

# IETTI-112 – AC Circuit Experiments (Semester 2 EXPERIMENTS)

NAME: \_\_\_\_\_

Last update 26 February 2024

Activity #	Due by session #12	Score
00 Experiment	Introduction ( <i>complete this “experiment” first!</i> )	— — —
01 Experiment	Demonstrate Ohm’s Law in a simple AC circuit	
02 Experiment	AC line power conductor identification	
03 Experiment	Test soldered wire joint integrity	
04 Experiment	Test soldered PCB joint integrity	
05 Experiment	Demonstrate AC frequency measurement using an oscilloscope	
06 Experiment	Demonstrate Lissajous figures using an oscilloscope	
07 Experiment	Demonstrate meter vs oscilloscope voltage measurement	
08 Assessment	Troubleshoot loaded voltage divider (simulation)	
09 Assessment	Demonstrate lock-out/tag-out procedure	

Activity #	Due by session #24	Score
10 Experiment	Demonstrate oscilloscope probe compensation	
11 Experiment	Demonstrate phase shift in series RC circuit	
12 Experiment	Demonstrate phase shift in parallel RC circuit	
13 Experiment	Demonstrate resonance	
14 Experiment	Demonstrate harmonic frequencies	
15 Experiment	Demonstrate high-pass or low-pass filtering	
16 Experiment	Demonstrate band-pass or band-stop filtering	
17 Assessment	Design and build RC filter network	
18 Assessment	Produce a signal with specified harmonics	

Activity #	Due by session #36	Score
19 Experiment	<i>Choose your own</i>	
20 Experiment	Demonstrate transformer ratio and polarity	
21 Experiment	Demonstrate boost or buck transformer configuration	
22 Experiment	Demonstrate harmonic content of AC line power	
23 Experiment	Demonstrate capacitive coupling within a cable	
24 Experiment	Demonstrate inductive coupling within a cable	
25 Experiment	Demonstrate three-phase Delta and Wye networks	
26 Assessment	Troubleshoot loaded transformer circuit	
27 Assessment	Design and build a boost/buck transformer circuit	

Activity #	Due by session #48	Score
28 Experiment	<i>Choose your own</i>	
29 Experiment	Demonstrate full-wave bridge rectification	
30 Experiment	Demonstrate ripple voltage filtering	
31 Experiment	Demonstrate thyristor control of AC load power	
32 Experiment	Demonstrate PWM power control	
33 Experiment	Demonstrate DC-AC power conversion	
34 Experiment	Demonstrate DC-DC power conversion	
35 Assessment	Troubleshoot brute force AC-DC power supply circuit	
36 Assessment	Design and build voltage regulator for maximum thermal loading	

Activity #	Due by the last day	Score
37 Experiment	<i>Choose your own</i>	
38 Experiment	Demonstrate 7-segment decoder	
39 Experiment	Demonstrate multiplexer implementing arbitrary truth table	
40 Experiment	Demonstrate functionality of a JK flip-flop	
41 Experiment	Demonstrate multi-digit counting	
42 Experiment	Demonstrate PLC counter instruction	
43 Experiment	Demonstrate PLC timer instruction	
44 Assessment	Troubleshoot multi-digit counter circuit	
45 Assessment	Design and build PLC-based motor control system	

46 Lab clean-up	Clean and organize the entire lab room	
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#### Essential information about this course:

- This course is based on *empirical learning*: acquiring knowledge and skill through direct hands-on experience. In it you will be challenged not only to apply concepts learned in your Theory coursework but also explore and discover new concepts by testing ideas on hardware. Your instructor will offer advice on how to solve these problems, but the actual solving of these problems is your responsibility.
- 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 is 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 prescribed 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 IETTT-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 digital counter circuits 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 236 (Projects)

