IETTI-221 – Intermediate Electronics Experiments (Semester 3 EXPERIMENTS)

NAME: _____ Last update 26 September 2026

Activity #	Due by theory session #12	Score
01 Experiment	Polyphase AC generator system	
02 Assessment	Analyze multiple series-parallel DC resistor circuits	
03 Assessment	Design, model, and build RC time-delay circuit	

Activity #	Due by theory session #24	Score
04 Experiment	Discrete-component multi-stage audio power amplifier	
05 Assessment	Design, model, and build a transistor amplifier with specified gain	
06 Assessment	Troubleshoot audio power amplifier	

Activity #	Due by theory session #36	Score
07 Experiment	Radio beacon using microcontroller programmed in C	
08 Assessment	Design, model, and build RC filter network	
09 Assessment	Test cable impedance and length	

Activity #	Due by theory session #48	Score
10 Experiment	Analog signal conditioning system	
11 Assessment	Design, model, and build precise-gain operational amplifier circuit	
12 Assessment	Troubleshoot analog signal system	

Activity #	Due by theory session #60	Score
13 Experiment	Electric power control/monitoring system	
14 Assessment	Wire and configure a VFD for motor speed control	
15 Assessment	Troubleshoot power control/monitoring system	

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

Essential information about this course:

- The purpose of this entire program is for you to learn your chosen craft. To do that, you must do your own work. Relying on classmates and/or artificial intelligence (AI) to read, write, or think for you defeats this purpose and will be considered plagiarism. Asking for help is perfectly acceptable, but while receiving help that challenges you to think for yourself is beneficial, "help" that simply gives you answers is not. Bear this in mind both when asking for help and when giving help.
- This is a laboratory course, but *the experiments are multi-concept systems rather than single-concept experiments.*
- These experimental systems follow concepts taught in that semester's theory course, which means the theory course outline and source texts are essential resources for you here.
- Grades, certificates, and degrees are nothing more than imperfect symbols of learning, and do not constitute the substance of learning. Those who prioritize symbols over substance always fail to achieve the latter and usually fail to achieve the former as well. Your priority in this course, therefore, should be mastering first principles of circuits, safe work habits, technical reading and writing, troubleshooting, and experimental reasoning.
- Half of your course grade comes from the number of attempts necessary to correctly complete each demonstration. Clarifying questions are welcome, but all results presented to the instructor will be assessed just like answers submitted on an exam.
- Half of your course grade comes from the number of attempts necessary to correctly complete each assessment activity (e.g. skills demonstrations and circuit troubleshooting). Just like the experiments, each assessment activity must be eventually completed correctly to pass the course.
- You should budget a minimum of 12 hours per week for this course. The lab is yours to use during all open-school hours. *Do not let the lack of fixed hours for this course lead to procrastination – manage your time wisely!*
- Successful students (1) review relevant theory before planning experiments, (2) prioritize hands-on lab time, (3) read instructions carefully, (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.

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.

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`

Course description

This course reinforces the content of IETTI-222 (Intermediate Electronics Theory) by way of experimental system design and construction, starting with only a block diagram and a general description of the system's intended function. Students then engineer all details of the system, building and testing it in stages. 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 experimental systems 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)
- Design, construct, document, and test complex electronic systems based on general specifications and high-level design ideas developed in partnership with the instructor, these systems incorporating polyphase AC networks, analog amplifiers, RF communication, microcontrollers, and high-current load control. (Addresses Program Learning Outcomes 1, 2, 3, 4, 5, 6, 7)
- Edit and write procedural code in a text-based programming language to simulate DC resistor circuits, resistor-capacitor delay networks, passive filters, and amplifier circuits. (Addresses Program Learning Outcomes 2, 4, 6, 7)
- Construct analog electronic and AC power circuits meeting specifications set by the instructor and demonstrate proper test equipment usage including multimeters, signal generators, and oscilloscopes. (Addresses Program Learning Outcomes 4, 5, 6)
- Troubleshoot faulted audio amplifier circuits, analog signal conditioning systems, and high-current load control systems 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.

Expectations for each experimental system

In the EET program the initial Experiments courses are based on small-scale experiments, each one designed to explore a single concept. Here in the later Experiments courses you build experimental *systems* involving multiple concepts, requiring research and design similar to that of real challenges on the job. The purpose of the introductory Experiments courses is to build competence in discrete skills; here the purpose is to develop a higher level of problem-solving and professionalism.

The systems you will build in this course borrow heavily from concepts and designs explored in previous courses, so you will find your previous coursework extremely useful as reference material.

Stand-alone demonstrations should be performed using *minimal* hardware – meaning the bare minimum of components connected together to perform each demonstration, ideally with that portion of the system functioning in complete isolation from all others. The purpose of this is to build the habit of building and testing large systems in stages which is a proven way to develop complex systems with as little troubleshooting as necessary. A deduction of -5% per re-try is levied on each unsuccessful stand-alone demonstration.

Complete system demonstrations must be performed after every stand-along demonstration has been completed for that experimental system. All portions of the system must be in good working order, proven by having you demonstrate all bullet items listed for the complete system demonstration. If any portion of the complete system demonstration is faulty or otherwise incorrect, the instructor's inspection will stop and a deduction of -10% will be levied. You will then revisit your system and make all necessary corrections and reviews, and are welcome to re-try as many times as necessary. The same -10% deduction applies to all failed re-tries.

