This page intentionally left blank as with all other content free even-numbered pages at the end of a chapter. Except that this one isn’t actually blank, as you can see.

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Introduction

0.1 Course Description

Physics 240, “Design, Fabrication, and Use of Scientific Apparatus,” is the third course in the BYU Physics laboratory sequence. It is intended to provide experience in building and using moderately complex laboratory equipment.

The primary activities in the course include

- Machine the components for a simple thermal measurement system.
- Build a heater on the thermal measurement system.
- Build circuitry and develop a LabVIEW Virtual Instrument to record the temperature of the thermal system using a 1N4148 diode as a sensor.
- Measure the response of the system to both heating and cooling.
- Write a technical report describing the thermal response measurements.
- Build a temperature controller for the thermal system using LabVIEW.
- Determine the critical temperature of a BSCCO (Bi_{2−x}Pb_{x}Sr_{2}Ca_{y−1}Cu_{y}O_{δ}) superconductor sample.
- Participate in a discussion of scientific ethics including responding to several APS case studies.
- Write a report in the style of a journal article describing the superconductor measurements.
- Write a proposal for a student-designed experiment.
- Carry out the proposed experiment.
- Give a 12-minute oral presentation regarding the student-designed experiment.

0.2 Course Learning Outcomes

- **Design and Build:** Design, build, and interface experimental apparatus.
• **Measurements:** Make involved physical measurements and analyze experimental results.

• **Record Keeping:** Document in a personal lab notebook the procedures, methods, results, and analysis of laboratory exercises.

• **Presentation:** Present work in writing and through oral presentations.

• **Ethics:** Demonstrate understanding of professional ethics guidelines for research activities and presentation of results.

### 0.3 About the Course Packet

This packet serves as a stand-alone document describing the exercises and materials used in the Physics 240 laboratory.

The class is usually organized using the Brigham Young University Learning Suite system with considerable instruction included in addition to the formal handouts. These instructions have been included as much as possible in this packet. The difficulty is that the instructions in Learning Suite can frequently be changed whereas this packet will be much more stable and increasingly stale as time goes on.

The packet consists of 9 chapters and 19 appendices. Each chapter covers the fundamental material required for one of the exercises, experiments, or discussions.

The appendices contain supplemental information that supports the lab exercises. The appendices are in the order they are first referenced by the materials in the preceding chapters.

It is likely that you will not be able to complete any of the exercises unless you consult both the appropriate chapter and the associated appendices.

There are Internet URLs included in the packet that were current and worked at the time the packet was assembled. It is possible that some of those URLs are no longer working although every effort has been made to use those that appear to be stable over the long term.

A PDF copy of this packet is available at [https://www.physics.byu.edu/faculty/petersonb/Phys240/240Packet.pdf](https://www.physics.byu.edu/faculty/petersonb/Phys240/240Packet.pdf). In that copy, the table of contents, references to other portions of the packet, and URLs are all active links that simplify finding materials.

There are also references to “the text” in several portions of the packet. These refer to the book *Building Scientific Apparatus*.\(^1\)

---

Chapter 1

The Machining Lab

1.1 Expected Learning Outcomes

- Understand how to operate common machine shop equipment safely.
- Demonstrate capability to use machine shop equipment to fabricate simple experimental apparatus.
- Demonstrate ability to understand standard mechanical design documents and to use them to guide fabrication of moderately complex items.

1.2 Grading

The grading for this portion of the class will be as follows:

- Lathe projects (heater block, cooling rod, brass cap) – 30 pts.
- Mill project (jack-in-a-cube) – 20 pts.

1.3 Introduction to the machine shop

Before you can work in a machine shop, it is necessary to be trained in proper safety procedures. It is also necessary to be trained in the operation of the particular machines you will be using. During our first class period in the shop, we will complete the safety training. The safety guidelines are included in section 1.4.
We will also provide training for the machines we use in our projects. The training will be given when you are ready to use a particular machine, so it is fresh in your memory as you begin.

Several resources are available to introduce the machines and give an overview of their operations. Having a general understanding of the machines can also help in understanding the rules and regulations described in this chapter.

Links to a Virtual Machining Tutorial can be found at https://www.physics.byu.edu/faculty/petersonb/Phys240/VirtualMachiningTutorial.html to make it possible to review the machines and operations that are available in the machine shop.

It will also be useful to read Sections 1.1.2 to 1.1.4 (Machines for Making Holes, The Lathe, and Milling Machines) and 1.4.1 (Threaded Fasteners) in the text.

1.4 Machining lab regulations and safety

One of the most important responsibilities of each student in the laboratories on campus is to learn and observe appropriate safety procedures. The machines with which you will work in the machine shop are designed to manipulate all forms of materials. They can cause serious injury if not used correctly.

1.4.1 The basic rules

One simple rule:

If you do not know how to use the machine, DO NOT USE IT WITHOUT HELP!

Do not be afraid to ask questions of the TAs and machine shop staff.

1. Always protect your eyes. Safety glasses must be worn at all times in the lab. Eye protection must comply with the American National Standards Institute, ANSI Z87.1-1989 standard. You must be able to find the code Z87.1 stamped on or molded into the glasses somewhere for them to be acceptable.
   • Goggles or a face shield should be used when additional protection is needed.
2. Ear protection is not required but may be desirable for operating some machines or if you are sensitive to loud noises.
3. Ensure that other individuals are present in the lab before using any equipment.
4. Dress correctly.
   - Long pants and closed-toed shoes are required in the machine shop. Sandals, bare feet, shorts, skirts, capris, kilts, and mu’umu’us are not allowed.
   - Never wear loose clothing or long sleeves. Remove your necktie or tuck it into your shirt.
   - Keep your hair cut reasonably short or tied back to prevent it from contacting any moving parts.
   - Remove all jewelry such as rings and wristwatches.

5. Machines must be stopped before taking measurements or making adjustments.
7. Never start or stop a machine for someone else.
8. Never leave a chuck wrench in the chuck of a machine - if your hand is not on the wrench, the wrench must not be in the chuck.
9. Never use rags or hands to remove chips - chips are often hot and sharp.
10. Know your job and follow instructions. If you don’t understand the instructions, ask a TA or the instructor, NOT another student.
11. Remember: a shop is a place to work. Always attend strictly to business and keep your mind on what you are doing. “One moment of carelessness may mean a lifetime of sorrow.”
   - Never distract others who are using a machine.

12. Report all accidents to TAs and instructor.
13. Use only tools in good repair and report all tools that are not.
14. Never try to stop a revolving chuck with your hands.
15. Use only those pieces of equipment which have been demonstrated.
16. Never test the finish of revolving work with your finger.
17. Always check to see that spindles and chucks are tight before use.
18. Stay away from moving parts and equipment.
19. Work stock should not project more than 2.5 times the diameter out of the chuck or collet without being supported.
20. Permission must be obtained from a TA or instructor before any work is done in the lab.
21. Oily and greasy rags should be placed in a special covered container.
22. If you spill any liquids they should be cleaned up immediately.
23. When required to move long or heavy stock, get assistance.
24. Always use the proper tool for the job.
25. Sharp tools are safer because they require less force to perform the operation.
26. When cutting with a knife or hand tools always cut away from your body.
27. When cutting on a bandsaw, the work must rest flat on the table.
28. Make sure that stock, tool, and tailstock are properly tightened before an operation is started.
29. Keep work area clean.
   - There is a place for everything, and you must keep everything in its place.
   - Do not place tools where they may fall or be accidentally pushed into a running machine.
   - Keep tools properly arranged.
   - Keep the area around the machine clean and free of oil.
   - Keep benches, aisles, and floors clean and clear.
   - **Always clean up your machine when you finish using it**, as well as the surrounding area.
30. User proper feed and speed for the operation being performed.
31. Keep machine guards in place.
32. Know the location of fire extinguishers.

### 1.4.2 General safety guidelines

**Speeds and Feeds:** Choose and set the correct speeds and feeds. It is critical to many machine operations. If you do not know how to determine these parameters, ask for help. Appendix A, “Tool Speeds Chart,” gives guidance on choosing the proper tool speeds for various materials and operations.

**Unusual Noises:** Stop what you are doing if you hear something unusual or suspect something has changed and check it out. Pay close attention to what you are doing at all times.

**Broken or Damaged Tools:** Immediately report broken or damaged equipment and tools to the lab supervisor or TA. It is expected that tools will occasionally break, and equipment will suffer from wear and tear. It is important that these items be brought to our attention so that the equipment and tooling can be maintained and operated safely.

**Machine Operation:** Operate a machine only one person at one time. It is extremely hazardous for more than one person to work the controls of a machine. If assistance is needed to support material being processed, the assistant should only provide support and allow the operator to provide all motion to the workpiece or machine.

**Horseplay:** Never engage in horseplay of any kind.
Correct Tools: Always use the correct tool for the job. If you are not sure what is needed, please ask for assistance.

Sharp Tools: Sharp tools are safer, provide better results, and require less effort to accomplish a task. Ask for assistance to have tools sharpened or replaced.

Safety Equipment: Know the location of any safety equipment, such as fire extinguishers or emergency showers.

Emergency Situations: Call 911 on a BYU campus desk or wall phone or 801-422-2222 on a cell phone if there is any question about the seriousness of an emergency. Your first responsibility is to get as much assistance as possible to the situation while providing emergency care to the best of your knowledge.

First Aid: Immediately report all accidents to a lab supervisor, TA or faculty member. First aid kits are available for simple cuts or abrasions. BYU is not responsible for paying for medical services in response to accidents within its lab areas unless specific liability is established. You should make medical care decisions based on the assumption that you are responsible for payment.

Material Spills: Immediately clean up if you spill liquids or materials on the floor. If the materials are hazardous in nature, immediately notify the supervisor or TA to determine what course of action should be taken.

Disposing of Chemicals: Never put anything but water (and hand soap) down the drain. BYU has a chemical management department that will assist with the disposal of chemicals.

Mixing of Chemicals: Never mix chemicals of unknown origin or if you are in doubt about the outcome. Many chemicals are incompatible and become volatile or toxic when mixed improperly. If you are in doubt, get assistance.

1.4.3 Lathe operation safety guidelines

Chip Removal: Never remove chips with your hand. Use a brush, wire, or pair of pliers to remove chips.

Rotating Parts: Use extreme caution to keep away from the rotating parts. Lathe operations involve rotating chucks and workpieces. Never touch the workpiece or make measurements while the part is turning. Remove long, stringy chips only when the lathe is stopped. Turn the spindle by hand before turning the power on to ensure that there is no interference between the rotating parts and the machine.

*NOTE: If lathe chuck jaws are opened too far, they can come out of the chuck during lathe operation, causing serious injury.

Changing Speeds and Feeds: Never change gears while the lathe is running. If you cannot get the machine into gear, rotate the spindle or lead screw by hand to align the gear-set and allow the gears to engage.
Chuck Wrenches: Always remove the wrench from the chuck, even if you will be using it soon. You can only remove your hand from the chuck wrench if the wrench has been removed from the chuck. Make this a habit!

Mounting Stock in Chucks: make sure the stock does not protrude from the chuck or collet more than 2.5 times the stock diameter unless supported by a center or other rest.

Tool Alignment: Check the alignment of the tools and spindle. When stopped the tools should be aligned with the spindle. Proper tool alignment is critical for good material removal and finish. Tools should be mounted with a minimum overhang to provide maximum rigidity.

Automatic Feeds: Be sure you know in which direction and how fast the cross-feed or carriage will move before engaging the automatic feed. It is usually wise to verify motion by moving the tool away from the part and engaging the feed to check the direction and speed.

1.4.4 Milling machine operation safety guidelines

Variable Speed Heads: Only change speed with the spindle running on machines equipped with variable speed heads.

Removing Chips: Never remove chips with your hands. Use a brush to sweep chips from the part.

*CAUTION:* The chips produced by milling cutters are very hot and can be thrown some distance.

Measuring: Never measure parts with the spindle turning.

Climb (Up) vs. Conventional (Down) Milling: Use climb milling whenever possible. It causes less tool wear, requires less cutting force, and leaves a better surface finish. Conventional milling is best used when milling thin sections, using large cutters, or when the milling machine has excessive backlash in the feed screw.

To remove tooling from the spindle:
1. Ensure that the spindle is fully retracted.
2. Hold the tool with a towel or rag to protect your hand.
3. Press and hold the off button until the tool loosens into your hand.

To install a collet/tool in the spindle:
1. Ensure that the spindle is fully retracted.
2. Clean the inside of the spindle and the collet/tool.
3. Hold the tool with a towel or rag to protect your hand.
4. Insert the collet/tool into the spindle and rotate it until the keyway on the collet/tool lines up with the key on the spindle.
5. Press and hold the on button until the collet/tool fully engages into the spindle head.
1.4.5 Drill press operation safety guidelines

Clamp All Work: Secure all work in a vise or clamp it to the table. If the workpiece breaks free and begins to rotate, immediately turn the drill off and wait for the piece to stop rotating.

Chuck Key: Never leave the chuck key in the chuck.

Drilling Tip: Let up on the pressure as you approach breaking through material that you are drilling.

1.4.6 Cut-off band saw operation safety guidelines

Speed: Be sure the speed is set correctly for the type of material to be cut.

Clamp All Work: Verify that the piece is firmly clamped in the vise. Just because the clamp screw is tight (that is, it won’t turn any further), that doesn’t mean the piece is clamped.

Feed: Use the hand wheel or the power feed to feed the blade through the part after the coolant begins to flow. If using the power feed, choose the pressure that is appropriate for the material being cut. Typically material four inches thick requires about fifty pounds of cutting pressure. Thinner material requires proportionately less.

Thickness: Material must be thick enough so that at least two teeth of the blade are engaged in it at all times.

Retracting the Blade: Use caution when running the blade back after finishing the cut. If the back edge of the blade catches on your material, it could push the blade out of its guides. This destroys the blade and may propel broken saw teeth at the operator.
1.5 **SolidWorks project drawings and job sheets**

The following pages include the fabrication drawings for the lathe projects in the Machining Lab that were created using SolidWorks 2016.

There is also a job sheet for each item on the back of the drawing. It includes detailed, step-by-step instructions for that item. A beginning machinist should be able to carefully follow these instructions (*in order*, of course) to complete the project.

Read the complete instructions for each part *before* you begin work, so you understand the entire sequence.

No drawings for the project for the mills, the “jack in a cube,” are included because the detailed work will be done by the program in the CNC mill. The initial work done by the students is to use a milling machine to make a 1.00 inch aluminum cube for the CNC mill to process.
# Brass Cap Machining Job Sheet

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NOTE: you do not use the cut-off saw to cut the brass. You will build your cap on a longer piece of brass (necessary to be able to work on your piece). The cap is then cut off the longer piece in step 8 below.</td>
</tr>
<tr>
<td>2</td>
<td>Place the 1&quot; diameter brass rod in the lathe and face (machine) one end of the rod with the right-handed tool.</td>
</tr>
<tr>
<td>3</td>
<td>Drill a 0.281&quot; diameter hole in the piece to an edge depth of 0.625&quot;</td>
</tr>
<tr>
<td>4</td>
<td>Drill to a tip depth of 0.5&quot; with successively larger drills (typically 1/2&quot; and 3/4&quot; - do not exceed 3/4&quot;). Because the drill is large and the hole shallow it is not necessary to back out the drill to remove chips. A slow, continuous feed usually works best with the large drills on brass.</td>
</tr>
<tr>
<td>5</td>
<td>Finish machining the inner surface of the hole to tolerance with the boring bar (Note the tight tolerance of this surface). Be sure to check the drawing for the depth of the finished hole. To set the proper height of the boring bar, move the boring bar to the back side of the brass rod so the cutting point will contact the side of the brass. To zero the display in the x direction it is easiest to move the bar so the cutting surface is just inside the 3/4&quot; hole and, with the lathe running, slowly move it out until the tool just starts to cut the brass and set zero at that point. Nominally you will be adding 0.050&quot; to the diameter of the hole from this point - but be sure to measure frequently.</td>
</tr>
<tr>
<td>6</td>
<td>Machine the outer surface of the rod down ten mils (0.010&quot;) to produce a clean surface. Do not remove more than necessary to get a clean surface. Do this over about 0.6&quot; of the part.</td>
</tr>
<tr>
<td>7</td>
<td>Round edges with emery cloth or fine sandpaper, using a slower speed.</td>
</tr>
<tr>
<td>8</td>
<td>Cut the part a little longer than the final length (add ~ 0.020&quot; to the 0.5&quot; part length) using the parting tool. Be sure you are getting at least 0.5&quot; of material before you start cutting.</td>
</tr>
<tr>
<td>9</td>
<td>Place the part back in the lathe to face the parted surface of the piece. Wrap the piece in brass shim stock (a thin brass sheet) to protect the outside finish when clamping in the lathe. Be careful not to clamp the part too hard or you will deform the open end of the cap.</td>
</tr>
<tr>
<td>10</td>
<td>Use emery cloth or fine sandpaper to round the edges on the top edge of the cap by hand. Also use a deburring tool to clean up the inside of the small hole in the cap.</td>
</tr>
</tbody>
</table>
Threaded 3/8-24 NF

Dimensions are in inches. Tolerances:

- Fractional: ±0.001
- Two Place Decimal: ±0.005
- Three Place Decimal: ±0.002

Material: Copper

Physics 240
Cooling Rod

Cosmetic Thread

Unless otherwise specified:

- Weight:
- RevDWG. No.: A
- Size: 1
- Title: Physics 240
- Comments: Q.A., MFG APPR., ENG APPR.
- Drawing: Drawn
- Checked
- Reproduction in part or as a whole is prohibited.

The information contained in this drawing is the sole property of BYU Physics and Astronomy. Any reproduction in part or as a whole without the written permission of BYU Physics and Astronomy is prohibited.
## Cooling Rod Machining Job Sheet

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cut the 3/8&quot; diameter copper rod to 3.50&quot; length in the cut-off saw (leaves 1/8&quot; extra material on each end).</td>
</tr>
<tr>
<td>2</td>
<td>Place the 3/8&quot; copper rod in the lathe and face (machine) one end of the rod with the right-handed tool. <strong>Don’t allow the rod to extend very far from the chuck when facing it - it WILL bend.</strong> To get a good finish on copper you need to take no more than 0.010&quot; on your last cut. If the surface is still rough you may need to put a little oil on the rod before finishing it (and possibly take 0.002&quot; or less).</td>
</tr>
<tr>
<td>3</td>
<td>Round edges with a file, <strong>using a slower speed.</strong></td>
</tr>
<tr>
<td>4</td>
<td>Turn the copper rod end-for-end and place it back in the chuck. Face the other end of the rod. You also will make it the correct length in this step.</td>
</tr>
<tr>
<td>5</td>
<td>Round edges with a file, <strong>using a slower speed.</strong></td>
</tr>
<tr>
<td>6</td>
<td>Extend the copper rod from the chuck a little more than the length of the threads.</td>
</tr>
<tr>
<td>7</td>
<td>Using a 3/8-24 NF die, thread the end of the rod <strong>with the power off.</strong> Ask for a die, handle, and a can of TapMagic. It is necessary to apply pressure on the die to get it to cut into the copper. However, too much or too little pressure will result in you just chewing up the end of the rod. You will need to find a way to get the threads the correct length. One possibly useful bit of information is that the “-24” in the die specification indicates the number of threads per inch. 24 full turns of the die handle will advance the die exactly 1&quot;.</td>
</tr>
<tr>
<td>8</td>
<td>If you want to take about ten mils (0.010&quot;) off the surface of the rod to make it look nice you may. <strong>HOWEVER,</strong> you will bend the rod if you don’t use a live center to support the “free” end of the rod. <strong>This step is optional.</strong></td>
</tr>
</tbody>
</table>
Physics 240
Heater Block

TITLE:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES

TOLERANCES:

FRACTIONAL

ANGULAR: MACH 2

TWO PLACE DECIMAL: 0.05

THREE PLACE DECIMAL: 0.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL:

6061 aluminum

SECTION A-A

SCALE 1.5 : 1

3/8-24 NF Tapped Hole
(thread must extend through hole)

1.75

0.75

0.000

0.002

0.800

0.125

0.125

0.6875

0.330

0.375

3.00

1.00

UNLESS OTHERWISE SPECIFIED:

WEIGHT:

REVDWG. NO.

ENG APPR.

CHECKED

DRAWN

MFG APPR.

Q.A.

COMMENTS:

6061 aluminum

SCALE: 1:1

21 January 2016

SHEET 1 OF 1

DO NOT SCALE DRAWING
UNLESS OTHERWISE SPECIFIED:
# Heater Block Machining Job Sheet

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cut the 1″ diameter aluminum rod to 3.25″ length in the cut-off saw (this leaves 1/8″ extra material on each end for finishing).</td>
</tr>
<tr>
<td>2</td>
<td>Place the 1″ aluminum rod in the lathe and face (machine) one end of the rod with the right-hand tool. Note that the other end isn’t faced until we get to step 7 below.</td>
</tr>
<tr>
<td>3</td>
<td>Drill a hole <strong>through</strong> the center axis of the piece using the <strong>tap drill bit</strong> for a 3/8-24 NF thread. <strong>This is not a tap and is not a 3/8″ drill bit; you will need to look it up on the chart in the shop or in Appendix 1.2, pg. 71, in the text.</strong> It is the drill bit used to prepare a hole of the correct size to be tapped with a 3/8-24 NF thread. Go slowly and <strong>remove chips regularly</strong> to avoid breaking the drill. It is necessary to pull the drill <strong>entirely</strong> out of the block to remove the chips. We strongly advise that you use a lubricant when drilling this hole.</td>
</tr>
<tr>
<td>4</td>
<td>Drill to a depth of 1.75″ (<strong>edge depth</strong>) with a 1/2″ drill and then with an 11/16″ drill. Remember that larger drills require slower speeds on the lathe.</td>
</tr>
<tr>
<td>5</td>
<td>Turn the right 0.375″ of the piece down to 0.800″ outside diameter using the right-hand tool. (<strong>Note the tight tolerance of this surface as specified on the drawings</strong>).</td>
</tr>
<tr>
<td>6</td>
<td>Round edges with emery cloth or fine sandpaper, <strong>using a slower speed</strong>.</td>
</tr>
<tr>
<td>7</td>
<td>Take the piece out of the lathe, flip it end-for-end, and again place it in the lathe. Face the end of the rod with the right-hand tool (you also have to make it the correct overall length in this step).</td>
</tr>
<tr>
<td>8</td>
<td>Using a 3/8-24 NF tap (<strong>NOT a tap drill</strong>), tap (thread) the hole with the block in the lathe <strong>with the power off</strong>. You should ask for a tap, a tap handle, a spring center, and a can of TapMagic. Go slowly and remove chips often. You remove chips by backing the tap out about 1/2 turn every 1-2 turns. It is <strong>not</strong> necessary to remove the tap entirely to clear the chips. This hole must be threaded <strong>all the way through</strong> so an object can be screwed in from either the inside or the outside of the block. Screw an item with a 3/8-24 NF thread into the inside of the block to verify that the threads go clear through. <strong>It may</strong> be necessary to use a <strong>bottoming tap</strong> to finish the hole.</td>
</tr>
<tr>
<td>9</td>
<td>Round edges with a file, <strong>using a slower speed</strong>.</td>
</tr>
<tr>
<td>10</td>
<td>Drill the off-center 0.125″ hole with the drill press or mill. <strong>Go very slowly and remove chips often; many students have broken drills on this operation.</strong> If you break a drill here, it probably won’t come out.</td>
</tr>
</tbody>
</table>
1.6 SpaceClaim project drawings and job sheets

The following pages include the fabrication drawings for the lathe projects in the Machining Lab that were created using SpaceClaim 2017.

There is also a job sheet for each item on the back of the drawing. It includes detailed, step-by-step instructions for that item. A beginning machinist should be able to carefully follow these instructions (in order, of course) to complete the project.

Read the complete instructions for each part before you begin work, so you understand the entire sequence.

No drawings for the project for the mills, the “jack in a cube,” are included because the detailed work will be done by the program in the CNC mill. The initial work done by the students is to use a milling machine to make a 1.00 inch aluminum cube for the CNC mill to process.
## Brass Cap Machining Job Sheet

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NOTE: you do not use the cut-off saw to cut the brass. You will build your cap on a longer piece of brass (necessary to be able to work on your piece). The cap is then cut off the longer piece in step 8 below.</td>
</tr>
<tr>
<td>2</td>
<td>Place the 1” diameter brass rod in the lathe and face (machine) one end of the rod with the right-handed tool.</td>
</tr>
<tr>
<td>3</td>
<td>Drill a 0.281” diameter hole in the piece to an edge depth of 0.625”.</td>
</tr>
<tr>
<td>4</td>
<td>Drill to a tip depth of 0.5” with successively larger drills (typically 1/2” and 3/4” - do not exceed 3/4”). Because the drill is large and the hole shallow it is not necessary to back out the drill to remove chips. A slow, continuous feed usually works best with the large drills on brass.</td>
</tr>
<tr>
<td>5</td>
<td>Finish machining the inner surface of the hole to tolerance with the boring bar (Note the tight tolerance of this surface). Be sure to check the drawing for the depth of the finished hole. To set the proper height of the boring bar, move the boring bar to the back side of the brass rod so the cutting point will contact the side of the brass. To zero the display in the x direction it is easiest to move the bar so the cutting surface is just inside the 3/4” hole and, with the lathe running, slowly move it out until the tool just starts to cut the brass and set zero at that point. Nominaly you will be adding 0.050” to the diameter of the hole from this point - but be sure to measure frequently.</td>
</tr>
<tr>
<td>6</td>
<td>Machine the outer surface of the rod down ten mils (0.010”) to produce a clean surface. Do not remove more than necessary to get a clean surface. Do this over about 0.6” of the part.</td>
</tr>
<tr>
<td>7</td>
<td>Round edges with emery cloth or fine sandpaper, using a slower speed.</td>
</tr>
<tr>
<td>8</td>
<td>Cut the part a little longer than the final length (add ~ 0.020” to the 0.5” part length) using the parting tool. Be sure you are getting at least 0.5” of material before you start cutting.</td>
</tr>
<tr>
<td>9</td>
<td>Place the part back in the lathe to face the parted surface of the piece. Wrap the piece in brass shim stock (a thin brass sheet) to protect the outside finish when clamping in the lathe. Be careful not to clamp the part too hard or you will deform the open end of the cap.</td>
</tr>
<tr>
<td>10</td>
<td>Use emery cloth or fine sandpaper to round the edges on the top edge of the cap by hand. Also use a deburring tool to clean up the inside of the small hole in the cap.</td>
</tr>
</tbody>
</table>
## Cooling Rod Machining Job Sheet

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cut the (\frac{3}{8})&quot; diameter copper rod to (3.50)&quot; length in the cut-off saw (leaves (\frac{1}{8})&quot; extra material on each end).</td>
</tr>
<tr>
<td>2</td>
<td>Place the (\frac{3}{8})&quot; copper rod in the lathe and face (machine) one end of the rod with the right-handed tool. <strong>Don’t allow the rod to extend very far from the chuck when facing it - it WILL bend.</strong> To get a good finish on copper you need to take no more than (0.010)&quot; on your last cut. If the surface is still rough you may need to put a little oil on the rod before finishing it (and possibly take (0.002)&quot; or less).</td>
</tr>
<tr>
<td>3</td>
<td>Round edges with a file, <strong>using a slower speed.</strong></td>
</tr>
<tr>
<td>4</td>
<td>Turn the copper rod end-for-end and place it back in the chuck. Face the other end of the rod. You also will make it the correct length in this step.</td>
</tr>
<tr>
<td>5</td>
<td>Round edges with a file, <strong>using a slower speed.</strong></td>
</tr>
<tr>
<td>6</td>
<td>Extend the copper rod from the chuck a little more than the length of the threads.</td>
</tr>
<tr>
<td>7</td>
<td>Using a 3/8-24 NF die, thread the end of the rod <strong>with the power off.</strong> Ask for a die, handle, and a can of TapMagic. It is necessary to apply pressure on the die to get it to cut into the copper. However, too much or too little pressure will result in you just chewing up the end of the rod. You will need to find a way to get the threads the correct length. One possibly useful bit of information is that the “-24&quot; in the die specification indicates the number of threads per inch. 24 full turns of the die handle will advance the die exactly (1)&quot;.</td>
</tr>
<tr>
<td>8</td>
<td>If you want to take about ten mils (0.010&quot;) off the surface of the rod to make it look nice you may. HOWEVER, you will bend the rod if you don’t use a live center to support the “free” end of the rod. <strong>This step is optional.</strong></td>
</tr>
</tbody>
</table>
3/8-24 NF tapped hole
Thread must extend through hole
<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cut the 1″ diameter aluminum rod to 3.25″ length in the cut-off saw (this leaves 1/8″ extra material on each end for finishing).</td>
</tr>
<tr>
<td>2</td>
<td>Place the 1″ aluminum rod in the lathe and face (machine) one end of the rod with the right-hand tool. Note that the other end isn’t faced until we get to step 7 below.</td>
</tr>
<tr>
<td>3</td>
<td>Drill a hole through the center axis of the piece using the tap drill bit for a 3/8-24 NF thread. This is not a tap and is not a 3/8″ drill bit; you will need to look it up on the chart in the shop or in Appendix 1.2, pg. 71, in the text. It is the drill bit used to prepare a hole of the correct size to be tapped with a 3/8-24 NF thread. Go slowly and remove chips regularly to avoid breaking the drill. It is necessary to pull the drill entirely out of the block to remove the chips. We strongly advise that you use a lubricant when drilling this hole.</td>
</tr>
<tr>
<td>4</td>
<td>Drill to a depth of 1.75″ (edge depth) with a 1/2″ drill and then with an 11/16″ drill. Remember that larger drills require slower speeds on the lathe.</td>
</tr>
<tr>
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<td>Turn the right 0.375″ of the piece down to 0.800″ outside diameter using the right-hand tool. (Note the tight tolerance of this surface as specified on the drawings).</td>
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<td>6</td>
<td>Round edges with emery cloth or fine sandpaper, using a slower speed.</td>
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<td>Take the piece out of the lathe, flip it end-for-end, and again place it in the lathe. Face the end of the rod with the right-hand tool (you also have to make it the correct overall length in this step).</td>
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<td>Using a 3/8-24 NF tap (NOT a tap drill), tap (thread) the hole with the block in the lathe with the power off. You should ask for a tap, a tap handle, a spring center, and a can of TapMagic. Go slowly and remove chips often. You remove chips by backing the tap out about 1/2 turn every 1-2 turns. It is not necessary to remove the tap entirely to clear the chips. This hole must be threaded all the way through so an object can be screwed in from either the inside or the outside of the block. Screw an item with a 3/8-24 NF thread into the inside of the block to verify that the threads go clear through. It may be necessary to use a bottoming tap to finish the hole.</td>
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<td>Drill the off-center 0.125″ hole with the drill press or mill. Go very slowly and remove chips often; many students have broken drills on this operation. If you break a drill here, it probably won’t come out.</td>
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</table>
Chapter 2

Computer-Aided Design

2.1 Expected Learning Outcomes

- Demonstrate proficiency in developing mechanical drawings using common computer-aided-design software.
- Demonstrate ability to develop a mechanical drawing of an existing object by accurately measuring and reproducing the object.

2.2 Introduction

These exercises will give you a basic working understanding of a 3-D computer-aided-design (CAD) system. It is expected that you will be able to generate mechanical drawings of simple systems after completing these exercises.

It is recommended that you read Section 1.5 (MECHANICAL DRAWING) in the text in preparation for these exercises.

Three CAD programs are available for designing. They are SolidWorks, a product of Dassault Systemes, SpaceClaim, a product of Ansys, Inc., and DesignSpark Mechanical, available from rs-online.com.

The first two, SolidWorks and SpaceClaim, are commercial products that are installed on the computers in C460 ESC. If you want your own copy of SolidWorks, a 12-month student license is available from www.studica.com for $89.00 (“on sale” as of 13 August 2018).

DesignSpark Mechanical is available for free from https://www.rs-online.com. You will be required to create a free account to get a copy. They also have DesignSpark Electrical and DesignSpark PCB. There are a few others that may be less interesting to students. Their
United States representative is Allied Electronics. The DesignSpark software is a slightly modified version of SpaceClaim made available through an agreement with RS Components. The differences between SpaceClaim and DesignSparkMechanical can be found at http://www.spaceclaim.com/en/Products/DesignSparkMechanical.aspx.

The primary drawback of DesignSpark Mechanical is that it is not possible to make a drawing of your object. You can take the files for the object to a computer and create drawings using SpaceClaim if you have access. There are also several of the function tabs that are missing but could be considered important for creating a good model.

All three are designed with 3-D modeling in mind. You build your part in roughly the same way you would build it in the machine shop: drilling, cutting, boring, facing, etc. The difference is in the details of how the operations are completed.

The packages have significant relative advantages and disadvantages. SpaceClaim and DesignSpark Mechanical is reported to be quicker to use and to have a softer learning curve. I have not been able to verify that claim.

The Physics Department machinist currently uses SpaceClaim for his work, but he does have the capability to load SolidWorks files if you use SolidWorks to specify a job you need to have done.

You can use any of the packages for creating your drawings. Below are instructions for SolidWorks (section 2.4) or SpaceClaim and DesignSpark Mechanical (section 2.5).

As you do the exercises, you will be told to save various files (and you should save your work often). You can only save files on your P: drive or on an external USB drive. You are not allowed to save on the C: or L: drives (if you manage to save on one of these drives, the files probably won’t be there tomorrow).

### 2.3 Grading

The grading for this portion of the class will be as follows:

- Completion of the mechanical drawings for the four machine shop projects (heater block, cooling rod, brass cap, jack-in-a-cube) – 20 pts.

### 2.4 SolidWorks CAD exercises

The following exercises are to be completed in SolidWorks. It would be wise read the STRONG HINTS (subsection 2.4.1) section before you work on items two and three below.

1. Complete lessons 1-3 in the online tutorial. To get to the tutorials:
• Click on the down-arrow by the "?” in the upper right-hand corner.
• Select SOLIDWORKS Tutorials.
• Select Lesson 1 - Parts and complete the exercises.
• Select Lesson 2 - Assemblies and complete the exercises.
• Select Lesson 3 - Drawings and complete the exercises.

2. Duplicate the drawings of the heater block, brass cap, and cooling rod.

For the drawings for the machine shop projects produced using SolidWorks 2016, see section 1.5.

3. Make a drawing of the jack-in-a-cube by taking measurements from one of the cubes available in the lab or your cube.

4. Show your completed drawings of the machine shop projects to one of the TAs for credit. **You do not need to print your drawings.**

### 2.4.1 Some strong hints for SolidWorks

Some strong hints for SolidWorks

• You may need to switch the parts, assemblies, and drawings to use inches as the units.
  1. Select Tools along the top menu bar
  2. Select Options
  3. Click on the Document Properties tab
  4. Click on Units down the left-hand side
  5. Change the units to IPS (inches/pounds/seconds)
  6. You probably also want to change the number of digits for lengths to 3 by clicking on the number next to lengths and picking “.123” as the value.

• When you are making drilled or tapped holes you will save yourself a LOT of time if you use the Hole Wizard.

• To draw realistic external threads on the copper rod select “Insert” ⇒ “Feature” ⇒ “Thread” to open the thread feature panel. You will select the circle that defines the end of the rod as the place to make the threads. You should use cut threads, the length of the thread, and the thread diameter and pitch.

You can also use a “Cosmetic Thread” indicated by various dashed and solid lines on your drawing by selecting “Insert” ⇒ “Annotations” ⇒ “Cosmetic thread.” You will select the circle at the end of the rod and specify the thread characteristics. A cosmetic thread will be shown on a drawing as a circle on the end of the rod that is about the radius of the bottom of the thread and there will be a line on the side of the rod indicating the length of the thread.

• When you create a drawing, it gives you four paper size choices by default. Size “A4” is the non-US paper that is slightly narrower and slightly longer than the standard U.S. letter paper.
Since you are working in the U.S. and the printer is loaded with letter paper, you want to unclick the box that says **Only show standard formats** to see a longer list of choices. Then you scroll down and select an appropriate paper. Size A (**ANSI**) is 8.5''x11'' (letter), size B (**ANSI**) is 11''x17'' (ledger), etc.

A common choice in the U.S. is **A (ANSI) Landscape**. The letters after the size (**ANSI, JIS, DIN, etc.**) specify the standard for all the information put in the title and legend boxes along the bottom of the sheet.

