**Modular Electronics Learning (ModEL) Project**

Encoders and Decoders

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Chapter 1

Introduction

Encoder and decoder circuits translate between binary digital words and 1-of-n discrete digital states. For example, an 8-line to 3-line encoder circuit has eight input lines, one of which must be activated to generate a corresponding three-bit output word. A decoder does just the opposite: activate one of its n output lines in response to the binary word it receives at its input (e.g., a 3-line to 8-line decoder receives a three-bit binary word and activates the one output line out of eight corresponding to the binary word’s value).

Important concepts related to encoders and decoders include binary numeration, BCD numeration, powers of two, seven-segment displays, display driver circuitry, diode behavior, cathode versus anode terminals, and liquid crystal displays.

Here are some good questions to ask of yourself while studying this subject:

- Why is binary the preferred numeration system for digital electronic circuits?
- How does the concept of a place-weight apply to multiple numeration systems?
- How do the functions of encoders and decoders differ from each other?
- What distinguishes a priority encoder from a regular encoder?
- Which form of digital number representation is more efficient in terms of wiring, binary or one-of-n?
- How does BCD numeration differ from binary?
- What does it mean for a numerical code to be undefined?
- How are seven-segment displays used to represent decimal digits?
- Why are resistors necessary in conjunction with an LED seven-segment display?
- How do liquid-crystal displays operate?
- What is the “blanking” feature used for in a seven-segment decoder IC?
• What is the purpose of the “driver” circuitry within a seven-segment decoder IC?

Difficult concepts for students include the following:

• Confusing encoders, decoders, multiplexers, and demultiplexers. Students often mix up the identities of encoders, decoders, multiplexers, and demultiplexers. It is important for them to realize that while multiplexers and demultiplexers contain decoders, they are not the same as decoders (or encoders). In essence, muxes and demuxes “steer” signals to/from different locations, while encoders and decoders convert data from one format to another.
Chapter 2

Case Tutorial

The idea behind a Case Tutorial is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain why the circuits behave as they do?
2.1 Example: demonstration circuit using the CD4511

The model CD4511 is a CMOS integrated circuit providing a BCD-to-7-segment decoding function, along with several useful features. In this next diagram we see a simple proof-of-concept circuit showing how to make the CD4511 drive the seven LED segments of a display to show decimal digits:

![Diagram of CD4511 demonstration circuit]

Toggling the four switches between their different states causes the 7-segment display to show the following patterns:

<table>
<thead>
<tr>
<th>D C B A</th>
<th>Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0</td>
<td>0</td>
</tr>
<tr>
<td>0 0 0 1</td>
<td>1</td>
</tr>
<tr>
<td>0 0 1 0</td>
<td>2</td>
</tr>
<tr>
<td>0 0 1 1</td>
<td>3</td>
</tr>
<tr>
<td>0 1 0 0</td>
<td>4</td>
</tr>
<tr>
<td>0 1 0 1</td>
<td>5</td>
</tr>
<tr>
<td>0 1 1 0</td>
<td>6</td>
</tr>
<tr>
<td>0 1 1 1</td>
<td>7</td>
</tr>
<tr>
<td>1 0 0 0</td>
<td>8</td>
</tr>
<tr>
<td>1 0 0 1</td>
<td>9</td>
</tr>
</tbody>
</table>

Note the use of resistors in this demonstration circuit: four “pulldown” resistors necessary for providing an unambiguous “low” logic state when the respective toggle switch is open, and seven “current-limiting” resistors acting to limit each LED’s current to a safe maximum value when the respective output line goes “high”.
2.1. EXAMPLE: DEMONSTRATION CIRCUIT USING THE CD4511

The Ripple Blanking Input (RBI) pin acts to blank the 7-segment display whenever it is placed in its active state. Being an active-low input, we must make the RBI input “high” in order to allow the display to show us anything at all.

The Lamp Test (LT) input is another active-low input terminal, designed to energize all seven of the LED segments regardless of the ABCD input states. We tie this “high” as well in order to allow the display to function normally.

The Latch Enable (LE) input (also known as the Strobe input) causes the decoder to latch, holding its last ABCD input states when this terminal goes to the “high” state. In order to allow the decoder to read new input states on its ABCD terminals, we must leave this input tied “low”.