The "schematic diagram challenge" deserves elaboration here. Sketching a complete and accurate schematic diagram is vitally important for every system you design and build, but it takes too long for the instructor to perform a wire-by-wire inspection of every student's diagram on every system built. Instead, the instructor tests the accuracy of your schematic diagram by selecting random portions of your system and having you predict and measure signals there. These could be individual components or test points, they could be assuming normal operation or some special condition (e.g. a simulated fault), they could be selected from the physical system with you having to reference the schematic diagram, or vice-versa. In all cases, you must show an accurate correspondence between what you have built and what you have drawn, and demonstrate a thorough understanding of your system's behavior. Preparation consists of thoroughly reviewing both your system and your diagram, predicting what kinds of signals you ought to measure at all points in your system and making absolutely sure your schematic diagram is complete and accurate.

Each experimental system you build will be a testament to your knowledge and skill as an electronics technician, and will be thoroughly documented in your Experiment Journal which you may show to employers as a portfolio of your experimental capabilities.

As always, questions are welcome throughout the research, design, and construction process. You will never lose points for asking a question prior to an assessment, and your instructor will always clarify expectations so that you know what is being asked of you, but the moment you deem any part of your system ready the instructor's job is to grade your work. This is the same as on a job: when you present a finished product to a supervisor or client, it must actually be ready. The time to ask for clarification is before the inspection, not during.

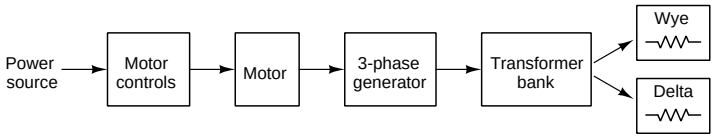
file `eet_experimentalsystem`

01 Experiment

NAME: _____ **DUE DATE:** _____

Design and build an experimental motor-generator system to generate three-phase AC electricity. The motor's speed shall be adjustable by the user, and the three-phase generator's output will be stepped up to higher voltage by a transformer bank wired from three individual transformers. Consult the "Experimental motor-generator set" described in the Case Tutorial chapter of the *Polyphase AC* module for ideas.

Block diagram:



☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate start-stop control of the motor, using two momentary pushbutton switches (one Start and one Stop).

☐ *Instructor certifies* – Demonstrate variable-speed control of the motor, using either a pushbutton or a potentiometer user interface to increase and decrease the speed.

☐ *Instructor certifies* – Demonstrate and record balanced phase/line voltages output by the generator, as well as measurement of generator phase sequence (also known as "phase rotation", either ABC or CBA). Demonstrate reversed phase rotation after re-wiring connections to the generator.

☐ *Instructor certifies* – Demonstrate how to infer the generator shaft speed by oscilloscope-based measurement(s). Record a screenshot of the oscilloscope along with the inferred shaft speed.

☐ *Instructor certifies* – Demonstrate voltage transformation (step-up) by the three-phase transformer bank, with all phase/line voltages balanced.

☐ *Instructor certifies* – Demonstrate and record the mathematical relationship between line and phase quantities for Wye and Delta resistive loads energized by the transformer bank's output. *The instructor may challenge you a randomized problem to test your mastery of this concept!*

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Pushbutton start/stop as well as variable-speed control of motor
- Precautionary test protocols applied throughout, as though the circuit harbored dangerous voltage levels
- Balanced voltage step-up by transformer bank
- A single *Experiment Journal* document containing all information about the system
- Schematic diagram challenge

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02 Assessment

NAME: _____ **DUE DATE:** _____

Analyze three consecutively-assigned series-parallel resistor circuits energized by DC sources, each one generated by a circuit simulator such as `sp.c`.

This exercise tests your ability to apply Foundational Concepts such as *Ohm's Law*, *Joule's Law*, *Kirchhoff's Voltage Law*, *Kirchhoff's Current Law*, *properties of series networks*, *properties of parallel networks*, and *behaviors of sources versus loads* in circuit scenarios sufficiently complex that passing is impossible by following any memorized procedure. Basic *calculator usage* is also tested, as well as skill with handling *metric prefixes*. This is why `sp.c` is recommended as the simulator, as this program only provides given resistor values, a schematic, and just one randomly-selected voltage, current, or power value for just one randomly-selected resistor. This makes the necessary procedure unique to each combination of given value (voltage, current, or power) and particular location within the circuit.

Your instructor will run the circuit simulation software on their computer, and will also provide ample blank paper for your use. You must provide your own calculator and writing tools.

Three-resistor series-parallel circuit = _____

Four-resistor series-parallel circuit = _____

Five-resistor series-parallel circuit = _____

SEQUENCE: (1) Instructor uses circuit simulation software to provide a problem for you to solve; (2) You solve for all necessary quantities in the simulated circuit from the randomized data provided by the simulation and explain the principles applied in obtaining those results; (3) Instructor uses the same circuit simulation software to generate answers to compare against yours; (4) If your answers match the simulation's to within $\pm 1\%$ you have successfully passed this problem and are ready to proceed to the next.

Successfully answering consecutive simulation problems in one school day constitutes *one* successful attempt of this assessment. Re-tries require solving all given problems again, not just the one(s) missed last time.

