IETTI-103 – DC Circuit Experiments (Semester 1 EXPERIMENTS)

NAME: _____ Last update 22 September 2026

Activity #	Due by theory session #12	Score
00 Experiment	Introduction (*complete this "experiment" first!*)	– – –
01 Experiment	Testing electrical conductivity	
02 Experiment	Demonstrate electrical connections on a solderless breadboard	
03 Experiment	Demonstrate voltages in a switched circuit	
04 Experiment	Demonstrate Ohm's Law	
05 Experiment	Demonstrate effects of open and shorted faults	
06 Experiment	Demonstrate proper fuse operation and testing	
07 Experiment	Demonstrate voltages in multi-source network	
08 Assessment	Troubleshoot simple one-resistor circuit (simulation)	
09 Assessment	Demonstrate lock-out/tag-out procedure	

Activity #	Due by theory session #24	Score
10 Experiment	Demonstrate a voltage divider network	
11 Experiment	Demonstrate a current divider network	
12 Experiment	Demonstrate voltmeter loading	
13 Experiment	Demonstrate KVL in a series-parallel DC circuit	
14 Experiment	Demonstrate a Wheatstone bridge circuit	
15 Experiment	Demonstrate a Kelvin-Varley voltage divider	
16 Experiment	Constrained variable-resistance range	
17 Assessment	Troubleshoot 3-resistor voltage divider (simulation)	
18 Assessment	Design and build light or temperature sensing circuit	

Activity #	Due by theory session #36	Score
19 Experiment	Demonstrate current measurement using shunt resistor	
20 Experiment	Demonstrate source internal resistance	
21 Experiment	Demonstrate Thévenin's or Norton's theorem	
22 Experiment	Demonstrate oscilloscope used as a voltmeter	
23 Experiment	Demonstrate right-hand rule of electromagnetism	
24 Experiment	Demonstrate electromagnetic induction	
25 Experiment	Demonstrate resistor-capacitor time delay	
26 Assessment	Troubleshoot RC time-delay circuit	
27 Assessment	Design and build voltage divider circuit	

Activity #	Due by theory session #48	Score
28 Experiment	*Choose your own*	
29 Experiment	Demonstrate diode action	
30 Experiment	Demonstrate BJT β	
31 Experiment	Demonstrate heavy load control using BJT	
32 Experiment	Demonstrate heavy load control using MOSFET	
33 Experiment	Demonstrate astable 555 circuit	
34 Experiment	Demonstrate thyristor action	
35 Assessment	Troubleshoot transistor switching circuit	
36 Assessment	Design and build 555-based pulse generator	

Activity #	Due by theory session #60	Score
37 Experiment	*Choose your own*	
38 Experiment	Demonstrate a relay-based logic function	
39 Experiment	Demonstrate an IC gate logic function	
40 Experiment	Demonstrate a PLC-based logic function	
41 Experiment	Demonstrate logic gate propagation delay	
42 Experiment	Demonstrate IC logic implementing arbitrary truth table	
43 Experiment	Demonstrate PLC implementing arbitrary truth table	
44 Assessment	Troubleshoot combinational logic circuit	
45 Assessment	Design and build 120 VAC load-controlling relay circuit	

46 Lab clean-up	Clean and organize the entire lab room	

Essential information about this course:

- The purpose of this entire program is to empower you with knowledge, skill, and habits for your chosen craft, and doing your own work is absolutely necessary to that end. Relying on other people and/or artificial intelligence (AI) to read, write, design, plan, analyze, diagnose, or in any other way *think for you* defeats this purpose and will be considered plagiarism. Appropriate help always sharpens and never replaces a person's own ability to think and to do. Bear this in mind both when seeking help and when assisting classmates!
- The difference between *education* and *training* is learning to reason from principles versus following instructions. This course focuses on *empirical learning*: acquiring knowledge and skill through direct hands-on experience. In keeping with the educational focus, these experiments are not pre-designed but are planned by you just like real scientific experiments where the final outcome is unknown. You will carefully document your plans, your recorded data, and your conclusions in the same manner technicians document their experimental work on the job.
- Assignments and assessments are just means to an end, and that end is learning. Similarly, grades, certificates, and degrees are just symbols of that same end. Prioritize *learning* and you will do well on your assignments and assessments, and your grades will reflect that. If you instead treat activity completion as the goal and grades as a prize, you'll not only sacrifice learning but also struggle to complete the assignments and obtain the grades you desire. Don't confuse the means versus the end; don't chase symbols in lieu of what they're supposed to represent.
- 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. The other 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, with answers being accurate *and* well-reasoned from appropriate principles to count as correct.
- Late completions of work will result in point deductions. Demonstrations of unprofessional behavior will trigger private meetings with your instructor(s).
- You should budget a minimum of 12 hours per week for this course, and aim to complete one course activity (one experiment, one assessment) per day to stay ahead of deadlines. The lab is yours to use during all open-school hours, but be aware that each experiment requires planning work that can be done anywhere because it doesn't require access to test equipment. *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, (4) build up their experiments step by step instead of trying to do it all at once, (5) document data neatly and accurately, and (6) double-check their work for correctness before submitting for assessment.

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.

file `eet_values`

EET Program Learning Outcomes

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

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

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

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

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

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

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

Course description

This course reinforces the content of IETTI-101 (DC 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

- Complete experiments and assessments on or before their associated deadlines, communicating professionally with instructors for the timely certification of those activities. (Addresses Program Learning Outcomes 1, 2)
- Rigorously demonstrate fundamental circuit principles (e.g. Ohm's Law, Kirchhoff's Laws, network theorems), semiconductor device characteristics, and Boolean algebra relations by means of scientific experimentation. (Addresses Program Learning Outcomes 2, 4, 6, 7)
- Construct DC circuits meeting specifications set by the instructor and demonstrate proper test equipment usage including multimeters and AC-DC power supplies. (Addresses Program Learning Outcomes 4, 5, 6)
- Troubleshoot faulted voltage dividers, DC bridge circuits, time-delay circuits, transistor switching circuits, and combinational logic 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)
- Create, maintain, and reference textual records (i.e. an Experiment Journal) documenting important principles and lessons learned. (Addresses Program Learning Outcomes 1, 6)

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)

Tool, Supply, or Software installation	Thy 101	Exp 103	Prj 102	Thy 104	Exp 112	Prj 105	Thy 222	Exp 221	Prj 220	Thy 223	Exp 225	Prj 236
$5 mechanical pencil and eraser	X	X	X	X	X	X	X	X	X	X	X	X
$5 permanent marker			X			X			X			X
$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
$190 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
$15 utility knife			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: text editor		X			X			X			X	
$0 software: `NGSPICE` circuit sim.		X			X			X			X	
$0 software: `WSL`	X	X		X	X		X	X			X	
$0 software: `tshoot` fault sim.	X	X		X	X			X			X	
$0 software: `sp.c` simulator	X			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 – we use computers every day for applications such as teleconferencing software (e.g. Zoom), document reading and creation, coding, and circuit simulation. Having your own portable computer is therefore essential. Most operating systems, hard drive capacities, RAM memory sizes, and screen sizes are appropriate, but your computer must have a keyboard and mouse (i.e. no tablets). Avoid ChromeBooks. Useful but non-essential features include an RJ-45 Ethernet port and multiple USB ports.

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. Cost is a strong function of accuracy, additional features, frequency range, and safety ("Category" ratings for over-voltage exposure). The Fluke model 17B+ is an excellent choice for digital multimeters, and the Simpson 260 is an excellent professional-grade choice for analog multimeters. The best *minimal-cost* multimeter I've found is the model DT-830B which sells for less than $20, with the test leads being the weakest component (but easily upgraded).

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

Soldering – the equipment you purchase for soldering need not be expensive, *if* you purchase the right solder. For electronics work you *must* use rosin-core solder. Kester is an excellent brand, and you should avoid cheap imported solders. For lead-based solder, a 63% tin and 37% lead alloy (Sn63/Pb37) works very well. A one-pound roll is likely more solder than you will need in these courses, so I recommend buying just a small tube instead. 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.