<b>Tool, Supply, or Software installation</b>	Thy 101	Exp 103	Prj 102	Thy 104	Exp 112	Prj 105	Thy 222	Exp 221	Prj 220	Thy 223	Exp 225	Prj 236
\$25 scientific calculator	X	X	X	X	X	X	X	X	X	X	X	X
\$300 personal computer	X	X	X	X	X	X	X	X	X	X	X	X
\$10 USB “flash” drive	X	X	X	X	X	X	X	X	X	X	X	X
\$50-\$400 digital multimeter		X	X		X	X		X	X		X	X
\$150 USB-based oscilloscope		X	X		X	X		X	X		X	X
\$10 solderless breadboard (e.g. Busboard BB830)		X	X		X	X		X	X		X	X
\$25 grounding wrist strap		X	X		X	X		X	X		X	X
\$10 slotted screwdrivers (1/8”,1/4”)		X	X		X	X		X	X		X	X
\$10 Phillips screwdrivers (#1,#2)		X	X		X	X		X	X		X	X
\$10 jeweler’s screwdriver set		X	X		X	X		X	X		X	X
\$10 wire strippers, 18-24 AWG		X	X		X	X		X	X		X	X
\$10 needle-nose pliers		X	X		X	X		X	X		X	X
\$20 diagonal wire cutters		X	X		X	X		X	X		X	X
\$10 metal rule (inches & mm)		X	X		X	X		X	X		X	X
\$10 alligator-clip jumper wires (package of at least ten)		X	X		X	X		X	X		X	X
\$15 batteries: 6 Volt and 9 Volt		X	X		X	X		X	X		X	X
\$15 illuminated jeweler’s loupe		X	X		X	X		X	X		X	X
\$10 safety glasses			X		X	X			X			X
\$25-\$100 soldering iron (pencil-tip), 30 Watts or less			X		X	X			X			X
\$15 tube/spool of rosin-core solder			X		X	X			X			X
\$90 PLC I/O card		X			X			X			X	
\$15 microcontroller and software								X			X	X
\$0 software: Python interpreter	X			X			X			X	X	X
\$0 software: schematic editor		X	X		X	X		X	X		X	X
\$0 software: Notepad++ text editor		X			X			X			X	
\$0 software: NGSPICE circuit sim.		X			X			X			X	
\$0 software: WSL		X			X			X			X	
\$0 software: tshoot fault sim.		X			X			X			X	
\$0 software: PCB layout editor											X	X
\$0 software: packet-sniffing software										X	X	X
\$0 archive: EETREF collection	X			X			X			X		

## 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 either the Texas Instruments model TI-36X Pro or the Casio model fx-115ES because they easily perform complex-number arithmetic necessary for AC circuit analysis and are 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. Most operating systems, size of hard drive, amount of RAM memory, and screen size is appropriate, but your computer must have a keyboard and mouse (i.e. no tablets). Avoid ChromeBooks. 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),  $\pm 100$  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 IETTL-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.

**PLC I/O card** – any DC combo input-output card designed for use with Automation Direct Koyo “CLICK” PLC processors, such as the model C0-16CDD1 or C0-16CDD2 eight-point DC I/O cards.

**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 (MSP430G2553IN20 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 and documentation required for these courses is free, and much of it is open-source.

**Python interpreter** – available from `python.org` as a free download, Python is an interpreted programming language that works exceptionally as a scientific calculator. When installing, be sure to enable “Add python.exe to PATH” option.

**Schematic editor** – this is used to draft schematic diagrams for circuits. KiCad offers an excellent schematic editor as well as other tools useful for creating printed circuit board (PCB) layouts.

**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. **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. 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`

**tshoot** – this is a 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`

**EETREF document collection** – an archive of manufacturer datasheets, manuals, tutorials, application notes, whitepapers, regulatory standards, and other documents in electronic form stored on every computer in the lab, in a folder marked “EETREF”. Copy this collection to your own computer for future reference.

**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. Again, KiCad is highly recommended.

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

**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 on a microcontroller. For the Texas Instruments MSP430 we use **Code Composer Studio** as it supports assembly language, C, and C++. A third-party add-on called **Energia** supports Sketch programming, identical to that used by the popular Arduino microcontroller.

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## 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 unfinished by 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.

## Getting help in the lab

Success in this career is largely a function of your ability to *independently* solve complex problems and to *empirically* learn new concepts and techniques. You will find the design, construction, testing, and diagnosis of real circuits and systems catalyze these abilities. During this course you may at times find yourself faced with a seemingly unsolvable problem. Your instructor's job is to provide practical advice useful for solving these problems, without directly solving them for you. Although this may feel frustrating for your instructor to withhold a solution from you, know that letting others solve these problems for you actually hinders your own professional development and limits your career opportunities.