Circuit analysis 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 circuits, different component values). Scoring is based on the number of attempts necessary to successfully analyze *multiple consecutive* circuit simulations and correctly explain the relevant principles 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_1201

03 Assessment

NAME: _____ **DUE DATE:** _____

Design, build, and demonstrate a resistor-capacitor circuit that achieves a specified voltage between its output terminals within a specified range of time following the actuation of a switch, also writing a text-based computer program (e.g. C, C++, Python) modeling this same circuit and predicting output voltage at multiple points in time.

This exercise tests your ability to apply inverse-exponential functions to RC networks, use an oscilloscope to measure voltage over time, properly organize all electrical connections, and write a computer algorithm to predict RC network behavior.

The following components and materials will be available to you: **DC power supply** with variable voltage output ; **digital oscilloscope** with test probes ; an assortment of **capacitors** ; an assortment of **resistors** ; **switches** ; **potentiometers** ; and lengths of **hook-up wire**. You must provide your own tools, a digital multimeter (DMM), a computer with programming software installed, and a solderless breadboard or terminal blocks as well as a copy of this page for your instructor to mark design criteria.

Source voltage (instructor chooses) = _____ V

Output voltage trajectory (instructor chooses one) = ____ Rises or ____ Falls after actuation

Output voltage within time range (instructor chooses) = _____ V

Time range (instructor chooses) = between _____ seconds and _____ seconds

The performance of your circuit will be judged on whether or not the output voltage reaches the specified value at any time within the specified window, and whether this happens as it rises or falls. The performance of your modeling program will be judged by its output showing a series of printed voltage values calculated at different times covering at least the specified time period.

SEQUENCE: (1) Instructor chooses criteria and verifies all components are disconnected from each other; (2) You write and test the modeling program; (3) Instructor observes your program's output while you correctly explain how the source code works; (4) You build and test your circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

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

Circuit design assessments are *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, demonstrate, and correctly explain the relevant principles of a circuit simulation 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).*

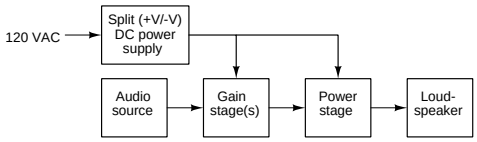
file we_1114

04 Experiment

NAME: _____ **DUE DATE:** _____

Design and build an experimental multi-stage power amplifier using discrete transistors and no integrated circuits. The circuit must receive an input signal from some audio-frequency source (e.g. microphone, radio audio output, musical instrument pickup) and output to a loudspeaker. It is recommended to modify your Development Board to serve as the split +V/−V power supply for your amplifier.

Block diagram:



☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate and record that the DC power supply circuit outputs "clean" DC with negligible ripple voltage on both +V and −V rails when unloaded.

☐ *Instructor certifies* – Demonstrate and record measurement of audio source for maximum voltage amplitude, to be used for amplifier gain calculation.

☐ *Instructor certifies* – Demonstrate the effect of varying DC bias voltage on the AC output signal of a common-emitter amplifier circuit.

☐ *Instructor certifies* – Demonstrate the gain-stage operating on its own without any power stage(s).

☐ *Instructor certifies* – Demonstrate and record *just the gain stage* operating with a maximum voltage gain suitable for amplifying the audio source at maximum volume (i.e. output waveform does not "clip" when given maximum audio source as the input signal at maximum adjustable voltage gain setting).

☐ *Instructor certifies* – Demonstrate and record *just the power stage* driving a "dummy" load equivalent to the loudspeaker (so as to not make an annoying/loud sound) with minimal signal distortion measured both in the time-domain and in the frequency domain, and no over-heating of the transistors.

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Amplifier system reproduces the audio source's to the loudspeaker clearly with no audible distortion
- Minimal "hum" present at the loudspeaker from power supply ripple voltage
- Volume control potentiometer in the amplifier circuit, adjustable down to zero (silence)
- Components do not overheat when operated near full power for extended periods of time
- A single *Experiment Journal* document containing <u>all</u> information about the system
- Schematic diagram challenge

  <u>file we_3003</u>

05 Assessment

NAME: _____ **DUE DATE:** _____

Design, build, and demonstrate a discrete transistor amplifier circuit exhibiting a pre-specified voltage gain. Additionally, you will write a text-based computer program (e.g. C, C++, Python) modeling the amplifier's input impedance, its output impedance, and its voltage gain based on user-specified component values.

This exercise tests your ability to properly design and build a transistor amplifier circuit, select components necessary to achieve a specified voltage gain, use a signal generator to properly stimulate the amplifier, use an oscilloscope to measure signal voltage and from those measurements infer voltage gain, properly organize all electrical connections, and write a computer algorithm to predict amplifier performance parameters. You will find the "Amplifier design example: swamped common-emitter" section of the *Single-Stage BJT Amplifiers* module tutorial to be helpful.

The following components and materials will be available to you: **digital oscilloscope** with test probes ; audio-frequency **signal generator** ; assortment of **resistors** ; **potentiometers** ; **capacitors** ; **batteries** ; and **discrete transistors**. You must provide your own tools, a digital multimeter (DMM), a computer with programming software installed, and your Development Board as well as a copy of this page for your instructor to mark design criteria.

