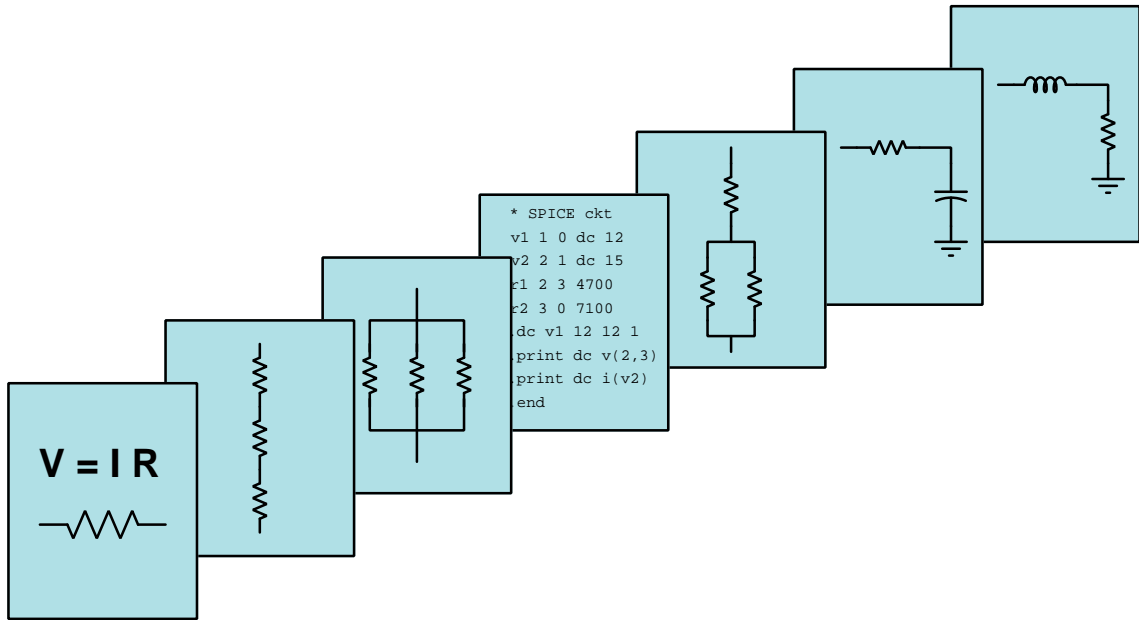


MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



PRINCIPLES OF ROBUST TECHNICAL EDUCATION

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Chapter 1

Ingredients for robust technical education

1.1 First Principles

- **No Prejudice** – Assume every student is capable of learning anything they desire given sufficient time and proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- **Culture of Learning** – Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one’s own fallibility.
- **Feedback on Learning** – Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow.
- **Document Learning** – Maintain detailed records on each student’s performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- **Sound Reasoning** – Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Ask “*Why?*” often.
- **Functional Literacy** – Include extensive reading into the curriculum in order to cultivate the functional literacy necessary for life-long advancement of knowledge and skill, in a society where the written word remains the most accessible medium of human knowledge.
- **Functional Communication** – Require frequent, clear, and well-reasoned communication in all modes appropriate to the subject(s), including detailed documentation of all experiments and projects. *If you can’t clearly explain it, you don’t understand it; If it’s not clearly*

documented, it's not complete. Like functional literacy, clear and accurate exposition of one's thoughts is a skill born of practice, and just as valuable to any person's life.

- **Experimentation** – Spend at least as much time experimenting and building projects as studying theory, students using scientific method as a tool to solve real problems they encounter along the way. Avoid scripted, pre-engineered “lab exercises” where outcomes are fully known in advance. *Never* have students merely assemble kits or complete exercises merely by following step-by-step instructions.
- **Concept Progression and Review** – Design the curriculum to regularly review those concepts known to be especially challenging and/or frequently misunderstood. Concepts and the logical relationships between them become clearer with every iteration. Courses should be cumulative in their scope, a student's final coursework applying and assessing all knowledge and skills learned since the beginning.
- **Mastery** – Assess and enforce *mastery* at multiple stages in the students' journey, with unambiguous performance expectations at each stage and plenty of opportunities to re-try, designing the curriculum so no one moves to the next stage without mastering the previous. No task is complete until it's done right, and no one graduates who cannot do the job.
- **External Accountability** – Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc.
- **Patience** – Finally, *never rush learning*. Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery!

1.2 Proven Strategies

- Replace lecture with “inverted” instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Use “mastery” as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students’ experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab experience as possible: building test equipment, building test assemblies¹, and building complete working systems (no kits!). In order to provide this same “ground-up” experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.
- Require students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution).
- Require all students attend all technical advisory committee meetings and dialogue with the industry representatives attending.
- Repeat instructional sessions on difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build understanding.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.

¹In the program I teach, every student builds their own “Development Board” consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

Chapter 2

Teaching technical theory

Learning is not merely a process of information transfer. Of far more significance is the transformation of one's thinking that comes with deep study of any subject. That is to say, when we learn something substantial it alters the way we perceive and interact with the world around us. Learning any subject also involves a substantial accumulation of facts in one's memory, but memorization alone is not really learning (at least it isn't learning at the college level). Transmitting facts into a student's memory is easy, and doesn't even require a live human presenter. A well-written book or a well-edited video can do a far better and far more consistent job of conveying facts and concepts than any live presentation¹. A more appropriate role for any human teacher, therefore, is to foster higher-order thinking skills such as problem-solving, logical reasoning, diagnostic techniques, and metacognition (critiquing one's own thinking).

Rather than devote most of your classroom time to lecture-style presentations – where the flow of information goes primarily from you to your students – place the responsibility for fact-gathering on your students. Have them read² and arrive at the classroom *prepared* to discuss what they have already read.

When students are with you in the classroom and in the lab, probe their understanding with questions – lots of questions. Give them realistic problems to solve. Challenge them with projects requiring creative thought. Get your students to reveal how they think, both to you and to their peers. This will transform your classroom atmosphere from a monologue into a dialogue, where you engage with the minds of your students as partners in the learning process instead of lecturing to them as subordinates.

¹To be sure, there are some gifted lecturers in the world. However, rather than rely on a human being's live performance, it is better to capture the brilliance of an excellent presentation in static form where it may be peer-reviewed and edited to perfection, then placed into the hands of an unlimited number of students in perpetuity. In other words, if you think you're great at explaining things, do us all a favor and capture that brilliance in a format capable of reaching more people!

²Textbooks, tutorials, primers, whitepapers, reference manuals, datasheets, patents, and any other technical literature you deem appropriate are all fair game as source material. If you possess knowledge that your students need to know that isn't readily found in any book, *publish it for everyone's benefit!*

2.1 Inverted instruction

A format I have used with great success is to assign homework exploring new topics, so students much research those topics in advance of our coverage of it in class. The pedagogical term for this is an *inverted classroom*, where communication of facts occurs outside of class, and higher-order activities such as problem-solving occur inside the classroom. This stands in contrast to traditional learning structures, where the instructor spends most of the class time transmitting facts and working example problems, while subsequent homework questions (ostensibly completed on the students' own time) stimulate the development of problem-solving skills.

Homework in my “inverted” classroom comes in the form of question sets designed to lead the student on a path to acquiring the necessary facts and exposing them to certain problem-solving techniques. Some of these questions point students directly to specific texts to read, while others allow students to choose their own research material. Many of the questions are simply conceptual or quantitative problems to solve, without reference to source materials. When my students arrive for class, I survey each of their written notes (from the reading) and query each one to check their basic comprehension of that session's material. After that, I invite questions they may have about the material, and help them make sense of anything they found confusing. Then I have students share their solutions to assigned problems, and together we explore multiple problem-solving strategies. My role as instructor is to identify and correct misconceptions, offer practical advice, and continually challenge students to apply sound reasoning through the use of Socratic dialogue.

An inverted classroom structure shifts the burden of transmitting facts and concepts from a live teacher to static sources such as textbooks³. This shift in responsibility frees valuable class time for more important tasks, namely the refinement of higher-order thinking skills. It makes no sense to have a subject-matter expert (the instructor) spend most or all of the students' valuable time at school doing what a book or a video could do just as well⁴. It is far better to apply that same subject-matter expertise to challenges no book or video can meet: actively identifying student misconceptions, dispensing targeted advice for overcoming difficulties, and stimulating students' minds with follow-up questions designed to illuminate concepts in further detail.

Several important advantages are realized by managing a classroom in this way. First, the instructor enjoys a privileged view of each students' comprehension, struggles, and misconceptions. If you are accustomed to teaching in a lecture or other “stand-up-in-front” classroom format, you will be utterly amazed to see what your students do and do not comprehend when you watch them dialogue and problem-solve in small groups. Much of what goes on inside your students' minds is hidden from you when they are seated in neat rows watching you in the front of the classroom. When students are free to work together in more intimate settings, you get to see how they think, what they understand, and most importantly what they mis-understand.

Another important advantage of an inverted classroom is its economy of classroom time. Expect to spend approximately half the amount of time you would in an equivalent lecture to conduct a full “inverted” theory session. This frees up valuable class time for troubleshooting exercises, experimentation, and project work.

Perhaps the most important benefit of an inverted classroom is that students learn how to

³And multimedia resources, too! With all the advances in multimedia presentations, there is no reason why an instructor cannot build a library of videos, computer simulations, and other engaging resources to present facts and concepts to students outside of class time.

⁴Any instructor who can be replaced with a book or a video *should* be replaced by a book or a video!

independently research, which is no small feat. In a complex field where technology advances on a daily basis, your students will need to be able to learn new facts on their own (without your assistance!) after they graduate. Employers have consistently advised me that this is the single most important skill any person can learn in school: how to independently acquire new knowledge and new abilities. Such a skill not only prepares them for excellence in their chosen career, but it also brings great benefit to every other area of life where the acquisition of new information is essential to decision-making (e.g. participation in the democratic process, legal proceedings, medical decision-making, investing, parenting, etc.). In this way, the inverted classroom is not just a “better mousetrap” but in fact is really catching a “better mouse.”

2.2 The problem with lecture

I speak negatively of lecture as a teaching tool because I have suffered its ineffectiveness from a teacher's perspective for several years. The problem is not that students cannot learn from an instructor's eloquent presentation; it's that following the lead of an expert's presentation obscures students' perception of their own learning. Stated in simple terms, *lecture forces every student into the role of spectator when they should be participants*. Students observing a lecture cannot tell with certainty whether they are actually learning from an expert presentation, or whether they are merely being stimulated. This is not an obvious concept to grasp, so allow me to elaborate in more detail.

When I began my professional teaching career, I did what every other teacher I knew did: I lectured daily to my students. My goal was to transfer knowledge into my students' minds, and so I chose the most direct method I knew for that necessary transference of information.

My first year of teaching, like most teachers' first year, was a trial by fire. Many days I was lecturing to my students on some subject I had just reviewed (for the first time in a long time) no more than a few days before. My lesson plans were chaotic to non-existent. By my second and third years, however, I had developed lesson plans and was thereby able to orchestrate my lectures much more efficiently. These lesson plans were complete enough to support live demonstrations of concepts during almost every lecture, listing all the materials, components, and equipment I would need to set up in preparation. If an extensive amount of set-up was required for some demonstration, instructions would be found in lesson plan(s) multiple days in advance in order to give me adequate time. The result was a very smooth and polished presentation in nearly every one of my lectures. I was quite proud of the work I had done.

However, I noticed a strange and wholly unintended consequence of all this preparation: with each passing year, my students' long-term recall of concepts presented in lecture seemed to grow worse. Even my best students, who demonstrated an obvious commitment to their education by their regular study habits, outstanding attendance, and quality work, would shock me by asking me to re-explain basic concepts we had covered in extensive detail months before. They never complained about the lectures being bad – quite to the contrary, their assessment of my lectures was always “excellent” in my performance surveys.

An increasingly common lament of students as they tried to do the homework was “*I understand things perfectly when you lecture, but for some reason I just can't seem to figure it out on my own.*” This baffled me, since I had made my presentations as clear as I could, and students seemed engaged and attentive throughout. It was clear to me as I later worked with these students that often they were missing crucial concepts and/or harbored severe misconceptions, and that there was *no way* things should have made sense to them during lecture given these misconceptions.

Another detail that caught my attention was the fine condition of their textbooks. In fact, their textbooks were looking better and better with each passing year. At the conclusion of my first teaching year, my students' textbooks looked as though they had been dragged behind a moving vehicle: pages wrinkled, binding worn, and marks scribbled throughout the pages. As my lectures became more polished, the textbooks appeared less and less used. My reading assignments were no less thorough than before, so why should the books be used less?

One day I overheard a student's comment that made sense of it all. I was working in my office, and just outside my door were two students conversing who didn't think I could hear them talking. One of them said to the other, “*Isn't this class the best? The lectures are so good, you don't even*

have to read the book!” At the sound of this, my heart sunk. I began to realize what the problem was, what was needed to fix it, and how I had unwittingly created a poor learning environment despite the best of intentions.

The fundamental problem is this: students observing an expert presentation are fooled into thinking the concepts are easier to grasp and the processes easier to execute than they actually are. The mastery and polish of the lecturer actually hinders student learning by veiling the difficulty of the tasks. Matters are no different watching a professional athlete or musician at work: a master makes any task look effortless. It isn’t until you (the spectator) actually try to do the same thing (as a participant) that you realize just how challenging it is, just how much you have to learn, and how much effort you must invest before you achieve a comparable level of proficiency.

When students told me “for some reason” they just couldn’t seem to solve the same problems I did during lecture “even though they understood it perfectly” as I lectured, they were being honest. This was not some excuse made up to cover a lack of effort. From their perspective, they truly believed they grasped the concepts while watching me work through them in front of class, and were genuinely mystified why it was so hard for them to perform the same problem-solving tasks on their own.

The simple fact of the matter was that my students did *not* actually grasp the concepts as they watched me lecture. If they had, the solution of similar problems after lecture should have presented little trouble for them. Lecture had generated a *false sense of understanding* in their minds. This made my lectures worse than useless, for not only did they fail to convey the necessary knowledge and skill, but they actually *created an illusion of proficiency* in the minds of my students powerful enough to convince them they did not need to explore the concepts further (by reading their textbooks). This served to hinder learning rather than foster learning.

What I needed to do was shatter this illusion if my students were to learn from me more effectively, and especially if they were ever to become independent learners. Thus began my own personal quest of educational reform.

2.3 A more accurate model of learning

A humbling fact every teacher eventually learns is that the depth of a student’s learning is primarily a function of the student’s effort and not the teacher’s. Even the most dedicated and talented instructor cannot make a student learn if that student does not invest the necessary time and effort. Conversely, even an unmotivated or incompetent instructor cannot prevent a self-motivated student from learning on their own.

However, a great many students enter college with the belief that learning is a passive activity: *“It’s the instructor’s job to give us information – all we’re supposed to do is attend and observe.”* Unfortunately, this flawed model of learning seems embedded in modern American culture, anchored in students’ minds from years of compulsory lecture-based education. The role of teacher as expert presenter is so relentlessly reinforced that we have difficulty recognizing its flaws, much less conceiving better alternatives. Teachers choosing to depart from this model invite suspicion and even anger from students accustomed to the status quo of lecture.

One way to help see past one's own biases on a subject is to consider the same (or similar) subject in a different context. Here, the absurdity of passive learning becomes obvious if we simply switch contexts from academic instruction to athletic instruction. It would be laughable if a coach or fitness trainer were the one performing all the weight-lifting, sprints, stretching, and practice movements while the student never did anything but observe. It would be only slightly less humorous if the trainer spent the whole of every session modeling these activities, leaving the student to practice those activities on their own time as "homework." Instead, effective physical training sessions *always* place the student in an active role as soon and as often as possible, so that the instructor's valuable expertise may be applied toward identifying errors and recommending corrections. Instructor-led demonstration is minimized in order to maximize time spent with the student *practicing* their craft.

Academic learning really isn't much different. If we want students to learn new skills and acquire new mental abilities, students must *practice* those skills and mental processes, and it is during this practice time that an instructor's expertise becomes most valuable. Accurate self-perception is another reason to immediately engage students in practicing the skills and processes they seek to learn. When students directly experience just how challenging any concept or task is to master, they immediately recognize how much they have to learn. This self-awareness is a vital first step to learning, proving the need for committed action on their part. Only after this recognition is the student psychologically prepared for the hard work of learning.

This is why I favor the "inverted classroom" approach. Students must engage with the new subject(s) *prior* to every classroom session. From the very moment they arrive, they recognize the challenges of the subject matter, and where they need help understanding it. With the presentation of facts occurring before class time, the bulk of that time may be spent actually *applying* the concepts instead of *encountering* them. The relatively mundane task of fact-gathering is relegated to students' time outside of class, while the more challenging and meaningful tasks of problem-solving and analysis happen where the instructor can actually observe and coach.

In order for an inverted classroom structure to work, though, each student must have access to the necessary information in static form (e.g. textbooks, videos, etc.), and be held accountable for doing the necessary preparations. Access and accountability are absolutely essential to ensuring an inverted classroom will work. Without the former, students will become frustrated; without the latter, some students won't engage.

2.4 The ultimate goal of education

As I have transitioned from a traditional lecturer to a “reform-minded” educator, my general philosophy of education has shifted. My teaching techniques and classroom organization changes preceded this philosophical shift, to be sure, but more and more I am realizing just how important it is to have an educational philosophy, and how such a philosophy helps to guide future reforms.