Any time you request help, 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 prompt 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!

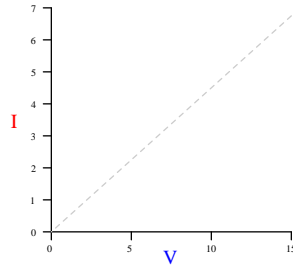
A final suggestion to help you complete experiment and project assignments is to consult the Case Tutorial, Tutorial, and Questions chapters of the learning modules referenced your Theory course sessions for circuit ideas. If you find yourself unsure of where to begin for assigned experiments and/or projects, these references are almost always sure to help because they directly relate to the foundational concepts and principles taught in this program. Be sure to consult these references *before* requesting help from your instructor and/or classmates.

## Example experiment report – Stage #1 (planning)

Experiment: Demonstrate Ohm's Law

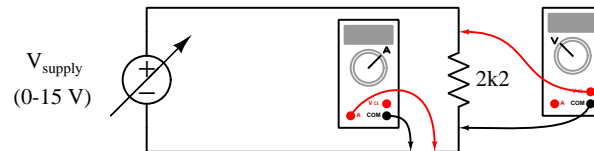
**Hypothesis** Current will be directly proportional to voltage applied across a resistor, in accordance with the formula  $I = \frac{V}{R}$  using a  $2.2 \text{ k}\Omega$  resistor:

Applied Voltage	Predicted current	Measured current	Comparison
0 V	0 mA		
5 V	2.2727 mA		
10 V	4.5455 mA		
15 V	6.8182 mA		



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

### Experimental plan



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!

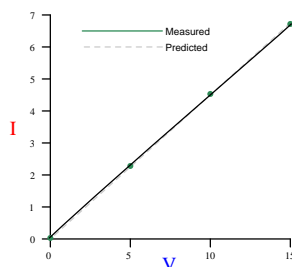
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## Example experiment report – Stage #2 (data recording)

Experiment: Demonstrate Ohm's Law

Recorded data

Applied Voltage	Predicted current	Measured current	Comparison
0 V	0 mA	0.01 mA	+0.01 mA error
5 V	2.2727 mA	2.28 mA	+0.321% error
10 V	4.5455 mA	4.56 mA	+0.319% error
15 V	6.8182 mA	6.80 mA	−0.267% error



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

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

Analysis

Hypothesis is confirmed, as measured current is shown to be well within  $\pm 5\%$  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.

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## Example experiment report – Stage #3 (presentation)

*Experiment: Demonstrate Ohm's Law*

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Presentation and review
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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 competely 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!*

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## 00 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Here you will research and explain how this course functions, as a prerequisite to starting any of the experiments. Your instructor will certify each of these as complete when answered correctly.

- ☐ 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?
  - Why will your instructor insist you do all these things *before* requesting help?
  
- ☐ Read the “Grading standards for Experiment courses” in this course document and answer the following questions:
  - How is your grade for this course calculated?
  - Are all activities equally weighted, or do some count for a larger percentage of the grade than others?
  - What happens if you fail to complete one or more experiments or assessments by the deadline date?
  - What happens if you proceed with stage 2 of an experiment before the instructor certifies stage 1?
  - How can you submit work electronically if you cannot meet with the instructor in-person?

## 01 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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.

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 calculate voltage, current, or resistance from the other two given values (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to properly and safely measure voltage using a multimeter
- Demonstrate how to properly and safely measure current using a multimeter

file we\_0133

## 02 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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



### 03 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

---

#### Learning objectives for this experiment:

- Demonstrate the Kelvin 4-wire resistance-measuring technique (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate destructive testing of a soldered joint by applying enough tensile force to break the wire (but not the soldered joint)
- Demonstrate proper technique for cleaning and “tinning” the tip of a soldering iron

## 04 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate destructive testing of a soldered joint by applying enough tensile force to break the wire (but not the soldered joint)
- Demonstrate the effect(s) of insufficient dwell time (i.e. time spent heating the material to be soldered) when soldering

## 05 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to measure the period of different wave-shapes using an oscilloscope, those different wave-shapes output by the same signal source (Note: the instructor may challenge you with a problem different than your experimental circuit)

## 06 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)

## 07 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Plan and conduct an experiment to demonstrate the relationship between multimeter and oscilloscope measurements of AC voltage. Note: keep the frequency of these signals near power-line (60 Hz) frequency, as many handheld multimeters are optimized to register AC quantities most accurately at these frequencies.

