### Experiment 00: Introduction
*Complete this "experiment" first!*

### Experiment 01: Demonstrate Ohm’s Law in a simple AC circuit

### Experiment 02: AC line power conductor identification

### Experiment 03: Test soldered wire joint integrity

### Experiment 04: Test soldered PCB joint integrity

### Experiment 05: Demonstrate AC frequency measurement using an oscilloscope

### Experiment 06: Demonstrate Lissajous figures using an oscilloscope

### Experiment 07: Demonstrate meter vs oscilloscope voltage measurement

### Assessment 08: Troubleshoot loaded voltage divider (simulation)

### Experiment 09: Demonstrate lock-out/tag-out procedure

### Experiment 10: Demonstrate oscilloscope probe compensation

### Experiment 11: Demonstrate phase shift in series RC circuit

### Experiment 12: Demonstrate phase shift in parallel RC circuit

### Experiment 13: Demonstrate resonance

### Experiment 14: Demonstrate harmonic frequencies

### Experiment 15: Demonstrate high-pass or low-pass filtering

### Experiment 16: Demonstrate band-pass or band-stop filtering

### Assessment 17: Design and build RC filter network

### Assessment 18: Produce a signal with specified harmonics

### Experiment 19: Choose your own

### Experiment 20: Demonstrate transformer ratio and polarity

### Experiment 21: Demonstrate boost or buck transformer configuration

### Experiment 22: Demonstrate harmonic content of AC line power

### Experiment 23: Demonstrate capacitive coupling within a cable

### Experiment 24: Demonstrate inductive coupling within a cable

### Experiment 25: Demonstrate three-phase Delta and Wye networks

### Assessment 26: Troubleshoot loaded transformer circuit

### Assessment 27: Design and build a boost/buck transformer circuit
<table>
<thead>
<tr>
<th>Activity #</th>
<th>Due by session #48</th>
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<tbody>
<tr>
<td>28 Experiment</td>
<td>Choose your own</td>
<td></td>
</tr>
<tr>
<td>29 Experiment</td>
<td>Demonstrate full-wave bridge rectification</td>
<td></td>
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<tr>
<td>30 Experiment</td>
<td>Demonstrate ripple voltage filtering</td>
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<tr>
<td>31 Experiment</td>
<td>Demonstrate thyristor control of AC load power</td>
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<td>32 Experiment</td>
<td>Demonstrate PWM power control</td>
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<td>33 Experiment</td>
<td>Demonstrate DC-AC power conversion</td>
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<tr>
<td>34 Experiment</td>
<td>Demonstrate DC-DC power conversion</td>
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<tr>
<td>35 Assessment</td>
<td>Troubleshoot brute force AC-DC power supply circuit</td>
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<tr>
<td>36 Assessment</td>
<td>Design and build voltage regulator for maximum thermal loading</td>
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<tr>
<td>37 Experiment</td>
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<tr>
<td>38 Experiment</td>
<td>Demonstrate 7-segment decoder</td>
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<td>39 Experiment</td>
<td>Demonstrate multiplexer implementing arbitrary truth table</td>
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<td>40 Experiment</td>
<td>Demonstrate functionality of a JK flip-flop</td>
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<tr>
<td>41 Experiment</td>
<td>Demonstrate multi-digit counting</td>
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<tr>
<td>42 Experiment</td>
<td>Demonstrate PLC counter instruction</td>
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<tr>
<td>43 Experiment</td>
<td>Demonstrate PLC timer instruction</td>
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<tr>
<td>44 Assessment</td>
<td>Troubleshoot multi-digit counter circuit</td>
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<tr>
<td>45 Assessment</td>
<td>Design and build PLC-based motor control system</td>
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| 46 Lab clean-up | Clean and organize the entire lab room |       |

**Essential information about this course:**

- This is a laboratory course, but the experiments are not pre-designed. You will plan and execute each experiment, just like a real scientific experiment where the outcome not necessarily known.

- These experiments follow concepts taught in that semester’s theory course, which means the theory course outline and source texts are essential resources for you here.

- Half of your course grade comes from the number of attempts necessary to correctly complete each stage of each experiment. Clarifying questions are welcome, but all results presented to the instructor will be assessed just like answers submitted on an exam.

- Half of your course grade comes from the number of attempts necessary to correctly complete each assessment activity (e.g. skills demonstrations and circuit troubleshooting). Just like the experiments, each assessment activity must be eventually completed correctly to pass the course.

- You should budget a minimum of 12 hours per week for this course. The lab is yours to use during all open-school hours. Do not let the lack of fixed hours for this course lead to procrastination – manage your time wisely!

- Successful students (1) review relevant theory before planning experiments, (2) prioritize hands-on lab time, (3) read instructions carefully, and (4) document data neatly and accurately.
Values

This educational program exists for one purpose: to empower you with a comprehensive set of knowledge, skills, and habits to unlock opportunities in your chosen profession. The following values articulate personal attitudes guaranteed to fulfill this purpose, and the principles upon which this program is designed. They embody what I like to call a strong learning ethic, similar to a strong work ethic but applied to the learning process rather than a job.

Ownership – you are the sole proprietor of your education, of your career, and to a great extent your quality of life. No one can force you to learn, make you have a great career, or grant you a fulfilling life – these accomplishments are possible only when you accept responsibility for them.

Responsibility – ensuring the desired outcome, not just attempting to achieve the outcome. Responsibility is how we secure rights and privileges.

Initiative – independently recognizing needs and taking responsibility to meet them.

Integrity – living in a consistently principled manner, communicating clearly and honestly, applying your best effort, and never trying to advance at the expense of others. Integrity is the key to trust, and trust is the glue that binds all relationships personal, professional, and societal.

Perspective – prioritizing your attention and actions to the things we will all care about for years to come. Never letting short-term concerns eclipse the long-term.

Humility – no one is perfect, and there is always something new to learn. Making mistakes is a symptom of living, and for this reason we need to be gracious to ourselves and to others.

Safety – assessing hazards and avoiding unnecessary risk to yourself and to others.

Competence – your ability to consistently and independently apply knowledge and skill to the solution of practical problems. Competence includes the ability to verify the appropriateness of your solutions and the ability to communicate so that others understand how and why your solutions work.

Diligence – exercising self-discipline and persistence in learning, accepting the fact there is no easy way to absorb complex knowledge, master new skills, or overcome limiting habits. Diligence in work means the job is not done until it is done correctly: all objectives achieved, all documentation complete, and all root-causes of problems identified and corrected.

Community – your actions impact other peoples’ lives, for good or for ill. Conduct yourself not just for your own interests, but also for the best interests of those whose lives you affect.

Respect is the acknowledgment of others’ intrinsic capabilities, responsibilities, and worth. Everyone has something valuable to contribute, and everyone deserves to fully own their lives.
EET Program Learning Outcomes

(1) **COMMUNICATION and TEAMWORK** – Accurately communicate ideas across a variety of media (oral, written, graphical) to both technical and non-technical audiences; Function effectively as a member of a technical team.

(2) **SELF-MANAGEMENT** – Arrive on time and prepared; Work diligently until the job is done; Budget resources appropriately to achieve objectives.

(3) **SAFE WORK HABITS** – Comply with relevant national, state, local, and college safety regulations when designing, prototyping, building, and testing systems.

(4) **ANALYSIS and DIAGNOSIS** – Select and apply appropriate principles and techniques for both qualitative and quantitative circuit analysis; Devise and execute appropriate tests to evaluate electronic system performance; Identify root causes of electronic system malfunctions.

(5) **PROBLEM-SOLVING** – Devise and implement solutions for technical problems appropriate to the discipline.

(6) **DOCUMENTATION** – Interpret and create technical documents (e.g. electronic schematic diagrams, block diagrams, graphs, reports) relevant to the discipline.

(7) **INDEPENDENT LEARNING** – Select and research information sources to learn new principles, technologies, and/or techniques.
Course description

This course reinforces the content of IETTI-104 (AC Circuit Theory) through student-designed experiments. All experiments employ scientific method: proposing falsifiable hypotheses, devising procedures, gathering data, analyzing results, and developing documentation. Students also apply foundational circuit principles to the diagnosis of simulated and real faults in these same types of circuits. Mastery standards applied to all experimental and diagnostic activities guarantee attainment of learning outcomes.

Course learning outcomes

- Rigorously demonstrate AC amplitude measurement, reactance, power factor, resonance, filtering, transformation of voltage and current, harmonics, and semiconductor switching principles by means of scientific experimentation. (Addresses Program Learning Outcomes 2, 4, 6, 7)
- Construct AC circuits meeting specifications set by the instructor and demonstrate proper test equipment usage including multimeters, signal generators, and oscilloscopes. (Addresses Program Learning Outcomes 4, 5, 6)
- Troubleshoot faulted filter networks, transformer circuits, transistor switching circuits, and AC motor starters from measurements taken at test points with circuit components and connections hidden from view. (Addresses Program Learning Outcomes 4, 6)
- Articulate diagnostic reasoning while troubleshooting these same circuits. (Addresses Program Learning Outcomes 1, 3)
### Required Tools, Supplies, and Software

Listed by IETTI course number and course type (Thy = theory, Exp = Experiments, Prj = Projects).

Semester 1 = IETTI-101 (Theory), 103 (Experiments), and 102 (Projects)
Semester 2 = IETTI-104 (Theory), 112 (Experiments), and 105 (Projects)
Semester 3 = IETTI-222 (Theory), 221 (Experiments), and 220 (Projects)
Semester 4 = IETTI-223 (Theory), 225 (Experiments), and 106 (Projects)

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Required Tools, Supplies, and Software

Scientific calculator – at minimum your calculator must perform trigonometric functions (sine, cosine, tangent, etc.), offer multiple memory registers, and display values in both scientific and “engineering” notations. I recommend the Texas Instruments model TI-36X Pro because it easily performs complex-number arithmetic necessary for AC circuit analysis and is inexpensive.