AC voltage gain (instructor chooses) = _____ (unitless)

When demonstrating voltage gain in your powered amplifier circuit, you are free to choose whatever levels of test signal voltage you wish, and you are also welcome to make bias adjustments to ensure your amplifier is operating in Class-A mode (i.e. no visible distortion). All gain-setting component values must be fixed, however, from your building of the amplifier circuit prior to power-up. With bias and signal values properly adjusted, the exhibited gain should not deviate from the instructor-chosen specification more than ±10% based on component values selected/adjusted prior to power-up.

SEQUENCE: (1) Instructor chooses criteria and verifies all components are disconnected from each other; (2) You write and test the modeling program; (3) Instructor observes your program's output while you correctly explain how the source code works; (4) You build and test your circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

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

Circuit design assessments are *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, demonstrate, and correctly explain the relevant principles of a circuit simulation 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_1123

06 Assessment

NAME: _____ **DUE DATE:** _____

Troubleshoot a fault within a *multi-stage audio power amplifier* circuit. This circuit shall be constructed in such a manner that all circuit components and simulated faults must be hidden from view (e.g. covering it up with a box or towel) but test points will be available for contact with instrument probes. A schematic diagram showing the circuit and its test points will be allowed for use during the troubleshooting exercise.

The circuit shall be powered by the 120 Volt AC line, and will provide easy access to the gain control when the fault is hidden from view. Possible faults include:

- Any cable failed open
- Any cable failed shorted
- 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).*

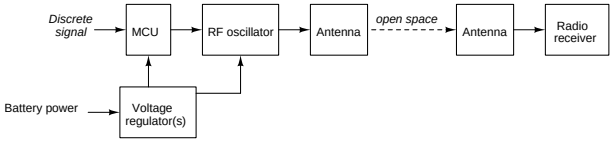
file we_1018

07 Experiment

NAME: _____ **DUE DATE:** _____

Design and build an experimental radio beacon sensing at least one discrete (on/off) input signal and broadcasting a modulated radio signal to a pre-constructed receiver, the transmitting entirely powered by a single battery. A recommended design uses a packaged RF oscillator IC, an MSP430 microcontroller, and a software-defined radio (SDR) unit for the receiver.

Block diagram:



☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Identify and explain the meaning of those portions of Part 15 of Title 47 of the Code of Federal Regulations (CFR) applicable to this experimental system. Copy this text to your document.

☐ *Instructor certifies* – Demonstrate and record microcontroller (MCU) program written in the C language generating a signal suitable for modulating the RF oscillator. An audio-frequency tone for AM or FM is acceptable, as is a pulse signal for a Morse Code message. A pushbutton switch must enable this signal via one of the microcontroller's discrete inputs.

☐ *Instructor certifies* – Demonstrate and record *far-field* tests of two different antenna lengths, also calculating ideal antenna length based on oscillator frequency and antenna type.

☐ *Instructor certifies* – Demonstrate and record *far-field* tests of antenna polarization (i.e. received signal strength with antennas oriented properly versus improperly)

☐ *Instructor certifies* – Demonstrate power conditioning circuit operating for several minutes with stable output voltage(s) and without overheating; calculate fresh battery life based on DC current draw and battery milliAmpere-Hour capacity.

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Microcontroller generates the audio modulating signal, controlled by discrete input signal
- Received signal is intelligible as a beacon, of any modulation type (e.g. AM, FM, LSB, USB) suitable for the receiver
- Beacon works with transmitter outside lab room and receiver inside lab room
- All power for the transmitting side supplied by a single battery
- A single *Experiment Journal* document containing <u>all</u> information about the system
- Schematic diagram challenge

  <u>file we_3006</u>

08 Assessment

NAME: _____ **DUE DATE:** _____

Design, build, and demonstrate a filter network with a specified "pass" characteristic and cutoff frequency, also writing a text-based computer program (e.g. C, C++, Python) modeling this same circuit and predicting its performance.

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

The following components and materials will be available to you: a **signal generator** with variable voltage and frequency ; a dual-channel **oscilloscope** with ×10 probes ; an assortment of **non-polarized capacitors** ; an assortment of **fixed resistors** ; and lengths of **hook-up wire**. You must provide your own tools, a computer with programming software installed, and a solderless breadboard or terminal blocks as well as a copy of this page for your instructor to mark design criteria.

Filter characteristic (instructor chooses one) = ____ Low-pass ____ High-pass

Cutoff frequency (instructor chooses) = _____ Hz

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

SEQUENCE: (1) Instructor chooses criteria and verifies all components are disconnected from each other; (2) You write and test the modeling program; (3) Instructor observes your program's output while you correctly explain how the source code works; (4) You build and test your circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

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

Circuit design assessments are *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, demonstrate, and correctly explain the relevant principles of a circuit simulation 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_1110

09 Assessment

NAME: _____ **DUE DATE:** _____

Demonstrate the measurement of a cable's characteristic impedance and physical length, the particular cable being chosen at random by the instructor. You are welcome to research properties of the cable (e.g. velocity factor) prior to connecting any test equipment to it.

This exercise tests your ability to properly configure and connect appropriate test equipment to a random cable for introducing test signals and measuring the cable's response, and to properly interpret the results of the test to determine the cable's actual parameters of characteristic impedance and length.

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

SEQUENCE: (1) Instructor identifies which system you will perform your challenge on; (2) You configure and connect the necessary test equipment to that system with no power applied; (3) Instructor energizes circuit for the very first time; (4) You perform your tests/measurements for the instructor, correctly interpreting the results and correctly explaining any relevant principles involved.