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

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### Learning objectives for this experiment:

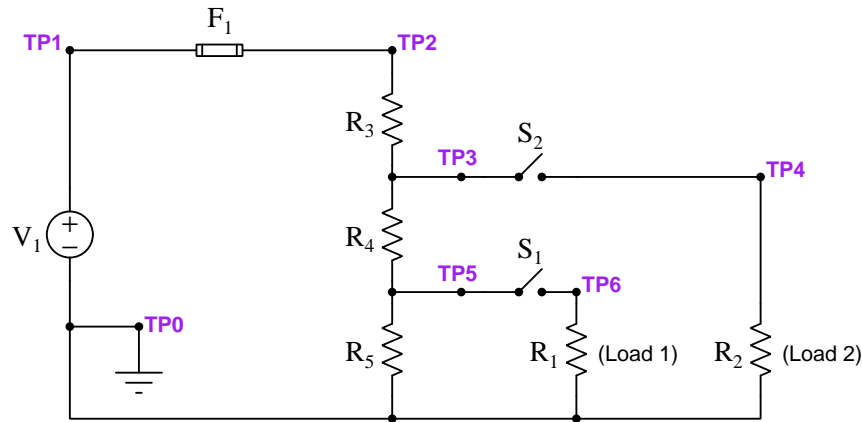
- Calculate error between predicted vs. measured values ( $\text{Error} = \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\%$ ), commenting on the sign of the error and also identifying possible causes
- Demonstrate the mathematical relationship between peak and RMS voltage measurements for a sine wave (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate the mathematical relationship between peak and RMS voltage measurements for a triangle wave (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate the mathematical relationship between peak and RMS voltage measurements for a square wave (Note: the instructor may challenge you with a problem different than your experimental circuit)

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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

### Circuit #004



Nominal component values:

$V_1 = \text{_____ Volts } +/- \text{ _____ } \%$

$R_1 = \text{_____ Ohms } +/- \text{ _____ } \%$

$R_2 = \text{_____ Ohms } +/- \text{ _____ } \%$

$R_3 = \text{_____ Ohms } +/- \text{ _____ } \%$

$R_4 = \text{_____ Ohms } +/- \text{ _____ } \%$

$R_5 = \text{_____ Ohms } +/- \text{ _____ } \%$

The **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 *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 **tshoot** software, being free and readily available for your use.

file we 1003

## 09 Assessment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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, with the purpose of securing all electrical energy from reaching the load so that the load conductors are safe for you to touch with your hands. 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. No skin-to-conductor contact is allowed until the entire procedure is complete, and then only contacting the load's conductors.

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:

[http://ibiblio.org/kuphaldt/socratic/model/mod\\_ohm.pdf](http://ibiblio.org/kuphaldt/socratic/model/mod_ohm.pdf)

**SEQUENCE:** (1) Design and build a simple circuit with one source, one load (e.g. motor or lamp), an on/off control switch, and at least one means of safety disconnection (e.g. fuse holder, circuit breaker, etc.); (2) Test this circuit to ensure it works as you intend; (3) Instructor observes you beginning with an energized load and step-by-step securing this circuit for a zero-energy state at the load, carefully following each and every step in the standard LOTO procedure, correctly explaining the rationale for each step.

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 1102

## 10 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Plan and conduct an experiment to demonstrate how to adjust the compensation on a  $\times 10$  oscilloscope probe. A helpful reference on oscilloscope probes is found in your EETREF/Tutorials collection, “ABCs of Probes” by Tektronix.

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate the effect of under-compensating and over-compensating an oscilloscope probe
- Demonstrate proper measurement of AC voltage using an oscilloscope with a  $\times 1$  probe
- Demonstrate proper measurement of AC voltage using an oscilloscope with a  $\times 10$  probe



## 11 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Plan and conduct an experiment to demonstrate phase shift within a series resistor-capacitor AC circuit. Recommend choosing component values such that each of the individual component impedances lie between 1 k $\Omega$  and 100 k $\Omega$  at the chosen operating frequency.