### 2.5 SpaceClaim and DesignSpark Mechanical CAD exercises

The following exercises are to be completed in SpaceClaim or DesignSpark Mechanical.

1. **SpaceClaim Tutorial Exercises**

   (a) Click on the question mark in a blue circle in the upper right-hand corner of the screen or press the F1 key. This will open a web browser to the ANSYS SpaceClaim documentation and tutorials.

   (b) Down the right-hand side you will find several links to different sections of the documentation.

   - **Quick Reference Card** is a printable 2-sheet reference to the basic operations and keyboard shortcuts for the interface.
   - **Mouse and touch gestures** covers the mouse “gestures” that can be used as shortcuts for commands. It provides a printable sheet of possible “gestures.”
   - **The SpaceClaim interface** contains twelve subsections describing each of the sections of the interface, and what operations or information are included in each section.
   - **Selecting** covers how to select specific items or structures in a drawing. This includes selecting an object (line, vertex, face, etc.), an edge loop, a solid, or various other combinations.
   - **SpaceClaim objects** describes all the different objects that are referred to in the documentation and tutorials.
   - **Working with components** describes working with various combinations of objects that can be combined into a named component for reuse or duplication.
   - **Tutorials** contains two tutorial exercises. You should complete the *Bracket and knob assembly* tutorial. This will involve creating two separate parts that are then assembled into a single assembly.

2. **DesignSpark Mechanical Tutorial Exercises**

   (a) Click on the question mark in a blue circle in the upper right-hand corner of the screen or press the F1 key.
3. Duplicate the drawings of the heater block, brass cap, and cooling rod.
   For the drawings for the machine shop projects produced using SpaceClaim 2016, see section 1.6.

4. Make a drawing of the jack-in-a-cube by taking measurements from one of the cubes available in the lab or your cube.

5. Show your completed drawings of the machine shop projects to one of the TAs for credit. **You do not need to print your drawings.**
Chapter 3

LabVIEW Programming

3.1 Expected Learning Outcomes

- Demonstrate basic proficiency in LabVIEW programming and data acquisition.
- Understand important hardware and software considerations affecting data acquisition.
- Become acquainted with common sources of electrical noise and ways to control or mitigate the effect of noise on measurements.
- Understand the source and behavior of uncertainty in measurements and be able to use basic statistical principles to estimate the uncertainty in results derived from measurements.

3.2 Grading

- Complete the LabVIEW Basics course – 30 pts.

3.3 Introduction to LabVIEW

LabVIEW is a programming environment with an unusual GUI (graphical user interface) for an underlying compiled language (G) that is specifically designed for interfacing with the physical world through data inputs and outputs. The signals involved can be either digital or analog. This makes LabVIEW an ideal candidate for any system that must acquire data from the physical world, control items in the physical world, or both.
Some of the tools available in LabVIEW also make it quite straightforward to rapidly
develop software for laboratory exercises. These tools make LabVIEW a reasonable choice
for beginning exercises in acquiring signals and controlling devices.

The LabVIEW GUI uses “wires” to indicate data paths between code blocks. Each wire
can only have one data source, but it can provide data to as many other code blocks
as you desire. Wires have data types and “form” or “shape” just like variables in more
typical sequential languages, and it is not possible to connect wires to terminals that have
incompatible shapes or data types. Some of the possible shapes are

- narrow line ⇒ single value
- wide line ⇒ one-dimensional array
- two parallel lines ⇒ two-dimensional array
- two parallel lines connected by diagonal hatching ⇒ complex data type such as dy-
namic data type or waveform.

Available basic data types and the associated wire colors include

- orange: single precision (32-bit), double precision (64-bit), and extended precision
  (nominally 128-bit but it is platform dependent) floating-point and complex floating-
  point numbers
- blue: 8-, 16-, 32-, and 64-bit signed and unsigned integers
- green: boolean values
- pink: strings.

Some of the complex data types you may encounter are waveforms (brown), dynamic data
(dark blue), clusters (brown), and time stamps (brown).

3.3.1 Execution sequencing

You may have already written a computer program in a language such as C, C++, Java,
Basic, Matlab, etc. These are often described as sequential languages because the lines
in the program are executed sequentially through the source file except as specified by
control structures such as loops and conditional statements. You, as the programmer, have
complete control over the order of execution in the way you place the statements in your
code.

*LabVIEW is not a sequential language. It is a data-driven language.* The order of
execution is determined by the availability of all the data inputs for a code block (function,
sub-VI, or control structure). The relative positions of the code blocks on the diagram have
no effect on the order of execution.

A code block can not execute until all its input data are available, and it will be scheduled
for execution as soon as all the required inputs have become available. If more than one
code block becomes executable at once (i.e., all the required inputs for those blocks become available simultaneously), then the order of execution of those specific code blocks may be random and will be determined by the computer operating system scheduling algorithm. They may even execute simultaneously if the computer has multiple processors.

The outputs from a code block do not become available until the execution of that block is complete.

Understanding the difference in sequencing – and keeping that difference in mind as you develop your program – will allow you to create a program that works correctly. As with all programming languages, you need to understand the language, use the constructs properly, and be careful that you tell the computer what you want it to do.

### 3.3.2 Some LabVIEW resources

As you start, you may want to look at one graduate student’s view of learning LabVIEW (http://foolooo.wordpress.com/2010/07/20/labview-study-curve/?sf4100787=1). Note that the real message of this is the note near the right end of the curve: “It’s a tool.” *LabVIEW is a tool that excels at communicating with hardware.*

National Instruments also has a couple of articles for beginning LabVIEW programmers that you may find interesting and useful:

- **Top 5 LabVIEW Rookie Mistakes** (http://www.ni.com/newsletter/51735/en/)
- **Going With the (Data) Flow** (http://www.ni.com/newsletter/51770/en/)

### 3.4 LabVIEW Basics Course

You will use the LabVIEW Basics Course developed by National Instruments to get a start in LabVIEW programming. The printed manuals provided in the lab are for LabVIEW 2008. The exercises in the manual require some minor changes to account for changes incorporated in newer versions of LabVIEW. These changes will be described in subsection 3.5.1.

If you are working in the Physics labs and using the manuals, the files associated with the course are found in the directory L:\LabVIEW Basics I on the physics file server. You are not allowed to write to this directory, so you will need to make your own copies of any files you modify. It is strongly recommended that each of you keep your own copies of any files generated by you and your partner(s).

If you do not have access to the printed manuals or prefer to work with computer-based instruction, you may find the LabVIEW Basics Course on the computer. If present, it is usually located in the Start Menu under LabVIEW Basics1\LVBasic1. This course is also
based on LabVIEW 2008 and requires some of the exercise-specific instructions found in subsection 3.5.1.

The computer-based course covers most of the topics from the printed manual except some information on measurement fundamentals that is usually important to consider in any data acquisition application. These fundamentals are discussed briefly in Appendix B, “Considerations for Analog Input and Output.” The printed manual usually provides more insight into the details of data acquisition in Chapter 7.

### 3.5 LabVIEW exercises

If you have completed Physics 145 you have probably already worked through the “Getting Started With LabVIEW” manual. This version for LabVIEW 2013 is the last pdf version produced by National Instruments. It has been replaced by an online version at [https://www.ni.com/getting-started/labview-basics](https://www.ni.com/getting-started/labview-basics).

If you have not been through that manual or the newer online getting started materials, you may need to go through chapters 1 and 2 of the LabVIEW Basics 1 printed manual or Sections 1, Programming Fundamentals, and 2, Navigating LabVIEW, in the computer-based course before continuing with these exercises.

You will **complete chapters 3 through 8 in the printed manual**. You should also **complete all the exercises except those explicitly labeled as “optional.”**

If you are using the computer-based LabVIEW Basics Course instead of the printed manuals you should **complete Sections 3 (Using LabVIEW) through 9 (Acquiring Data).** We do not use any external instruments in Physics 240 for which the section on Instrument Control would be appropriate so you can safely stop when you get to that section. **Be sure that you complete all the “Do it Yourself” exercises.**

If you have access to the printed manual, it is strongly recommended that you complete chapter 7 in that manual even if you choose the computer-based course.

### 3.5.1 Exercise specific instructions

The following instructions are to correct changes between LabVIEW 2008 and the current version. They also cover some changes due to the hardware we are using. We have a general multi-IO module (USB-6221-BNC with analog and digital input and output), but the course was designed for a very specific interface system referred to in the printed manuals as the “DAQ Signal Accessory.”

All the changes except those for Exercise 3.3 apply to the printed manual as well as to the computer-based course in the specified “Do it Yourself” exercises.

**Chapter 3 and Creating VIs**
• **Exercise 3.3** (pp. 3-37 and 3-38)
  - step 2:
    * Set the value in the **Number to Match** control to 50.
    * Right-click the **Number to Match** control, select **Data Operations** and **Make Current Value Default**.
    * Right-click the **Number to Match** control and select **Data Entry** from the shortcut menu. The **Data Entry** page of the **Numeric Properties** dialog box will appear.
    * Uncheck the **Use Default Limits** checkbox.
    * Set the **Minimum** value to 0 and select **Coerce** from the **Response to value outside limits** pull-down menu.
    * Set the **Maximum** value to 1000 and select **Coerce** from the **Response to value outside limits** pull-down menu.
    * Set the **Increment** value to 1 and select **Coerce to Nearest** from the **Response to value outside limits** pull-down menu.
    * Select the **Display Format** tab.
    * Select **Floating Point** and change **Precision Type** from **Significant digits** to **Digits of precision**.
    * Enter 0 in the **Digits** text box and click **OK**.
  - step 4:
    * Right-click the **Current Number** indicator and select **Advanced** and **Synchronous Display**.
    * Right-click the **Current Number** indicator and select **Display Format** from the shortcut menu. The **Display Format** page of the **Numeric Properties** dialog box appears.
    * Select **Floating Point** and change **Precision Type** to **Digits of precision**.
    * Enter 0 in the **Digits** text box and click **OK**.

• **Exercise 3.5, item 1** (pg. 3-52) and the 3rd “Do it Yourself” in Creating VIs⇒Using Loops (pg. 30 of 30)
  - You can emulate some of the features of the DAQ signal accessory by connecting a 10 kΩ pot (potentiometer or variable resistor, available from the cabinet in the back of C460 ESC) so that the “ends” of the pot connect to the +5 V and **GND** screw terminals and the **wiper** connects to the **USER 1** screw terminal. The voltage on the **wiper** will vary between 0 V and 5 V as you turn the knob. Be sure that you use a small screwdriver to clamp the wires into the terminals. **Note:** The wires on a pot are usually grouped together with the center wire connecting to the wiper. You can (should?) check this by connecting an ohmmeter to the other two wires: the resistance should remain constant as you rotate the knob. If you are uncertain – ASK.
  - Connect a coaxial cable from the **USER 1** BNC connector to the **AI 0** input. Be sure that the switch below **AI 0** is set to **GS** (grounded source). Rotating the pot will apply a voltage of 0 to 5 V to input **AI 0**.
  - The file **Temperature Monitor.vi** has been modified so this input range will produce a temperature in the range of 60 to 100°F (the conversion is \(T[^\circ C] = 4.5V_{in} + 15\) – note this gives the temperature in °C).
It is NOT possible to add noise to the temperature signal; you change the temperature by rotating the knob on the pot.

Chapter 6 and module Creating and Using SubVIs in Developing Modular Applications

- Section 6B (Icon and Connector Pane, pp. 6-4 and 6-6) and the Icon Editor (pg. 8 of 20) and Setting Up the Connector Pane (pg. 9 of 20) in Creating and Using SubVIs

National Instruments modified the appearance of the Icon and Connector Pane on the front panel window. The Icon is located in the upper-right corner just above the top of the vertical scroll bar on the right side of the front panel. The Connector Pane is adjacent and to the left of the Icon. It is a collection of little boxes of various sizes very similar to the figure on page 6-4 of the manual or the examples shown in the computer-based course.

You access the Icon Editor by right-clicking on the icon as described in the manual and the computer-based course. The Icon Editor has been significantly enhanced beyond what is described in both versions of the course. For instance, there is a region to the left of the icon in the editor where you can enter up to four lines of text to be placed on the icon. It is fairly easy to change the font, size, and justification for this text. The remaining editing tools work essentially as described in both versions of the course.

You can change the pattern in the connector by right-clicking on the Connector Pane. The process is as described in both versions of the course.

Chapter 7

When you work through chapter 7 of the LabVIEW Basics manual, there are three concepts that you need to understand:

- Grounded Source vs. Floating Source
- Smallest Detectable Change (we use a 16-bit analog-input board)
- Signal Aliasing

If you don’t understand these, be sure that you ask.

Refer to Appendix B, “Considerations for Analog Input and Output,” for more information. You may find it useful to go through National Instruments’ “Is Your Data Inaccurate Because of Instrumentation Amplifier Settling Time?” (http://www.ni.com/white-paper/2825/en/)–this will be important when we get to the superconductor measurements later in the course.

You may also find it useful to review the information found on the device specifications datasheets and the device user manuals. Manuals that will likely be of interest:
• NI 6221 Specifications (http://www.ni.com/pdf/manuals/375201c.pdf)
• E-series User Manual (http://www.ni.com/pdf/manuals/370503k.pdf) – the PCI-6040E is an E-series device

At this point, you should also look at Appendix C, “Uncertainty, Errors, and Noise in Experimental Measurements,” for a discussion of how to handle noise and uncertainties in measurements.

Chapter 8 and Acquiring Data

Some of the exercises in chapter 8 and the Acquiring Data module refer to a PCI-MIO-16E-4 device. In the Physics 240 lab (C460 ESC), you will find that Dev1 is the USB-6221-BNC. Any exercises that specify using Dev1 can be completed using the USB-6221-BNC and the modified instructions given below.

Depending on what you have available for data acquisition hardware, you may have a different device indicated. Even if you have data acquisition hardware available, you will find that some of the exercises can only be done using simulated hardware.

Since the USB-6221-BNC is an externally-powered device, you will need to power it on before it can be used. The power switch is on the back of the box next to the power and USB cables. It takes a few seconds for the device to be properly configured by the drivers after you turn on the power.

• Exercise 8.1 (pg. 8-9) and the 1st “Do it Yourself” (pg. 30 of 32) in the Acquiring Data module
  – Part B
    * Steps 5 through 8 can be completed as described in the manual and the implementation instructions in the computer-based course. The “Device Routes” button is at the bottom of the screen. The “Calibration” button shown at the bottom of the screen in the instructions has been replaced by a “Self-Calibration” button at the top of the screen.
  – Part C, step 10
    * 1st box: Use the “No Hardware” method unless you wish to use the connections specified for exercise 3.5 (described above).
    * 2nd and 3rd boxes: These steps are replaced by obtaining an HP 3311A Function Generator or a similar general function generator. The HP Function Generator can usually be found on the shelves at the rear of C460 ESC.
      • Connect a coaxial cable from the 600 Ω output of the function generator to the AI 1 input.
· The terminal labeled L0 or the grounded side of the output should be connected to the ground/black banana plug/shield on the cable.
· Make sure the switch below AI 1 is set to GS (grounded source).
· Connect a second coaxial cable from the PULSE OUTPUT (a 0 – 5 V pulse signal synchronized with the output signal) of the function generator to the PFI 0/P1.0 input.
· The terminal labeled L0 or the grounded side of the output should be connected to the ground/black banana plug/shield on this cable as well.

* 4th and 5th boxes: Use the hardware instructions (the device you should use is shown as the USB-6221-BNC – if this doesn’t show up on your list you need to turn on the device).

* 6th and 7th boxes: There are no digital indicators on the USB-6221-BNC. If you wish to observe your digital output you will use a voltmeter to check the output (+5 V for digital “one” and 0 V for digital “zero”). Digital lines are labeled Pm.n where “m” is the port number (range of 0 to 2) and “n” is the line number (range of 0 to 7). For example, P1.3 is line 3 of port 1. The digital input/output terminals for ports 0 and 2 are in the line of screw terminals down the right side of the box. You will have to fasten a wire in the terminal to measure the voltage. Those for port #1 are the BNC terminals across the top of the box. If you select this port, you can use the BNC connectors that are much easier to access. Unlike most TTL devices, these digital inputs do not float high. It will be necessary to connect a wire from “+5 V” to the desired input to switch it to a digital “1.”

* 8th box: The USB-8221 uses PFI 8 as the source for counter 0 and PFI 3 for counter 1. To use counter 0 put a jumper wire from PFI 8 to the USER 2 terminal. Then connect a cable from the PULSE OUTPUT of the HP 3311A Function Generator (or some other device capable of generating periodic digital trigger signals) to the User 2 terminal. As noted above, the output terminal labeled L0 (or the ground on your function generator) should be attached to the ground/black banana plug/shield on the cable. You select the count rate using the dial and range buttons on the function generator.

· Exercise 8.2 (pg. 8-17) and the 2nd “Do it Yourself” (pg. 31 of 32) in the Acquiring Data module

For this exercise, the external connections should be made in the same configuration used for Exercise 8.1, part C, step 10 using an HP 3311A Function Generator or a similar general function generator.

The instructions in the printed manual for parts 5 through 8 are no longer correct. Follow these instructions:

– Place the DAQ Assistant Express VI on the block diagram. Click on the “+” sign next to Acquire Signals, then on Analog Input and Voltage.
– Click on the “+” sign next to Dev1 (USB-6221-BNC). If this device isn’t present you probably haven’t turned on the power for the external DAQ box—turn it on and wait for the computer to indicate that the device is ready.
– Select input ai1.
– Click the Finish button.
– On the Settings tab set the Signal Input Range values to a range of −1 to 1 V.
– In the Timing Settings section along the bottom of the window, set the Acquisition Mode to Continuous, the Samples to Read to 5000, and the Rate (Hz) or sample rate to either 20k or 20000 (LabVIEW understands standard SI prefixes like k, M, m, etc.).
– Switch to the Triggering tab, set the Trigger Type in the Start Trigger section to Digital Edge, the Trigger Source to PFI0 and the Edge to Rising.
– Click the OK button in the lower-right corner to close the dialog box and wait for LabVIEW to finish the configuration.
– Place a While Loop around the DAQ Assistant. This will usually create a Power Switch in the While Loop to control the loop execution.
– Place an Unbundle by Name function below and to the right of the DAQ Assistant. This will become the box containing the arrow and the word Status once you connect it to the Error Out terminal on the DAQ Assistant VI.
– You will also need to find a boolean OR function to combine the signals from the Unbundle by Name and the previously created Power Switch.
– Now continue with item 9 in the instructions.

With the function generator attached to AI 1 and PFI 0/P1.0 as indicated above, you can use the “Hardware” option in the “Testing” section. It is not necessary to press a digital trigger button (which doesn’t exist on our hardware) since the function generator is providing a continuous trigger signal.

- Exercise 8.3 and the 3rd “Do it Yourself” (pg. 32 of 32) exercise in the Acquiring Data module

This exercise will work using an external “Quadrature Encoder” from the equipment cabinet in C460 ESC. The encoder is nearly identical to the one described in the “Design” section of this exercise. The encoder has four wires that need to be connected as follows

– RED: connects to the “+5 V” screw terminal.
– BLACK: connects to one of the “D GND” screw terminals.
– GREEN: connects to the “PFI 8/P2.0” screw terminal. This is the counter input (Phase A of the encoder).
– WHITE: connects to the “PFI 10/P2.2” screw terminal. This is the “UP/DOWN” or “DIRECTION” terminal that determines whether the counter should count up or down as it receives pulses (Phase B of the encoder).

NOTE: The encoder is not well debounced (you may remember that term from Physics 140). It may get multiple counts from switch bounce. It will count up if you turn it clockwise and down if you turn it counterclockwise.

- Optional Exercise 8.4 in the printed manual uses the same connections for the encoder as exercise 8.3. Unfortunately, there is no digital output to show the count. If you wish, you could configure the Digital I/O>>Line Output Express VI to use “port 1” and monitor the voltages on the appropriate BNC connectors to see the voltage (and the digital value).
Chapter 4

Thermal Measurements Lab:
Heating and Cooling of the Cryostat Assembly

4.1 Expected Learning Outcomes

- Design and fabricate a heating coil for use with the aluminum heater block from the machine shop exercises.
- Build and calibrate a practical temperature sensor system to monitor the aluminum heater block.
- Understand and account for systematic errors in experimental measurements.
- Acquire thermal data using a computer-based data acquisition system.
- Develop a simple model for a thermal system.
- Use the acquired data and the model to determine the constants of the thermal system (heat capacity, rate, and routes of heat loss, and equilibrium temperature).
- Write a technical report describing the thermal measurements and the results of the analysis.

4.2 Introduction

The goal of this experiment is to measure and model the thermal behavior of your cryostat assembly (heater block, cooling rod, and cap) as it is heated and cooled. We are making these measurements in preparation for the development of a temperature controller in a future lab exercise. Understanding the thermal behavior of the cryostat assembly helps in arriving at a working controller.
There are several steps required to prepare the heater block and the necessary hardware and software before you can begin taking measurements. These steps include building a heater coil on your heater block, developing a method of measuring the temperature of the heater block, and developing a method of recording the temperature of the block as a function of time using the computer. It is then necessary to analyze those measurements to compare them with a simple model of the thermal behavior of the heater block assembly and determine the thermal constants for that system.

Finally, you will write a report describing your experiment and the results.

In preparation for this exercise, you should read Section 8.1 (THE MEASUREMENT OF TEMPERATURE) in the text. Pay particular attention to Section 8.1.4 (Semiconductor Thermometers).

If you do not have access to the text, you can read the short comparison of thermometers found in “Temperature Transducers,” Appendix H.

### 4.3 Equipment

Each group should have one complete cryostat (heater block, cap, cooling rod).

In the storage cabinet in the lab:

- Fluke or Cen-Tech digital thermometer
- thermocouples for thermometers
- plastic storage box (one/group)
- Cen-Tech multimeters
- cardboard toolkit boxes (one/group)
- needle-nose pliers
- diagonal cutters
- wire strippers
- two small screwdrivers
- desoldering pump
- two teasing needles
- scissors
- cardboard boxes of connection wires (shared)
- various wire and cables
- soldering iron (one/group)
- various electronic components

In the lab:

- 5 L LN2 (as needed)
- Styrofoam insulating containers: octagonal and rectangular
- hot plate
- stainless steel cup
- gray/dark brown Tenma or GW Laboratory DC Power Supply, (0-20 V, 0-3 A for 4-lead measurements)

At each station:

- brown/tan +5/+15/-15 power supply
- gray Kepco ATE36-8M power supply
4.4 Grading

The grading for this portion of the class will be as follows:

- Heating coil built and characterized – 10 pts.
- Build constant current source for diode temperature measurements – 10 pts.
- LabVIEW VI built to measure temperature and diode correctly calibrated – 10 pts.
- Measure heating and cooling curves, determine $C$, $\gamma$, $T_{eq}$ – 20 pts.
- Lab notebook – 40 pts.
- Report on results – 40 pts. broken down as follows
  - Report format followed – 5 pts.
  - Report clearly written (flow, grammar, spelling, etc.) – 15 pts.
  - Content, questions in the handout answered reasonably – 20 pts.

4.5 Summary of steps to carry out the measurements

1. Build a heater coil on your aluminum heater block (section 4.9).
2. Read the description of how to use a silicon diode to measure temperature (Appendix I).
3. Build a 100 $\mu$A constant current source to provide the current for a temperature measurement diode (Appendix J).
4. Create a VI to acquire the voltage across the temperature measurement diode and to accumulate those voltages in a data file for analysis (section 4.11).
5. Use ice water, boiling water, and boiling liquid nitrogen to determine a calibration equation to convert the diode voltage to temperature (Appendix L).
6. With the cryostat fully assembled and the diode in place in the 1/8” hole on the bottom, record the temperature as a function of time as you heat the block to about 120°C and then allow it to cool for about 20 minutes (subsection 4.12.1).
   - Use the Kepco ATE-36-8M power supply to provide current to your heater coil.
   - Set the supply to provide about 70-90 W to the coil so that it takes about 2 minutes to reach the designated temperature.
7. Fit the equation from the model for the cryostat assembly to the temperature vs. time data. Determine the values of $C$ (heat capacity), $\gamma$ (heat loss coefficient), and $T_{eq}$ (the equilibrium temperature) (subsection 4.12.3).
8. Write the technical report describing your measurements (section 4.7).
4.6 Lab notebooks

This is the first exercise in Physics 240 that requires the use of a lab notebook. It is *strongly* recommended that you review the materials in “Your Lab Notebook,” Appendix E. The lab notebook is a significant portion of your final grade since it is a critical part of physics research.

4.7 Your technical report on the experiment

After you complete your measurements and analysis, you will turn in a typed, double-spaced description of the temperature measurement experiment. It is unlikely that you will be able to write an adequate report that isn’t *at least* two pages long.

Please remember: *Most writing assignments in Physics 240 are done individually - there is only 1 group writing assignment and this one is not it.*

This report is based on a simplified technical report of the type usually used for internal communications or communication with a contractor. It is often not intended for general public consumption, so it is possible to make some assumptions regarding your audience. In the case of this report, you can assume that the reader has some acquaintance with the overall project but not with your specific measurements.

Most descriptions of technical report contents and formats are for the engineering disciplines, but they apply equally well to such reports in the physical sciences. You can search for descriptions of technical reports (search term “Technical Report”). Some potentially useful descriptions would include

- How to Write a Technical Report by Alan Smithee ([http://www.physics.byu.edu/faculty/petersonb/Phys240/HowToWriteATechnicalReport-AlanSmithee.pdf](http://www.physics.byu.edu/faculty/petersonb/Phys240/HowToWriteATechnicalReport-AlanSmithee.pdf)) (9 January 2017). Note: I’m not sure where this came from. It is found on many websites, and I haven’t found one with any attribution.
- Boris Korsunsky, “The Results Were the Results of Errors, Promoting Good Writing by Bad Example,” The Physics Teacher, vol. 48, pp. 10-11, [https://doi.org/10.1119/1.3274349](https://doi.org/10.1119/1.3274349).

We are simplifying this report somewhat by not requiring an Executive Summary, Table of Contents, List of Figures, or List of Tables. The report does need to be complete and divided into the following sections as appropriate for your content.

1. **Title Page** *(The title of your report and who you are – this is a separate page with no other content except possibly your abstract)*
2. **Abstract** *(One paragraph describing what was done, why it was done, and the key results.)*

3. **Introduction** *(What is this measurement about?)*

4. **Experimental Methods** *(What did you use to make the measurement? How did you make the measurement?)*

5. **Experimental Results** *(This is your data and a description of your data.)*

6. **Analysis and Discussion** *(This is a determination of what your data means.)*

Some important additional reminders:

- Use units with all data (we really can’t say this too often – it is very important).

  There are two online documents that are very valuable regarding the use of SI units. The NIST Guide for the use of the International System of Units *(https://www.nist.gov/physical-measurement-laboratory/special-publication-811)* and Writing with Metric Units *(https://www.nist.gov/pml/weights-and-measures/writing-metric-units)*

- **Use labels for graph axes.** These labels should include both what is represented by the axis and the associated units if applicable. Use arrows and describe what is significant on the graphs.

  “Give every figure [graphs, pictures, etc.] a caption, complete and intelligible in itself without reference to the text.”

- Describe any analysis models and approximations completely.

- Indicate uncertainty in your data and subsequent results as accurately as possible.

- Answer all questions that are found in this handout. It is not expected that the answers be given explicitly *(i.e., “the answer to question xxx is yyyy.”)*. It is expected that the answers will at least show up somewhere in the discussion.

### 4.8 Building Models in experimental physics

Anytime you interact with the physical world you are building models to help you analyze and understand those observations. These models may be mental, mathematical, diagrams, or some combination of these. These models can help to identify underlying assumptions or limitations in your understanding of the observations.

Without some model to use in interpreting your observations, it is not possible to draw meaningful conclusions regarding the system you are observing.

As you progress through measurement and analysis of a system or experiment, it is often necessary to go back and tweak your models as you learn more about the system. You

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may also find that your models will guide you in revising either the measurement system or the physical apparatus to improve your results. This iterative process is common in any experimental project.

You will find that this is also true in both computational and theoretical projects. It is often necessary to go back and modify computer codes or assumptions in your theory (both of which can be described as models) to achieve the desired results.

4.8.1 Modeling the measurement tools

In physics, mental models are often inadequate for a complete understanding. For example, if we wish to make a measurement using a computer and some transducer, we have to understand how the transducer responds to the phenomenon of interest as well as the way the computer interface and acquisition system respond to the signals from the transponder.

In this lab exercise, we will use a transducer to measure the temperature of the heater block and record it in a file so that the results can be further analyzed. We will develop a model describing how the output of the transducer is related to the temperature of the block. We may also have to include the behavior of the transducer if the supply voltage or current varies.

For example, using a silicon diode to measure the temperature requires some understanding of how the diode responds to varying temperature. The development of a model for the temperature dependence of a diode’s characteristics is described in Appendix I, “Measuring Temperature with a Silicon Diode.” This appendix also includes some information on estimating the uncertainty in the measured temperature that you will find useful.

To complete the model, you will follow the instructions in “Calibrating a Silicon Diode for Temperature Measurement,” Appendix L. This will allow you to quantify the model for the diode so that you can use the voltage across the diode to determine the temperature of the heater block.

We also have to consider how our data acquisition hardware affects the measurements. Considerations may include sample rates, input range, resolution (minimum resolvable voltage change), intrinsic errors in the electronics, the presence of electronic noise, and filtering (both intentional and unintentional). Some of these are easily quantified and should be. Some will remain uncertain and difficult to characterize, but it is important to identify their effect on your results as carefully as possible.

4.8.2 Modeling the physical apparatus

It is also necessary to model the physical apparatus with which you are working. This will allow you to relate the measured parameters to any outside influences or fundamental characteristics of the apparatus. These outside influences may be intentional, such as driving an oscillator, or out of your control, such as air currents due to building ventilation or
vibrations from external forces. In any case, the more complete your model, the better you will be able to understand the measurements.

In the case of our experiment, we need to have a model for the way the temperature of the heater block/heater coil/cooling rod/ice water/brass cap system changes when we change the power in the heating coil. We will develop a simple model for this system in subsection 4.12.2 on page 53 in this chapter.

It is important to look carefully at this model, so you understand the limitations in its application to our system.

4.9 Constructing a heater coil on your aluminum heater block

The first step in carrying out this lab is to build and characterize a heating coil on your heater block. The instructions for building the coil are in Appendix F, “Heater Construction Handout.”

To characterize the heater coil, you need to know (and record in your lab notebook) the final dimensions and resistance of your coil. It usually doesn’t work very well to measure the resistance of your coil with an ohmmeter. You should read Appendix G, “Four-Lead Measurement of Resistance,” for the proper way to accurately determine the resistance. It is often necessary to use the Four-Lead technique for measuring resistance if you have a very small resistance (like your heater coil) or if the connections to the device being measured are resistive (“poor connections”).

Do NOT use the beige/black $+15/-15/+5\text{ V}$ supply to provide the current for the four-lead measurement – these supplies dislike being attached to a low-resistance load. It is best to use a supply that can be adjusted to provide a constant current. A supply with a current control knob will be available in the lab for this purpose.

Note that you are measuring the resistance of a heater. Running a current through it is supposed to change the temperature. Changing the temperature of the material can change its resistivity.

4.10 Measuring the temperature of the heater block

You should review Section 8.1.4 (Semiconductor Thermometers) in the text. Pay particular attention to the relative advantages of semiconductor devices for temperature measurement in terms of sensitivity and linearity.
Because of the simplicity and easy availability of a 1N4148 silicon diode, we will be using this diode for our temperature measurements. The small off-center hole in the aluminum heater block is specifically provided to hold a diode for recording the temperature of the block.

- Consult Appendix I, “Measuring Temperature with a Silicon Diode,” to understand why a diode thermometer works and some of the limitations of that device. This appendix also includes some information on estimating the uncertainty in the measured temperature that you will probably find useful.
- For the diode to reliably measure the temperature, it is necessary to drive it with a constant current. This current should be near 100 µA (in the range of roughly 90 µA to 110 µA) for the range of temperatures in which we are interested. The instructions for building a reliable constant current supply for operation in this range are given in Appendix J, “A Constant Current Source.”
- For detailed instructions on calibrating your diode to make reasonably accurate temperature measurements see “Calibrating a Silicon Diode for Temperature Measurement,” Appendix L.
- Thin Teflon spaghetti tubing is available to insulate the leads on the diode so it can be inserted into the aluminum heater block. When you bend one of the leads back so they both point in the same direction, be careful that you don’t bend the lead right at the plastic surface or kink it. As sharp bend can weaken the lead sufficiently that it will break.

### 4.11 Data collection using LabVIEW

Most of the data for this experiment will be collected using LabVIEW so you can more easily analyze the results. You will need to build a data acquisition VI for this purpose using (at a minimum) an input VI, a “while loop,” a time delay, a chart to display the voltage measurements, and a function to save the results to a file.

**Please note the terminology here.** You are writing a VI that includes a sub-VI that is called the “DAQ Assistant.” This phrase refers to a software “wizard” that simplifies the connection between the computer and the external hardware to allow you to acquire signals from the external hardware.

The piece of external hardware that connects between the computer and whatever signals you wish to acquire is known as a data acquisition module or data acquisition board. The abbreviation for this object may be a DAQ module or a DAQ board.

The DAQ board has a model name/number. **When you are describing your experiment in a document or publication, you should refer to it by manufacturer and model name or number, not as just “the DAQ board” and especially not as the “DAQ Assistant” (remember that the “DAQ Assistant” is the sub-VI “wizard”).**
Considerations for your analog input VI:

1. The analog input devices that we use can only directly measure voltages. When you configure your DAQ Assistant Express VI it will give you the option of measuring several different types of signals including current, resistance, and temperature.

   If you have configured it to measure anything but voltage, it will be necessary further to configure the series resistance (for current measurement), the current (for resistance measurement), or the calibration equation (for temperature measurement). **If you select anything but voltage measurement, it will be necessary to verify every class period that the configuration is the same as you used in previous measurements.**

2. Determine the input range you need for your analog input VI to accurately measure the signals you are going to acquire.
   - For DC signals, a voltmeter is adequate to determine the range. Measure the maximum and minimum signals for a range of experimental conditions and use those to set the input range (allow a little extra just to be sure).
   - For AC signals, you may need to temporarily set the input range to some large value (like ±10 V), acquire the signal under several conditions. You can then use these signals to determine the appropriate input range.

3. Right-click on the VI to get the configuration panel (if you don’t do this in the initial configuration) and set the input limits to something that is appropriate for the data you will be acquiring.

   If you choose a range that is too small, it will clip your data. If you choose a range that is too large, it will lead to poor results due to digitization noise.

4. The connectors on the USB-6221-BNC and the PCI-6040E with the BNC-2120 are configured for **differential** mode only. Your analog input VI must also be configured for differential mode. You should verify that the Terminal Configuration option in the lower-right of the DAQ Assistant Express VI configuration panel is set to **differential**.

5. If you don’t need to read rapid changes in T, you can average over many points (maybe for a second or so depending on the rate your temperature is changing) before displaying T. Averaging many samples is especially useful when calibrating the temperature sensor to reduce the noise in your readings (when you are acquiring calibration data the temperature should no longer be changing).

   Set the Acquisition Mode to “N Samples” and the Number of Samples and Sample Rate to appropriate values for your experiment.

Since one of the items included in the instructions for the paper is to include estimated uncertainties in your results, use the **Std Deviation and Variance** VI to get both the mean value and the standard deviation of the acquired voltages. For help on properly handling the uncertainties and propagating them through any calculations, you should see “Uncertainties, Errors, and Noise in Experimental Measurements” in Appendix C. Especially note what needs to be done if you average N values to get the Mean from this VI.

If you wish to wait for a specified time between temperature readings you have a couple of options. One is the **Wait Until Next ms Multiple** that waits the specified
number of milliseconds. Another is the Time Delay express VI for which you specify the number of seconds to wait. In both cases, you just add the timing VI inside your while loop. The VI does not need to connect to any other VI in the loop. The loop will not continue until all code contained within the loop is completed; you will wait at least the specified time per iteration of the loop (you may wait longer if the other code in the loop takes longer to finish than the timing VI).