The Ripple Blanking Output (RBO) terminal is unused in this demonstrate circuit.
Chapter 3

Tutorial
3.1 Binary and BCD numeration

Modern digital electronic circuits represent numerical values by means of discrete (i.e. high or low) voltage states by treating those individual states as characters in a multi-digit pattern. Instead of calling the individual characters *digits* as we do for our common decimal numeration system, we call them *bits* and use the ciphers 1 and 0 to represent those high and low voltage states in a *binary* number. Each of these characters occupies a “place” in the number, each successive place-weight differing from the preceding by a factor of two.

A four-bit binary counting pattern from zero to fifteen represents sixteen different combinations ($2^4 = 16$), and is shown here in conjunction with their decimal and hexadecimal equivalent values:

<table>
<thead>
<tr>
<th>Binary</th>
<th>Decimal</th>
<th>Hex</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0 0 0 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0 0 1 0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0 0 1 1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0 1 0 0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>0 1 0 1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>0 1 1 0</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>0 1 1 1</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>1 0 0 0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>1 0 0 1</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>1 0 1 0</td>
<td>10</td>
<td>A</td>
</tr>
<tr>
<td>1 0 1 1</td>
<td>11</td>
<td>B</td>
</tr>
<tr>
<td>1 1 0 0</td>
<td>12</td>
<td>C</td>
</tr>
<tr>
<td>1 1 0 1</td>
<td>13</td>
<td>D</td>
</tr>
<tr>
<td>1 1 1 0</td>
<td>14</td>
<td>E</td>
</tr>
<tr>
<td>1 1 1 1</td>
<td>15</td>
<td>F</td>
</tr>
</tbody>
</table>
For applications where we only need to represent a single decimal character, we may use an abbreviated counting scheme called Binary-Coded Decimal (BCD) where four bits represent the decimal digits 0 through 9:

<table>
<thead>
<tr>
<th>BCD</th>
<th>Decimal</th>
<th>Hex</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0 0 0 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0 0 1 0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0 0 1 1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0 1 0 0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>0 1 0 1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>0 1 1 0</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>0 1 1 1</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>1 0 0 0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>1 0 0 1</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

In a BCD system the bit combinations 1010, 1011, 1100, 1101, 1110, and 1111 are undefined.

### 3.2 One-of-$n$ numeration

There are applications, though, where it is either useful or necessary to digitally represent a numerical value without using a binary code. For example, we could have a sixteen-position selector switch with one common terminal and sixteen individual terminals, representing the values of zero through fifteen simply by which of the sixteen lines is “high”:

![Binary representation](image1)

![One-of-sixteen representation](image2)

Both of these electrical switching networks are digital, in that they represent numerical values in discrete steps. However, their respective design philosophies are quite different: binary is very efficient in terms of switch contacts and wiring but requires an understanding of binary coding to interpret; one-of-$n$ is very inefficient but is practically self-evident in its presentation of the number.
3.3 Encoding and decoding

A digital logic circuit designed to receive a one-of-\( n \) digital signal and translate it into a binary code is called an *encoder*. A digital circuit receiving a binary code and outputting a one-of-\( n \) (or any other non-binary representation of that same number) is called a *decoder*. Examples of each are shown in the following (simplified) schematic diagrams:

![Encoder Diagram](image1)

![Decoder Diagram](image2)

Some encoders and decoders operate on the full binary range available with four bits, having 4 input lines and 16 output lines (decoder), or 16 input lines and 4 output lines (encoder). Others operate on a BCD range, having 4 input lines and only 10 output lines (BCD decoder), or only 10 input lines and 4 output lines (BCD encoder).

Encoders and decoders alike are available as integrated circuits (ICs), and only for very unusual applications would be constructed from separate logic gates.

Even though the basic encoder concept relies on a single input being activated to the exclusion of all others (literally, one-of-\( n \)), some encoder designs anticipate the possibility of multiple inputs being activated whether intentionally or by accident. Such encoders are called *priority encoders*, and they translate the highest-order active input into a binary output. For example, if the “eight” and “nine” inputs were simultaneously activated on a priority encoder, only the number 1001 (nine) would appear at its output terminals. If multiple inputs activate on a non-priority encoder, the resulting binary will likely be nonsensical, representing *none* of the activated input terminals.
3.4 7-segment display decoders

Decoders also exist in more than one type. The most fundamental decoder receives a binary or BCD input word and activates one-of-n output lines. However, other forms of decoders exist to convert binary word inputs into specialized bit states necessary to drive decimal indicators such as 7-segment LCD (Liquid Crystal Display) and LED (Light Emitting Diode) displays. A typical array of red LED 7-segment displays appears on the face of this digital clock, each digit powered by the output lines of a 7-segment decoder:

![Digital Clock with 7-Segment Displays](image)

Each decimal digit represented by one 7-segment display is equivalent to a four-bit BCD value.