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 phase shift between two AC signals (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Sketch a phasor diagram for all voltages ( $V_{source}$ ,  $V_R$ , and  $V_C$ ) in a given circuit (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)

## 12 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 each of the individual component impedance values lie between 1 k $\Omega$  and 100 k $\Omega$  at the chosen operating frequency.

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 =  $\frac{Measured - Predicted}{Predicted} \times 100\%$ ), 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Sketch a phasor diagram for all currents ( $I_{source}$ ,  $I_R$ , and  $I_C$ ) in a given circuit (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)

## 13 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Plan and conduct an experiment to demonstrate the principle of electrical resonance. Recommend choosing component values such that each of the individual component impedances lie between 1 k $\Omega$  and 100 k $\Omega$  at the resonant frequency.

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 =  $\frac{Measured - Predicted}{Predicted} \times 100\%$ ), 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Sketch a phasor diagram for a given circuit, showing any quantities you choose (e.g. a phasor diagram for voltages, or for currents, or for impedances, etc.; note that the instructor may challenge you with a problem different than your experimental circuit)

## 14 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Identify whether the height of your spectrum analyzer's peaks indicate the *peak* value of the waveform in the time-domain, or the *RMS* value of the waveform in the time-domain
- Explain how the symmetry of a waveform (about the horizontal axis) in the time domain relates to the presence or absence of even-numbered harmonics in the frequency domain

## 15 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 each of the individual component impedances lie between 1 k $\Omega$  and 100 k $\Omega$  at the cutoff frequency.

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 how to measure AC signal voltage using an oscilloscope (Note: the instructor may challenge you with a problem different than your experimental circuit)
- 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)

## 16 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 each of the individual component impedances lie between 1 k $\Omega$  and 100 k $\Omega$  at the center frequency.

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

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### Learning objectives for this experiment:

- Explain what the “quality factor” ( $Q$ ) is for a band-pass or band-stop filter, and what factor(s) in the circuit influence that performance parameter.
- 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)

## 17 Assessment

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 k $\Omega$  and 100 k $\Omega$  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 and verifies all components are disconnected from each other; (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

## 18 Assessment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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). Determining the proper wave-shape is very simple and straightforward, and so you will be expected to state your solution immediately upon receiving the instructor-chosen harmonics. After this, the other steps in the sequence (2 through 4) naturally follow:

**Wave-shape** (you declare) = \_\_\_\_\_ (e.g. square, sine, triangle, sawtooth, pulse, etc.)

**SEQUENCE:** (1) Instructor chooses criteria and verifies all components are disconnected from each other; (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



## 19 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

*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

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

---

### Learning objectives for this experiment:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
- 
-

## Checklist for computer simulation

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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 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:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
- 
-

### 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other sources

☐ *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 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:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
- 
-

## 20 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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.

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 ( $\text{Error} = \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\%$ ), commenting on the sign of the error and also identifying possible causes
- Demonstrate how to empirically determine a transformer's winding turns ratio (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Explain how *Faraday's Law* relates to the operation of transformers, and 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

## 21 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Plan and conduct an experiment to demonstrate the behavior of either a boost or buck transformer configuration.

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 ( $\text{Error} = \frac{\text{Measured} - \text{Predicted}}{\text{Predicted}} \times 100\%$ ), 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 a transformer's nameplate ratings (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to change a boost circuit into a buck circuit, or vice-versa (Note: the instructor may challenge you with a problem different than your experimental circuit)

## 22 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 *voltage* or in the load *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 *differential* measurement mode so that you will not connect the instrument's "ground" clip directly to any portion of the 120 VAC circuit.

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

---

### 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to safely measure AC load current using an oscilloscope (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Predict the expected harmonic frequencies of a waveform arbitrarily chosen by the instructor with a given shape and given period.