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++` and Microsoft's `VS Code` are both excellent options.

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 upgrade`
- `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 one "tar" file you unpack and compile using the following three commands within a Unix-type operating system or within `WSL`. The fourth command runs the application:

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

sp.c – this is a specialized circuit-simulator program for series/parallel DC resistor circuit analysis practice. The download consists of a single C-language source file that you may paste into an online C compiler to run, or compile on your own computer within WSL. The first command compiles, and the second one runs:

- `gcc -o sp sp.c -lm`
- `./sp`

EETREF archive – several gigabytes of 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.

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.

file `eet_tools`

Grading standards for Experiment courses

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

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

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

Carefully follow the instructions associated with each experiment! If there is a prescribed order, you must follow this order of steps or else you will receive a 0% score for that experiment. The same is true if you plagiarize any part of it (i.e. rely on another's work instead of 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.

Assessments must be completed with demonstrated understanding of the underlying concepts. This means answers arrived at by guessing, or even correct answers accompanied by incorrect reasoning, will be counted as incorrect. If it is evident by repeated mistakes that you do not adequately understand the concepts involved, the instructor may refuse re-tries until after you have completed more preparatory work. This is not intended to be punitive, but rather to ensure you complete the activity with the full competence appropriate for your chosen career.

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 without 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 behavior that would result in being fired from a job, including false testimony (lying), cheating on any assignment or assessment, plagiarism (relying on another's work instead of your own, including artificial intelligence), willful violation of a safety policy, habitual tardiness or absenteeism, theft, harassment, sabotage, destruction of property, or intoxication.

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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 usually creates problems that are more difficult to solve than if the system were built and tested piece by piece.
- **Document** – draw a diagram before building any system, and use this to guide your analysis and design decisions. If and when you make changes to your circuit, update your diagrams accordingly. Also, have any other relevant documents available for reference, such as datasheets, tutorials, etc. A common mistake is to begin building systems without first sketching what is to be built, and also not using the documentation for troubleshooting.
- **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.
- **First Principles** – always apply First Principles 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 First Principles) 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.

Instructor guidelines

The design and structure of this course is quite unconventional, but proven to deliver robust outcomes.

In addition to imparting practical knowledge and skill related to the subjects of electricity and electronics, this course seeks to also teach students how to think scientifically. To this end, students develop their own hypotheses and experimental procedures rather than following pre-designed procedures as is typical for traditional lab courses. Your job as the instructor is to verify that the students' hypotheses are scientifically valid (i.e. testable and relevant to the given concept) and their procedures are safe and effective prior to the experiment being run. After students run their experiments, your job as the instructor is to verify they have correctly analyzed the data, confirmed or disproven their hypotheses, and learned what was expected from the experiment.

Every experiment begins with a statement of the concept or technique the student is intended to experimentally explore. Students then develop and document their own hypotheses and procedures which you will review in "Stage #1" against the listed criteria. Failure to meet any of the listed criteria for this stage results in a -10% deduction and a re-inspection after the student makes revisions. The purpose of this stage is to give students freedom and license to make "risky" predictions (i.e. predictions that might not end up being correct) which is the essence of scientific investigation. Note that your "Stage #1" inspection does *not* assess the correctness of student hypotheses. Incorrect hypotheses are to be expected when one is honestly exploring an uncertain topic. Your job is to simply ensure the experiment will clearly reveal the correctness or incorrectness of the hypothesis when run. Students who are unsure of where to begin are recommended to consult the "Case Tutorial" chapter within the associated *Modular Electronics Learning Project* module for ideas. Another source of ideas is the list of learning objectives at the bottom of each experiment outline page which students will be expected to demonstrate and/or explain. Designing an experiment with these objectives in mind will not only make the final inspection go faster but will also provide practical tips on how to design a good experiment.

Stage #2 of the experiment does not necessarily require instructor assistance. If the experiment is well-designed and the student knows how to use the equipment, chances are they will complete this stage all on their own. Questions of the instructor are, of course, welcome, but you should assist by directing the student toward their instruments and the collected data. Again, the purpose of this course is for students to *learn from experimentation* rather than be told by an expert whether they are correct or incorrect. Students will find that they may often have to revise their hypotheses and procedures if the initial results reveal any errors. This means Stage #2 may take longer than expected to complete – a completely normal feature of the scientific method. Experience has shown to budget an average of *four hours of time per experiment*, including planning (Stage #1), execution (Stage #2), and final review (Stage #3).

Stage #3 is where students present the results of their experimentation to the instructor for review. Students must explain whether or not their hypothesis was correct, referencing data they collected during Stage #2 and documented within their Experiment Journals. Furthermore, students are required to demonstrate and/or explain every one of the learning objectives listed in the experiment's outline. Just as in Stage #1, a deduction of -10% is levied against their experiment score for any re-tries. The major difference between the Stage #1 and Stage #3 review processes is that in Stage #3 the student's conclusions and demonstrations must all be *correct*. Stage #1 allows for incorrect hypotheses with the expectation that all will be made clear as the experiment is run, but by Stage #3 the expectation is that the student will have gained a correct understanding by experimentation.

This course also includes *assessments* in addition to experiments, where students demonstrate something they've previously learned in a hands-on manner. Each assessment comes complete with a full description of what is to be demonstrated by the student. Students are urged to *practice* these on their own before attempting for credit, as each re-try results in a score deduction of -20%. During each assessment it is important for students to follow the prescribed sequence of steps, both to ensure safety and to ensure integrity of the assessment. These assessments are also closed-note, to ensure students actually understand how to run them and are not just following instructions.

file `we_instructor`

Experiment rubric

This rubric defines what is acceptable and unacceptable for the planning stage (Stage 1) of each experiment. It may be used as a check-list by student and instructor alike to manage clear expectations on experiment planning. *All* `Acceptable` criteria must be met or exceeded to proceed with the experiment. *Any* `Retry` deficiency will trigger a re-try with points deducted.

Written hypothesis

`Exemplary:` In addition to meeting all `Acceptable` criteria, the basic prediction is clear and concise (1 sentence), with no more than 1-2 additional sentences addressing the learning objectives listed at the end. Table/graph is expandable to accommodate additional tests that might arise. Mathematical work is fully shown for every single predicted value (e.g. embedded spreadsheet formulae and data, calculator steps listed).

`Acceptable:` A grammatically correct and testable prediction related to the thesis statement. A table and/or graph exists containing both calculated predictions and space for recording corresponding measurements (quantitative experiments only). All necessary formulae listed for calculating those predicted values.

`Retry:` Prediction is unclear, unfalsifiable, and/or unrelated to the thesis statement. Missing or incomplete table/graph (quantitative experiments only). Missing mathematical formula(e) necessary for prediction.

Written experimental plan

`Exemplary:` In addition to meeting all `Acceptable` criteria, the schematic diagram is aesthetically pleasing and drafted using CAD software (e.g. KiCad). Written plan is professional in tone and sufficiently clear that no clarifying questions need be asked in order to replicate all results, and where applicable describes how to build and test the circuit in increments complete with schematics showing each of those stages. All test equipment models, serial numbers, and environmental conditions (e.g. ambient room temperature) listed.

`Acceptable:` Schematic diagram complete with all components shown, all component values clearly specified, and all test points shown that are necessary for testing the hypothesis. Written plan is clear and complete enough that any other student should be able to follow it and tell by the results whether or not your hypothesis is correct. Where applicable, the plan describes how to build and test the circuit in incremental stages rather than all at once, as this keeps problems small and easier to find.

`Retry:` Schematic diagram missing any components or necessary test fixtures (e.g. test point terminals), and/or contains any debilitating flaws such as open- or short-circuits. Written plan is vague, missing steps, or contains instructions not relevant to this experiment.

Written risk analysis

`Exemplary:` In addition to meeting all `Acceptable` criteria, mathematical work is fully shown for every single calculated risk value (e.g. embedded spreadsheet formulae and data, calculator steps listed).

