, lock–in amplifiers are capable of distinguishing signal and noise that have overlapping frequency spectra.

(!)



Connect a biased photodiode or a phototransistor to a I–to–V–converter. Connect an LED to the TTL output of the FG set at about 500 Hz. Do not connect the external noise source (NM on the job board) yet.
Use the scope to observe the output of the converter and adjust the position of the photodiode and/or the gain of the amplifier until the square–wave component of 50 to 100 mV is obtained at the output.
Make note of the DC level, the square–wave amplitude (p–p), and the approximate noise amplitude (p–p) in the output signal.

[?] Why is there a DC component in the output of the I–to–V–converter?



(!) Now connect the AF100 tuned amplifier circuit to the output of the I–to–V converter. Observe the tuned amplifier output with the scope. Adjust the FG frequency to get the maximum output from the tuned amplifier. Record your values of tuned amplifier output voltage (p–p), waveshape appearance, DC component of the output voltage, and the FG frequency setting.

[?] You should have observed a sine wave at the tuned amplifier output. The input, however, was a noisy square wave with a DC component. Explain the difference in input and output waveforms.

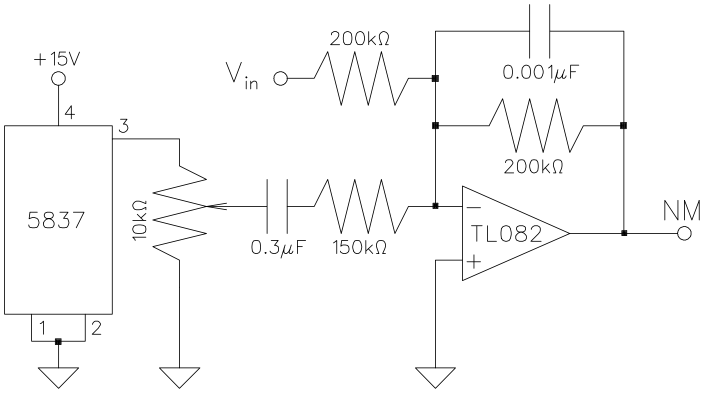
(!) The analog multiplier and low pass filter (phase–locked demodulator) should now be connected. The tuned amplifier output is multiplied by a square wave that is synchronous with the LED modulation. Adjust the FG square wave output to supply a ±10 V reference signal to the multiplier. Observe the multiplier output. Adjust the FG frequency carefully to obtain a waveform that most closely approximates a full–wave rectified sine wave. Draw the observed multiplier output waveform. Label the axes.

(!) Connect the active low–pass filter to the multiplier output. Observe the DC output with the scope. Record the DC level observed with the modulated LED on and off.

(!) Look again at the I–to–V converter output and measure the ratio of the square–wave amplitude to noise amplitude.

[?] Calculate the signal–to–noise (S/N) ratio improvement obtained with the lock–in amplifier.

(!) To better demonstrate the noise rejection capabilities of the lock–in amplifier, still more noise will be intentionally added to the signal. This noise will be obtained from the noise generator circuit available on the reference job board.



The relevant part of the reference job board circuit is shown. The 5837 digital noise generator IC produces 10 V pulses that have varying durations. The pulse durations are random integer multiples of 20 μs. The 10 kΩ potentiometer selects a fraction of the noise generator output amplitude. The noise signal is AC–coupled into a summing amplifier that also serves as an active low–pass filter.

The additional input to the summing amplifier allows the noise generator signal to be added to another signal: $V_{\mathrm{NM}} = V_{\mathrm{in}} + \mathrm{noise}$

Vary the 10 kΩ potentiometer to obtain maximal noise amplitude. Sketch the waveform observed on both sides of the coupling capacitor and at the output of the summing amplifier. An oscilloscope time base of 20 μs/div is recommended.

Also observe the output of the summing amplifier at a sweep speed of 500 μs/div. This output is labelled NM on the job board, for Noise Mixer output.

? Calculate the cut–off frequency of the low–pass filter in the NM. What is the attenuation of this filter for the frequency component that results from transitions every 20 μs (25kHz)?

(!) Connect the NM output through a 100 kΩ resistor to the summing point of the I–to–V converter (in the noisy signal source). Observe the converter output with a scope and adjust the noise generator output from zero until the square wave becomes difficult to see. (Trigger the scope from a clean square–wave or TTL output of the FG to avoid loss of synch.) Measure the DC output voltage of the lock–in amplifier, with the modulated LED on and then off. Compare again the signal–to–noise (S/N) ratios at the input and output of the lock–in amplifier.

? Explain why it is necessary to modulate the signal in order to obtain the improvement in S/N through the lock–in technique.