## 23 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- 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



## 24 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

---

### Learning objectives for this experiment:

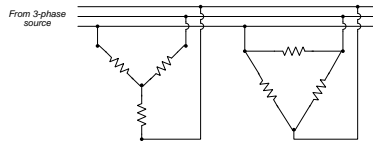
- Demonstrate how to configure an oscilloscope to measure an AC voltage signal (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to configure a different model of oscilloscope to measure an AC voltage signal
- Identify methods to reduce this coupling if it is undesired

## 25 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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:

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 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 such as voltage and current (Note: the instructor may challenge you with a problem different than your experimental circuit)

## 26 Assessment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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

## 27 Assessment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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  $\pm 5\%$  of measured voltage)

**SEQUENCE:** (1) Instructor chooses criteria and verifies all components are disconnected from each other; (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

## 28 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

*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

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

---

### Learning objectives for this experiment:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
- 
-

## Checklist for computer simulation

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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 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:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
- 
-

### 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other sources

☐ *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:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
- 
-



## 29 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Plan and conduct an experiment to demonstrate the behavior of a full-wave bridge rectifier network comprised of multiple discrete diodes.

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to calculate AC period from a given frequency value (Note: the instructor may challenge you with a problem different than your experimental circuit)
- 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)

## 30 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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  $\_\ \mu F$  on a rectifier powering a  $\_\ \Omega$  load will result in a peak-to-peak ripple voltage of  $\_\$  Volts.”

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

---

### 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)

## 31 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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

## 32 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Plan and conduct an experiment to demonstrate the principle of pulse-width modulation control of power to a load (e.g. LED for brightness control, motor for speed control, heater for temperature control).

---

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to measure the duty cycle of a pulse signal from an oscillograph (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate the mathematical relationship between duty cycle and average load power (Note: the instructor may challenge you with a problem different than your experimental circuit)

### 33 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

Plan and conduct an experiment to demonstrate the principle of DC-to-AC power conversion (“inversion”).

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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
- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)

## 34 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 mathematical relationship between duty cycle and output/input voltage ratio (Note: the instructor may challenge you with a problem different than your experimental circuit)
- 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 for any given power-converter circuit (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)

### 35 Assessment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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
- 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%).

file we 1016

## 36 Assessment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 significant amounts of heat (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. It is recommended that you *not* push the device to its rated thermal limits, but aim for a case temperature that will be uncomfortably hot to touch while still remaining well below the absolute maximum temperature specified in the datasheet!

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 and verifies all components are disconnected from each other; (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



### 37 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

*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

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

---

### Learning objectives for this experiment:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
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-

## Checklist for computer simulation

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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 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:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
- 
-

### 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other sources

☐ *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 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)

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### Learning objectives for this experiment:

- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the components failing shorted (chosen at random by the instructor)
- 
-

## 38 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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.

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

- ☐ Written hypothesis:
  - Makes clear prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ 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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 how to convert between binary and decimal notations (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to choose appropriate current-limiting resistors for the LEDs in a 7-segment display (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to determine (using test equipment) whether your 7-segment display is *common-cathode* or *common-anode*
- Accurately predict and then demonstrate the effect(s) of one of the components failing open (chosen at random by the instructor)

## 39 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that data!

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

---

### Learning objectives for this experiment:

- Demonstrate how to design a gate-based logic circuit to implement a given truth table (Note: the instructor may challenge you with a problem different than your experimental circuit)
- 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”

## 40 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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

- ☐ Was the original hypothesis confirmed? If not, identify why.
- ☐ Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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 using the J and K input lines of the flip-flop
- 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 (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to measure the rise time and fall time of a digital pulse signal

## 41 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 prediction(s) sure to be either proven or disproven by the results of this experiment
  - 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 *prior to building it*
  - 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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other trustworthy sources

☐ *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/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data, using a calculator or appropriate software to analyze that 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



## 42 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other sources

☐ *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 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)

## 43 Experiment

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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 (e.g. excessive voltage, current, and/or power) and mitigations, citing applicable component ratings from datasheets and/or other sources

☐ *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)

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### Learning objectives for this experiment:

- Demonstrate the operation of an off-delay timer instruction
- Demonstrate the operation of a “retentive” on-delay timer instruction
- Demonstrate the operation of a “non-retentive” on-delay timer instruction
- Demonstrate how to monitor the timer's accumulated time value in formats other than decimal (e.g. binary, hex)

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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

NAME: \_\_\_\_\_

DUE DATE: \_\_\_\_\_

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, and the electric motor must be powered from a different source than what is powering the PLC so that the PLC’s supply voltage does not “sag” or become “noisy” as the load energizes. 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** ; batteries. 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. The instructor chooses specific I/O channels for you to connect switches and relay.