When I began teaching, my belief was that teaching was a matter of knowledge and skills transference: it was my job as an educator first and foremost to transfer information into my students’ minds. Now, it is my belief that my primary task is to help my students become *autonomous*: able to analyze complex data, turn their thoughts into practical action, and continue learning long after they have left my classroom. If all I accomplish is helping my students memorize facts, procedures, and formulae, I have utterly failed them. My real job is to challenge them to become autonomous, critical thinkers and doers, so they will be able to fully take responsibility for their own lives and their own careers.

This shift in philosophy happened as a result of contact with many employers of my students, who told me the most important thing any student could learn in school was *how to learn*. In life, learning is not an option but a necessity, especially in highly technical careers. Any technician or engineer who stagnates in their learning is destined for obsolescence. Conversely, those with the ability and drive to continually learn new things will find opportunities opening for them all throughout their careers.

A former classmate of mine I studied electronics with told me of his path to success in this field. Despite his many struggles with mathematics, he was always very determined and goal-oriented. His first job was as an electronics technician at a company doing automotive research and development, where he was responsible for “instrumenting” heavy-duty trucks with sensors to perform both destructive and non-destructive tests on them. The sensors and data-collection systems he used at this job were usually quite different from the systems studied in school, and so he found himself having to constantly refer to textbooks and equipment manuals to learn how the technology worked. This was true even when he was “on the road” doing field-service work. He told me of many evenings spent in some tavern or pub, a beer in one hand and an equipment manual in the other, learning how the equipment was supposed to work so he could fix the customer’s problem the next day.

This hard work and self-directed learning paid off handsomely for my friend, who went on to set up an entire testing department for a major motorcycle manufacturer, and after that started his own testing company specializing in power-sport vehicles. He now works as an engineer at an aerospace corporation, all without ever having earned a bachelor’s degree which is standard for engineering careers. None of this would have been possible for my friend had he relied exclusively on others to teach him what he needed to know, taking the passive approach to learning so many students do. The lesson is very general and very important: *continual learning is a necessary key to success*.

One of the corollaries to my philosophy of education is that individual learning styles are ultimately not to be accommodated. This may come as a shock to many educators, who have learned about the various styles of learning (auditory, kinesthetic, visual, etc.) and how the acquisition of new information may be improved by teaching students according to their favored modes. Please understand that I am not denying the fact different people prefer learning in different ways. What I am saying is that we fail to educate our students (i.e. empower them with *new* abilities) if all we

ever do is teach to their preferences, if we never challenge them to do what is novel or uncomfortable.

The well-educated person can learn by listening, learn by watching others, *and* learn by direct hands-on experimentation. A truly educated person may still retain a preference for one of these modes over the others, but that preference does not *constrain* that person to learning in only one way. This is our goal as educators: nothing short of expanding each student's modes of learning.

If a student experiences difficulty learning in a particular way, the instructor needs to engage with that student in whatever mode makes the most sense for them *with the goal of strengthening the areas where that student is weak*. For example, a student who is weak in reading (visual/verbal) but learns easily in a hands-on (kinesthetic) environment should be shown how to relate what they perceive kinesthetically to the words they read in a book. Spending time with such students examining a device to learn how it functions, then reading the service manual or datasheet for that device to look for places where it validates the same principles, is one example of how an instructor might help a student build connections between their strong and weak modes of learning. Investigating subjects through multiple approaches such as this also shows students the value of each learning mode: a student might find they easily grasp "how" a device works by directly observing and experimenting with it, but that they more readily grasp "why" it was built that way by reading the manufacturer's "theory of operation" literature.

Keeping the goal of life-long learning in mind, we must ask ourselves the question of how our students will need to learn new things once they are no longer under our tutelage. The obvious answer to this question is that they will need to be able to learn in any mode available to them, if they are to flourish. Life is indifferent to our needs: reality does not adapt itself to favor our strengths or to avoid challenging our weaknesses. Education must therefore focus on the well-rounded development of learning ability.

By far the greatest amount of resistance I encounter from students in terms of learning styles is learning by reading. It is rare to find a student who reads well, for example, but struggles at learning in a hands-on environment (kinesthetic) or struggles to understand spoken information (auditory). The reason for this, I believe, is that reading is a wholly unnatural skill. Entire cultures exist without a written language, but there is not a culture in the world that lacks a spoken one. Interpreting the written word, to the level of proficiency required for technical learning, is a skill born of much practice.

Unfortunately, the popular application of learning styles in modern education provides students with a ready-made, officially-sanctioned excuse for not only their inability ("That's just not how my brain works"), but also for continued tolerance of that inability ("I shouldn't have to learn in a way I'm not good at"). The challenge for the instructor is helping students develop their ability to learn in non-favored modes despite this psychological resistance.

My general advice for educators is to never compromise the “big picture” philosophy of empowering your students’ thinking. Some key points I always try to keep in mind are:

- **Lead by example:** Regularly showcase for your students your own excitement for the subject and your own continual learning adventures. Likewise, you need to model the same learning modes you ask them to develop: let them see you learn new things, demonstrating how multiple modes are necessary to be an effective self-educator.
- **Teach by asking questions:** Socrates had the right idea – if you want to make people examine their assumptions and discover misconceptions, ask lots of challenging questions. This is how I have conditioned myself to respond to student questions: I generally answer with a question of my own seeking the heart of the student’s confusion. Posing “thought experiments” for students to conduct is another form of questioning that not only clarifies concepts, but also builds good critical-thinking habits. Anyone familiar with Socrates’ fate knows, however, that people tend to react defensively when their assumptions are challenged by persistent questions. A helpful hint for avoiding this kind of reaction is to give the student adequate time and personal space to contemplate your questions. If the student ever feels uncomfortable either with your observation of their efforts or the rapidity of your questioning, they will “lock up” and refuse to engage. Sometimes the best way to manage this behavior is to pose a question to the student, then tell them you will get back to them after a few minutes, rather than to watch them struggle answering your question(s).
- **Be willing to provide the help they need:** If students struggle at certain tasks or with thinking in certain ways, devote extra time with them to practice these skills. Let them know in very practical ways how you are willing to work just as hard as you are asking them to work. Note that this does not mean giving in to demands for lecture. That would be giving students what they *want*, rather than what they *need*. Instead, it means focusing directly on whatever weaknesses are hindering their growth as learners, and aggressively working to strengthen those weaknesses. If it means reserving time to read with students who say they can’t understand the text, then that is your job as their teacher.
- **Nothing builds confidence and dissolves apprehension like success:** Remind your students of the challenges they have already overcome, and the progress they have already made.
- **Be patient:** That same student who complains now about having to read, to think independently, and tackle challenging problems will come back to thank you years later. Just as you expected them to think long-term while they were in your class, so you need to think long-term with regard to their appreciation for your standards and efforts. Transformative education is a marathon, not a sprint!

2.5 How to begin teaching inverted

Teachers new to the concept of inverted instruction often wonder how they might go about creating inverted learning sessions. Years spent honing lecture skills do not necessarily prepare one for this very different approach to instruction, and so making this transition is a non-trivial task. As any instructor knows, even making major revisions to a course while leaving the instructional mode unchanged can be a monumental task, and so the prospect of re-working an existing course or even an entire program of instruction from lecture-based to discussion-based can be daunting.

Five “ingredients” I have found essential to robust inverted teaching sessions are as follows:

- **Culture of learning** – transitioning from lecture to inverted learning requires a wholesale shift in roles and responsibilities. This is both the strength of inverted instruction as well as its cost: students must embrace a higher level of responsibility for their learning, and instructors must relinquish their prior status as the primary font of knowledge for their students.
- **Good source material** – the source material your students engage with prior to class must be easily accessed, clear to understand, centered on effective problem-solving, and ideally will be comprehensive in its scope.
- **Clear instructions** – your students need to know what is expected of them during and after digestion of the source material, and what they will be held accountable for when they arrive to class. For example, if your source text for a session is a complete book, what portions of the book should your students read in preparation? A list of prompting questions given for that reading is also an effective way to guide students’ pre-work: the expectation being that if students have properly understood the source material, they should be able to confidently answer those questions you provide.
- **Accountability for pre-work** – this is especially vital when initiating a new group of students to inverted learning, but is still important as time goes on. Somehow you need to check your students’ engagement with the source material. This is important not only to keep your students honest in their academic pursuit, but also for you to see where and how students might be struggling with the material.
- **Problem-solving activities for the class session** – since your class time will no longer be filled with you talking (i.e. lecture), you need engaging activities to keep you and your students centered on the topic at hand. If your check of students’ pre-work suggests confusion following good effort, then you might spend a fair amount of class time exploring those ideas with your students in more depth. However, a well-designed inverted session should not result in too many of your students arriving to class in a state of confusion, so if you find confusion the order of the day it means you need to re-visit your source material and expectations.

The following subsections elaborate on each of these “ingredients” for successful inverted instruction.

2.5.1 Learning culture

Changing from lecture-based instruction to inverted instruction requires a major shift in roles and responsibilities for students and instructors alike.

In a lecture-based system, students typically arrive to class with few expectations. Even when there is assigned reading, most students don't bother doing it because they see it as redundant to the content of the lecture. Instructors bear the heavy burden of being a performer on stage, tasked with accurate and comprehensive presentation of all content in addition to maintaining student interest. Student learning is evident through homework given after the lecture.

In an inverted system, students arrive to class with definite expectations and the knowledge they will be held accountable for learning, yet they also know it's okay to arrive without a completely accurate understanding of the material (unless the topic at hand is very simple). Students also know they must actively participate in the class session, and that their reasoning will be exposed. Instructors function as moderators of class conversations, ever attentive to misconceptions and confusion, ready to delve into challenging topics with ready questions and an inquisitive attitude. Student learning is evident through active participation.

The importance of establishing a new culture for this sort of learning cannot be understated. Inverted instruction is not a set of tips or tricks, but rather a fundamental shift in how students and instructors alike perceive their roles and responsibilities. This cultural shift can be jarring to students, so patience and grace is essential on the part of the instructor to help students navigate this shift. The cultural difference between lecture-based and inverted learning also complicates programs where students experience both, and if not presented carefully and accurately there is the potential for students to feel resentful for being asked to do more than what a lecture would demand when they know other courses don't ask as much of them. This is especially true when the same instructor switches from one mode to another: to tell students the importance of being fully responsible for their learning can sound like hypocrisy if the same instructor turns around and abandons inverted teaching for lecture in other courses.

2.5.2 Source material

For any inverted course you will need sufficiently complete source material for students to read (or watch, if in video form). Examples of good source material for technical topics, many of them free of US copyright restrictions, include:

- Existing textbooks
- Existing slideshow “deck” documents explaining concepts – *Note: this is an excellent way for lecturers to re-use their previous work!*
- Patents describing relevant inventions
- Publicly-available course documents from reputable instructional programs (e.g. MIT’s OpenCourseWare project)
- Historical documents (e.g. *Cassier’s Magazine* issues)
- US government agency tutorials and primers (e.g. Department of Energy, NASA, NOAA, armed forces instructional texts)
- Government regulatory documents (e.g. EPA, FCC, FAA, OSHA)
- Industrial accident investigative reports (e.g. NTSB, CSB)
- Device datasheets, user manuals, service manuals, primers, etc. from manufacturers
- Application notes and technical whitepapers from manufacturers
- Scientific research papers
- Industrial standards documents (e.g. NFPA, IPC, IEC, ANSI)
- Instructional videos, including videorecorded lectures
- Data collected by your own or students’ previous experiments

2.5.3 Text-based versus video-based source material

Anyone familiar with my work as an educator knows I emphasize text-based source material over video, especially for the materials I create on my own. Many people ask me why this is, as internet-based video services such as YouTube have made publication of video content extremely easy (and even monetizable!), and modern “smart phone” technology practically places video-production technology within everyone’s hands at little or no marginal cost. My preference for the written word over video as source material for inverted instruction is not an accident, and deserves explanation.

First and foremost, one of the major factors I see impairing students’ ability to learn highly technical subjects such as electronics is a wide-spread deficit in functional literacy. By “functional” I mean literacy beyond the basic decoding of words, but a fluency deep enough to be a ready tool for the absorption of complex information from densely-written documents. I have yet to encounter a student so illiterate that they struggle reading individual words on a page, but many do struggle to locate and comprehend specific information contained in a multi-page document, and many go to great lengths in order to avoid reading documents at their ready disposal. This is nothing short of a liability for any technical career where the majority of necessary technical information *only* exists in print (e.g. datasheets, patents, whitepapers, lab notebooks, textbooks, regulatory standards, customer specifications, business contracts).

At first the poor literacy skills of some students may seem to be a reason *not* to teach from written documents, but rather to use video or other presentation formats requiring less interpretational skill. This only makes sense however, if one views the role of technical education as nothing but *training* for highly specific technical tasks. For anyone interested in truly *educating* their students to be life-long learners, to have the full tool-set necessary to continually advance in their knowledge without professional tutelage, enabling and/or encouraging an aversion to reading makes little sense. Providing work-arounds for functional literacy not only sets students up for later failure, but also insults the student by tacitly assuming they *cannot* become powerful readers.

This is my main argument for prioritizing text-based source material, but it is not my only argument. Here are several others:

- Professional-quality prose requires less time, less skill⁵, and less-expensive equipment to create than professional-quality video. Amateur-quality video is arguably easier to shoot than amateur-quality prose is to write, but at the professional level suitable for college instruction the balance tips strongly in favor of writing.
- Written documents require *far* less effort to maintain as one continually updates and improves their materials. Touching up or updating video-recorded presentations is quite complex compared to editing a written document! Some forms of updating for documents are easy to automate as well, such as global search-and-replace operations for specific words, and also spell-checking and grammar-checking. It would be a monumentally complex task to pronounce-check and grammar-check a spoken presentation in a video, and/or perform similar corrections on written text captured within that video!

⁵Professional-quality technical writing is of course a skill requiring much time to learn, but speaking flawlessly into a camera is even more difficult because it requires all the same mastery of language with the additional requirement of being able to present with flawless diction. This is what *actors* spend years learning to do, and most actors don’t even have to write their own lines!

- On a related note, the relative simplicity of the written word also enhances open-source collaboration between educators, since digital encoding formats for textual data are highly standardized (e.g. ASCII, Unicode) and text-editing tools are easy to use, while video-editing tools tend to be far more complex and may even be unique to the video file’s digital format. Simply put, it is far easier for someone to copy, modify, and re-purpose a section of open-source text than it is to do the same with an open-source video. The same logic holds for proprietary resources maintained within an organization by a succession of writers and editors: it’s easy for the next person to continue the development of a written work, but updating video incurs many discontinuities (especially when the video in need of editing features a speaker who no longer with the organization or has aged considerably).
- Text requires *far* less digital data than video to convey the same human-intelligible information⁶. This means text-based resources will *always* require less digital drive space, less communication bandwidth, and less processing power than video regardless of technological development. These gains are measured in orders of magnitude!
- Locating information is a much simpler task in a lengthy text document than in a comparably long video. A simple example of this is the common hot-key combination *Control-F* to **find** a particular string of text. The same is true for jumping back and forth between two or more different portions of the presentation for comparison: this is clumsy at best in a video, but quite easy with split-screen text reading software or in printed-paper form.
- Digitally generating speech from text is a much more reliable process than digitally generating text from speech, as anyone who has ever read computer-generated video captions can attest. This is an important factor for students with sensory disabilities, who may require *both* visual and audio input to process information at practical speeds.
- Within any given language (e.g. English) there will be variations in word spelling, in colloquialisms, and so on which may render any particular text more difficult for some to understand than for others. However, *spoken* presentations additionally burden the listener with regionalisms such as accents and filler-sounds (e.g. “um” and “uh” in American English) serving to potentially distract and confuse.
- Any programming language source-code embedded in a text document (e.g. C++, Python, Matlab) is easily copied-and-pasted into a compiler for immediate execution, thereby aiding reader understanding by enabling experimentation with that code. Lines of code may be presented in a video, but video playback software (at least at the time of this writing, 2023) typically does not allow copying-and-pasting of that code for convenient experimentation.

One final note on this topic regards generational attitudes toward video versus written documents. It is very common at the time of this writing (2023) to hear people argue in favor of video over text on the basis that the latest generation of college students learn best this way, having grown up in the internet era using video-based online platforms to communicate. These “digital natives”, we

⁶To illustrate, when writing this I ran an experiment where I created a very brief video recording of me saying “*This is a test*”. This simple video clip lasting less than two seconds occupied a file 1.134592 megabytes in size. To compare, that exact same line of text encoded using ASCII only requires 15 bytes, a 75,000-fold reduction! Encoding that same sentence in a more sophisticated document format such as PDF would of course require more than 15 bytes (actually, 2715 bytes), but the point still stands: text is brutally more efficient than video for conveying words.

are told, are uniquely adapted to video. I could not disagree more with this sentiment, and my reason for categorically rejecting it is the verifiable fact that older generations are just as able to comprehend videos as younger generations. If the latest generation of learners were somehow more adept at learning from video than older-generation learners, this argument might have validity, but I have seen absolutely no evidence of such. On the contrary, an aversion to reading is a *serious liability* in a world where vast quantities of important information only exist in written form.

2.5.4 Instructions

Clear instructions of what text(s) to read and/or what video(s) to watch prior to class are essential. Providing a set of prompting questions⁷ to guide their pre-work and to provide definite points of discussion once you meet in class are also very helpful. Some examples include:

- Devise your own question based on the text⁸, suitable for posing to someone encountering this subject for the first time
- What did the author mean when they said _____?
- Describe some of the problem-solving strategies presented in the text/video
- How might an experiment be designed and conducted to explore the concept of _____? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some practical applications of _____ described in the text/video?
- How might you alter one of the example analyses shown in the text/video, and then determine the behavior of that altered circuit?
- Explain in your own words the principle of _____
- Identify where the author applies the principle of _____ in the text/video
- Describe the author's strategy in explaining _____ – how did they clarify this concept?
- Identify points you found confusing about the text/video, and explain why you found them so
- Identify points you found interesting about the text/video, and explain why you found them so
- Identify an easy misconception one could make when first learning about this subject
- Explain how the (*diagram, graph, chart, illustration*) on page __ relates to the text on page __
- Write a simple outline of the text/video listing major ideas

⁷For example, all of my topical learning modules hosted on the Modular Electronics Learning Project contain an "Introduction" chapter listing key terms and prompting questions that readers may use to check their own understanding as they read the Tutorial chapter(s).