- Add a Write Delimited Spreadsheet VI to save your data in a file. To properly set up this VI:
  1. Increase the number of significant figures for data saved by right-clicking on the format terminal (on the top of the VI) and creating a constant with the value “%.6f” (fixed-point notation with six digits to the right of the decimal) or “%.6e” (scientific notation with six digits to the right of the decimal – this one is preferred). This is critical when you are taking small signal data as you eventually will do in the superconductivity measurements. Keeping more digits than the measurement justifies is not a problem – you can always throw away the digits that are beyond the actual precision of the measurement. You can’t recover significant digits that you didn’t save.
  2. The default column delimiter is a tab character. If you wish to use a different delimiter you can change it with the “delimiter” input along the bottom of the VI. A reasonable alternative is to use the comma (“,”) character as the delimiter. Excel uses the “.txt” extension for tab-delimited files and the “.csv” extension for comma-delimited files.
  3. If you do not include an output file name (upper left-hand corner), you will be prompted for a file name every time the spreadsheet VI is called. If you put this VI inside a while loop, provide it with a file name, or it will prompt for a name on every iteration of the loop.
  4. Set the “append to file” input to an appropriate value. If this is set to false, the VI will create a new file (and delete the old copy) every time it is called. If your spreadsheet VI is inside a loop, set this input to true.
  5. The files are most useful if the data are in column format. The transpose input on the bottom of the VI will allow you to change the file format if the data are not in the desired column format.

- Some of the tutorials have you use the Write to Measurement File VI for saving data. The difficulty of using this arises from the available output file formats. These formats are not a portable as the tab-delimited or comma-delimited files.
  - Text File (LVM) – create a text-based “LabVIEW Measurement File.” The data are in columns with significant text headers in the file. With a proper choice of parameters it is possible to get something that Logger Pro, MATLAB, or Mathematica can read if you are willing to modify the file some. The format is discussed in http://www.ni.com/tutorial/4139/en/.
  - Binary (TDM) – a binary LabVIEW Measurement File containing the same information as an LVM file with an XML header.
  - Binary (TDMS) – a binary file in LabVIEW “TDM Streaming” format. This is a modification of the TDM file.

- **Excel (xlsx)** – a binary file in Excel format. It can be read by Excel and converted to other format that may be more appropriate for a particular analysis program.

  - Since you are recording data as a function of time, it is useful to record the elapsed time in one column of your spreadsheet file. You do this by combining the time and temperature into an array using the **Build Array VI**. You can expand the **Build Array VI** to have more inputs if you wish to include the standard deviation of the value.

### 4.11.1 Diode calibration: analysis questions and requests

1. How much does the constant \( b \) differ from \( E_g/q \)? \( E_g \) is the band-gap energy of the silicon used in the diode. It is approximately 1.19 eV. \( q \) is the charge on the electron. The constant \( b \) is from the model equation \( V = mT + b \) with \( T \) in Kelvins. (Refer to section I.1 in Appendix I, ‘Measuring Temperature with a Silicon Diode,” for the derivation of this equation.) If your equation is in a different form or uses different units, you will have to rearrange your equation in this form to determine \( b \) from your fitting constants.

2. How far off is the calibrated diode temperature measurement at each of the three calibration points? Give your response in degrees. This is found by looking at the temperatures predicted from the measured voltages by your calibration equation and comparing them to the corresponding measured temperatures.

3. Is this error consistent with the estimated uncertainty of your calibration constants? (see the temperature uncertainty section of “Using a Semiconductor Diode As a Temperature Sensing Device” (Appendix I). You may also want to look at the **Mathematica** notebook **SuperconductorParametersAndUncertainty.nb** in Content ⇒ Superconductivity Measurements Lab on Learning Suite or at [https://www.physics.byu.edu/faculty/petersomb/Phys240/SuperconductorParametersAndUncertainty.nb](https://www.physics.byu.edu/faculty/petersomb/Phys240/SuperconductorParametersAndUncertainty.nb) for help in finding the uncertainty in your temperature measurements.

   Look at the second section in the notebook: “Calculate the uncertainty in a temperature determined from a diode”; you will need to enter appropriate values for the parameters and data if you use this notebook.

4. How would you improve your calibration?

5. Include a plot of your calibration data and fit – including the calibration constants – in your notebook and in your report.
4.12 Measuring the thermal parameters of the cryostat assembly

4.12.1 Determining the heating and cooling rate of the cryostat assembly

Eventually, you will be asked to design and build a temperature controller for your cryostat assembly using LabVIEW. To design a controller, it is useful to know how the heater block assembly behaves in cooling and heating. Since every assembly is different, it is necessary to measure the behavior of the block assembly you will use in the controller experiments.

You should have already constructed a heater on your heater block, built a VI to record the temperature of the block as a function of time, and calibrated a 1N4148 diode for temperature measurements.

- Support the heating block with the cooling rod in ice water in an insulated container. Be careful that the diode and its leads are not immersed in the water as that will modify the apparent temperature of the block by allowing some of the current to flow through the water instead of flowing through the diode.
- *(Do not use your analog output on the analog I/O module to drive the heater - it can’t deliver the necessary current).*
- Connect your heater to the large Kepco ATE36-8 power supply.

Your goal is to heat the cryostat to about 120 °C. The applied power should be low enough to take several minutes for the cryostat to reach this temperature and high enough to get to the desired temperature. About 70-90 W is a good starting point.

Determine the settings for voltage or current that will apply a known power to the heater. You can set either the current or voltage to be the controlling value in the power supply. The other output parameter will be determined by the resistance of the heater and Ohm’s Law. The knob for the other output parameter will be set to some large value, so it won’t control the output.

- Simultaneously measure the current and voltage to calculate the power. *Do not trust the meters on a power supply until you have verified that they are accurate.*
- While recording the temperature of the aluminum heater block vs. time (take at least one temperature reading every 3 seconds), apply a known power (in other words, a power that you have set and recorded) to heat the heater block assembly
- Take heating data until you reach about 120 °C. Turn off the supply and take about 20 minutes of cooling data.
- Save your heating and cooling data to disk and print plots of $T(t)$ for heating and cooling (these will be useful items to put in your lab notebook).
- Remember to report your data in the technical report on the experiment.
4.12.2 A model for analyzing the heating/cooling data

As noted above, we are interested in estimating the heat capacity, cooling coefficient, and equilibrium temperature for the heater block assembly. We need a mathematical model that will relate the measured behavior of the heater block to the desired parameters.

The basic ideas you will use to model the assembly are Newton’s law of cooling and the concept of heat capacity. For simplicity, we will assume this is a one-dimensional system. Since our system is a rather complex three-dimensional one, this is a dubious assumption, but a full model is beyond the scope of this class.

Newton’s law of cooling: The flow of heat out of or into a body is given by

\[
\frac{dQ}{dt} = -\gamma(T - T_{eq}) .
\]

dQ/dt is energy flow. \(\gamma\), the cooling coefficient, is a constant related to the cross-sectional area, the thickness, and the thermal conductivity of the material between the hot and cold regions. \(T\) is the temperature of the body and \(T_{eq}\) is the temperature when the body is in equilibrium with the surroundings.

Heating and cooling: If you are also providing heat to the body, which you will do with your heater, you will need to add that term to the equation and the above equation becomes

\[
\frac{dQ}{dt} = P - \gamma(T - T_{eq})
\]

where \(P\) is the power being put into the body. Note that \(T_{eq}\) is the equilibrium temperature when \(P = 0\) so it would have the same value irrespective of the value of \(P\).

The definition of heat capacity, \(C\):

\[
dQ = C \,dT .
\]

Recall that the heat capacity depends on the mass of the object and the specific heat(s) of the material(s) of which it is made.

Combining these equations you get

\[
C \frac{dT}{dt} = P - \gamma(T - T_{eq}) .
\]

Using your data from heating and cooling the cryostat you can fit the solution of this differential equation to your data and determine the constants \(C\), \(\gamma\), and \(T_{eq}\). Note that you have to have both the heating and the cooling data to be able to uniquely determine \(C\) and \(\gamma\).
4.12.3 Fitting a theoretical model to your experimental results

The values of the constants $C$, $\gamma$, and $T_{eq}$ for your heater block assembly will be determined by fitting the model from the previous section to the measured behavior of the heater block.

A warning regarding the process of fitting parameters: if you have parameters that show up only in simple algebraic relationships involving only those parameters and constants, the fitting process can choose any values that provide the same result from the algebraic relationship.

For instance, you will find the ratio $\gamma/C$ with no other occurrence of either of the parameters $\gamma$ or $C$ in one of the model equations. The fitting process can arrive at any values of $\gamma$ and $C$ as long as the ratio has the correct value. You can not get any information about the individual parameters in this case.

Instructions for fitting your data to the model equation are given in four separate Appendices, one for each of four different software packages that provide nonlinear fitting capabilities (the model equation is very definitely nonlinear). See “Logger Pro” (Appendix M), “Mathematica” (Appendix N), “MATLAB” (Appendix O), “Python” (Appendix P), or “Excel” (Appendix Q). Note that Excel can model the cooling curve but will not be able to model the heating curve without significant manual help. Excel also does not provide estimated uncertainties in the fitting parameters.

4.12.4 Thermal parameters: analysis questions and requests

1. What is the solution to the equation that governs $T(t)$ with both the heating and the cooling terms present?
2. What are the values you obtained for $C$, $\gamma$, and $T_{eq}$ for the curves? What are the estimated uncertainties in each of these values?
3. Do the constants agree well for the heating and cooling curves? Is that expected?
4. How good are the fits and how should you quantify the goodness of the fits?
   Strong Hint: a reasonable way to at least subjectively show the quality of your fit is to have a graph of the equation for the fit on the same plot with the experimental data so that it is easy to see if the line does or does not pass through the data in a reasonable way.
5. From your data, try to estimate the thermal conductivity (represented by either $\kappa$ or $k$) of the copper rod, from $\gamma = \kappa A/L$ where $A$ is the cross-sectional area of the rod and $L$ is roughly the length of the rod between the bottom of the heater block and the surface of the water. If needed, review an introductory physics text or the hyperphysics website http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html on heat conduction (Heat and Thermodynamics ⇒ Conduction).
6. How does $\kappa$ compare with values of some materials in the accompanying table?
<table>
<thead>
<tr>
<th>Material</th>
<th>Typical thermal conductivity (W/(m·°C))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>401</td>
</tr>
<tr>
<td>Aluminum</td>
<td>237</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>50</td>
</tr>
<tr>
<td>Steel (common)</td>
<td>20</td>
</tr>
<tr>
<td>Glass</td>
<td>0.8</td>
</tr>
<tr>
<td>Fiberglass batt</td>
<td>0.04</td>
</tr>
<tr>
<td>Wood</td>
<td>0.1</td>
</tr>
<tr>
<td>Styrofoam</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Chapter 5

Controlling Temperature and the Controller Contest

5.1 Expected Learning Outcomes

- Gain experience in using a computer to control external hardware.
- Develop a real-time control system for an experiment.

5.2 Introduction

You will build a computer-based temperature controller that will be used to control the temperature of your cryostat assembly in the range from 50°C to 100°C.

Sections 6.7.8 (Control Systems) and 8.2 (The Control of Temperature) in the text contains information that will be useful in completing this exercise. In fact, you will find this information useful in nearly anything you do that requires controlling hardware. This may include your self-driving car, the neat self-landing drone you purchased, or an advanced automatic lawn sprinkling system that uses temperature, wind, and soil moisture to determine when and for how long to water. Some of this even comes into play in the mental processes you use to negotiate a busy freeway in a car.

5.3 Temperature controller contest

To give you the incentive to develop a quality computer-based temperature controller, we will have a contest between the teams. The required sequence to complete the contest is to
1. Begin at a temperature below 50 °C. The contest time will start when the temperature reaches 50 °C.

2. Raise the temperature to 100 °C.

3. Hold the temperature within ±0.5 °C for 2.5 continuous minutes – if the temperature goes out of range, the timer must be restarted.

4. Cool the temperature to 70 °C.

5. Hold the temperature within ±0.5 °C for 2.5 continuous minutes. The contest time will end when this time elapses.

The contest will be to see which team can achieve the shortest time to complete the above sequence. Each member of the team that does this in the shortest time will win a prize. The contestants may use any means at their disposal to make their cryostat heat up or cool down quickly with the following limitations:

1. The contestants may not manually disturb the cryostat system (including the coolant) after they start the run. Any action that can be completed entirely under computer control without any manual intervention is allowed.

2. The contestants may not change anything on the computer once the run starts.

3. Any modified cryostat heating blocks must retain the original outside and inside diameters and lengths. The cap may not be modified. The internal cavity walls must not be perforated.

4. No power source other than one Kepco ATE36-8m supply may be used for the actual heater power.

5. Your LabVIEW program must make all the decisions on whether you are in range of the target value, when you have been in range long enough, and when to switch to a new target value.

6. Your program must maintain a total elapsed time counter showing the total time that has elapsed since the temperature went above 50 °C.

5.4 Equipment

The available equipment for this exercise includes all the equipment necessary for the Thermal Measurements Lab.
5.5 Grading

The grading will be as follows:

- Successfully controlling the temperature of your cryostat assembly over the specified sequence – 40 pts.
- Lab notebook – 40 pts.

You will receive full credit for the controller (for grading purposes) if your computer completes the sequence, regardless of how long it takes to get there (within the bounds of the 170-minute length of a standard class period). The contest is intended to see how creative you can get in making your controller work well.

Your lab notebook entries for the controller and contest will be graded. It is good practice to keep track of

- why you chose the particular method of controlling
- any special information on how you wrote your controller
- any constants needed to make your controller work
- since you will likely be changing these constants in the process of tuning your controller, it is good to keep track of how you have changed them in case you have to revert to a previous set of values.

*Valid heating time trials must be made while the instructor or one of the TAs is monitoring your controller.*

5.6 Selecting the proper control variable

If possible, your control equation should provide an output controlling value (power supply output) that is linearly related to your controlled value (temperature in this case).

Solving the differential equation derived in subsection 4.12.2 gives the expression

\[ T(t) = T_{eq} + \frac{P}{\gamma} + Ae^{-\gamma t/C} \]

where \( A \) is a constant determined by the temperature at \( t = 0 \).

Note that \( T \) and \( P \) are linearly related in this equation since \( T_{eq} \) is a constant, and the exponential term is essentially constant over the control update interval. That means the power would be the logical choice for a controlling variable.
Since we can only control the output voltage of the power supply, it will be necessary to convert the power specified by the control equation to the power supply output voltage necessary to deliver that much power to the heating coil. It may be useful to remember that $P = \frac{V^2}{R}$ where $R$ is the resistance of your heating coil and $V$ is the voltage across the coil.

Also, remember that $P$ may be negative (i.e. your temperature is too high, and the controller wants to reduce the temperature by removing power). If $P$ is negative, you will end up with the square root of a negative number to arrive at $V$. If the power is negative, you want to have the supply provide no power.

5.7 Controlling the Kepco power supply

The power for your heating coil will be provided by the large gray Kepco ATE-36-8M power supply (the manual for this supply can be found at [http://www.kepcopower.com/support/ate-operator-half-rack-r1.pdf](http://www.kepcopower.com/support/ate-operator-half-rack-r1.pdf).

- This supply is capable of simultaneously supplying 0-36 V and 0-8 A if the load allows that to happen. In other words, once the supply is providing 8 A, any attempt to increase the voltage by adjusting the power supply controls will result in no change. Similarly, once it is providing 36 V any attempt to increase the current will result in no change. You can use the voltage and current control knobs to change the maximum allowed output voltage or output current respectively. Once the output reaches one of the two maxima, the light above the appropriate knob will be illuminated. For instance, if you have the current knob set to allow a maximum of 6 A, when the supply is providing the specified 6 A the light above the current knob will be illuminated indicating that the output is being controlled by the value set with that knob.

- On the back of the Kepco power supply, there is a black box with a switch and a BNC connector on it. The switch determines whether the output voltage is set by the knob on the front panel or by the control voltage applied to the BNC connector. Most of the power supplies are configured so that the switch is down for remote control. Only the voltage can be externally controlled. The current is always controlled by either the current knob or the resistance of the load, whichever results in the smaller current.

Note: You can determine the status of the supply (whether remote or local control) by turning the voltage control knob and seeing if the output voltage changes. Before you try this, turn the current knob clockwise several turns so that the light above the voltage knob is on, indicating that the supply is controlling on voltage and not current.

It is strongly recommended that you not perform this test with the power supply connected to your heater coil.

- As noted above, you can only control the output voltage with the voltage applied to the BNC connector. The current is determined by the load resistance unless your
current exceeds either the current set by the current control knob or the maximum limit of the supply (8 A) is reached.

- The control voltage must be in the range of 0–10 V to achieve an output voltage of 0–36 V. Thus, the output voltage is given by $V_{\text{output}} = 3.6 \times V_{\text{control}}$.

**Caution**: the circuit breaker on the supply will turn off the power supply if you try to output 36 V. It is usually best to limit the control voltage to about 9.8 V or less.

## 5.8 Controlling the heater with a simple model

It is possible to use the simple analytical model and your knowledge of differential equations to develop a method to control the temperature of the cryostat. This is a powerful method that is used to control a wide variety of systems including robotics.

As noted above, the equation that governs the temperature of the heater block (with a few key assumptions) is

$$T(t) = T_{\text{eq}} + \frac{P(t)}{\gamma} + A e^{-\gamma t/C}.$$  

We have explicitly noted that the power will be a function of time when we are controlling.

You should have already determined $T_{\text{eq}}$, $\gamma$, and $C$ by fitting this equation to your heating and cooling curves in the previous exercise. You can control the temperature using the following algorithm:

$$e(t) = T_{\text{target}} - T(t)$$

where $T$ is the current temperature, $T_{\text{target}}$ is the desired temperature, and $e(t)$ is the error term giving the difference between the two. For $e(t)$ to approach zero in a fast but smooth way, we require it to decrease exponentially, *i.e.*, 

$$e(t) = B e^{-\alpha t}$$

where $B$ is the initial value of $e(t)$. The advantage of this is that it has a very simple derivative

$$\frac{de(t)}{dt} = -\alpha e(t).$$
When $T_{\text{target}}$ is constant we obtain the following expression linking power $P$, temperature $T$, and desired temperature $T_{\text{target}}$

\[
\alpha(T_{\text{target}} - T) = \alpha e(t) = \frac{d[T_{\text{target}} - T(t)]}{dt} = \frac{dT(t)}{dt} = \frac{1}{\gamma} \frac{dP(t)}{dt} - A \frac{\gamma}{C} e^{-\gamma t/C} .
\]

If we solve the original equation for $A e^{-\gamma t/C}$ and substitute that into this equation we get

\[
\alpha e(t) = \frac{1}{\gamma} \frac{dP(t)}{dt} - \frac{\gamma}{C} \left(T - T_{\text{eq}} - \frac{P(t)}{\gamma}\right) = \frac{1}{\gamma} \frac{dP(t)}{dt} + \frac{P(t)}{C} - \frac{\gamma}{C} (T - T_{\text{eq}}) .
\]

We can then solve this equation for $P(t)$

\[
P(t) = C \alpha e(t) + \gamma(T - T_{\text{eq}}) - \frac{C}{\gamma} \frac{dP(t)}{dt} .
\]

In a real experiment, this controller can be sensitive to changes in the constants ($C$, $\gamma$, and $T_{\text{eq}}$). $C$ and $\gamma$ are mostly associated with the physical dimensions and materials of your heater block and rod. $T_{\text{eq}}$ is a little trickier because it depends on what your ice bath is doing, such as how much ice you have left in the bath at any given time.

### 5.9 PID controller model

A PID controller is a common control method that works very well with essentially no information on the physics of the process being controlled.

The name, PID controller, is an acronym for the three terms used to determine the control output value.

- **P=proportional** - this term produces a control output that is proportional to the difference between the target value and the current value.

  This term gets the controlled value close to the target value as quickly as possible.
Controlling Temperature and the Controller Contest

**I = integral** - this term produces a control output that is proportional to the integral over some period of the difference between the target value and the current value.

This term does the last little bit to bring the value to the target value if there is a residual error.

In some cases, the integral term can cause a controller to become unstable and begin to oscillate. If the controller becomes unstable, it may be possible to stabilize the controller by reducing the constant $K_I$ or changing the interval over which the error is being integrated.

**D = derivative** - this term produces a control output that is proportional to the rate of change of the difference between the target value and the current value.

This term helps to suppress overshoot by slowing down the change as you approach the target value and to damp out oscillations.

Sometimes it is necessary to reduce the constant $K_D$ or leave the derivative term out if the controller becomes unstable.

Mathematically, this process looks something like

$$\text{control}(t + \delta t) = K_P e(t) + K_I \int_{t_0}^{t} e(\tau) d\tau + K_D \frac{d e(t)}{d t}$$

where $e(t)$, the error term, is given by

$$e(t) = T_{\text{target}} - T(t).$$

Since we are controlling power (the linear variable) this equation becomes

$$P(t + \delta t) = K_P e(t) + K_I \int_{t_0}^{t} e(\tau) d\tau + K_D \frac{d e(t)}{d t}. $$

A good introduction to a PID controller can be found in the text in Section 8.2.2 (Temperature Control at Variable Temperatures) and in the Wikipedia article on this topic.

In the paragraph before equation 8.7 in Section 8.2.2 of the text, there is a reference to “background power.” In our case, we know that maintaining a constant temperature requires a background power roughly equal to $P_B = \gamma (T - T_{eq})$ which is approximately the power that is being lost to the ice bath at temperature $T$. This may be useful in designing your temperature controller.
5.9.1 Tuning a PID controller

The most difficult aspect of this controller is determining the values of $K_P$, $K_I$, and $K_D$. There is no obvious physics in the controller. You can get some guidance in picking the constants, especially $K_P$, by looking at the equation on p. 62. You can also find guidance in determining the constants in the Wikipedia article, but it is necessary to tune the controller constants specifically for your particular system and algorithm.

Opto 22, a company the manufactures PID control modules, has some very good information on PID controllers including an excellent technical note (http://documents.opto22.com/2171_PID_Loop_Tuning_Technical_Note.pdf) describing the controllers and some guidelines on tuning them. They also have an online PID loop tuner (http://www.opto22.com/site/pid.aspx) that you may find useful.

5.10 Some useful LabVIEW functions

**In Range and Coerce** is a very useful function. This function will accept a value as well as an allowed range for that value. It will provide an output value that is forced to be within the specified range. If the value is too large, the output will be set to the maximum value of the specified range. If the value is too small, it will be set to the minimum value of the range. If the input value is within the specified range, it will be passed to the output unchanged. The function will also return a boolean value indicating whether the value is within the specified range.

A separate **DAQ Assistant** VI is used to provide an output voltage. This VI is separate from the DAQ Assistant VI you use to acquire the voltage across the diode.

- Set the **Generation Mode** in the configuration screen to **1 Sample (On Demand)**. In this mode, the VI will continue to output the last value set by the VI until a new value is specified.

The **Elapsed Time** VI is a handy timing VI (the “<execution control>” and “<timing>” versions are the same VI). Look carefully at the **Reset**, **Auto Reset**, and **Time Target** (s) inputs as well as the **Time has Elapsed** and **Elapsed Time (s)** outputs. By correctly specifying the values on the inputs and monitoring the correct output(s) you can have this VI perform some of the apparently magical things required for your controller to function properly.

A “shift register” can be an effective way to preserve a value between successive executions of your while loop.

When you are working on tuning the constants for your controller, it is often useful to make any constants front-panel controls. Using controls allows you to make changes to the controller without having to stop it.
5.11 Integrals and derivatives of experimental data

Because real (noisy) data is used in the control process, it is necessary to be very careful when taking derivatives. The derivative of noisy data using adjacent points will result in very large swings in the derivative. It is often possible to use smoothing techniques to reduce that noise and achieve a better value. For example, if we use the most recent \( j \) points we will get a derivative that is effectively averaged over \( j - 1 \) time intervals:

\[
\frac{de(t)}{dt} = \frac{e(t_i) - e(t_{i-j+1})}{(j - 1)\Delta t}
\]

where \( \Delta t \) is the time between successive samples in the \( e(t) \) array. Note that it is necessary to have some past values to take this derivative.

The integral term also requires some consideration in the PID controller since you will start with the temperature far from the target temperature and it may not be desirable to integrate up a lot of large error that doesn’t correlate with the behavior of the system when near the target temperature.

Remember that the integral is just a Riemann sum:

\[
\int_{t_0}^{t} e(\tau) \, d\tau = \sum_{\tau=t_0}^{t} e(\tau) \Delta t.
\]

The integral can either be computed from an array of recent past values or by keeping a running sum of \( e(t) \times \Delta t \). It may be necessary to limit the number of past values used for the integral. It is usually necessary to reach back at least far enough in time to integrate over several oscillations of the temperature. If the integration interval is too short, this term can act as a positive feedback for any oscillations.

5.12 Making your controller work

Once you have the controller program written, it is necessary to tweak it to work properly. Hopefully, you have taken the advice given earlier and made all the constants governing the operation of your controller into front panel controls. This will allow you to make changes to the controller’s operation without having to stop and edit the program. It also means that you will need to keep a record of what you have been using as constants because the computer won’t remember them for you.

You should probably read the section on debugging software in Appendix K, “The Art of Debugging.”
The use of indicators to watch how the output power is calculated can be very handy in determining whether your choice of constants is correct.

The Wikipedia article on PID controllers referenced earlier in this chapter has some good hints on how to determine the initial constants for a PID controller. The technical note from Opto 22 should also be useful.
Chapter 6

Resistivity vs. Temperature of a Superconductor

6.1 Expected Learning Outcomes

- Calibrate a transducer (silicon diode) for low-temperature measurements and measure temperatures down to that of boiling liquid nitrogen.
- Accurately measure very low voltages, including techniques for reducing or compensating for electronic noise.
- Identify the source of and compensate for systematic error(s) in measurements.
- Examine the behavior of a high-T_c superconductor sample during the transition between the superconducting and normally-conducting states.
- Report the results of your measurements in a format appropriate for submission to a journal for publication.

6.2 Introduction

WARNING

Take extreme caution when handling the superconductor lead wires.

- Gently push the cable through the brass cap, being careful that you don’t damage the connectors on the end of the cable and that you don’t kink or unnecessarily flex the cable.
- Put a thin coating of the anti-seize compound on the threads of the superconductor assembly before you screw it into the aluminum heater block. This will ease the process when you eventually remove the superconductor from the heater block.
• Screw the superconductor assembly into and out of the heater block using a *large* screwdriver in the back slot.

The small yellow or gray screwdrivers are *not appropriate* for inserting or removing the superconductor from the block.

*Never* twist it in or out by the wires.

• It is usually good to use the screwdriver to hold the superconductor assembly stationary with respect to the room and rotate the aluminum heater block when you assemble or disassemble them. This will avoid the problem of wrapping the wires around the screwdriver and reduces the likelihood that you will break one or more wires during the assembly/disassembly process.

• *Never, never, NEVER,* bend the superconductor lead wires when frozen.

In this lab, you will measure the resistivity of a high-critical-temperature superconductor as a function of temperature. These amazing materials have a resistivity that drops to zero below a certain critical temperature. The high-critical-temperature material we will examine is \((\text{Bi,Pb})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_δ\) or \(\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{Ca}_{y-1}\text{Cu}_y\text{O}_δ\). This is often written as just \(\text{BiPbSrCaCuO}\) or BSCCO (pronounced “bisco”) for short. This material has a critical temperature about 30 K above the temperature of boiling liquid nitrogen, a very high critical temperature. This high critical temperature makes it quite technologically relevant. Several companies are producing commercial products from this material including mammoth electrical motors for the Navy.

Note: when you are referring to this material in your paper, it is acceptable to use the abbreviation BSCCO as long as you define it the first time you use it. Three ways of doing this: BSCCO \((\text{BiPbSrCaCuO})\), BSCCO \((\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{Ca}_{y-1}\text{Cu}_y\text{O}_δ)\), or BSCCO \(((\text{Bi,Pb})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_δ)\).

### 6.3 Equipment

In addition to the equipment used for the Thermal Measurements Lab, the following equipment will be available.

Each laboratory group will be given:

A superconductor assembly including a sample of BSCCO material, a 1N4148 temperature measurement diode, and color-coded connection wires. The assembly is mounted on an aluminum post using heat shrink tubing to hold it place. The post has 3/8-24 NF threads to facilitate mounting inside the aluminum heater block. You will retain the same assembly throughout the experiment.

In the storage cabinet in the lab:

Superconductor interface cables with three color-coded BNC connectors on one end and a DB-9 connector on the other end to accept the connection pins on the superconductor assembly. Connector pin assignments are shown in Figure 6.2 and Figure 6.3.
6.4 Grading

- Build a constant current circuit for resistivity measurements – 10 pts.
- Calibrate the diode in the superconductor assembly for low-temperature measurements – 10 pts.
- Measure the resistivity of the superconductor as a function of temperature – 20 pts.
- Lab notebook – 40 pts.

You will also write a formal report as described in chapter 7, similar to a journal article, of your results. This report will count as 10% of your final grade broken up as follows.

- Annotated bibliography – 8%
- First (not rough) draft – 40%
- Final draft – 52%

The points for each of the report drafts will be divided roughly as follows.

- Content: completeness, relevancy, and insight – 50%
- Style: clarity, flow, and appropriateness for genre – 30%
- Format: format guidelines followed – 20%; see chapter 7 for formatting information.

6.5 Literature search

When performing scientific research, you should always start with a literature search. This means that you will search the journals for similar measurements or calculations to see what has been previously done. This will both guide your research as well as help you avoid unnecessarily repeating previous research.

The material we are using is well developed and commercially produced by several companies. However, for the purposes of our exercise we will assume that we are working on a relatively new material and examine the literature from the period around 1990 as this material was being initially investigated.

From the research literature (i.e., journals, not web pages) find at least five articles that discuss measurements of resistivity vs. temperature on this superconductor (BSCCO). These articles will be used in your annotated bibliography discussed in chapter 7, “Superconductor Formal Report.”

You should note the behavior of the resistivity, \( \rho(T) \), and the temperatures and conditions involved. There is some terminology that varies between papers. Be sure you know how a particular author has used the terms “transition temperature” and “critical temperature.” This will give you an idea of what to expect in your measurements and how other groups have been measuring the transition temperature of this material.
6.5.1 How to read a journal article

Reading a journal article can be a daunting task. But there are some techniques than can help you approach difficult material. Following this sequence can make the process more productive.

1. Read the abstract. The abstract is a one-paragraph summary of the paper. It should include information on what was done in the research, possibly why it was done, and the key results.

   This is a good way to get a broad overview of the paper.

2. Read the introductory material. Most recent articles include a section specifically indicated as the introduction. This should include extensive discussion of the background to the research done, including citations of work done previously and the relationship of the current work to other research.

3. Read the conclusions. This should give the primary results from the research including the author’s interpretation of those results.

4. Look at all the figures and tables and read the captions. These will often give useful information on how the research was done and what the results were.

   Figure and table captions, if properly done, should give you enough information to understand what is presented without reference to the body of the text. The standard for a caption is “complete and intelligible in itself without reference to the text.”

5. Read the first sentence of each paragraph (the topic sentence).

6. Read selected paragraphs in detail. These are selected from the previous step as being the potentially most useful.

   It is not unusual to only go part way through this list because you may determine that the paper does not include information that will be useful for your research.

6.6 Preparation for the measurement

Your superconductor samples are mounted on aluminum sample holders. A diode is mounted next to the superconductor to measure temperature. Fig. 6.1 illustrates the arrangement of the superconductor sample and the temperature measurement diode as they are placed on the aluminum mounting post. Fig. 6.2 illustrates the connections of the leads to the sample and the diode. Fig. 6.3 shows the pin assignments on the adapter cable.

There are several steps that need to be taken before you can begin your measurements.

It is strongly recommended that you examine and follow, the checklist given in “Superconductor Transition Measurement Hints,” Appendix R. It will help ensure that you will have valid data after completing your measurements – and will help you avoid damaging your sample.

6.6.1 Calibrating the diode for temperature measurement

You will calibrate the diode mounted with your superconductor sample using the same technique you used in the previous labs. You can use the same LabVIEW VI to acquire the calibration data as you used in the Thermal Lab.

Calibrate your diode before you put the superconductor assembly in the aluminum heater block.

The calibration constants will be near those found in the Thermal Lab but not exactly since you are using a different diode. Note that you DO NOT put the superconductor sample in boiling water. You will only calibrate using ice water and boiling liquid nitrogen. Do not
put the superconductor sample assembly directly in water – it must be in a plastic bag or you will have to wait for all the water to evaporate out of the assembly before continuing.

### 6.6.2 A constant current supply for measuring the resistance

If you have followed the hints for the superconductor measurements, you will notice that the measured resistance of the sample is difficult to determine with an ohmmeter. To make a real measurement of the resistance, you will need to use the four-lead method. Put a measured current through the outer two leads (white and black), measure the voltage across the inner two leads (orange and red), and compute the resistance. This removes the problem of contact resistance and contact voltage.

For a four-lead measurement, you need to have a known current in the sample. Measuring current with LabVIEW is a little involved because most data acquisition hardware can only measure voltages. Using a known constant current will make it unnecessary to use LabVIEW to monitor that current.

You have already made a constant-current source (Appendix J). It is fairly simple to **add a second constant-current supply** to the existing $\approx 100\, \mu$A source you already built for measuring the temperature using a diode. **You will still need the first supply to**
Figure 6.3: The connections for the adapter cable. The notation in parenthesis on each connection indicate whether it is the center conductor or the shield on the attached coaxial cable. The shield is the outer conductor which is connected to the outer shell on a BNC connector. The constant current for the four-lead measurement of the resistance is applied to the white/black cable. The voltage is measured across the orange/red cable. The yellow/violet cable is used to measure the temperature using the 1N4148 diode attached to the superconductor.

measure the temperature using the diode packaged inside the superconductor assembly.

The second current supply for the four-lead measurement can use the other half of the TL3472 op amp (you only used one of the two amplifiers for the 100 $\mu$A supply you already built). You can also use a jumper to connect the same voltage divider for the reference voltage on both supplies.

The second supply should provide a current somewhere in the 10 – 50 mA range. Do not exceed 100 mA or you will burn out the 2N3906 transistor in your supply.

You will have two separate output stages consisting of R3, a 2N3906 transistor, C3, and C4, and the output BNC connector. The only shared components between the two supplies are the TL3472 op amp, C1, and the voltage divider for the reference voltage. The value of R3 will be different for the two supplies to provide the different output currents.
6.7 Acquiring the data

Create a LabVIEW VI (Virtual Instrument) that will simultaneously measure the temperature and the resistance of the superconductor as it warms up from the temperature of boiling liquid nitrogen to room temperature.

Your program should take an average over a short period to reduce noise. The duration of the averaging period should be chosen to not smooth out the natural variations in the temperature of the sample.

The voltage across the superconductor sample is very small, and you will be taking the sample to the superconducting state where this voltage is zero. Be sure that the range specified in your analog input VI is appropriate for the signals. Your VI should save the data into a spreadsheet file to allow for analysis and reproduction.

After calibrating the temperature-sensing diode, you are ready to make the resistivity measurement. Put the superconductor in the cryostat heater block (see warnings above) to reduce temperature gradients across the sample and to mechanically protect the sample and the leads.

Use one of the Styrofoam containers to contain the liquid nitrogen. It will be necessary to submerge the heater block almost completely in the liquid nitrogen to get the sample sufficiently cold.

When you are allowing the sample to warm up (as you are taking data), you may want to apply a little heater power to reduce the time required for some portions of this measurement.

1. Survey a large temperature range. Measure $\rho(T)$ from 75 K to 280 K. This does not need to be done by scanning slowly. You should be able roughly to find the superconducting transition temperature (where resistivity goes to zero).

   It will be necessary to immerse the heater block/superconductor assembly completely in the liquid nitrogen to get below 80 K.

2. Do a slow scan from about 75 K to about 130 K (you can start a little lower and go a little higher). The scan speed should be $\leq 0.5$ K/sec. You can do this by insulating the cryostat better, placing it in the vapor from the liquid nitrogen, or with whatever method you can come up. Scanning slowly will reduce temperature gradients across the sample and reduce the temperature difference between the diode and the sample to improve the accuracy of your measurement.

   Measure the resistivity curve at least twice to check for reproducibility.