Personal computer – all course materials are available in electronic format and are free (most are also open-source), making a portable computer extremely useful. The school provides personal computers for on-campus use, but having your own will enable you to work outside of school. Any operating system, any size hard drive, any amount of RAM memory, and any screen size is appropriate, but your computer needs to have a keyboard and mouse (i.e. no tablets). Useful features worth higher cost include an RJ-45 Ethernet port and an EIA/TIA-232 (9-pin) serial port.

Multimeter – this is your first and most important electronic test instrument. At minimum it must measure DC and AC voltage, DC and AC current (milliAmpere range), resistance, and “diode check” voltage drop. Useful features worth higher cost include microAmpere current measurement, true-RMS AC measurement (for second-semester courses and above), frequency measurement, capacitance measurement, and minimum/maximum value capture. Cost is a strong function of accuracy, frequency range, and safety (“Category” ratings for over-voltage exposure). The Fluke model 87-V is an excellent professional-grade choice for digital multimeters, and the Simpson 260 is an excellent professional-grade choice for analog multimeters. Note that Fluke offers a 25% educational discount for students.

Oscilloscope – once too expensive for student purchase, entry-level USB-based oscilloscopes now cost less than a textbook. Pico Technology is an excellent brand, and their model 2204A comes with high-quality probes as well. Plugged into your personal computer using a USB cable, the Picoscope turns your computer’s monitor into a high-resolution oscilloscope display. Features include two measurement channels, 10 MHz bandwidth, built-in arbitrary waveform generator (AWG), ± 100 Volt over-voltage protection, digital “cursors” for precise interpretation of amplitude and frequency, meter-style measurement capability, Fast Fourier Transform algorithm for frequency-domain measurement, export ability to several graphic image formats as well as comma-separated variable (.csv) files, and serial communications signal decoding. Together with your multimeter, solderless breadboard and Development Board (which you will construct in the IETTI-102 Project course and is yours to keep) this forms a complete electronics laboratory for doing experiments and projects outside of school.

Soldering – the equipment you purchase for soldering need not be expensive, if you purchase the right solder. For electronics work you must use rosin-core solder. Kester is an excellent brand, and you should avoid cheap imported solders. For lead-based solder, a 63% tin and 37% lead alloy (Sn63/Pb37) works very well. A one-pound roll is likely more solder than you will need in these courses, so I recommend buying just a small tube or small roll. I recommend a fine-tipped soldering iron (15 Watts continuous power, although some with adjustable temperature controls may have higher power ratings to get up to soldering temperature more quickly) and a solder diameter 0.031 inches or smaller for doing fine printed-circuit board work. Also, keep the tip of your soldering iron clean by wiping it against a damp sponge or paper towel when hot, and not leaving it hot any longer than necessary. Hakko, X-tronic, and Lonove are all recommended brands.

Microcontroller – these courses are not brand- or model-specific, but the Texas Instruments MSP430 series is highly recommended for their powerful features, modern design, and programmability in multiple languages (assembly, C, C++, and Sketch). I particularly recommend the model MSP-EXP430G2ET “LaunchPad” development board (MSP430G25531N20 microcontroller chip) with Code Composer Studio for the IDE software. A hobbyist-grade microcontroller such as the popular Arduino and Parallax BASIC Stamp are permissible only in first-year courses, but not in second-year courses.
Required Tools, Supplies, and Software

All software required for these courses is free, and some of it is open-source.

Schematic editor – this is used to draft schematic diagrams for circuits. A good one is TinyCAD, but there are also web-based CAD tools such as circuitlab.com that are very effective and easy to use.

Text editor – this is used to create plain-text files, kind of like a word processor but lacking formatting features such as typeface, font size, etc. It is absolutely necessary for writing code of any kind. Notepad++ is a very good editor, but others work well too.

NGSPICE – this is a modern adaptation of the venerable SPICE circuit simulator which uses a text-coded “netlist” rather than a visual schematic diagram to describe circuits. Very powerful, and with decades of netlist examples from earlier versions of SPICE to use as references. The installer lacks sophistication, being nothing more than a compressed (zip) file that you unpack. Once installed, you should instruct your computer’s operating system to automatically associate any files ending in the extension .cir with the NGSPICE executable file ngspice.exe so that all of your netlist files will appear with the NGSPICE icon and will automatically load into NGSPICE when double-clicked.

WSL – Windows Subsystem for Linux is a “virtual machine” Linux operating system that runs within the Windows operating system, giving you a command-line user environment mimicking that of a Unix operating system. It is a free application from Microsoft, with instructions available from Microsoft on how to install. I recommend installing the “Debian” distribution of WSL. Once installed, you will issue these commands in the following order to install all the necessary programming tools:

- sudo apt update
- sudo apt install build-essential
- sudo apt install indent
- sudo apt install python3

packetsniffing software – this is specialized circuit-simulator program that inserts faults into circuits and tests your ability to locate them. The download consists of a single “tar” archive file which you must unpack and compile using the following two commands within a Unix-type operating system or within WSL. The fourth command listed below starts and runs the application:

- mkdir tshoot ; mv -v *.tar tshoot ; cd tshoot
- tar xvf *.tar
- make
- ./tshoot

IDE software – an “Integrated Development Environment” is a software package used to write code, and for our purposes this would be code meant to run in a microcontroller. For the Texas Instruments MSP430 series, the main IDE is called Code Composer Studio, and it supports programming in assembly language, C, and C++. A third-party add-on to Code Composer Studio called Energia supports programming in the Sketch language, identical to that used by the popular Arduino microcontroller series.

PCB layout editor – this is specialized drafting software intended for creating graphic files to be sent to printed circuit board (PCB) manufacturers so you can order your own custom PCBs. PCB Artist is free and exceptionally easy to use, but only exports files to the manufacturer Advanced Circuits. Free PCB layout editors capable of exporting “Gerber” format files which are universally accepted by PCB manufacturers include EasyEDA, KiCAD (very powerful but hard to learn), and pcb. Of these I recommend EasyEDA for beginners, or PCB Artist if you don’t mind being locked into one manufacturing option.

Packet-sniffing software – this is specialized software for monitoring network communications. An excellent (and free) option is Wireshark.

file eet tools
Grading standards for Experiment courses

Your grade for this course is based on percentage scores (in every calculation rounded down to whole-numbered values), with each category weighted as follows:

- **Experiment scores = 50%** (Note: all Experiments are mastery-based, which means they must be eventually completed at 100% competence in order to pass the course)
- **Assessment scores = 50%** (Note: all Assessments are mastery-based, which means they must be eventually completed at 100% competence in order to pass the course)

Please note the importance of completing all Experiments and all Assessments on or before their respective deadline dates. If any Experiment or Assessment is incomplete by the end of the school day of the deadline date, it will receive a 0% score. If any Experiment or Assessment is incomplete by the end of the last day of the course, you will earn a failing grade (F) for the course. All Experiments and Assessments must be complete by the end of the last day of the course to receive a passing grade for the course.

Carefully follow the instructions associated with each experiment! If there is a prescribed order, you must follow this order of steps or else you will receive a 0% score for that experiment. The same is true if you plagiarize any part of it (i.e. present someone else’s work as your own). For every experiment there will be multiple demonstrations, explanations, and/or challenges you must complete in the instructor’s presence, and these are all mastery-based which means they all must be completed with 100% competence. Multiple opportunities are given to master each, with a point deduction levied for every re-try. You are welcome and encouraged at any time to seek clarification from the instructor so that you understand what is being asked of you, but you are solely responsible for doing the work and solving the problems. This is similar to the policy during written exams in a Theory course: the instructor will happily clarify expectations, but will not solve the problems for you nor confirm if an answer is correct prior to scoring it.

Electronic submissions of Experiments and Assessments are acceptable for full credit. The standards are just as high for electronic submissions as for face-to-face demonstrations. For Experiments, video documentation of you completing all objectives in their proper order will count as full credit. For Assessments your work must either be videorecorded in one seamless take or performed on a live video stream so the instructor is able to ensure you are doing the work yourself with no aid.

This course is based on experiments and hands-on assessments, and does not have scheduled meeting times as is the case with instructor-facilitated theory sessions. However, your punctual and consistent attendance is important for your success, as these activities require significant time-on-task to complete.

If you must be late or absent, it is imperative that you contact your instructor as well as any classmates you may be coordinating with so plans may be adjusted. It is still your responsibility to meet all deadlines.

A failing (F) grade will be earned for the entire course if any experiment or assessment is not completed on or before the deadline date, or for any of the following behaviors: false testimony (lying), cheating on any assignment or assessment, plagiarism (presenting another’s work as your own), willful violation of a safety policy, theft, harassment, sabotage, destruction of property, or intoxication. These behaviors are grounds for immediate termination in this career, and as such will not be tolerated here.

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file eet_grading_e

9
Getting help in the lab

Success in this career is largely a function of your ability to independently solve complex problems. You will find that the design, construction, testing, and diagnosis of systems for experiments and projects are prime opportunities to hone this skill. Many times you will find yourself faced with a problem that you do not think you can solve. Your instructor’s job is to provide practical strategies and techniques you can use to solve the problem, without directly solving the problem for you. Although this may feel frustrating because the instructor is withholding a solution from you, know that if the instructor were to solve the problem for you it would actually hinder your own development.

Any time you call for help to diagnose a problem, your instructor will first check to see you have done the following:

- **Simplify** – make problems manageable by building and testing your system in stages, by dividing large systems into smaller sections to isolate problems, and by avoiding complexity that isn’t absolutely necessary to the function you are trying to obtain at that time. A common mistake is to build large systems without testing along the way in an attempt to save time, but this strategy almost never works!

- **Document** – draw a diagram before building any system, and use this to guide your analysis and design decisions. Also, have any other relevant documents available for reference, such as datasheets, tutorials, etc. A common mistake is to build systems without first building up this documentation, again in a futile effort to save time.