⁸I have found this to often be the most fruitful assignment for students new to an inverted instructional format. It asks students to engage with the source material but also gives room for them to safely express their own points of confusion if that is their state of mind when arriving to class. Furthermore, if a student did indeed understand the source material this provides them the opportunity to explore any facet of it to a deeper level.

2.5.5 Accountability

The purpose of accountability is strictly to test for good-faith effort on the part of each and every student to complete the pre-work for each inverted instruction session, not necessarily a completely correct understanding of the day's topic. Ways of measuring student preparation include:

- Direct inspections of each student's written outline of the source material
- A simple quiz (simple enough that any student who has done the required work should be able to ace it)
- Querying students on their answers to any of the prompting questions previously listed
- Challenge students to formulate their own question(s) based on the source material for which they believe they possess correct answers, then have other students in the session try to answer those questions
- Challenge students to formulate their own question(s) based on the source material, for which they do not know the answer(s)
- Challenge students to explain in their own words any key concepts presented in the source material
- Challenge students to apply previously-learned concepts to the current session's topic (e.g. when studying transformers for the first time, ask them to identify concepts they already know such as Joule's Law or the Conservation of Energy that apply to transformers, and exactly how and where those familiar concepts apply)
- Challenge students to identify any *new* concepts presented in the source material, as well as practical applications of them
- Pick a specific paragraph from the source material and challenge students to express that paragraph's general meaning in their own words
- Pick a specific illustration/graphic from the source material as well as an associated paragraph, and challenge students to show how that paragraph relates to and explains the illustration (or vice versa)
- Have each student choose what they thought was the easiest-to-understand section of the source material and explain specifically why that is
- Have each student choose what they thought was the hardest-to-understand section of the source material and explain specifically why that is

If you find yourself with a group of students collectively shy about engaging in dialogue, I have found that asking students to pose questions based on the source material – especially questions devised by them – is one of the best ways to break through this reluctance because it offers a way for them to demonstrate their preparatory effort while leaving room for each to express misgivings or confusion.

As you can see, there are *many* ways in which you as the instructor may probe your students' comprehension of the source material and judge their effort in understanding it. As a course progresses and you begin to identify each of your student's strengths and weaknesses, you may begin to cater your accountability-checks to your students as a way of differentiating instruction to best assist each one of them in becoming an autonomous learner!

Some of these accountability techniques work best when shared in an open environment (i.e. all students listening and watching), while others lend themselves well to private expressions (i.e. students responding only to the instructor and not in a way where their classmates can see or hear). If your teaching environment supports private messaging between students and instructor, it becomes possible to pose one challenge to all students rather than having to choose a different challenge for each student.

2.5.6 In-class activities

A wide range of options exist for student activities following the accountability check. In all your interactions I strong recommend a Socratic style whereby you probe students' understanding and encourage deeper thinking by asking questions rather than by dispensing answers. Always require students to defend their answers with sound reasoning by asking follow-up questions, whether you know those answers to be correct or incorrect. Challenge students to problem-solve with the least amount of assistance as is appropriate for the topic and their developmental progress.

- Think-Group-Share problem-solving – *Pose a problem to solve, then have students work in small groups to solve it and present their answers. This is a way to gently introduce inverted instruction to anxious students.*
- Moderated problem-solving – *Pose a problem to solve, solicit problem-solving steps from students, and document those steps in a form where all can see. This is also a gentle way to develop problem-solving and presentation prowess, but if used to excess will impede active engagement in the same manner as lecture.*
- Solo, private problem-solving – *Pose a problem to solve and let students work by themselves to solve it while you privately monitor each student's progress and offer constructive criticism.*
- Solo, public problem-solving – *Pose a problem to solve and select one student to solve it without assistance in front of the group.*
- Design a circuit or some other system to meet a specified need – *Very similar to solving practical problems, this is where you challenge students either individually or in groups to devise a system per specifications defined by you.*
- Pose a debatable topic, and have students debate different sides or perspectives of this topic – *For example, the merits of DC versus AC for electric power transmission, or perhaps the merits of different circuit designs.*
- Analyze a computer simulation of some circuit or system – *Use simulation software to model the behavior of some relevant system, and then have students analyze the results.*
- Run a physical experiment – *In the subject of electronics this is often very easy to do because the components and test equipment is so readily available and inexpensive. Hypotheses for such experiments could include principles taught within the source material (e.g. when studying electric motor controls, an easy experiment would be to test the principle of DC injection braking on an AC induction motor). As much as possible, have your students state the hypothesis for themselves, devise the test procedure, take real measurements in class, and analyze the results. You as the instructor need only pose the principle and have suitable equipment on hand to run the experiment.*
- Diagnose a faulty system – *This could be a computer simulation of a faulty system, a hypothetical scenario where some system is not behaving properly and where the results of certain diagnostic tests are known, or even a real system you have pre-faulted just for the class session.*

2.6 Challenging questions and problems to solve

One of the great benefits of teaching in an “inverted” fashion as opposed to lecturing is that it frees up classroom time for problem-solving. This means you will need challenging questions to ask your students and challenging problems for them to solve. A problem you’ll likely encounter when developing an inverted curriculum is a dearth of such questions and problems in most textbooks. In this section I’ll share some types of questions and problems I’ve found especially useful for evoking strong problem-solving habits and skills.

Most of the challenges I provide to students may be classified as belonging to one of three major categories, and in fact nearly every module contained in the Modular Electronics Learning Project collection groups questions under these headings:

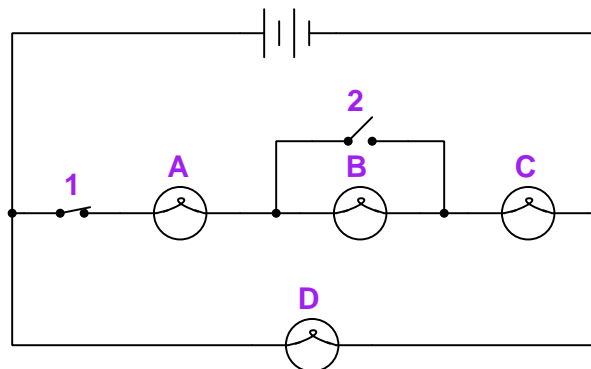
- Conceptual
- Quantitative
- Diagnostic

We will explore each of these question types in the following subsections.

2.6.1 Conceptual questions

Conceptual questions challenge students to identify foundational principles applicable to specific problems. If there are any calculations involved, they are intentionally kept simple so that math cannot become a distraction. These questions often involve *qualitative* reasoning, where students are asked to determine if quantities will *increase*, *decrease*, or *remain the same* after some change is made to a circuit or other system. Two former colleagues of mine⁹ teaching electricity courses developed a set of problems he called *No Math Path* which were circuits consisting of little more than lamps and switches, the challenge being for students to identify what would happen to the brightness of those lamps if certain switches were either turned on or off. For example:

No Math Path circuit example:



What happens when switch 2 is closed?

Closing switch 2, of course, shorts past lamp B which forces its voltage to zero and causes it to extinguish. By KVL, this means lamps A and C must now receive greater voltage than before and will therefore both increase in brightness. Lamp D's brightness remains unchanged, assuming a constant voltage output by the source.

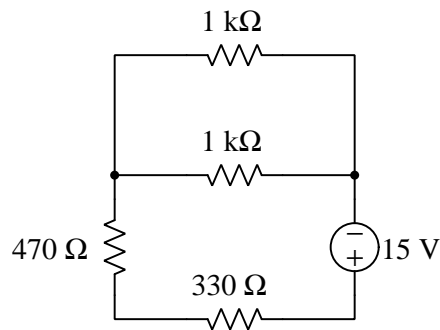
Multiple levels of complexity exist in this question, too. For example, a *real* battery contains internal resistance which means that the increased source current resulting from closing switch 2 will actually cause the source's terminal voltage to sag a bit, and this in turn will cause lamp D to dim slightly.

⁹Brad Burdick and Brad Willbrandt.

2.6.2 Quantitative questions

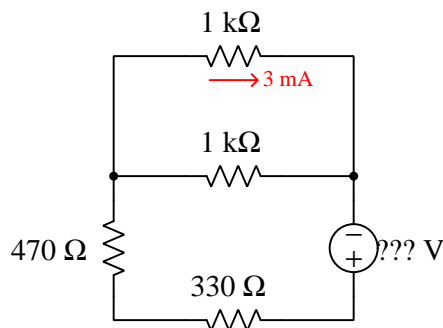
Quantitative questions are exactly what they sound like: problems requiring some form of numerical and/or algebraic methods to solve. Quantitative problems are commonplace in technical education, but even here there is room for improvement over conventional approaches. Far too many quantitative problems assigned to students are solvable using well-worn procedures, and if those procedures are already known to students then the benefit of working through such problems is diminished. A better approach to quantitative problem-solving is pose problems requiring students to make judgments as to the most appropriate *principles* to apply to the problem(s) at hand, and let those judgments guide the mathematical work.

This distinction is easy to illustrate by example. Consider the following circuit-analysis problem where students are tasked with identifying all voltages and currents in a series-parallel resistor circuit given a source voltage and all resistance values:



Once a student learns the procedure for reducing such a circuit down to a single equivalent resistance, then applying Ohm's Law and Kirchhoff's Laws to the reduced and expanded versions of the circuit, there isn't much to do but apply that procedure and trudge through all the calculations. Most electricity and electronics courses contain many such problems, with students spending hours and hours working through them until the procedure is mastered.

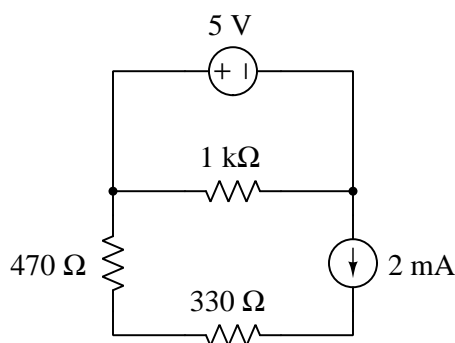
A better approach to take once the basic procedure is understood is to set up the initial conditions of the problem in such a way that the same procedure will not longer work. For example:



Here, the source's voltage value is unknown, but current through one of the resistors is provided.

Posing the same circuit configuration in this manner forces students to carefully apply foundational concepts (in this case, first applying Ohm's Law to calculate 3 Volts across that 1 k Ω resistor, then applying properties of parallel networks to determine that the other 1 k Ω resistor must experience the same 3-Volt drop.)

An even better form of problem is to pose a circuit containing multiple voltage and/or current source components in such a way that the resistances cannot be condensed into a single equivalent resistance at all. In such circuits the analytical goal is to solve for every component's voltage, current, and identity as either an electrical energy source or an electrical energy load. The following schematic shows one such example:



Most electrical engineering majors seeing a problem like this will immediately want to apply Superposition Theorem or some other analytical technique such as Mesh or Node analysis, but this is merely a higher-level version of the basic electronics student performing standard series-parallel network analysis: *applying a well-worn algorithm to a familiar problem*. Instead, what I challenge my students to do is to analyze such circuits by judiciously applying principles from the following list:

- Ohm's Law
- Kirchhoff's Voltage Law
- Kirchhoff's Current Law
- Properties of sources versus loads (voltage polarities versus current directions)
- Properties of series-connected components (equal current, additive voltages)
- Properties of parallel-connected components (equal voltage, additive currents)

Circuits may be designed such that a different sequence of steps is necessary to solve each one, where a single algorithm won't work for all circuit versions. This challenges students to *think* about how and why all these principles work, and quickly reveal where their conceptual understanding may be weak. The benefits of practicing the solution of such problems becomes evident when students explore more advanced topics such as operational amplifier circuits¹⁰, where mastery of these principles (especially Kirchhoff's Laws) becomes indispensable.

¹⁰So-called "op-amp" circuits have a reputation in electronics education as being particularly difficult, but in my

2.6.3 Diagnostic questions

Diagnostic thinking, or *troubleshooting* as it's commonly called, represents one of the highest levels of technical proficiency, much like skillful improvisation in musical performance. To be a good troubleshooter means mastering a broad range of foundational concepts and principles, applying scientific method of hypothesis-testing, and also exercising judgment as to the most efficient course of action for a given scenario.

There is so much to say about this modality of thinking and the types of questions/problems evoking mastery of it that I've devoted an entire chapter in this document to it. Refer to chapter 4 beginning on page 43 for more details!

experience this is true only if students never mastered the foundational concepts of Kirchhoff's Laws and similar principles. No amount of algorithmic practice builds fluency with first principles – instead, students must practice solution of problems requiring them to select appropriate principles based on their applicability, with a variety of circuits defying solution by any one algorithm.

2.7 A personal timeline of inverted instruction

- **1998-1999** – began my full-time teaching career using lecture, with absolutely no preparation for the courses I was assigned to teach. I was hired late, arriving on the job two weeks into the Fall term, and had nothing but course syllabi to guide my work. The former instructor left no notes or lesson plans whatsoever.
- **1999-2001** – created and used lesson plans for my lectures, and by 2001 almost every lecture contained live demonstrations of concepts with ample notes in prior sessions to prepare for upcoming demos. Student feedback was extremely positive, but knowledge retention was wanting. Frequently heard students lament that the lectures made perfect sense to them, but “for some reason” they could not do the homework problems on their own. One student admitted my lectures made the class *“So easy that you don’t even have to read the book!”*
- **2001-2002** – one of my program’s industry advisors stated that the primary task of a technical program is to teach students how to learn on their own to solve novel problems, but admitted he did not know how one might actually do that. After learning of my school’s Nursing program which used something they called “Group Method” to teach anatomy and physiology, I began visiting their class sessions to explore alternatives to lecture. The “Group Method” was inverted instruction, with Nursing students reading assigned sections of their textbooks prior to class and then sharing what they learned with each other in groups of 10 students each. One Nursing instructor would manage two groups (20 students total) simultaneously, alternating back and forth between those two groups over a period of about 90 minutes. An interesting feature of this method is that students assessed all their group peers on preparation at the end of each term, and this became part of the grade. Faculty told me that everyone leaned toward leniency the first term, but in subsequent terms would critique their classmates more thoroughly once it became clear who didn’t work as hard as others and the negative impact of that poor preparation became more acute.
- **2002-2003** – during this academic year I first attempted non-lecture instruction, having students do research prior to the class session and then using Socratic dialogue in class to make sense of what they found. I had students do their research in the school’s library with me, then afterward meet in a regular classroom to discuss what they found. Interestingly, these discussions proved to require only about one-half the amount of time as a lecture, leaving the other half of the class period free for research. Encountered some stiff resistance at first (one student told me *“If I’d wanted to study, I would have gone to a real college!”*). Comparisons of my students’ learning against a control group taught via lecture by a veteran instructor revealed staggering improvements using the Socratic method: much deeper understanding of concepts, longer retention, and smoother transfer of knowledge from theory to hands-on practice.
- **2003-2004** – took a sabbatical to earn a degree at a different college from the one I taught at. Noted that many students at this other college harbored the same passive views of education as my own.
- **2004-2006** – tried to apply Socratic teaching method in my classes once again. Encountered fresh difficulty getting students on-board with the idea, but instead of standing firm I allowed

classroom discussions to devolve into mostly-lecture. Student performance was better than with lecture, but not as good as the 2002-2003 year.

- **2006-2007** – this year I was assigned to teach a different segment of the program, and resolved to apply Socratic method exclusively. Discovered that some students did not prepare for discussions nearly as well as others, but at the time I had no mechanism for enforcing preparation.
- **2007-2008** – tried using simple ungraded inspections of homework (e.g. examining notes students had taken) before discussion. This turned out to be nearly useless.
- **2008-2009** – began holding quizzes at the start of each class session to hold students accountable for doing the pre-work, this counting for 5% of their grades. Unfortunately, this 5% weighting was not significant enough for students to take seriously.
- **2009-2010** – after imploring students for weeks to arrive to class better-prepared and seeing no improvement, I changed the quiz weighting from +5% of the grade to a –1% deduction on each failed quiz. This had an immediate positive effect on preparation (cutting the first-attempt mastery exam fail rate by half!), but a few of my chronically-underprepared students filed a formal grievance to Dean, one of them calling the new policy “Draconian”. The Dean reviewed the case and sided against the students after seeing the documented improvement in exam scores, and the new grading policy held. Incidentally, the student who called the quiz policy “Draconian” ended up thanking me, but only after graduating and landing a good job with a semiconductor firm.
- **2010-2014** – switched from holding all-class Socratic dialogue to a small-group format. All students would enter the class at the start of the period for their quiz, followed by a brief question-and-answer session for the entire group. Then, students would break into small groups within the same classroom. When a group was ready to discuss with me, I would come to them and together we would engage in Socratic dialogue. Frequently I would manage multiple groups, leaving one group with a challenging question while I went to another to review their work. Each group was free to leave as soon as they finished their “checkoff” with the instructor, incentivizing preparation. This format worked, but with all the small groups in the same room it made for a noisy classroom.
- **2014-2018** – after observing the small-group dynamics within a large class, I decided to switch the format to one where small groups of students (no more than five per instructor) met during pre-scheduled 30-minute timeslots rather than everyone meeting for a 120-minute class session. This created a much more intimate environment in which to hold Socratic dialogue, and furthermore liberated students’ schedules by not requiring them to attend a long class session. It also meant I could hold class sessions in *any space* big enough to comfortably seat five students, which meant I didn’t need a classroom at all. Most days we met in the lab room, with other students working in the lab simultaneous to these small-group sessions.
- **2018-2019** – once again re-assigned to teaching a different set of courses, but this time I was prepared with a well-functioning format of assigning small groups of students to short class

sessions for Socratic dialogue. This was very well received, and the learning outcomes were as high as ever.