You may notice that the title of this chapter includes the word “Resistivity” rather than “Resistance.” The results are usually given as resistivity rather than resistance because the resistance of an object depends on its geometry whereas the resistivity only depends on the intrinsic characteristics of the material. Resistivity ($\rho$) is related to the resistance (R) of
the material by the equation \( R = \rho L / A \) where \( L \) is the distance between the voltage probe electrodes and \( A \) is the cross-sectional area of the sample. **Your final results should be given in terms of resistivity.**

*The dimensions for the individual superconductor samples are not consistent.* We used the dimensions from a collection of ten samples and found that the cross-section is approximately \( 3.01 \pm 0.04 \text{ mm} \) by \( 2.04 \pm 0.012 \text{ mm} \) with about \( 9.47 \pm 0.09 \text{ mm} \) between the inner contact rings. For example, the range for the distance between the contact rings varied from \( 9.35 \text{ mm} \) to \( 9.59 \text{ mm} \). You will need to assume that these values are appropriate for your sample.

### 6.8 Analysis to prepare to write your formal report

Several items to consider as you analyze your results:

1. This superconductor is BiPbSrCaCuO, primarily in the 2223 phase although it may have some 2212 phase present. The “2223” specifies the rough ratio of the different elements in the superconductor (compare the formula given at the start of this handout).

   As far as we know, these samples are doped with Pb to increase the fraction of the 2223 phase, but the doping fraction is unknown.

2. How do your results compare with those given in the papers you consulted in your literature search? Can you determine anything about your sample by comparing your results with those from other groups?

3. An ideal conventional superconductor will have an abrupt change in \( \rho(T) \) at the transition temperature. Is the change in your sample abrupt? If not, do you think it is due to your measurement (such as not being able to resolve a fast change in \( \rho \), or change \( T \) slowly enough), or is it a true property of the sample? (Hint: As noted above, there are several different phases of BSCCO, and it’s possible that you have more than one phase present in your sample.)

4. What is the behavior of \( \rho(T) \) above the transition temperature? Does it behave like a metal or a semiconductor? Find a fit for the behavior in this region.

5. It is not possible to fit an analytic solution to the superconducting transition because there is not a good analytical model for that region.
Resistivity vs. Temperature of a Superconductor
Chapter 7

Superconductor Formal Report

Though the experiment was done in groups, the report will be written up individually. This is to allow you each to work on your writing skills. Though you are writing the paper, you are encouraged to have others read your paper and give you feedback on it.

You will turn in the report assignments in the following stages.

1. The first thing you will turn in is an annotated bibliography of Bi-Sr-Ca-Cu-O superconductors and Pb-doped Bi-Sr-Ca-Cu-O superconductors. The bibliography will consist of at least five references and the annotations of one paragraph per article summarizing the most important points of the article.

   These articles should focus on the first measurements (~1986-1990) as these are the closest to the types of measurements we are making. This will comprise 8% of the grade for the paper.

2. The First Report is the best paper you can write. It is to be a polished paper rather than a rough draft. The instructor will read, edit, and grade this version for 40% of your overall paper grade.

3. After you receive the graded first report, you will then have about a week to revise your paper and turn it back in as the Final Report. At the end of that week, you will turn in your final paper, and it will be graded for the remaining 52%. The instructor will be happy to read your paper again before the Final Report due date and give you feedback.

7.1 Grading

Your paper grade will be determined roughly as follows

- Content: completeness, relevancy, and insight – 50%.
7.2 Annotated bibliography instructions

You are to find at least five journal articles regarding measurements of the parameters of Pb-doped BSCCO superconductor \((\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_x\text{Ca}_{y-1}\text{Cu}_y\text{O}_\delta\text{ or Bi(Pb)}-\text{Sr-Ca-Cu-O})\). At least three of these papers must be in addition to any used from the list of references below.

Your bibliography will consist of the complete references for these papers accompanied by a paragraph for each one describing the main results reported in that paper.

Note that when you give the name of a journal in a citation it is usually expected that you use a standard abbreviation for that journal (like “Appl. Phys.” for the journal “Applied Physics”). You can find a list of standard abbreviations at http://images.webofknowledge.com/images/WOS/A_abrvjt.html. There is another list devoted to just journals in Science and Engineering at http://woodward.library.ubc.ca/research-help/journal-abbreviations.

Below are some sample papers on BSCCO for you to peruse. These links are to the abstracts for the articles. If you are using a computer on BYU campus you should be able to access the full text from the “PDF” or “Download PDF” link on the page. If you are not on campus, you can access the full text by authenticating through the BYU library website (or some other site that has digital subscriptions to the specified journals). You can then access the articles using their links and finding the provided references.


These papers can be useful in finding other papers by looking for papers they have cited or for papers that have cited them. You may find the BYU Library Subject Guide for Physics and Astronomy (http://guides.lib.byu.edu/physics) useful in finding other papers. Look under the “Finding Articles/Using Databases” and “Finding Information on the Web” tabs for a wide range of online sources for locating scientific articles.

My favorite index is the “Web of Science” (on the list you get if you click on the tab “Finding Articles/Using Databases”) which includes the rather extensive Science Citation Index. It
seems to do a better job of finding papers related to physics than others I have tried. Your mileage will vary.

### 7.3 The formal report

You will write a report that is in the format and style of a journal article. The format is often a function of the target journal and the particular field. It is expected that you will use a format that is appropriate for your chosen field of study.

#### 7.3.1 Preparing to write

You may want to consult *A Brief Guide to Writing at BYU* (http://writing.byu.edu/brief-guide-writing) before you begin your paper. It has a lot of good information on writing. Especially read the section on “Writing about Research” (http://writing.byu.edu/writing-curriculum/brief-guide-writing/writing-research).


Also, look over the instructions for preparing a manuscript for AIP journals (http://publishing.aip.org/authors/preparing-your-manuscript). There is a link on Learning Suite under Content ⇒ Superconductivity Measurements Lab ⇒ The Formal Paper to this guide. Although this guide is specific to AIP journals, it will give you useful guidelines for a paper intended for nearly any journal. This document also includes a link to guidelines for specific AIP journals such as the Journal of Applied Physics. You may also find the *AIP Style Manual* (https://www.physics.byu.edu/faculty/petersonb/Phys240/AIP_Style_4thed.pdf) useful because it contains extensive information useful in formatting scientific papers (it is considered “out of print” but remains available on the Internet because it is so useful).

Some other style guides that may be useful to you depending on your chosen field of study:

- **American Journal of Physics** (http://ajp.dickinson.edu/Contributors/manFormat.html)
- **American Chemical Society** (http://pubs.acs.org/isbn/9780841239999). This can also be found at https://doi.org/10.1021/bk-2006-STYG.

“Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results” (https://www.nist.gov/pml/nist-technical-note-1297) is useful for properly reporting uncertainties in your results.

You can learn a great deal from reading actual scientific journal articles. It is usually best to look at articles from your targeted journal since some aspects of the style will vary between journals.

7.3.2 Medium and length

The report must be compiled in a digital format (journals rarely accept anything other than digital files now). Figures and graphs must be computer generated. It will be submitted electronically.

Double-space your report to allow for editing and comments. It will likely be between five and seven pages long.

7.3.3 Audience

The primary audience for this assignment is a scientific peer that has experience in general physics but not specific knowledge about this experiment or the materials and measurement techniques used. The secondary audience is your instructor in the course who will grade the report.
7.3.4 Content and organization

You should develop a detailed outline for your report following the format laid out below. It is permissible to modify the outline as appropriate for your report and content. This will organize your report in a fashion commonly used for reporting scientific results.

1. Title page containing, at a minimum, the title of the article and the name(s) and affiliation(s) of the author(s).
2. Abstract (which can be put on the title page).
   This is one paragraph stating:
   - The problem or question addressed by the research
   - The most important results
   - The principal conclusions

   You can include a few words about which method you used to get the results, but no details. Don’t put the motivation for the research here. Don’t review previous research.

3. Introduction
   - A review of the literature describing previous work on the problem you are investigating. You should focus on reviewing the articles that are closest to the work you are presenting.
   - Briefly state the nature and scope of the problem you are investigating. Include the motivation for the investigation and the background physics needed to understand it.
   - Briefly state the methods of your investigation and your principal results. Do not keep the reader in suspense.

4. Experimental (or theoretical/computational) Methods (sometimes Materials and Methods)
   - Description of experimental, computational or theoretical techniques.
   - Details of how techniques were implemented. You must give the reader the details needed to repeat the experiment and get the same results you did; reproducibility is essential for good science.

   Do not put results in the methods section.

5. Results
   - Concise, clear presentation of data and observations in words, tables, and graphs.
   - Put each table and graph in a figure containing a table or figure number and caption.

   The caption should be a standalone description of the figure or table. Avoid repetition of figure data or captions in the body of the text.
6. Discussion of Results. This is the often the hardest section to get right. Day recommends the following points: [Robert A. Day, How to write & publish a scientific paper, (Oryx Press, Phoenix, 1998)]

- Present the principles, relationships, and generalizations shown by the results.
- Discuss the results. Don’t recapitulate them.
- Point out exceptions or lack of correlations and define unsettled points.
- Show how your results and interpretations agree or contrast with previously published work.
- Don’t be shy to discuss the theoretical implications of your work, as well as possible practical applications.
  Exception: Applications that apply to the field in general and have been previously described should be placed in the introduction.
- State your conclusions as clearly as possible.
- Summarize your evidence for each conclusion.

7. References (for articles cited): use a format you’ve seen in a paper from the field you are writing in or follow the AIP style guide.

Do not include your annotation paragraphs from the annotated bibliography submitted earlier in the bibliography for your paper.

Illustrations and graphs are often very helpful and sometimes essential in the introduction, methods, results, and discussion. If you have a significant amount of data or need to show relationships, graphs are essential.

Don’t leave out the figures just because your paper is getting too long. There are no page charges for papers submitted as part of the class. There is no grade penalty for long papers, but there is a penalty for papers that are inadequate because something is left out.

7.3.5 Report dos and don’ts

Do describe your experimental techniques in detail. Describe each of the procedures that lead to the results you got. Data is not useful if the procedure used to obtain it is not understood or documented. If there was a significant issue in getting your experiment to work, it should be an issue in your write up. Someone else should be able to reproduce your measurement from your write up and the papers referenced by it.

Do use drawings of your apparatus if appropriate.

Do label tables and graphs. Each table or graph should include units, error bars (if appropriate), a unique figure or table number, and a caption. The caption should be a complete, standalone description of the table or figure without reference to the body of the text.

It is essential that any text on figures be large enough to be legible. The standard usually used is that the text must be at least 8 pt (about 1/8” tall) when the figure
is reduced to journal publication size. A common journal size is 8.5 cm or $3\frac{3}{8}$" wide for a double column format (figures are usually printed in a single column although they can be wider in some journals).

Do put units and uncertainties on all data.


Do carefully review the experimental literature on this material (BiPbSrCaCuO) and particularly those describing measurements similar to those you have made. This careful review makes a huge difference in the quality of the reports.

Do break your experimental section down into subheadings on each component and technique.

Don’t write about what you were not able to do or what you wanted to do.

Do focus on what you did.

Don’t come out of character and talk about why the lab was designed. Write it like a real journal article.

Don’t use long tables of data. Your plots summarize the data. Tables should include only relevant results that cannot be displayed graphically.

Don’t make generic statements. “These are good results” or “this needs to be done carefully” are of no help.

Don’t include tables or graphs you never refer to by name or number in the article.

Don’t make jokes. Your tone should be straightforward and professional. (Do make jokes in talks).

Don’t be obsessed with using only passive (3rd person). Use we or I once in a while, particularly when pointing out your main results and conclusions.

Don’t structure it like a travelog or personal journal. “We did this, then we did this, and then we did this” is not only painful to read but is rarely the cleanest way to write up your work. In many cases, the order in which things were done is unimportant.

Don’t neglect the results section; this is the heart of your report. Do guide your reader through the details of the results in words.
Chapter 8

Ethics Discussion

“The only ethical principle which has made science possible is that the truth shall be told all the time. If we do not penalize false statements in error, we open up the way, don’t you see, for false statements by intention. And of course a false statement of fact, made deliberately, is the most serious crime a scientist can commit.”


8.1 Expected Learning Outcomes

- Understand the ethical standards expected in performing and publishing scientific research.
- Understand the importance of following ethical standards both personally and for the benefit of the broader scientific community.
- Examine several case studies to determine how these standards could be applied to sample ethical questions.

8.2 Grading

- The pre-class quiz on ethics – 30 pts.
  Note: that this may look like a regular reading quiz, but it goes well beyond a reading quiz. It is intended to get you started thinking about ethical questions before the class discussion.
- Participation in the class ethics discussion – 60 pts.
8.3 Introduction

To introduce the ethics discussion you can first see Calvin’s ethics dilemma (15 September 2013) (that’s Calvin of Calvin and Hobbes). Or, from the scientific standpoint, you may want to learn about the great mathematician Lobachevsky as told by Tom Lehrer. After you view the video, you should probably look up Lobachevsky on Wikipedia. He was a very accomplished mathematician.

Ethics is a difficult, and quite serious, topic. Even being accused of unethical behavior can haunt you for the rest of your life thanks to the infinite memory of the Internet.

Ethical decisions are not as simple as one might imagine. For instance, in the BYU Studies article “Moral Choices and their Outcome” (BYU Studies, v. 30, no. 2, pp. 17-31, 1990, https://byuscholarsarchive.byu.edu/byusq/vol30/iss2/3/), William R. Swinyard and Thomas J. DeLong discuss the differences in the basis of moral choices between students at BYU and those at the National University of Singapore. The effect of cultural differences is quite pronounced. And yet we try to define what constitutes ethical behavior for scientists on a worldwide basis.

8.4 Ethics resources

The following references are intended to give a basis for scientific ethics from a variety of viewpoints. Several of them are statements from particular scientific societies regarding what they consider ethical behavior. Others are articles discussing the question.

Since this is a physics class, I would recommend that you review two of these in particular.

- **APS Guidelines for Professional Conduct** (http://www.aps.org/policy/statements/02_2.cfm) is a short statement adopted by the American Physical Society regarding scientific, and specifically publishing ethics. It is closely related to the statement by the American Institute of Physics and the American Geophysical Society.

- **Ethics resources from the American Physical Society** (http://www.aps.org/programs/education/ethics/resources.cfm) contains links to books and studies on ethics. Probably the most useful for a student is the “Ethics Case Studies” (http://www.aps.org/programs/education/ethics/) that illustrate some of the ethical dilemmas you may encounter both as a student and as a scientist.

For those in other fields of science, the following professional ethics statements may also be of interest.

- **Statement of ethics and responsibilities of authors submitting to AIP Journals** (http://publishing.aip.org/researchers/policies-and-ethics/).
• Professional and ethical standards for the AAS (American Astronomical Society) journals (http://journals.aas.org/policy/ethics.html).

• Online Ethics Center for Engineering and Science at the National Academy of Engineering (http://www.onlineethics.org).


The remaining references may help to illustrate some of the concerns regarding scientific ethics and some possible responses to observed ethical concerns.

• The National Academies of Sciences has released several books on ethics in science in both print and electronic form. These include:
  
  – *Fostering Integrity in Research* (2017). This can be downloaded from https://www.nap.edu/catalog/21896/fostering-integrity-in-research.


- Ethics and the Welfare of the Physics Profession, Physics Today **57**(11), 42, 2004 ([https://doi.org/10.1063/1.1839376](https://doi.org/10.1063/1.1839376)).


- **A Retraction: We Gave Bad Advice**, an article by Adam Marcus and Ivan Oransky on what to do if you suspect scientific misconduct. This is actually a retraction of a previous article “How to Report Alleged Scientific Misconduct” ([http://www.labtimes.org/labtimes/ranking/dont/2015_06.lasso](http://www.labtimes.org/labtimes/ranking/dont/2015_06.lasso)).


- **Self-plagiarism case prompts calls for agencies to tighten rules**, Eugenie Samuel Reich, *Nature* **468**, 745, 2010 ([https://doi.org/10.1038/468745a](https://doi.org/10.1038/468745a)).

- **Ethics in Engineering**, an article by Eric Butterman at the American Society for Mechanical Engineering ([https://www.asme.org/engineering-topics/articles/asme-engineering-ethics/ethics-in-engineering](https://www.asme.org/engineering-topics/articles/asme-engineering-ethics/ethics-in-engineering)).

- An interactive video produced by the Health and Human Services Office of Research Integrity ([http://ori.hhs.gov/TheLab/](http://ori.hhs.gov/TheLab/)). You get to make decisions in the position of Research Integrity Officer, Graduate Student, Postdoc, or Principal Investigator and see what the outcomes of those decisions are.

And two references from the journal Applied Physics giving examples of a retraction and an erratum for previously published work.

- **Retraction**: “Nucleation-controlled low-temperature solid-phase crystallization for Sn-doped polycrystalline-Ge film on insulator with high carrier mobility ($\approx 550 \text{cm}^2/\text{Vs}$)” [*Appl. Phys. Lett.* 112, 242103 (2018)] ([https://doi.org/10.1063/1.5046407](https://doi.org/10.1063/1.5046407)), a retraction of an earlier article because some experimental mistakes rendered the results and conclusions incorrect.
• Erratum: “Insights into collaborative separation process of photogenerated charges and superior performance of solar cells” [Appl. Phys Lett. 109, 043906 (2016)] (https://doi.org/10.1063/1.5046186), an erratum indicating that the authors and collaborators had published three closely-related papers at nearly the same time including duplication of one figure and significant similarities in the samples. They apologized for improperly dividing the work between several publications which is “...not in the best interest of readers...” (quoted from the last sentence of the author’s statement).

If you are curious about other fields, Dallin H. Oaks gave a speech at the beginning of the third year of the BYU Law School’s existence. It was titled “Ethics, Morality, and Professional Responsibility” (BYU Studies, v. 16, no. 4, pp. 507-516, 1976, http://scholarsarchive.byu.edu/byusq/vol16/iss4/7/).

It is a very enlightening view of what should be expected in the legal profession.

The Business Ethics group at BYU has developed the book The Business Ethics Field Guide: The Essential Companion to Leading Your Career and Your Company to Greatness, by Brad Agle, Aaron Miller, and Bill O’Rourke. They discuss a broad range of typical ethical problems that can arise in business. Many of these are also a problem in the STEM fields. Their list of 13 common ethical problems (essentially the Table of Contents for the book) can be found at https://www.ethicsfieldguide.com/pages/about-us.
Chapter 9

Group Projects and Presentations

9.1 Expected Learning Outcomes

- *As a group*, write a proposal describing your project, the required resources, and the expected outcomes.
- Independently design and complete the proposed project *with your group*.
- *As a group*, present your results in an oral presentation. The format will be similar to that used for the College Student Research Conference.

9.2 Project guidelines

You are expected to pick a project that is substantial (*i.e.*, it will take most of the allotted time on the schedule), and in which you are interested. This means that there is usually a wide range of project topics in the class because interests vary. There are several rules:

- It must contain an experimental component (*i.e.*, you must actually measure something)
- A proposal for your project must be submitted to the course instructor before you begin.
- The project must be approved by the course instructor before you begin.
- You can not violate any EPA regulations (*i.e.*, you are limited in what chemicals can be used)
- You can not attract the attention of either BATF or the Department of Homeland Security (*i.e.*, no explosives)
- You can not attract the attention of the Campus Risk Management and Safety Office (*i.e.*, nothing that endangers the class, sets off smoke or fire alarms, etc.)
• No more than three individuals are allowed to participate in a single project.
  – You are not required to work with the same lab partner(s) with whom you have worked in previous lab exercises.

Finding supplies and equipment for some projects can be a limitation on whether they can be done as your group project. Some things can be found from various sources within the department. We will help you find as much as we can to make your project possible.

It may be necessary to visit some of the local scientific supply stores (Maceys, Home Depot, Lowes, Deseret Industries, etc.). Unless you consider your project well in advance, it is often not possible to have items ordered online and delivered in time.

9.3 Oral presentation

9.3.1 Scheduled presentation time

Your presentation will be given during the scheduled final exam period for your section.

9.3.2 Presentation audience

Your primary audience is the other students in Physics 240. Your secondary audience is the instructor or the TAs that will be evaluating your presentation. This means your presentation should be at a level to be understood by the other students in the class.

9.3.3 Presentation guidelines

• Time limit: 12 minutes followed by 3 minutes for questions and discussion; 15 minutes total.
• The group members must present roughly equal portions.
• Your primary medium of presentation will be graphics and text in PowerPoint, Acrobat, or similar presentation software.
• You may use other audiovisuals to get your points across effectively in limited time. The whiteboard should not be used in short presentations, except to answer questions.
• A general rule for how many slides to prepare is one slide per minute. Don’t forget to allow time for any included videos.
• Don’t be late for the presentations; get your reports and presentations done before the last minute.
9.3.4 Grading of presentations/projects

- The project proposal (50 points, 27.8% of total points for the project, 4% of class points). Note that all the components of the proposal are submitted as a group. Consult Appendix S, “Project or Research Proposals,” for more information on the proposal. The proposal is submitted in three stages:

  1. Project abstract (10 points). The abstract is a short description of your project and what you wish to accomplish. The abstract is due about three weeks before the projects start.
  2. Project proposal draft (15 points). The draft should be as complete as you can make it so the feasibility and appropriateness of the project can be evaluated. You should also include any special equipment or materials needed so they can be obtained if it is possible. The draft is due about a week before we start the projects.
  3. Project proposal (25 points). This is the final, polished version of your project proposal. The final proposal is due on the day we start the projects.

- Lab notebook for your project (40 points, 22.2% of project total, 3.2% of class total).

- The actual project (30 points, 16.7% of project total, 2.4% of class total). This is based on how your group carried out your project and evidence of roughly equal participation of group members on the project. Much of the evidence for how the project was done will come from your presentation. It is not based on whether your project was successful.

- The project presentation (60 points, 33.3% of project total, 4.8% of class total).
  - Effective use of PowerPoint slides or other media in your presentation (20 points)
    * No distractions, concise (4 points)
    * Good graphics (8 points)
    * Readable text (the instructor will be sitting in the back of the room to evaluate this point) (8 points)
  - Good use of time (15 points)
    * Reasonable length (roughly 12 ± 2 minutes) (6 points)
    * Equal share of all participants (6 points)
    * No fluff (3 points)
  - Presentation clarity and completeness (25 points, 16.7% of total)

The following format for your presentation is suggested:

1. Introduce problem (6 points)
2. Describe method (6 points)
3. Present results (6 points)
4. Tell us what it means (That is, what physics is illustrated and how well did the experiment work.) (7 points)
9.3.5 Suggested reading

The following two articles from Physics Today contain pointers on giving physics talks. Though not all that is said will apply to the presentations on your student designed experiments, much of it will. These are issues you should consider when presenting your research.


The second article, “What’s Wrong with Those Talks?”, by N. David Mermin, Physics Today 41(11), 9-11 (November 1992) doi:10.1063/1.2809861, is a response to the first article. If David Mermin’s talks are as entertaining as his writing, then he must be a fun speaker.

Note: as of the writing of this document, access to the full text of Physics Today articles directly from a BYU on-campus IP address appears to be blocked unless you are willing to pay $30 per article. However, if you look up Physics Today on the BYU library website (“Journals”) and select “EBSCOhost Academic Search Premier” you will be able to find the correct issues from the references above and read the articles. You will have to sign in on the library website if you are coming from off campus.


Another is materials from a talk “Preparation of Effective Scientific Talks” given by J. D. Callen from the University of Wisconsin-Madison in October 2014. They can be found at http://homepages.cae.wisc.edu/~callen/talks.html.
Appendix A

Machine Tool Speeds and Feeds

<table>
<thead>
<tr>
<th>Material</th>
<th>Drill</th>
<th>Lathe</th>
<th>Mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>300</td>
<td>400-800</td>
<td>200-400</td>
</tr>
<tr>
<td>Aluminum</td>
<td>250</td>
<td>350-700</td>
<td>250-500</td>
</tr>
<tr>
<td>Brass &amp; Bronze</td>
<td>200</td>
<td>250-500</td>
<td>150-450</td>
</tr>
<tr>
<td>Copper</td>
<td>70</td>
<td>100-250</td>
<td>100-200</td>
</tr>
<tr>
<td>Cast Iron (soft)</td>
<td>120</td>
<td>100-250</td>
<td>80-120</td>
</tr>
<tr>
<td>Cast Iron (hard)</td>
<td>80</td>
<td>50-150</td>
<td>50-100</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>110</td>
<td>100-250</td>
<td>70-120</td>
</tr>
<tr>
<td>Cast Steel</td>
<td>50</td>
<td>70-150</td>
<td>80-100</td>
</tr>
<tr>
<td>Alloy Steels (hard)</td>
<td>60</td>
<td>50-150</td>
<td>30-60</td>
</tr>
<tr>
<td>Tool Steel</td>
<td>60</td>
<td>50-150</td>
<td>40-70</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>30</td>
<td>60-180</td>
<td>30-60</td>
</tr>
<tr>
<td>Titanium</td>
<td>30</td>
<td>90-200</td>
<td>40-60</td>
</tr>
<tr>
<td>High Manganese Steel</td>
<td>15</td>
<td>40-100</td>
<td>20-40</td>
</tr>
</tbody>
</table>

*In surface feet per minute at the periphery of the tool for HSS (high-speed-steel) tools. For carbide-tipped tools, speeds can be twice those given. Carbide-tipped tools do not operate properly at low speeds; operate at or above the minimum speed if possible.

To calculate rpm from sfpm:

\[
rpm = \frac{3.8 \times \text{speed}}{d} \sim \frac{4 \times \text{speed}}{d}
\]

where \( \text{speed} \) is given in sfpm and \( d \) is the diameter of the tool (mill or drill) or workpiece (lathe) in inches.
### Suggested Depth of Cut in Inches

<table>
<thead>
<tr>
<th>Material</th>
<th>Lathe HSS</th>
<th>Lathe Carbide</th>
<th>Mill HSS</th>
<th>Mill Carbide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Plain Carbon Steel</td>
<td>0.03</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Alloy Steels</td>
<td>0.025</td>
<td>0.045</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>0.03</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Brass</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### Recommended Feeds for Turning (lathe)

<table>
<thead>
<tr>
<th>Tool Feed (ipr(b))</th>
<th>Rough Cut</th>
<th>Finish Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.015-0.025</td>
<td>0.005-0.010</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.015-0.025</td>
<td>0.005-0.010</td>
</tr>
<tr>
<td>Brass &amp; Bronze</td>
<td>0.015-0.025</td>
<td>0.003-0.010</td>
</tr>
<tr>
<td>Copper</td>
<td>0.010-0.020</td>
<td>0.004-0.008</td>
</tr>
<tr>
<td>Cast Iron (soft)</td>
<td>0.015-0.025</td>
<td>0.005-0.010</td>
</tr>
<tr>
<td>Cast Iron (hard)</td>
<td>0.010-0.020</td>
<td>0.003-0.010</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>0.010-0.020</td>
<td>0.003-0.010</td>
</tr>
<tr>
<td>Cast Steel</td>
<td>0.010-0.020</td>
<td>0.003-0.010</td>
</tr>
<tr>
<td>Alloy Steel (hard)</td>
<td>0.010-0.020</td>
<td>0.003-0.010</td>
</tr>
<tr>
<td>Tool Steel</td>
<td>0.010-0.020</td>
<td>0.003-0.010</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>0.010-0.020</td>
<td>0.003-0.010</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.010-0.020</td>
<td>0.003-0.010</td>
</tr>
<tr>
<td>High Manganese Steel</td>
<td>0.010-0.020</td>
<td>0.003-0.010</td>
</tr>
</tbody>
</table>

\(b\) In inches per revolution of the spindle.

### Recommended Feeds for Milling

<table>
<thead>
<tr>
<th>Tool Feed (ipt(c))</th>
<th>Face Mill</th>
<th>Side Mill</th>
<th>End Mill</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.005-0.020</td>
<td>0.004-0.010</td>
<td>0.005-0.010</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.005-0.020</td>
<td>0.004-0.010</td>
<td>0.005-0.010</td>
</tr>
<tr>
<td>Brass &amp; Bronze</td>
<td>0.004-0.020</td>
<td>0.004-0.010</td>
<td>0.005-0.010</td>
</tr>
<tr>
<td>Copper</td>
<td>0.04-0.010</td>
<td>0.004-0.007</td>
<td>0.004-0.008</td>
</tr>
<tr>
<td>Cast Iron (soft)</td>
<td>0.004-0.016</td>
<td>0.004-0.009</td>
<td>0.004-0.008</td>
</tr>
<tr>
<td>Cast Iron (hard)</td>
<td>0.004-0.010</td>
<td>0.002-0.006</td>
<td>0.002-0.006</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>0.004-0.010</td>
<td>0.002-0.007</td>
<td>0.002-0.010</td>
</tr>
<tr>
<td>Alloy Steel (hard)</td>
<td>0.004-0.010</td>
<td>0.002-0.007</td>
<td>0.002-0.006</td>
</tr>
<tr>
<td>Tool Steel</td>
<td>0.004-0.008</td>
<td>0.002-0.006</td>
<td>0.002-0.006</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>0.004-0.008</td>
<td>0.002-0.006</td>
<td>0.002-0.006</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.004-0.008</td>
<td>0.002-0.006</td>
<td>0.002-0.006</td>
</tr>
<tr>
<td>High Manganese Steel</td>
<td>0.004-0.008</td>
<td>0.002-0.006</td>
<td>0.002-0.006</td>
</tr>
</tbody>
</table>

\(c\) In inches per tooth on the tool.
### Recommended Feeds for Drilling

<table>
<thead>
<tr>
<th>Drill Diameter (inches)</th>
<th>Drill Feed (ipr)(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1/8</td>
<td>0.001-0.002</td>
</tr>
<tr>
<td>1/8-1/4</td>
<td>0.002-0.004</td>
</tr>
<tr>
<td>1/4-1/2</td>
<td>0.004-0.007</td>
</tr>
<tr>
<td>1/2-1</td>
<td>0.007-0.015</td>
</tr>
<tr>
<td>&gt;1</td>
<td>0.015-0.025</td>
</tr>
</tbody>
</table>

\(^d\)In inches per revolution of the drill bit.

This chart is posted on the wall in several places in the Machine Shop in 101 CTB. The original source is unknown. It supersedes drilling speeds from the first page in this section when manually drilling.
Appendix B

Considerations for Analog Input and Output

Useful information can be found in the text in Sections 6.7.1 (Data Rates), 6.7.5 (Analog Input Signals), 6.7.6 (Multiple Signal Sources: Data Loggers), 6.7.9 (Personal Computer Control of Experiments), and 6.9 (GROUND AND GROUNDING).

B.1 Input Connections

The data acquisition equipment we use in Physics 240 in C460 ESC is the National Instruments USB-6221-BNC, which is an M-Series device. The equipment used in Physics 245 in C435 ESC is the National Instruments PCI-6040E or PCI-MIO-16E-4, which is an E-Series device. For more information on the connections in these devices you should see either page 4-12 of the DAQ M-series manual (http://www.ni.com/pdf/manuals/371022l.pdf) or page 2-21 of the DAQ E-series manual (http://www.ni.com/pdf/manuals/370503k.pdf).

The connections for our analog input devices are configured to be used only in the differential mode. This means that they will measure the voltage difference between the two leads of an input connection but does not assume that either of those leads is at ground potential. This is beneficial for two reasons.

1. It doesn’t matter if the ground reference of the external circuit is different from the ground for the analog input device as long as the difference is sufficiently small.

2. If there is a noise voltage picked up by the leads, it will not be included in the measurement as long as both leads pick up the same noise. The use of either a shielded cable such as coaxial cable or twisted pair wires will increase the likelihood that both leads will pick up the same noise, so it will not be included in the measurement with a differential device.
B.1.1 Grounds

Note: If you haven’t read Section 6.9 in the text you should do so. It expands on and is complementary to the following information.

In electronic and electrical circuits, the concept of a “ground” is very important. In electrical power distribution circuits, the ground is required for safety as a path for “errant” current to follow rather than through the user.

Ground, as used in the code for electrical wiring, is a reference to a direct connection to a conducting stake driven into the ground somewhere nearby. The AC power distribution system is designed to use the earth as part of the return current path to the generating stations.

The ground connection for individual devices is usually provided by the power distribution ground connections. In some cases, a local dedicated ground connection may be provided for specific equipment or a particular laboratory. This is especially true for equipment that deals with high-frequency signals. In those cases, a very low-inductance ground is necessary for reliable operation.

Ground or Common?

In electronic circuits, the term “ground” often refers to the “common” portion of a circuit and not necessarily to that point connected to an earth ground. The common terminal usually serves as a reference point from which most voltages are measured since voltage only has meaning when given with respect to some known reference point. This reference point may be but is not necessarily connected to the “earth ground.”

The common for a circuit is represented in most circuit diagrams by the symbol on the left, and the earth ground is represented by the symbol on the right.

\[
\begin{array}{c}
\text{Common} \\
\downarrow \\
\text{Ground (Earth)}
\end{array}
\]

The analog interface devices we use will typically have two to four grounds specified. They can include analog input ground (AI GND), analog output ground (AO GND), digital ground (D GND), and chassis ground (CHS GND). These grounds are not guaranteed to be equal in voltage. The first three are common terminals for the specified sections of the interface device. Chassis ground is the true or earth ground (connected to a stake in the ground through the AC power distribution system) described above – assuming that your device is properly grounded to the distribution system.
These grounds are explicitly separated in the analog interface board to avoid interactions between the digital and analog sections of the devices. It is good practice to keep your analog and digital grounds separate if possible.

### B.1.2 Ground loops

If you have a ground connection both on the source of the signal and on the analog input device, you create what is called a ground loop. That is, you have a wire that connects your signal source to the analog input device as well as a parallel connection between the grounds. This parallel connection will usually involve the building electrical ground system. These parallel wires create a potentially very large loop (also known as an antenna) that serves to introduce noise signals on your input. Under some conditions, these noise signals can get very large.

You want to ensure that you have only one ground connection in your circuits. A much too common exercise in experimental measurements is looking for ground loops to reduce noise signals.

### Analog input configuration

When you use these devices, you will need to determine whether to use the “grounded source” (GS) or the “floating source” (FS) configuration for analog inputs.

Keep in mind that “grounded source” can mean either that one side of the signal is grounded or that it is held at a particular voltage with respect to ground. For example, for this circuit

![Circuit Diagram](image)

you should select the GS configuration, or you will modify the effective value of R2 by the presence of the grounding resistor provided by the analog input device. In the devices we use, a resistance of 5 kΩ is connected from the “low” or “−” input to AI GND in the FS configuration.
B.2 Signal conditioning

Most sensors require some form of signal conditioning before the value is compatible with the DAQ input. The National Instruments document “The Engineer’s Guide to Signal Conditioning” (http://www.ni.com/engineers-guide-to-signal-conditioning) provides useful information regarding signal conditioning. (Note: you will be asked to create a free account on the web site before you can download the document.)


Appropriate signal conditioning can make the difference between a marginally useful measurement and an accurate measurement.

B.3 Device specifications


When you are deciding if a device will work for your application, there are several particular specifications you need to consider.

B.3.1 Overvoltage protection

Note the values given for the “overvoltage protection.” If you exceed these values, you will likely cause expensive damage to the device. For both devices, this is ±25 V if they are powered on and ±15 V if powered off. To be safe, always keep the input voltages within ±15 V of ground.

B.3.2 Maximum working voltage

For both devices, the “maximum working voltage” is specified as ±11 V measured with respect to the analog input ground. This means that the combination of all the voltages applied to an input (both the “high” and “low” inputs) must not exceed ±11 V from analog input ground. If you exceed that voltage range, the device will give very unpredictable – and wrong – results. One of the common causes of exceeding the ±11 V limit is having no ground reference in a circuit so that it can drift uncontrollably. This is an especially important consideration if you have the device set to the GS configuration.
B.3.3 Device resolution

The number of bits used to specify a number for a given device will be specified in the documentation. This value indicates the number of discrete levels into which the input voltage range will be divided. The number of levels will be given by $2^b$ where $b$ is the specified number of bits. For instance, a 12-bit device will use $2^{12} = 4096$ levels to represent the input signal. A 16-bit device will use $2^{16} = 65536$ levels.