A typical schematic diagram showing how such a decoder/driver IC would connect to a 7-segment display appears next:

![Schematic Diagram](image)

7-segment LED displays typically have seven lines (one for each segment), with either all the LED anodes or all the LED cathodes connected to an additional “common” line. Additional inputs such as LT (Lamp Test), LE (Latch Enable), and RBI (Ripple Blanking Input)\(^1\) provide practical functions for disabling and testing the display regardless of the binary input. In this case, the IC also has an output line called RBO to extend the “blanking” function on to successive decimal digits.

Aside from the special logic features of a 7-segment decoder, these integrated circuits often contain special driver circuitry on the output lines matching the needs of the 7-segment display. For example, LED displays require more current per LED than what a typical logic gate might output in order to achieve full brightness, and so a decoder/driver IC contains additional transistor stages on the output lines to handle the extra current demand. Similarly, liquid-crystal displays (LCDs) actually require AC voltage rather than DC to darken each segment, and so decoder/driver ICs designed for LCD applications provide a phase input line (PH) to receive the square-wave signal from a low-frequency oscillator.

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\(^1\) Blanking refers to an optional feature to make leading zero digits blank in a multi-digit display.
Chapter 4

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read\(^1\) the tutorials and attempt to answer questions on their own prior to the instructor’s interaction with them. In place of lecture\(^2\), the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is independence, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of experimentation and computer simulation (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of metacognition within these statements: they are designed to foster a regular habit of examining one’s own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

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\(^1\)Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students’ reading prowess through intentional effort and strategy is the book Reading for Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

\(^2\)Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.
CHAPTER 4. QUESTIONS

General challenges following tutorial reading

- **Summarize** as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.

- **Simplify** a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.

- Where did the text **make the most sense** to you? What was it about the text’s presentation that made it clear?

- Identify where it might be easy for someone to **misunderstand the text**, and explain why you think it could be confusing.

- Identify any **new concept(s)** presented in the text, and explain in your own words.

- Identify any **familiar concept(s)** such as physical laws or principles applied or referenced in the text.

- Devise a **proof of concept** experiment demonstrating an important principle, physical law, or technical innovation represented in the text.

- Devise an experiment to **disprove** a plausible misconception.

- Did the text reveal any **misconceptions** you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.

- Describe any useful **problem-solving strategies** applied in the text.

- **Devise a question** of your own to challenge a reader’s comprehension of the text.
General follow-up challenges for assigned problems

• Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.

• Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.

• Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?

• Is there more than one way to solve this problem? Which method seems best to you?

• Show the work you did in solving this problem, even if the solution is incomplete or incorrect.

• What would you say was the most challenging part of this problem, and why was it so?

• Was any important information missing from the problem which you had to research or recall?

• Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?

• Examine someone else’s solution to identify where they applied fundamental laws or principles.

• Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).

• For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.

• For quantitative problems, try approaching it qualitatively instead, thinking in terms of “increase” and “decrease” rather than definite values.

• For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.

• Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?

• Identify where it would be easy for someone to go astray in attempting to solve this problem.

• Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

• In what way(s) was this experiment or project easy to complete?

• Identify some of the challenges you faced in completing this experiment or project.
• Show how **thorough documentation** assisted in the completion of this experiment or project.

• Which **fundamental laws or principles** are key to this system’s function?

• Identify any way(s) in which one might obtain **false or otherwise misleading measurements** from test equipment in this system.

• What will happen if *(component X)* fails *(open/shorted/etc.)*?

• What would have to occur to make this system **unsafe**?
4.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor’s task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student’s needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your reasoning than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that you are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

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3Analytical thinking involves the “disassembly” of an idea into its constituent parts, analogous to dissection. Synthetic thinking involves the “assembly” of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.
4.1.1 Reading outline and reflections

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

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

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

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

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

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

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

✔ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.
4.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module’s full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

- Binary number
- Encoding
- Decoding
- Lamp test
- Enable
- Strobing
- Blanking
- Light-emitting diode
- Liquid crystal display
4.1.3 OR-based encoder circuit

Explain how the following decimal-to-BCD encoder circuit works:

Also, determine which output (D or A) is the most significant bit of the BCD output.