`Acceptable:` All personal risks relevant to the experiment are identified (e.g. shock, burn, inhalation) as well as mitigations for each. All hardware risks relevant to the experiment are quantified with relevant formulae shown (e.g. component voltage, current, power limitations), applicable ratings cited from component datasheets or other trusted sources, and practical mitigations described. *Note: any risks known to the instructor extending beyond what has been taught will trigger an edit of the risk analysis, but neither a re-try nor deducted points.*

`Retry:` Missing any personal or hardware risks, and/or mitigations. Risks described that are irrelevant to the experiment at hand.

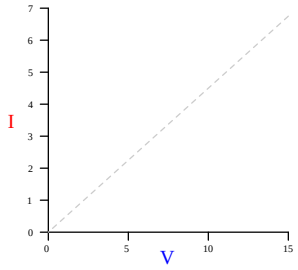
file `we_rubric`

Example Experiment Journal entry – Stage #1 (planning)

Experiment: Demonstrate Ohm's Law

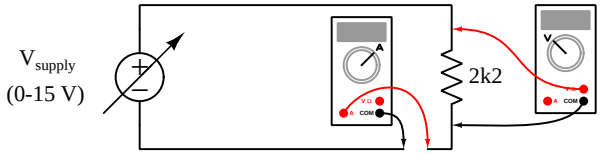
Hypothesis Current will be directly proportional to voltage applied across a resistor, in accordance with the formula $I = \frac{V}{R}$ using a 2.2 kΩ, 1/4 Watt resistor:

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		



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

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!

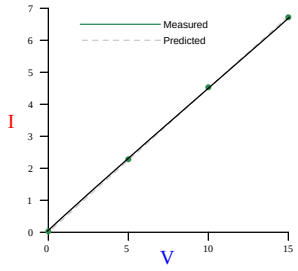
file we_0201

Example Experiment Journal entry – 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



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

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

Analysis

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

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

Helpful hints for your own Journals:

- Keep your Experiment Journals 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 Journal*!
- Never discard data! If you make a mistake, just note the error and then record the good data in a new place on the Journal. 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 Journal 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 Journal 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.

file we_0202

Example Experiment Journal entry – Stage #3 (presentation)

Experiment: Demonstrate Ohm's Law

Presentation and review

Nothing needs to be written in your Experiment Journal 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 Journal, 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!*

file we_0203

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?
- Why must stage 1 be certified by the instructor *before* running the experiment in stage 2?
- How is each experiment graded?

◯ Read the "Experiment rubric" page and answer the following questions:
- What specific deficiencies in the written hypothesis will trigger a re-try?
- What specific deficiencies in the written experimental plan will trigger a re-try?
- What specific deficiencies in the written risk analysis will trigger a re-try?

◯ Read the "Example Experiment Journal entry" pages and answer the following questions:
- In what format do you think you will prefer to write your Journals? 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 Journals 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 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 "Getting help in the lab" page 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" page 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?
- How can you submit work electronically if you cannot meet with the instructor in-person?

◯ 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

◯ Test a multimeter for DC voltage-measurement accuracy against a trusted voltage standard in the lab.
- Document the voltage standard's trusted output value in Volts DC, with full precision (all digits)
- Document the multimeter's measured voltage value in Volts DC, with full precision (all digits)
- Calculate and document the *error percentage* based on these voltage values using the method shown in the Example Experiment Journal entry
- Confirm whether this error percentage falls within the accuracy rating specified by the multimeter's manufacturer, showing where that accuracy rating is found in the manufacturer's literature

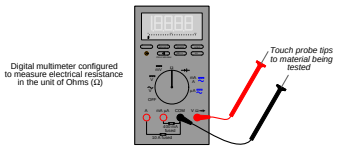
file we_0200

01 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to test the electrical conductivity of different materials. **Sample hypothesis:** *"The following materials (__, __, __) should conduct electricity and the following materials (__, __, __) should not."*. There are no risks in this experiment.

Sample diagram:



Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Identify multiple materials that conduct electricity, in order of most to least conductive
- Identify multiple materials that do not conduct electricity

file we_0127

02 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the pattern of electrical connections within a solderless breadboard. There are no risks in this experiment.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how to properly and safely determine electrical continuity using a multimeter
- Demonstrate which holes on a solderless breadboard connect to each other
- Demonstrate which holes on a solderless breadboard do *not* connect to each other
- Demonstrate how to strip the insulation off the end of a wire

file we_0211

03 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate voltages in a circuit where a load (e.g. lamp, motor) is controlled by a switch. **Sample hypothesis:** *"When the switch is closed, source voltage should be measurable between the following points (__); when open, source voltage should be measurable between the following points (__)."* Risk analysis should include the potential for a short-circuit and how the circuit should be constructed to avoid this.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- What is prohibited within a circuit (either voltage or current) by a switch in its open condition?
- What is prohibited within a circuit (either voltage or current) by a switch in its closed (shorted) condition?
- Demonstrate how to test the status of a switch (outside of any circuit) using an ohmmeter
- Demonstrate why it is impossible to accurately measure the electrical resistance of an energized component

file we_0129

04 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate Ohm's Law using a resistor value between 1 kΩ and 100 kΩ. **Sample hypothesis:** *"A simple circuit with a __ Volt DC source and a __ Ohm resistor should exhibit a current of __ milliAmperes."* Recommend measuring source voltage using your multimeter rather than assuming the battery's label voltage or the power supply's indicated voltage, before calculating the expected current. Risk analysis **must** include the potential to blow your meter's fuse if improperly connected as an ammeter, and how to avoid this result.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

☐ *Instructor certifies* – Re-try if any demonstration 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 algebraically manipulate Ohm's Law and then calculate voltage, current, or resistance from the other two given values in a problem created by the instructor
- Demonstrate how to properly and safely measure voltage using a multimeter
- Demonstrate how to properly and safely measure current using a multimeter

file we_0038

05 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the effects of both shorted faults and open faults, using a power source tolerant of short-circuit conditions (e.g. current-limited power supply, solar panel). Your hypothesis should predict multiple effects (e.g. voltages between multiple sets of points) for each fault condition. A table format will work well to organize the predictions and experimental data (e.g. each row representing a unique fault placed in the circuit, and containing columns for measurement location, predicted measurement, and actual measurement), and it will also be helpful to label all points in your circuit between which a fault may be installed.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- What is the guaranteed effect(s) of a break ("open") within a circuit?
- What is the guaranteed effect(s) of a "short" within a circuit?
- Demonstrate how to test whether two points in an unpowered circuit are either shorted together or isolated (open) from each other using an ohmmeter

file we_0039

06 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate how a fuse interrupts excessive current, as well as how to test a fuse's condition using a multimeter. Choose a fuse value less than 1 Ampere for safety. **Sample hypothesis:** *"The fuse in this circuit will blow if __, and a blown fuse will be electrically distinguishable from a healthy fuse by __."* Risk analysis **must** include the potential to blow your meter's fuse if improperly connected as an ammeter and how to avoid this result, as well as the ampacity rating of the wires you'll use and any connection hardware (e.g. terminal block current rating, fuseholder current rating, etc.).