- **Measure and record** – take measurements using appropriate test equipment, because these measurements will reveal what your senses alone cannot perceive. Record those test results so you will not have to rely on memory to recall what you did.

- **Foundational Concepts** – always apply Foundational Concepts such as the guaranteed effects of opens and shorts, Ohm’s Law, Joule’s Law, Conservation of Energy and of Electric Charge, Kirchhoff’s Laws, properties of series and of parallel networks, etc. when solving problems. Reference a list of these if necessary, checking them one by one to stimulate and guide your reasoning.

A good way to remember these is to use the phrase, “Slow Down My Friend!” (Simplify, Document, Measure/record, and Foundational Concepts) which is also a reminder that problem-solving requires patience.
A great many student problems are caused by impatience and an urge to take shortcuts!
Example experiment report – Stage #1 (planning)

**Experiment: Demonstrate Ohm’s Law**

**Hypothesis** Current will be directly proportional to voltage applied across a resistor, in accordance with the formula \( I = \frac{V}{R} \) using a 2.2 kΩ resistor:

<table>
<thead>
<tr>
<th>Applied Voltage</th>
<th>Predicted current</th>
<th>Measured current</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 V</td>
<td>0 mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 V</td>
<td>2.2727 mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 V</td>
<td>4.5455 mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 V</td>
<td>6.8182 mA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\frac{0}{2200} = 0.00 \quad \frac{5}{2200} = 0.0022727 \quad \frac{10}{2200} = 0.0045455 \quad \frac{15}{2200} = 0.0068182
\]

**Experimental plan**

![Multimeter circuit diagram]

Applied voltage will be measured using my multimeter connected in parallel with the resistor, since I don’t trust the cheap voltmeter indication built in to the power supply. Circuit current will be measured using the multimeter connected in series with the resistor.

**Risk analysis**

- **Electric shock:** limit source voltage to less than 30 Volts!
- **Overheating resistor:** limit source voltage to less than 23.45 Volts \((P = \frac{V^2}{R})\)
  
  \[
  V = \sqrt{PR} = \sqrt{0.25 \times 2200} = 23.45
  \]

- **Blowing meter fuse:** ammeter must be in SERIES with the resistor!
Example experiment report – Stage #2 (data recording)

Experiment: Demonstrate Ohm’s Law

<table>
<thead>
<tr>
<th>Applied Voltage</th>
<th>Predicted current</th>
<th>Measured current</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 V</td>
<td>0 mA</td>
<td>0.01 mA</td>
<td>+0.01 mA error</td>
</tr>
<tr>
<td>5 V</td>
<td>2.2727 mA</td>
<td>2.28 mA</td>
<td>+0.321% error</td>
</tr>
<tr>
<td>10 V</td>
<td>4.5455 mA</td>
<td>4.56 mA</td>
<td>+0.319% error</td>
</tr>
<tr>
<td>15 V</td>
<td>6.8182 mA</td>
<td>6.80 mA</td>
<td>−0.267% error</td>
</tr>
</tbody>
</table>

$$\text{Error} = \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\%$$

$$\frac{0.01-0}{0} = (\text{undefined}) \quad \frac{2.28-2.2727}{2.2727} = +0.321\% \quad \frac{4.56-4.5455}{4.5455} = +0.319\% \quad \frac{6.80-6.8182}{6.8182} = -0.267\%$$

Analysis

Hypothesis is confirmed, as measured current is shown to be well within ± 5% of predicted values.

The +0.01 mA error is clearly due to the multimeter, as the power supply was turned off for that measurement. Most of the other errors follow that same offset, and so is likely due to meter error.

Helpful hints for your own reports:

- Keep your experiment reports simple – record all data, but don’t write elaborate explanations unless absolutely necessary. The goal here is to spend most of your time experimenting with the circuit, not drafting a report!
- Never discard data! If you make a mistake, just note the error and then record the good data in a new place on the report. Feel free to use colored text to distinguish errors from good data. Remember that scientific method is all about learning, and mistakes are a normal and expected part of every learning process. Also, sometimes what you think is a mistake at first may later be revealed as an important discovery!
- Spreadsheet software (e.g. Microsoft Excel) works wonderfully well to make tables, and it can easily calculate values for you! In fact, you could write the entire report in a spreadsheet if you wish.
- If portions of the documentation are best written/drawn by hand, simply photograph them and paste the graphic images into the electronic document.
- Do not request the instructor to certify any portion of the report until you believe it to be complete and correct! You may ask for help at any time without incurring a score deduction, but you will be graded when you declare your work to be done.
Experiment: Demonstrate Ohm’s Law

Presentation and review

Nothing needs to be written in your report for this. A list of learning objectives is given on every experiment page, specific to that experiment. Your task is to completely and accurately calculate, explain, demonstrate, identify, and otherwise articulate to the instructor your competence related to the subject of that experiment.

Helpful hints for your own presentations:

- Design your experiment with the presentation in mind. Review these learning objectives while drafting your hypothesis and experimental procedure, and this way you will derive more learning from the experiment.
- Check the list of learning objectives again after completing your experiment report, to make sure you’ve explored all those points. If not, continue to experiment and test these ideas until you are confident in your ability to articulate them to your instructor.
- Do not disassemble your experiment until this stage is complete, because your instructor needs to see your experiment function as part of the demonstration!
- Feel free to record any demonstrated learning objectives on video, as a way to accelerate this stage of the experiment. If your videos are detailed and clear enough to show you have adequately learned those objectives, they may substitute for live demonstration and thus save time. This is especially true on days where your instructor is busy evaluating other students’ experimental presentations. Please positively identify yourself in your videos so the instructor can be sure it is actually you doing the demonstrations!
Learn how to design and execute an experiment in this course. Your instructor will certify each of these as complete when you answer them correctly and show where you found the information. No experimental work will be permitted until you have successfully done the following:

○ Read any of the numbered experiment pages in this course document and answer the following questions:
  - How many stages are there in each experiment?
  - What are your responsibilities within each stage?
  - How is each experiment graded?

○ Read the “Example experiment report” pages in this course document and answer the following questions:
  - In what format do you think you will prefer to write your reports? Examples include using a word processor, using a spreadsheet, writing a blog page, etc. Whatever format you use, it must support the embedding of graphic images, and should easily export to PDF format for sharing with others!
  - How lengthy and/or detailed should your reports be?
  - Why do you suppose you’re required to record all data and never discard, even when the experiment does not work the way you expect it to?

○ Read the “General troubleshooting advice” page in this course document and answer the following questions:
  - Identify the categories of electronic circuit faults
  - Describe some practical troubleshooting strategies
  - Explain what is meant by “root cause”

○ Read the user’s manual for your multimeter and answer the following questions:
  - Identify its maximum voltage measurement range(s), as well as the measurement accuracy
  - Identify its maximum current measurement range(s), as well as the measurement accuracy
  - Identify its maximum resistance measurement range(s), as well as the measurement accuracy
  - Identify other parameters it can measure other than voltage, current, and resistance

○ Read the “Getting help in the lab” page in this course document and answer the following questions:
  - What things should you do before asking for help?
  - What is the ultimate purpose in your instructor’s insistence that you do these things before requesting help?
Plan and conduct an experiment to demonstrate Ohm’s Law in a simple AC circuit. **Sample hypothesis:** “A simple circuit using the secondary winding of the Development Board power supply as the AC voltage source (___ Volts) and a ___ Ohm resistor should exhibit a current of ___ milliAmperes AC.” **Sample acceptance criteria:** “Measured current should equal predicted current, not deviating more than the rated tolerance of the resistor.” Recommend using the brute-force power supply circuit on your Development Board as the AC voltage source (connecting to the transformer’s secondary terminals), and measuring its voltage using your multimeter rather than assuming the labeled AC voltage is accurate, before calculating the expected current. Also recommend designing the circuit for a current no less than 10 mA because many AC multimeters lack accuracy measuring small AC currents. Risk analysis must include the potential to blow your meter’s fuse if improperly connected as an ammeter, as well as overheating the resistor.

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**Stage #1 – Experiment planning documented in report**
- **Written hypothesis:**
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- **Written experimental plan:**
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- **Written risk analysis:**
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

**Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ____ (−10% per re-try)**

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**Stage #2 – Experimental run and data recorded in report**
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

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**Stage #3 – Presentation and review**
- **Correctly demonstrate and explain** every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

**Instructor certifies – Re-try if any answer incorrect or incomplete = ____ (−10% per re-try)**

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**Learning objectives for this experiment:**
- Calculate error between predicted vs. measured values (Error = \(\frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\%\)), commenting on the sign of the error and also identifying possible causes
- Demonstrate the ability to calculate voltage, current, or resistance from the other two given values
- Demonstrate how to properly and safely measure voltage using a multimeter
- Demonstrate how to properly and safely measure current using a multimeter

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file we_0133
Plan and conduct an experiment to identify the “hot”, “neutral”, and “ground” conductors of an AC line power receptacle using a multimeter. **Sample hypothesis:** “The ‘hot’ conductor should be the ___ colored conductor of the power cord and should measure ___ Volts between the ___- and ___-colored conductors using the meter when plugged into an energized power receptacle.” **Risk analysis** should include electric shock and arc hazards (mitigated by using good-quality test probes, properly securing the power cord conductors in rated terminal blocks, and using the one-hand rule) as well as the potential to harm the multimeter by having the range and/or test leads incorrectly configured.

### Stage #1 – Experiment planning documented in report

- **Written hypothesis:**
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- **Written experimental plan:**
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- **Written risk analysis:**
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

  **Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ____ (−10% per re-try)**

### Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a **learning process**. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

### Stage #3 – Presentation and review

- **Was the original hypothesis confirmed?** If not, identify why.
- **Correctly demonstrate and explain** every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

  **Instructor certifies – Re-try if any answer incorrect or incomplete = ____ (−10% per re-try)**

**Learning objectives for this experiment:**

- Identify which of these conductors is supposed to carry load current
- Demonstrate how to properly and safely measure voltage using a multimeter
- Demonstrate how to apply the “one-hand rule” for electrical safety
Plan and conduct an experiment to test the mechanical and electrical integrity of a soldered wire joint. 