Challenges

- What would have to be modified in order to turn this into a hexadecimal-to-binary (16 line to 4 line) encoder? Would any additional OR gates have to be added to the circuit?

4.1.4 74HC147 encoder

Identify the necessary input states to make a 74HC147 decimal-to-BCD encoder generate the binary code for the number *seven*, and how that quantity would be represented on the output (Y) lines.

Challenges

- Identify the acceptable power supply voltage range for this IC.
4.1.5 Pendant control

Suppose a crane has fifteen hydraulic solenoid valves controlling its motion:

- Tilt up (fast)
- Tilt down (fast)
- Tilt up (slow)
- Tilt down (slow)
- Turn left (fast)
- Turn right (fast)
- Turn left (slow)
- Turn right (slow)
- Cable up (fast)
- Cable down (fast)
- Cable up (slow)
- Cable down (slow)
- Bucket open (fast)
- Bucket open (slow)
- Bucket close (slow)

You are part of a team building a remote “pendant” control for this crane with fifteen buttons on it for controlling each of the fifteen solenoid valves. This control pendant connects to the main system by a multi-conductor cable, but you really want to limit the number of conductors in this cable to keep it as light-weight as possible:
Draw a simple schematic diagram showing how a digital encoder and decoder circuit pair could be used to relay the same fifteen commands across fewer cable conductors, compared to if we used one conductor per pushbutton switch.

**Challenges**

- Identify a disadvantage of this crane control strategy, compared to using a thicker cable where each pushbutton has its own dedicated conductor?
- Describe some of the safety hazards intrinsic to this project, and specifically identify at least one circuit fault that could result in a destructive outcome.
4.1.6 74HC154 decoder
The type 74HC154 integrated circuit is a standard TTL decoder, 4-line to 16-line. Its block symbol looks like this:

What do the “wedge” symbols next to the output lines represent? Also, what purpose do the $G_1$ and $G_2$ inputs serve, and why is there an ampersand character ($\&$) next to them?

Challenges

- Explain how you could combine two of these ICs to create a 5-line to 32-line decoding circuit.
4.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as “test cases” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely on an answer key!

---

4 In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial’s answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

5 This approach is perfectly in keeping with the instructional philosophy of these learning modules: teaching students to be self-sufficient thinkers. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be “answer keys” available for the problems you will have to solve.
4.2. QUANTITATIVE REASONING

4.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, Avogadro’s number given as $6.02214179(30) \times 10^{23}$ means the center value ($6.02214179 \times 10^{23}$) plus or minus 0.00000030 × $10^{23}$.

Avogadro’s number ($N_A$) = $6.02214179(30) \times 10^{23}$ per mole (mol⁻¹)

Boltzmann’s constant ($k$) = $1.3806504(24) \times 10^{-23}$ Joules per Kelvin (J/K)

Electronic charge ($e$) = $1.602176487(40) \times 10^{-19}$ Coulomb (C)

Faraday constant ($F$) = $9.64853399(24) \times 10^{4}$ Coulombs per mole (C/mol)

Magnetic permeability of free space ($\mu_0$) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space ($\varepsilon_0$) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space ($Z_0$) = $376.730313668(57)$ Ohms (Ω)

Gravitational constant ($G$) = $6.67428(67) \times 10^{-11}$ cubic meters per kilogram-seconds squared (m³/kg-s²)

Molar gas constant ($R$) = $8.314472(15)$ Joules per mole-Kelvin (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant ($h$) = $6.62606896(33) \times 10^{-34}$ joule-seconds (J·s)

Stefan-Boltzmann constant ($\sigma$) = $5.670400(40) \times 10^{-8}$ Watts per square meter-Kelvin⁴ (W/m²·K⁴)