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).*

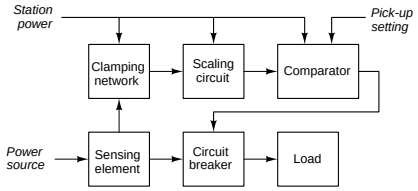
file we_1120

10 Experiment – protective relay option

NAME: _____ **DUE DATE:** _____

Design and build an experimental *protective relay* system using operational amplifiers to condition a signal representing the status of some electrical power network and comparators to automatically trigger a circuit breaker when certain conditions are met. For experimental-scale power systems, a latching electromechanical relay works well as a circuit breaker, with "trip" and "close" coils to actuate the latching power contact(s). Note: you will want to include in your design some provision for mitigating the inductive "kickback" transient voltage that will be generated by either circuit breaker coil when de-energizing!

Block diagram:



☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate manual control of the circuit breaker using pushbuttons.

☐ *Instructor certifies* – Demonstrate and record the system's "tripping" or "closing" time (i.e. the time delay between when the prescribed condition is met and the circuit breaker power contacts change state).

☐ *Instructor certifies* – Identify opamp/comparator limitations from datasheet: *power supply voltage limits*, *max/min output voltage*, *max output current*, *max range of input signal voltages*.

☐ *Instructor certifies* – Demonstrate and record clamping network limiting fault signal amplitude to a level safe for the scaling circuit.

☐ *Instructor certifies* – Demonstrate and record scaling circuit amplifying the signal to a level suitable for the comparator.

☐ *Instructor certifies* – Demonstrate the comparator successfully actuating the circuit breaker.

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Protective relay system is both demonstrably *dependable* and *secure*
- "Trip" and "Close" pushbuttons provide manual control of the circuit breaker
- Green and red LEDs illuminate when "trip" and "close" signals received
- A single *Experiment Journal* document containing <u>all</u> information about the system
- Schematic diagram challenge

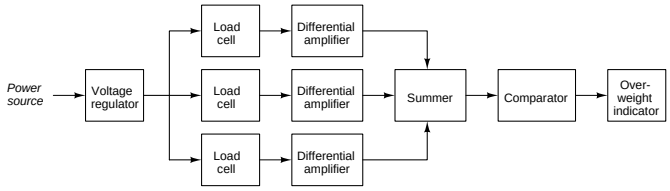
<u>file we_3007</u>

10 Experiment – weigh scale option

NAME: _____ **DUE DATE:** _____

Design and build an experimental *weigh scale* using multiple load cells as the sensing elements and an operational amplifier network to sense and sum together the load cells' signals to yield a total weight, and that triggers an "over-weight" indicator if the total weight sensed by all load cells exceeds a pre-determined threshold.

Block diagram:



☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate and record signal range of a single load cell, establishing its mV/V per kilogram-force or pound calibration.

☐ *Instructor certifies* – Identify opamp/comparator limitations from datasheet: *power supply voltage limits*, *max/min output voltage*, *max output current*, *max range of input signal voltages*.

☐ *Instructor certifies* – Demonstrate the use of a differential amplifier to accurately sense and amplify the signal from a single load cell, outputting a constant V/lb or V/kgf ratio.

☐ *Instructor certifies* – Demonstrate a comparator triggering an LED based on the amplified signal from a single load cell.

☐ *Instructor certifies* – Demonstrate and record an opamp-based analog signal summer circuit accurately summing multiple signals together.

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Indicator reliably shows when a certain amount of weight is exceeded, regardless of how that weight is distributed over the multiple load cells
- Analog summer outputs a reliable V/lb or V/kgf ratio, regardless of how that weight is distributed over the multiple load cells
- The "over-weight" threshold is easily adjusted by the user
- A single *Experiment Journal* document containing <u>all</u> information about the system
- Schematic diagram challenge

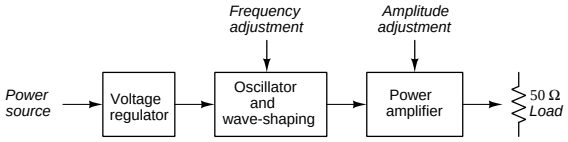
<u>file we_3008</u>

10 Experiment – signal generator option

NAME: _____ **DUE DATE:** _____

Design and build an experimental signal generator covering the human audio frequency range outputting at least two different types of wave-shapes (e.g. sine, square, triangle, ramp, PWM) using operational amplifiers and other components.

Block diagram:



☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate simple adjustable-frequency oscillator covering the human audio frequency range (20 Hz to 20 kHz).

☐ *Instructor certifies* – Identify opamp/comparator limitations from datasheet: *power supply voltage limits*, *max/min output voltage*, *max output current*, *max range of input signal voltages*.

☐ *Instructor certifies* – Demonstrate wave-shaping circuit converting one shape of voltage waveform into another (e.g. triangle to square, triangle to sine, non-square to PWM) independent of frequency.

☐ *Instructor certifies* – Demonstrate ability to adjust output signal amplitude to a powered load.

☐ *Instructor certifies* – Demonstrate DC power conditioning for the signal generator circuit, including "rail-splitting" if a split DC supply is necessary from a single supply such as a battery. Voltages must be regulated and ripple minimal.

☐ *Instructor certifies* – Demonstrate correct harmonic spectrum for each wave-shape (e.g. for a square wave this would mean third harmonic at $\frac{1}{3}$ amplitude of fundamental, fifth harmonic at $\frac{1}{5}$ amplitude, etc.).