**Sample hypothesis:** “Electrical resistance should be less than 0.1 Ohms across the soldered joint; when subjected to tensile stress the wire should break before the joint fails.” Use the “Kelvin” 4-wire technique to infer the joint’s low resistance by passing a relatively high current through the joint and measuring voltage drop across it. **Risk analysis** should include inhalation hazards of soldering fumes, as well as electrical risks from high-current testing.

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**Stage #1 – Experiment planning documented in report**

- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions

- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully

- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

[ ] Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

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**Stage #2 – Experimental run and data recorded in report**

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a **learning process**. Record **all** data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

---

**Stage #3 – Presentation and review**

- Was the original hypothesis confirmed? If not, identify why.

- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

[ ] Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

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**Learning objectives for this experiment:**

- Demonstrate the Kelvin 4-wire resistance-measuring technique
- Demonstrate destructive testing of a soldered joint
- Demonstrate proper technique for cleaning and “tinning” the tip of a soldering iron
Plan and conduct an experiment to test the mechanical and electrical integrity of a soldered joint on a printed circuit board. **Sample hypothesis:** “Electrical resistance should be less than 0.1 Ohms across the soldered joint; when subjected to tensile stress the wire lead should pull out of the PCB-mounted component before the joint fails.” Use the “Kelvin” 4-wire technique to infer the joint’s low resistance by passing a relatively high current through the joint and measuring voltage drop across it. **Risk analysis** should include inhalation hazards of soldering fumes, as well as electrical risks from high-current testing.

**Stage #1 – Experiment planning documented in report**
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

**Stage #2 – Experimental run and data recorded in report**
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

**Stage #3 – Presentation and review**
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

**Learning objectives for this experiment:**
- Demonstrate the Kelvin 4-wire resistance-measuring technique
- Demonstrate destructive testing of a soldered joint
- Demonstrate the effect(s) of insufficient dwell time (i.e. time spent heating the material to be soldered) when soldering
Plan and conduct an experiment to demonstrate the measurement of an AC signal’s frequency using the graphical display of an oscilloscope.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (-10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (-10% per re-try)

Learning objectives for this experiment:
- Demonstrate how to configure an oscilloscope to measure an AC voltage signal
- Demonstrate how to configure a different model of oscilloscope to measure an AC voltage signal
- Demonstrate how to measure the frequency of an AC voltage signal using an oscilloscope
- Demonstrate how to measure the period of different wave-shapes using an oscilloscope, those different wave-shapes output by the same signal generator

file we_0134
Plan and conduct an experiment to demonstrate the comparison of two different frequencies using Lissajous figures displayed on an oscilloscope.

**Stage #1 – Experiment planning documented in report**

- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions

- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully

- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

  Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

**Stage #2 – Experimental run and data recorded in report**

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

**Stage #3 – Presentation and review**

- Was the original hypothesis confirmed? If not, identify why.

- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

  Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

**Learning objectives for this experiment:**

- Demonstrate how to configure an oscilloscope for the X-Y mode to compare two AC signals
- Demonstrate how to configure a different model of oscilloscope for the X-Y mode to compare two AC signals
- Demonstrate how to interpret Lissajous figures to determine frequency ratio
Plan and conduct an experiment to demonstrate the relationship between multimeter and oscilloscope measurements of AC voltage.

Stage #1 – Experiment planning documented in report

○ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions

○ Written experimental plan:
  • Includes schematic diagram showing everything you will build
  • Lists any special steps or conditions necessary for the experiment to run successfully

○ Written risk analysis:
  • Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  • Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

○ Was the original hypothesis confirmed? If not, identify why.

○ Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:

• Calculate error between predicted vs. measured values (Error = \( \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\% \)), commenting on the sign of the error and also identifying possible causes

• Demonstrate the mathematical relationship between peak and RMS voltage measurements for a sine wave

• Demonstrate the mathematical relationship between peak and RMS voltage measurements for a triangle wave

• Demonstrate the mathematical relationship between peak and RMS voltage measurements for a square wave

file we_0100
Troubleshoot a computer-simulated fault within a loaded voltage divider circuit. The schematic diagram for this circuit as simulated in the \textit{tshoot} troubleshooting simulator software is shown below:

\begin{center}
\textbf{Circuit #004}
\end{center}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{circuit.png}
\end{figure}

Nominal component values:
\begin{align*}
V_1 &= \underline{\phantom{000}} \text{ Volts +/- } \underline{\phantom{00}} \% \\
R_1 &= \underline{\phantom{000}} \text{ Ohms +/- } \underline{\phantom{00}} \% \\
R_2 &= \underline{\phantom{000}} \text{ Ohms +/- } \underline{\phantom{00}} \% \\
R_3 &= \underline{\phantom{000}} \text{ Ohms +/- } \underline{\phantom{00}} \% \\
R_4 &= \underline{\phantom{000}} \text{ Ohms +/- } \underline{\phantom{00}} \% \\
R_5 &= \underline{\phantom{000}} \text{ Ohms +/- } \underline{\phantom{00}} \%
\end{align*}

The \textit{tshoot} software randomly selects the fault and the circuit component values for you, after which you will have a limited amount of time to perform measurements and other tests. The software tracks each diagnostic step you take, the amount of time you needed to take each step, and assigns a “cost” to each step based on its complexity and risk. A successful troubleshooting exercise consists of both correctly identifying the location and nature of the fault, as well as logically defending the necessity of each diagnostic step. Incorrect fault identification, unnecessary steps, and/or incorrect defense of any step will result in a failed attempt. “Par” scores exist for the number of steps taken, time, and cost of correctly diagnosing the fault. You must achieve at par or better.

For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Troubleshooting is \textit{mastery-based}, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try begins with another randomized fault on the same circuit. Scoring is based on the number of attempts necessary to successfully troubleshoot a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). You are encouraged to practice using the \textit{tshoot} software, being free and readily available for your use.
Design and build a simple circuit consisting of a DC source, fuse, switch, and a load with visible or audible indication (e.g. DC motor, lamp). Then, once the circuit has been proven to work, demonstrate a full lock-out/tag-out procedure using the fuse as the safety disconnect. Note that since fuses generally aren’t lockable this will require placing a tag on the fuse as well as on the on/off switch (i.e. double-tagging in lieu of locking).

This exercise tests your ability to properly size a fuse for a given load and supply voltage, operate a digital multimeter, and follow industry-standard safety procedures.

The following components and materials will be available to you: DC voltage source; an assortment of panel-mount switches; a power resistor; an inline fuse holder; an assortment of AGC-style glass fuses; and lengths of hook-up wire. You must provide your own tools, Development Board, and digital multimeter (DMM) as well as a copy of this page for your instructor to mark design criteria.

A full lock-out/tag-out (LOTO) procedure is described in the “Full Tutorial” chapter of the Ohm’s and Joule’s Laws, Resistor Ratings, and Electrical Safety learning module, although you will not be allowed to reference any notes during your demonstration:


**SEQUENCE:** (1) Instructor chooses criteria; (2) You build and test your circuit (using a multimeter) without any power sources at all; (3) Instructor observes circuit energizing for the very first time; (4) You prove to the instructor that the circuit fulfills its intended function, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are **mastery-based**, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.
Plan and conduct an experiment to demonstrate how to adjust the compensation on a ×10 oscilloscope probe.

Stage #1 – Experiment planning documented in report

- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Instructor certifies – Re-try if any answer incorrect or incomplete = ____ (−10% per re-try)

Learning objectives for this experiment:

- Demonstrate how to configure an oscilloscope to measure an AC voltage signal
- Demonstrate the effect of under-compensating and over-compensating an oscilloscope probe
- Demonstrate proper measurement of AC voltage using an oscilloscope with a ×1 probe
- Demonstrate proper measurement of AC voltage using an oscilloscope with a ×10 probe
Plan and conduct an experiment to demonstrate phase shift within a series resistor-capacitor AC circuit. Recommend choosing component values such that all component impedances lie between 1 kΩ and 100 kΩ at the chosen operating frequency.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ___ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = ___ (−10% per re-try)

Learning objectives for this experiment:
- Calculate error between predicted vs. measured values (Error = \( \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\% \)), commenting on the sign of the error and also identifying possible causes
- Demonstrate how to configure an oscilloscope to measure phase shift between two AC signals
- Sketch a phasor diagram for all voltages \( V_{\text{source}}, V_R, \text{and } V_C \) in this circuit
Plan and conduct an experiment to demonstrate phase shift within a parallel resistor-capacitor AC circuit. Recommend using low-resistance shunt resistors to infer branch currents while using an oscilloscope as the measuring instrument, as well as ensuring that the branch impedance values lie between 1 kΩ and 100 kΩ at the chosen operating frequency.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
- Calculate error between predicted vs. measured values (Error = \( \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\% \)), commenting on the sign of the error and also identifying possible causes
- Demonstrate how to use shunt resistors to allow an oscilloscope to accurately infer AC current
- Sketch a phasor diagram for all currents (\( I_{\text{source}} \), \( I_R \), and \( I_C \)) in this circuit
Plan and conduct an experiment to demonstrate the principle of electrical resonance. Recommend choosing component values such that all component impedances lie between 1 kΩ and 100 kΩ at the resonant frequency.