- **2019-2020** – took a new job teaching at a different college, and began applying the same small-group inverted teaching method with individual pre-work followed by Socratic dialogue and problem-solving. During the spring of 2020 the global SARS-CoV2 pandemic hit, and we discovered that this instructional format translates wonderfully to distance-learning. Believe it or not, we were actually able to make this work via *email*, with students sending me their pre-work for inspection, me quizzing them in return, followed by a text-based dialogue.
- **2020-present** – learned to use Zoom as a digital tool for managing remote Socratic dialogue. As it turns out, the shared-annotation and text-based “chat” features of Zoom lend themselves quit well to inverted instruction – so well, in fact, that I continue to use Zoom even when meeting with students face-to-face! Students all bring their laptop PCs, and within the classroom (and/or remotely for students who cannot attend for any reason) we use Zoom to pose questions, share answers, and generally solve problems together. This proved especially helpful for students with chronic medical problems, one student in particular being able to continue his studies unabated despite a week-long stay in a hospital for major surgery and recovery!

2.8 Common difficulties in theoretical coursework

This is a list of the most common misconceptions, weaknesses, and other difficulties students face when learning about electricity and electronics. Anticipate these problems, and be sure your curriculum addresses each of them directly!

Difficult technical concepts:

- **Confusing voltage and current** – particularly, mistakenly thinking that voltage *moves* in a circuit. Interestingly, I see this same confusion when students study fluid dynamics, confusing pressure and flow. Ditto when studying mechanics, confusing force and displacement. The misconception seems to stem from an over-simplified view of mechanics, where the flow or motion of anything is assumed to be synonymous with force and also with energy.
- **Thinking voltage can be measured at a single point** – voltage is an expression of a *difference in electrical potential between TWO points*. Whereas current may be quantified at any single location, voltage is fundamentally a *relative* measurement between two points, like distance. See the above misconception!
- **Fractions** – of all the rudimentary mathematical principles students struggle with, nothing comes close to the confusion and bewilderment I encounter with elementary fractional arithmetic and algebra. I’m not sure if this is a reflection of the public educational system in the United States where I teach, but a substantial percentage of my students tell me they never really learned fractions in elementary school, the teachers opting instead to let students use calculators and handle everything as decimal quantities!
- **Translating between diagrams and real circuits** – this is an application of spatial-reasoning skill, and one that I’m happy to report all students can master with sufficient practice. The most obvious way to build such skill is to construct many real circuits from schematic diagrams, and also to troubleshoot real circuits using schematics. However, there are “virtual” methods to build this skill as well which lend themselves to theory-based coursework. One such method is to practice sketching wire connections between pictorial representations of components, where the locations and orientations of those components don’t match that of their schematic counterparts. I usually include many such problems on written exams, such is the importance of this skill!
- **Switch “normal” status** – the way in which spring-return electrical switches are designated as being either “normally-open” or “normally-closed” tends to confuse many students in that they tend to conflate the “normal” (resting) state of the switch with its *typical* state when in use. These are often different things.
- **Transistor action** – bipolar junction transistors (BJTs) and field-effect transistors (FETs) behave very differently from each other, and with the multiple varieties of each type it can be confusing to students first learning about these devices how each of them is turned on or off. The only solution I’ve found to this problem is *lots* of practice designing and analyzing transistor circuits, identifying the foundational principles of their operation (i.e. charge carrier injection for BJTs and electric field modulation of a channel for FETs).

- **Efficiency versus power factor** – although these two concepts are related, they are actually distinctly different from each other. Power factor describes the ratio of energy dissipated at a load versus that energy plus any energy returned to the source by reactive components such as inductors and capacitors. Efficiency describes the ratio of energy dissipated at an intended load versus total energy expended by a source.
- **Network theorems** – a difficult concept for students to grasp is how two different networks of electrical components are able to be *equivalent* to each other, which lies at the heart of certain network theorems such as Thévenin’s and Norton’s. I have found that emphasizing this concept of electrical equivalence is best done early, long before network theorems are formally introduced. The analysis of basic series-parallel combination circuits provides an excellent introduction to this concept, where each step of circuit “reduction” one parallel or series network at a time is really just a way to express a collection of resistance values as single resistances.
- **Operational amplifiers** – a notoriously difficult concept for new students, this is actually another difficulty in disguise: non-mastery of Kirchhoff’s Laws. Usually the troubles students encounter studying opamp circuits stem from a lack of fluency with Kirchhoff’s Voltage Law and Kirchhoff’s Current Law.

Poor habits and behavioral difficulties:

- **Ignoring context in calculations** – a common problem many students struggle with when first learning to apply mathematical formulae (e.g. Ohm’s Law) is ignoring the context of each variable. It is important to emphasize how every variable in an equation must relate to the same thing or the same portion of a larger system, and to avoid mixing contexts. A common example of this fallacy is trying to calculate current with Ohm’s Law ($I = \frac{V}{R}$) in a multi-resistor circuit by taking the source’s voltage and dividing by one of the resistance values not experiencing that full source voltage.
- **Failing to consider all symptoms** – a very common mistake people make when identifying possible faults in a malfunctioning system is to over-focus on just one of the symptoms rather than considering *all* the known symptoms. Related to this fallacy is the tendency to assign different faults to every symptom rather than considering the least number of faults that could explain the most symptoms. The proper principle here is *Occam’s Razor*, where we look for the simplest explanation accounting for the largest range of phenomena.
- **Aversion to reading** – another rudimentary skill I find lacking in many students is fluent reading ability, and correspondingly a poor ability to locate important information in text form coupled with a strong preference for instructional videos that are so commonly available on the internet. The goal here is for every one of your students to develop and refine *functional literacy*, where the ability to identify and extract useful information from dense, technical text becomes a comfortable tool at their disposal, applied autonomously without prompting from you or anyone else.
- **Thinking with your feet** – when students encounter difficulties solving any type of problem, a common instinct is to immediately go to someone else and ask for help rather than patiently

work at the problem solo. One colleague of mine refers to this as “thinking with your feet instead of with your head”, in reference to the use of feet in tracking down someone else to offer help. The root-cause problem here seems to be one of focus and perspective: many students believe all that matters in the moment is to get a solution to the problem, while not realizing the problem in question is merely a means to an end in building a wide range of skills.

- **Preferring procedures over principles** – procedural problem-solving techniques are less daunting than problem-solving based on the appropriate selection of foundational principles to the problem at hand, because procedures require less thought and assume less responsibility on the part of the problem-solver. Procedures may be memorized and executed algorithmically, whereas the application of first principles to problems requires careful analysis of context and may lead to dead-ends and re-starts. Not only is following step-by-step procedures more comforting than having to carefully and thoughtfully select principles appropriate to the problem at hand, but procedural techniques are often the default within technical education which means there is a cultural expectation as well. In other words, students may *expect* you to provide algorithmic procedures for every new type of problem they encounter, drawing from their previous educational experiences. This comfort and this expectation must be challenged if your students are to become powerful problem-solvers.

Chapter 3

Teaching practical skills

In addition to theory, students of any technical discipline must also learn the practical “hands-on” aspects of their craft. In the field of electronics, two types of “laboratory” activities work well to develop the necessary practical skill for success in the career: *experiments* and *projects*. Experiments are where students explore foundational concepts by means of scientific method, learning first-hand the power of scientific inquiry as a self-educational tool. Projects are where students design, build, and test systems for practical purposes, learning first-hand how to manage time and resources to bring ideas to fruition.

An extremely important lesson I have learned about all forms of practical skill-building is that *minimal direction* is a very good thing. A common trend in American technical education is an over-reliance on pre-designed, pre-scripted laboratory exercises that insulate students from the realities of true experimentation and project management, coupled with an over-reliance on pre-built “simulator” hardware and software applications. Just as lecture fails to develop professional patterns of thinking and problem-solving, these “fool-proof” laboratory solutions similarly fail to develop the discipline necessary to thrive in a complex workplace with ill-defined problems requiring novel solutions.

3.1 Experiments

A laboratory experiment should be a *real scientific experiment*, which means the outcome(s) should not be obvious to students. Students should devise their own testable hypotheses, plan their own experimental procedures, and assess the outcomes without assistance. The instructor's role is to propose relevant principles to explore, and supply the student with adequate parts and test equipment to explore these principles, as well as supervise for safety and guide students in formulating good experiments. Every hypothesis should be falsifiable, not just as a matter of scientific principle, but in the very real sense that the student's prediction(s) might actually turn out to be incorrect. The goal is not to formulate hypotheses that never fail, but rather to make "risky" predictions and then learn from the real outcomes. Science is above all a method for *learning*.

A format I have found to work well is to have each experiment outline occupy one page of text (maximum), with an extremely simple statement of purpose at the beginning and "checkpoints" for use in assessing students' design and execution of the experiment. The next page shows a generic template (in blue-colored text) for one of these single-page experimental outlines, the bulk of it being items the instructor will certify as properly complete before the student proceeds to the next stage of the experiment. Grading is a simple function of how many attempts the student must make before all items in each stage are properly completed. *Note that nowhere is the student's original hypothesis assessed for technical accuracy – only that it is well-formed.*

The entirety of the experiment needs to be clearly documented by the student, just as real experimental work in a research and development job must be documented in a lab notebook or journal of some kind. In my experience, students entering a two-year program of study typically struggle to articulate themselves clearly and compellingly in text, which means these student-written lab reports also represent a means to an end for developing strong written communication skill.

Plan and conduct an experiment to demonstrate . . . (*insert principle here*)

Stage #1 – Experiment planning documented in report

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

Stage #2 – Experimental run and data recorded in report

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

Stage #3 – Presentation and review

- Was the original hypothesis confirmed? If not, identify why.
- Correctly demonstrate and/or explain every learning objective (see below) for the instructor, either live or by electronically recorded data. Note: have a calculator or appropriate software ready for analyzing the data!
- Learning objectives for this experiment:
 - Demonstrate . . . (*insert skill here*)
 - Explain . . . (*insert concept here*)
 - etc., etc.*

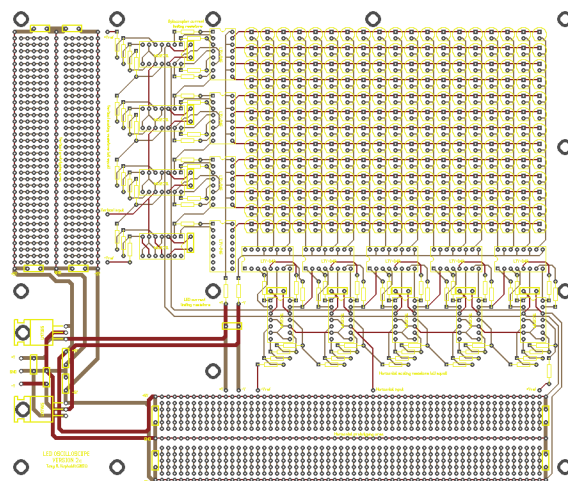
3.2 Projects

Electronics technicians invariably participate in the management of complex projects, requiring a non-trivial range of skill and experience to execute. This means an electronics technician’s education should include the management of realistic projects as a means to gain experience and to build these non-trivial skills.

Like experimental work, the planning, design, testing, and general execution of a project should be documented by students themselves. The scope and complexity of every student’s project should be chosen collaboratively between the student and instructor. Projects that are too simple for a student’s capabilities will not challenge that student sufficiently for gainful learning; projects that are too complex for a student will only frustrate them. The instructor will have insight here that the student, in their inexperience, lacks.

Another important similarity between experiments and projects is that they should never be pre-designed to ensure success. *This means kits are forbidden!* Remember that the purpose of an educational project is to challenge the student appropriately, and for electronics technicians this means having to figure out aspects of the project’s design, material sourcing, and testing without the guidance and structure that a kit would provide.

A caveat to the barring of kits is that a kit is permissible only if the student intends to significantly alter, expand upon, or otherwise modify the kit in question for educationally valid purposes. In my own teaching I encourage the use of what I call *half-kits* which are pre-made PCBs etched with circuitry fulfilling just a part of a complete project’s function, with prototyping areas or other means of expansion for the student to incorporate their own design features. For certain complex projects, a “half-kit” saves the student a lot of time while still allowing them the opportunity for technical challenge and creativity. An example of a “half-kit” might be an LED-matrix oscilloscope, where the pre-made PCB has pads for all the LEDs as well as the vertical and horizontal driver ICs, but nothing more – the student being responsible for designing, building, and testing the horizontal sweep circuitry, vertical amplifier circuitry, and triggering circuitry:



3.3 Common difficulties in practical coursework

This is a list of the most common misconceptions, weaknesses, and other difficulties students face when building practical skill with electrical and electronic circuits. Anticipate these problems, and be sure your curriculum addresses each of them directly!

- **Building circuits before sketching schematic diagrams** – this is a bad habit most students need to overcome. The root of this problem seems to be a “lottery mindset” where students believe if they simply assemble a circuit without doing any pre-work they will get lucky and have a fully functioning circuit without having to create documentation for it. The reality, though, is schematic diagrams function as a *map* to help you find your way out of the troubles that inevitably arise.
- **Translating between diagrams and real circuits** – this is an application of spatial-reasoning skill, and one that I’m happy to report all students can master with sufficient practice. However, a significant percentage of new students do struggle at first to build circuits according to schematics and also to develop schematics from as-built circuits, which is one of the reasons it is so important for students of electronics to build real circuits.
- **Visually searching for faults** – since the vast majority of problems encountered with circuits students build is in the construction process itself (e.g. wires connecting to the wrong component terminals, missing wires, poor wire connections), the natural course of events tends to bias students toward visual fault location. In other words, if the circuit doesn’t work, they immediately start *looking* for what is wrong. A much better approach is to rely on test equipment to measure signals, and then reason from those measurements where the fault might be located, using visual inspection as the very final step.
- **Failing to do simple connection-integrity tests** – wiring mistakes account for a large share of problems experienced by students as they build new circuits. A simple way to detect and correct some of these mistakes is a simple “tug test” on every wire attached to a terminal block or screw to make sure that connection is mechanically sound.
- **Assuming all terminals on a device must be connected to something** – it’s often the case that terminals on a component or larger device go unused in an application, and this seems to generate a sense of unease with many students.
- **Changing more than one parameter at a time** – when making changes to any system in an effort to get it to function properly, a poor habit among students is to make a series of changes without un-doing any previous changes that don’t yield results. The problem with this approach is that unsuccessful changes often introduce *new* problems to a system, so following this course of action ends up riddling the system with more faults than it began with. Better to make one change at a time and assess the effects of that change, so determine whether to maintain it or to revert back to its original state (if it did not help at all).
- **Thinking with your feet** – when students encounter difficulties solving any type of problem, a common instinct is to immediately go to someone else and ask for help rather than patiently work at the problem solo. One colleague of mine refers to this as “thinking with your feet instead of with your head”, in reference to the use of feet in tracking down someone else to offer

help. The root-cause problem here seems to be one of focus and perspective: many students believe all that matters in the moment is to get the circuit working, while not realizing the circuit in question is merely a means to an end in building a wide range of skills.

Chapter 4

Teaching diagnostic thinking

Diagnostic ability is arguably the most difficult skill to develop within a student, and also the most valuable skill a working technician can possess¹. In this section I will outline several principles and practices teachers may implement in their curricula to teach the science and art of troubleshooting to their students.

First, we need to define what “troubleshooting” is and what it is not. It is *not* the ability to follow printed troubleshooting instructions found in equipment user’s manuals². It is *not* the ability to follow one rigid sequence of steps ostensibly applicable to any equipment or system problem³. Troubleshooting is first and foremost the practical application of *scientific thinking* to repair of malfunctioning systems. The principles of hypothesis formation, experimental testing, data collection, and re-formulation of hypotheses is the foundation of any detailed cause-and-effect analysis, whether it be applied by scientists performing primary research, by doctors diagnosing their patients’ illnesses, or by technicians isolating problems in complex electro-mechanical-chemical system. In order for anyone to attain mastery in troubleshooting skill, they need to possess the following traits:

- A rock-solid understanding of relevant, fundamental principles (e.g. how electric circuits work, how feedback control loops work)
- Close attention to detail
- An open mind, willing to pursue actions led by data and not by preconceived notions

The first of these points is addressed by any suitably rigorous curriculum. The other points are habits of thought, best honed by months of practice. Developing diagnostic skill requires much time and practice, and so the educator must plan for this in curriculum design. It is not enough

¹One of the reasons diagnostic skill is so highly prized in industry is because so few people are actually good at it. This is a classic case of supply and demand establishing the value of a commodity. Demand for technicians who know how to troubleshoot will always be high, because technology will always break. Supply, however, is short because the skill is difficult to teach. This combination elevates the value of diagnostic skill to a very high level.

²Yes, I have actually heard people make this claim!

³The infamous “divide and conquer” strategy of troubleshooting where the technician works to divide the system into halves, isolating which half the problem is in, is but *one particular procedure: merely one tool in the diagnostician’s toolbox*, and does not constitute the whole of diagnostic method.

to sprinkle a few troubleshooting activities throughout a curriculum, or (worse yet!) to devote an isolated course to the topic. Troubleshooting should be a topic tested on every exam, present in every lab activity, and (ideally) touched upon in every day of the student's technical education.