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate what condition(s) may result in a blown fuse
- Demonstrate how to use a multimeter to test a fuse removed from the circuit
- Demonstrate how to properly and safely measure current using a multimeter
- Demonstrate how to read the rated current of a fuse from its labeling

file we_0040

07 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment using multiple voltage sources (e.g. dry-cell batteries) to create a total voltage greater than any one source alone, predicting and then demonstrating where you could connect the red and black test leads of a digital voltmeter to measure both positively-signed and negatively-signed voltages.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

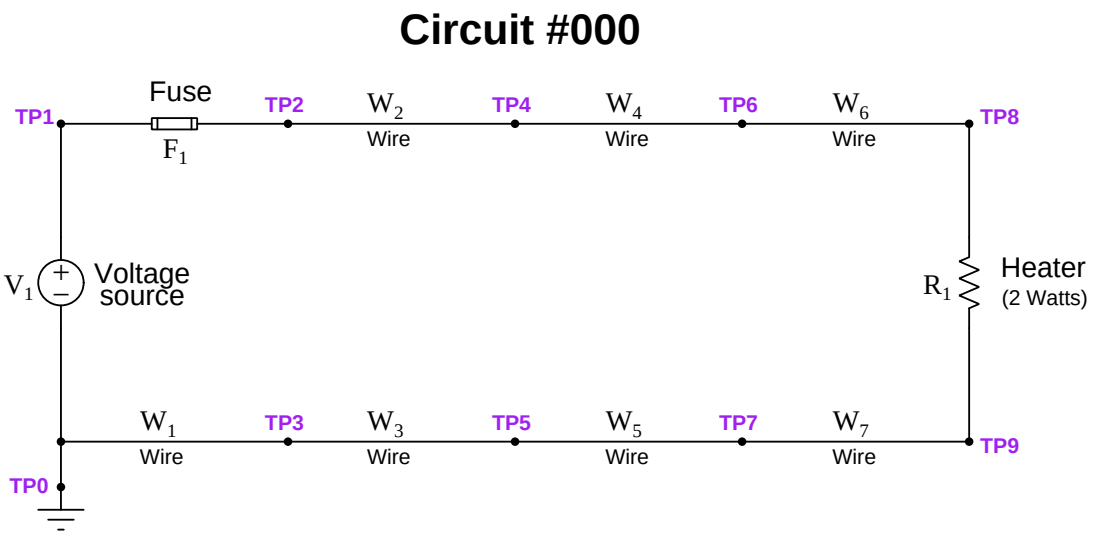
- Calculate error between predicted vs. measured values (Error = $\frac{Measured-Predicted}{Predicted} \times 100\%$), commenting on the sign of the error and also identifying possible causes
- Predict and measure potentials with respect to a "ground" point arbitrarily chosen by the instructor
- Explain the significance of the mathematical sign shown by a digital multimeter with regard to its test lead placement
- Demonstrate how you would safely assemble and test your circuit if you happened to be using a *great many* batteries to create a dangerously high voltage

file we_0204

08 Assessment

NAME: _____ **DUE DATE:** _____

Troubleshoot a computer-simulated fault within a simple one-resistor circuit. The schematic diagram for this circuit as simulated in the `tshoot` troubleshooting simulator software is shown below:



Nominal component values:

V_1 = _____ Volts +/- _____ %

R_1 = _____ Ohms +/- _____ %

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 exists 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 logically 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. *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

file we_1009

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, correctly operate a digital multimeter, follow industry-standard LOTO procedures, and to correctly explain the principles behind those procedures. No skin-to-conductor contact is allowed until the entire procedure is complete, and then only contacting the de-energized 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 for you to study:

`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; (4) Properly identify which points of the circuit are now safe for you to touch, and explain why.

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, demonstrate, and correctly explain the principles of a circuit following the sequence shown (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

file we_1102

10 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the behavior of a voltage divider circuit, using resistor values between 1 kΩ and 100 kΩ. **Sample hypothesis:** *"For an applied voltage of __ Volts the divider should output __ Volts."* **Risk analysis** should include resistor power dissipation ratings, showing that no resistor will be over-powered in this experiment.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how the voltage-division ratio may be computed from given resistor values
- Accurately predict and then demonstrate the effect(s) of one of the resistors failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the resistors failing shorted (chosen at random by the instructor)
- Demonstrate how to calculate power dissipation for any single resistor in a multi-resistor series network (Note: the instructor may challenge you with a problem different than your experimental circuit)

file we_0042

11 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the behavior of a current divider circuit, using resistor values between 1 kΩ and 100 kΩ. **Risk analysis** should include resistor power dissipation ratings, showing that no resistor will be over-powered in this experiment.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

☐ *Instructor certifies* – Re-try if any demonstration 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 the current-division ratio may be computed from given resistor values
- Identify any sources of error in your experiment, and how to avoid as much error as possible in future quantitative experiments
- Demonstrate how to calculate power dissipation for any single resistor in a multi-resistor parallel network (Note: the instructor may challenge you with a problem different than your experimental circuit)

file we_0044

12 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate how a voltmeter "loads" a circuit to yield a connected voltage measurement that is not the true voltage in the circuit when the voltmeter is disconnected. Normally we recommend keeping every experimental-circuit resistor value no lower than 1 kΩ to avoid ammeter loading effects and no greater than 100 kΩ to avoid voltmeter loading effects, but in this experiment we will violate this rule in order to demonstrate voltmeter loading. A simple voltage divider network with very high-valued resistors works well for this.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how to calculate the *actual* insertion resistance of your voltmeter based on the data gathered from this experiment, and then compare this value against the insertion resistance specification (sometimes called insertion *impedance*) in your meter's documentation
- Demonstrate how this loading effect varies with the specific model of voltmeter used to measure voltage
- A best-practice recommendation for experimental circuits is to avoid resistor values exeeding 100 kΩ. How do the results of this experiment help justify that recommendation?
- A best-practice recommendation for experimental circuits is to avoid resistor values under 1 kΩ in resistance. How might the use of resistors less than 1 kΩ in an experimental circuit adversely affect the accuracy of *ammeter* measurements?

file we_0205

13 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the principle of Kirchhoff's Voltage Law in a DC series-parallel resistor circuit, using resistor values between 1 kΩ and 100 kΩ. Your demonstration should validate KVL within multiple loops in the circuit, at least one of them excluding the power source.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

☐ *Instructor certifies* – Re-try if any demonstration 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 properly calculate voltage drops in a series-parallel circuit (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate the mathematical relationship between voltages measured in a loop containing the source
- Demonstrate the mathematical relationship between voltages measured in a loop containing no source

file we_0006

14 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the behavior of an adjustable Wheatstone bridge circuit, using resistor values between 1 kΩ and 100 kΩ.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate the operation of a potentiometer using an ohmmeter to measure its varying resistances as the wiper is moved
- Demonstrate how to "balance" a bridge circuit
- Accurately predict and then demonstrate the effect(s) of one of the resistors failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the resistors failing shorted (chosen at random by the instructor)

file we_0045

15 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the functionality of a Kelvin-Varley voltage divider network.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Predict and measure potentials with respect to a "ground" point arbitrarily chosen by the instructor
- Demonstrate how to predict the proper potentiometer connections and wiper position setting necessary to obtain any instructor-specified voltage from your Kelvin-Varley voltage divider network
- Accurately predict and then demonstrate the effect(s) of one of the resistors failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the resistors failing shorted (chosen at random by the instructor)

file we_0206

16 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to constrain the adjustable resistance range of a potentiometer between two limits (specified by the instructor) by connecting multiple standard-size fixed resistors together in a network with the potentiometer. When the experiment is finished your measured resistance value must be within ±1% of the instructor-specified value. There are no risks in this experiment.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

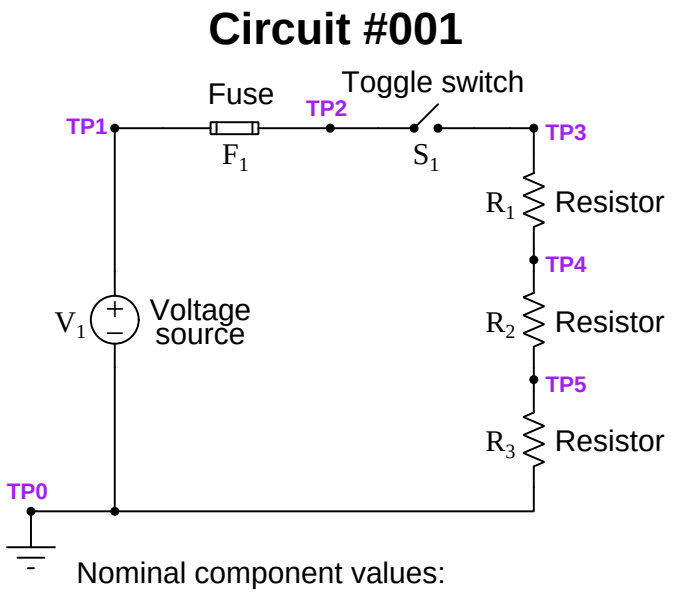
- Demonstrate how to algebraically manipulate the parallel resistance equation to solve for one of the individual resistances given the other resistances and the total (parallel) resistance, for a scenario created by the instructor
- Demonstrate how to *precisely* measure resistance using a multimeter, using the meter's "relative" or "null" mode to cancel out test lead resistance
- Accurately predict and then demonstrate the effect(s) of one of the resistors failing open (chosen at random by the instructor)
- Accurately predict and then demonstrate the effect(s) of one of the resistors failing shorted (chosen at random by the instructor)

file we_0126

17 Assessment

NAME: _____ **DUE DATE:** _____

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



Nominal component values:

V_1 = _____ Volts +/- _____ %

R_1 = _____ Ohms +/- _____ %

R_2 = _____ Ohms +/- _____ %

R_3 = _____ Ohms +/- _____ %

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 exists 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 logically 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. *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

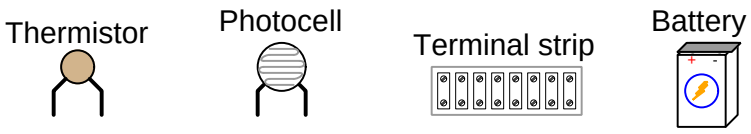
file we_1002

18 Assessment

NAME: _____ **DUE DATE:** _____

Design, build, and demonstrate a simple circuit using either a light sensor (photocell) or a temperature sensor (thermistor) connected to a fixed-value resistor and a battery such that a variable output voltage will be generated as the sensor is stimulated. Your circuit must either make the voltmeter indication increase with increasing sensor stimulus (more voltage for more light or heat – direct action), or do the exact opposite (reverse action), as specified by the instructor. You will also need to demonstrate how to record and display the lowest and highest voltages output by this circuit using your digital multimeter's "min/max" recording function. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, etc.) "Alligator" clips are permitted for making connections to battery terminals only.

This exercise tests your ability to properly identify the operating characteristics of a light or temperature sensor, properly size a resistor to form a voltage divider circuit with the sensor, properly connect a voltmeter into the circuit to achieve the specified response direction, properly use a DMM to capture minimum and maximum voltage values, and use a terminal strip to organize all electrical connections.



The following components and materials will be available to you: assorted CdS **photocells** and **thermistors** ; **terminal strips** ; lengths of **hook-up wire** ; **battery**. You must provide your own tools and digital multimeter (DMM) as well as a copy of this page for your instructor to mark design criteria.

Sensor type (instructor chooses one): ____ Photocell ____ Thermistor

Meter response (instructor chooses one): ____ Direct ____ Reverse

Captured value (instructor chooses one): ____ $V_{minimum}$ ____ $V_{maximum}$

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, and correctly explain how the circuit works.

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, demonstrate, and correctly explain the relevant principles of a circuit while following the sequence shown (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

file we_1103

19 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the use of a shunt resistor to infer current within a series-parallel resistor circuit. Your hypothesis should contrast the predicted current versus the direct measurement of current using an ammeter versus the inferential measurement of current using a low-resistance shunt resistor and a voltmeter. **Sample hypothesis:** *"Based on the calculations shown, I predict a current of ____ milliAmperes through point ____ in the circuit. An ammeter should verify that same current when connected as shown in the first schematic diagram. If I insert a shunt resistor of ____ Ohms as shown in the second diagram, I should be able to infer approximately that same amount of current by measuring the shunt's voltage drop and applying Ohm's Law."*

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Calculate error between direct (ammeter) current measurement and shunt (voltmeter) current measurement (Error = $\frac{Measured - Predicted}{Predicted} \times 100\%$)
- Identify advantages and disadvantages in using a shunt resistor to infer current, as opposed to direct (ammeter) measurement
- Explain how you might select an appropriate shunt resistor value (in Ohms) for any particular current-measurement application
- Demonstrate how you would safely assemble and test your circuit if you happened to be using the shunt resistor to measure a very high current (e.g. *hundreds* of Amperes)

file we_0141

20 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to measure the internal resistance of an unregulated voltage source (e.g. battery, Development Board power supply, solar panel). **Risk analysis** should include possible harm from overcurrent, mitigating harm by using a procedure limiting the amount of time that overcurrent might exist.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how to reliably measure voltage using a multimeter's Min/Max mode or an oscilloscope while over-loading the voltage source for very brief moments of time
- Demonstrate how to properly and safely measure current using a multimeter
- Demonstrate how to model the internal resistance of a source in a schematic diagram

file we_0047

21 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the principle of *either* Thévenin's or Norton's Theorem, showing how an Thévenin or Norton equivalent circuit will deliver the same voltage and current to a load resistance as the more complex series-parallel original circuit to the identical load resistance.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

☐ *Instructor certifies* – Re-try if any demonstration 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
- Explain how you successfully reduced the original circuit down to the Thévenin or Norton equivalent circuit
- Demonstrate how to prove by empirical measurement(s) that a Thévenin or Norton equivalent network is indeed equivalent to the original network it was derived from

file we_0048

22 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the use of an oscilloscope as a graphical voltmeter. You will find the Simplified Tutorial chapter of the *Oscilloscopes* learning module helpful to this experiment:

`http://ibiblio.org/kuphaldt/socratic/model/mod_oscope.pdf`

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate which of the probe contacts functions as the "red" versus "black" test leads
- Demonstrate the effect of altering the horizontal sweep rate of the oscilloscope
- Demonstrate how to accurately interpret voltage based on the divisions of the oscilloscope's screen
- Identify the maximum voltage rating of your oscilloscope based on manufacturer documentation, and explain how you might be able to creatively use that oscilloscope to accurately measure a circuit voltage exceeding the oscilloscope's maximum rating

file we_0207

23 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the right-hand rule of electromagnetism, optionally disassembling a motor or generator and using its internal components to do so. **Risk analysis** should include the potential to damage the motor or generator during disassembly or reassembly if you choose to do this, refraining from excessive force as a primary method to mitigate.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate what conditions are necessary to generate a magnetic field using electricity
- Demonstrate how to reverse the polarity of the magnetic field produced by an electromagnet
- Demonstrate how to map magnetic field vectors using a magnetic compass

file we_0049

24 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the principle of electromagnetic induction, optionally disassembling a motor or generator and using its internal components to do so. **Risk analysis** should include the potential to damage the motor or generator during disassembly or reassembly if you choose to do this, refraining from excessive force as a primary method to mitigate. If you choose to disassemble a Delco-Remy automotive alternator and use the rotor or stator for this experiment, you will find the Tutorial chapter of the *AC Generators* learning module helpful to this experiment:

`http://ibiblio.org/kuphaldt/socratic/model/mod_acgen.pdf`

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate electromagnetic induction, using the Right-Hand Rule and Lenz's Law to correctly predict the polarity of voltage induced in a coil by a changing magnetic field
- Demonstrate the use of a multimeter to register voltage produced by electromagnetic induction
- Demonstrate the use of an oscilloscope to register voltage produced by electromagnetic induction
- Explain why the shaft of an electromechanical machine (e.g. generator) must be in *motion* in order to generate voltage and why it generates zero voltage when stationary

file we_0050

25 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the principle of inverse-exponential growth and decay in a resistor-capacitor network.