Stage #1 – Experiment planning documented in report
○ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions
○ Written experimental plan:
  • Includes schematic diagram showing everything you will build
  • Lists any special steps or conditions necessary for the experiment to run successfully
○ Written risk analysis:
  • Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  • Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
○ Was the original hypothesis confirmed? If not, identify why.
○ Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Learning objectives for this experiment:
• Calculate error between predicted vs. measured values (Error = \( \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\% \)), commenting on the sign of the error and also identifying possible causes
• Demonstrate series resonance versus parallel resonance, explaining how they differ in behavior from one another
• Demonstrate how to configure an oscilloscope to measure an AC voltage signal
• Sketch a phasor diagram for this circuit, showing any quantities you choose (e.g. a phasor diagram for voltages, or for currents, or for impedances, etc.)
Plan and conduct an experiment to demonstrate the harmonic series of a non-sinusoidal waveshape.

Sample hypothesis: “A ___-shaped waveform with a peak value of ___ Volts will exhibit a harmonic of ___ Hz with an amplitude of ___ Volts, another harmonic of . . . , etc.”

Stage #1 – Experiment planning documented in report

- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions

- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully

- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ____ (-10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = ____ (-10% per re-try)

Learning objectives for this experiment:

- Demonstrate the Fourier series for a given wave-shape as expressed on a frequency-domain plot
Plan and conduct an experiment to demonstrate the behavior of either a high-pass or low-pass filter circuit. Recommend choosing component values such that all component impedances lie between 1 kΩ and 100 kΩ at the cutoff frequency.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Learning objectives for this experiment:
- Demonstrate how to measure AC signal voltage using an oscilloscope
- Demonstrate how to create a Bode plot from filter signal data
- Demonstrate how to test any filter network using a signal generator and oscilloscope, determining its pass-characteristics (i.e. low-pass, high-pass, etc.) and cutoff frequency from the measured signals without needing to know anything about the network’s topology or component values
- Demonstrate the mathematical relationship between component values and the filter’s cutoff frequency
Plan and conduct an experiment to demonstrate the behavior of either a band-pass or band-stop filter circuit. Recommend choosing component values such that all component impedances lie between 1 kΩ and 100 kΩ at the center frequency.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
- Demonstrate how to measure AC signal voltage using an oscilloscope
- Demonstrate how to create a Bode plot from filter signal data
- Demonstrate how to test any filter network using a signal generator and oscilloscope, determining its pass-characteristics (i.e. low-pass, high-pass, etc.) and cutoff frequency from the measured signals without needing to know anything about the network’s topology or component values
- Demonstrate the mathematical relationship between component values and the filter’s pass- or stop-band frequency
NAME: ___________________________  DUE DATE: _______

Design, build, and demonstrate a filter network with a specified “pass” characteristic and cutoff frequency.

This exercise tests your ability to design a simple filter network per specification, combine resistors to form a desired equivalent resistance, operate an oscilloscope, operate a signal generator, and test a filter network for proper function.

The following components and materials will be available to you: a signal generator with variable voltage and frequency; an oscilloscope with probe; an assortment of non-polarized capacitors; an assortment of fixed resistors; and lengths of hook-up wire. You must provide your own tools and a solderless breadboard or terminal blocks as well as a copy of this page for your instructor to mark design criteria.

Filter characteristic (instructor chooses) = ___ Low-pass  ___ High-pass

Cutoff frequency (instructor chooses) = _______ Hz

Your live testing must show the filter’s behavior below, at, and above the specified cutoff frequency. It is strongly recommended that you design your filter circuit such that all component impedance values lie between 1 kΩ and 100 kΩ at the cutoff frequency, to avoid measurement errors as well as excessive signal generator loading. If your design’s resistance value is not the same as any standard resistor size, you must use some combination of fixed resistors to achieve that necessary resistance (i.e. no potentiometers allowed in the real circuit).

SEQUENCE: (1) Instructor chooses criteria; (2) You build and test your circuit (using a multimeter) without any power sources at all; (3) Instructor observes circuit energizing for the very first time; (4) You prove to the instructor that the circuit fulfills its intended function, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we__1111

31
Connect a signal generator to a spectrum analyzer and configure that signal generator to output a signal containing certain harmonic frequencies. The instructor will arbitrarily select a fundamental frequency, and then specify sequential harmonics that are either all odd (e.g. 3rd, 5th, 7th), or both even and odd (e.g. 2nd, 3rd, 4th).

This exercise tests your ability to properly use a signal generator and spectrum analyzer, and also predict harmonic frequencies based on signal wave-shape and fundamental frequency.

The following components and materials will be available to you: signal generator; oscilloscope with spectrum analysis capability; and an assortment of cables for connecting these instruments. You must provide a copy of this page for your instructor to mark design criteria.

**Fundamental frequency** (instructor chooses) = _____ Hz

**Harmonic frequency** (instructor chooses) = _____ Hz

**Harmonic frequency** (instructor chooses) = _____ Hz

**Harmonic frequency** (instructor chooses) = _____ Hz

The harmonic frequencies specified by the instructor (above) should be the only significant harmonics within that frequency range (i.e. there should be no harmonics of significant magnitude with frequencies lying between any of those specified above).

**SEQUENCE:** (1) Instructor chooses criteria; (2) You build and test your circuit (using a multimeter) without any power sources at all; (3) Instructor observes circuit energizing for the very first time; (4) You prove to the instructor that the circuit fulfills its intended function, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we_1106
You may choose your own experiment, ideally one that will help you strengthen your understanding of one or more foundational principles. One suggestion is to choose a concept misunderstood or misapplied on a previous assessment (e.g. a failed exam question).

Checklists for physical experiments, computer simulations, and microcontroller-based experiments appear on the following three pages. Your choice may be any of these types. The instructor will help you identify learning objectives for the experiment you choose.
Checklist for physical experiment

Stage #1 – Experiment planning documented in report

☐ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions

☐ Written experimental plan:
  • Includes schematic diagram showing everything you will build
  • Lists any special steps or conditions necessary for the experiment to run successfully

☐ Written risk analysis:
  • Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  • Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

☐ Was the original hypothesis confirmed? If not, identify why.

☐ Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:

•

•

•
Checklist for computer simulation

Stage #1 – Experiment planning documented in report

☐ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions

☐ Written experimental plan:
  • Includes schematic diagram of simulated circuit in full detail
  • Cites any sampled source code and properly credits that code’s author

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

☐ Was the original hypothesis confirmed? If not, identify why.

☐ Correctly demonstrate every learning objective (see below) in the instructor’s presence, referencing the final data consisting of screen captures from the execution of your code and/or the final version of the source code. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:

•
•
•
Checklist for microcontroller-based experiment

Stage #1 – Experiment planning documented in report

- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions

- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
  - Cites any sampled source code and properly credits that code’s author

- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

- Was the original hypothesis confirmed? If not, identify why.

- Correctly demonstrate every learning objective (see below) in the instructor’s presence, referencing the final data consisting of live demonstration and/or captured images from the instrument(s). Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:

- 
- 
- 

file we_0002
Plan and conduct an experiment to test a transformer’s windings for both turns ratio and polarity. If using a power transformer connected to an AC voltage source such as line voltage, and using an ammeter to measure winding current(s), note that there is a phenomenon you will have to contend with in your experiment called magnetizing current. Know that alternative methods exist, however, for testing turns ratio and polarity.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
- Calculate error between predicted vs. measured values (Error = \( \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\% \)), commenting on the sign of the error and also identifying possible causes
- Demonstrate how to empirically determine a transformer’s winding turns ratio
- Explain why transformers are AC-only devices and cannot “transform” steady DC
- Demonstrate how to properly and safely measure voltage using a multimeter
- Demonstrate how to properly and safely measure voltage using an oscilloscope
Plan and conduct an experiment to demonstrate the behavior of either a boost or buck transformer configuration.

Stage #1 – Experiment planning documented in report

- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions

- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully

- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

  Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

  Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:

- Calculate error between predicted vs. measured values (Error = \( \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\% \)), commenting on the sign of the error and also identifying possible causes
- Demonstrate how to properly and safely measure voltage using a multimeter
- Demonstrate the mathematical relationship between primary and secondary voltages/currents based on the transformer’s nameplate ratings
- Demonstrate how to change a boost circuit into a buck circuit, or vice-versa
Plan and conduct an experiment to demonstrate the measurement of harmonic waveforms in a circuit powered by AC line voltage (120 VAC). At your discretion this may be measurement of harmonics in the line \textit{voltage} or in the load \textit{current}. Risk analysis should include the personal dangers of electric shock as well as the equipment dangers implicit in connecting test equipment to 120 VAC line-powered loads. A recommended precaution is to use the oscilloscope’s \textit{differential} measurement mode so that you will not connect the instrument’s “ground” clip directly to any portion of the 120 VAC circuit.

\textbf{Stage #1 – Experiment planning documented in report}

- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions

- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully

- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

- Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ____ (−10\% per re-try)

\textbf{Stage #2 – Experimental run and data recorded in report}

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a \textit{learning process}. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

\textbf{Stage #3 – Presentation and review}

- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

- Instructor certifies – Re-try if any answer incorrect or incomplete = ____ (−10\% per re-try)

\textbf{Learning objectives for this experiment:}

- Demonstrate proper lock-out/tag-out (LOTO) procedure including how to safety-check your meter before and afterward
- Demonstrate how to safely measure AC line voltage using an oscilloscope
- Demonstrate how to safely measure AC load current using an oscilloscope
- Demonstrate the mathematical relationship between a waveform’s fundamental frequency and its harmonic frequencies
Plan and conduct an experiment to demonstrate the principle of capacitive signal coupling between conductors.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
- Demonstrate how to configure an oscilloscope to measure an AC voltage signal
- Demonstrate the effect of varying signal frequency on the severity of the coupling
- Demonstrate the effect of different signal wave-shapes (e.g. sine, square) on the severity of the coupling
- Identify methods to reduce this coupling if it is undesired
Plan and conduct an experiment to demonstrate the principle of inductive signal coupling between conductors.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
- Demonstrate how to configure an oscilloscope to measure an AC voltage signal
- Demonstrate how to configure a different model of oscilloscope to measure an AC voltage signal
- Identify methods to reduce this coupling if it is undesired
Plan and conduct an experiment to demonstrate line and phase voltage and current magnitudes in both Delta and Wye 3-phase resistive networks.