Speed of light in a vacuum ($c$) = **299792458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data “Fundamental Physical Constants – Extensive Listing”, from [http://physics.nist.gov/constants](http://physics.nist.gov/constants), National Institute of Standards and Technology (NIST), 2006; with the exception of the permeability of free space which was taken from NIST’s **2018 CODATA recommended values** database.
4.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), spreadsheet software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell B3, cell A8). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Distance traveled</td>
<td>46.9</td>
<td>Kilometers</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Time elapsed</td>
<td>1.18</td>
<td>Hours</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Average speed</td>
<td>= B1 / B2</td>
<td>km/h</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Text labels contained in cells A1 through A3 and cells C1 through C3 exist solely for readability and are not involved in any calculations. Cell B1 contains a sample distance value while cell B2 contains a sample time value. The formula for computing speed is contained in cell B3. Note how this formula begins with an “equals” symbol (=), references the values for distance and speed by lettered column and numbered row coordinates (B1 and B2), and uses a forward slash symbol for division (/). The coordinates B1 and B2 function as *variables*\(^6\) would in an algebraic formula.

When this spreadsheet is executed, the numerical value 39.74576 will appear in cell B3 rather than the formula = B1 / B2, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell B1 or a different value for time is entered into cell B2, cell B3’s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell B3 may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in B1 and B2. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

\(^6\)Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels “names”), but for simple spreadsheets such as those shown here it’s usually easier just to use the standard coordinate naming for each cell.
4.2. QUANTITATIVE REASONING

Common arithmetic operations available for your use in a spreadsheet include the following:

- Addition (+)
- Subtraction (-)
- Multiplication (*)
- Division (/)
- Powers (^)
- Square roots (sqrt())
- Logarithms (ln(), log10())

Parentheses may be used to ensure proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the quadratic formula, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$x_{1}$ = (-B4 + sqrt((B4^2) - (4<em>B3</em>B5))) / (2*B3)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$x_{2}$ = (-B4 - sqrt((B4^2) - (4<em>B3</em>B5))) / (2*B3)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>a =</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>b =</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>c =</td>
<td>-2</td>
</tr>
</tbody>
</table>

This example is configured to compute roots of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells B3, B4, and B5, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of any second-degree polynomial expression simply by entering the new $a$, $b$, and $c$ coefficients into cells B3 through B5. The numerical values appearing in cells B1 and B2 will be automatically updated by the computer immediately following any changes made to the coefficients.

---

Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

Reviewing some algebra here, a root is a value for $x$ that yields an overall value of zero for the polynomial. For this polynomial $(9x^2 + 5x - 2)$ the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells B1 and B2, respectively upon execution of the spreadsheet.
Alternatively, one could break up the long quadratic formula into smaller pieces like this:

\[
y = \sqrt{b^2 - 4ac} \quad z = 2a
\]

\[
x = \frac{-b \pm y}{z}
\]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x_1 \equal{} \frac{(-B4 + C1)}{C2}</td>
<td>sqrt((B4^2) - (4<em>B3</em>B5))</td>
</tr>
<tr>
<td>2</td>
<td>x_2 \equal{} \frac{(-B4 - C1)}{C2}</td>
<td>2*B3</td>
</tr>
<tr>
<td>3</td>
<td>a = 9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>b = 5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>c = -2</td>
<td></td>
</tr>
</tbody>
</table>

Note how the square-root term \((y)\) is calculated in cell \(C1\), and the denominator term \((z)\) in cell \(C2\). This makes the two final formulae (in cells \(B1\) and \(B2\)) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary\(^\text{10}\) – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

\(^{10}\)My personal preference is to locate all the “given” data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out how I constructed a solution. This is a general principle I believe all computer programmers should follow: document and arrange your code to make it easy for other people to learn from it.
4.2. QUANTITATIVE REASONING

4.2.3 SOP expressions for decoder circuit

The truth table shown here is for a 4-line to 16-line *binary* decoder circuit:

<table>
<thead>
<tr>
<th>D</th>
<th>C</th>
<th>B</th>
<th>A</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
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<tbody>
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<td>1</td>
</tr>
</tbody>
</table>

For each of the sixteen output lines, there is a Boolean SOP expression describing its function. Just for example, write the Boolean expressions for output lines 2, 5, 8, 11, 13, and 14.

**Challenges**

- Based on what you see here, what kind of logic gate circuitry is a decoder such as this comprised of?
4.2.4  5-line to 32-line decoder

Each of these 74HC154 decoder ICs is 4-line to 16-line:

Show how they could be connected together to form a 5-line to 32-line decoder circuit.

