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 larger.

- **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 technical reading into the curriculum in order to cultivate the functional literacy necessary for life-long advancement of knowledge and skill.

- **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.

• **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, job shadows, 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.

- 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 assemblies\(^1\), 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.

- Include a cumulative exam at the end of every term, covering all concepts back to the start of the program.

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\(^1\)In 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 presentation. 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 read 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.

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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 textbooks. 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 well. 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

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3 And 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.

4 Any 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. HOW TO BEGIN TEACHING INVERTED

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
- Historical documents (e.g. Cassier 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
2.5. HOW TO BEGIN TEACHING INVERTED

2.5.3 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 questions to guide their pre-work and to provide definite points of discussion once you meet in class are also very helpful. Some examples include:

- 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
- Devise your own question based on the text, suitable for posing to someone encountering this subject for the first time
- 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

2.5.4 Accountability

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

- Inspecting students’ written outlines of the text/video
- 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
2.5.5 In-class activities

A wide range of options exist for activities for students to engage in following the accountability check. These include:

- **Socratic dialogue with individuals** – *I strongly recommend adopting a Socratic style for the entire class session regardless of the specific activity, where you probe students’ understanding and encourage deeper thinking by asking questions rather than by dispensing answers!*

- **Think-Group-Share with small student teams** – *This is a way to encourage students to speak up in class, especially when individuals may feel anxious about doing so. All this means is that you pose a challenging question for students to answer, but instead of having them answer individually you instead have them get together in small groups to*

- **Solve practical problems** – *This is where you pose realistic problems for students to solve together or individually. Compare solutions and debate the merits of each.*

- **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 a given design.*

- **Analyze a computer simulation of some circuit or system** – *Use simulation software to model the behavior of some relevant system, and then analyze the results together by applying the principles you’ve been studying.*

- **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 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.

• 2020-2022 – 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 quite 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!
2.7 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!

- **Confusing voltage and current** – 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 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!

- **Calculations in context** – 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.

- **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 an 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!

- **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.

• **Considering 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 faults that could explain multiple 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.

• **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.
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.
3.1. EXPERIMENTS

Plan and conduct an experiment to demonstrate . . . \((\text{insert principle here})\)

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 . . . \((\text{insert skill here})\)
  - Explain . . . \((\text{insert concept here})\)
  - 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.

- **Visual location of 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.

- **Trying one change 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 possess. 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 manuals. It is not the ability to follow one rigid sequence of steps ostensibly applicable to any equipment or system problem. 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

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1 One 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.

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

3 The 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 true.

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.

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4 Other 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: |
| Schematic |

```
| V_supply | R_1 | R_2 | R_3 |
```

| Given conditions |

```
V_supply = R_1 = R_2 = R_3 =
```

| Parameters |

```
| L_supply | Predicted | Measured | I_R1 | Predicted | Measured |
| V_R1 | | | | I_R2 | | |
| V_R2 | | | | I_R3 | | |
```

| Analysis |

```
Relationship between resistor voltage drops and total voltage:
```

| Fault analysis |

```
Suppose component fails open shorted other
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:

![Circuit Diagram](diagram.png)

<table>
<thead>
<tr>
<th>Fault</th>
<th>Possible</th>
<th>Impossible</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$ failed open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_2$ failed open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_3$ failed open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_1$ failed shorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_2$ failed shorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_3$ failed shorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage source dead</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Fault</th>
<th>Possible</th>
<th>Impossible</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$ failed open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_2$ failed open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_3$ failed open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_4$ failed open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_1$ failed shorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_2$ failed shorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_3$ failed shorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_4$ failed shorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage source dead</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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. DEDUCTIVE DIAGNOSTIC EXERCISES

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.”

<table>
<thead>
<tr>
<th>Diagnostic test</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure $V_{AC}$ with power applied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $V_{JK}$ with power applied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $V_{CK}$ with power applied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $I_{R1}$ with power applied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $I_{R2}$ with power applied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $I_{R3}$ with power applied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $R_{AC}$ with source disconnected from $R_1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $R_{DF}$ with source disconnected from $R_1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $R_{EG}$ with source disconnected from $R_1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $R_{HK}$ with source disconnected from $R_1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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. INDUCTIVE DIAGNOSTIC EXERCISES

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:

![Schematic Diagram]

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.
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 themself to achieve the extraordinary. Most often, the expectations are external: someone else demands extraordinary performance. 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 “fooled” 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.
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 of information 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 an order 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 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 tasks 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 method 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 goal of the team is to complete the task, not to ensure education of its members. 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 all but 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 basis. I will not attempt to deconstruct the various theories of

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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 than 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. I have never read nor heard anyone suggest alter someone’s learning style. How do we know this to be true?

   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 isn’t real.

   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 would failed to accomplish what their learning style ostensibly prohibited. At the risk of sounding cynical, I am convinced learning styles are far too often used as excuses for avoiding challenges.
6.8 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 most often made up of a series of discrete courses, each one encapsulating a particular topic, often taught by different instructors with widely varying standards of achievement. This design is not born out of a concern for maximizing learning, but rather is the result of optimizing school 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 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 difficulty of maintaining consistently high standards 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 are easier than 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.
6.9 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 backed up by actionable knowledge and skill.
Chapter 7

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.
7.1 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. Abound studia in mores

Nay, there is no stond 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. 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.

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1Studies pass into and influence manners.
2Splitters of hairs.
Chapter 8

References

Bacon, Francis, *On Studies*, 1625.
CHAPTER 8. REFERENCES
Chapter 9

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.

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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