Sample diagram:

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (–10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (–10% per re-try)

Learning objectives for this experiment:
- Calculate error between predicted vs. measured values (Error = \( \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\% \)), commenting on the sign of the error and also identifying possible causes
- Demonstrate how to properly and safely measure voltage using a multimeter
- Demonstrate how to properly and safely measure current using a multimeter
- Demonstrate the mathematical relationship between different phase and line parameters (voltage, current)
Troubleshoot a fault within a *loaded AC transformer* circuit. This circuit shall be constructed in such a manner that all circuit components and simulated faults must be hidden from view (e.g. covering it up with a box or towel) but test points will be available for contact with a multimeter’s probes. A schematic diagram showing the circuit and its test points will be allowed for use during the troubleshooting exercise.

The circuit shall be powered by the 120 Volt AC line through a glass-cartridge fuse, stepping that voltage down to a level suitable to energize a low-power load (e.g. power resistors). The secondary circuit shall also be fuse-protected. *You are welcome to use your Development Board power supply for this activity.* Possible faults include:

- Any conductor failed open
- Dead power receptacle
- Primary winding failed open
- Secondary winding failed open
- Primary fuse blown
- Secondary fuse blown
- Load failed open

First, you will demonstrate that the system functions properly. Then the instructor will either set up or supervise other students setting up a random fault in that system (hidden from view) while you are out of the room. You will then have a limited amount of time to independently perform measurements and other tests while under the continuous observation of the instructor. A successful troubleshooting exercise consists of both correctly identifying the location and nature of the fault, as well as logically defending the necessity of each diagnostic step. Incorrect fault identification, unnecessary steps, and/or incorrect defense of any step will result in a failed attempt. Your only access to the faulted circuit will be via the test points, and only one unpowered test will be permitted.

If you must work remotely rather than in-person, the faulted system must be at the instructor’s location while you request measurements and other diagnostic tests of the instructor via teleconferencing system (e.g. videoconference, telephone, text messaging).

Troubleshooting is *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try begins with another randomized fault on the same circuit. Scoring is based on the number of attempts necessary to successfully troubleshoot a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%).

file we 1015
Design, build, and demonstrate a transformer circuit that either boosts or bucks AC line voltage. All electrical connections must be made using a terminal strip for safety (no twisted wires, crimp splices, wire nuts, spring clips, or “alligator” clips permitted). The incoming power (120 VAC) must be fused for overcurrent protection.

This exercise tests your ability to determine transformer winding polarity, to correctly wire a voltage-boosting or voltage-bucking transformer circuit, compute winding voltages based on known ratios, and to properly account for a transformer’s voltage regulation (percentage) rating in your calculations.

The following components and materials will be available to you: Variac for varying line voltage; a small power transformer; an inline fuse holder; an assortment of AGC-style glass fuses; lengths of hook-up wire; and a 120 VAC power cord. You must provide your own tools, Development Board, and digital multimeter (DMM) as well as a copy of this page for your instructor to mark design criteria.

Transformer ratio = _______ (known from previous experimentation)

Line voltage (instructor chooses) = _______ Volts RMS

Boost or Buck (instructor chooses) = _______

Output voltage (you predict) = _______ Volts (should be within ±5% of measured voltage)

SEQUENCE: (1) Instructor chooses criteria; (2) You build and test your circuit (using a multimeter) without any power sources at all; (3) Instructor observes circuit energizing for the very first time; (4) You prove to the instructor that the circuit fulfills its intended function, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we_1109
You may choose your own experiment, ideally one that will help you strengthen your understanding of one or more foundational principles. One suggestion is to choose a concept misunderstood or misapplied on a previous assessment (e.g. a failed exam question).

Checklists for physical experiments, computer simulations, and microcontroller-based experiments appear on the following three pages. Your choice may be any of these types. The instructor will help you identify learning objectives for the experiment you choose.
Checklist for physical experiment

Stage #1 – Experiment planning documented in report

☐ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions

☐ Written experimental plan:
  • Includes schematic diagram showing everything you will build
  • Lists any special steps or conditions necessary for the experiment to run successfully

☐ Written risk analysis:
  • Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  • Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

☐ Was the original hypothesis confirmed? If not, identify why.

☐ Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = ____ (−10% per re-try)

Learning objectives for this experiment:

•
•
•
### Checklist for computer simulation

**Stage #1 – Experiment planning documented in report**
- **Written hypothesis:**
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- **Written experimental plan:**
  - Includes schematic diagram of simulated circuit in full detail
  - Cites any sampled source code and properly credits that code’s author

☐ *Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ___ (−10% per re-try)*

**Stage #2 – Experimental run and data recorded in report**
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a *learning process*. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

**Stage #3 – Presentation and review**
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate every learning objective (see below) in the instructor’s presence, referencing the final data consisting of screen captures from the execution of your code and/or the final version of the source code. Note: have a calculator or appropriate software ready for analyzing the data!

☐ *Instructor certifies – Re-try if any answer incorrect or incomplete = ___ (−10% per re-try)*

**Learning objectives for this experiment:**

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- 
-
Checklist for microcontroller-based experiment

Stage #1 – Experiment planning documented in report

☐ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions

☐ Written experimental plan:
  • Includes schematic diagram showing everything you will build
  • Lists any special steps or conditions necessary for the experiment to run successfully
  • Cites any sampled source code and properly credits that code’s author

☐ Written risk analysis:
  • Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  • Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

☐ Was the original hypothesis confirmed? If not, identify why.

☐ Correctly demonstrate every learning objective (see below) in the instructor’s presence, referencing the final data consisting of live demonstration and/or captured images from the instrument(s). Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:

•
•
•

file we_0002
Plan and conduct an experiment to demonstrate the behavior of a full-wave bridge rectifier circuit.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
- Demonstrate how to calculate frequency from AC period measured on an oscilloscope
- Demonstrate how to calculate AC period from a given frequency value
- Demonstrate the “hot chassis” phenomenon (hint: building your circuit on two different chassis – such as terminal blocks clamped on different DIN rails – helps with this demo!)
- Demonstrate the mathematical relationship between peak AC voltage and peak rectified voltage for a bridge rectifier circuit
Plan and conduct an experiment to demonstrate the reduction of ripple voltage from a rectifier circuit by using a filter capacitor. **Sample hypothesis:** “Using a filter capacitor of __ µF on a rectifier powering a __ Ω load will result in a peak-to-peak ripple voltage of __ Volts.”

<table>
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**Learning objectives for this experiment:**

- Demonstrate the uses of DC versus AC versus Ground coupling modes on an oscilloscope
- Demonstrate multiple triggering options on an oscilloscope
- Demonstrate the mathematical relationship between ripple voltage, load current, and capacitor rating
Plan and conduct an experiment to demonstrate the control of AC power to a load using one or more thyristors.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
- Demonstrate how to capture a transient voltage waveform on a digital oscilloscope screen, and then measure its rate-of-change of any portion of a the wave (i.e. \( \frac{dV}{dt} \))
- Demonstrate multiple triggering options on an oscilloscope
- Demonstrate how to “trigger” or “fire” a thyristor
- Demonstration how a thyristor turns off
Plan and conduct an experiment to demonstrate the principle of pulse-width modulation power control.

**Stage #1 – Experiment planning documented in report**

- **Written hypothesis:**
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- **Written experimental plan:**
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- **Written risk analysis:**
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

  **Instructor certifies ready to run** – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

**Stage #2 – Experimental run and data recorded in report**

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

**Stage #3 – Presentation and review**

- **Was the original hypothesis confirmed?** If not, identify why.
- **Correctly demonstrate and explain** every learning objective (see below) for the instructor, either live or by electronically recorded data. **Note:** have a calculator or appropriate software ready for analyzing the data!

  **Instructor certifies** – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

**Learning objectives for this experiment:**

- Demonstrate how to configure a digital oscilloscope to capture a pulse signal
- Demonstrate how to measure the frequency of a pulse signal from an oscillograph
- Demonstrate how to measure the duty cycle of a pulse signal from an oscillograph
- Demonstrate the mathematical relationship between duty cycle and average load power
Plan and conduct an experiment to demonstrate the principle of DC-to-AC power conversion ("inversion").

Stage #1 – Experiment planning documented in report
○ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions
○ Written experimental plan:
  • Includes schematic diagram showing everything you will build
  • Lists any special steps or conditions necessary for the experiment to run successfully
○ Written risk analysis:
  • Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  • Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

□ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
○ Was the original hypothesis confirmed? If not, identify why.
○ Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

□ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
  • Demonstrate how to capture the shape of the AC waveform output by your experimental circuit
  • Demonstrate multiple triggering options on an oscilloscope
  • Demonstrate control over the AC output’s frequency
  • Demonstrate how to measure the harmonic content of the AC waveform output by your experimental circuit
Plan and conduct an experiment to demonstrate the principle of DC-to-DC power conversion.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Learning objectives for this experiment:
- Demonstrate the mathematical relationship between duty cycle and output/input voltage ratio
- Demonstrate how to capture a pulse signal using a digital oscilloscope
- Demonstrate multiple triggering options on an oscilloscope
- Demonstrate how to empirically measure power conversion efficiency ($\frac{P_{out}}{P_{in}}$)
Troubleshoot a fault within a brute-force AC-DC power supply circuit. This circuit shall be constructed in such a manner that all circuit components and simulated faults must be hidden from view (e.g., covering it up with a box or towel) but test points will be available for contact with a multimeter’s probes. A schematic diagram showing the circuit and its test points will be allowed for use during the troubleshooting exercise.