**Challenges**

- Identify how to connect four 74HC154 decoders together to form a 6-line to 64-line decoder circuit.
4.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what’s wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

As always, your goal is to fully explain your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor’s responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.
4.3.1 Customer complaint

Having learned how to build simple encoder circuits using diode networks, you set out to form your own encoder manufacturing company: Encoders, Inc. After agreeing on a policy of truth in advertising, your board of directors drafts this slogan:

“Our encoder circuits are better because there’s less to break”

After months of hard work, you unveil your latest masterpiece, the 16-line to 4-line encoder:

![Diagram of the 16-line to 4-line encoder]

However, your first customer has a complaint with your encoder circuit. He claims it often outputs false codes. After sending it back to your workshop for warranty repair, you determine there is nothing wrong with the encoder circuit itself: it always outputs the correct codes when you energize the appropriate inputs. Perhaps the problem is in how the customer is using it.

You then telephone the customer and ask him how he is using the encoder. He tells you it is used as part of a fault diagnostic circuit for an important piece of machinery. Each input of the encoder is connected to a different sensor on the machine (low oil pressure switch, high temperature switch, out-of-limit travel switches, etc.), and then the encoder outputs drive a four-LED display for maintenance technicians to view. They would have rather used a separate LED for each “trouble”
sensor, but the display panel was too small to accommodate fifteen LEDs, so they decided to use four LEDs and an encoder, having their technicians interpret a binary code to determine which of the fifteen sensors is activating.

To the best of your ability, determine why your company’s flagship encoder circuit sometimes produces false codes in this application. Then, recommend a solution for your customer.

**Challenges**

- Is this encoder design compatible with TTL logic, CMOS logic, or both?
4.3.2 Faulted encoder circuit

Identify which diode is failed in this circuit, given the following truth table (showing the actual operation of the encoder circuit, not what it should do):

<table>
<thead>
<tr>
<th>Switch position</th>
<th>Output code</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>000</td>
</tr>
<tr>
<td>1</td>
<td>001</td>
</tr>
<tr>
<td>2</td>
<td>010</td>
</tr>
<tr>
<td>3</td>
<td>011</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>001</td>
</tr>
<tr>
<td>6</td>
<td>110</td>
</tr>
<tr>
<td>7</td>
<td>111</td>
</tr>
</tbody>
</table>

Be sure to specify whether you think the failed diode is open or shorted.

Challenges

• Suppose that same diode was failed in the opposite mode. How would that fault manifest in the encoder’s operation?
4.3.3 Another faulted encoder circuit

Identify which diode is failed in this circuit, given the following truth table (showing the actual operation of the encoder circuit, not what it should do):

Be sure to specify whether you think the failed diode is open or shorted.

**Challenges**

- Suppose that same diode was failed in the opposite mode. How would that fault manifest in the encoder’s operation?
• Explain how we can tell the diode connecting position 7 to line 2 is not failed.

4.3.4 Failed OR gate in encoder

Suppose OR gate $U_3$ were to fail with the output terminal always high. Which output codes would be affected by this fault?

[Diagram of an encoder with OR gates $U_1$, $U_2$, $U_3$, and $U_4$.]

Challenges

• If you didn’t know which gate was faulted, but only had access to the list of codes generated for each input activation, how would you diagnose the fault?
Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- **Study principles, not procedures.** Don’t be satisfied with merely knowing how to compute solutions – learn why those solutions work.

- **Identify** what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any “missing pieces” to a solution. **Annotate** all diagrams with this data.

- **Sketch a diagram** to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function before constructing it.

- **Follow the units of measurement and meaning of every calculation.** If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don’t understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.

- **Perform “thought experiments”** to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform **diagnostic tests** rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.

- **Simplify the problem** until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.

- **Check for exceptions** to see if your solution is incorrect or incomplete. A good solution will work for all known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to challenge that new idea to see if it holds up under a battery of tests. The philosophical
principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- **Work “backward”** from a hypothetical solution to a new set of given conditions.

- **Add quantities** to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.

- **Sketch graphs** illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).

- **Treat quantitative problems as qualitative** in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?

- **Consider limiting cases.** This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system’s response.

- **Check your work.** This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.
Appendix B

Instructional philosophy

“The unexamined circuit is not worth energizing” – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is always more important than particulars of any subject matter, because its application is universal.

- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.

- Articulate communication is fundamental to work that is complex and interdisciplinary.

- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student’s minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.

- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.
These learning modules were expressly designed to be used in an “inverted” teaching environment where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student’s understanding to ensure they are truly reasoning and not just memorizing. This is why “Challenge” points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn’t been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students’ reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

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1In a traditional teaching environment, students first encounter new information via lecture from an expert, and then independently apply that information via homework. In an “inverted” course of study, students first encounter new information via homework, and then independently apply that information under the scrutiny of an expert. The expert’s role in lecture is to simply explain, but the expert’s role in an inverted session is to challenge, critique, and if necessary explain where gaps in understanding still exist.

2Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato’s many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on any topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

3This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).
from “first principles”. Again, this reflects the goal of developing clear and independent thought in students’ minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another characteristic of these learning modules is a lack of step-by-step instructions in the Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where step-by-step instructions are prescribed for each experiment, these modules take the approach that students must learn to closely read the tutorials and apply their own reasoning to identify the appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as a set of enumerated points. At other times certain steps are implied, an example being assumed competence in test equipment use where the student should not need to be told again how to use their multimeter because that was thoroughly explained in previous lessons. In some circumstances no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are foundational principles of this learning series, and in keeping with this philosophy all activities are designed to require those behaviors. Some students may find the lack of prescription frustrating, because it demands more from them than what their previous educational experiences required. This frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which must be corrected if the student is ever to become a self-directed learner and effective problem-solver. Ultimately, the need for students to read closely and think clearly is more important both in the near-term and far-term than any specific facet of the subject matter at hand. If a student takes longer than expected to complete a module because they are forced to outline, digest, and reason on their own, so be it. The future gains enjoyed by developing this mental discipline will be well worth the additional effort and delay.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the “compartmentalization” of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

This methodology of assigning text-based modules to students for digestion and then using Socratic dialogue to assess progress and hone students’ thinking was developed over a period of several years by the author with his Electronics and Instrumentation students at the two-year college level. While decidedly unconventional and sometimes even unsettling for students accustomed to a more passive lecture environment, this instructional philosophy has proven its ability to convey conceptual mastery, foster careful analysis, and enhance employability so much better than lecture that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this “inverted” format where students must articulate and logically defend their reasoning. This, too, may be unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the “inverted” session instructor in order that students never feel discouraged by having their errors exposed. Everyone makes mistakes from time to time, and learning is a lifelong process! Part of the instructor’s job is to build a culture of learning among the students where errors are not seen as shameful, but rather as opportunities for progress.
To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, *the fundamental goal of education is for each student to learn to think clearly and independently*. This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student’s responsibility to do that hard work ultimately limits that student’s potential and thereby does real harm.

- It is not only permissible, but encouraged, to answer a student’s question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.

- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one’s own reasoning.

- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an “Outline and reflections” question as well as a “Foundational concepts” question in the Conceptual reasoning section, to prompt reflective reading.

- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to *variations* of that question. This is why module questions typically contain multiple “Challenges” suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own “Challenges” as they are able, in order to have a multitude of ways ready to probe students’ understanding.

- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done “live” before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.
Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea in your own words, using your own examples.

- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.

- Never take the easy path of highlighting or underlining important text. Instead, summarize and/or comment on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.

- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least imagine yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.

- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of circuit simulation software, checking to see if your simulated results agree with the results shown in the text.

- Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge one another.

To high standards of education,

Tony R. Kuphaldt

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4 As the old saying goes, “Insanity is trying the same thing over and over again, expecting different results.” If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

5 Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one’s life through the improvement of clear and independent thought, literacy, expression, and various practical skills.
Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward code. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature extensible, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The GNU/Linux computer operating system

There is so much to be said about Linus Torvalds’ Linux and Richard Stallman’s GNU project. First, to credit just these two individuals is to fail to do justice to the mob of passionate volunteers who contributed to make this amazing software a reality. I first learned of Linux back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is free, it is completely configurable, and it permits the continued use of highly efficient Unix applications and scripting languages (e.g. shell scripts, Makefiles, sed, awk) developed over many decades. Linux not only provided me with a powerful computing platform, but its open design served to inspire my life’s work of creating open-source educational resources.