Note: pay close attention to the tolerance rating of your capacitor(s), as this may very likely be "looser" than the ±5% common for carbon-composition resistors! Electrolytic capacitors are the worst offenders in this regard.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how a capacitor behaves when initially subjected to a transient event in a DC circuit (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how a capacitor behaves after a long period of time has passed from some transient event in a DC circuit (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to algebraically manipulate either the growth or the decay equation to solve for either t or τ as selected by the instructor

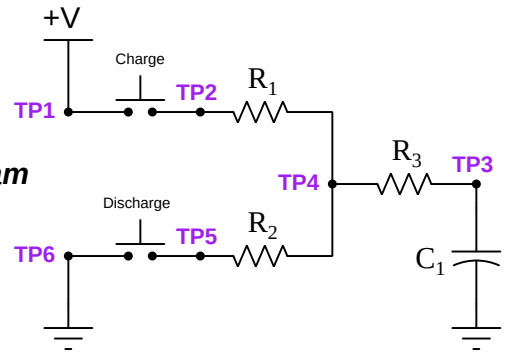
file we_0008

26 Assessment

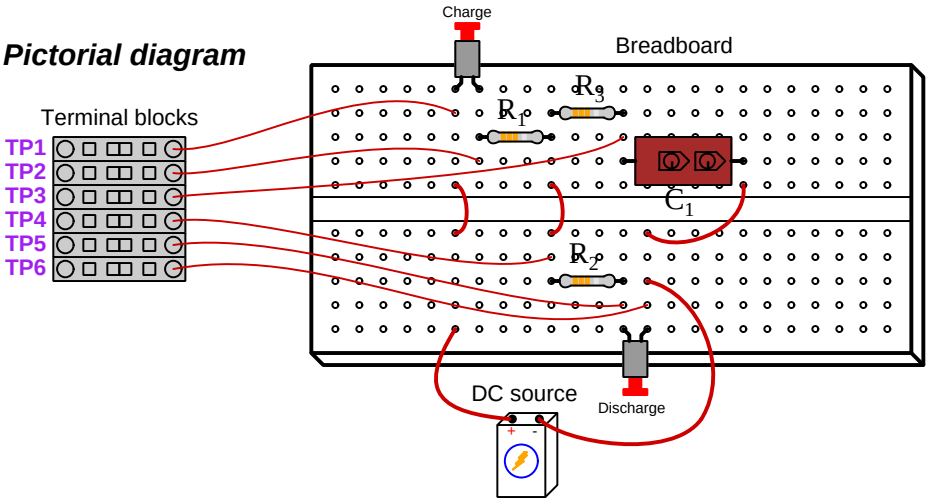
NAME: _____ **DUE DATE:** _____

Troubleshoot a fault within the following resistor-capacitor time delay network, where a pair of normally-open pushbutton switches cause a capacitor to slowly charge and discharge, respectively. 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) while leaving the pushbuttons and test points accessible. It is highly recommended to use your Development Board to construct this circuit, placing the capacitors, pushbutton switches, and resistors on a solderless breadboard while using the terminal blocks as test points, and that you select resistor and capacitor values resulting in a time constant (τ) value reasonable for viewing voltage rise and fall using a multimeter (e.g. all resistors 10 kΩ, capacitor 100 μF). These diagrams will be allowed for use during the troubleshooting exercise:

Schematic diagram



Pictorial diagram



Possible faults include:

- Power supply failure
- Any component failed open
- Any component failed shorted
- Any component value altered

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 logically 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%). *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

file we_1007

27 Assessment

NAME: _____ **DUE DATE:** _____

Design, build, and demonstrate a voltage divider network to produce a specified output voltage from a voltage source of random value (e.g. a primary-cell battery or adjustable voltage source). You will be allowed to measure the voltage of the battery before beginning your circuit design if that is the source the instructor chooses. One resistor in your circuit must be the common value randomly chosen by your instructor.

This exercise tests your ability to properly design and build a voltage divider circuit, use a multimeter to measure both source and output voltages, and properly organize all electrical connections.

The following components and materials will be available to you: lengths of **hook-up wire** ; assortment of **resistors** ; **potentiometers** ; and a **fixed voltage source** provided by the instructor. You must provide your own tools, digital multimeter (DMM), and solderless breadboard or terminal blocks as well as a copy of this page for your instructor to mark design criteria.

Source voltage (instructor chooses): _____ Volts

Fixed-value resistance (instructor chooses): _____ Ohms

Divider circuit output voltage (instructor chooses): _____ Volts

The measured output voltage should deviate from the instructor-specified value by no more than the greatest tolerance of any of the resistors.

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, and correctly explain how the circuit works.

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, demonstrate, and correctly explain the relevant principles of a circuit while following the sequence shown (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

file we_1105

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

Checklist for physical experiment

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

☐ *Instructor certifies* – Re-try if any demonstration 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

Stage #1 – Experiment planning documented in Journal

◯ 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 Journal

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)
-
-

Checklist for microcontroller-based experiment

Stage #1 – Experiment planning documented in Journal

◯ 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 Journal

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)
-
-

Checklist for equipment repair

Stage #1 – Repair planning documented in Journal

◯ Written assessment of equipment malfunction:
- Documents your own observations of the equipment malfunctioning
- Includes an hypothesis accounting for this malfunction

◯ Written theory of operation:
- Describes the basic principle(s) by which the equipment is supposed to function
- Includes references to relevant documentation from the manufacturer

◯ Written risk analysis:
- Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
- Identifies hardware risks (e.g. ways in which your repair work might cause further damage)

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

Stage #2 – Repair work recorded in Journal

Investigate the cause(s) of the equipment malfunction and repair where possible. 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

◯ Were you able to repair the equipment? If not, identify why.

◯ Identify the root cause of the problem; i.e. that which when corrected will prevent this same malfunction from occurring again in the future.

☐ *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)
-
-

file we_0002

29 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the basic characteristics of a semiconductor diode: how it passes current in one direction but not the other, the amount of voltage it drops while conducting, etc.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how to identify the anode and cathode terminals of a diode using a multimeter
- Identify relevant performance parameters on a datasheet for the model of diode chosen
- Demonstrate how to properly and safely measure current using a multimeter
- Demonstrate the effect of temperature on the forward voltage drop of a diode

file we_0208

30 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the principle of current gain (β) in a bipolar junction transistor. Your hypothesis should include a prediction of β based on datasheet ratings for the model of transistor you happen to choose. *Hint: the transistor needs to operate in its "active" mode where substantial V_{CE} voltage exists!*

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

☐ *Instructor certifies* – Re-try if any demonstration 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 properly and safely measure current using a multimeter
- Demonstrate how the controlling current influences the controlled current in a bipolar junction transistor circuit
- Demonstrate how the controlled current, if limited by some external means, does not influence the controlling current in a bipolar junction transistor circuit

file we_0053

31 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the principle of using a bipolar junction transistor to control current through a "heavy" load, the transistor being controlled by the action of a manual switch carrying far less current than the load. **Risk analysis** should include an assessment of the transistor's power disspation and beta (h_{FE}) ratings. *Hint: with the switch positioned to energize the load, the transistor needs to operate in its "saturated" mode where the pathway between collector and emitter is as free-flowing as possible – i.e. using more I_B than is strictly necessary to pass the expected load current!*

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Identify whether your circuit is a high-side or a low-side switching configuration, and explain what would need to change to make it the other type
- Demonstrate which current controls which in a bipolar junction transistor circuit
- Demonstrate the use of a low-value "shunt" resistor to infer load current assuming your multimeter were incapable of measuring that much current on its own (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)

file we_0209

32 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the principle of using a MOSFET to control current through a "heavy" load, the transistor being controlled by the action of a manual switch carrying far less current than the load. **Risk analysis** should include an assessment of the transistor's power disspation rating and maximum V_{GS}. *Hint: with the switch positioned to energize the load, the transistor needs to operate in its "saturated" mode where the pathway between drain and source is as free-flowing as possible – i.e. using more V_{GS} than is strictly necessary to pass the expected load current!*

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Identify whether your circuit is a high-side or a low-side switching configuration, and explain what would need to change to make it the other type
- Demonstrate which signal controls which in a field-effect transistor circuit
- Demonstrate the use of a low-value "shunt" resistor to infer load current assuming your multimeter were incapable of measuring that much current on its own (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Calculate the amount of power dissipated by the MOSFET when turned on

file we_0210

33 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the behavior of an astable 555 timer circuit. Risk analysis for this experiment and all future experiments using integrated circuit (IC) components **must** include relevant ratings of the integrated circuit "chip", for example its power supply voltage range and its output pin current limitations (if driving a load). A "decoupling" capacitor connected between the IC's DC supply pins is recommended, to stabilize its source voltage for more accurate and consistent operation. You will find the Tutorial of the following learning module very helpful for the general planning of your experiment, as well as any good (20+ page) manufacturer datasheet for the 555 timer IC showing example applications:

`http://ibiblio.org/kuphaldt/socratic/model/mod_555.pdf`

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis
◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video
◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how to use a multimeter to verify connections between IC pins and other components in the circuit (i.e. testing the integrity of the connections made within the solderless breadboard)
- Demonstrate how to use an oscilloscope to measure the pulse signal at the Output pin of this IC
- Demonstrate how to use an oscilloscope to verify the stability of the DC source voltage, with and without a decoupling capacitor
- Accurately predict and then demonstrate the effect(s) of one of the components failing open or shorted (chosen at random by the instructor)

file we_0009

34 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the operating principle of a thyristor. Base your predictions from ratings published in the thyristor's datasheet.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how to "trigger" or "fire" a thyristor
- Demonstration how to turn off a thyristor
- Demonstrate how to empirically determine the actual "holding current" value for your circuit's thyristor, and then compare that measured parameter against the datasheet specification(s)
- Demonstrate how you would safely assemble and test your circuit if you needed to use a dangerously high voltage power source to fully test the thyristor

file we_0056

35 Assessment

NAME: _____ **DUE DATE:** _____

Troubleshoot a fault within a circuit using a transistor as a switch to control the energization of a relatively heavy load. 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 utilize a pushbutton switch to serve as the input and some load such as a small DC motor or low-valued resistor as the controlled output. Possible faults include:

- Power supply failure
- Any component failed open
- Any component failed shorted
- Any component value altered

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 logically 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%). *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

file we_1008

36 Assessment

NAME: _____ **DUE DATE:** _____

Design, build, and demonstrate an astable (oscillator) circuit based on a model 555 timer IC to produce a pulsing signal at the IC's output terminal matching the specification shown below.

This exercise tests your ability to properly design and build a 555-based oscillator, use an oscilloscope or other test equipment to measure pulse parameters, and use a solderless breadboard to organize all electrical connections.

The following components and materials will be available to you: **555 timer** ICs ; lengths of **hook-up wire** ; assortment of **resistors** ; **potentiometers** ; assortment of **capacitors** ; and **battery**. You must provide your own tools, digital multimeter (DMM), solderless breadboard, and 555 timer datasheet as well as a copy of this page for your instructor to mark design criteria.

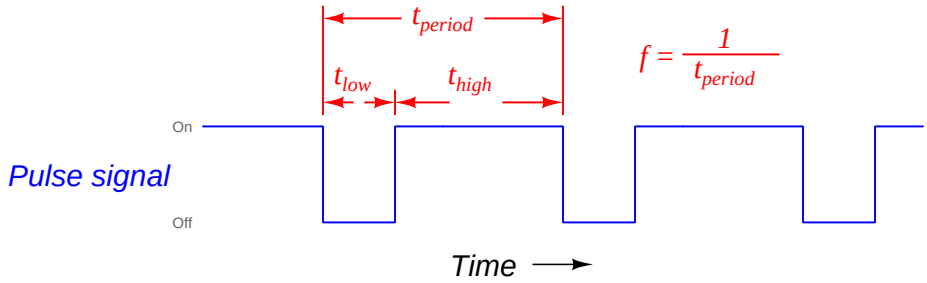
Pulse parameter (instructor chooses one):

____ "high" time = _____ milliseconds

____ "low" time = _____ milliseconds

____ period = _____ milliseconds

____ frequency = _____ cycles per second (Hertz)



The measured time/frequency should deviate from the instructor-specified value by no more than the greatest tolerance of any of the resistors or capacitors.

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, and correctly explain how the circuit works.

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, demonstrate, and correctly explain the relevant principles of a circuit while following the sequence shown (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

file we_1104

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

Checklist for physical experiment

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

☐ *Instructor certifies* – Re-try if any demonstration 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

Stage #1 – Experiment planning documented in Journal

◯ 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 Journal

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)
-
-

Checklist for microcontroller-based experiment

Stage #1 – Experiment planning documented in Journal

◯ 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 Journal

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)
-
-

Checklist for equipment repair

Stage #1 – Repair planning documented in Journal

◯ Written assessment of equipment malfunction:
- Documents your own observations of the equipment malfunctioning
- Includes an hypothesis accounting for this malfunction

◯ Written theory of operation:
- Describes the basic principle(s) by which the equipment is supposed to function
- Includes references to relevant documentation from the manufacturer

◯ Written risk analysis:
- Identifies all personal risks (e.g. shock, burns, inhalation) and mitigations
- Identifies hardware risks (e.g. ways in which your repair work might cause further damage)

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

Stage #2 – Repair work recorded in Journal

Investigate the cause(s) of the equipment malfunction and repair where possible. 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

◯ Were you able to repair the equipment? If not, identify why.

◯ Identify the root cause of the problem; i.e. that which when corrected will prevent this same malfunction from occurring again in the future.

☐ *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)
-
-

file we_0002

38 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the behavior of a logic circuit built from electromechanical relays, implementing a logic function of your choosing (e.g. AND, OR, NAND, NOR, XOR, etc.). Your plan should explain how to build and test this circuit in incremental stages rather than trying to wire everthing up at once. This is an extremely valuable habit when creating complex circuits, as it allows you to find problems while the circuit is smaller than it will be in its final form!

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate the behavior of a simple logic function (e.g. AND, OR, NAND, NOR, XOR, etc.) and how that behavior is described in the form of a truth table
- Demonstrate how to test the coil of a relay for an "open" fault using a multimeter
- Interpret the contact type (SPST, SPDT, DPST, DPDT, etc.) for this relay based on its nameplate or its datasheet

file we_0011

39 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the behavior of an IC logic gate, implementing a logic function of your choosing (e.g. 74LS11 or CD4081 AND gates, CD 4071 OR gates, 74LS10 or CD4011 NAND gates, CD4001 NOR gates, 74LS86 or CD4070 XOR gates, etc.). Risk analysis for this experiment and all future experiments using integrated circuit (IC) components **must** include relevant ratings of the integrated circuit "chip", for example its power supply voltage range and its output pin current limitations (if driving a load).

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate the behavior of a simple logic function (e.g. AND, OR, NAND, NOR, XOR, etc.) and how that behavior is described in the form of a truth table
- Demonstrate how to use a multimeter as a logic probe to sense "high" and "low" logic states in a circuit
- Demonstrate where to make gate input and output connections to the pins on the IC based on the IC's datasheet
- Identify maximum ratings of each gate within the IC based on the IC's datasheet

file we_0012

40 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate the use of a programmable logic controller (PLC) to implement a multi-input digital logic function, energizing a small load (e.g. LED) to indicate the logical function's output state. Your plan should explain how to build and test this circuit in incremental stages rather than trying to wire everthing up at once. This is an extremely valuable habit when creating complex circuits, as it allows you to find problems while the circuit is smaller than it will be in its final form!

You will find sample code in the *Introduction to PLCs* learning module:

`http://ibiblio.org/kuphaldt/socratic/model/mod_plc.pdf`

Stage #1 – Experiment planning documented in Journal

◯ 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 Journal

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

Stage #3 – Presentation and review

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

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

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

Learning objectives for this experiment:

- Demonstrate the behavior of a simple logic function (e.g. AND, OR, NAND, NOR, XOR, etc.) and how that behavior is described in the form of a truth table
- Demonstrate how to use color-highlighting to show "contact" and "coil" states in the PLC's ladder diagram program, and explain what those colored states represent for each
- Explain why the PLC's inputs and output(s) are wired up as they are; i.e. why your wiring is necessary for their proper function

<u>file we_0212</u>

41 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to measure the propagation delay of a logic gate.