Scientific, diagnostic thinking is characterized by a repeating cycle of *inductive* and *deductive* reasoning. Inductive reasoning is the ability to reach a general conclusion by observing specific details. Deductive reasoning is the ability to predict details from general principles. For example, a student engages in deductive reasoning when they conclude an "open" fault in a series DC circuit will cause current in that circuit to stop. That same student would be thinking inductively if they measured zero current in a DC series circuit and thus concluded there was an "open" fault somewhere in it. Of these two cognitive modes, inductive is by far the more difficult because multiple solutions exist for any one set of data. In our zero-current series circuit example, inductive reasoning might lead the troubleshooter to conclude an open fault existed in the circuit. However, an unpowered source could also be at fault, or for that matter a malfunctioning ammeter falsely registering zero current when in fact there is current. Inductive conclusions are *risky* because the leap from specific details to general conclusions always harbor the potential for error. Deductive conclusions are *safe* because they are as secure as the general principles they are built on (e.g. *if* an "open" exists in a series DC circuit, there will be *no* current in the circuit, guaranteed). This is why inductive conclusions are always validated by further deductive tests, not vice-versa. For example, if the student induced that an unpowered voltage source might cause the DC series circuit to exhibit zero current, they might elect to test that hypothesis by measuring voltage directly across the power supply terminals. If voltage is present, then the hypothesis of a dead power source is incorrect. If no voltage is present, the hypothesis is provisionally true⁴.

Scientific method is a cyclical application of inductive and deductive reasoning. First, an hypothesis is made from an observation of data (inductive). Next, this hypothesis is checked for validity – an experimental test to see whether or not a prediction founded on that hypothesis is correct (deductive). If the data gathered from the experimental test disproves the hypothesis, the scientist revises the hypothesis to fit the new data (inductive) and the cycle repeats.

Since diagnostic thinking requires both deductive and inductive reasoning, and deductive is the easier of the two modes to engage in, it makes sense for teachers to focus on building deductive skill first. This is relatively easy to do, simply by adding on to the theory and practical exercises students already engage in during their studies.

Both deductive and inductive diagnostic exercises lend themselves very well to Socratic discussions in the classroom, where the instructor poses questions to the students and the students in turn suggest answers to those questions. The next two sections demonstrate specific examples showing how deductive and inductive reasoning may be exercised and assessed, both in a classroom environment and in a laboratory environment.

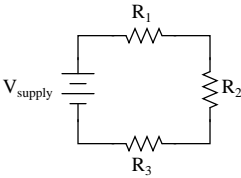
⁴Other things could be at fault. An "open" test lead on the multimeter for example could account for both the zero-current measurement and the zero-voltage measurement. This scientific concept eludes many people: it is far easier to *disprove* an hypothesis than it is to *prove* one. To quote Albert Einstein, "No amount of experimentation can ever prove me right; a single experiment can prove me wrong."

4.1 Deductive diagnostic exercises

Deductive reasoning is where a person applies general principles to a specific situation, resulting in conclusions that are logically necessary. In the context of electronics, this means having students predict the consequence(s) of specified faults in systems. The purpose of building this skill is so that students will be able to quickly and accurately test “fault hypotheses” in their minds as they analyze a faulted system. If they suppose, for example, that a cable has a break in it, they must be able to deduce what effects a broken cable will have on the system in order to formulate a good test for proving or disproving that hypothesis.

4.1.1 Example: predicting consequence of a single fault

For example, consider a simple three-resistor series DC circuit, the kind of lab exercise one would naturally expect to see within the first month of education in an electronics program. A typical lab exercise would call for students to construct a three-resistor series DC circuit on a solderless breadboard, predict voltage and current values in the circuit, and validate those predictions using a multimeter. A sample exercise is shown here:

Competency: Series DC resistor circuit		Version:	
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Schematic</div>			
			
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Given conditions</div>			
$V_{\text{supply}} =$	$R_1 =$	$R_2 =$	$R_3 =$
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Parameters</div>			
	Predicted	Measured	
I_{supply}	<input type="text"/>	<input type="text"/>	I_{R1}
V_{R1}	<input type="text"/>	<input type="text"/>	I_{R2}
V_{R2}	<input type="text"/>	<input type="text"/>	I_{R3}
V_{R3}	<input type="text"/>	<input type="text"/>	
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Analysis</div>			
Relationship between resistor voltage drops and total voltage:			
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Fault analysis</div>			
Suppose component <input style="width: 50px;" type="text"/> fails <div style="display: inline-block; vertical-align: middle; margin-left: 10px;"> <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted </div>			
What will happen in the circuit?			

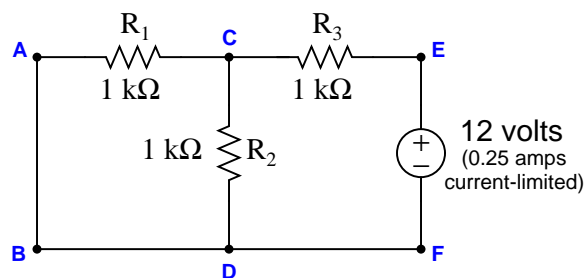
Note the **Fault Analysis** section at the end of this page. Here, after the instructor has verified the correctness of the student's mathematical predictions and multimeter measurements, he or she would then challenge the student to predict the effects of a random component fault (either quantitatively or qualitatively), perhaps one of the resistors failing open or shorted. The student makes their predictions, then the instructor simulates that fault in the circuit (either by pulling the resistor out of the solderless breadboard to simulate an "open" or placing a jumper wire in parallel with the resistor to simulate a "short"). The student then uses his or her multimeter to verify the predictions. If the predicted results do not agree with the real measurements, the instructor

works with the student to identify why their prediction(s) were faulty and hopefully correct any misconceptions leading to the incorrect result(s). Finally, a different component fault is chosen by the instructor, predictions made by the student, and verification made using a multimeter. The actual amount of time added to the instructor's validation of student lab completion is relatively minor, but the benefits of exercising deductive diagnostic processes are great.

4.1.2 Example: identifying possible faults

A more challenging type of deductive troubleshooting problem easily given in homework or on exams appears here. It asks students to examine a list of potential faults, marking each one of them as either “possible” or “impossible” based on whether or not each fault is independently capable of accounting for all symptoms in the system:

Suppose a voltmeter registers 6 volts between test points **C** and **B** in this series-parallel circuit:



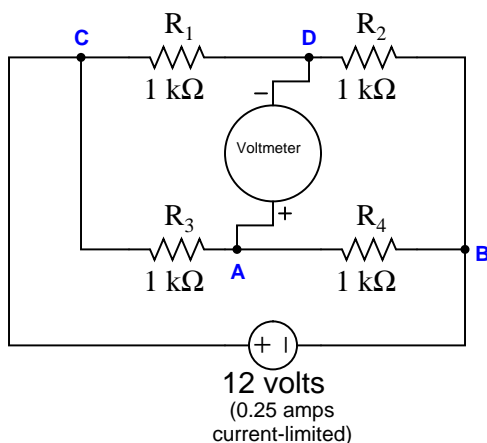
Fault	Possible	Impossible
R_1 failed open		
R_2 failed open		
R_3 failed open		
R_1 failed shorted		
R_2 failed shorted		
R_3 failed shorted		
Voltage source dead		

This is still a *deductive* thinking exercise because each of the faults is given to the student, and it is a matter of deduction to determine whether or not each one of these proposed faults is capable of accounting for the symptoms. Students need only apply the general rules of electric circuits to tell whether or not each of these faults would cause the reported circuit behavior.

True to form for any deductive problem, there can only be one correct answer for each proposed fault. This makes the exercise easy and unambiguous to grade, while honing vitally important diagnostic skills.

One of the benefits of this kind of fault analysis problem is that it requires students to consider *all* consequences of a proposed fault. In order for one of the faults to be considered “possible,” it must account for all symptoms, not just one symptom. An example of this sort of problem is seen here:

Suppose the voltmeter in this circuit registers a strong *negative* voltage. A test using a digital multimeter (DMM) shows the voltage between test points **D** and **B** to be 6 volts:



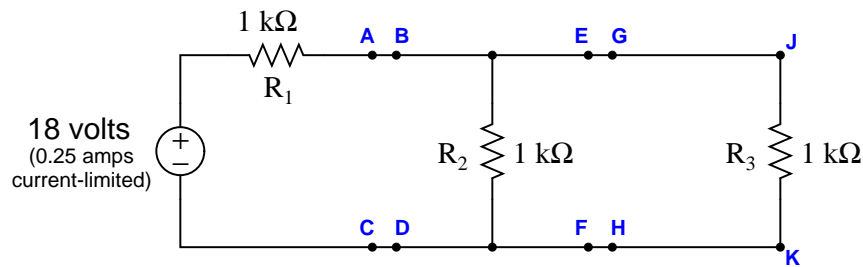
Fault	Possible	Impossible
R_1 failed open		
R_2 failed open		
R_3 failed open		
R_4 failed open		
R_1 failed shorted		
R_2 failed shorted		
R_3 failed shorted		
R_4 failed shorted		
Voltage source dead		

Several different faults are capable of causing the meter to read strongly negative (R_1 short, R_2 open, R_3 open, R_4 short), but only two are capable of this while not affecting the normal voltage (6 volts) between test points D and B: R_3 open or R_4 short. This simple habit of checking to see that the proposed fault accounts for *all* apparent conditions and not just some of them is essential for effective troubleshooting.

4.1.3 Example: assessing the value of diagnostic tests

A variation on this theme of determining the possibility of proposed faults is to assess the usefulness of proposed diagnostic tests. In other words, the student is presented with a scenario where something is amiss with a system, but instead of selecting a set of proposed faults as being either possible or impossible, the student must determine whether or not a set of proposed *tests* would be diagnostically relevant. An example of this in a simple series-parallel resistor circuit is shown here:

Suppose a voltmeter registers 0 volts between test points **E** and **F** in this circuit. Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark “yes.” Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark “no.”



Diagnostic test	Yes	No
Measure V_{AC} with power applied		
Measure V_{JK} with power applied		
Measure V_{CK} with power applied		
Measure I_{R1} with power applied		
Measure I_{R2} with power applied		
Measure I_{R3} with power applied		
Measure R_{AC} with source disconnected from R_1		
Measure R_{DF} with source disconnected from R_1		
Measure R_{EG} with source disconnected from R_1		
Measure R_{HK} with source disconnected from R_1		

This form of diagnostic problem tends to be much more difficult to solve than simply determining the possibility of proposed faults. To solve this form of problem, the student must first determine all possible component faults, and then assess whether or not each proposed test would provide *new information* useful in identifying which of these possible faults is the actual fault.

In this example problem, there are really only a few possible faults: a dead source, an open resistor R_1 , a shorted resistor R_2 , a shorted resistor R_3 , or a broken wire (open connection) somewhere in the loop E-B-A-C-D-F.

The first proposed test – measuring voltage between points A and B – would be useful because it would provide different results given a dead source, open R_1 , shorted R_2 , or shorted R_3 versus an open between A-E or between C-F. Any of the former faults would result in 0 volts between A and B, while any of the latter faults would result in full source voltage between A and B.

The next proposed test – measuring voltage between points J and K – would be useless because we already know what the result will be: 0 volts. This result of this proposed test will be the same no matter which of the possible faults causing 0 voltage between points E and F exists, which means it will shed no new light on the nature or location of the fault.

Despite being very challenging, this type of deductive diagnostic exercise is nevertheless easy to administer and unambiguous to grade, making it very suitable for written tests.

4.2 Inductive diagnostic exercises

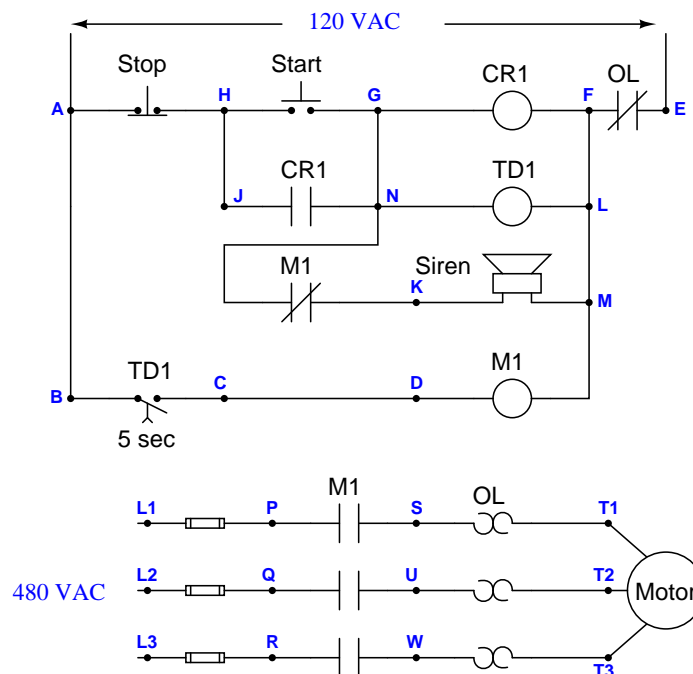
Inductive reasoning is where a person derives general principles from a specific situation. In the context of electronics, this means having students propose faults to account for specific symptoms and circuit measurements. This is actual troubleshooting, as opposed to deductive diagnosis which is an enabling skill for effective troubleshooting.

While real hands-on exercises are best for developing inductive diagnostic skill, much learning and assessment may be performed in written form as well.

4.2.1 Example: “virtual troubleshooting”

An excellent supplement to any hands-on troubleshooting activities is to have students perform “virtual troubleshooting” with you, the instructor. This type of activity cannot be practiced alone, but requires the participation of someone who knows the answer. It may be done with individual students or with a group.

A “virtual troubleshooting” exercise begins with a schematic diagram of the system such as this, containing clearly labeled test points (and/or terminal blocks) for specifying the locations of diagnostic tests:



Each student has their own copy of the diagram, as does the instructor. The instructor has furthermore identified a realistic fault within this system, and has full knowledge of that fault's effects. In other words, the instructor is able to immediately tell a student how much voltage will be read between any two test points, what the effect of jumpering a pair of test points will be, what will happen when a pushbutton is pressed, etc.

The activity begins with a brief synopsis of the system's malfunction, narrated by the instructor. Students then propose diagnostic tests to the instructor, with the instructor responding back to each student the results of their tests. As students gather data on the problem, they should be able to narrow their search to find the fault, choosing appropriate tests to identify the precise nature and location of the fault. The instructor may then assess each student's diagnostic performance based on the number of tests and their sequence.

When performed in a classroom with a large group of students, this is actually a lot of fun!

4.2.2 Example: “virtual troubleshooting” using NGSPICE

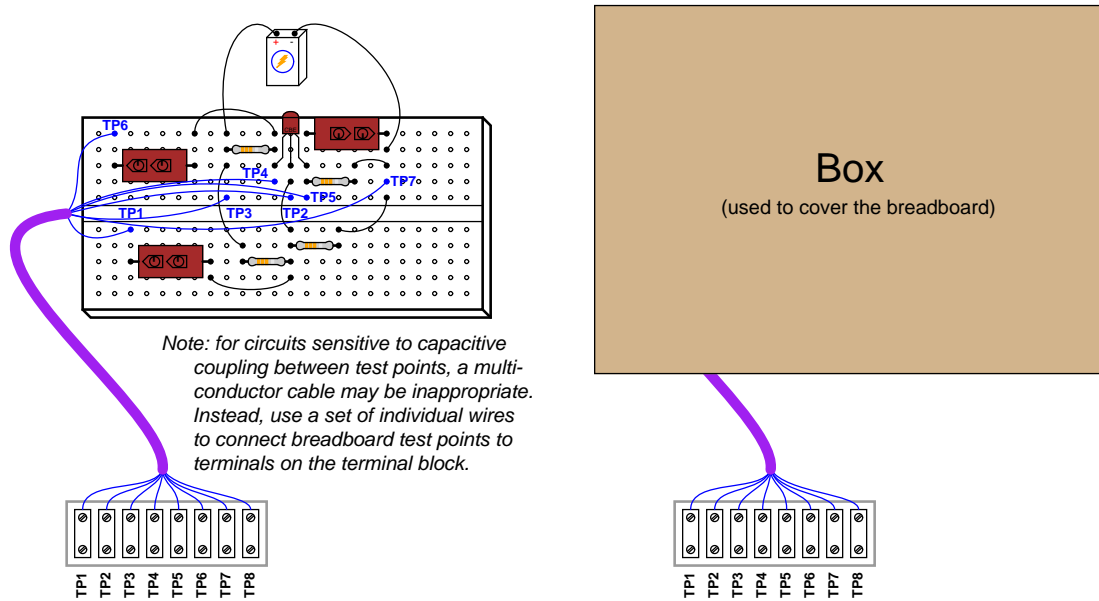
Using interactive circuit-simulation software such as NGSPICE allows for realistic troubleshooting scenarios by letting a computer determine the effects of the fault rather than relying on a human expert (e.g. the instructor) to tell students what measured values their proposed tests would reveal. In the specific case of using NGSPICE, the instructor modifies a proven circuit netlist to have a faulty component (e.g. an incorrect component value, a low resistance placed in parallel with a component to simulate a short, or a large resistance placed in series with a component to simulate an open) and then loads this netlist into NGSPICE and runs the simulation. Students then propose diagnostic measurements of voltage between specified nodes, the instructor typing those `print` or `plot` commands into the interactive command-line environment of NGSPICE and displaying the results for all to see.