The circuit shall be powered by the 120 Volt AC line through a glass-cartridge fuse, stepping that voltage down to a level suitable to energize a low-power load (e.g., power resistors). The secondary circuit shall also be fuse-protected. Possible faults include:

- Any conductor failed open
- Dead power receptacle
- Primary winding failed open
- Secondary winding failed open
- Primary fuse blown
- Secondary fuse blown
- Any diode failed open
- Load failed open
- Capacitor failed shorted

First, you will demonstrate that the system functions properly. Then the instructor will either set up or supervise other students setting up a random fault in that system (hidden from view) while you are out of the room. You will then have a limited amount of time to independently perform measurements and other tests while under the continuous observation of the instructor. A successful troubleshooting exercise consists of both correctly identifying the location and nature of the fault, as well as logically defending the necessity of each diagnostic step. Incorrect fault identification, unnecessary steps, and/or incorrect defense of any step will result in a failed attempt. Your only access to the faulted circuit will be via the test points, and only one unpowered test will be permitted.

If you must work remotely rather than in-person, the faulted system must be at the instructor’s location while you request measurements and other diagnostic tests of the instructor via teleconferencing system (e.g., videoconference, telephone, text messaging).

Troubleshooting is mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try begins with another randomized fault on the same circuit. Scoring is based on the number of attempts necessary to successfully troubleshoot a circuit (e.g., 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%).
Design, build, and demonstrate a voltage-regulated DC circuit using a three-terminal linear voltage regulator IC, choosing a load resistance sufficient to cause the regulator to dissipate as much heat as it can bear (with no heat sink attached) without going into thermal shutdown mode.

This exercise tests your ability to properly calculate electrical loading based on given voltage parameters and thermal ratings specified in the device’s datasheet, as well as apply basic electrical principles (e.g. Ohm’s Law, Joule’s Law, thermal resistance calculations) and build a load out of resistors suitable for the purpose.

The following components and materials will be available to you: DC power supply with variable voltage output; an assortment of 3-terminal regulator ICs (e.g. 7805, 7808, 7812, 7815, 78M33, etc); lengths of hook-up wire; and an assortment of power resistors. You must provide your own tools, a digital multimeter (DMM), and a solderless breadboard as well as a copy of this page for your instructor to mark design criteria.

**DC power supply voltage** (instructor chooses) = _______ V

**Regulated load voltage** (instructor chooses) = _______ V

When operating, the regulator’s metal tab should become hot to the touch, but the load voltage should remain at the regulated value, proving that the IC does not go into thermal shutdown mode. Note that ambient room temperature is an important variable here and must be considered in your calculations.

**SEQUENCE:** (1) Instructor chooses criteria; (2) You build and test your circuit (using a multimeter) without any power sources at all; (3) Instructor observes circuit energizing for the very first time; (4) You prove to the instructor that the circuit fulfills its intended function, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we_1108
You may choose your own experiment, ideally one that will help you strengthen your understanding of one or more foundational principles. One suggestion is to choose a concept misunderstood or misapplied on a previous assessment (e.g. a failed exam question).

Checklists for physical experiments, computer simulations, and microcontroller-based experiments appear on the following three pages. Your choice may be any of these types. The instructor will help you identify learning objectives for the experiment you choose.
Checklist for physical experiment

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Learning objectives for this experiment:
- 
- 
-
Checklist for computer simulation

Stage #1 – Experiment planning documented in report
○ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions
○ Written experimental plan:
  • Includes schematic diagram of simulated circuit in full detail
  • Cites any sampled source code and properly credits that code’s author
    ☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
○ Was the original hypothesis confirmed? If not, identify why.
○ Correctly demonstrate every learning objective (see below) in the instructor’s presence, referencing the final data consisting of screen captures from the execution of your code and/or the final version of the source code. Note: have a calculator or appropriate software ready for analyzing the data!
  ☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
•
•
•
Checklist for microcontroller-based experiment

Stage #1 – Experiment planning documented in report

☐ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions

☐ Written experimental plan:
  • Includes schematic diagram showing everything you will build
  • Lists any special steps or conditions necessary for the experiment to run successfully
  • Cites any sampled source code and properly credits that code’s author

☐ Written risk analysis:
  • Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  • Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

☐ Was the original hypothesis confirmed? If not, identify why.

☐ Correctly demonstrate every learning objective (see below) in the instructor’s presence, referencing the final data consisting of live demonstration and/or captured images from the instrument(s). Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:

•
•
•
Plan and conduct an experiment to demonstrate the behavior of a 7-segment decoder IC (e.g. 74LS47, CD4511) used to drive the seven segments of an LED digit display based on a four-bit binary code.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings
- Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!
- Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:
- Demonstrate how to use a multimeter as a logic probe to sense “high” and “low” logic states in a circuit
- Demonstrate the conversion between binary and decimal notations
- Demonstrate how to choose appropriate current-limiting resistors for the LEDs in the 7-segment display
- Demonstrate how to determine (using test equipment) whether your 7-segment display is common-cathode or common-anode
Plan and conduct an experiment to demonstrate an arbitrary truth table implemented using a digital multiplexer IC. The truth table will have three inputs and be randomly assigned by the instructor. The gate circuit must drive a DC load requiring more current than the multiplexer alone can source or sink.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

Learning objectives for this experiment:
- Demonstrate how to design a gate-based logic circuit to implement a given truth table
- Demonstrate how to use a multimeter as a logic probe to sense “high” and “low” logic states in a circuit
- Demonstrate and explain what will happen if any of the multiplexer’s inputs becomes electrically “floating”
Plan and conduct an experiment to demonstrate the functionality of a JK flip-flop IC.

Stage #1 – Experiment planning documented in report

○ Written hypothesis:
  • Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  • Table or graph ready to receive data and easily compare with predictions
  • Shows all supporting mathematical work for all quantitative predictions

○ Written experimental plan:
  • Includes schematic diagram showing everything you will build
  • Lists any special steps or conditions necessary for the experiment to run successfully

○ Written risk analysis:
  • Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  • Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

☐ Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

○ Was the original hypothesis confirmed? If not, identify why.

○ Correctly demonstrate and explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

☐ Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

Learning objectives for this experiment:

• Demonstrate each of the following modes: set, reset, and toggle
• Demonstrate how to use a multimeter as a logic probe to sense “high” and “low” logic states in a circuit
• Demonstrate the principle of frequency division using a JK flip-flop
• Demonstrate how to measure the rise time and fall time of a digital pulse signal
Plan and conduct an experiment to demonstrate a multi-digit counter using 4-bit counter ICs and 7-segment decoder/driver ICs.

Stage #1 – Experiment planning documented in report

- **Written hypothesis:**
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions

- **Written experimental plan:**
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully

- **Written risk analysis:**
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

- **Instructor certifies ready to run** – Re-try if detail(s) missing or incomplete = ______ (−10% per re-try)

Stage #2 – Experimental run and data recorded in report

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a *learning process*. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review

- **Was the original hypothesis confirmed?** If not, identify why.
- **Correctly demonstrate and explain** every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!

- **Instructor certifies** – Re-try if any answer incorrect or incomplete = ______ (−10% per re-try)

Learning objectives for this experiment:

- Demonstrate how to clear the counter to a value of zero
- Demonstrate how to preset the counter to a non-zero value
- Demonstrate whether this counter is synchronous or asynchronous
- Demonstrate propagation delay from the simultaneous measurement of two different signals in this counter circuit

file wc_0217
Plan and conduct an experiment to demonstrate a PLC counter instruction controlling the energization of a suitable load based on the counter instruction’s count value.

Stage #1 – Experiment planning documented in report
- Written hypothesis:
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- Written experimental plan:
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
  - Cites any sampled source code and properly credits that code’s author
- Written risk analysis:
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = ______ (-10% per re-try)

Stage #2 – Experimental run and data recorded in report
Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a learning process. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

Stage #3 – Presentation and review
- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate every learning objective (see below) in the instructor’s presence, referencing the final data consisting of live demonstration and/or captured images from the instrument(s). Note: have a calculator or appropriate software ready for analyzing the data!

Instructor certifies – Re-try if any answer incorrect or incomplete = ______ (-10% per re-try)

Learning objectives for this experiment:
- Demonstrate how to clear the counter to a value of zero
- Demonstrate how to preset the counter to a non-zero value
- Demonstrate how to make the counter count both up and down
- Demonstrate how to monitor the counter’s count value in formats other than decimal (e.g. binary, hex)
Plan and conduct an experiment to demonstrate a PLC timer instruction controlling the energization of a suitable load based on the timer instruction’s accumulated time value.

**Stage #1 – Experiment planning documented in report**

- **Written hypothesis:**
  - Makes clear, original, and verifiable prediction(s) addressing all learning objectives
  - Table or graph ready to receive data and easily compare with predictions
  - Shows all supporting mathematical work for all quantitative predictions
- **Written experimental plan:**
  - Includes schematic diagram showing everything you will build
  - Lists any special steps or conditions necessary for the experiment to run successfully
  - Cites any sampled source code and properly credits that code’s author
- **Written risk analysis:**
  - Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
  - Identifies/calculates hardware risks and mitigations, citing applicable datasheet ratings

- Instructor certifies ready to run – Re-try if detail(s) missing or incomplete = _____ (−10% per re-try)

**Stage #2 – Experimental run and data recorded in report**

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a **learning process**. Record all data, including any mistakes, in a single digital document along with your instructor-certified planning work from stage #1.

**Stage #3 – Presentation and review**

- **Was the original hypothesis confirmed?** If not, identify why.
- **Correctly demonstrate every learning objective** (see below) in the instructor’s presence, referencing the final data consisting of live demonstration and/or captured images from the instrument(s). Note: have a calculator or appropriate software ready for analyzing the data!