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Output signal amplitude linearly adjustable from zero to full
- Output signal frequency adjustable over a range (minimally) covering the human-audio spectrum
- Must be able to drive a 50 Ohm load at full amplitude with negligible time-domain distortion
- Signal wave-shape does not change significantly as frequency is adjusted
- A single *Experiment Journal* document containing <u>all</u> information about the system
- Schematic diagram challenge

<u>file we_3014</u>

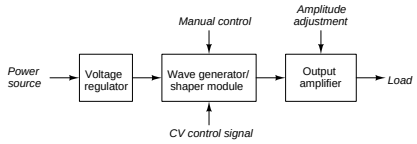
10 Experiment – musical synthesizer option

NAME: _____ **DUE DATE:** _____

Design and build an experimental analog music synthesizer utilizing at least one operational amplifier capable of producing musical tones, or capable of modifying tones in musically useful ways generated by other instruments. The synthesizer module you make must have at least one manual (e.g. knob) control as well as at least one CV signal input.

Functional ideas include *voltage-controlled amplifier (VCA)*, *voltage-controlled filter (VCF)*, *voltage-controlled oscillator (VCO)*, *envelope generator*, *sequencer*, etc.

Block diagram:



☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate DC power conditioning for the signal generator circuit, including "rail-splitting" if a split DC supply is necessary from a single supply such as a battery. Voltages must be regulated and ripple minimal.

☐ *Instructor certifies* – Identify opamp/comparator limitations from datasheet: *power supply voltage limits*, *max/min output voltage*, *max output current*, *max range of input signal voltages*.

☐ *Instructor certifies* – Demonstrate proof-of-concept circuit for wave generation and/or shaping.

☐ *Instructor certifies* – Demonstrate manual control exerting the intended effect on the audio tone.

☐ *Instructor certifies* – Demonstrate CV control signal spanning a voltage range standard to "Euro-rack" modules exerting the intended effect on the audio tone.

☐ *Instructor certifies* – Demonstrate final amplifier with provision for adjusting maximum output voltage to be compatible with common "Euro-rack" analog synthesizer modules.

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Output signal limited to maximum voltage allowed by "Euro-rack" synth module inputs
- Manual control functions properly
- CV control functions properly
- It sounds cool!
- A single *Experiment Journal* document containing all information about the system
- Schematic diagram challenge

  file we_3015

11 Assessment

NAME: _____ **DUE DATE:** _____

Design, build, and demonstrate an operational amplifier circuit exhibiting a precise voltage gain, also writing a text-based computer program (e.g. C, C++, Python) modeling this same circuit and predicting its performance.

This exercise tests your ability to properly design and build an amplifier circuit, select components necessary to achieve a specified voltage gain, use a multimeter to measure voltage and from those measurements infer voltage gain, properly organize all electrical connections, and write a computer algorithm to predict amplifier voltage gain given component values.

The following components and materials will be available to you: assortment of **resistors** ; **potentiometers** ; **batteries** to build a "split" power supply for the opamp if necessary ; and **operational amplifier ICs**. You must provide your own tools, a digital multimeter (DMM), a computer with programming software installed, and your Development Board as well as a copy of this page for your instructor to mark design criteria.

DC voltage gain (instructor chooses) = _____ (unitless)

Characteristic (instructor chooses one) = ____ Inverting *or* ____ Noninverting

When demonstrating voltage gain, you are free to choose whatever levels of test signal voltage you wish, provided that you conduct the test using multiple voltages to prove that your circuit's voltage gain is reliable for all signals within its range. Your test voltage must be provided by a potentiometer powered by the opamp power supply. Your modeling software must accept user input at start-up so that the user may test different amplifier designs without having to edit the source code.

SEQUENCE: (1) Instructor chooses criteria and verifies all components are disconnected from each other; (2) You write and test the modeling program; (3) Instructor observes your program's output while you correctly explain how the source code works; (4) You build and test your circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

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

Circuit design assessments are *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, demonstrate, and correctly explain the relevant principles of a circuit simulation 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_1116

12 Assessment

NAME: _____ **DUE DATE:** _____

Troubleshoot a fault within the analog system you made. This circuitry 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. The external stimulus driving the system will also be adjustable during troubleshooting. A schematic diagram showing the circuit and its test points will be allowed for use during the troubleshooting exercise.

Possible faults include:

- Any cable failed open
- Any cable failed shorted
- 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_1020

13 Experiment – PLC-based motor starter option

NAME: _____ **DUE DATE:** _____

Design and build an experimental motor control circuit using a Programmable Logic Controller (PLC). The PLC program must make use of both counter and timer instructions, and "latch" the motor's state so that the user pushbutton switches may be momentary contact. An "emergency stop" toggle or latching pushbutton switch must also be included that overrides the PLC, such that even if the PLC's motor-control output bit were forced **on** the E-Stop button would still interrupt power to the motor.

☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate the action of a latching on/off PLC control program, where momentary-contact "start" and "stop" switches toggle the motor's state.

☐ *Instructor certifies* – Demonstrate the action of an up/down counter PLC instruction.

☐ *Instructor certifies* – Demonstrate the action of an on-delay timer PLC instruction.

☐ *Instructor certifies* – Demonstrate the action of an off-delay timer PLC instruction.