Experiment 6

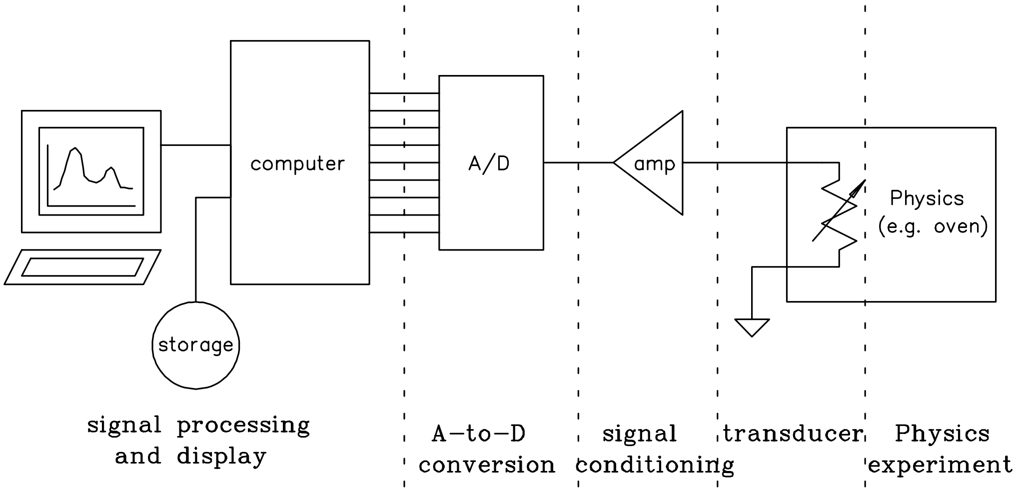
An introduction to using microcomputers in a physics laboratory

To use microcomputers as laboratory instruments, we need to learn the basics of their architecture, and the ways to control them at the level of electrical signals. We "look under the hood" of a computer-based data acquisition system and learn how to control its hardware through low-level programming.

Introduction

Hardware

- microcomputers as lab instruments



- inside an IBM PC
  - the mother board: CPU, RAM, BIOS, some I/O & timing circuits
  - the I/O bus: expansion cards
    Note: CPU often has a separate, faster & wider bus to access memory (RAM)
  - I/O card and the connection to the outside world
  - operation of the computer boils down to controlled transfer and manipulation of bits (digital on/off, 0V/5V levels) among various components