The number of bits is combined with the available input range(s) to determine the device resolution in terms of volts/level. This is referred to as the “Code Width” in Chapter 7 of the LabVIEW Basics 1 Course. For comparison, the resolutions at the various input ranges for our two devices are listed in Table B.1. Input ranges for which there is no code width entry are not available for the specified device. The code width, or minimum resolvable voltage change, is given by the total input voltage range ($V_{max} - V_{min}$) divided by the number of levels minus 1 ($2^N - 1$ where $N$ is the number of bits in the input converter).

For most devices, there are specific input ranges available due to hardware limitations. The software will usually select the input range with limits greater than or equal to the requested range. For instance, if you request a range of -1 V to +3 V, the USB-6221 will be set to a range of ±5 V since your requested range will not fit entirely in the next available range of ±1 V.

To get the best results you want to specify the input range to be as close to the expected range of your signal as possible. This will result in the smallest possible code width.

B.3.4 Input impedance

The PCI-6040E has an input resistance of 100 GΩ in parallel with 100 pF. The USB-6221 has an input resistance of 10 GΩ in parallel with 100 pF. The input resistance of both devices is sufficiently large that the analog input will have a negligible effect on the circuit in most cases.

The capacitance in parallel with the input resistance can cause problems at high frequencies. For instance, at 100 kHz the reactance of that capacitor is about 16 kΩ – a value that can be important in many cases.

B.3.5 Sample rate and aliasing

The “maximum sampling rate” indicates the fastest acquisition rate you can use with the device. For the PCI-6040E this is specified as 500 kS/s (kilosamples/sec) for a single channel and 250 kS/s for multiple channels.

For the USB-6221 it is given as 250 kS/s for a single channel and 250 kS/s “multichannel aggregate” when acquiring multiple channels. This means that the A/D converter and input
Table B.1: Code widths for the available input ranges for the PCI-6040E (12-bit) and USB-6221 (16-bit) devices. The design of the USB-6221 makes the code width about 5% greater than the specified values. For instance at an input range of ±1 V, the standard formula would give 30.52 µV while the actual code width was about 32.45 µV for one device that was tested. Input ranges for which there is no code width entry are not available for the specific device.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>±10 V</td>
<td>4.9 mV</td>
<td>305 µV</td>
</tr>
<tr>
<td>0 − 10 V</td>
<td>2.44 mV</td>
<td></td>
</tr>
<tr>
<td>±5 V</td>
<td>2.44 mV</td>
<td>153 µV</td>
</tr>
<tr>
<td>0 − 5 V or ±2.5 V</td>
<td>1.22 mV</td>
<td></td>
</tr>
<tr>
<td>0 − 2 V</td>
<td>488 µV</td>
<td></td>
</tr>
<tr>
<td>±1 V</td>
<td>488 µV</td>
<td>31 µV</td>
</tr>
<tr>
<td>0 − 1 V or ±0.5 V</td>
<td>244 µV</td>
<td></td>
</tr>
<tr>
<td>0 − 0.5 V or ±0.25 V</td>
<td>122 µV</td>
<td></td>
</tr>
<tr>
<td>±0.2 V</td>
<td>6 µV</td>
<td></td>
</tr>
<tr>
<td>0 − 0.2 V or ±0.1 V</td>
<td>49 µV</td>
<td></td>
</tr>
<tr>
<td>0 − 0.1 V or ±0.05 V</td>
<td>24 µV</td>
<td></td>
</tr>
</tbody>
</table>

switching electronics can only handle 250 kS/s overall. If you are acquiring four channels, the fastest you can acquire each channel is 250/4 = 62.5 kS/s.

The sample rate is important for deciding if you can accurately acquire the signals in which you are interested. Chapter 7 in the LabVIEW Basics 1 Course manual discusses the **Nyquist frequency**. This is the **minimum sample rate** you need to detect the presence of a particular frequency and is **given by twice the highest frequency component of the signal**. Sampling below this frequency can result in some very interesting – and wrong – results.

It is also necessary to consider signals that are present but may not be of interest. For instance, if you are sampling a 10 kHz signal, you may select a sample rate of 30 kS/s. However, if there is a 50 kHz signal present this sample rate will alias the higher frequency signal to 10 kHz and it will contaminate the signal in which you are interested. You need to be cautious when selecting a sample rate to avoid aliasing in the results.

If you wish to record an AC signal with a frequency of 10 kHz, you will need a sample rate of **AT LEAST** 20 kS/s. This sample rate will only give two samples/cycle – which does not provide a good picture of the signal other than indicating the presence of some component at that frequency. You would probably want to have four or more samples/cycle (a sample
rate greater than 40 kS/s for this example) to get a reasonable representation of the signal. For some examples of the effect of sampling rate on the recorded signal, see Figures B.1 and B.2.

B.3.6 Settling time

If you are taking data from multiple channels, you also need to be concerned whether there is adequate time after the input multiplexer switches for the voltage to settle properly. This is partially due to the input capacitance of the amplifier following the multiplexer and the output impedance of the device providing the signal to be recorded. It is also a function of the quality of the input amplifier and how fast it can settle after an abrupt jump in the input voltage.

The input amplifier that National Instruments uses in most of their analog input boards is very good with a settling time of a few microseconds.

Minimize the effects of the external circuit if possible. For example, if the external circuit has an output impedance of 5 kΩ and you consult the chart for settling time on page 2 of the specifications for the USB-6221-BNC, you will find that the expected settling time is about 20 μs.

If you are acquiring several channels with a USB-6221-BNC, the default time between sampling successive channels is 14 μs as long as the aggregate sampling rate is less than 72 kS/s. This time comes from the shortest sample interval the device is capable of, $1/250 \text{ kS/s} = 4 \text{ μs}$, plus 10 μs according to the documentation for the DAQ Assistant VI in LabVIEW.

The interchannel sampling time is less than the settling time found in the previous paragraph. It may not be possible to get the desired accuracy with the default delay unless the output impedance of the source is reduced.

An alternate method of getting the desired accuracy would be to sample the same channel several times in a row, effectively increasing the available settling time, and keeping only the final reading as the correct one.

B.4 Analog output

Both devices are capable of 2 independent channels of analog output. The PCI-6040E uses a 12-bit digital-to-analog (D/A) converter with an output range of either ±10 V or 0-10 V. These give a minimum voltage increment (similar to the Code Width on an analog input) of 4.88 mV or 2.44 mV respectively.

The USB-6221 uses a 16-bit D/A converter with an output range of ±10 V and a minimum voltage increment of 305 μV.
Considerations for Analog Input and Output

The PCI-6040E has a maximum update rate of 1 MS/s and the USB-6221 has a maximum rate of 833 kS/s. Most applications of the analog outputs will not be able to achieve the maximum update rate.

For both devices, the maximum current available from each analog output is 5 mA. This is a very low current. It is often necessary to use an op-amp or a transistor on the output to provide adequate current for the device being driven. If your external circuit draws more than 5 mA from the analog output your output voltage will be incorrect.

B.5 Input offset voltage

Because of the imperfections in analog electronics, you will find that your analog input device has a small input offset voltage. That is, if you short across the input to get a 0 V signal you will record some small non-zero voltage with the input device. This voltage may drift from day to day due to electronic and environmental conditions.

It is not unusual for the offset to drift significantly as a device warms up after being turned on. For most devices, after turning them on you will want to wait about 15 minutes for them to stabilize. Once the device is up to operating temperature, it is usually very stable for periods of at least several hours.

*If you are concerned about the absolute value of your measurements, you should always measure the offset voltage and subtract it from your signal to ensure that the recorded values are correctly measured with respect to the ground in your circuit.*

B.6 Dithering

Dithering is a technique for improving the resolution of a measurement. Some analog input devices will provide the capability for hardware dithering that can be enabled. Dithering is done by adding a small, random voltage to the signal at the input of the analog-digital converter and averaging the measured values over a sufficiently long period to remove that added random signal. This is frequently used for high-resolution measurements when the signal of interest is slowly varying.

Both the USB-6221 and the PCI-6040E are capable of dithering but enabling that feature requires some relatively advanced LabVIEW programming. It is not possible to enable dithering with the DAQ Assistant input VI.
B.7 Electrical noise

Noise on an electrical signal is unavoidable. There are many sources of noise, but most of them result in a random voltage signal. If you are involved in measuring low-level signals, you will spend considerable time removing noise from those signals.

One method of removing noise is to average over many samples if the signal of interest is slowly varying. This will remove some portion of the noise signals because of their random nature.

Another method of reducing noise signal levels is to filter your input signal. Depending on the nature of your signal and that of the noise, you may choose a high-pass filter, a low-pass filter, a band-pass filter, or a notch filter.

Low-level random noise may be beneficial in some circumstances because it serves almost the same purpose as dithering by providing a random shift in the signal. If you acquire many samples and average them, the random noise signal will average to zero and you will be left with the actual value of the desired signal. This will often result in a value that is not exactly at one of the standard code levels and you have effectively increased the resolution of the device.

For more information on noise in signals see Appendix C, “Uncertainty, Errors, and Noise in Experimental Measurements.”
Figure B.1: Result of sampling various frequency sine waves at 10 kilosamples/s.
Figure B.2: Result of sampling various frequency sine waves at 10 kilosamples/s.
Appendix C

Uncertainty, Errors, and Noise in Experimental Measurements

“... as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don’t know we don’t know. And if one looks ... it is the latter category that tend to be the difficult ones.”


In the text, Sections 6.8.1 to 6.8.5 (Signal-to-Noise Ratio, Optimizing the Signal-to-Noise Ratio, The Lock-In Amplifier and Gated Integrator or Boxcar, Signal Averaging, Waveform Recovery) all provide additional and complementary information to the discussion here. If you are interested in counting experiments (radiation or low-level photon counting) you may also want to look at Section 6.8.6 (Coincidence and Time-Correlation Techniques).

Consult Appendix D for a review of statistical principles relevant to experimental measurements.

C.1 Introduction

Experimental measurements will inherently be somewhat uncertain. One of the challenges of experimental work is to minimize the uncertainty in our measurements. Several sources of uncertainty are discussed below as well as some ways to reduce the effect of those sources.

Another challenge is to properly report the uncertainty in measurements as correctly as
possible. There are three ways uncertainty or estimated error may be reported. The value of the gravitational constant, G, will be used to illustrate them.

1. The value of the gravitational constant, G, has been through a progression of values:
   - Henry Cavendish: $6.754 \times 10^{-11} \text{m}^3/(\text{kg} \cdot \text{s}^2)$.
   - 1973 CODATA-recommended value: $6.6720(41) \times 10^{-11} \text{m}^3/(\text{kg} \cdot \text{s}^2)$.
   - 1986 CODATA-recommended value: $6.67259(85) \times 10^{-11} \text{m}^3/(\text{kg} \cdot \text{s}^2)$.
   - 1998 CODATA-recommended value: $6.673(10) \times 10^{-11} \text{m}^3/(\text{kg} \cdot \text{s}^2)$.
   - 2002 CODATA-recommended value: $6.6742(10) \times 10^{-11} \text{m}^3/(\text{kg} \cdot \text{s}^2)$.
   - 2006 CODATA-recommended value: $6.67428(67) \times 10^{-11} \text{m}^3/(\text{kg} \cdot \text{s}^2)$.
   - 2010 CODATA-recommended value: $6.67384(80) \times 10^{-11} \text{m}^3/(\text{kg} \cdot \text{s}^2)$.
   - 2014 CODATA-recommended value: $6.67408(31) \times 10^{-11} \text{m}^3/(\text{kg} \cdot \text{s}^2)$.

2. The value of the gravitational constant, G, is given as $6.67408(31) \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$ (the 2014 CODATA recommended value). This is an expression of the officially accepted value of this constant. In this case the “31” in parentheses means that the uncertainty in the last two digits is 31 ($6.67408 \pm 0.00031 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$).

3. The value of G could be given as $(6.6741 \pm 0.0003) \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$. This form is traditionally used where the listed uncertainty is indicating an interval corresponding to a high level of confidence (usually a statement that about 68% of a random set of measurements of the value will fall within the given range).

Remember that the value of the uncertainty in a measurement or result of a calculation is also somewhat uncertain. It is common practice to give the uncertainty with two digits of precision if the first digit is a “1” or a “2” and one digit of precision otherwise.

4. In some cases, it is adequate to indicate the uncertainty by the number of significant digits given in the value. The value of G would be given as $6.6741 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$. With the stated uncertainty in the value, it may be appropriate to write it as $6.674 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$. In these cases the least significant digit given is uncertain. That is, the uncertainty is some fraction of the least significant digit given. This form is usually inadequate for work where the values given are the crux of the work.

For further information on uncertainties, see “Evaluation of measurement data – Guide to the expression of uncertainty in measurement”, Joint Committee for Guides in Metrology 100:2008. This document can be found at http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf. This is a very detailed document describing determining and reporting uncertainty in measurements. NIST (the National Institute of Standards and Technology) has a shortened version of this document at https://www.nist.gov/pml/nist-technical-note-1297.

### C.2 Some sources of error and uncertainty in measurements

To reduce the uncertainty in your measurements, it is useful to understand some of the common sources of error and uncertainty in those measurements. There are two significant
sources that are present in almost every measurement – instrument precision and accuracy, and electronic noise. These will be discussed below, but this is not an exhaustive list of sources of uncertainty.

C.2.1 Limitations in measurement precision

Even if you have a perfectly accurate measurement device (voltmeter, ohmmeter, etc.) there are limits to the precision with which you can make a measurement. For instance, if you have what is known as a $3\frac{1}{2}$-digit voltmeter where the first digit can be either a 1 or a 0 followed by three digits, your precision is limited by the number of digits available. If you measure a voltage of 1.250 V using this meter, the actual value could fall anywhere within the range $1.250 \pm 0.0005$ V simply due to the number of available digits.

In Appendix D, it is shown that the uncertainty in the above value can be more precisely given under the assumption that any value within the given range is equally probable. In that case, the uncertainty is given by $\sigma = c/\sqrt{12}$ where $c$ is the interval between successive values of the least significant digit ($0.001$ in this case). This results in a value with uncertainty of $1.250 \pm 0.0003$ V.

You can always buy a more precise instrument such as a Keysight model 3458A $8\frac{1}{2}$-digit Digital Multimeter (starting at $9750$), a Keithley 2002 Series $8\frac{1}{2}$-digit multimeter (about $6800$), or a National Instruments PXIe-4081 $7\frac{1}{2}$-digit multimeter (about $3690.00$). You can also use techniques such as dithering to get a little more precision. But there will always be limits to the precision with which you can make a measurement. In any case, the uncertainty in your measurement will be close to one-half of the last significant digit in the value.

This uncertainty will be present in any digital measuring device. There will be a similar uncertainty if you are reading the value from an analog device such as a pressure gauge or a d’Arsonval voltmeter. The uncertainty will then involve your estimate of the precision with which you can read the device.

C.2.2 Limitations in measurement accuracy

There may be an added uncertainty in your measured value due to the calibration of your instrument. Instruments often include in their specifications the required interval for calibration to maintain the expected accuracy of the device. In critical measurements, regularly scheduled calibration of instruments is a requirement.

The specification sheet for a measuring device will often have information on the absolute accuracy of the device and an expectation of the drift after calibration. This can become critical to your results if high accuracy measurements are expected.
Remember that a measurement may be very precise (i.e., successive measurements are very close together) but may not be very accurate (i.e., very close to the correct value) if the instrument hasn’t been recently calibrated.

### C.2.3 Uncertainty due to electrical noise

The presence of electrical noise is a common source of uncertainty. This noise may be due to external influences (e.g., radio interference, pickup of the 60-Hz AC supply voltage) or circuit design problems. This can be reduced by proper electrical design (look up “Ground Loop” for an important example) and by shielding techniques (using shielded cables and metal cabinets for electrostatic and electromagnetic shielding). If it is a circuit design problem, you will have to fix the circuit.

**Johnson-Nyquist noise**

There are also several sources that are inherent to electronic circuits. One common source is known as Johnson-Nyquist noise or just Johnson noise. This noise results from thermal motions of the charge carriers in a conductor and is independent of applied voltages or currents. It is also independent of frequency (true up to a few THz), so it is considered “white noise.” It can show up as a noise voltage signal on any resistor or capacitor. It is often given in terms of a power spectral density or mean square voltage variance per Hz of circuit bandwidth:

\[
\overline{v^2_R} = 4 k_B T R
\]

with SI units of V^2/Hz, where \( k_B \) is Boltzmann’s constant \( (1.38 \times 10^{-23} \text{ J/K}) \), \( T \) is the temperature of the resistor in K, and \( R \) is the resistance in \( \Omega \).

If you have a circuit with a bandwidth \( \Delta f \) that is something other than 1 Hz you can find the root mean square (RMS) noise voltage across a resistor by

\[
v_n = \sqrt{4 k_B T R \Delta f}.
\]

The thermal noise in an RC filter circuit has a particularly simple form:

\[
v_n = \sqrt{\frac{k_B T}{C}}.
\]

The resistance in the filter isn’t in the equation because it adds noise to the signal but simultaneously decreases the bandwidth due to the filtering effect.

There are three ways to reduce this noise: reduce the temperature, reduce the resistance, or reduce the circuit bandwidth (changing \( k_B \) isn’t really an option).
Shot noise

In low-level signals, shot noise can be a problem. It is caused by the discrete nature of signal carriers (such as electrons in a circuit or photons in an optical experiment). For example, the arrival of individual photons or the conduction of individual electrons follow Poisson statistics as will be discussed below. In these cases, the statistical nature of the signal means that the standard deviation in a signal consisting of $N$ photons or electrons is $\sqrt{N}$.

Often we aren’t counting individual electrons but if we are trying to measure a small current shot noise can become a significant problem. In general, if a current $I$ is flowing through a conductor the RMS fluctuations in that current are given by

$$\sigma_i = \sqrt{2qI \Delta f}$$

where $q$ is the charge on an electron and $\Delta f$ is the detection circuit bandwidth in Hz.

In an average circuit the way to reduce the importance of shot noise is to increase the current (or arrival rate of photons) so that the noise is a smaller fraction of the signal or to reduce the circuit bandwidth.

1/f noise

The third common noise is merely referred to as “1/f noise” or “pink noise.” This refers to the typical spectrum of the noise – the power in the noise is roughly proportional to $1/f$, so it is often only important at low frequencies when it exceeds the magnitude of the Johnson-Nyquist noise. This is also sometimes referred to as “flicker noise.”

The source of this noise is not definite. It shows up in meteorological data, E-M radiation from some astronomical bodies, almost all electronic circuits, heart beat rhythms, statistics of DNA sequences, financial data, most natural images, and almost all musical melodies. There is no known lower frequency bound in pink noise – it seems to be everywhere. It is best avoided by operating at a sufficiently high frequency (e.g., using a high-pass filter to remove low-frequency components from the signal).

A rough example of 1/f noise is shown in Figure C.1. The noise spectrum shown in the figure falls off slower than 1/f but illustrates the way the noise behaves with frequency.

C.3 A summary of relevant statistics

Estimating the uncertainty in a particular measurement often requires an understanding of the statistical nature of the measurement. The nature of a given measurement will depend on the type of measurement and the type of error sources that are present.
The bandwidth of the spectrum analyzer was set to $300 \text{ Hz}$, the minimum available. The trace is distorted somewhat by the large bandwidth relative to the frequency width of the noise signal. At very low frequency the amplitude levels off because the integration time is too short to represent the signal accurately. By $1500 \text{ Hz}$ the amplitude is approximately equal to the noise floor of the spectrum analyzer ($1.0 \times 10^{-9}$).

The following is a summary of results from Appendix D. You should consult that Appendix for details on the definitions and derivations of the materials in this section.

As discussed above, whenever we make a measurement there is usually a range of possible values that have a finite probability of occurring. Sometimes this range is very small and sometimes it is very large. In either case, the probabilities for the possible values can be used to provide an estimate of the uncertainty in our measurement. The probability of a given value occurring is usually represented by a distribution function. Since the distribution function represents a probability it must be properly normalized:

\[
\sum_s P(s) = 1 \\
\int P(s) \, ds = 1
\]

where $P(s)$ is a distribution function. The sum (the first equation) represents the normalization of a distribution over discrete values and $s$ must go over the entire possible range
of values. The integral (the second equation) is for a distribution over a continuous set of values and \( s \) must go over the entire range of values.

Once we know the expected distribution function for a measurement we can determine what the expected or average value from a collection of measurements will be and the variance in that group. The expected uncertainty in the measurements is usually related to the standard deviation of the measurements which is the square root of the variance. If our experiment involves only discrete possible values, such as non-negative integers, then we can calculate the expected value from the equation

\[
\bar{s} = \sum_{s} s P(s)
\]

where the sum is over all possible values of \( s \). With some effort it can be shown that the variance, denoted by \( \sigma^2 \) and defined by \( \sigma^2 = (s - \bar{s})^2 \), is given by

\[
\sigma^2 = \sum_{s} s^2 P(s) - \bar{s}^2.
\]

If the experiment involves continuous possible values, you replace the sums by integrals

\[
\bar{s} = \int_{s_1}^{s_2} s P(s) \, ds
\]

\[
\sigma^2 = \int_{s_1}^{s_2} s^2 P(s) \, ds - \bar{s}^2.
\]

It is important to remember that this discussion of distributions assumes that the individual measurements are completely independent and uncorrelated so that any variations between successive measurements are random.

### C.3.1 Binomial distribution

Suppose we measure something that can either succeed or fail on any given trial (there can be only two possible results) such as flipping a coin. If we denote the probability that a given trial succeeds by the variable \( p \), the probability of failure by \( q = 1 - p \), and complete \( n \) trials, then the probability of having \( s \) successes in those \( n \) trials is given by the binomial distribution

\[
P(s \text{ successes in } n \text{ trials}) = B_{n,p}(s) = \frac{n!}{s!(n-s)!} p^s q^{n-s}.
\]
The average value is

\[ \bar{s} = np \]

and the variance is

\[ \sigma^2 = np(1 - p). \]

C.3.2 Poisson distribution

The Poisson distribution is associated with counting randomly occurring events that have an average rate of occurrence over a particular interval (time, distance, area, etc.). Examples of this type of measurement would be measuring the rate of decay of a radioactive sample or counting photons in a low-level optical experiment. It can be shown that

\[ P_{\mu}(n) = e^{-\mu} \frac{\mu^n}{n!} \]

where \( P_{\mu}(n) \) represents the probability that exactly \( n \) events occur in the specified interval.

The mean value is given by

\[ \bar{n} = \mu \]

and the variance is given by

\[ \sigma^2 = \mu. \]

This is a somewhat surprising, but very useful, result for this distribution since the variance is the same as the expected value.

C.3.3 The uniform distribution

When any value within a particular range of values is equally likely we have what is called a uniform distribution with a distribution function given by

\[ P(s) = \begin{cases} 1/c & \text{for } (\bar{s} - c/2) \leq s \leq (\bar{s} + c/2) \\ 0 & \text{otherwise.} \end{cases} \]
The denominator in $P$ is a normalization so that the integral of $P(s)$ over all $s$ is equal to one (1). It is apparent that the average value is $\bar{s}$ (you can do the integral if you would like). The variance is not as obvious (the derivation of this expression can be found in Appendix D):

$$\sigma^2 = \frac{c^2}{12}.$$  

As an example, if a $3.1/2$-digit voltmeter is used to measure a voltage and it reads 1.250 V, the actual value could lie anywhere within the range of 1.2495 to 1.2505 V with equal likelihood. If there is no reason to believe that any value in that range is more likely than any other value we have a continuous distribution. The average or expected value is then 1.250 V and the standard deviation is $\sigma = c/\sqrt{12} = 0.001/3.464 = 0.00029$ V since $c = 0.001$ V is the interval between successive least-significant digits on the meter. With modern digital equipment this uncertainty will always be present because we only record discrete values from a continuous signal.

If you are using the National Instruments USB-6221-BNC to measure a signal with the input range set to ±1 V, the code width is about 32 $\mu$V, so any single measurement will have an uncertainty of approximately $\pm 16/\sqrt{3} = \pm 9.2 \mu$V.

### C.3.4 The normal or Gaussian distribution

According to the authors of the *Introductory Statistics* online text, “The normal, a continuous distribution, is the most important of all the distributions. It is widely used and even more widely abused. Its graph is bell-shaped. You see the bell curve in almost all disciplines. ... The normal distribution is extremely important, but it cannot be applied to everything in the real world.”[^1]

The Gaussian distribution is given by

$$P(s) = \frac{1}{\sigma \sqrt{2\pi}} e^{- (s-\bar{s})^2 / (2\sigma^2)}.$$  

Using the integral equations, it is easy to show

$$\bar{s} = \int_{-\infty}^{\infty} s P(s) \, ds$$

and

$$\sigma^2 = \int_{-\infty}^{\infty} s^2 P(s) \, ds - \bar{s}.$$  

Many measurements of continuous variables in physics exhibit a Gaussian distribution. If you are in doubt, you can collect a large number of measurements, bin the values, plot a histogram of the number of times the value fell within each of the bins, and compare this to a Gaussian curve.

If your measurements are truly Gaussian the meaning of $\sigma$ is very specific. If you take many measurements, 68.3% of them will fall within the range of $(\bar{s} \pm \sigma)$, 95.4% will fall within the range of $(\bar{s} \pm 2\sigma)$, and 99.7% will fall in the range of $(\bar{s} \pm 3\sigma)$.

### C.4 Propagating errors

Often a measured value will be used as a parameter in some calculation to give the desired result. For example, if you have a temperature transducer that produces a voltage related to the temperature, you apply some calibration equation to the voltage to arrive at the actual temperature. That equation may simply be a linear function, or it can involve exponentials or logarithms, depending on the type of transducer. It will be necessary to analyze how the uncertainty in the final temperature is related to any uncertainty in the measured voltage and uncertainties in the calibration parameters.

The process of propagating errors through a calculation is fairly straightforward in many cases. For instance, if the value $y$ is a function of the inputs $x_1, x_2, \ldots, x_n$

$$y = f(x_1, x_2, x_3, \ldots, x_n),$$

and we know the uncertainties of the $x_i$ are given by $\delta_i$, then the uncertainty in $y$, $\delta y$, can be found by generating a first-order Taylor series expansion about the average value $\bar{y}$. Then, since $\delta y = y - \bar{y}$ we can write

$$\delta y = \sum_{i=1}^{n} \delta_i \left( \frac{\partial f}{\partial x_i} \right).$$

In this form, the uncertainty is incorrectly estimated because it is not expected that all the error terms will simply sum (i.e., some of them may have different signs, or they may all have the same sign). You can get a better estimate by considering the results from a random walk where the square of the distance covered is approximately equal to the sum of the squares of each of the individual steps. Then we have

$$\delta y^2 = \sum_{i=1}^{n} \delta_i^2 \left( \frac{\partial f}{\partial x_i} \right)^2.$$

We are assuming here that the variables $x_i$ are independent – that is any change in one of them does not cause a change in any of the others. If they are not independent, there will
be another term involving the cross correlation of the form

\[ \sum_{i=1}^{n} \sum_{j=1(j\neq i)}^{n} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} \delta_{ij} \]

where \( \delta_{ij} \) is called the covariance of \( x_i \) and \( x_j \) and arises from correlations between those variables (a change in one of them causes a change in the other). If the \( \delta_i \) values are uncorrelated (e.g., \( \delta_1 \) doesn’t correlate in any way with \( \delta_2 \) so \( \delta_{12} = 0 \)), then we don’t have the extra term in the equation.

There are also some pitfalls in this equation if the function \( f \) is nonlinear or the uncertainties \( \delta_i \) are large in some sense. This is because the propagation equation is based on a first-order Taylor expansion of the equation for \( y \) under the assumption and we only kept the lowest order powers of \( \delta_i \).

### C.5 Dealing with noise in measurements

One of the efforts in experimental measurements is to reduce the uncertainty as far as possible, so the measurements are as precise as possible.

The first step in reducing the uncertainty is to reduce the noise sources as far as possible. This means you have to be sure that your electronic circuitry is well designed; there are no ground loops, all electronic and electrical components are shielded, and all cables and leads are shielded.

#### C.5.1 Signal averaging to “remove” noise

Even after careful design, there will be some noise remaining on your signal. Most common electrical noise sources result in a random signal – common exceptions are RF noise and 60-Hz AC noise. If the noise is random and your signal of interest is “slowly varying” you can often use signal averaging to improve your measurement since the random noise signals will average to zero.

Using the standard process of error propagation reviewed above, it can be shown that averaging \( N \) measurements of the value \( y \), where each sample has a standard deviation of \( \sigma_y \) (usually the sample standard deviation of the \( N \) samples that were averaged), will result in a value

\[
\bar{y} = \frac{1}{N} \sum_{i=1}^{N} y_i
\]

\[
\sigma_y = \sqrt{\frac{\sum_{i=1}^{N} (y_i - \bar{y})^2}{N - 1}}
\]
with standard deviation

\[ \sigma_{\bar{y}} = \frac{\sigma_y}{\sqrt{N}}. \]

See Appendix D, “Statistics Review for Experimental Measurements,” for the derivation of this result.

Thus, averaging 100 samples will result in a factor of 10 reduction in the standard deviation of the resulting average. Unfortunately, the square-root dependence on \( N \) means that rather large values of \( N \) are required to significantly improve the standard deviation. For \( N = 100 \) we get a factor of 10 reduction, but it requires \( N = 10000 \) to get a factor of 100 reduction and \( N = 10^{16} \) to get a factor of 1000 reduction.

An illustration of the effects of signal averaging can be seen in Figures C.2 through C.4. One million points were acquired from a measurement of the voltage across a 2.2 kΩ resistor with a current of 100 µA. The values were acquired with a National Instruments USB-6221-BNC data acquisition module. The channel was set to a range of ±1 V with a resolution (code width) of 32.4 µV at a sample rate of 10,000 samples/s. The average value is 0.214901 V and the standard deviation is 71.2 µV. Figure C.2 shows the histogram of the entire collection of data. The bin width was set to the device code width with the bins centered on the possible discrete values from the data acquisition module. A best-fit Gaussian determined using Matlab’s cftool is overlaid on the data. The equation for the Gaussian was

\[ n(V) = 2.224 \times 10^{-5} e^{-\frac{(V-5.44 \times 10^{-6})^2}{2(5.41 \times 10^{-7})^2}} \]

(amplitude = 2.224 \times 10^{-5}, \( \sigma = 54.1 \mu V \), and the peak is shifted by 5.44 \times 10^{-6} V). As can be seen, the Gaussian is narrower than the original data in the wings (the lower 1/3 of the peak).

The data were then divided into 1000 sets of 1000 points each, and a similar analysis was performed on the means of each of these 1000 sets. Figure C.3 shows a histogram of these 1000 averages. They are plotted on the same horizontal scale as those in Figure C.2 to illustrate the improvement from averaging. Figure C.4 is the same histogram on an expanded scale so the details can be better seen. The best-fit Gaussian curve for the collection of means is overlaid on the data. This curve has the equation

\[ n(V) = 102.4 e^{-\frac{(V-1.14 \times 10^{-7})^2}{2(9.63 \times 10^{-9})^2}} \]

(amplitude = 102.4, \( \sigma = 9.63 \mu V \), and the peak is shifted by 0.1143 µV). The Gaussian fit to the collection of means is considerably better than to the original data. The average of the means is the same as that for the original data (0.214901 V) as would be expected. The standard deviation is 9.96 µV, quite close to that of the best-fit Gaussian and a factor of 7.1 smaller than that of the original data. The theory says the improvement should be a
Figure C.2: A histogram of one million points acquired from a measurement of the voltage across a 2.2 kΩ resistor with a current of 100 µA passing through it. The average value is 0.214901 V with a standard deviation of 71.2 µV. For plotting, the data have been shifted so they are centered on the average value. A best-fit Gaussian is overlaid on the data (the solid line). The Gaussian has an amplitude of $2.224 \times 10^5$ and $\sigma = 54.1 \mu V$. As can be seen, the distribution is close to a Gaussian but with slightly broader wings.

Further illustrations of the effects of number of samples, sampling rate, and sampling duration on signal averaging can be found at https://www.physics.byu.edu/faculty/petersonb/Phys240/NoisePlots.html.

C.5.2 Filtering to reduce noise

If you have noise that is not random, such as 60-Hz AC noise or RF noise from radios or computers, you may be able to use a high-pass filter if your signal of interest is higher frequency or a low-pass filter if your signal is lower frequency. It is also possible to use a bandpass filter to reduce the offending noise signal if the signal of interest is in a small frequency range or a notch filter if the noise is only present in a small frequency range.

Filtering the signal will reduce the bandwidth (smaller $\Delta f$) which will significantly reduce the Johnson-Nyquist, shot, or $1/f$ noise and improve the sensitivity to small signals.
Figure C.3: A histogram of $10^3$ averages of $10^3$ points each using successive subsets of the $10^6$ values represented in Figure C.2. The data have been shifted, so they are centered on the average value. The mean of the collection of average values is 0.214901 V and the standard deviation of the average values is 9.96 $\mu$V. For illustration purposes, this histogram was plotted on the same horizontal scale as Figure C.2. From the theoretical effect of signal averaging discussed here we would expect $\sigma_{\bar{v}} = \sigma_v / \sqrt{N}$ where $\sigma_{\bar{v}}$ is the standard deviation of the group of averages, $\sigma_v$ is the standard deviation of the original data (71.2 $\mu$V), and $N$ is the number of points used to determine each individual average (1000). This gives an ideal value of $\sigma_{\bar{v}} = 2.25 \mu$V. The actual standard deviation is a factor of 4 larger than the predicted value but still a factor of 7 better than without averaging.

### C.6 Systematic errors

It is possible that you will have an uncertainty in your measurements due to what are known as systematic errors. These are usually design errors or electronic features that cause a systematic shift in the measurement. If these effects are relatively constant over the duration of the measurement, you may be able to determine them in some fashion and properly compensate for the error in your measurements (an offset voltage in an amplifier is an example). It is more complex if these errors vary over the course of the experiment and compensation becomes a difficult problem you will have to solve.

Unfortunately, systematic errors are usually unique to a particular measurement and there are no standard methods for dealing with these errors. The better you understand the details of your experiment and the measurements, the more likely it will be that you can find and overcome systematic errors.
Figure C.4: The same histogram as shown in Figure C.3 but on an expanded scale to show the detail in the distribution. A best-fit Gaussian is overlaid on this data (the solid line). It has an amplitude of $102.4 \times 10^{-6}$ and $\sigma = 9.63 \times 10^{-6}$. The collection of averages is fairly close to a Gaussian distribution.
Uncertainty, Errors, and Noise in Experimental Measurements
Appendix D

Statistics Review for Experimental Measurements

It is important to be able properly to estimate the uncertainty in an experimental result. This is true of both the actual measurement as well as any other results that may be derived from that measurement. An understanding of the statistical nature of the measurement will allow us to better approximate these uncertainties and to evaluate the accuracy of a given measurement.

D.1 Probability distributions

Anytime a measurement is made there is a range of possible values that have a finite probability of occurring. Understanding this range and the principles that govern that range will help in evaluating the result. Usually, we will estimate a probability distribution function for the measurement that will provide us with an understanding of this range of possible values and the likelihood of each occurring.

First, we need to define several terms. The first two apply to a collection of discrete data values. The second two apply to items determined from a statistical distribution that describes a particular continuous data set.

average: The technical name of this is the arithmetic mean but may also be called just the mean. It is given by

\[
\bar{y} = \frac{1}{N} \sum_{i=1}^{N} y_i
\]

where \(\bar{y}\) is the average of the \(N\) values \(y_i\).
**standard deviation:** Most commonly this refers to the *sample standard deviation* or the *corrected sample standard deviation*. It is given by

\[
\sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (y_i - \bar{y})^2
\]

where \(\sigma\) is the standard deviation of the \(N\) data values \(y_i\) from the average value \(\bar{y}\). \(\sigma\) represents the RMS (root mean square) deviation of the values from the average and provides an indicator of the uncertainty or the error in the values.