4.2.3 Example: realistic faults in solderless breadboards

Solderless breadboards are universally used in the teaching of basic electronics, because they allow students to quickly and efficiently build different circuits using replaceable components. As wonderful as breadboards are for fast construction of electronic circuits, however, it is virtually impossible to create a realistic component fault without the fault being evident to the student simply by visual inspection. In order for a breadboard to provide a realistic *diagnostic* scenario, you must find a way to hide the circuit while still allowing access to certain test points in the circuit.

A simple way to accomplish this is to build a “troubleshooting harness” consisting of a multi-terminal block connected to a multi-conductor cable. Students are given instructions to connect various wires of this cable to critical points in the circuit, then cover up the breadboard with a five-sided box so that the circuit can no longer be seen. Test voltages are measured between terminals on the block, not by touching test leads to component leads on the breadboard (since the breadboard is now inaccessible).

The following illustration shows what this looks like when applied to a single-transistor amplifier circuit:



If students cannot visually detect a fault, they must rely on voltage measurements taken from terminals on the block. This is quite challenging, as not even the shapes of the components may be seen with the box in place. The only guide students have for relating terminal block test points to points in the circuit is the schematic diagram, which is good practice because it forces students to interpret and follow the schematic diagram.

4.3 Common difficulties in diagnostic coursework

This is a list of the most common misconceptions, weaknesses, and other difficulties students face when building diagnostic skill with electrical and electronic circuits. Anticipate these problems, and be sure your curriculum addresses each of them directly!

- **Visually searching for faults** – since the vast majority of problems encountered with circuits students build is in the construction process itself (e.g. wires connecting to the wrong component terminals, missing wires, poor wire connections), the natural course of events tends to bias students toward visual fault location. In other words, if the circuit doesn't work, they immediately start *looking* for what is wrong. A much better approach is to rely on test equipment to measure signals, and then reason from those measurements where the fault might be located, using visual inspection as the very final step.
- **Failing to consider all symptoms** – a very common mistake people make when identifying possible faults in a malfunctioning system is to over-focus on just one of the symptoms rather than considering *all* the known symptoms.
- **Ignoring Occam's Razor** – Sir William of Occam (sometimes spelled *Ockham*) was a medieval philosopher known for using the principle that the simplest explanation for some effect is usually the correct one. Students new to diagnostics tend to entertain complicated explanations for faults rather than looking for the simplest and most direct causes. One common form of this error is to assume multiple coincidental causes must be at work to explain the symptom(s), rather than taking the time to identify single causes capable of accounting for all symptoms.
- **Thinking with your feet** – when students encounter difficulties solving any type of problem, a common instinct is to immediately go to someone else and ask for help rather than patiently work at the problem solo. One colleague of mine refers to this as “thinking with your feet instead of with your head”, in reference to the use of feet in tracking down someone else to offer help. The root-cause problem here seems to be one of focus and perspective: many students believe all that matters in the moment is to fix the problem rather than build personal skills. It's helpful to remind students that you, the instructor, don't *need* the problem fixed – what you really do *need* is to see the student develop the skill to fix the problem.
- **Not documenting steps** – it is easy to forget or to misinterpret prior tests when spending substantial time diagnosing a problem. A good antidote to this is to build the habit of documenting all your steps when troubleshooting. Not only is this directly helpful to oneself, but also to anyone else solicited to help.

Chapter 5

Assessing student learning

As a general rule, *high achievement only takes place in an atmosphere of high expectations*. Sometimes these expectations come from within: a self-motivated individual pushes themselves to achieve the extraordinary. Most often, though, the expectations are external: someone else demands extraordinary performance of the student. One of your responsibilities as a teacher is to hold the standard of student performance high (but reasonable!), and this is done through relevant, valid, and rigorous assessment.

When the time comes to assess your students' learning, prioritize performance assessment over written or verbal response. In other words, require that your students *demonstrate* their competence rather than merely explain it. Performance-based assessment generally requires more time than written exams, but the results are well worth it. Not only will you achieve a more valid measurement of your students' learning, but they will experience greater motivation to learn because they know they must put their learning into action.

Make liberal use of *mastery* assessments in essential knowledge and skill domains, where students must repeat a demonstration of competence as many times as necessary to achieve perfect performance. Not only does this absolutely guarantee students will learn what they should, but the prospect of receiving multiple opportunities to demonstrate knowledge or skill has the beneficial effect of relieving psychological stress for the student. Mastery assessment lends itself very well to the measurement of diagnostic ability.

A written *mastery exam* is one requiring requiring 100% accuracy in order to pass, with multiple opportunities given for re-try (with different versions of the exam, of course). If a grade must be given, for example at a public college, the student's grade on the exam may be based on the score of their first attempt, or on the number of re-tries necessary to demonstrate mastery, or some similar criteria.

My philosophy on assessment is that good assessment is actually more important than good instruction. If the assessments are valid and rigorous, student learning (and instructor teaching!) will rise to meet the challenge. However, even the best instruction will fail to produce consistently high levels of student achievement if students know their learning will never be carefully measured. In a phrase, *assessment drives learning*.

For those who might worry about an emphasis on assessment encouraging teachers to "teach to the test," I offer this advice: there is nothing wrong with teaching to the test so long as the test

is valid! Educators usually avoid teaching to the test out of a fear students might pass the test(s) without actually learning what they are supposed to gain from taking the course. If this is even possible, it reveals a fundamental problem with the test: it does not actually measure what you want students to know. A valid test is one that cannot be “foiled” by teaching in any particular way. Valid tests challenge students to think, and cannot be passed through memorization. Valid tests avoid asking for simple responses, demanding students articulate reasoning in their answers. *Valid tests are passable only by competence.*

Another important element of assessment is long-term review. You should design the courses in such a way that important knowledge and skill areas are assessed on an ongoing basis up through graduation. Frequent review of foundational concepts is a best practice for attaining mastery in any domain.

5.1 Mastery exams

I used to give written exams in the conventional style, where a certain minimum “cut score” was deemed passing. The setting of this cut score threshold was always an uncertain and arbitrary matter. Where, exactly, should this threshold be set? At what point of achievement does one consider the student to be “competent” in that subject? Disturbing also was the tendency for students who scored low on early exams to repeatedly score low on subsequent exams because they never fully mastered those earlier concepts. In other words, a too-lenient standard merely created later problems for students.

Now, of course, one could simply set the “cut score” bar high enough so that nothing less than perfection constitutes a passing score on an exam. However, this would unnecessarily fail some students for making minor mistakes. I remember well the sleepless nights when I debated these details in my own head, worried that I would bring to an untimely end students’ academic careers if I set the cut score too high, or set them up for later failure if I set the cut score too low.

A solution I’ve found to this problem is the use of “mastery” exams, where students must answer all questions correctly, but have multiple opportunities to re-try. This ensures their eventual competence while allowing for human frailty. In order to incentivize preparation for these exams, my policy is that student’s grade comes from the *first* version of the exam they take, but that any subsequent re-takes bear no penalty at all. I maintain no cut score whatsoever, but simply average all exam scores together in calculating the theory course grade. If a student must re-take an exam, they must do so in its entirety (not just the parts they failed before). I typically maintain a minimum of eight versions of every exam for this purpose, and those versions are not just the same problems with different numbers but rather similar problems using the same concepts.

5.2 Mastery demonstrations

Assessing practical hands-on work done by students takes a similar form in my courses: all standards for “lab work” must be met with 100% competence, but students are allowed multiple opportunities to re-try until they achieve the standard. In order to incentivize preparation for these assessments, the students’ grade is simply based on the number of times they must re-try to get everything right. As with mastery exams, I will randomize elements of the assessment such that the student must actually apply their knowledge and skill (rather than memorize a procedure) in order to pass. For example, if the assessment includes a demonstration of proper current measurement using an ammeter, each time the student re-tries I will have them do so taking a different current measurement on a different circuit or a different portion of the same circuit.

The reason I degrade a student’s practical work score with every unsuccessful re-try but apply no penalty to every re-take of a written mastery exam is due to the vastly different time commitments by the instructor for each. Written exams are relatively easy to administer and grade, and so may be re-taken without burdening the instructor too much. Practical demonstrations, however, require the instructor’s undivided attention in observing the student perform some task, and this means re-tries take the instructor away from students who may need the attention. Thus, there is a real need to de-incentivize casual re-tries for practical demonstrations.

Chapter 6

Common educational fallacies

When I began teaching full-time in 1998, most of what I thought I understood about good teaching was actually wrong. Some of this was due to ignorance and inexperience on my part, but a lot of what I thought was good teaching was nothing more than convention. I reflected on my experiences as a student and believed that was a sufficient model to follow as a teacher. What I ended up discovering is that much of what is considered conventional wisdom regarding technical education is quite wrong, and actually harmful if followed. The following sections document some of these fallacies.

6.1 Fallacy: the sufficiency of presentation

A common fallacy in education is that clear presentation is sufficient for learning. While it is important to present information very clearly and accessibly, this surprisingly is not as important as one might think. It becomes even less important as the student grows in their ability to seek and absorb information on their own.

In fact, it is actually possible for presentations to be *too clear* for their own good. A presentation that makes complete and perfect sense at the first encounter may fool the receiver into believing the topic is simpler than it is. A presentation that does not inspire follow-up questions has failed to achieve its ultimate goal, which is to foster the critical thinking necessary to become an autonomous learner.

6.2 Fallacy: labs must be well-equipped

Whenever an educational institution offers tours of a new program, the first stop on the tour is always the laboratory where students apply their learning. This is especially true for technical programs such as Electronics. A school will brag about how much money they spent to equip the facility, how modern the components and tools are, and how similar the lab environment is to the intended work environment. Surprisingly, almost none of these things matter.

I learned this important lesson by teaching at a college starved of resources. I simply could not afford to purchase modern lab equipment, and so I was forced to make do with equipment we built ourselves. What I discovered in this process is that a site-built system offers more learning than

one that is pre-packaged and typically costs orders of magnitude more. This is especially true if students get involved in the design and construction of the lab system(s), because they see the entire development process rather than just the finished product.

This is not to say that all lab facilities may be built on a shoestring budget. For some topics of study there simply is no choice but to invest in the right (expensive) equipment. However, what matters most is how you *use* that equipment. The best-equipped lab is nearly useless without the right assignments and exercises to challenge students on its use; with the right curriculum in place, however, even a meager lab will yield phenomenal learning.

I especially urge caution to technical educators considering the purchase of pre-built “trainer” units, which are offered by a number of manufacturers (e.g. Festo, Lab-Volt, Hampden Engineering, etc.) at exorbitant prices. In almost every case it is possible to build your own equivalents to these trainer units at a mere fraction of the cost, and with *far* greater gains in learning.

6.3 Fallacy: teach what they’ll most often do

This fallacy is frequently seen in *skill standards* generated by industry and educational organizations: job tasked are ranked by frequency (i.e. how often an employee will have to perform that task) with the implication that the curriculum should mirror that frequency. This is just nonsense, and for the simplest of reasons: if a task is frequently performed on the job, then the new employee will readily learn that task by working that job. In other words, the repetitive nature of the task naturally translates into on-the-job training (OJT) and renders any time spent on those tasks in formal education rather questionable.

It should be rather obvious that the purpose of formal education for the workplace is to teach students how to do things that are *not* easily learned on the job. Otherwise, why not just hire in as an apprentice and learn your trade entirely by working it?

What skill standard surveys and other rankings of job tasks ought to do is sort these job functions both by importance and by how difficult they are to learn. When building a formal curriculum, you should first identify which of the tasks rank high in important, then skip (or only touch on) the easy stuff and focus aggressively on those important tasks that are difficult to master.

6.4 Fallacy: successful completion equals learning

Students are masters at figuring out how to maximize their own personal grade-to-effort ratio. In recognition of this fact, we as educators must ensure the tasks we give them to complete cannot be completed unless and until the desired learning occurs.

A good example of this is any mathematical problem given to students to solve. Suppose the correct answer consists of a number or a formula. If a student completes the activity by presenting the correct formula, does it mean they actually understand the intended principles of this problem? It is surprisingly difficult to design valid learning activities and assessments due to the difficulty of discerning another person’s understanding. Perhaps the student is able to arrive at the same correct answer through incorrect reasoning. Perhaps they copied the result from a classmate. Perhaps they just made a *guess*, which is likely when the answer consists of selecting between a few choices.

6.5 Fallacy: students learn best in teams

The ability to function well on a work team is obviously important, and should be nurtured along with other interpersonal skills and habits in any educational program aiming to place graduates into the workforce. However, teamwork is far from ideal as a *condition of instruction*. The reason for this is quite simple: students tend to help one another in ways that do not lead to genuine learning, even when their intent is pure. What you will almost always find in team environments is that the team becomes focused solely on *completing the task* rather than *ensuring every person learns*. This is really the “Successful completion equals learning” fallacy in a different form. For those of you who have taught before with students working in teams, how often do you see a team collectively decide to sacrifice their group progress for the sake of ensuring a weaker teammate learns an important concept? I’ll wager this is a rare event in any teacher’s experience.

Moreover, teamwork masks individual student weaknesses from the instructor’s sight. If a student is weak in one or more areas of their understanding, this deficit stands in hard relief when the student must individually demonstrate their understanding, but is hidden when all you see is the product of the group.

From my own practice as an instructor, I have found that when students are forced by circumstance to complete a task normally reserved for a team, the learning is vastly greater. No longer can a student rely on the strengths of their peers, and because of this the student must address their own weaknesses directly.

6.6 Fallacy: tutoring is a panacea

When a student’s grades fall below normal, a common instinct among educators is to provide some form of tutoring to that student. Tutoring sessions often consist of one-on-one meetings with a qualified person to review whatever subject(s) are posing the problem. The problem with this seemingly rational response is that tutoring usually resembles the worst form of instruction: enhancing the presentation of information without enhancing the degree or type(s) of challenge.

Tutoring can be useful, but only when properly executed and assigned to the correct students. There are many ways in which students may be ill-suited to benefit from tutoring. One example I have witnessed too many times is when a student struggles with coursework for non-cognitive reasons such as outside stress, lack of motivation, or poor judgment and/or personal habits. The key to successful tutoring is to first diagnose the true nature of the impediment hampering a student’s progress, and then connecting the student to the right tutor only if that is what will actually help them.

6.7 Fallacy: cater to learning styles

Much could be said on this currently popular topic. It seems one cannot read any modern literature on student learning without encountering something about learning styles: the notion that each person absorbs information best in unique ways, and therefore optimum instruction tailors its presentation on a style-by-style basis¹. I will not attempt to deconstruct the various theories of

¹This latter concept is called the *mesh hypothesis*: that learning is enhanced when one’s learning style meshes well with instruction given in that style

learning styles, for I am not qualified to do so. What I *will* do, though, is highlight the fallacy of learning styles as they are commonly practiced.

When a student explains to me as their instructor that they have a specific learning style, it is always in the context of a larger discussion about why they are struggling to learn something. In other words, their learning style is not being accommodated, and that's why they are experiencing trouble in school. A few errors usually surface at this point:

1. The first error is confusion of what learning styles are even supposed to be. The most common scenario I encounter as an instructor is that the student claims it's difficult for them to learn new information by reading, *because they are a "visual" learner and must see a concept being demonstrated in order to grasp it*. This has always struck me as odd, since reading is an intrinsically visual activity (unless one reads in Braille). The real problem is that the student is not adept at extracting ideas from text, and this is a *reading deficit*. What they are essentially claiming is that they cannot learn anything new without some other person showing it to them. This has absolutely nothing to do with their *visual senses*, but rather has everything to do with *interpreting language*: an entirely different problem.
2. The second error is in equating ease of learning with efficacy of learning. Just because something is made easy for you does not mean (in any way) that accomplishment holds greater benefit for you later. In fact, one might argue that an educational experience tailored around one's strengths will only set up students for later failure when they enter less accommodating environments. One can easily imagine an educational environment in which nothing is presented to you that doesn't cater to your strengths, and then the utter shock experienced when you step into your new role as a technical employee only to discover you must continue to learn without this assistance.
3. The third error is that the student's learning style is simply assumed to be fixed for life. But how do we know this to be true? Many other aspects of personality and cognition are known to evolve over one's life, so why should learning style (if it exists at all) be different?

It is an incontrovertible fact that the field of Electronics requires continuous learning and skill improvement. This is true for any field subject to the evolution of technology and of applications. It is also an incontrovertible fact that life does not adjust itself to suit our proclivities, and as such it would be unreasonable to expect to have one's learning style accommodated throughout a career.

Suppose learning styles are both real and immutable: a person who is simply unable to learn in multiple ways is therefore unsuitable for this career and should not even bother pursuing it. Suppose learning styles are real but malleable: this would mean the educational program has an obligation to *challenge* the student's learning styles in order to make them a more versatile learner. Suppose learning styles aren't real, but are merely *habits*: in this case our best option is to ignore them entirely lest we cripple our students' futures by accommodating something that doesn't actually exist.

I have yet to meet a student who was willing to give up their career in Electronics because they were convinced their learning style made reading (or any other learning activity) impossible. I have also never met a student who failed to accomplish what their learning style ostensibly inhibited. At the risk of sounding cynical, I am convinced learning styles are far too often used as excuses for avoiding challenges, and that this is the innate appeal driving their popularity.

6.8 Fallacy: we can identify and sort different types of students

When I began my teaching career, I was impressed by how perceptive my seasoned colleagues were regarding student capability. They would tell me, without any apparent hesitation or doubt, that “some people just aren’t cut out to learn certain things” when commenting on a particular student’s poor performance. I was told there was such a thing as a “math person” to whom mathematics was as natural as breathing, and by contrast others who “would never get it”. I was told some people were “mechanically inclined” whereas others would never be able to grasp how mechanisms worked.