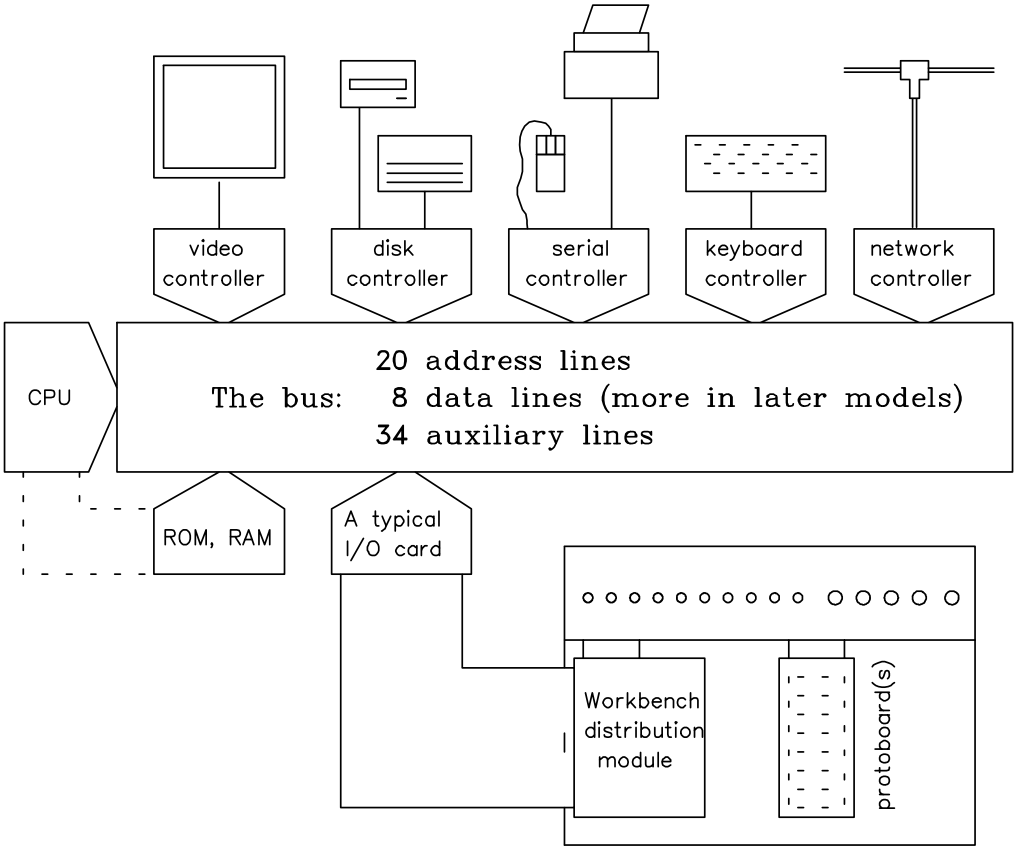


Figure 6.1: Essential elements of a personal computer

  - complex operations: many clock cycles; some devices may have to wait; computer is not a "real-time" device! — but latency is small
  - structure of a computer bus: *address lines* — which device is getting/sending data; *auxiliary* — the timing of the transfer, handshaking; *data lines* AD0–AD7 — the data may be a real number, a machine instruction, a part of an address, *etc.*

- A typical I/O interface:
  - I/O card inside a PC
  - ribbon cables
  - distribution module at the workstation
  - optoisolators and separate commons
  - 4 x 8-bit input & 4 x 8-bit output parts
  - multiplexed 4-input, 12-bit A/D converter (bipolar ± 10V)
  - 2 x 12-bit D/A outputs (bipolar ± 10V)
  - counter & timer circuits

Software

- Programming languages: see the summary in Table 6.1

Table 6.1: The hierarchy of programming languages

Language	Examples	Comments	C†
4th generation	code generators, AI	large projects, productivity	
High-level	Fortran, Pascal, Basic	easy on humans, hw independent	●
Low-level	Assembler (mnemonics)	hard, but full control of hw	●
Machine	operation codes	"understood" by the CPU	
Hardware	bits, 0/5V voltage levels		

† C bridges the two layers; is a high-level language but allows low-level extensions.

- Compilers: computer programs that translate the human-readable source code into machine-executable op-codes.
- Op-codes: for example, about 300 in six functional groups for 8088/8086:

data transfer	`mov, in, out, xchg`
arithmetic	`add, sub, inc, dec, mul, div`
logical	`and, or, xor, not`
string manipulation	
control transfer	`jmp, call`
processor control	

- 8088/8086 registers: Table 6.2 shows a list of 14 internal (to CPU) memory locations with very fast access used to keep track of where in the program the CPU is. Each register is 16-bit wide. However, General Registers (see Table 6.2) can also be addressed in two 8-bit chunks (`xL` and `xH` for Low and High bits, respectively).
- SEGMENT:OFFSET addressing: 16 bits can address 65,536 locations = size of segment; 20 bits can address 1MB

segment (16 bits)																	0	0	0	0
+																				
offset (16 bits)	0	0	0	0																
=																				
address (20 bits)																				

- IBM PC memory map is summarized in Table 6.3

This is just an example of a particular architecture (IBM PC); other microprocessors and microcontrollers differ in the details, but are fundamentally similar to the above description.
More to come...

Table 6.2: 8086/8088 CPU registers

16-bit segment	high 8 bits	low 8 bits	comments
General registers:			
AX	AH	AL	accumulator register
BX	BH	BL	
CX	CH	CL	
DX	DH	DL	
Addressing registers:			
SI	–	–	
DI	–	–	
BP	–	–	
Control registers:			
SP	–	–	
IP	–	–	
Flags[†]	–	–	
Segment registers:			
CS	–	–	Code Segment pointer
DS	–	–	Data Segment pointer
ES	–	–	
SS	–	–	

[†] Flags: consists of individual bits which flag certain conditions. *E.g.*, bit `ZF=on` (`Z`ero `F`lag) means the last instruction yielded a 0 as a result.

Table 6.3: IBM PC memory map

`00000 - 003FF`	I/O
`00400 - 0047F`	BIOS Ram
`00480 - 005FF`	RAM for special purposes (ROM Basic)
`00600 - 9FFFF`	Program memory
`A0000 - AFFFF`	VGA video expansion
`B0000 - B0FFF`	IBM monochome video
`B8000 - BFFFF`	CGA video memory
`C0000 - CFFFF`	reserved for video expansion
`D0000 - D7FFF`	ROM, usually not all installed
`D8000 - DFFFF`	”
`E0000 - E7FFF`	”
`E8000 - EFFFF`	”
`F0000 - F3FFF`	reserved for ROM
`F4000 - F5FFF`	”
`F6000 - FDFFF`	Basic in ROM in the original IBM PC
`FE000 - FFFFF`	BIOS ROM

Experiment 7

Building and using a digital thermometer

Some things happen so fast that one simply cannot monitor them without help from a fast computer in the role of a data taker. One example is a rapid quench which occurs when a hot body is immersed into a cold fluid. Is the rate of cooling still proportional to the temperature difference?

add details here

(!) Assemble the thermistor circuit as shown in Fig.7.1.