**expected value:** The is the most likely value to occur as indicated by the probability distribution representing some random variable. It is often referred to as the average since it usually corresponds to the arithmetic mean of the values as the number of repetitions of the measurement goes to infinity. It is also referred to as the probability-weighted average of all possible values. It is given by

\[
\bar{s} = \sum_s s P(s)
\]

for a collection of discrete values where \(P(s)\) represents the probability distribution function for \(s\) and is normalized so

\[
\sum_s P(s) = 1
\]

and where the sum is over all possible values of \(s\). If the possible values are continuous the expected value is given by

\[
\bar{s} = \int_s s' P(s') \, ds'
\]

with the normalization condition

\[
\int_s P(s') \, ds' = 1.
\]

**variance:** The variance is analogous to the standard deviation of a collection of data and is usually indicated by \(\sigma^2\). The square root of the variance will be approximately equal to the standard deviation for a large collection of random values that are properly represented by the probability distribution used to calculate the variance. It is given by

\[
\sigma^2 = \sum_s (s - \bar{s})^2 P(s)
\]

for a discrete distribution and

\[
\sigma^2 = \int_s (s' - \bar{s})^2 P(s') \, ds'
\]

for a continuous distribution.
Since we are dealing with probabilities, the distribution functions should be properly normalized as noted in the above definitions. In the following discussion, we assume that $P(s)$ is always properly normalized.

We can also simplify the form for the variance:

$$
\sigma^2 = \sum_s (s - \bar{s})^2 P(s)
= \sum_s (s^2 - 2 \bar{s} s + \bar{s}^2) P(s)
= \sum_s s^2 P(s) - 2 \bar{s} \sum_s s P(s) + \bar{s}^2 \sum_s P(s)
= \sum_s s^2 P(s) - 2 \bar{s}^2 + \bar{s}^2
= \sum_s s^2 P(s) - \bar{s}^2
$$

using the definition of $\bar{s}$ and the normalization of $P(s)$.

It can be similarly shown that the same simplification applies to the integrals for a continuous probability distribution function:

$$
\sigma^2 = \int_{s_1}^{s_2} s^2 P(s') ds' - \bar{s}^2
$$

were $s_1$ and $s_2$ cover the entire range of possible values of $s$.

It is important to remember that this discussion of distributions assumes that the individual measurements are completely independent and uncorrelated so that any variations between successive measurements are random.

### D.1.1 Binomial distribution

The binomial distribution represents the results from a system where any given trial can result in either a success or a failure – there are no other options. An example of this type of experiment would be flipping a coin. We will denote the probability that a given trial succeeds by the variable $p$, the probability of failure by $q = 1 - p$, and complete $n$ trials. Then the probability of having $s$ successes in those $n$ trials is given by

$$
\text{probability of } s \text{ successes in } n \text{ trials} = \binom{n}{s} p^s q^{n-s}
$$
where \( \binom{n}{s} \) is the binomial coefficient. This is properly normalized so

\[
\sum_{s=0}^{n} B_{n,p}(s) = 1.
\]

The expected value is

\[
\bar{s} = \sum_{s=0}^{n} s B_{n,p}(s)
\]

\[
= \sum_{s=0}^{n} s \frac{n!}{s!(n-s)!} p^s q^{n-s}
\]

\[
= n p \sum_{s=1}^{n} \frac{n!}{s!(n-s)!} p^{s-1} q^{n-s}
\]

\[
= n p \sum_{j=0}^{n-1} \frac{(n-1)!}{j!(n-1-j)!} p^j q^{n-1-j}
\]

\[
= n p \sum_{j=0}^{n-1} B_{n-1,p}(j)
\]

\[
\bar{s} = n p.
\]

Because \( B \) is properly normalized, the sum in the next to last line evaluates to one (1). The variance is

\[
\sigma^2 = \sum_{s=0}^{n} s^2 B_{n,p}(s) - \bar{s}^2
\]

\[
= \sum_{s=0}^{n} s^2 \frac{n!}{s!(n-s)!} p^s q^{n-s} - \bar{s}^2
\]

\[
= \sum_{s=1}^{n} s^2 \frac{n!}{s!(n-s)!} p^s q^{n-s} - \bar{s}^2
\]

\[
= \sum_{s=1}^{n} \frac{n!}{(s-1)!(n-s)!} p^s q^{n-s} - \bar{s}^2
\]

\[
= n p \sum_{s=1}^{n} \frac{(n-1)!}{(s-1)!(n-s)!} p^{s-1} q^{n-s} - \bar{s}^2
\]

\[
= n p \sum_{j=0}^{n-1} (j + 1) \frac{(n-1)!}{j!(n-1-j)!} p^j q^{n-1-j} - \bar{s}^2
\]
\[
\begin{align*}
\bar{s}^2 &= np \left[ \sum_{j=0}^{n-1} \frac{(n-1)!}{j!(n-1-j)!} p^j q^{n-1-j} + \sum_{j=0}^{n-1} \frac{(n-1)!}{j!(n-1-j)!} p^j q^{n-1-j} \right] - s^2 \\
&= np \left[ \sum_{j=1}^{n-1} j B_{n-1,p}(j) + \sum_{j=0}^{n-1} B_{n-1,p}(j) \right] - s^2 \\
&= np \left[ (n-1) p + 1 \right] - (np)^2 \\
\sigma^2 &= np (1-p)
\end{align*}
\]

since the first sum represents the expected value of \( j = (n-1)p \) and the second sum is again equal to one (1) since \( B \) is normalized.

### D.1.2 Poisson distribution

The Poisson distribution is usually associated with counting randomly occurring events that have an average rate of occurrence over a particular interval (time, distance, area, etc.). Some examples of this type of measurement would be determining the rate of decay of a radioactive sample, counting photons in a low-level optical experiment, or counting how customers arrive at the teller in a bank.

The Poisson distribution can be found from the limit of the binomial distribution if the number of trials, \( n \), is large and the probability of success, \( p \), is small. Typically this is satisfied if \( n \geq 100 \) and \( (np) \leq 10 \). First, define \( \mu = np \), substitute \( (1-p) \) for \( q \), and factor \( \mu^s/s! \) out of the binomial distribution

\[
B_{n,p}(s) = \frac{n!}{s!(n-s)!} p^s q^{n-s}
\]

\[
\begin{align*}
&= \frac{\mu^s}{s!} \frac{n!}{(n-s)!} \left( \frac{1}{n} \right)^s \left( 1 - \frac{\mu}{n} \right)^{n-s} \\
&= \frac{\mu^s}{s!} \left[ \frac{n!}{(n-s)!} \left( \frac{1}{n} \right)^s \right] \left[ \left( 1 - \frac{\mu}{n} \right)^n \right] \left[ (1 - \frac{\mu}{n})^{-s} \right]
\end{align*}
\]

If we now take the limit of this equation as \( n \to \infty \), and with a little help from Mathematica, we find the limits of the three terms in square brackets to be

\[
\begin{align*}
\lim_{n \to \infty} \frac{n!}{n^s (n-s)!} &= 1 \\
\lim_{n \to \infty} \left( 1 - \frac{\mu}{n} \right)^{-s} &= 1 \\
\lim_{n \to \infty} \left( 1 - \frac{\mu}{n} \right)^n &= e^{-\mu}.
\end{align*}
\]
Combining these results we get

\[ P_\mu(s) = e^{-\mu} \frac{\mu^s}{s!} \]

where \( P_\mu(s) \) represents the probability that exactly \( s \) events occur in the specified interval.

The expected value is found by

\[
\bar{s} = \sum_{s=0}^{\infty} s P_\mu(s)
\]
\[
= \sum_{s=1}^{\infty} s e^{-\mu} \frac{\mu^s}{s!}
\]
\[
= \sum_{s=1}^{\infty} e^{-\mu} \frac{\mu^s}{(s-1)!}
\]
\[
= \sum_{s=1}^{\infty} \mu e^{-\mu} \frac{\mu^{s-1}}{(s-1)!}
\]
\[
= \mu e^{-\mu} \sum_{j=0}^{\infty} \frac{\mu^j}{j!}
\]

where \( j = s - 1 \). Note that the normalization of the distribution provides the relationship

\[
\sum_{j=0}^{\infty} e^{-\mu} \frac{\mu^j}{j!} = 1
\]
\[
\sum_{j=0}^{\infty} \frac{\mu^j}{j!} = e^\mu
\]

which, when substituted into the expression for \( \bar{s} \) gives

\[
\bar{s} = \mu e^{-\mu} e^\mu
\]
\[
= \mu.
\]

One of the surprising, but very useful, results for this distribution is that

\[
\sigma^2 = \sum_{s=0}^{\infty} s^2 P_\mu(s) - \bar{s}^2
\]
\[
= \sum_{s=1}^{\infty} s^2 e^{-\mu} \frac{\mu^s}{s!} - \bar{s}^2
\]
\[\begin{align*}
&= \sum_{s=1}^{\infty} s e^{-\mu} \frac{\mu^s}{(s - 1)!} - \bar{s}^2 \\
&= \mu \sum_{s=1}^{\infty} s e^{-\mu} \frac{\mu^{s-1}}{(s - 1)!} - \bar{s}^2 \\
&= \mu \left[ \sum_{j=0}^{\infty} (j + 1) e^{-\mu \frac{j}{j!}} \right] - \bar{s}^2 \\
&= \mu \left[ \sum_{j=0}^{\infty} j P_{\mu}(j) + \sum_{j=0}^{\infty} P_{\mu}(j) \right] - \bar{s}^2 \\
&= \mu [\mu + 1] - \mu^2 \\
\sigma^2 &= \mu
\end{align*}\]

where \(j = s - 1\) again, the first sum finds the expected value of \(j\) and the second is equal to one (1) because this distribution is also normalized.

### D.1.3 The uniform distribution

When any value within a particular range of values is equally likely we have what is called a uniform distribution with a distribution function given by

\[P(s) = \begin{cases} 
1/c & \text{for } (\bar{s} - c/2) \leq s \leq (\bar{s} + c/2) \\
0 & \text{otherwise.}
\end{cases}\]

The denominator in \(P\) is a normalization so that the integral of \(P(s)\) over all \(s\) is equal to one (1). It is apparent that the expected value is \(\bar{s}\) (you can do the integral if you would like). The variance is not as obvious:

\[\sigma^2 = \int_{\bar{s} - c/2}^{\bar{s} + c/2} s^2 \frac{1}{c} ds - \bar{s}^2\]

\[= \frac{c^2}{12} + \bar{s}^2 - \bar{s}^2\]

\[= \frac{c^2}{12}.\]

This distribution is very common when recording values with modern digital equipment since we can only record discrete values but we are usually measuring a continuous function. \(c\) is the minimum spacing between the possible values on a digital voltmeter or the spacing between levels returned from an analog-to-digital converter.

As an example of this distribution, if a digital voltmeter is used to measure a voltage, and it reads 0.001 V, the actual value could lie anywhere within the range of 0.0005 to 0.0015 V
with equal likelihood. The average or expected value is $0.001\,\text{V}$ and the standard deviation is $\sigma = c/\sqrt{T_2} = 0.001/\sqrt{T_2}$ since $c = 0.001$ is the interval between successive least-significant digits on the meter.  With modern digital equipment, this uncertainty will always be present because we only record discrete values from continuous signals.

### D.1.4 The normal or Gaussian distribution

As noted in the discussion of measurements and noise above, the authors of the *Introductory Statistics* online text stated, "The normal, a continuous distribution, is the most important of all the distributions. It is widely used and even more widely abused. Its graph is bell-shaped. You see the bell curve in almost all disciplines. ... The normal distribution is extremely important, but it cannot be applied to everything in the real world." 

The normalized Gaussian distribution is given by

$$P(s) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(s-\bar{s})^2}{2\sigma^2}}.$$

It is fairly easy to show using the integral equations that

$$\int_{-\infty}^{\infty} s\, P(s)\, ds = \bar{s}$$

and

$$\int_{-\infty}^{\infty} s^2\, P(s)\, ds - \bar{s}^2 = \sigma^2.$$

Many measurements of continuous variables in physics will exhibit a Gaussian distribution. If you are uncertain if your signal does have a Gaussian dependence, you can collect a large number of measurements. You then bin the values, plot a histogram of the number of times the value falls within the appropriate bin, and compare this to a Gaussian curve.

If your measurements are truly Gaussian the meaning of $\sigma$ is very specific. If you integrate the distribution over some range that is centered on $\bar{s}$ you can get the fraction of measurements that will typically fall in that range:

$$f = \frac{1}{\sigma \sqrt{2\pi}} \int_{\bar{s}-\Delta}^{\bar{s}+\Delta} e^{-\frac{(s-\bar{s})^2}{2\sigma^2}} \, ds.$$
If we let \( t = \frac{s - \bar{s}}{\sqrt{2} \sigma} \) this integral becomes

\[
f = \frac{1}{\sigma \sqrt{2\pi}} \int_{-\Delta/(\sqrt{2} \sigma)}^{\Delta/(\sqrt{2} \sigma)} e^{-t^2} \sqrt{2} \sigma \, dt \\
= \frac{1}{\sqrt{\pi}} \int_{-\Delta/(\sqrt{2} \sigma)}^{\Delta/(\sqrt{2} \sigma)} e^{-t^2} \, dt.
\]

Since the integrand is symmetrical about zero (0) and the integral limits are also symmetrical about zero we can just use twice the integral from zero to the upper limit:

\[
f = \frac{2}{\sqrt{\pi}} \int_{0}^{\Delta/(\sqrt{2} \sigma)} e^{-t^2} \, dt.
\]

If we now express \( \Delta \) as a multiple of \( \sigma \), \( \Delta = n \sigma \), the integral becomes

\[
f = \frac{2}{\sqrt{\pi}} \int_{0}^{n/\sqrt{2}} e^{-t^2} \, dt
\]

where \( \text{erf}(x) \) is the Gaussian error function that is well known. Most mathematical packages include this as one of the standard functions.

If we look at the fraction of the values that fall within a given number of standard deviations we find

\[
\begin{align*}
\Delta & = \sigma, \quad \text{erf}(1/\sqrt{2}) = 0.6826894921370858 \\
\Delta & = 2\sigma, \quad \text{erf}(2/\sqrt{2}) = 0.954499736103642 \\
\Delta & = 3\sigma, \quad \text{erf}(3/\sqrt{2}) = 0.99730020393674 \\
\Delta & = 4\sigma, \quad \text{erf}(4/\sqrt{2}) = 0.999936657516334 \\
\Delta & = 5\sigma, \quad \text{erf}(5/\sqrt{2}) = 0.999999426696856 \\
\Delta & = 6\sigma, \quad \text{erf}(6/\sqrt{2}) = 0.99999998026825
\end{align*}
\]

As you can see, virtually all the measurements of a signal that exhibits Gaussian behavior should fall within the range of \( \bar{s} \pm 6\sigma \).
Figure D.1: A graph of the binomial distribution (circles) overlaid on the normal distribution (solid line). Both have been calculated to have a mean value of 4 and a variance of 2. For the binomial distribution this corresponds to $n = 8$, $p = q = 0.5$. The vertical dotted line shows the mean value and the vertical dashed lines show the mean plus or minus $\sigma (\sqrt{2})$. You will notice that the binomial distribution has a lower peak value, is broader about halfway down, but goes to zero faster on the tails. At $s = 8$ and $s = 0$ the binomial distribution has a value of 0.003906 while the normal distribution has a value of 0.005167. The differences are not large.

\section*{D.2 Comparison of distributions}

It may be instructive to look at graphs of the distributions. First, we will compare the binomial distribution with the normal distribution. To emphasize the differences, I have chosen both to have a mean value of 4. Since the maximum variance of the binomial distribution would then be 2 ($\bar{s} = np$, $\sigma^2 = npq$ with the largest value at $p = q = 0.5$), both distributions in Figure D.1 have been drawn with these values.

The Poisson distribution requires that the mean value and the variance be equal. In Figure D.2 we use a mean value of 4 and a variance of 4 to compare the Poisson distribution and the normal distribution.

Figure D.3 is included to show the uniform distribution with the same values (mean = variance = 4). In this case, the value of $c$ (the width of the distribution and the reciprocal of the amplitude) is found from $\sqrt{12\sigma^2} = 6.9282$. 
Figure D.2: A graph of the Poisson distribution (circles) overlaid on the normal distribution (solid line). Both have been calculated to have a mean value of 4 and a variance of 4. The vertical dotted line shows the mean value and the vertical dashed lines show the mean plus or minus $\sigma (\sqrt{4})$. You will notice that the Poisson distribution has about the same peak value and that the peak is shifted toward lower values of $s$. On the right side of the peak (higher values of $s$) the Poisson distribution is lower than the normal distribution, consistent with the peak being shifted to the left. But the Poisson goes to zero more slowly as $s$ increases. At $s = 12$ the Poisson and normal distribution values are $6.415 \times 10^{-4}$ and $6.692 \times 10^{-5}$ respectively. At $s = 16$ the values are $3.760 \times 10^{-6}$ and $3.038 \times 10^{-9}$ respectively.

### D.3 Propagating errors

Often a measured value will be used as a parameter in some equation to give the desired result. For example, if you have a temperature transducer that produces a voltage related to the temperature, you may be required to apply some calibration equation to the voltage to arrive at the actual temperature. That equation may simply be a linear function, or it can involve exponentials or logarithms, depending on the type of transducer. It is necessary to analyze how the uncertainty in the final temperature is related to any uncertainty in the measured voltage and uncertainties in the calibration parameters.

The process of propagating errors through a calculation is fairly straightforward in many cases. For instance, if the value $y$ is a function of the inputs $x_1, x_2, \ldots, x_n$

\[ y = f(x_1, x_2, x_3, \ldots, x_n), \]

and the uncertainties of the $x_i$ are given by $\delta_i$, we can use a Taylor expansion of $y$ about $\bar{y}$,
Figure D.3: A graph of the normal distribution. This was calculated to have a mean value of 4 and a variance of 4 to match the values in Figure D.2. The vertical dotted line shows the mean value and the vertical dashed lines show the mean plus or minus $\sigma (\sqrt{4})$. $c$, the width of the distribution and the inverse of the amplitude was calculated from the specified variance: $c = \sqrt{12} \times \text{variance} = 6.9282$.

keeping only first order terms we get

$$
\delta_y = y - \bar{y} = \sum_{i=1}^{n} \delta_i \left( \frac{\partial f}{\partial x_i} \right).
$$

Because the signs of the $\delta_i$ are random, this will usually incorrectly estimate the uncertainty since they can have alternating signs such that it sums to zero or they all have the same sign so that it sums to a large number. You can get a better estimate of the uncertainty by considering the results from a random walk where the square of the distance covered is approximately equal to the sum of the squares of each of the individual steps. This gives us

$$
\delta^2_y = \sum_{i=1}^{n} \delta^2_i \left( \frac{\partial f}{\partial x_i} \right)^2.
$$

In this equation, we have assumed that the $x_i$ are independent and there is no cross-correlation between different $x_i$. If this not true, we will have to add one or more terms to the sum of the form

$$
\sum_{i=1}^{n} \sum_{j=1 (j \neq i)}^{n} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} \delta_{ij}
$$
where $\delta_{ij}$ is called the covariance of $x_i$ and $x_j$ and arises from correlations between those variables where a change in one of them causes a change in the other. If the $\delta_i$ values are uncorrelated we don’t have the cross-correlation terms in the equation.

There are also some pitfalls in this equation if the function $f$ is nonlinear or the uncertainties $\delta_i$ are large in some sense. This is because the propagation equation is based on a first-order Taylor expansion of the equation for $y$ under the assumption that we only need to keep the lowest order powers of $\delta_i$ because $\delta_i^2 \ll \delta_i$.

### D.3.1 Offset voltage

An application of this method can be seen if you have determined an offset voltage, $v_{off}$, associated with an amplifier but that voltage has an uncertainty, $\delta_{off}$, possibly due to noise on the signal. Then the corrected voltage will be given by

$$v_c = v - v_{off}.$$  

Applying the above propagation technique to this equation is straightforward and results in the uncertainty

$$\delta_{v_c} = \sqrt{\delta_v^2 + \delta_{off}^2}.$$  

### D.3.2 Signal averaging

Returning to the case of averaging a signal over some period to reduce noise, it is straightforward to derive the effect on the standard deviation of the average.

If we are averaging $N$ points together so

$$\bar{y} = \frac{1}{N} \sum_{j=1}^{N} y_j$$  

we can also obtain the standard deviation of those $N$ points given by

$$\sigma_y = \sqrt{\frac{\sum_{j=1}^{N} (y_j - \bar{y})^2}{N - 1}}$$  

(the sample standard deviation). If we took a single sample $y_i$, we would expect it to have a standard deviation of $\sigma_y$ as long as the number of points, $N$, in the original data set is
large enough and the acquisition sample rate fast enough to get a good sample of the signal and any noise present.

If we then take an average of \( N \) samples (which conveniently can be the same set of samples we used in determining the standard deviation of each of the samples) we would find

\[
\bar{y} = \frac{1}{N} \sum_{j=1}^{N} y_j
\]

\[
\sigma_{\bar{y}} = \sqrt{\sum_{j=1}^{N} \left( \sigma_y \frac{\partial \bar{y}}{\partial y_j} \right)^2}
\]

\[
= \sqrt{\sum_{j=1}^{N} \left( \sigma_y \frac{1}{N} \right)^2}
\]

\[
= \sqrt{\frac{\sigma_y^2}{N^2} \sum_{j=1}^{N} 1}
\]

\[
= \sqrt{\frac{\sigma_y^2}{N}}
\]

\[
\sigma_{\bar{y}} = \frac{\sigma_y}{\sqrt{N}}.
\]

Averaging a slowly-varying signal can significantly improve the uncertainty in the resulting value.

You can combine other errors, in the same way, to arrive at a total error in your final value. Care in accounting for the possible errors in a measurement will significantly improve your understanding of the quality and usefulness of that measurement.
Appendix E

Your Lab Notebook

Why keep a lab notebook (besides a grade, we mean?). The lab notebook should be a complete record of what you have done. As such it serves as both a memory aid and an archival record.

Following is a summary of the results from interviews with 13 graduate students who were actively involved in experimental research. They were chosen because they were involved in almost daily hands-on engagement with the experiments.
"Researchers generally had a consensus view of the purpose for lab notebooks in their research. The notebook is intended to serve as a record of precisely what one did (both successfully and unsuccessfully) throughout the course of one’s experiment—it was described as being the memory of the experiment. It was emphasized that the complexity of their experiments made it too difficult to remember all of the daily details, and so the notebook was essential for keeping track of them. Additionally, in order to make progress in their work, researchers had to synthesize results from different days—by comparing and contrasting different measurement, they were able to make sense of the subtleties of their experiments. This required that the details of various days’ efforts were adequately recorded. These different measurements may have been taken over the course of days, weeks, or months. Also, from a summative perspective, information in the notebook was essential to corroborate anything that would ultimately be published. For many of the researchers, the notebook also serves as a place to develop new ideas for the future trajectory of the project, so that they could revisit and further refine these ideas as new results arose. Furthermore, the notebook served to communicate the researcher’s efforts to others involved in the project either at present or to those in the future. In essence, the purpose of the notebook was to help make sense of the experiment, think through future directions of the project, create a foundation for publications, and communicate progress with others."


As a memory aid, it will help you remember exactly what you were doing and what the previous results were. It is amazing how quickly those details disappear from memory. Even a week later, it can take you several minutes to remember what you have already done. If you are away for a month or a year, it is almost the only way to get back up to speed. Maintaining a good lab notebook will always improve your productivity, even if you are a theorist or a computationalist.

As an archival record of your work, the lab notebook will help you establish what and when you did things if it ever becomes important to your employer (which might be you!). Many employers require their workers to keep appropriately detailed lab notebooks.

"Remember kids, the only difference between [fiddling] around and science is writing it down."

Alex Jason, Mythbusters ballistics expert used by Adam Savage on Mythbusters
E.1 What to include in your lab notebook

It is expected that you will have your lab notebook available anytime you are working in the lab. The lab notebook is your record of what was done and when it was done. The details should be recorded as the work is done. Going back to reconstruct a lab notebook after the fact is counterproductive and results in a sketchy, and often inaccurate, description of the work.

You should record any information that would be necessary for someone to duplicate your experiment with only your lab notebook (and possibly the various lab handouts) as a guide.

Some of the items that should be recorded in your notebook:

- The actual date the work being described was done (every page should be dated).
- Your purpose in doing the experiment. This should be a few sentences describing what you hope to measure, calculate, or derive and how you are going to do it.
- Details on any equipment that you assemble for the experiment.
  - Relevant dimensions, materials, and characteristics for hardware used. A reference to a published fabrication drawing would be adequate if such is available and necessary. Draw a sketch of the experimental layout.
  - Commercial equipment should be identified by manufacturer and mode number. Lab equipment that is standard for the class can be identified by function rather than in detail. For example, you could put down “Digital Multimeter” in place of full identifying information if you use the standard class multimeter.
  - Circuit diagrams for any electronics you fabricate. A reference to a published diagram would be adequate if it is complicated. Simple circuit diagrams should always be included.
  - Details for any parameters in the above items that are not specified or given as “optional” in the diagram or drawing.
- Details on any transducers used to record information for the experiment.
  - If a transducer requires any calibration, the method of calibration and the results of the calibration must be included in the notebook.
- Details on any software written or used in the course of the experiment.
  - A listing for the software (for example, for Python or C++ code) or a printout of the block diagram (for LabVIEW code) may be appropriate if it illustrates important aspects of the acquisition or analysis.
  - Details on choices made in the software. For example, if it is a data acquisition program, you should include, as appropriate,
    - the specific hardware used for the acquisition
    - signal acquisition rates
    - data averaging details (if applicable)
    - input ranges specified
    - the format of any output files
Your Lab Notebook

* any special methods used in the course of the acquisition.

- Details of any models used in analyzing the data. Completely describe the model(s) and any approximations made in arriving at the model(s).
  It is often appropriate to include a derivation of the model. If the model is derived somewhere else, include a reference to that derivation.

- **Your actual data.**
  An experiment with no data is not complete, even if the data show that the experiment was a failure. Lists or tables of numbers are reasonable if they are short. For large collections of data, there should be properly labeled graphs.
  It is perfectly acceptable to print items for inclusion in your notebook and tape them in. They should be firmly attached to the notebook pages. Loose papers are not acceptable since they can’t be considered part of the permanent record of the experiment.

- Your thoughts and interpretations of the data.
  It is completely appropriate to mention what you understand and what you don’t about the data, and consider possible interpretations of what you are seeing. (“This data looks strange. Is there another source of noise that I haven’t considered?”)

A few reminders on content:

- **Use units with all data** unless the data are actually without units such as ratios of voltages. Any data without units are assumed to be in furlongs/fortnight.
  There are two online documents that are very valuable regarding the use of SI units. The NIST Guide for the use of the International System of Units (https://www.nist.gov/physical-measurement-laboratory/special-publication-811) and Writing with Metric Units (https://www.nist.gov/pml/weights-and-measures/writing-metric-units)

- **Use labels for graph axes.**
  These labels should include both what is represented by the axis and the associated units if applicable. Use arrows and describe what is significant on the graphs as appropriate.

- **Indicate uncertainty in your data and subsequent results** as accurately as possible. See the document “Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results” (https://www.nist.gov/pml/nist-technical-note-1297) for the proper way to handle and report uncertainty.

If you decide something in your notebook is in error, don’t scribble it out or remove it. Just put a large ‘X’ through the erroneous material and leave it readable. Write in an explanation of why you think it is wrong. (“We didn’t have the secondary power supply turned on, so the widget wobbled instead of precessing.”)

Remember that your notebooks will be graded at the completion of each experiment group (comprising multiple lab sessions). You should have your notebook complete and ready to be graded when you finish the group of experiments.
You are supposed to be writing your notebook as you perform the experiments.

E.2 Notebook grading

Your notebook will be graded with the following scale. This scale assumes each lab is worth 40 points. Deductions can be in 1 point increments. If the lab is not worth 40 points, the points given below will be scaled appropriately.

- Remember that every page is to be dated indicating when the work was done.
- Description of the experimental setup. This includes clarity and completeness. 8 points.
- Description of any models used and the analysis methods. 8 points.
- Completeness of data recording. If any data is not to be used, is it clearly marked that way, with a reason why? 8 points.
- Error analysis. This includes error sources, sizes, and propagation. 8 points.
- Conclusions and understanding. This includes answers to any questions that are asked in the lab description. 8 points.
1. Before putting the heater on your aluminum heater block you, ensure that the 3/8-24 threads extend all the way through the block. If you don’t do this now, you may have to do it later, and it is much easier to do if the heater hasn’t been put on yet.

2. Wrap the outside of the aluminum heater block with brown adhesive-coated, 3-mil Teflon sheet to electrically insulate it. It is only necessary to have a single layer of tape but be sure there are no gaps in it.

3. Select a strip of 0.005” thick Hastelloy X stock for your heater. The strip is 5/16” wide and needs to be cut down to about 1/8” to 5/32” wide. You should be able to get two heater strips from a single piece 33” to 36” long. You can cut the strip using regular scissors. **CAUTION:** these strips can have sharp edges from the cutting process. **BE VERY CAREFUL** with them to avoid cutting your fingers or other important parts of your body.

4. Cut the strip to the proper length, so it will wrap on the block without overlap.
5. Measure the resistance of your heater strip using a 4-lead measurement technique.

6. Using small copper crimp sleeves attach a 6-8” length of 18-gauge Teflon-insulated wire to each end of the heater coil. You may need to fold the end of your heater strip to fit into the sleeve. The sleeves can be crimped on using a pair of pliers. Be sure that you have good contact with both the wire and the heater strip in the sleeve. You will need to compress the sleeve fairly hard. Using just the corner of the pliers to compress a small region at a time will help.

7. Carefully wrap the heater around the heater block. If your heater strip has a noticeable ridge along one edge, place the strip so that ridge is placed facing out, so it will not puncture the 3-mil Teflon tape. Be sure that the individual wraps are separated to avoid contact between them. Also, do not wind the heater all the way to the end of the aluminum block. After the heater is placed on the block, you need to wrap it with a layer of white Teflon tape to hold it in place. It is almost guaranteed that it will take at least two people to do this.

8. Lay the wires down along the cryostat and wrap everything with another layer of white Teflon tape to hold it all in place. Cover the crimp sleeves to avoid electrical contact with them as well.

9. Attach the leads to a binding post connector to facilitate connection to the power supply.

10. Repeat the measurement of the resistance of your assembly using a 4-lead technique to be sure that you haven’t introduced any high-resistance junctions in the connections or short circuits between the coil windings.
Appendix G

Four-Lead Measurement of Resistance

Most of the time we use a common ohmmeter to measure a resistance. The ohmmeter passes a known current through the object and measures the voltage drop produced by that current. Then, remembering the correct form of Ohm’s Law, \( R = \frac{V}{I} \).

The ohmmeter works well for large resistances (greater than a few 10s of ohms) and when it is possible for the probes to make good connections to the object.

If the resistance is very small, if it is difficult to make a good connection, or both, it is necessary to use a more complicated method to measure the resistance properly. The main problem in these two cases is that the resistance in the probes and connections becomes comparable to, or larger than, the resistance being measured.

G.1 Four-lead measurement technique

What is referred to as the “four-lead measurement” may also be known as “four-terminal sensing,” “four-wire sensing,” “four-point probes method,” “four-probe measurement,” and even “Kelvin sensing” after Lord Kelvin, who originated the technique. They are equivalent names for this method of making the measurements.

As shown in Figure G.1, the four-lead measurement technique uses a separate current source (schematically shown in the figure as a battery but any current source will work), ammeter, and voltmeter to determine the resistance.

The advantage of this method involves controlling the flow of current through all the connections – especially those used to measure the voltage. The measurement current flows through one set of connections, usually those that are farthest apart. If these connections are resistive (i.e., the connections are poor) there will be significant voltage drop across them.
Figure G.1: A schematic of a 4-lead measurement. Note that the current and voltage leads have separate connections to the object for which the resistance is to be determined. This is critical to the proper measurement of the voltage. Although the schematic indicates a battery in the lead with the ammeter, this can be replaced by any reasonable current source.

However, this voltage drop doesn’t matter as long as the power supply has a sufficiently high output voltage since the only parameter in which we are interested for these connections is the actual current flowing through the object. This current is being accurately measured by the ammeter in series between the object and the current source.

The voltage measurement uses a separate set of connections and the large input resistance (typically 10 MΩ for a digital voltmeter) means that the current flow through those connections will be very small. Thus, the voltage drop across these connections will be very small compared to the voltage drop across the object of interest unless the resistance being measured is comparable to the input resistance of the voltmeter. This means that we can get an accurate measurement of the resistance even if the resistance is very small or if it is not possible to make good connections.

Note: the small clip leads do NOT make good connections. If you are using an ohmmeter to measure a resistance less than 10 Ω or 20 Ω you will not get good results. You can see this by just clipping the leads together and looking at the measured resistance – often 1 to 1.5 Ω.
Appendix H

Temperature Transducers

There are several different sensors or transducers that can be used for computer-based acquisition of temperature. In general, these transducers must be able to provide a voltage that can be related to the temperature to be useful since most computer acquisition systems can only directly measure voltage. A few of these transducers are discussed here.

A more complete discussion of temperature transducers is found in Section 8.1 (THE MEASUREMENT OF TEMPERATURE) of the text.

H.1 Thermocouple

Thermocouples are quite common because they are useful over a very wide range of temperatures and are quite robust. A junction of two dissimilar metals will generate a voltage that is usually temperature dependent but not necessarily linear. There are several well-defined thermocouple combinations that are in common use, each with particular characteristics that may be desirable for a given application. Some use expensive metals such as platinum. Others use common metals like iron, copper, aluminum, nickel, and chromium in various alloys and combinations. Those that use common metals are quite inexpensive to use.

Two common combinations are a type K thermocouple made of chromel (nickel/chromium alloy) and alumel (nickel/manganese/aluminum/silicon alloy). It has a useful range of 73 K to 1523 K (−200 °C to 1250 °C) with a sensitivity of 41 μV/K. The type J thermocouple is made of iron and constantan (copper/nickel alloy). It has a useful range of 233 K to 1023 K (−40 °C to 750 °C) with a sensitivity of 55 μV/K.

These thermocouples will measure temperatures below the specified lower limit but with reduced accuracy. Both of these thermocouples include magnetic materials that undergo a phase transition at the Curie temperature (632 K for type K and 1023 K for type J). The major drawback of thermocouples is the low sensitivity.
A major advantage is that the junction volume is very small, so they respond very rapidly to changing temperature.

### H.2 Thermistor

A thermistor (thermal resistor) is a resistor designed to have a large change of resistance with a change of temperature. They come in several different forms with some designed to have the resistance increase with increasing temperature (PTC, positive temperature coefficient) and some to have the resistance decrease with increasing temperature (NTC, negative temperature coefficient).

PTC devices often have abrupt resistance changes and are not useful as a temperature sensor. NTC devices usually have a nonlinear relationship between resistance and temperature (often of the form $R \approx R_0 \exp[B(1/T - 1/T_0)]$).

The useful range for these devices depends on the construction, with the most common devices operating roughly 230 K to 400 K ($-40^\circ$C to $130^\circ$C) but devices are available that cover some portion of the range of 0.01 K to 2000 K. Most thermistors are physically quite small and thus respond rapidly to changing temperature.

### H.3 RTD, resistance temperature detector

An RTD (resistance temperature detector) also uses the temperature dependence of the resistance of a material (usually a metal in this case) to determine the temperature. A laboratory-grade RTD is often made with platinum wire, but other pure metals can be used. Common RTDs will have a sensitivity in the range of 0.375 to 0.392 Ω/K with a resistance of either 100 Ω or 1000 Ω at 0°C.

Due to the fragile nature of the metal filament used in these devices, they are usually in a protective case that reduces the rate at which they can respond to external temperature changes.

### H.4 Silicon diode

A silicon diode can also be used as a temperature transducer although one made for use in electronics will not be as accurate or as reproducible as some of the previously discussed sensors. There are diodes designed specifically for use as a temperature sensor, and they are quite accurate.

A common signal diode does have the advantage that it is very cheap and most small signal diodes have very small packages, so they respond reasonably quickly to changing
temperature. A 1N4148 diode has a temperature sensitivity of about 2 mV/K when a constant current is passing through the forward-biased diode. Specially designed diodes can have an accuracy of ±0.25 K over a range of 30 K to 100 K with decreased accuracy above 100 K. This may increase to 0.5% of the measured temperature in the 300 K to 500 K range). The 1N4148 is not likely to achieve this level of accuracy.
Appendix I

Measuring Temperature with a Silicon Diode

Due to the high sensitivity, nearly linear response, and easy availability, we will use a 1N4148 diode for the temperature transducer in our measurements.