As with learning styles, I am skeptical of such claims. For the sake of argument, there may in fact be such a thing as a person who will *never* be able to learn a particular concept or skill no matter how hard they try and no matter how long they attempt to learn it. However, it seems both premature and dismissive to render such sweeping judgments from a paucity of information. How can anyone really adjudicate what someone else will *never, ever* be able to accomplish?

The origin of my skepticism is rooted less in optimism than it is in my own (and others!) demonstrated failure to make sound judgments in such matters. Many, many times I have been wrong about students’ capabilities, thinking some of them would never find success in their chosen field only to discover later on that they did in fact succeed marvelously. Colleagues of mine in candid moments have told me the exact same thing: they too have grossly underestimated some students’ capabilities.

My advice on this point is to be highly skeptical of one’s own powers of foresight with regard to others’ abilities to learn. Human beings are complex creatures, and the circumstances bearing on a person’s learning are vast, complex, and inter-related. If we see a student struggling to learn something, it may very well be for reasons quite unrelated to innate potential. Perhaps they lack the prerequisite knowledge to tackle the subject at hand. Perhaps they are suffering under stresses you cannot perceive. Perhaps they engage in negative self-talk where they convince themselves what they cannot ever do. *Perhaps they aren’t being taught well.* Simply put, no human being is qualified to declare that others cannot ever do what they themselves have in fact done. The very fact that a great many people have accomplished that thing ought to be taken as evidence that it is likely possible for all given the requisite time and effort.

6.9 Fallacy: reductionistic program design

This fallacy finds itself embedded into the very structure of modern American higher education, and may be defined in the context of this discussion as the belief that *understanding the constituent parts necessarily results in understanding the whole*. Programs of study are comprised of discrete courses, each one usually focused on a single topic, often taught in multiple sessions by different instructors with widely varying standards of achievement. This design is not intended to maximize learning, but rather optimize enrollment. Simply put, it is far easier to manage enrollment at a college where students are free to choose from a smorgasbord of courses and instructors are regarded as fungible assets for the delivery of these courses, than it is to manage enrollment with monolithic programs of study.

Some areas of study are amenable to teaching in reductionist fashion. Certain mathematical topics (e.g. trigonometry) as well as certain discrete skills (e.g. sensor calibration) lend themselves well to dedicated courses. Other areas, however, do not. When the knowledge or skill in question

spans a wide range of applications and involves changes of habit, one course in that subject is rarely sufficient.

A good example of this is *safety*. You can hardly find a workplace program that doesn't include a safety course, but yet this is a terrible way to teach safety. While it's possible to convey certain safety procedures and knowledge in a single course, many safety applications require extensive knowledge in other areas (e.g. electricity, chemistry) and so must be addressed at multiple points in a program of study. Moreover, safety is first and foremost a matter of *attitude* and *habit*, and as such requires persistent emphasis over long periods of time to fully cultivate.

Another good example of this is *troubleshooting*. Like safety, the ability to diagnose faults in complex systems requires specific knowledge of those systems and therefore troubleshooting must be taught at multiple points throughout any complex program of study. Also like safety, troubleshooting necessitates the cultivation of certain mental habits and attention to detail that requires persistent effort over long periods of time.

In short, topics such as safety and troubleshooting are simply too complex and too important to relegate to single courses.

Another problem with reductionist program design is abstraction: cognitive research reveals how difficult it is for students to absorb a concept and then apply that one concept ("transfer") to different applications. One of the dangers of reductionism is that concepts may be taught in complete isolation from their practical contexts, which the hope that students will "make the leap" from general principle to application, but this is a tall order. It is far more effective in my experience to embed important concepts into multiple lessons across the program in order to reinforce those concepts and help students learn to see how that abstract concept gets applied.

Another problem with reductionist program design is the notion that students should be able to master a specific area of knowledge or skill in a single setting (or a single course). This *may* be possible if the course in question covers a small number of knowledge areas or skills, but those areas of knowledge and skill that are the most valuable (precisely because they are difficult to master) generally require multiple exposures to learn. If, for example, one relegates a topic as challenging as "troubleshooting" to a single course, the tacit assumption is that the student will completely learn how to troubleshoot within the span of that course and will have no need for later review or re-instruction. However, the learning of deep concepts simply does not work this way. People learn difficult things by *repeated exposure* and *repeated application* which means any effective program of study must be designed in such a way as to revisit those difficult knowledge areas and skills multiple times across multiple courses rather than relegating each one to its own course.

Yet another problem with reductionist program design is the difficulty of maintaining consistently high standard of learning across the entirety of a program. This problem is especially pronounced when temporary faculty are employed to teach these courses. If students know what some faculty teaching a subject won't hold students to the same high expectations as other faculty teaching that same subject, you create pathways of least resistance where the students who most need challenging instruction in order to develop as thinkers don't get the challenge they need. This fragments the learning culture at the institution and deprives students of the challenge they require to excel.

6.10 Fallacy: credentials matter

They don't, unless some statutory requirement demands credentialing for employment. Even then, it's still the *ability* of the individual to do the job that holds true and lasting value. A badge is ultimately worthless unless it accurately reflects actionable knowledge and skill.

Academic culture is shot through with the *Cult of the Credential*. One cannot be hired into many administrative and faculty positions without the right letters following their name². This cult-like attitude seeps down to students at all levels, which explains why some are incentivized to cheat, to plagiarize, and to seek the easiest-to-pass courses. Cheating, plagiarism, and avoidance of academic challenge makes no sense whatsoever if the student's goal is to actually learn, but it makes perfect sense if the goal is to merely obtain that score, that grade, that mark, and eventually that credential. We have placed value on a mere symbol rather than the thing it is supposed to symbolize.

For a refreshing contrast, spend some time observing how people learn within environments where credentials are non-existent, and where the *only* rational goal is actual learning. Observe, for example, people *voluntarily* learning an athletic skill, learning to play a musical instrument, improving their literacy, etc. and you will behold an entirely different culture and approach to education. The Cult of the Credential is always and everywhere destructive.

6.11 Fallacy: good instruction is measured by student surveys

Feedback is important for all professionals, to let them know where they have room for improvement. However, most educational institutions in my experience place excessive emphasis on student survey results as a measure of instructor performance. Student feedback is actually quite important, but only for very specific aspects of an instructor's performance and not as a general measure of instructional effectiveness.

Here is a list of common performance parameters surveyed of students, along with my opinion of each one's value and validity:

- **Respect for students** – this is very important to measure, as it is imperative for students to feel respected in their learning environment.
- **Timeliness of grading** – quick feedback loops are incredibly important for student learning, so this is also important to measure.
- **Clear instructions** – while clear instructions are important for learning, some students will perceive challenging assignments as being “unclear” if those assignments demand deeper thinking, challenge previous assumptions, and/or require more initiative for completion than what the student is accustomed to.

²We see this most grotesquely in the Doctor of Education (EdD) credential which is at this date almost universally required for someone to obtain a job in a college's upper levels of administration. A consequence of this credentialism has been the offering of EdD study programs designed to help lower-level administrators achieve the needed credential for advancement without having to leave their current jobs. A credential becomes an assumed requirement, and then colleges rush to meet that market demand. Meanwhile, possession of said credential doesn't seem to make any actual difference in job performance within these roles.

- **Learning new knowledge/skill** – this has surprisingly little value, as the student will never know whether what they are learning is actually useful until they enter their chosen career.
- **Instructor’s knowledge of subject** – this has surprisingly little value as well, for the exact same reason as mentioned above: the students aren’t going to know whether or not their instructor is truly knowledgeable until they enter their chosen career and see for themselves the validity of what they’ve been taught. It’s quite possible for an instructor to be weak in technical knowledge but nevertheless convincing to students due to strength of personality and presentation!
- **Variety of instructional methods** – this measurement is closely related to the prevailing theory of learning styles, namely that students with different learning styles should be taught to those particular styles (i.e. the *mesh hypothesis*), which means instructors must deliver instruction in many different ways in order to accommodate as many different learning styles as may exist in one classroom. However, the way in which this question is often interpreted by students is that the instructor isn’t doing this unless all instruction matches their preferred style. If students are challenged to learn in any way(s) they aren’t comfortable with – no matter how many different methods or modalities the instructor might employ during the span of a particular course – this rating will often be low.

A major caveat to the usefulness of student survey results is whether or not the surveys are anonymous. When students are free to express their opinions with complete anonymity and no accountability, what you sometimes find is abuse of the survey process, where students angry at the instructor for some perceived injury (e.g. holding them to higher academic standards than they’re used to) will rank the instructor as poor-performing in areas where this is actually not the case. This is fundamentally why so many comments on the internet are mean and abusive: many people lash out at others when they know there are no consequences, social or otherwise, to pay for such action.

A recommendation to improve student feedback is to add some form of accountability to it. Of course it’s understandable to keep student identity hidden from the instructor so as to guard against retaliation if the instructor is indeed disrespectful of students, but *someone* holding the instructor accountable to good teaching should be able to identify who said what so as to follow up on legitimate complaints. One way to do this is to require all negative comments be backed up with specific examples, and also to trigger follow-up by the instructor’s supervisor. If students know they cannot lodge baseless complaints under the protection of full anonymity, they will be far less likely to do so, and the only complaints received will be those with at least some validity.

By far the best feedback I’ve consistently received for my own instruction comes from *graduates* and not from *current students*. Graduates can speak to all the same inter-personal and organizational merits of their former instructor, but also enjoy the superior perspective of actually having worked in their chosen career and therefore are better-equipped to comment on the value of what they’ve learned, the effectiveness of the instructional methods and sources used, etc. The reason this source of feedback is rarely if ever sought by educational institutions is quite simple: good data on this is elusive. Unlike graduates of 4-year universities who are often more inclined to associate with their alma maters via Alumni Associations and the like, 2-year technical school graduates don’t typically maintain contact with their graduating institutions, and are thus more difficult for those institutions to reach after graduation.

Another under-utilized data source on instructional effectiveness is *employer satisfaction*. This is one area where professional-technical programs should have a natural advantage in feedback over more traditional academic programs where employment is not necessarily the goal, yet educational institutions often struggle to gather this feedback on an appropriate scale. Unlike students who comprise a captive audience of survey-takers, employers are free to ignore requests for surveys, and it can be challenging for a school's survey to actually reach the best person(s) at each company to give the survey. Often the easiest-to-interpret feedback from employers comes in the form of recruiting visits: employers don't make special trips to recruit from schools known to release poorly-prepared graduates, but they will go out of their way to recruit from the best schools, often traveling hundreds of miles and crossing state lines to do so.

6.12 Fallacy: good instruction is measured by the strongest graduates

Another common fallacy you will see educators engaging in is to judge the strength of a program by the successes of its *best* graduates. You will often find this fallacy employed by directors and faculty of weak programs who cite a few star-performer graduates as purported proof that their programs are strong. The reason why this is a poor indicator of programmatic strength is due to the fact that *even a poorly designed and/or executed instructional program cannot hold back self-motivated students*. A student who is self-disciplined and intensely interested in the subject matter will inevitably learn well on their own, with or without a school's assistance. This means even weak programs will occasionally output strong students.

A much better measure of instructional rigor and excellence is the performance of its *worst* graduates. This indicates how *little* a person can learn in the program and still pass. Strong programs don't graduate weak students, whether by the strength of their instruction and/or by the strength of their assessments and accountability to learning. Weak programs, on the other hand, allow students who haven't learned much to graduate, and you will see this clearly in the form of disappointed employers interviewing (and maybe even hiring) those students.

6.13 Fallacy: forms and procedures equal quality control

In nearly every circumstance I've had opportunity to analyze, whether it's at one of the multiple colleges I've taught at, or discussing/observing how other colleges function, meaningful quality control at the college level is elusive. Instead of actual assessing educational outcomes – which in the case of skilled-trades work is finally assessed at the employment stage when the graduate must perform to real-world demands – what you typically find are policies and procedures that fall woefully short of actually detecting (much less correcting) educational deficits. *Rather than quality control, what most colleges have is Quality Control Theater*: largely performative activities that not only fail to help students attain their professional goals but cause real harm by taking time away from more productive efforts.

Things should not be such. Of all the areas of higher education, skilled-trade education should be the easiest to assess quality of because we have external tests in the form of *employment* and *employer satisfaction*. A large barrier to robust monitoring and control of quality is the disconnect that exists between industry and educational institutions. Unless a technical program has a proven record of graduating exceptionally high-quality technicians, most industry partners just don't seem to want to invest the time and effort to provide consistent, measurable, year-after-year feedback. Meanwhile, state agencies tasked with oversight of educational outcomes (e.g. Boards of Education) are so far removed from the “action” of instruction happening on campuses that they *cannot* monitor and make any necessary corrections where needed.

Quality control works when those with the greatest influence over quality (in this case, the instructors) have both the correct incentives to boost quality and the means to do so. If instructors and their collegiate supervisors were paid according to how well their graduates performed, for example, much would change!

Chapter 7

Self-directed learning

For a great many people interested in becoming electrical or electronic professionals, formal schooling is simply not an option. Cost of tuition is certainly a barrier for some, and the opportunity cost¹ of attending formal courses is certainly a barrier for many. Potential students with young families of their own are often the most limited, as good parenting is a full-time job in itself and many people are understandably unwilling to sacrifice time spent with their children and spouse in order to attend courses.

What is one to do, then, if formal schooling is impractical or unavailable? On this point I can speak with some degree of authority as I myself am largely self-taught. My only formal instruction in electricity or electronics consists of two years spent studying at a private (non-profit, non-accredited) technical school, and then many years later taking a few electronics courses at a community college necessary to earn a two-year Associate's degree.

Important caveats about self-directed learning include:

- The learning journey will typically go slower than with formal instruction, as one of the benefits of formal instruction is the curricular design leading to most-efficient learning.
- Your own determination and curiosity are the most important factors in determining how far and how fast you progress. You will need to be patient with yourself when progress becomes slow, and persistent in locating resources when those resources are difficult to find. Curiosity, while definitely a strength for the self-directed learner, can also cause one's learning pathway to meander. This is not necessarily a bad thing, as tangents often lead to deep discoveries, but if your goal is to learn a set of specific concepts in a set amount of time you may find your own curiosity getting in the way of that itinerary.
- When learning is self-directed, your knowledge and skill will tend to be uneven. In other words, it is easy to unintentionally specialize as you follow your own interests and curiosity, learning some things well and others not-so-well.

¹This is a useful economics concept describing whatever high-valued sacrifice(s) you must make in order to take some course of action. If attending a school means you must give up a job or at least reduce your working hours, that lost income constitutes an opportunity cost of attending school.

7.1 Learning theory

As a self-directed learner you will need to locate high-quality source information to digest. All the resources suggested in the “Source material” subsection of the “How to begin teaching inverted” section of the “Teaching technical theory” chapter in this document apply to self-directed learning as well. The world-wide internet has made finding such resources very easy, but it unfortunately has also made it easy to find poor-quality tutorials. Limit yourself to information sources with a proven reputation rather than to random websites and videos!

Collect old as well as contemporary sources as you build your library: old textbooks, patents, papers, and other texts are often just as useful – and in some cases are *more* useful – than modern writings. Also, do not hesitate to collect “redundant” resources, for example multiple texts by different authors on the exact same subject, as you will often find one author expresses some detail in far clearer prose than another, so that reading multiple texts on the same subject can give you the best-of-all benefit. Your personal library should grow to a *huge* size, in both paper and digital forms.

Simply digesting technical information, however, is not as effective as one might think for learning any subject. In order to deeply understand something it is necessary to *express that something in your own terms*. Expression of concepts may take many forms, perhaps the most recognized for self-directed technical learning being the application of digested learning to the construction of functional systems (i.e. building things that utilize those principles), but there are others as well. These include:

- Writing your own journal/text explaining in your own words what you are learning
- Teaching other people what you are learning
- Running computer simulations applying what you are learning

All three of these techniques (plus building functional circuits, of course) have been invaluable in my own self-directed learning. The first two of these listed became most prominent when I became a full-time instructor of electronics. When I first started to teach I was made acutely aware of how much I did *not* know about electricity and electronics, and being in a job where it was my responsibility to present accurate information on these topics I had both the incentive and the daily opportunity to practice expressing what I knew in my own words. Being in a position where I needed to ensure my students had a well-rounded exposure to the subject forced me to critically survey what I knew and what I did not know, and to spend significant time strengthening my subject-matter weaknesses.

I have even found that *imagining myself teaching something to another person* aids in my own learning. Rehearse how you would describe concepts to another person, and the process of you hearing your own words often works well to identify misconceptions and areas where your own understanding is not as strong² as you’d like it to be.

²The very first time I needed to teach transistor theory to my students (in 1999) was an episode of painful self-discovery for me: I realized when rehearsing what I would say during lecture that I really had no clear idea of *how* transistors functioned, and that I really only knew how to use them in circuits! This showed me what I needed to focus on in my own studies at that time.

7.2 Strategies for effective technical reading

“Reading maketh a full man; conference a ready man; and writing an exact man” – Francis Bacon

Francis Bacon’s advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner’s thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, write their own outline and reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

✓ Briefly **OUTLINE THE TEXT**, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do not comprehend.