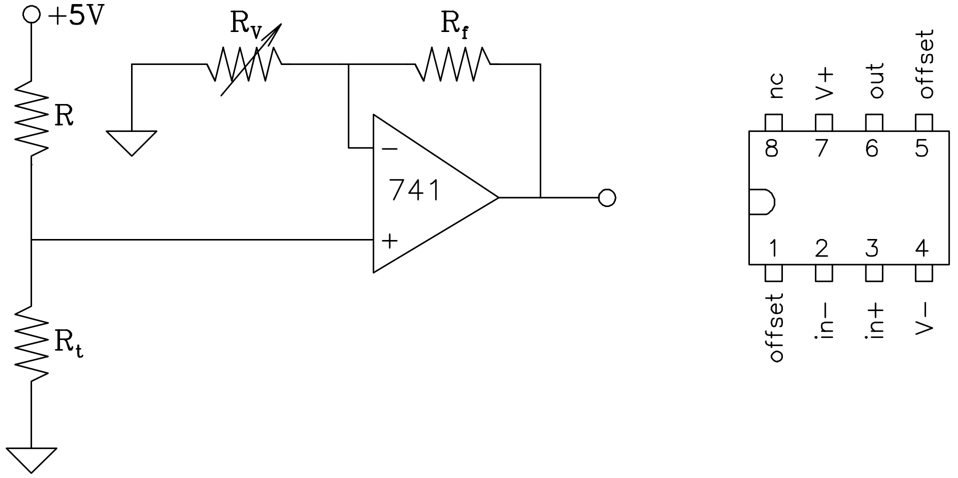


Figure 7.1: **Thermistor circuit.**
R, $R_f \sim 10\mathrm{k}\Omega$; $R_V = 10\mathrm{k}\Omega$ potentiometer; R_t = thermistor, R_t decreases as temperature increases

(!) Immerse thermistor and mercury thermometer into a beaker of ice-water at $t = 0°\mathrm{C}$. Adjust R_V so that $V \approx 9.5\,\mathrm{V}$ at 0°C.

Calibrate V as a function of t. Slowly heat the water — so as to maintain thermal quasi-equilibrium — and measure V and t at $\sim 5\,\mathrm{s}$ intervals. Heat to $\sim 60°\mathrm{C}$. Use little water for speed. Use the program you have written to measure V; record temperature readings from the mercury thermometer by hand.

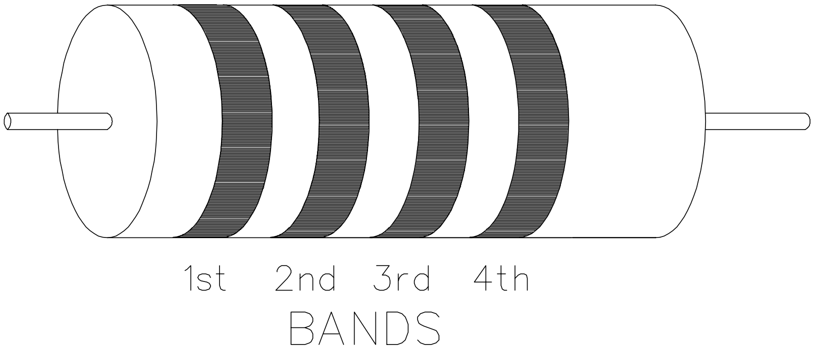
(!) Plot and analyze your data and create the temperature calibration plot of the thermistor circuit.

(!) *Optional:* modify your program to report true temperature in °C.

(!) Prepare two beakers, one with ice-water, one at a moderately high temperature. Immerse the thermistor/mercury thermometer assembly into the hot one. Modify your program to perform a frame grab of a large number of points. Start the program and rapidly transfer the assembly into the ice-water beaker. Use your calibration data to plot true temperature as a function of time and analyze your data, attempting to verify Newton's law of cooling (the rate of cooling is proportional to the temperature difference). Note and comment on the deviations from the exponential behaviour.

Appendix A

Resistor colour code



Colour	First Band	Second Band	Third Band
Black	0	0	10^0
Brown	1	1	10^1
Red	2	2	10^2
Orange	3	3	10^3
Yellow	4	4	10^4
Green	5	5	10^5
Blue	6	6	10^6
Violet	7	7	10^7
Gray	8	8	10^8
White	9	9	10^9
Gold	-	-	10^{-1}
Silver	-	-	10^{-2}

	Silver is	±10% tolerance
Fourth Band:	Gold is	±5% tolerance
	No band is	±20% tolerance

For example, the resistance of a resistor whose bands are red, red, red, silver is

$$22 \times 10^2 \longrightarrow 2.2\,\mathrm{k}\Omega \pm 10\%$$