I.1 Analysis of the thermal dependence in the diode equation

The current conducted through an ideal diode is described by the Shockley ideal diode equation:

\[ I_D = I_S \left[ \exp \left( \frac{qV_D}{nk_B T} \right) - 1 \right] \]

where \( q \) is the electron charge, \( k_B \) is Boltzmann’s constant, \( T \) is the temperature of the diode junction, and \( V_D \) is the voltage across the diode (positive voltage indicates a forward-biased diode). \( n \) is a quality factor or emission coefficient that typically lies in the range of 1–2 and is usually assumed to be approximately 2 for a diode.

\( I_S \) is the reverse bias saturation current given approximately by

\[ I_S = A \exp \left( -\frac{E_g}{2k_B T} \right) \]

where \( A \) depends primarily on the geometry and doping of the junction region and \( E_g \) is the semiconductor band gap. The band gap for silicon is usually given as 1.17 eV at 0 K and 1.11 eV at 300 K. For the 1N4148 diode we usually measure a value of \( \sim 1.20 \) eV.
Although the equation for $I_D$, the diode current, appears to be very nonlinear (a product of exponentials appears to dominate the equation), it is possible to find operational parameters that produce a very linear behavior, at least over a reasonable range of temperatures.

We can solve this for the voltage $V_D$ assuming that $n = 2$:

$$V_D = \ln \left[ \frac{I_D}{A} + \exp \left( -\frac{E_g}{2k_B T} \right) \right] \frac{2k_B T + E_g}{q}.$$  

Since $E_g \sim 1.20$ eV and $k_B T \sim 0.025$ eV at room temperature, $\exp[-E_g/(2k_B T)] \sim 10^{-10}$ and it can probably be neglected. So we arrive at the expression

$$V_D = \frac{\ln \left( \frac{I_D}{A} \right) 2k_B T + E_g}{q}.$$  

If the current through the diode is held constant, there is now a simple linear relationship between voltage and temperature. If the diodes we will use were ideal, this expression would be all we need. For real diodes, the functional form is still quite linear, e.g.,

$$V = m T + b$$

where $m$ and $b$ are constants. However, $b$ may be slightly different from $E_g/q$ and the parameter $A$ in $\ln(I_D/A)$ is unknown. The constants $m$ and $b$ will need to be determined experimentally for accurate temperature measurement.

I.2 Checking the validity of the linear assumption

It is advisable to verify that our assumption of linearity in the calibration equation is correct. We have found that $A \approx 90$ is a lower limit on the value for a “typical” 1N4148 diode. Any nonlinearity in the equation will result primarily from the logarithmic term in the numerator:

$$\ln \left[ \frac{I_D}{A} + \exp \left( -\frac{E_g}{2k_B T} \right) \right].$$

Figure I.1 shows a graph of the temperature dependence of this term for four values of $I_D$ assuming a value of $A = 90 \, \text{A}$ to help in determining an appropriate diode current for linear behavior.

From this analysis, it is apparent that $I_D = 10 \, \mu\text{A}$ would be adequate for measurements from less than 70 K up to about 300 K (room temperature). It becomes noticeably nonlinear by the time we get to 370 K (boiling water). $I_D = 100 \, \mu\text{A}$ will allow the use of the diode up to about 370 K but that is at the start of exponentially increasing error. Since we are interested in temperatures from 75 K (boiling liquid nitrogen) to 370 K, we can reasonably use $I_D = 100 \, \mu\text{A}$ for our measurements.
Figure I.1: \( \ln\left[ \frac{I_D}{A} + \exp(-\frac{E_g}{(2k_bT)}) \right]/\ln[I_D/A] - 1 \), the fractional error due to neglecting the exponential function in the logarithmic term of the voltage equation as a function of temperature for several values of the diode current \( I_D \). These curves assume a value of \( A = 90 \) A and \( E_g \sim 1.19 \) eV.

### I.3 Estimating the error in the measured temperature

Any measurement is guaranteed to have some error associated with it (review Appendix C, “Uncertainty, Errors, and Noise in Experimental Measurements”). The obvious problem is that we can’t measure a voltage with infinite precision. But there are other concerns that may crop up in a careful analysis of the errors.

There are two approaches to determining the calibration constants for the diode.
I.3.1 Calibrating with $V=mT+b$

For this form of the equation, the constants are directly related to the theoretical equation derived earlier in this chapter. Rearranging to get the temperature from the value of the diode voltage, $T = (V_d - b)/m$, the error analysis is slightly complicated.

\[
(\Delta T)^2 = \left( \frac{\partial T}{\partial V_D} \Delta V_D \right)^2 + \left( \frac{\partial T}{\partial b} \Delta b \right)^2 + \left( \frac{\partial T}{\partial m} \Delta m \right)^2
\]

\[
= \left( \frac{1}{m} \Delta V_D \right)^2 + \left( \frac{-1}{m} \Delta b \right)^2 + \left( \frac{-(V_D - b)}{m^2} \Delta m \right)^2
\]

\[
= \frac{1}{m^2} (\Delta V_D^2 + \Delta b^2) + \left( \frac{V_D - b}{m^2} \right)^2 \Delta m^2.
\]

Using the original equation for $T$ and rearranging somewhat we get

\[
(\Delta T)^2 = \left( \frac{T}{V_D - b} \right)^2 (\Delta V_D^2 + \Delta b^2) + \left( \frac{T}{m} \right)^2 \Delta m^2
\]

\[
\left( \frac{\Delta T}{T} \right)^2 = \frac{\Delta V_D^2 + \Delta b^2}{(V_D - b)^2} + \left( \frac{\Delta m}{m} \right)^2.
\]

This form of the equation is not useful if you are using temperatures in Celsius because of the problem of dividing by 0. It is useful with Kelvin temperatures. The previous form without the explicit presence of $T$ in the equation can be used with temperatures in Celsius.

As an example, data taken for a calibration in ice water resulted in the values $T = 273.15 \text{ K}$ and $V_D = 0.5586857 \text{ V}$. For these values 10000 samples were acquired at 100000 samples/s and averaged to arrive at the final value. For each sample, it was found that $\sigma_V = 54 \mu \text{ V}$. Since we averaged 10000 samples to arrive at $V_D$, $\sigma_{V_D} = \sigma_V/\sqrt{10000} = 0.5424 \mu \text{ V}$. The Mathematica script NLSQFit240 will return estimated uncertainties in the fitting parameters if we include uncertainties in the measurements in the third column of the input file. Doing so with the estimated uncertainties in the measurements resulted in

As an example, data taken for a calibration in ice water resulted in the values $T = 273.15 \text{ K}$ and $V_D = 0.5586857 \text{ V}$. For these values 10000 samples were acquired at 100000 samples/s and averaged to arrive at the final value. For each sample, it was found that $\sigma_V = 54 \mu \text{ V}$. Since we averaged 10000 samples to arrive at $V_D$, $\sigma_{V_D} = \sigma_V/\sqrt{10000} = 0.5424 \mu \text{ V}$. The Mathematica script NLSQFit240 will return estimated uncertainties in the fitting parameters if we include uncertainties in the measurements in the third column of the input file. Doing so with the estimated uncertainties in the measurements resulted in $m = -0.0023776 \text{ V/K}, \sigma_m = 9.8 \times 10^{-7} \text{ V/K}, b = 1.2053 \text{ V},$ and $\sigma_b = 2.64 \times 10^{-4} \text{ V}$. Using these values in the above equation, we get

\[
\left( \frac{\Delta T}{T} \right)^2 = \frac{(5.424 \times 10^{-7})^2 + (2.64 \times 10^{-4})^2}{(0.5586857 - 1.2053)^2} + \frac{(9.8 \times 10^{-7})^2}{(-2.377 \times 10^{-3})^2}
\]

\[
= 1.667 \times 10^{-7} + 1.748 \times 10^{-7}
\]

\[
= 3.415 \times 10^{-7}
\]

\[
\Delta T = 5.84 \times 10^{-4} T.
\]
At $T = 273.15 \text{ K}$ we get $\Delta T = 0.160 \text{ K}$. If we use the measured $V_D$ in the fitting equation we get

$$T = \frac{0.5586857 - 1.2053}{-0.002377} = 272.03 \text{ K}.$$ 

This is not within the expected error, so the fit appears to be marginal (at least for ice water).

### I.3.2 Calibrating with $T=m'V+b'$

If you have fit your data using the equation $T = m'V_D + b'$ the error analysis is significantly easier:

$$(\Delta T)^2 = \left( \frac{\partial T}{\partial V_D} \Delta V_D \right)^2 + \left( \frac{\partial T}{\partial b'} \Delta b' \right)^2 + \left( \frac{\partial T}{\partial m'} \Delta m' \right)^2$$

$$= (m' \Delta V_D)^2 + (\Delta b')^2 + (V_D \Delta m')^2.$$ 

In this format the fitting parameters are $m' = -420.6 \text{ K}/\text{V}$, $\sigma_{m'} = 0.17 \text{ K}/\text{V}$, $b' = 506.9 \text{ K}$, and $\sigma_{b'} = 0.12 \text{ K}$. Using the measured values at 273.15 K with $V_D = 0.5586857 \text{ V}$ and $\sigma_{V_D} = 5.424 \times 10^{-7} \text{ V}$ we find

$$\Delta T = \sqrt{(-420.6 \times 5.424 \times 10^{-7})^2 + 0.121853^2 + (0.5586857 \times 0.174364)^2}$$

$$= 0.16 \text{ K}$$

and the temperature from the measured voltage and fitting equation is

$$T = -420.6 \times 0.5586857 + 506.9$$

$$= 271.92 \text{ K}.$$ 

The estimated error in the temperature is comparable for this method, but the difference between the measured temperature and the calculated temperature is larger than the first method.
I.4 Estimating the effect of varying diode current on the measured temperature

The diode current, $I_D$ will only affect the value of the constant $m$. Note that this is using the value of $m$ from fitting the equation $V_D = m T + b$. Recall that

$$m = \frac{2 k_B}{q} \ln \left( \frac{I_D}{A} \right)$$

(ignoring the small exponential term) and that $A$ is a geometry and composition dependent constant of the diode ($q$ and $k_B$ are still constants of the universe), so we only have $I_D$ dependence

$$(\Delta m)^2 = \left( \frac{\partial m}{\partial I_D} \Delta I_D \right)^2 = \left( \frac{2 k_B}{q I_D} \Delta I_D \right)^2.$$

Using the original equation for $m$ and rearranging some we get

$$(\Delta m)^2 = \left[ \frac{m}{I_D \ln(I_D/A)} \Delta I_D \right]^2$$

$$\left( \frac{\Delta m}{m} \right)^2 = \left[ \frac{\Delta I_D}{I_D \ln(I_D/A)} \right]^2.$$

With the target value of $I_D = 100 \mu A$, the equation for $m$ and the fitting parameters we can estimate the value of $A$. Solving for $A$ we get $A = I_D \exp[-m q/(2 k_B)] = 98.3$ for the value of $m$ given above.

Using these values, we get

$$\left| \frac{\Delta m}{m} \right| = \left| \frac{\Delta I_D}{I_D \ln(I_D/A)} \right| = \frac{\Delta I_D}{1.38 \times 10^{-3}}.$$

For a change in $I_D$ of $0.5 \mu A$ we get (approximately)

$$\left| \frac{\Delta m}{m} \right| = 3.62 \times 10^{-4}$$

$$\Delta m = 8.60 \times 10^{-7}.$$
This value for $\Delta m$ is an order of magnitude smaller than the value found from the calibration of the diode. It will not significantly affect the uncertainty in the temperature. If we do include it, the uncertainty in the temperature at 273 K will increase by roughly 0.1 K. This gives us a rough measurement of the accuracy with which we must regulate the diode current.
Measuring Temperature with a Silicon Diode
Appendix J

A Constant-current Source

Frequently, such as when you want to measure temperature with a silicon diode, it is desirable to have an easily reproducible source of a constant current. Many laboratory power supplies can be used as constant current sources. The difficulties you may encounter are reproducibility or a requirement for very small currents.

The circuit in Figure J.1 results in a reproducible current and can reliably provide currents in the µA range.

The operation of this circuit is fairly straightforward. The function and selection of the individual components of the circuit are described below.

R1 and R2 A voltage divider composed of R1 and R2 provides a reference voltage, $V_{\text{ref}}$, at the non-inverting input of the op-amp.

When selecting resistors, it is usually necessary to verify the power rating and power consumption for the selected value. If we assume that R1 and R2 could both experience a voltage of 15 V (worst case), we can place limits on acceptable values. The resistors we use are rated at 1/4 W continuous power. At this power the resistor will warm significantly, which will also slightly change the value of the resistor. If we design for 1/8 W, we can reduce the amount of heating and have a more stable value.

Since $P = V^2/R$, $R_{\text{min}} = \frac{V^2_{\text{max}}}{P_{\text{max}}}$. Assuming $V_{\text{max}} = 15$ V and $P_{\text{max}} = 1/8$ W we can determine the minimum recommended values for R1 and R2.

Note: When using the TL3472 op-amp in this circuit, $V_{\text{ref}}$ must be less than 13.2 V for a 15 V supply voltage.

2N3906 transistor A bipolar transistor like the 2N3906 is a current amplifier. The emitter-collector current will be the parameter $h_{FE}$ times the emitter-base current. For the 2N3906 $h_{FE}$ is about 175 (range of 60 to 300).

The op-amp can vary the emitter-base current by changing the base voltage on the 2N3906 transistor. When the circuit is operating properly and the design current is
Figure J.1: A simple constant current source using an op-amp. The op-amp can be any general purpose op-amp. For Physics 240 we will use the TL3472. C1, the bypass capacitor on the power supply line, is usually necessary for stable operation. C1 is typically 0.1 µF. C2, C3, and C4 in combination with associated resistors provide low-pass filters for high-frequency noise control. The two vertical lines, labeled “Vcc+” and “Vcc-” extending from the center of the op-amp symbol indicate the power supply connections. The upper one is for the positive supply and the lower one for the negative supply. Because all the voltages on the op-amp are positive, it is possible to run this circuit with a unipolar power supply (the negative supply input is grounded). If you connect Vcc- to −15 V, it is necessary also to provide a bypass capacitor to ground on that line.

provided to a load, the base voltage should be about 0.6 V below the emitter voltage. The emitter-collector voltage is usually greater then about 0.3 V.

The maximum current for a 2N3906 transistor is about 100 mA. Do not try to design the circuit for larger currents.

R3 The voltage feedback circuit for the op-amp is comprised of R3, the 2N3906 transistor, and the connection from the emitter of the transistor to the inverting input. The combination of the value of R3 and $V_{ref}$ provided to the noninverting input by R1 and R2 determine the output current of the supply.

- The op-amp will act to make the voltage difference between the inverting and noninverting inputs as small as possible. Nominally, the voltage at the emitter will be equal to $V_{ref}$ if the circuit is working properly.

The output current (the current provided at the current output terminals) is then set by

$$i_{out,R3} = V_{cc+} - V_{ref}$$
\[ i_{\text{out}} = \frac{V_{\text{cc}} - V_{\text{ref}}}{R3}. \]

As with R1 and R2, you should check the power in R3. In this case \( V_{\text{max}} \approx V_{\text{cc}} - V_{\text{ref}}. \)

Since you are designing for a constant current, you could use the equation \( P = i_{\text{out}}^2 R3. \)

If the power is too large, you can put correct resistors in parallel to get the desired value of R3 with the power then divided between the resistors.

C1 Capacitor C1, known as a bypass capacitor, is connected between the power supply line (Vcc+) and ground. 0.1 \( \mu \)F is typical. This capacitor is absolutely necessary for loads that draw significant currents, especially if those currents change rapidly. For low output currents, the supply may work properly without a bypass capacitor, but it is good practice to always include bypass capacitors placed as near the power supply pins on integrated circuits as possible.

C2 C2 is in parallel with the current output. This capacitor in combination with the output impedance of the current supply provides a low-pass filter to reduce high-frequency noise in the current.

The value of this capacitor combines with the output impedance to set the cutoff frequency for the low-pass filter. The output impedance is approximately R3 in parallel with the effective impedance of your current load (such as a 1N4148 diode). Typical output impedances with a diode load are a few kΩ. Assuming a value of 3 kΩ and C2=1.0 \( \mu \)F gives a value of \( \tau = RC = 3 \text{ms} \) or 53 Hz. The shortest expected variation time in your output current should be several times greater than \( \tau. \)

When you use a similar supply circuit to provide current for measuring the resistance of a superconductor, the load impedance is very small (about 0.1 Ω). It may be necessary to use a larger capacitor to achieve adequate filtering for this supply.

C3 C3 is a 0.01 \( \mu \)F capacitor from the base of the 2N3906 to ground. This combines with the output resistance of the op-amp to create a low-pass filter for the control signal applied to the base of the transistor.

According to the data sheet for the TL3472, the output resistance is less than 20 Ω depending on the feedback circuit. With a 0.01 \( \mu \)F capacitor the cutoff frequencies would be about 800 kHz (\( \tau \) would be 0.2 μs).

Note that op-amps don’t work well with large capacitive loads connected directly to the output. Trying to further lower the cutoff frequency of the low-pass filter composed of capacitor C3 and the output resistance of the op-amp too far may result in a sufficiently large value of C3 to make the op-amp unstable.

The data sheet for the TL3472 specifies a maximum load capacitance of 10,000 pF.

C4 C4 is a 0.1 \( \mu \)F capacitor to filter power supply noise from \( V_{\text{ref}}. \) If you set R1 = R2 = 2.2 kΩ, the output impedance of the divider circuit is 1.1 kΩ (R1 and R2 in parallel). This impedance combined with C4 gives \( \tau = 0.1 \text{ms} \) and \( f = 1.4 \text{kHz}. \) A larger capacitance or larger values of R1 and R2 may be desirable to lower the cutoff frequency.

“C5” If you operate this circuit with a bipolar power supply (i.e., 15 V attached to Vcc+ and −15 V attached to Vcc−), you will also have to include a bypass capacitor between Vcc- and ground. (This would be labeled C5 if it were present in the circuit.)
Current Output  The load for the current supply attaches to the current output terminals. The lower terminal is connected to ground – the current will flow out of the top terminal and return to ground through the lower terminal.

Optional Voltage Monitor  The circuit diagram includes an optional item labeled “Voltage Monitor”. For some applications, this would not be included. Note that this output is connected in parallel with the current output to provide the voltage across the load element.

For our temperature measurements, this should be included to provide a connection for monitoring the voltage across the diode to determine the temperature of the diode. Including this output for the temperature measurement diode will allow you to have a single set of clip leads attached to the diode. Having multiple clips on each lead of the diode will usually result in some frustration with clips coming off the leads.

Note: Experience with this circuit has shown that you really want all four capacitors (C1, C2, C3, and C4) to avoid noisy or erratic operation.

J.1 Getting your circuit to work

If your constant current source doesn’t work after you finish assembling it, you probably want to consult the electronics section of Appendix K, “The Art of Debugging.” Two common problems with the constant current sources are solder bridges between pins and cold solder joints. By methodically going through your circuit you should be able to find the errors.
Appendix K

The Art of Debugging

One of the most important skills you will acquire is debugging. Although it can be frustrating, debugging is one of the most intellectually rich, challenging, and interesting parts of [programming or circuit design or experiment design].

In some ways, debugging is like detective work. You are confronted with clues, and you have to infer the processes and events that led to the results you see.

Debugging is also like an experimental science. Once you have an idea what is going wrong, you modify your [program or circuit or experiment] and try again. If your hypothesis was correct, then you can predict the result of the modification, and you take a step closer to a working [program or circuit or experiment]. If your hypothesis was wrong, you have to come up with a new one. As Sherlock Holmes pointed out, “When you have eliminated the impossible, whatever remains, however improbable, must be the truth.” (A. Conan Doyle, The Sign of Four). (quoted with slight modification from “Think Python, 2nd Edition,” Allen B. Downey, pg. 30, O’Reilly Media, Inc., Sebastopol, CA, 2016. A free PDF version is available at http://www.thinkpython2.com/thinkpython2.pdf)

Although these comments come from a computer programming text, they apply to any debugging process as denoted by the addition of “[program or circuit or experiment]” whenever the above paragraphs refer to the object being debugged. You may be debugging an electronic circuit, a computer code, a homework problem, or a complicated experimental setup. The fundamental processes and skills are very similar.

If a [program or circuit or experiment] you are building or testing doesn’t work the way you think it should, you need to go methodically through the [program or circuit or experiment] to locate the error(s). The error(s) could be in the design of the [program or circuit or experiment], how you [coded the program or wired up the circuit or assembled the experiment], or faulty components. You should follow the following steps as you approach
If you would rather randomly change things to see if you can make it work, you will find that the probability of making the proper corrective change is fairly small (vanishingly small if you have a complex [program or circuit or experiment]).

Some of these steps may not apply to all of the choices (program, circuit, or experiment). Only skip the step if it obviously doesn’t apply.

### K.1 Debugging electronics

1. Safety first! In classes, we usually don’t deal with high voltages or high currents, but you should be aware of possible dangers in working with electrical devices. Also, think about whether you might damage any components as you are working on the circuit. You should always power the circuit off when swapping out components.

2. Think analytically about the circuit. Should your design work? What do you expect to measure at different parts of the circuit if it is working properly?

3. Check that your measurement device is set to read what you expect. For example:
   
   (a) Multimeter settings (voltage, current, resistance, etc.) are correct AND the meter is connected correctly (i.e., parallel for voltmeter, series for ammeter).
   
   (b) Oscilloscope settings (AC/DC coupling, triggering, active inputs, vertical gain, time base, trace intensity, etc.) are correct.
   
   (c) Verify that the battery and fuses on portable devices like multimeters are good.

4. Check voltages to identify the problem(s).
   
   (a) Check the voltages at the power supply with and without your circuit attached.

   If the voltages are incorrect without your circuit attached, you need a new power supply. If the voltages are incorrect with your circuit attached, you have a problem with your circuit – fix it before you reconnect your supply.

   (b) Check whether you are getting the expected voltages or currents at various places in the circuit. See item 2 above – you should have already thought about the circuit and what you expect to see at strategic points.

   It is best to check voltages on the component leads so you also detect poor connections.

5. Check the wires (including scope and multimeter leads). Wires can easily become shorted or broken. Sometimes this will result in intermittent problems.

6. Verify that the wires connect the things that you think should be connected and don’t connect things that shouldn’t be connected (this includes power supply buses on breadboards or circuit boards).
7. Check the board for bad connections. Breadboards can develop shorts between neighboring rows. The connectors can also be damaged so that components inserted into the board don’t connect reliably.

Circuit boards may have damaged copper traces, or you may have solder bridges. Cold solder joints will often result in intermittent problems until they just fail altogether.

8. Test the components.

**Note:** Don’t just randomly replace components. Sometimes the circuit itself is causing components to fail and just replacing a part will cause the new one also to fail.

(a) Some resistors have not learned the color codes (especially the tolerance portion). Verify the resistance with an ohmmeter *with the power off*. It is also best to at least disconnect one lead on the resistor so you don’t measure the resistance of everything else in the circuit at the same time.

If there is a discrepancy between the value measured with the ohmmeter and the color code, believe the ohmmeter.

(b) Capacitors should be removed from the circuit and discharged (*i.e.*, short the leads together) before they are measured.

(c) Check diodes, LEDs, transistors, etc. Most multimeters can be used to test these components. If you are not sure how to test them, you should ask for help.

9. Ask a classmate or TA to have a look at what you might be missing.

10. Invoke the “authority effect.” Circuits sometimes behave better if they are aware that you know what you are doing.

   Forcefully reciting Ohm’s Law may be effective. Be sure you have it right – if you get it wrong, the circuit knows you have no authority, and your best bet is to abandon all hope.

11. As a last resort, a gentle blow to an offending piece of equipment may help. Generally, a three-foot drop onto a concrete floor is adequate. *This technique is best left to the professionals.*

   If you feel this is necessary, indicate on the offending piece of equipment the problem as nearly as you can determine. This will assist the professional in determining the proper positioning for the gentle blow.

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**K.2 Debugging software**

The process of debugging software is very similar to that for electronics. The required steps may also differ depending on the programming language being used.

1. Think analytically about the program. Should your design work? What do you expect to happen at different points of the program if it is working properly?
2. Can you design a “toy problem” for which you know exactly what all the outputs should be? Does it work correctly?  
   Be very careful with testing. In many cases, it is not possible to test all possible conditions, and you may miss the one that matters.

3. Choose an appropriate “measurement” technique or tool. You need to evaluate what is happening (e.g., the values of appropriate variables) identified in the previous step. That may mean using a debugger, writing out some values, or inserting a graph in the code.

4. In step 1, you identified what you expect to have happen at different points. Is it happening?

5. Are the input values correct? If you are reading data from a file, is it formatted correctly? Are you reading it correctly?

6. Are variables that are supposed to be local actually local? Are variables that are supposed to be global actually global? Are global variables consistently named?

7. If you are not using a strongly-typed language, do you have any mistyped variable names?

8. If you are using LabVIEW, is your data flow between modules correct? Do you need to do something to control module execution that is not properly handled by the data flow?

9. Are your argument lists for functions or submodules correct?

10. Are you correctly using functions or submodules? Did you check the documentation?

11. Check low-level functions or submodules individually to ensure they are working properly. Work your way up through the program from there.

12. Ask a classmate or TA to have a look at what you might be missing.

13. Don’t bother with the “authority effect.” The computer already knows that we are all amateurs at telling it what we want done.

14. As a last resort, shutdown and restart the computer. Don’t just reboot. You want the power off to be sure there is nothing hiding in the RAM. It is best to avoid the use of a hammer on the computer.

You still need to be methodical about the process. Random changes will result in premature gray hair and nervous tics.

K.3 Debugging an experiment

It is not possible to write a generic process for debugging a complex experiment. There are too many parts, and the interactions are too complex to generalize. However, carefully thinking through the design, connections, hardware interactions, software interactions, etc. may lead you to an idea of where to start checking. Isolating the problem to a single subsystem or instrument will greatly simplify the process.

This is why you are studying physics – to be able to solve really hard problems!
K.4 A few things to remember

The following list of the six stages of debugging has been observed on the back of a t-shirt. (I don’t know where the t-shirt came from so I can’t properly attribute it – it was observed on a student wandering the halls of the ESC. A Google search on the title of the list reveals at least 20 vendors selling t-shirts with this list as well as several mugs, a couple of backpacks, a one-piece for an infant, and the cover on a spiral notebook.)

You really should remember these stages as you go through any debugging process.

Six Stages of Debugging

1. That can’t happen.
2. That doesn’t happen on my [machine or circuit or program or experiment].
3. That shouldn’t happen.
4. Why does that happen?
5. Oh, I see.
6. How did that ever work?
Appendix L

Calibrating a Silicon Diode for Temperature Measurement

The main disadvantage of using common silicon diodes for temperature measurement is that they need to be individually calibrated as each one has slightly different properties. If the operating parameters are chosen such that the response is nearly linear calibration is required at only a few points.

To use the diode as a temperature sensor, you will need a stable constant current source (see Appendix J, “Building a Constant Current Source”). According to Appendix I, you will want a source that provides about 100 µA (typically in the range of 90 to 110 µA is adequate). This current is chosen to minimize heating of the diode (it will deposit about 100 µW in the diode), to give an adequate range where the response is linear, and to give a reasonable output voltage. With this current, the voltage across the diode in boiling liquid nitrogen will be slightly above 1 V.

You can now perform the calibration through the following steps:

1. Connect the constant current source so that the entire output current flows through the diode. **NOTE:** Because the characteristics of electronic components vary with temperature you should allow the current to flow through the diode for several minutes to stabilize the temperature of both the diode and the power supply. Then measure the current to determine the output of your supply. Hint: *this is probably a value you will want to record in your notebook!*

2. Connect a voltmeter so that it measures the voltage across the diode. It is best to connect to the “Voltage Monitor” output on your constant current supply to avoid lots of clips on the diode leads.

   It should be around 0.5 V at room temperature. If the voltage is considerably higher than this, you probably have the diode reversed. Remember that the lead to ground on your supply, usually the black clip on the coax cable, should be connected to the cathode of the diode – the direction the current will flow out of the diode.
3. Replace the voltmeter with one of the computer analog inputs so the computer records the voltage across the diode. Because the tan power supplies connect the common output terminal to the chassis, you should have the input on the USB-6221-BNC set to the “GS” position.

4. Determine the temperature dependence of the voltage across the diode using LabVIEW when the diode is in boiling liquid nitrogen, ice water, and boiling water. Simultaneously measure the temperature of the liquid in each case with the digital thermometer.

**NOTE:** When you place the diode in water you need to protect it from the water - the resistance of the water is low enough that you may lose several µA through the water which will result in an incorrect calibration.

Refer to the sections of **Appendix C**, “Uncertainty, Errors, and Noise,” on uncertainties and averaging before you set up your LabVIEW VI to make your measurements.

5. Note that any reference to temperature in the equations in **Appendix I**, for the voltage across the diode are accompanied by a reference to $k_B$, Boltzmann’s constant. This should be taken as a **very strong hint** that the temperature should be given in Kelvins.

6. From this data determine the calibration constants $m$ and $b$ by fitting a straight line to your data. You can use any software that provides fitting capabilities – but it is strongly recommended that you do not use Excel because it won’t give you any possibility of recovering the uncertainties in the fitting parameters.

### L.1 Diode calibration: analysis questions and requests

1. How much does the constant $b$ differ from $E_g / q$? $E_g$ is the band-gap energy of the silicon used in the diode. It is approximately 1.19 eV. $q$ is the charge on the electron. The constant $b$ is from the model equation $V = mT + b$ with $T$ in Kelvins. (Refer to section I.1 in **Appendix I**, “Measuring Temperature with a Silicon Diode,” for the derivation of this equation.) If your equation is in a different form or uses different units, you will have to rearrange your equation into this form to determine $b$ from your fitting constants.

2. How far off is the calibrated diode temperature measurement at each of the three points? Give your response in degrees. This is found by looking at the temperature predicted by your calibration equation from the measured voltages and comparing them to the corresponding measured temperatures.

3. Is this error consistent with the estimated uncertainty of your calibration constants? (consult the temperature uncertainty section of “Measuring Temperature with a Silicon Diode” (**Appendix I**). You may also want to look at the Mathematica notebook **SuperconductorParametersAndUncertainty.nb** in Content ⇒ Superconductivity Measurements Lab on Learning Suite or at [https://www.physics.byu.edu/faculty/petersonb/Phys240/SuperconductorParametersAndUncertainty.nb](https://www.physics.byu.edu/faculty/petersonb/Phys240/SuperconductorParametersAndUncertainty.nb) for
help in finding the uncertainty in your temperature measurements (look at the second section “Calculate the uncertainty in a temperature determined from a diode”; you will need to enter the appropriate values of the parameters and data if you use this notebook).

4. How would you improve your calibration?

5. Include a plot of your calibration data and fit – including the calibration constants – in your notebook and in your report.
Appendix M

Fitting data with Logger Pro

1. If you are going to view and analyze data from a data file you need to
   
   (a) Generate a delimited text file (from LabVIEW, a text editor, Excel, or some other spreadsheet application) with the $x$ values in the first column and the $y$ values in the second column. You can also include the uncertainties in the $y$ values in the third column. 
   
   Note: the ordering of the columns is not critical but the instructions below will have to be modified according to the way you order the columns in your file. 
   
   The default tab delimiter in LabVIEW is a reasonable choice, but a comma delimiter will also work. If you save the data from Excel be sure to write it as either a Text (tab delimited) or a CSV (comma delimited) file. 
   
   (b) Start Logger Pro. 
   
   (c) Select File along the top bar, then Open, then find your data file and open it. You will likely need to change the Files of type entry to All Files. Importing a delimited file as a text file is usually successful even though Logger Pro will say that it is an incompatible file format. 

2. If you are using “generate” values you need to
   
   (a) Select Data along the top bar, then New Manual Column for a column that will contain entered values. You should give the column a meaningful name, units, and short name (short nm) since these are used in generating labels on the graphs. 
   
   The most useful part of this particular option is that you can automatically generate a column of values. 
   
   (b) If you need a column that is calculated from another column, select Data and New Calculated Column where you can specify a column name, the units, and a short name as well. But, most importantly, you specify the formula to calculate the values in the column. Note that you can select the desired column name from the drop-down box at the bottom to simplify writing the formula.
3. If your values for the $x$-axis are not in ascending order you need to select Data and Sort data set, pick the correct column to sort, and click on OK.

4. Name the data columns to get nice labels on your axes by right clicking on the data region, select Column Options and pick the desired data column. If you put the correct description for the values represented on that axis under Name (such as “Output”) and the units for those numbers under Units (such as “V”) you will get a label that is properly formatted (“Output (V”)). You can also give a more descriptive short name (such as “Out”) that will be used in the fitting equation.

Note: If you find that you need the Greek symbols in your labels or units, you can get them from the drop-down box.

5. If your file included a column of uncertainties in the $y$ values, you can have error bars included on your graphs by right clicking on the data region, selecting Column Options, and picking the column that includes your $y$ values. Then click on the Options tab at the top of the box, click on Error Bar Calculations and Use Column. The select the column containing the uncertainties in the drop-down box.

At this point, you can either just create a graph of the values or you can fit a model equation to those values.

- To create a graph of the values:
  1. Right click on the graph area and select Graph Properties. Here you can select which columns to use for the different axes, whether they are linear or logarithmic, the axis limits, and the axis labels if you don’t like the defaults.

- To fit a model to the values:
  1. Click on Analyze, Curve Fit... and select the desired equation such as Linear, Natural Exponent, or several other options. If the predefined functions don’t work for your model equation, you can choose Define Function where you can define your own equation. Click on Try Fit to see how well the fit worked.

Sometimes it is necessary to specify starting values by hand to get a good fit (this is evidenced by the line indicating the fit not properly passing through the data points). Fitting a nonlinear equation like an exponential to data can sometimes get lost unless you give it an adequately accurate starting point. You can manually enter values in the boxes for the parameters to adjust the fit as necessary. When you do so, it will switch to Manual fitting instead of Automatic. Adjust the parameters until the fit line is “reasonably close” to the data points. Then click on Automatic and Try Fit. Hopefully, it will now provide a fit that passes through (or at least near) the data points.

Once the fit looks good click on OK.

2. Right-click on the fit information box on the graph and select ... Fit Options, select the Show Standard Error and Show On Graph options. Also set the Displayed Precision to at least 4 significant figures (not 4 decimal places).
3. You will probably want to move the fit information box to a convenient place on the graph. If you are going to put the graph in a document, you probably want to remove the fit information box and put that information in the figure caption, the body of the text, or both instead.

- In both cases you need to complete most of the following instructions to make a usable graph.

1. You may want to right-click on the graph, select Graph Options, and select Point Symbols if you only have a few data points and wish to highlight them.
2. If you wish you can right click on the data area and select Data Set Options to change the name of the dataset. This is the name on the top line of the fit information box.
3. Do not put a title on the graph if you are going to put it into a document – that information will be in the figure caption. However, you may want to have a title on the graph that you put in your notebook to identify it.
4. Once you have the graph you can print it for your notebook, copy it to paste it into a document, or print it to a file. To print it to a file select File, Page Setup, then select either “Adobe PDF” or “Metafile to EPS Converter” (they should both be available in C460 ESC), select OK, select File, Print Graph and you will eventually be asked for an output file name. The file will not necessarily be put in the same folder as your original data file. The eps or pdf file can be included in your document with most document editing packages.
5. If you want to scale the text on your graphs (this is necessary if you want text large enough to see when the graph is included in a document) you can do this by changing the size of the graph. Logger Pro keeps the text the same size (the default is 12-point) as you change the size of the graph. When you print the graph or copy it to another document, it will keep the same ratio of text size to overall graph size. Reducing the size of the graph on the screen will result in larger text in the final printed figure.

For example, to have 8-point text (this is the minimum text size to be considered legible in a publication) on a graph with a final width of $3\frac{3}{8}$ inches (a single column in a printed journal) you would want to reduce the graph on the screen to a width of $3\frac{3}{8} \times 12/8$ inches.
Fitting data with Logger Pro
Appendix N

Fitting data with Mathematica

1. Generate a delimited text file (from LabVIEW, a text editor, Excel, or a similar spreadsheet application) with the \( x \) values (time) in the first column and the \( y \) values (temperature) in the second column. If you have uncertainties in the \( y \) values, they can be placed in the third column. The default tab delimiter in LabVIEW is the best choice. If you save files from Excel be sure to select the output as a “.txt” file. This will write a tab-delimited file.