- Instructor certifies – Re-try if any answer incorrect or incomplete = _____ (−10% per re-try)

**Learning objectives for this experiment:**

- Demonstrate the operation of an “on-delay” timer instruction
- Demonstrate the operation of an “off-delay” timer instruction
- Demonstrate the operation of a “retentive” timer instruction
- Demonstrate how to monitor the timer’s accumulated time value in formats other than decimal (e.g. binary, hex)
Troubleshoot a fault within a *multi-digit counter* circuit where the clock signal comes from either a manual switch or a signal generator set to low frequency. This circuit shall be constructed in such a manner that all circuit components and simulated faults must be hidden from view (e.g. covering it up with a box or towel) but test points will be available for contact with a multimeter’s probes. A schematic diagram showing the circuit and its test points will be allowed for use during the troubleshooting exercise.

Possible faults include:
- Power supply failure
- Any conductor failed open
- Any component failed open
- Any component failed shorted
- Any counter output pin failed high
- Any counter output pin failed low
- Any decoder output pin failed high
- Any decoder output pin failed low

First, you will demonstrate that the system functions properly. Then the instructor will either set up or supervise other students setting up a random fault in that system (hidden from view) while you are out of the room. You will then have a limited amount of time to independently perform measurements and other tests while under the continuous observation of the instructor. A successful troubleshooting exercise consists of both correctly identifying the location and nature of the fault, as well as logically defending the necessity of each diagnostic step. Incorrect fault identification, unnecessary steps, and/or incorrect defense of any step will result in a failed attempt. Your only access to the faulted circuit will be via the test points, and only one unpowered test will be permitted.

If you must work remotely rather than in-person, the faulted system must be at the instructor’s location while you request measurements and other diagnostic tests of the instructor via teleconferencing system (e.g. videoconference, telephone, text messaging).

Troubleshooting is *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try begins with another randomized fault on the same circuit. Scoring is based on the number of attempts necessary to successfully troubleshoot a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%).

file we 1026

67
Design, build, and demonstrate a circuit where a programmable logic controller (PLC) controls the on/off status of a small electric motor according to the state of one or more pushbutton switches. Your circuit must use an “ice-cube” relay to interpose between the PLC’s output channel and the electric motor. You must connect a “commutating” diode in parallel with the relay’s coil to prevent the phenomenon known as “inductive kickback,” which may otherwise damage the transistor output on a PLC. Note that incorrectly connecting this diode will present a short-circuit to the PLC, so you must get it right!

This exercise tests your ability to properly interface devices with a PLC, to create a ladder-logic program for a PLC, to interpose between the PLC’s current-limited output channels and a load requiring much more current, to properly install a commutating diode.

The following components and materials will be available to you: assorted “ice cube” relays with DC-rated coils and matching sockets; terminal blocks; 1N400X rectifying diodes; assorted pushbutton switches; lengths of hook-up wire. You will be expected to supply your own screwdrivers and multimeter for assembling and testing the circuit at your desk, as well as a copy of this page for your instructor to mark conditions.

“Start” switch to input: ___  “Stop” switch to input: ___  Relay to output: ___

PLC program (instructor chooses one of these options):

___ Motor starts after “start” switch pressed ___ times, stops with one press of “stop” switch
___ Motor starts with one press of “start” switch, stops when “stop” switch pressed ___ times
___ Motor starts after “start” switch held for ___ seconds, stops immediately when “stop” pressed
___ Motor starts immediately, stops if “stop” switch held for ___ seconds

Your program must be written such that every start/stop cycle behaves the same.

SEQUENCE: (1) Instructor chooses criteria; (2) You write the PLC program, testing it on a PLC to ensure it works properly; (3) Instructor observes you running your program with the chosen criteria and documenting its results; (4) You build and test the complete circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we 1125
46 Lab clean-up

NAME: __________________________

This list represents all of the major work-items that must be done at every semester’s end to prepare the lab space for the upcoming semester. Each student will have at least one task assigned to them.

**Non-technical tasks**

- Thoroughly clean whiteboard(s)
- Vacuum-clean the floor of all debris
- Clean all workbench surfaces
- Organize all cables, cords, test leads neatly into their storage locations
- Clean the interior of all electrical enclosures and cabinets with a vacuum cleaner and test equipment surfaces
- Clean all electrical panel and test equipment outer surfaces
- Note any depleted bins (electronic components, threaded fasteners, cables, etc.)
  → Report to instructor for re-ordering in preparation for next semester

**Technical tasks**

- Check fastener storage bins to ensure no fasteners are misplaced
- Check digital IC storage bins to ensure no ICs are misplaced
- Check resistor storage bins to ensure no resistors are misplaced
- Check inductor/transformer storage bins to ensure no inductors or transformers are misplaced
- Check capacitor storage bins to ensure no capacitors are misplaced
- Test oscilloscopes for basic functionality (e.g. all channels functional, all vertical sensitivity settings functional, all timebase settings functional, triggering functions properly)
- Test signal generators for basic functionality (e.g. all waveshapes functional, magnitude adjustment functional, frequency adjustment(s) functional)
- Test power supplies for basic functionality (e.g. voltage adjustments functional, current limits functional, voltage/current meters functional)
- Test benchtop multimeters for basic functionality (e.g. all voltage ranges functional, all current ranges functional, overcurrent fuse good)
- Test and clean all soldering stations (e.g. clean/replace sponge pads, check tips for wear, ensure correct temperature settings and that the tip solders well)
- Test permanently-installed demonstration projects for basic functionality (read instructions on each!) and secure for break; ensure each project has a printed schematic diagram in place
- Test renewable energy power grid (e.g. all circuit breakers trip and close, no fuses blown) and secure for break
When designing and constructing circuits for experimental and prototyping purposes, the following tips are recommended for success:

- **Sketch a schematic diagram before constructing anything.** You need to have a clear understanding of what it is you intend to build before you begin building, in order to avoid major errors and hazards, and planning your build in schematic form is an excellent way to do that. Having a clear diagram in hand also aids others who you might wish to help you if things don’t work as planned.

- **Build and test in stages.** If you try to build the entire system before testing it, you will very likely encounter multiple errors which will be more time-consuming to diagnose than if you took the time to build and test each portion of your circuit before building and testing the next portion.

- **Choose resistor values between 1,000 and 100,000 Ohms** unless there is some compelling design rationale for using a smaller or larger values. Reactance values within AC circuits should also fall within these same limits. Circuits built with low-value resistors tend to dissipate a lot of power when energized by constant-voltage sources, while circuits built with high-value resistors tend to exhibit “signal sag” when connected to loads and/or test equipment.

- **Use decoupling capacitors** connected in parallel with the DC power pins of every integrated circuit, to stabilize DC voltage for reliable operation. This is especially critical for high-speed digital circuits and sensitive analog circuits, where variations in DC supply voltage may compromise signal integrity. 1 µF ceramic capacitors work well for this purpose, and should be located as close to each IC’s power supply terminals as possible.

- **Diversify your learning experience** by using different types of test equipment (e.g. DMMs, VOMs, oscilloscopes), different types of construction techniques (e.g. solderless breadboards, soldered connections, terminal blocks), and different types of power sources. Remember, the reason you are in this course is to learn, not just to complete assignments!

When using sources of energy other than laboratory-quality power supplies, you may need to stabilize source voltage to ensure reliable circuit function. This is especially true when using chemical batteries, solar panels, and other electrical sources known for varying voltage output. A simple integrated circuit called a **three-terminal fixed voltage regulator** takes in power at some voltage larger than what your circuit needs, and dissipatively reduces the voltage level to a fixed value determined by the part number of the regulator IC. The popular **LM78xx** series of voltage regulators is recommended, where the last digits represent the fixed output voltage (e.g. 7805 = 5 Volts, 7812 = 12 Volts, etc.). An illustration showing how such a regulator might be installed in a solderless breadboard for general experiment/prototype use is shown here:

Capacitors $C_1$ and $C_2$ help stabilize the regulated voltage if your circuit’s current happens to pulse rather than be steady over time. Consult the regulator IC’s datasheet for pin designations, recommended capacitor sizes, and also for general maximum voltage and current ratings.
General Troubleshooting Advice

All electronic circuit faults fall into at least one of these categories:

- **Connection fault** – the components are not properly connected together.
- **Design flaw** – the circuit cannot work because something about it is incorrectly designed.
- **Lack of power/signal or poor quality** – the power and/or signal source is “dead” or “noisy”
- **Component fault** – one or more components is faulty.
- **Test equipment** – either the test equipment itself is faulty, or is not being used appropriately.

Of these categories, the one causing more problems for students initially learning about circuits than all the others is the first: *connection fault*. This is because the ability to translate an idea and/or a schematic diagram into a physical circuit is a skill requiring time to develop. Many such problems may be avoided by (1) drawing a complete schematic of what you intend to build before you build it, (2) marking that schematic to show which connections have been made and which are left to make as you are wiring it, and (3) using an ohmmeter (not your eyes!) to verify that every pair of points which should be connected are connected and that no points which should be electrically distinct from each other are in fact electrically common.

**Troubleshooting strategies**

- **Verify the symptom(s)** – Always check to see that the symptom(s) match what you’ve been told by others. Even if the symptoms were correctly reported, you may notice additional (unreported) symptoms helpful in identifying the fault.
- **Verify good power quality** – Is the source voltage within specifications, and relatively free of “ripple” and other noise?
- **Check signals at component terminals** – Use an oscilloscope or multimeter to check for proper signals at each of the component pins, to see if each one matches your expectations. An important check, especially for integrated circuits, is whether the measured output signal(s) are appropriate for the measured input signal(s).
- **Simply the system** – If possible, re-configure the circuit to be as simple as possible, because complexity makes faults harder to find.
- **Swap identical components** – If particular a component is suspected of being faulty, and you are able to swap another (identical) component for it, do so to see whether or not the problem moves with the old component. If so, that component is to blame; if not, the problem lies elsewhere.
- **Always look for Root Cause(s)** – don’t declare success simply by finding the proximate (i.e. the most direct) cause, but continue your search to find what design flaw, circumstance, or other distal cause led to it.