Bram Moolenaar’s Vim text editor

Writing code for any code-based computer application requires a text editor, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one’s choice of text editor seems to be a deeply personal matter within the programming world. I prefer Vim because it operates very similarly to vi which is ubiquitous on Unix/Linux operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.
Donald Knuth’s $\LaTeX$ typesetting system

Developed in the late 1970’s and early 1980’s by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. $\LaTeX$ is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, $\LaTeX$ is *a programmer’s approach to word processing*. Since $\LaTeX$ is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of $\LaTeX$ makes it relatively easy to learn how other people have created their own $\LaTeX$ documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft *Word* suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is All You Get).

Leslie Lamport’s $\textit{L} \LaTeX$ extensions to $\LaTeX$

Like all true programming languages, $\LaTeX$ is inherently extensible. So, years after the release of $\LaTeX$ to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was $\textit{L} \LaTeX$, which is the markup language used to create all ModEL module documents. You could say that $\LaTeX$ is to $\textit{L} \LaTeX$ as C is to C++. This means it is permissible to use any and all $\LaTeX$ commands within $\textit{L} \LaTeX$ source code, and it all still works. Some of the features offered by $\textit{L} \LaTeX$ that would be challenging to implement in $\LaTeX$ include automatic index and table-of-content creation.

Tim Edwards’ Xcircuit drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for Xcircuit, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.
**Gimp** graphic image manipulation program

Essentially an open-source clone of Adobe’s PhotoShop, I use **Gimp** to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although **Gimp** does offer its own scripting language (called **Script-Fu**), I have never had occasion to use it. Thus, my utilization of **Gimp** to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

**SPICE** circuit simulation program

**SPICE** is to circuit analysis as TeX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text “source file” is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer **SPICE** for the following reasons: it is free, it is fast, it is reliable, and it is a fantastic tool for teaching students of electricity and electronics how to write simple code. I happen to use rather old versions of **SPICE**, version 2g6 being my “go to” application when I only require text-based output. **NGSPICE** (version 26), which is based on Berkeley **SPICE** version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all **SPICE** example netlists I strive to use coding conventions compatible with all **SPICE** versions.

Andrew D. Hwang’s **ePiX** mathematical visualization programming library

This amazing project is a C++ library you may link to any C/C++ code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as **Mathematica** or **Maple** to do. It should be said that **ePiX** is not a Computer Algebra System like **Mathematica** or **Maple**, but merely a mathematical visualization tool. In other words, it won’t determine integrals for you (you’ll have to implement that in your own C/C++ code!), but it can graph the results, and it does so beautifully. What I really admire about **ePiX** is that it is a C++ programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a C++ library to do the same thing he accomplished something much greater.
**gnuplot** mathematical visualization software

Another open-source tool for mathematical visualization is **gnuplot**. Interestingly, this tool is *not* part of Richard Stallman’s GNU project, its name being a coincidence. For this reason the authors prefer “gnu” *not* be capitalized at all to avoid confusion. This is a much “lighter-weight” alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my **gnuplot** output format to default (X11 on my Linux PC) for quick viewing while I’m developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I’m writing. As with my use of **Gimp** to do rudimentary image editing, my use of **gnuplot** only scratches the surface of its capabilities, but the important points are that it’s *free* and that it *works well*.

**Python** programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I’m listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.
Appendix D

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Appendix E

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.

26 April 2022 – updated the Introduction chapter to be consistent in format with other modules, including a foundational concepts list and a list of recommended questions. Also added some instructor comments and corrected a minor typographical error.

18 February 2022 – corrected a typo where “LE” was defined as “Lamp Enable” when it should have been “Latch Enable”.

1 December 2021 – deleted redundant word “necessary” in the 74HC147 encoder Conceptual Reasoning question.

27 July 2021 – divided Tutorial into sections, and also added content to the Tutorial regarding BCD numeration as an alternative to binary. Also added a Case Tutorial chapter with a section showing how to use a CD4511 BCD-to-7-segment decoder/driver and common-cathode 7-segment LED display.

10 May 2021 – commented out or deleted empty chapters.


28 January 2020 – added Foundational Concepts to the list in the Conceptual Reasoning section.

20 November 2019 – continued writing Simplified Tutorial. The Full Tutorial is de-prioritized right now, because all I need for my immediate teaching purposes is a Simplified Tutorial.

19 November 2019 – document first created.
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