The statement regarding delimiters is true for the `Import` and `ReadList` commands. Your mileage will vary with other file input commands. You can make the `Import` command work for comma-delimited (.csv) files if you enter “CSV” as the second argument.

2. Download the Mathematica notebook NLSQfit240.nb from https://www.physics.byu.edu/faculty/petersonb/Phys240/NLSQfit240.nb. The notebook must be in the same folder as the data file generated in step 1.

Mathematica provides a very capable nonlinear fitting routine (NonLinearModelFit). There are simpler routines available (Fit, FindFit, LinearModelFit, etc.) but NonLinearModelFit has some extra features in flexibility and capabilities. For instance, it will accept weights to allow for including the effects of uncertainties in the data. And it will provide considerable information on the quality of the fit and the uncertainties in the final fitting parameters.

Due to the complexity of NonLinearModelFit, the notebook is provided so that you don’t have to deal with getting everything right for it while still benefiting from the added capabilities.

3. Open Mathematica.

4. Click on File and Open and open NLSQfit240.nb – be sure it is the one located in the folder with the data file.

5. Enter the name of your data file between the double quotes after the variable “datafilename” in the Input the experimental data section.

In this section, there are also three variables, \( xcol \), \( ycol \), and \( errorcol \), that tell the notebook how to interpret the file. These tell the script which column in your data
file correspond to the $x$ values, the $y$ values, and the uncertainty or errors in the $y$ values. If you do not wish to include the uncertainties set `errorcol` to zero (0).

6. In the **Define the theoretical model curve and plot the initial guess** section you will need to define the model equation in the variable “theory.” The independent variable is always referred to in this equation as $x$ (assumed to be the first column in your data file). You have to use *Mathematica* syntax for this equation. For instance an exponential curve $ae^{bx}$ would be represented as “a*Exp[b*x]” in this equation.

**Note:** The fitting routine used in NLSQfit240.nb requires that there be more data points available than the number of parameters in the equation to calculate the uncertainty in the fitting parameters. This means that if you want a linear fit ($a + bx$) with uncertainties, you will need at least three data points. It will still give you a fit to the points but some brown text will explain that you didn’t have enough points to determine the uncertainty in the fitting parameters. **However,** if you only give the notebook two data points to fit, it will assume you want a linear fit and will provide that fit in the form $fit = a + bx$ and will include uncertainties in the parameters if you have provided uncertainties in the $y$ values.

7. Define the initial guess for your parameters in the “params” variable. There must be an entry for each parameter in the equation defined in “theory.” With a nonlinear fit, it is usually wise to make as good a guess as you can so the fit will converge nicely.

8. There are also variables

- `logx` to determine if the $x$ axis should be logarithmic (“True”) or linear (“False”).
  [Safe value for Physics 240 is “False”]
- `logy` to determine if the $y$ axis should be logarithmic (“True”) or linear (“False”).
  [Safe value for Physics 240 is “False”]
- `showerror` to specify if error bars are to be shown if uncertainties in the $y$ values are provided.
- `Col3AreErrors` determines how the values provided in column 3, if present, are interpreted. If this variable is “True” it is assumed that they are errors or uncertainties in the $y$ values ($\sigma_y$), they are converted to a fitting weight ($weight = 1/(\sigma_y^2)$), and the fitting routine is told to treat these as variances. If it is “False” they are assumed to be actual fitting weights. A large weight for a given point will put more emphasis on that particular point than a point with a small weight. [Safe value for Physics 240 is “True”].
  If you have set `errorcol` equal to zero in the initial load, you need to set this to “False.”
- `XLabel` is the text used to label the $x$ axis on the plot.
  Note that an appropriate label will include both what is being represented by the values on the axis and the units for the values when appropriate.
- `YLabel` is the text used to label the $y$ axis on the plot.

9. In the section **Perform Non-Linear Least Squares fit and plot it together with the data**, there are two variables:

- `ShowEquation` which governs whether the equation for the fit is shown on the top of the plot as a title. This is useful for plots to be included in your lab notebook.
However, if you are creating a plot for publication it is usually best to leave this off (set to “False”) and give the equation for the fit in the figure caption or the body of the text.

FontPoints specifies the font size to use on the plot labels. The font size doesn’t change as you scale the size of a plot in Mathematica. The font size is important when you want to include a plot in a published document. For instance, most journals will use a finished plot width of $3\frac{3}{8}$ inches which is the width of a single column on a double-column page. All text on a plot (or any other figure) must be at least an 8-point font at the final plot size to be legible. If you use a 12-point font on your plot and want a $3\frac{3}{8}$ inch final width, you should make your plot on the screen $3\frac{3}{8} \times 12/8$ inches so that the 12-point text will scale to 8 points when you reduce the plot to the final width.

10. Click on Evaluation and Evaluate Notebook to give it a try. Answer “yes” if Mathematica asks if it should run the initialization cells.

11. If your initial guess isn’t adequate you can update it and run just the Define the theoretical model... section by clicking somewhere in that section and pressing either Shift-Enter or the Enter key on the keypad. Check the graph to see if your guess is any better and keep fiddling with the initial values until the solid line is vaguely similar to your data.

12. If you have changed your initial values after first running the notebook, you will need to execute the Perform Non-Linear Least Squares fit and plot it together with the data section by pressing either Shift-Enter or the Enter key on the keypad. Keep iterating these last two steps until you get a reasonable fit.

13. When the figure is the way you want (including changing the size to something more reasonable) you can right-click on the graph and select either Print Graphic... or Save Graphic As.... Printing the graphic will bring up a dialog to select the printer, etc. Save Graphic will bring up a dialog box to allow you to specify the name of the output file and the folder in which it should be placed. If you click on the Files of Type box near the bottom you can select the format for your file including jpeg, bmp, tiff, eps, png, pdf, or others. You should pick a format appropriate for your text processing software if it will be included in a document.

Be sure to properly size the plot before printing or saving.

14. Above the graph is the information on the fitting parameters and uncertainties in those parameters (“Standard Error” is the standard deviation). There is a section for 63% confidence ($\pm \sigma$) and 95% confidence ($\pm 2\sigma$) intervals. To the right, there is a square bracket enclosing those two sections. If you right-click on the bracket, you will have a drop-down box with many choices including Print Selection... and Save Selection As... just like those for the plot described above. This will allow you to have a nice copy for your notebook.

If you were performing a linear fit to two points, you would just get a section with three lines of text giving the parameters and standard error for the two parameters in the fit.
Fitting data with Mathematica
Appendix O

Fitting data with MATLAB

1. Generate a delimited text file (from LabVIEW, a text editor, Excel, or another spreadsheet application) with the $x$ values (time) in the first column and the $y$ values (temperature) in the second column. You can also include the uncertainties in the $y$ values in the third column. The default tab delimiter in LabVIEW is a reasonable choice. A comma delimiter will also work.

   - You don’t necessarily have to have the columns organized as indicated but you will have to modify how the file is loaded either in FitExperiment.m or the manual commands.

2. If you wish to use the script FitExperiment.m, you can download it from https://www.physics.byu.edu/faculty/petersonb/Phys240/FitExperiment.m. It is most convenient if you put it in the same folder as your data file(s).

3. Open MATLAB.

4. Use the browse button (...) in the upper right-hand corner to change to the folder where your data are stored.

5. If you downloaded FitExperiment.m:

   (a) You should be able just to type “FitExperiment” at the “>>” prompt to run the script. It will prompt you for the name of your data file after which it will load the data and start cftool.

       - If your data aren’t organized with the $x$ data in column 1, $y$ in column 2, and $dy$ (if present) in column 3, you will have to edit lines 10-24 and set “xcol,” “ycol,” or “errorcol” to the correct values. It is also possible to use a subset by selecting a range of $x$ values using “xmin” and “xmax.”

   (b) In cftool, you will need to select the type of fit in the upper-right panel. It usually defaults to “Polynomial” but there are several choices including “Custom Equation” if there isn’t one of the predefined fits that is appropriate for your equation. A fit will be attempted as soon as you select an equation.
If the fit isn’t correct or if you see the word “NaN” (not a number) in any of the entries in the “Results” box you may need to help find a starting point or place limits on the parameters. This can be done by selecting the Fit Options... box. Try entering different values in the StartPoint column until the fit looks right (this is trial-and-error but you can get some guidance from the graph if you look carefully at it – for example what is the value at long times for an exponential or at t=0).

(c) Once you are satisfied with the fit you should save the results by clicking on Fit on the top menu bar and select Save to Workspace.... You should keep the default MATLAB object names (“fittedmodel,” “goodness,” and “output”) so the script knows where to find the results.

(d) Exit from the Curve Fitting Tool by clicking File and Close Curve Fitting. After you exit from the Curve Fitting Tool you need to press any key to continue with the script. Be sure you have selected the “Command Window” if MATLAB doesn’t appear to be responding.

(e) The script will now generate a plot of your data and the fit as well as printing the results of the fit on the screen. MATLAB will give the results in terms of a 95% confidence level. That means that you will take the difference in the given range and divide by 4 to get the standard deviation if that is desired.

The plot that is generated will be 3.375 inches wide with all the text in an 8 point font. This is what is expected for publication in most journals with the plot the width of one column on a double-column page. There are entries right below the call to “cftool” that you can uncomment to create a plot that is 5.063 inches wide with the text in a 12 point font. This gives a plot that looks nicer in your notebook when printed but will have the correct font size when it is reduced to 3.375 inches wide for inclusion in a formal paper.

(f) If you look at the commands below “cftool” in the script you will see several commands including “legend,” “xlabel,” “ylabel,” and “title.” You can either edit these commands before running the script or reissue the desired commands to change the appearance of your plot. Remember that you should always properly label the axes on your graphs including what is represented by the numbers as well as giving the units for those numbers. For instance, you would use “Temperature (K)” for an axis representing the temperature in Kelvins.

If you are going to put the figure in a document you (usually) should NOT put a title on the graph. The information you would normally put in a title should be included in the (usually required) caption on the figure. A title would be appropriate for a graph that you are going to put in your lab notebook.

(g) You can print the figure by clicking on File and Print ... in the corner of the figure window. If you wish to save the figure in a file for inclusion in a document you should select File and Save As..., which will bring up a window to select a file name and folder for the file. Note that you can select several different file formats from the Files of Type box along the bottom of the window. Common formats include eps, pdf, jpg, tif, and png. You should choose a format compatible with the text processing software you will use for your documents.

(h) If you would like a nice copy of your final parameters you can print the screen
Fitting data with MATLAB

(File and Print... from the menu in the upper left corner of the main MATLAB window – you should have the “Command Window” selected before you select File). FitExperiment issues the “clc” command when it runs so you will have a fairly clean screen to print. If you want the values in a file you will need to use copy and paste to put them in your favorite text editor.

If you wish to enter the commands yourself, you enter the following. Text preceded by the symbols “>>” (the MATLAB prompt) indicate commands you should enter at the command prompt (don’t enter the “>>” – just the text that follows it). Any text not preceded by “>>” is an explanation and should not be entered in MATLAB. The sequence:

(a) >> data=load(‘filename’);
Replace “filename” with the name of your file. It must be enclosed in single quotes. Be sure to put the semicolon (;) at the end of the line, so it won’t print all your data on the screen.

(b) >> xvalues=data(:,1);
This gets the first column in the variable xvalues. If the desired values are not in the first column, replace the “1” with whatever column number those values are in.

For this command, as well as the following two commands, it is possible to extract just a subset of your data by using the command
>> xvalues=data(minind:maxind,1);
where minind and maxind are the minimum and maximum indices into the array of the data you wish to use in the fit. The same values of minind and maxind have to be used on all three of these commands.

(c) >> yvalues=data(:,2);
This gets the second column in the variable yvalues.

(d) If you have uncertainties in the third column give the command
>> weights=1.0./data(:,3).^2;
This properly defines the weights used in the fitting process from the uncertainties.

(e) >> cftool(xvalue,yvalues,[],[],weights);
This starts the interactive curve fitting tool. Replace “weights” with “[ ]” if you don’t have the uncertainties for your y values.

(f) In cftool, you will need to select the type of fit in the upper-right panel. It usually defaults to “Polynomial” but there are several choices including “Custom Equation” if there isn’t one of the predefined fits that is appropriate for your equation. A fit will be attempted as soon as you select an equation.

If the fit isn’t correct or if you see the word “NaN” (not a number) in any of the entries in the “Results” box you may need to help find a starting point or place limits on the parameters. This can be done by selecting the Fit Options... box. Try entering different values in the StartPoint column until the fit looks right (this is sort of trial-and-error but you can get some guidance from the graph if you look carefully at it – for example what is the value at long times for an exponential or at t=0).
Once you are satisfied with the fit you should save the results by clicking on **Fit** on the top menu bar and select **Save to Workspace**. You should keep the default **MATLAB** object names ("fittedmodel," "goodness," and "output") so the following instructions will work correctly.

Exit from the Curve Fitting Tool by clicking **File** and **Close Curve Fitting**. After you exit from the Curve Fitting Tool, you need to press any key to continue with the script. Be sure you have selected the “Command Window” if **MATLAB** doesn’t appear to be responding.

- **(g)** Once you are satisfied with the fit you should save the results by clicking on **Fit** on the top menu bar and select **Save to Workspace**. You should keep the default **MATLAB** object names ("fittedmodel," "goodness," and "output") so the following instructions will work correctly.
- **(h)** Exit from the Curve Fitting Tool by clicking **File** and **Close Curve Fitting**. After you exit from the Curve Fitting Tool, you need to press any key to continue with the script. Be sure you have selected the “Command Window” if **MATLAB** doesn’t appear to be responding.
- **(i)** >> plot(fittedmodel,xvalues,yvalues);
  This will generate a plot with your data values overlaid on the model fit.
- **(j)** >> legend('description of data','description of fit','Location','NorthEast');
  This will put up a legend for the plot. You should replace the two “descriptions” with appropriate descriptions of the items being plotted. The location is given by a compass point: “North” for the top of the graph, “NorthEast” for the upper-right corner, “SouthWest” for the lower-left corner, etc.
- **(k)** >> xlabel('Label for x axis (units)');
  Properly labels the $x$-axis. The axes of your graph should always be properly labeled with the item represented by the numbers on that axis as well as the units for those numbers.
- **(l)** >> ylabel('Label for y axis (units)');
  Properly labels the $y$ axis.
- **(m)** >> title('Plot title');
  Provides a title across the top of the graph. You should (usually) NOT title a graph if you are going to put it in a document. The information normally put in a title will be put in the (usually required) caption for the figure.
- **(n)** >> fittedmodel
  *Don’t put a semicolon on this line.* It will print on the screen the results of the fit giving the best fit parameters and the 95% confidence range in those parameters. That means you will take the difference in the given range and divide by 4 to get the standard deviation if that is desired.
- **(o)** >> goodness
  *Again, leave the semicolon off.* This will give parameters that indicate the goodness of the fit.
- **(p)** You can print the figure by clicking on **File** and **Print** in the corner of the **figure** window. If you wish to save the figure in a file for inclusion in a document you should select **File** and **Save As**., which will bring up a window to select a file name and folder for the file. Note that you can select several different file formats from the **Files of Type** box along the bottom of the window. Common formats include eps, pdf, jpeg, tiff, and png. You should choose a format compatible with the text processing software you will use for your documents.

At some point, you will need to adjust the dimensions and font size on your figures. The standard is generally that the text on the figure must be in at least 8-point font when printed to be legible. This means that you need to adjust the font size and figure dimensions so that you get the desired results when you put the figure in a document.
The APS recommends that the font size be 8-point when the figure is reduced to a width of either $3\frac{3}{8}$ inches or 8.5 cm, which is the width of a single column figure on a double column printed page.

(q) If you would like a nice copy of your final parameters you can just print the screen (File and Print... from the menu in the upper left corner of the main MATLAB window – you should have the “Command Window” selected before you select File). If you type the command “clc” before entering the last two commands (fittedmodel and goodness) you will have a fairly clean screen to print. If you want the values in a file you will need to use copy and paste to put them in your favorite text editor.
Fitting data with Python

1. Generate a delimited text file (from LabVIEW, a text editor, Excel, or another spreadsheet application) with the $x$ values (time) in the first column and the $y$ values (temperature) in the second column. You can also include the uncertainties in the $y$ values in the third column. The default delimiter in LabVIEW is a tab character. Using the default will work, but you may find that changing the delimiter to the comma character will work better.

   - A typical file will contain the $x$ values in the first column and the $y$ values in the second column. You can also include the uncertainties in the $y$ values in a third column.
   - You don’t necessarily have to have the columns organized as indicated but you will have to modify how the data array is accessed to match the column ordering.
   - The default delimiter in LabVIEW is a tab character. Using the default will work, but you may find that changing the delimiter to the comma character which will work better.

2. The best choice to read a text data file (considered the fastest choice by many) is to use the csv file reader from the pandas package. It is also best to put the data into a numpy array for easier access.

   For example:
   ```python
   import pandas as pd
   import numpy as np
   data = np.array(pd.read_csv("your-data-file-name"), sep='\t')
   xdata = data[:, 0]
   ydata = data[:, 1]
   dydata = data[:, 2]
   ```

   The “sep” argument in pd.read_csv specified the column separator. The default value is the comma character (sep=’,’). A tab-delimited file requires the separator indicated above (sep=’\t’).
The second index indicates the column in the data file containing the specified data. This may have to be modified to match the column ordering in your data file.

3. You will need to define a function that contains the model equation you wish to fit to your data.

```python
def model(x, a, b, c):
    return a + b * np.func(x * c)
```

where `np.func` would be any desired linear or nonlinear function. You can use any equation that is appropriate for your data.

4. One of the best choices for fitting your data is the `curve_fit` module in the `scipy.optimize` package.

```python
import scipy.optimize as op
p0 = (a0, b0, c0)
```

```python
popt, pcov = op.curve_fit(model, xdata, ydata, p0)
```

where `a0`, `b0`, and `c0` are the initial values of `a`, `b`, and `c` in the model equation.

5. If the model equation is nonlinear, it is usually important that you properly choose initial values to be in the neighborhood of the final values in some sense. A poor choice of initial values can result in a completely bogus fit to your data.

You can check how close your initial guess is with the commands

```python
from matplotlib import pyplot as plt
plt.plot(xdata, model(xdata, a0, b0, c0), 'r')
plt.plot(xdata, ydata, 'b')
plt.show()
```

6. `popt` is an array containing the optimized parameters for the curve. The best fit parameters are in the `popt` array in the same order as they were given in the definition of `p0` (the initial values) and in the definition of the model function.

`pcov` is the covariance matrix for the fit. The standard deviation in the individual parameters are given by the square root of the entries on the diagonal of this matrix.

7. If you want to include the effect of the errors in your `y` values, you would change the fitting command to

```python
p0 = (a0, b0, c0)
popt, pcov = op.curve_fit(model, xdata, ydata, p0, sigma=dydata)
```

8. A graph without any labels is of no value. You should add axis labels (`plt.xlabel` and `plt.ylabel`). If the graph is going in a notebook, it may be good to add a title with the `plt.title` function. Do not add a title if you are going to use the graph in a publication or paper.

`plt.xlabel` and `plt.ylabel` can include a “size=n” parameters to set the text size. You can also give the parameter “fontsize=n” in `set_xsticklabels` or `set_yticklabels`.

You can label the lines using a “label=name” entry in the `plt.plot` functions. And a legend can be added with the `plt.legend` function.

9. Don’t forget to get a copy of your final fitting parameters:

```python
print('The “best fit” parameters:')
print(' A = {}, B = {}, C = {}'.format(popt[0], popt[1], popt[2]))
```
Appendix Q

Fitting data with Excel

These instructions apply to Excel and, with minor modifications, to OpenOffice or LibreOffice.

1. Generate a delimited text file from LabVIEW, a text editor, or directly in a spreadsheet application) with the $x$ values (time) in the first column and the $y$ values (temperature) in the second column. You can also include the uncertainties in the $y$ values in the third column but Excel won’t use them for anything. The default tab delimiter in LabVIEW is a reasonable choice but a comma delimiter will also work.

If you save your file with a “.csv” extension, Excel will load it while assuming that it is comma-delimited. If you used the tab delimiter, the load will fail. It is possible to import a tab-delimited file, but you may have to select “tab” explicitly as the delimiter in the import screen.

2. After starting Excel open a new spreadsheet (if one is not already open). Click on Data (top menu list), then select From Text. Select the file you wish to load (delimited values and either tab or comma delimited).

3. Select the desired columns of data for the $x$ and $y$ axes, select Insert from the top menu, and Scatter Plot with straight lines and markers.

4. You should have your expected $x$ values (time) along the $x$-axis and the expected $y$ values (voltage) along the $y$-axis. If the choice of data is incorrect, you can right-click on the graph and select Select Data to change the selections.

5. Click on the graph, then select the “+” to the right of the graph (Chart Elements). Select Axis Titles to display the default titles. You can assign appropriate titles to each axis by clicking on the default title and editing it. An example would be “Temperature (K)” – the title should include both the descriptive name of what the numbers on that axis represent as well as the units for those numbers. You should also remove the Legend if it is checked.

6. Right-click on each axis, select Format Axis and set the axis limits to remove extra white space in the graph if necessary.
7. Either select Trendline from the Chart Elements or right-click on the data in the chart and select Add Trendline. Choose the desired regression type (for example, Linear for a diode calibration). Also, click on the entries Display Equation on chart and Display R-squared value on chart at the bottom of the menu. Note that there is no option to get uncertainties in the fitting parameters. If you are generating a plot for inclusion in a document, it is best not to have the equation displayed on the chart and provide that information in either the figure caption or in the body of the document.

8. The trendline equations usually gives you fixed point numbers with four digits after the decimal. This is not always adequate. It is usually better to right click on the equation display, select Format trendline label, select Scientific (under the Number tab) and set Decimal places to at least 3 or 4 depending on the desired accuracy.

9. You will probably need to drag the trendline equation display to a convenient location on the plot.

10. Do NOT (usually) put a title on the chart if you are going to include it in a paper – the information commonly found in the title should be in the (usually required) caption for the figure. If you are generating a graph to put in your lab notebook, a title would be appropriate as a way to label the graph.

11. Once you have the chart you can use copy and paste to get it into a document or to put it where you can print it for your notebook. You can also get a reasonably formatted file by copying the graph to a separate sheet and either printing that sheet using the “Adobe PDF” (for a pdf file) or “Metafile to EPS Converter” (for encapsulated postscript) printer drivers. You can also directly export the graph to a pdf file by selecting File ⇒ Export ⇒ Create PDF/XPS.
Appendix R

Superconductor Transition Measurement Hints

WARNING

Use extreme caution when handling the superconductor lead wires.

- **Gently** push the cable through the brass cap, being careful that you don’t damage the small connectors on the end of the cable and that you don’t kink or unnecessarily flex the leads.

- Put a **thin** coating of the anti-seize compound on the threads of the superconductor assembly before you screw it into the aluminum heater block. This will ease the process when you have to remove the superconductor from the heater block.

- Screw the superconductor assembly into and out of the heating block using a **large** screwdriver in the back slot.
  The small yellow or gray screwdrivers are **not appropriate** for inserting or removing the superconductor from the block.

  **Never** twist it in or out by the wires.

- It is usually good to use the screwdriver to hold the superconductor assembly stationary with respect to the room and rotate the aluminum heater block when you assemble or disassemble them. This will avoid the problem of wrapping the wires around the screwdriver and reduces the likelihood that you will break one or more wires during the assembly/disassembly process.

- **Never, never, NEVER**, bend the superconductor lead wires when frozen.
R.1 Some hints on making the superconductors work

1. When you build a constant-current supply for the four-lead measurement of the resistance, it should have an output current in the range of 10-50 mA, not to exceed 100 mA.

   Note: this constant-current supply is in addition to the supply you already built. When you finish, you will have one supply providing 90-110 µA for the temperature measurement diode and one providing 10-50 mA for the superconductor resistance measurement.

   Since you used a TL3472 op amp, you will use the second amplifier in the package for the second supply. The voltage divider providing the voltage reference on the non-inverting input can be connected to both amplifiers if you wish.

2. First, verify that your superconductor isn’t already broken.

   (a) Using an ohmmeter, check the resistance between the black, white, red, and orange leads. Check every possible combination. It should be about 1.5-2 Ω between any two leads (most of that is contact resistance).

   (b) When you connect the mA-range constant-current supply to the black and white leads on your superconductor sample, you should be able to read something around a mV on the red and orange leads (using a voltmeter is adequate for testing).

   (c) Use the diode-check setting on your multimeter to verify that the diode is functioning and that there are no broken leads. Most multimeters will read the voltage across the diode when it is forward biased (this should be about 0.5 V) and overload when it is reverse biased. The violet lead is the connected to the diode cathode.

3. Your analog input Express VI should be set to a range that is consistent with the voltage you measured in the previous step for the superconductor voltage. Since that was done at room temperature, the voltage measured with the voltmeter should be very near the maximum for the experiment. It is wise to specify a range that is slightly larger than this maximum voltage. Be sure to keep the voltage range bipolar. LabVIEW will set the range for the hardware to the smallest available setting that is greater than or equal to your specified range.

   It is best to keep your range as small as possible while allowing for the expected input signal. This will provide the best resolution for your measurement.

4. Remember that the range on the Express VI for the diode channel is supposed to be 0 to about 1.5 V (the upper voltage needs to be large enough for the voltage you measured when calibrating the diode in LN; this will likely be slightly more than 1 V for your diode with the 100 µA supply).

   With the USB-6221 the voltage range is slightly greater than what you specify. If you specify ±1 V it will be able to properly read voltages to about 1.02 V without truncating the data.
5. You will be using the A/D converters to read two different voltages for these measurements. These two voltages are very different in magnitude (a few mV compared to roughly 1 V). The analog inputs have only one A/D converter and the selected inputs are sequentially connected through an analog switch to that single converter. Due to source impedance, resistance in the analog switch, and capacitance from the various components to ground, the voltage at the input to the A/D converter will not change immediately to the new value. It is advisable to configure your analog input VI to allow adequate time for the voltage to settle before recording the value.

There is a chart in the datasheet for the USB-6221-BNC (the board we are using) indicating the approximate settling time to get within $\pm 1$ LSB (within one A/D converter level) for various source impedances. For example, with a 10 kΩ source impedance this comes out to about 30 to 40 µs.

As noted in our discussion of analog measurements during the LabVIEW exercises, the default settling time allowed by the USB-6221-BNC is 14 µs if the acquisition rate is slow enough. Maintaining this settling time puts a strong limit on the rate at which you can acquire these two channels in this experiment. This time is only possible if your sample rate is less than $1/(n \times 14 \times 10^{-6})$ samples/s where n is the number of channels being acquired. For our case with two channels, this would give a maximum sample rate of 35 kS/s.

It would be useful to look at the National Instruments document “Is Your Data Inaccurate Because of Instrumentation Amplifier Settling Time?” (http://www.ni.com/white-paper/2825/en/).

For example, if a 500 kΩ resistor was used for R3 in your supply for the temperature measurement diode, the effective resistance of the diode is 10 kΩ (1.0 V at 100 µA). If this is much smaller than R3, the effective output resistance is very close to 10 kΩ. If it is comparable to the size of R3, you will use the parallel combination of the diode and R3 for the output resistance. As noted above, the required settling time is about 30 to 40 µs.

**Strong Recommendation:** Since you can’t adjust the interchannel delay with the DAQ Assistant VIs, you will likely have to do something else to ensure that your signals are sufficiently settled to get accurate measurements. As noted above, we need probably 2 to 3 times as much settling time as that provided by the default period. One way to increase the settling time is to sample the same channel several times in a row and use only the last value measured. You may have to experiment with how many times to sample a given channel to get the desired accuracy.

As an example of how to do this if you are sampling two channels, you will have multiple “channels” defined in the DAQ Assistant but several successive channels will be set to the same physical input with the same input range. For instance, if you want to sample AI0 3 times and AI1 3 times you would set the channel list to be:

Dev1/ai0
Dev1/ai0
Dev1/ai0
Dev1/ai1
Dev1/ai1
Then to get the settled values from those provided by the DAQ Assistant VI, you would set the From DDT (From Dynamic Data Type) function to give you channel 2 for ai0 and 5 for ai1 (the channel numbers start with 0).

Note that you still require a sample rate that will allow the required settling time. Since we are now acquiring 6 channels, the maximum sample rate to still have 14 $\mu$s settling time would be about $(6 \times 14 \mu s / \text{sample})^{-1} = 11.9 \text{kS/s}$.

6. You also need to be sure that the inputs on your data acquisition hardware are properly configured. Below each input connector there is a switch labeled FS or GS. FS stands for floating source and indicates that there is no ground reference provided by the signal source. GS stands for grounded source and indicates that there is a ground reference provided by the signal source.

The power supplies used for the constant current circuits all have the ground terminals connected to chassis ground. Since the source is grounded, you should select the GS position for the diode voltage measurement.

You should also select GS for your superconductor voltage. The main reason for this is the return side of the current to your superconductor is connected to ground through the tan +15/-15/+5 V power supply (the current return is the black wire). If you connect the superconductor voltage measurement cable to a ground reference, some of the current through the superconductor will flow through that connection and the contact resistance will become important.

7. Most of the computers have an intrinsic offset voltage in the analog inputs (usually a few $\mu$V on the most sensitive scale). The best way to remove this is to

   (a) take the superconductor to LN temperature
   (b) disconnect the white wire from the superconductor adapter cable
   (c) measure the voltage across the superconductor (red/orange cable) using the data acquisition hardware
   (d) reconnect the white wire on the superconductor adapter cable.

Ideally this voltage is the intrinsic offset, and you can then subtract this voltage from the measured voltage to get the correct voltage.

Note that if you have any signal crossover between the diode and the superconductor this offset will appear to change between room temperature and LN temperature because of the change in diode voltage from about 0.37 V to slightly greater than 1 V.

If you disconnect the black wire from the adapter cable for a significant period, you may see the voltage drift. This is because the input is now floating (you don’t have a ground reference) and it will sometimes read the voltage difference incorrectly (recall the $\pm 11 \text{V}$ limit from the specification sheet).

8. You should save at least 6 significant figures in the superconductor voltage or superconductor resistance data. The best format to use is %.6e that saves 6 figures in exponential format. With %.6f, you will lose resolution when the resistance is near zero (loss of resolution is generally considered a bad thing).
Appendix S

Project or Research Proposals

It is difficult to be involved in scientific work of any kind, either academic research, industrial development, government work, or teaching without writing proposals for research or equipment. These may range from short internal documents describing proposed work to extensive proposals to outside clients for significant support for your research. They may range in length from a few sentences to many pages, although most funding sources do have maximum lengths for proposals. No matter what you do, you will have to convince someone that they want to pay for something that needs doing. This exercise gives you experience in developing such a document.

There are several items that are usually included in a proposal:

1. A statement of the problem to be addressed.
2. A statement of why the problem needs to be addressed.
3. A statement of how you intend to address the problem.
4. The proposed timeline for the research.
5. The resources needed to carry out the research.

The content associated with each of these items will vary significantly depending on the purpose of the proposal and the audience to which the proposal is directed. The format in which they are presented will also vary. For instance, if you are submitting a proposal to a governmental funding agency they may have very specific instructions describing how the proposal is formatted, the length, content, and ordering of each section, and the actual format submitted to the agency (Word document, PDF file, etc.). In many cases, failing to follow the prescribed format exactly will result in the proposal being rejected with no consideration.
S.1  A general format

The proposal will usually contain the following sections. They may not be exactly in the stated order since you need to meet the requirements of the client.

Title: This should provide a concise, but adequate, summary of the work. You must find a happy middle-ground between not enough information and too much information. It needs to contain enough information to convey the general purpose of the proposed activity and to differentiate it from other research.

Abstract: The abstract is a single paragraph describing the problem to be addressed and why the problem is interesting. The abstract has to be short enough that someone is willing to read it. It also has to contain enough information to get the reader interested in the problem and willing to read more.

In some proposals, the abstract may be either replaced or augmented with an executive summary. These tend to be longer and more detailed since they are intended for a manager or research coordinator to read to be able to know who else needs to see the proposal or who will be best suited to evaluating it.

Introduction: This section introduces the problem. It should initially provide background for the problem at a general level. This would be followed by background material specific to the proposed problem. You should include a review of relevant literature on previous work.

The writing style should be concise, clear, and lacking in embellishments. Whoever is reading your proposal doesn’t want to wade through lots of exposition to get the important information.

Don’t quote your literature sources directly. Summarize what the article includes that is pertinent to your problem and give a citation to the bibliography included as part of the body of your proposal.

It is likely that this section will be the longest one in your proposal.

Research Hypothesis or Research Problem: This is a statement of what you intend to do. What questions are you trying to answer? Based on the current state of the field, what do you hope to show in your research?

This section will also contain some indication that you have evaluated the difficulty of the problem and can state with some certainty that the anticipated effects can actually be measured in some sense. This analysis of the probability of success may include some theoretical background. It may also include some calculations backing up your claims. They can be either carefully done or back-of-the-envelope, depending on the audience for the proposal.

Methods and Resources: Here you will describe your proposed experiment in depth. How are you going to complete the research? What methods are going to be required? What kinds of equipment and supplies will be needed? Be thorough but not excessively descriptive.

Don’t forget to include an expected timeline for your work so those reading the proposal know whether it will fit within the constraints for whatever support or resources are being requested.
Conclusion and Justification: Explicitly state how your research will advance knowledge or understanding of the proposed problem or question. Are there any far-reaching effects? Why do you deserve support or resources for this research?

Bibliography: Include all the resources that you consulted in developing this proposal. This will provide evidence to those evaluating the proposal that you have a good understanding of the current state of the field of research and what has been done previously (important so you don’t unnecessarily repeat previous work).

The points on the rubric add up to 40 points. The score you receive will be scaled appropriately to match the allowed points on the assignment.

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<thead>
<tr>
<th>Paper part</th>
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<td>Clear statement of what will be done</td>
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<td>Theoretical background/calculations</td>
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<td>Statement of how research will advance scientific knowledge</td>
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<td>Is convincing that support or resources are deserved</td>
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Physics 240
Student-Designed Experiment
Equipment Request Form

Names: __________________________
___________________________
___________________________

Lab Period: ________________________________

For our Student-Designed Experiment we will need the following equipment and supplies:

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
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Appendix T

Bibliography

This bibliography provides additional sources that may be useful for each of the general topics in this course. It is not intended to be an exhaustive list.

Some of the references are to internet sources. Every effort has been made to use URLs that are stable but that is not always possible. A search may be necessary if the URL has changed.

All URLs listed below were verified in April 2017.

T.1 General experimental work

E. Bright Wilson Jr., *An Introduction to Scientific Research*, Dover Publications, New York, 1991. This is a “timeless” book originally published in 1952. Chapters 2 (Searching the Literature) and 12 (Numerical Computations) are completely obsolete but the rest of the book is still a useful collection of materials appropriate to scientific research.

T.2 Machining


### T.3 Computer-aided design


### T.4 LabVIEW and data acquisition


Amazon lists several books for LabVIEW, but most are based on earlier versions of LabVIEW and will not cover the more recently-added features.

### T.5 Uncertainty, errors, and noise in experimental measurements


T.6 Measurement fundamentals


T.7 Temperature measurements


T.8 Measuring temperature with a silicon diode


T.9 Theory of high-T$_C$ superconductivity


T.10 Data analysis and curve fitting


Wikipedia, “Non-linear least squares,” https://en.wikipedia.org/wiki/Non-linear_least_squares. This article is a good overview of fitting a set of data points with a non-linear model equation. The first three sections are fairly general. The remainder of the article involves specific fitting algorithms and is quite detailed.
T.11 Scientific writing


American Institute of Physics, “Author Resource Center,” online resource at https://publishing.aip.org/author. A pdf copy of the resource document can be found at https://publishing.aip.org/sites/default/files/aippub/files/PreparingMS.pdf. The materials in this guide apply to most of the AIP journals.

American Institute of Physics, “AIP Style Manual” fourth edition (1990), is no longer available from the AIP web site. Most of the content is included in the “Author Resource Center” indicated in the previous entry. There is a copy of the style manual available at https://www.physics.byu.edu/faculty/petersonb/Phys240/AIP_Style_4thed.pdf.


T.12 Scientific presentations


T.13 Material data sheets


1N4148 diode, data sheet available at https://www.fairchildsemi.com/datasheets/1N/1N914.pdf.


T.14 Equipment manuals