☐ *Instructor certifies* – Demonstrate proper lock-out/tag-out (LOTO) technique for safely performing work on the electric motor. Note: in the absence of a lockable disconnect, redundant *taggable* disconnects suffice to meet the NFPA 70E requirements.

☐ *Instructor certifies* – Demonstrate motor contactor safely controlling power to the motor at the command of a low-voltage (< 30 Volts), low-current control signal suitable for the PLC's output channel, with any transient-snubbing components installed as necessary to protect semiconductor switching devices.

☐ *Instructor certifies* – Demonstrate accurate measurement of motor line current, both inrush and running, using a current transformer (CT).

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Motor start control is fail-safe (i.e. won't start) in the event of a failed-open "start" switch circuit
- Motor stop control is fail-safe (i.e. immediately stops) in the event of a failed-open "stop" switch circuit
- Motor power is overcurrent-protected
- Motor "running" and "stopped" indicators controlled by the PLC
- PLC prevents motor from re-starting more than 5 times in 1 minute to limit inrush heating
- A single *Experiment Journal* document containing <u>all</u> information about the system
- Schematic diagram challenge

<u>file we_3012</u>

13 Experiment – protective relay option

NAME: _____ **DUE DATE:** _____

Design and build an experimental circuit using a protective relay to provide overcurrent protection for some suitable high-current AC load (e.g. line-powered AC induction motor).

☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate remote tripping and closing of a circuit breaker rated for the load's voltage and current.

☐ *Instructor certifies* – Demonstrate proper lock-out/tag-out (LOTO) technique for safely performing work on the load. Note: in the absence of a lockable disconnect, redundant *taggable* disconnects suffice to meet the NFPA 70E requirements.

☐ *Instructor certifies* – Demonstrate accurate measurement of load current using a current transformer (CT).

☐ *Instructor certifies* – Demonstrate proper operation of CT test switches in a live circuit.

☐ *Instructor certifies* – Demonstrate how to test a current transformer (CT), both turns ratio and winding polarity. *The instructor may challenge you a randomized problem to test your mastery of this concept!*

☐ *Instructor certifies* – Demonstrate how to set the protective relay's ANSI "50" function parameters.

☐ *Instructor certifies* – Demonstrate how to set the protective relay's ANSI "51" function parameters.

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Protective relay's "50" function works (set pick-up value low enough to trip on normal load current)
- Protective relay's "51" function works (set pick-up value low enough to trip on normal load current)
- Motor power is overcurrent-protected by fuses in addition to the relay-controlled circuit breaker
- Manual breaker "trip" and "close" pushbutton switches located remotely from the circuit breaker
- Circuit is constructed to as to minimize the probability of accidental contact with exposed conductors
- A single *Experiment Journal* document containing all information about the system
- Schematic diagram challenge

file we_3013

13 Experiment – motion control option

NAME: _____ **DUE DATE:** _____

Design and build an experimental motion-control system utilizing at least one servo or stepper motor, where the motor's power electronic circuitry is built up from individual components and not pre-manufactured.

☐ *Instructor consultation* – Discuss design options and strategies, responsibilities and expectations (including conditions for receiving help), safety considerations, etc. Be sure to maintain all records in a single "Experiment Journal" digital document, including test data, design changes, and lessons learned.

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Identify operational parameters of the servo motor from its datasheet: *maximum voltage*, *maximum current*, *maximum output torque*, *maximum speed*.

☐ *Instructor certifies* – Demonstrate power supply circuit's capability to provide ample power for the needs of the servo motor.

☐ *Instructor certifies* – Demonstrate crude manual control of servo motor (e.g. making the servo motor move using pushbutton switches with no electronics).

☐ *Instructor certifies* – Demonstrate proper lock-out/tag-out (LOTO) technique for safely performing work on the servo system. Note: in the absence of a lockable disconnect, redundant *taggable* disconnects suffice to meet the NFPA 70E requirements.

☐ *Instructor certifies* – Demonstrate position sensor action, whether covering the full range of motion or simply a discrete "home" position switch to indicate a starting position.

☐ *Instructor certifies* – Demonstrate overcurrent protection for the servo motor.

☐ *Instructor certifies* – Demonstrate automatic "homing" of the servo such that it seeks a reliable and safe starting position on command.

☐ *Instructor certifies* – Demonstrate automatic positioning of the servo to any specified point along its range of motion.

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Servo accurately and repeatedly controls motion to any specified position within its range
- System provides protection for servo motor against mechanical overloading
- Servo speed is controlled to specified limits
- A single *Experiment Journal* document containing <u>all</u> information about the system
- Schematic diagram challenge