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how to use an oscilloscope to sense "high" and "low" logic states in a digital circuit
- Demonstrate how to use a signal generator to generate a series of "high" and "low" logic states in a digital circuit
- Demonstrate how to configure an oscilloscope using two channels to compare two signals in time
- Demonstrate the effect of some factor such as power supply voltage (within the IC's limit) on propagation delay

file we_0214

42 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate an arbitrary 3-input truth table implemented in IC gate logic. 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 final gate alone can source or sink. Your plan should explain how to build and test this circuit in incremental stages rather than trying to wire everthing up at once. This is an extremely valuable habit when creating complex circuits, as it allows you to find problems while the circuit is smaller than it will be in its final form!

Stage #1 – Experiment planning documented in Experiment Journal before running

◯ 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 Experiment Journal

Only after your instructor certifies stage #1, you are cleared to 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 planning work from stage #1. Always (1) build and test your circuit in stages from simple to complex; (2) keep your schematic clear and up-to-date if you change anything; (3) use test equipment to see what your eyes cannot; and (4) reason from first principles in your Conceptual Toolbox concepts rather than guess. *Assistance is conditional on heeding this advice!*

Stage #3 – Presentation to and review by instructor

◯ Show recorded data in the Experiment Journal, explaining how it confirms or disproves the hypothesis

◯ Correctly demonstrate every learning objective (see below), either live or by pre-recorded video

◯ Instructor notes any advice for you to follow on future experiment page(s)

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

Learning objectives for this experiment:

- Demonstrate how to design a logic circuit that will 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 a gate's input becomes electrically "floating"

file we_0013

43 Experiment

NAME: _____ **DUE DATE:** _____

Plan and conduct an experiment to demonstrate an arbitrary 3-input truth table implemented in a programmable logic controller (PLC). The truth table will have three inputs and be randomly assigned by the instructor. The PLC must drive a DC load requiring more current than the output terminal alone can source or sink. Your plan should explain how to build and test this circuit in incremental stages rather than trying to wire everthing up at once. This is an extremely valuable habit when creating complex circuits, as it allows you to find problems while the circuit is smaller than it will be in its final form!

You will find sample code in the *Introduction to PLCs* learning module:

`http://ibiblio.org/kuphaldt/socratic/model/mod_plc.pdf`

Stage #1 – Experiment planning documented in Journal

◯ 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 Journal

Run and revise the experiment as often as necessary until you fully understand it, as scientific method is a *learning process*. Record <u>all</u> 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 derive a Boolean expression from a given truth table (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how a Boolean expression may be implemented in code (Note: the instructor may challenge you with a problem different than your experimental circuit)
- Demonstrate how to use color-highlighting to show "contact" and "coil" states in the PLC's ladder diagram program, and explain what those colored states represent for each

<u>file we_0213</u>

44 Assessment

NAME: _____ **DUE DATE:** _____

Troubleshoot a fault within a combinational logic circuit, of a complexity comparable to the logic-gate circuit used to implement the arbitrary 3-input truth table in a previous experiment. 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 have three inputs and drive a DC load requiring more current than the final gate alone can source or sink. Possible faults include:

- Any resistor failed open
- Any transistor terminal failed open
- Any gate output failed high
- Any gate output 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 logically 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%). *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

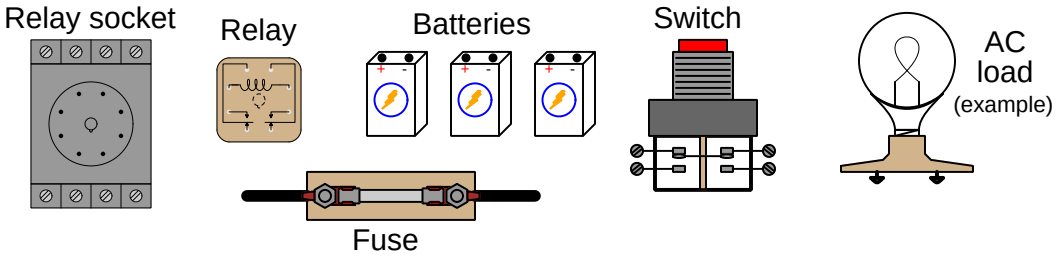
file we_1005

45 Assessment

NAME: _____ **DUE DATE:** _____

Design, build, and demonstrate a circuit controlling a 120 VAC load using a relay with a low-voltage DC coil controlled by a manual switch. The relay's coil must be energized by DC power from batteries, not an AC-DC power supply. Use a digital multimeter to either measure relay coil current or measure AC load current, as selected by the instructor. All 120 VAC electrical connections must be made using terminal blocks for safety (no twisted wires, crimp splices, wire nuts, spring clips, etc.). "Alligator" clips are permitted for making connections to low-voltage terminals only. The 120 VAC portion of the circuit must be fused for overcurrent protection.

This exercise tests your ability to properly interpret the "pinout" of an electromechanical relay, properly wire a switch to control a relay's coil, properly connect batteries together to create suitable voltage for the relay coil, properly wire a load to the contacts of a relay, properly select NO/NC contacts on both the switch and the relay, properly use a multimeter to measure current, and use terminal blocks to organize all electrical connections.



The following components and materials will be available to you: assorted "ice cube" **relays** with DC-rated coils and matching **sockets** ; assorted pushbutton **switches** ; lengths of **hook-up wire** ; **batteries** ; **fuseholder** and **fuse** ; and 120 VAC **lamp or other suitable load**. You must provide your own tools, digital multimeter (DMM), alligator clip "jumper" wires, and Development Board as well as a copy of this page for your instructor to mark design criteria.

Load/switch status (instructor chooses one): ____ On when pressed *or* ____ Off when pressed

Current measurement (instructor chooses one): ____ Relay coil *or* ____ AC load

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, and correctly explain how the circuit works.

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, demonstrate, and correctly explain the relevant principles of a circuit while following the sequence shown (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). *As with all other assessments, this must be completed without aid of any notes or other references (i.e. closed-note).*

file we_1101

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
- ◯ Clear the lab space of all personal projects including Development Boards
- ◯ Vacuum-clean the floor of all debris after picking up any components, wire pieces, etc.
- ◯ 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 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 or depleted
- ◯ Check terminal block, connector, and heat-shrink storage bins to ensure none are misplaced or depleted
- ◯ Check resistor storage bins to ensure none are misplaced or depleted
- ◯ Check fuse storage bins to ensure none are misplaced or depleted
- ◯ Check inductor/transformer storage bins to ensure none are misplaced or depleted
- ◯ Check capacitor storage bins to ensure none are misplaced or depleted
- ◯ Check semiconductor device storage bins to ensure none are misplaced or depleted
- ◯ Organize all wire spools and recycled wire bins, noting any that are depleted
- ◯ 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 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 RF equipment for basic functionality (e.g. VNAs, impedance analyzers, field monitors)
- ◯ Test all special lab systems for basic functionality ; ensure schematic diagrams are in place
  - Digital clock, public demonstration systems, etc.
  - Lab power grids (solar power grid, three-phase AC grid)

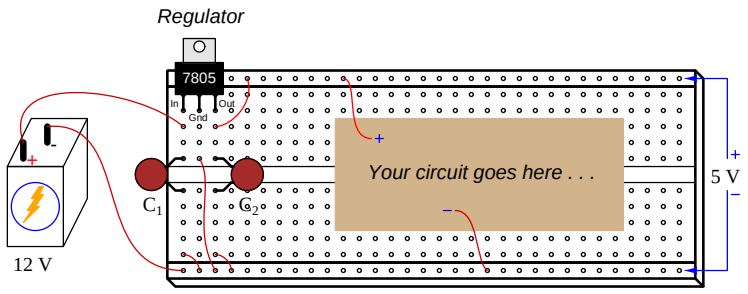
file we_2000

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 μF ceramic capacitors work well for this purpose, and should be located as close to each IC's power supply terminals as possible.
- **Diversify your learning experience** by using different types of test equipment (e.g. DMMs, VOMs, oscilloscopes), different types of construction techniques (e.g. solderless breadboards, soldered connections, terminal blocks), and different types of power sources. Remember, the reason you are in this course is to *learn*, not just to complete assignments!

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



Decoupling capacitors C_1 and C_2 help stabilize the regulated voltage if your circuit's load 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.

file `eet_tips`

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.

file `eet_troubleshooting`