✓ Demonstrate **ACTIVE READING STRATEGIES**, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

✓ Identify **IMPORTANT THEMES**, especially **GENERAL LAWS** and **PRINCIPLES**, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

✓ Form **YOUR OWN QUESTIONS** based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

✓ Devise **EXPERIMENTS** to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

✓ Specifically identify any points you found **CONFUSING**. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

7.3 Learning practical skill

In order to learn electricity and electronics well, you *must* build circuits of your own. Safety is the first and foremost concern for anyone intending to build circuits without the benefit of a supervising expert, so consult trusted sources for circuit ideas and pay heed to all warnings! Some tips for staying safe:

- Limit yourself at first to circuits powered only by small batteries, to limit the amount of energy in your circuit that could possibly cause harm.
- Always de-energize your circuit before touching any of its bare-metal conductors, even when the voltage levels are known to be safe. This builds good habits!
- Let 24 Volts be a practical maximum voltage to limit electric shock hazard.
- Never build a line-powered (i.e. wall-socket-powered) circuit without fully understanding the associated shock and burn hazards. Always use lock-out-tag-out (LOTO) procedure to bring your circuit to a zero-energy state before making any contact with its conductors. Follow best-practices in constructing your circuit, using properly-sized conductors according to current and properly-insulated connection points (e.g. terminal blocks) according to voltage. NASA provides public-domain standards on wiring and soldering practices, such as the *Inspector's Pictorial Reference*, which can be very helpful.
- Always sketch a schematic diagram of what you intend to build before actually building it. Doing so will help you identify potential hazards (as well as design flaws) before any damage can occur.

As you design, build, and test circuits you will find keeping a journal of your experimental and project work extremely valuable in learning, especially if circumstances force you to take a hiatus from your learning. Having a record of what you did, what you learned, and what problems you encountered will greatly assist you when the time comes to resume your learning.

7.4 Experiment and project ideas

The following list should be regarded as suggestive only, not prescriptive, and is shown merely to give ideas of where to start. These ideas are listed in rough order of conceptual simplicity (simplest first, most complex last). Learning modules contained on the ModEL website are a source of specific experiment and project examples, particularly the *Case Tutorial* and *Questions* chapters of those modules.

- Electroscopes for detecting static electricity
- Chemical battery made of different metals and a liquid electrolyte
- Multi-battery source made of multiple batteries connected in series (to obtain different voltages)
- Electromagnet made from wire and iron
- Battery-charger using solar cell (or panel) as the source
- Resistive voltage divider for reducing battery voltage down to a level suitable for a low-voltage load with a known current draw
- Relay-based low-voltage motor start-stop latching circuit
- Motor-generator set where a small DC motor spins a small generator to produce difference voltage/current levels, and/or convert DC into AC
- Small wind-turbine generator outputting enough power to illuminate a few LEDs
- Sound-powered telephone using dynamic (electromagnetic) speakers on each end as microphone/speaker elements for verbal communication
- Resistive-sensor bridge network for photocells, thermistors, strain gauges, etc.
- Kelvin-Varley voltage divider network
- Wheatstone bridge network for resistance measurement
- Simple logic functions (AND, OR, etc.) using electromechanical relays
- Transistor power switching circuit where a small switch controls current through a relatively high-current DC load
- Simple logic functions (AND, OR, etc.) using discrete transistors
- Voltage-regulator circuit suitable for reducing battery voltage down to 5 Volts or some other voltage suitable for powering digital logic ICs (using three-terminal regulator IC)
- Strobe light using ultra-bright LED and 555 timer IC, useful for visually “freezing” the motion of a rotating object such as an air fan
- PWM speed controller for a small DC motor

- Simple test equipment
 - Analog voltmeter using D’Arsonval meter movement and series “range” resistors
 - Analog ammeter using D’Arsonval meter movement and parallel “range” resistors
 - Analog ohmmeter using D’Arsonval meter movement, battery, and range resistors
 - Sensitive audio detector using earbuds (or headphones), transformer, resistors, and diodes to *hear* electronic signals
 - Signal generator producing square, triangle, and PWM waveforms
 - DC voltage reference using precision voltage regulator IC
 - Simple X-Y oscilloscope using grid of LEDs and dot-display driver ICs or other circuitry to drive array rows and columns with analog voltage signals
 - Simple oscilloscope using grid of LEDs and dot-display driver IC to drive array rows with analog voltage signals, a digital counter to drive array columns, and an adjustable-frequency 555 oscillator as the timebase clock signal
- Audio amplifier circuit (first using monolithic amplifier IC, then using operational amplifiers, then using nothing but individual transistors and other discrete components)
- Crossover network for audio speakers
- Bass and treble audio tone-control circuit (filter networks)
- Analog musical synthesizer modules (e.g. voltage-controlled oscillators (VCOs), voltage-controlled filters (VCFs), envelope generators, noise generators, etc.)
- Crystal-detector AM radio receiver
- Transformer wired to boost AC voltage or buck AC voltage
- Motor-generator set where a small DC motor spins a small three-phase AC generator to power Wye and Delta networks (including some powered through three-phase transformer banks)
- DC-AC power conversion circuit
- DC-DC “switch-mode” power conversion circuit
- SR latch made from individual logic gates
- Digital counter made from individual flip-flops
- Digital timer or clock using oscillator IC, counter ICs, 7-segment decoder ICs, and 7-segment LED display units
- “Chasing light” sequencer using shift register IC, string of LEDs, and 555 oscillator
- Arbitrary waveform generator using digital counter IC, adjustable-frequency 555 oscillator as the clock, analog multiplexer IC, and several potentiometers to set voltage-level points on the waveform

- Arbitrary waveform generator using EPROM IC programmed with “wavetable” values for the desired waveform, digital counter IC, R-2R resistor ladder network, and adjustable-frequency 555 oscillator as the clock (i.e. direct digital synthesis of waveforms)
- Voltage-boosting circuit using DC source, inductor, and pushbutton switch to generate short-duration pulses of sufficient voltage to energize a neon lamp
- Brute-force AC-to-DC power supply (only after thoroughly understanding the hazards of line-powered circuits!)
- Spark-gap broadband radio transmitter
- Carrier-wave AM or FM radio transmitter (use Software-Defined Radio (SDR) unit as an inexpensive broadband receiver and spectrum analyzer for reception testing)
- Construct and test different types of antennas for radio transmitters and receivers
- Finite-state machine using EPROM, shift register, and 555 oscillator clock
- Single-board computer built from individual microprocessor, RAM, ROM, and assorted logic ICs

7.5 Circuit construction best-practices

These are best-practice principles I enforce with student project construction, many of them derived from published standards but some simply gained from personal experience. They serve as a good starting point for your own self-directed experimentation and project-building.

7.5.1 General layout

- All electrical components shall be located to avoid accidental exposure to liquids.
- All manual controls (e.g. buttons, handles, knobs) shall be accessible and function without undue effort.
- Fragile components (e.g. heat-sensitive semiconductors) shall be easily accessed for replacement.

7.5.2 Fastening

- All threaded fasteners shall be properly engaged and tightened.
- A minimum of 1-1/2 threads shall extend beyond the threaded hardware (e.g., nut), unless otherwise specified otherwise.
- All cable ties shall be trimmed off, flush with the back end of the strap head. (*NASA-STD-8739.4, NFPA 79 2007 edition (13.1.5.6)*)

7.5.3 Thermal considerations

- Power-handling components shall have adequate cooling capacity, usually in the form of a heat sink.
- When mounted vertically, the hottest components shall be located on top so their convected heat does not warm other components.
- Components dissipating heat in quantities of 1 Watt or greater, or in quantities sufficient to damage a PCB shall be mounted with sufficient standoff [> 1.5 mm (0.060 in)] and shall be mechanically restrained.

7.5.4 Power wiring

- All electrical sources greater than 24 Volts shall be guarded against accidental contact (e.g. use recessed terminals with no exposed metal).
- All electrical sources capable of generating currents exceeding conductor ampacity ratings shall be overcurrent-protected, regardless of voltage.
- Overcurrent protection shall be on the ungrounded (“hot”) conductor(s) only (*NFPA 70 2017 edition (240.15(A))*). No grounded conductor shall be overcurrent-protected or switched (*NFPA 70 2017 edition (240.22)*).
- Small power transformers shall be overcurrent-protected on their primary windings, and optionally on their secondary windings. For primary currents less than 2 Amperes, exclusive primary overcurrent protection may be as high as 300% of full-load rating, 250% if secondary overcurrent protection also included. For secondary currents less than 9 Amperes, overcurrent protection may be as high as 167% of full-load rating. (*NFPA 70 2017 edition (450.3(B))*)
- All metallic panels and electrical enclosures receiving power from the AC line shall be bonded to earth ground for safety, and this bonding verified by electrical resistance measurement. Resistance between nearest facility ground point (e.g. plug ground prong) and chassis shall be $0.1\ \Omega$ or less. (*NASA-STD-4003A, NFPA 79 2007 edition (18.1)*)
- All power conductors shall be strain-relieved so that tension applied to them will not stress the electrical connections themselves (*NFPA 79 2007 edition (13.4.3.1.1)*). Permanent conductors not in a raceway shall be securely fastened at least every 6 inches using cable ties or other appropriate means.
- All conductors shall be prevented from chafing against any sharp edges (*NFPA 79 2007 edition (13.5.1.2)*).
- Proper use of colors for electrical power source wiring (e.g. red and black for DC + and –, black and white for AC “hot” and “neutral”, green for earth ground) (*NFPA 79 2007 edition (13.2)*). Colored tape is permissible at both ends of a wire whose insulation is not of the right color.

7.5.5 Other wiring and connections

- Proper wire sizes and insulation ratings throughout (e.g. sufficient wire gauge for the expected current, insulation over-rated for the highest voltages expected) (*NFPA 79 2007 edition (12.5)*).
- Compression terminals – crimping of solid wire, component leads, or stranded wire that has been solder-tinned, is prohibited. The conductor shall extend a minimum of flush with, and a maximum of one (1) wire diameter beyond the conductor crimp edge. No protruding wire strands outside the terminal barrel. (*NASA-STD-8739.4*)
- No splices allowed between terminals (*NFPA 79 2007 edition (13.1.2.1)*).
- Only solid wires shall be wrapped around a screw terminal, and this shall be clockwise. Wrap distance shall be between 180° and 270° (between $\frac{1}{2}$ and $\frac{3}{4}$ turn).
- Attached wires shall withstand being lightly pulled with fingers.
- Wire insulation shall be intact (i.e. no bare wires anywhere).
- After insulation removal, the remaining conductor insulation shall not exhibit any damage such as nicks, cuts, or charring. Conductors with damaged insulation shall not be used. Scuffing from mechanical stripping or slight discoloration from thermal stripping is acceptable. (*NASA-STD-8739.3*)
- Panel wiring shall be neat in appearance.
- Multiple conductors extending beyond an enclosure or panel shall be bundled together as a multi-conductor cable wherever possible.
- No use of solderless breadboards on permanent assemblies; use only for prototyping.
- No use of tape as electrical insulation; use heat-shrink tubing instead.
- Cables shall not be bent below the minimum recommended inside bend radius (6 diameters for flexible coaxial cable, 3 diameters for multi-wire harnesses 10 AWG and smaller). (*NASA-STD-8739.4*)

7.5.6 Soldered connections

- Visual Appearance – the appearance of the solder joint surface shall be smooth, non-porous, undisturbed and shall have a finish that may vary from satin to bright depending on the type of solder used (*NASA-STD-8739.3*). Overheated solder has a dull, gray, frosty and/or crystallized appearance (*NASA-STD-8739.2*).
- Solder Coverage – the molten solder shall flow around the conductor and over the termination areas. (*NASA-STD-8739.3*)
- Tinning – tinned surfaces, which are to become part of the solder termination, shall exhibit 100% coverage. When tinning stranded wires, the solder shall completely wet the conductor, penetrate to the inner strands, and exhibit 100% coverage. Wire strands shall remain distinguishable. Wicking of flux or solder shall be minimized. (*NASA-STD-8739.3* and *NASA-STD-8739.4*)
- Minimum Insulation Clearance – the insulation shall not be embedded in the solder joint. The contour of the conductor shall not be obscured at the termination end of the insulation. (*NASA-STD-8739.3*)
- Maximum Insulation Clearance – the insulation clearance shall be less than two wire diameters, including insulation, but in no case shall permit shorting between adjacent conductors. Insulation clearance shall be referenced from the first point of contact of the conductor to the terminal. (*NASA-STD-8739.3*)
- Mechanical Support and Strain Relief – wire bundles shall be supported so that the solder connections are not subjected to mechanical loads. Conductors shall be provided with sufficient slack to preclude tension on the solder termination or conductor. (*NASA-STD-8739.3*)
- Through-hole component leads terminated straight through a PCB shall extend 0.5 mm (0.020 in) to 2.29 mm (0.0900 in.) beyond the pad surface. Leads may be bend up to 30° from the vertical plane to retain the part during soldering. (*NASA-STD-8739.3*)
- Component bodies shall not be in contact with soldered terminations. (*NASA-STD-8739.3*)
- The radius of a bend in the lead of a component shall not be less than the lead diameter or lead thickness. (*NASA-STD-8739.3*)

Chapter 8

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . [page xi]

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

8.1 Francis Bacon on studies

This short essay, “On Studies”, was written by the philosopher Francis Bacon in 1625.

Studies serve for delight, for ornament, and for ability. Their chief use for delight is in privateness and retiring; for ornament, is in discourse; and for ability, is in the judgment and disposition of business. For expert men can execute, and perhaps judge of particulars, one by one; but the general counsels, and the plots and marshaling of affairs, come best from those that are learned. To spend too much time in studies is sloth; to use them too much for ornament, is affectation; to make judgment wholly by their rules, is the humor of a scholar. They perfect nature, and are perfected by experience: for natural abilities are like natural plants, that need pruning, by study; and studies themselves do give forth directions too much at large, except they be bounded in by experience. Crafty men condemn studies, simple men admire them, and wise men use them; for they teach not their own use; but that is a wisdom without them, and above them, won by observation. Read not to contradict and confute; nor to believe and take for granted; nor to find talk and discourse; but to weigh and consider. Some books are to be tasted, others to be swallowed, and some few to be chewed and digested; that is, some books are to be read only in parts; others to be read, but not curiously; and some few to be read wholly, and with diligence and attention. Some books also may be read by deputy, and extracts made of them by others; but that would be only in the less important arguments, and the meaner sort of books, else distilled books are like common distilled waters, flashy things. Reading maketh a full man; conference a ready man; and writing an exact man. And therefore, if a man write little, he had need have a great memory; if he confer little, he had need have a present wit: and if he read little, he had need have much cunning, to seem to know that he doth not. Histories make men wise; poets witty; the mathematics subtle; natural philosophy deep; moral grave; logic and rhetoric able to contend. *Abeunt studia in mores*¹ Nay, there is no stound or impediment in the wit but may be wrought out by fit studies; like as diseases of the body may have appropriate exercises. Bowling is good for the stone and reins; shooting for the lungs and breast; gentle walking for the stomach; riding for the head; and the like. So if a man’s wit be wandering, let him study the mathematics; for in demonstrations, if his wit be called away never so little, he must begin again. If his wit be not apt to distinguish or find differences, let him study the Schoolmen; for they are *cymini sectores*². If he be not apt to beat over matters, and to call up one thing to prove and illustrate another, let him study the lawyers’ cases. So every defect of the mind may have a special receipt.

¹Studies pass into and influence manners.

²Splitters of hairs.

Chapter 9

References

Bacon, Francis, *On Studies*, 1625.

Chapter 10

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

3 March 2025 – credited Brad Burdick and Brad Willbrandt as the colleagues of mine who created “No-Math Path” problems for their electrician students.

13 January 2025 – minor edit to the “First Principles” bullet-point on reading, as well as some other (very) minor edits throughout.

8 January 2025 – added more details on how to institute effective quality control in the curriculum.

5 January 2025 – minor addition to the “Mastery demonstrations” section of the “Assessing student learning” chapter.

11-12 December 2023 – added another “Fallacy: forms and procedures equal quality control” and made other minor edits to the text.

7 December 2023 – added more to the “Proven strategies” and “Fallacy: reductionistic program design” sections regarding the need for reviewing difficult-to-learn concepts.

1 December 2023 – minor edits to the “Ingredients for robust technical education” chapter and other chapters. Added a new section (“Fallacy: we can identify and sort different types of students”) to the “Common educational fallacies” chapter.

9 November 2023 – added more detail on in-class activities for instructors to organize when teaching inverted class sessions.

11-24 August 2023 – added several more examples of ways to hold students accountable to preparatory work in inverted teaching sessions, along with tips on how to administer these. Added another section to the “Common Educational Fallacies” chapter on the illusion of program strength

based on top graduates. Minor edits in other portions of the text, too.

4 August 2023 – minor edits courtesy of Scott Hodge.

30-31 July 2023 – added content discussing the merits of text-based versus video-based source material. Also added comments in two of the “Common difficulties” sections regarding the development of spatial reasoning necessary to translate between schematic diagram representations of circuits versus real (or pictorial illustrations of) circuits.

26 July 2023 – added more content to the “Teaching Technical Theory” chapter.

2 July 2023 – minor wording edits to the “Self-directed learning” chapter, and also added a section on best practices for circuit construction.

14 June 2023 – minor edits to the “Teaching technical theory” chapter. Also added a “Common difficulties in diagnostic coursework” section.

7-9 June 2023 – added a new chapter on Self-directed learning and added content to that chapter.

17 May 2023 – minor updates to text.

6 February 2023 – minor updates to text.

5 December 2022 – added more content to the “How to begin teaching inverted” section of the “Teaching technical theory” chapter.

5 September 2022 – added sections to the “Assessing student learning” chapter.

19 August 2022 – more minor edits to document.

15 August 2022 – minor edits to the format of the “First Principles” section.

21-27 July 2022 – more edits made to the text in order to adapt it from its prior context (instrumentation) to its current (electronics).

2-3 July 2022 – document first created.

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