“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 and verifies nothing is wired to the PLC’s I/O terminals; (2) You write the PLC program (offline) and test it for syntax errors without connecting to a PLC; (3) Instructor inspects your program for completion prior to wiring; (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.

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## 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) and all table/workbench surfaces
- ☐ Vacuum-clean the floor of all debris after picking any and all larger pieces
- ☐ Organize all wires, cables, power cords, and test leads neatly into their storage locations
- ☐ Vacuum-clean the exterior and interior of all electrical enclosures and cabinets
- ☐ Move test equipment to their proper places and clean their outer surfaces
- ☐ Note any depleted bins (electronic components, threaded fasteners, cables, etc.)
  - Check boxes and spools of components to see if depleted bins may be re-filled from these
  - Report to instructor for re-ordering in preparation for next semester
- ☐ Note any depleted PCBs (e.g. fuseholder PCBs, proto PCBs, etc.)
- ☐ Power up each lab PC to check for routine software updates, then power down for the break

### Technical tasks

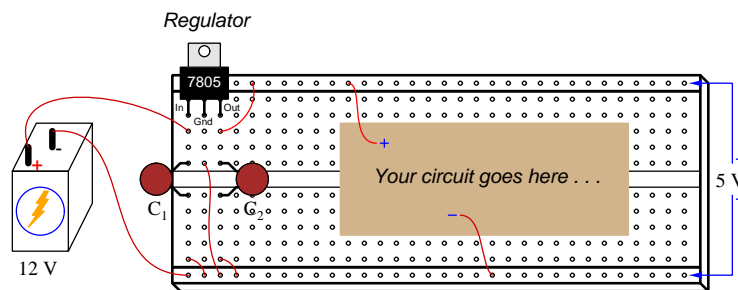
- ☐ Check fastener storage bins to ensure none are misplaced
- ☐ Check resistor storage bins to ensure none are misplaced
- ☐ Check fuse storage bins to ensure none are misplaced
- ☐ Check inductor/transformer storage bins to ensure none are misplaced
- ☐ Check capacitor storage bins to ensure none are misplaced
- ☐ Check semiconductor device storage bins to ensure none are misplaced
- ☐ Test power supplies and benchtop multimeters for basic functionality (e.g. all *power supply* voltage adjustments functional, current limits functional, voltage/current meters functional ; all *multimeter* all voltage ranges functional, all current ranges functional, overcurrent fuse good)
- ☐ Test oscilloscopes and signal generators for basic functionality (e.g. all *oscilloscope* channels functional, all vertical sensitivity settings functional, all timebase settings functional, triggering functions properly ; all *signal generator* waveshapes functional, magnitude and frequency adjustments functional)
- ☐ Test and clean all soldering stations (e.g. clean/replace porous and brass-wool cleaning pads, check tips for wear, ensure correct temperature settings and that the tip solders well)
- ☐ Test all lab power system (e.g. solar power grid, hand-crank generator) circuit breakers and fuses
- ☐ Test all special lab systems for basic functionality ; ensure schematic diagrams are in place
  - Digital clock, window crane system, window sensors, precision voltage reference

## General Circuit Design Tips

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  $\mu\text{F}$  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.
- **Use test equipment rather than your eyes to find problems** – your multimeter (and other tools) will show you things your eyes cannot see, and this will build habits and skills invaluable in situations where visual inspection is impossible.
- **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).
- **Simplify the system** – If possible, re-configure the circuit to be as simple as possible, because complexity makes faults harder to find.
- **Take more and different measurements to get un-stuck** – if the source of trouble is still not apparent, take measurements in places you haven’t tried yet to obtain new data. Also, use different test instruments that will show you other facets of the signals, for example try using an oscilloscope to test a signal if you’ve only been using a multimeter since an oscilloscope will reveal things a multimeter cannot.
- **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.

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