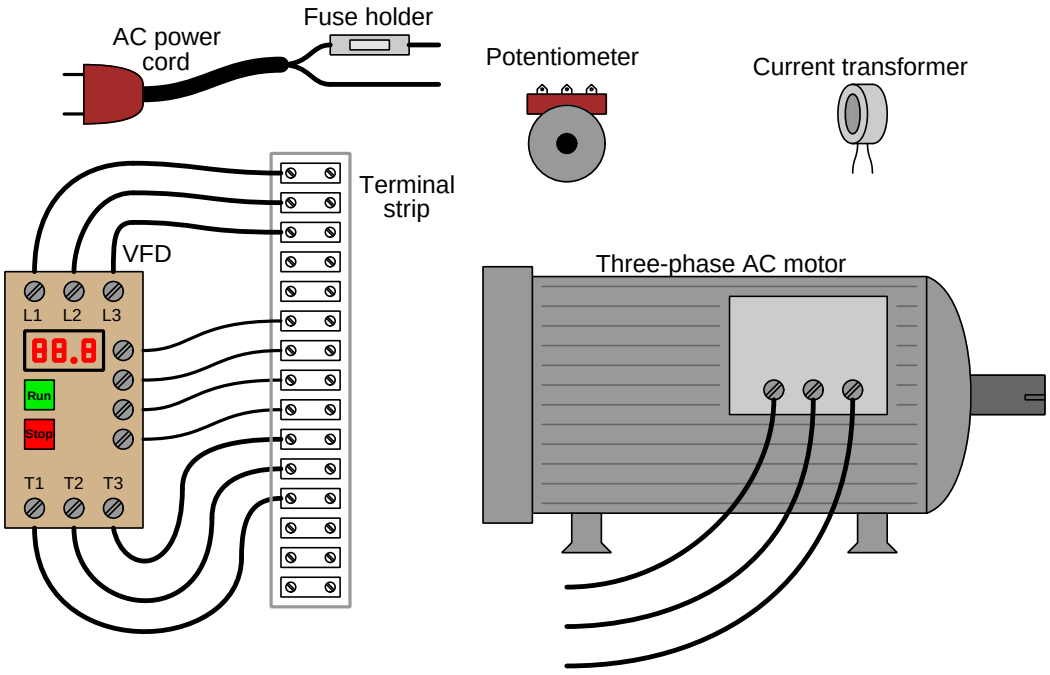
<u>file we_3017</u>

14 Assessment

NAME: _____ **DUE DATE:** _____

Connect a variable-frequency motor drive (VFD) to a source of single-phase 120 VAC power and a three-phase electric motor, then demonstrate variable-speed control over that motor. The motor will be switched between Stop and Run modes via the buttons (keypad) on the VFD, and the motor's acceleration/deceleration rates will be configured for gentle starts and stops. All electrical connections must be made using a terminal strip for safety (no twisted wires, crimp splices, wire nuts, spring clips, or "alligator" clips permitted). The 120 VAC portion of the circuit must be fused for overcurrent protection.

This exercise tests your ability to correctly wire a VFD to a power source and to a three-phase induction motor, reset VFD parameters to their default values, program correct parameters in a VFD to control it per specified criteria, and to use a current transformer to measure motor line current.



The following components and materials will be available to you: **variable-frequency motor drive** ; **three-phase electric motor** ; lengths of **hook-up wire** ; assorted **potentiometers**, and a **current transformer**. 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.

You are encouraged to practice setting up a VFD and testing its features before attempting the graded assessment, because these are complex devices with *many* parameters and options. The instructor will insist on a safety inspection of the wiring prior to power-up, and on checking your motor base parameters before running the motor!

Note that some VFDs require jumper wires installed in lieu of remote start/stop switches. The Allen-Bradley PowerFlex 4 VFD is an example of this, requiring a jumper wire between terminals 1 and 11 to take the place of an external "Stop" switch.

Note that there may be multiple parameters to set and/or DIP switches to set in order to properly configure the speed-control option. For example, nearly all VFDs offer the following options for frequency/speed control: front-panel pushbuttons/knob, data network, analog current signal, analog voltage signal; front-panel controls always being the default. *Perusal of ALL parameters and text regarding speed control is often necessary to locate all the necessary changes!*

Instructor chooses motor control options, which if course cannot be set in the drive until it is powered up:

Speed control options (instructor chooses one):

____ 0-10 V analog signal
____ Potentiometer (CW = faster)
____ Potentiometer (CCW = faster)

Acceleration/Deceleration rate to maximum speed (instructor chooses): ____ seconds (*5 seconds minimum!*)

Maximum motor speed (instructor chooses): _____ RPM

How to reset the VFD to factory defaults (you research and describe): _____

Instructor inspects wiring and powers up VFD, you reset VFD ____ (completed)

Base motor parameters (from nameplate):

V_{line} = _____ Volts
I_{line} = _____ Amps @ full load
Speed = _____ RPM @ 60 Hz

You show critical VFD parameters to instructor, then start motor and measure I_{line} ____ (completed)

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_1107

15 Assessment

NAME: _____ **DUE DATE:** _____

Troubleshoot a fault within an electric power control/monitoring system. 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, as will computer software used to monitor and configure any electronic controllers in the system.

- Electronic controller program/configuration error
- 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_1027

16 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)

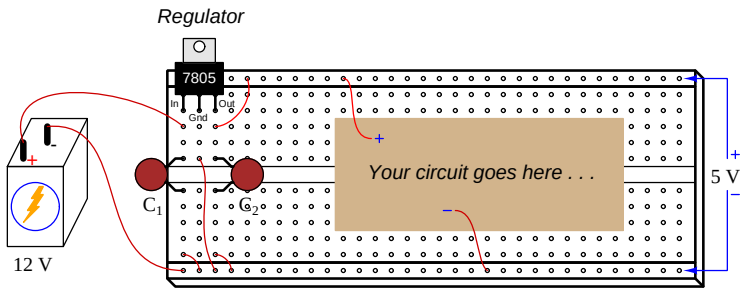
file we_2000

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`