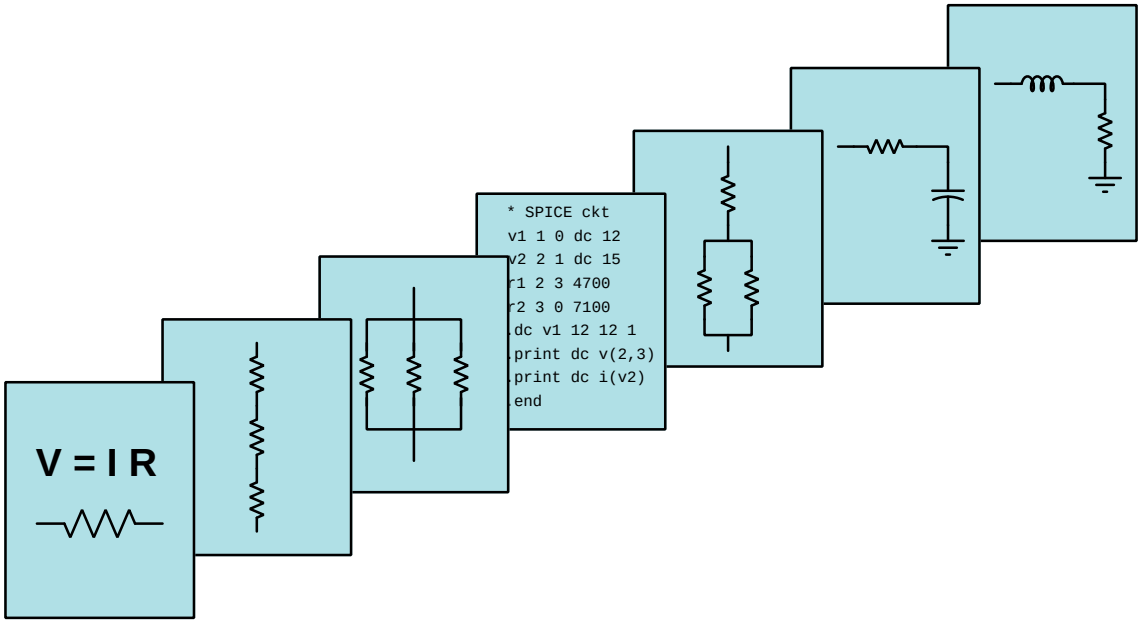
Modular Electronics Learning (ModEL) project



Multiplexers and Demultiplexers

© 2019-2026 by Tony R. Kuphaldt – under the terms and conditions of the Creative Commons Attribution 4.0 International Public License

Last update = 27 April 2026

This is a copyrighted work, but licensed under the Creative Commons Attribution 4.0 International Public License. A copy of this license is found in the last Appendix of this document. Alternatively, you may visit `http://creativecommons.org/licenses/by/4.0/` or send a letter to Creative Commons: 171 Second Street, Suite 300, San Francisco, California, 94105, USA. The terms and conditions of this license allow for free copying, distribution, and/or modification of all licensed works by the general public.

Contents

1 Introduction **3**
- 1.1 Recommendations for students . . . 3
- 1.2 Challenging concepts related to digital multiplexers and demultiplexers . . . 5
- 1.3 Recommendations for instructors . . . 6

2 Case Tutorial **7**
- 2.1 Example: arbitrary waveform generator using an analog multiplexer . . . 8

3 Tutorial **11**
- 3.1 Steering digital signals . . . 11
- 3.2 Data concentration . . . 13
- 3.3 Multiplexer and demultiplexer construction . . . 14
- 3.4 Multiplexing and demultiplexing words . . . 16
- 3.5 Common mux and demux symbols . . . 17
- 3.6 Arbitrary logic functions . . . 19
- 3.7 Microcontroller I/O expansion . . . 21

4 Questions **25**
- 4.1 Conceptual reasoning . . . 29
  - 4.1.1 Reading outline and reflections . . . 30
  - 4.1.2 Foundational concepts . . . 31
  - 4.1.3 Oscilloscope alternate and chop modes . . . 32
  - 4.1.4 Mux versus demux . . . 33
  - 4.1.5 Multiplexed accelerometers . . . 35
  - 4.1.6 Two-input selector logic . . . 37
  - 4.1.7 74HC151 mux . . . 38
  - 4.1.8 Address latching . . . 38
- 4.2 Quantitative reasoning . . . 39
  - 4.2.1 Miscellaneous physical constants . . . 40
  - 4.2.2 Introduction to spreadsheets . . . 41
  - 4.2.3 Arbitrary truth table . . . 44
  - 4.2.4 Arbitrary SOP expression . . . 45
  - 4.2.5 74HC154 decoder . . . 47
- 4.3 Diagnostic reasoning . . . 49

4.3.1 Faulted AWG circuit 50
4.3.2 Faulted concentrator circuit 51

A Problem-Solving Strategies **53**

B Instructional philosophy **55**
B.1 First principles of learning 56
B.2 Proven strategies for instructors 57
B.3 Proven strategies for students 59
B.4 Design of these learning modules 60

C Tools used **63**

D Creative Commons License **67**

E References **75**

F Version history **77**

Index **78**

Chapter 1

Introduction

1.1 Recommendations for students

Multiplexing in its broadest sense refers to the communication of multiple streams of data over a commonly-shared channel. Many different methods exist to do this, but in basic digital logic circuits the strategy is *time-division* multiplexing, where a common data channel conveys multiple data streams *one stream at a time*. A digital *multiplexer* ("mux") is a logic circuit "selecting" one-of-n inputs to be output to a single line. A digital *demultiplexer* ("demux") takes a single input and sends it to one-of-n output lines. Both muxes and demuxes are controlled by a binary input instructing which I/O is to be selected.

Important concepts related to multiplexing and demultiplexing include **binary numeration**, **analog** versus **digital** signals, **combinational logic**, **decoding**, **strobing**, **microcontrollers**, and **flip-flops**.

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

- How might an experiment be designed and conducted to test the proper operation of a multiplexer IC? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test the proper operation of a demultiplexer IC? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What is the fundamental difference between a multiplexer and a demultiplexer?
- How can multiplexing reduce the number of conductors necessary for communication?
- What is the function of an "enable" or "strobe" input to a digital logic circuit?
- Which function (mux or demux) is most similar to an decoder?
- How may multiplexing and demultiplexing be used to expand the effective number of I/O lines on another digital device?

- How may multiplexing be used to implement an arbitrary logic function?
- What are all the logical states of each gate within a multiplexer IC when selecting a particular channel (i.e. trace all the high and low states for given input conditions)?
- What is *set-up time* and *hold time*, and why are these parameters important in digital logic?

1.2 Challenging concepts related to digital multiplexers and demultiplexers

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **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.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Design an arbitrary logic function circuit

  Assessment – Sketch a schematic diagram of a circuit employing a digital multiplexer to implement a given truth table; e.g. pose problems in the form of the "Arbitrary truth table" Quantitative Reasoning question.

- **Outcome** – Identify logic states in digital circuits

  Assessment – Identify logic states for the outputs of a decoder IC given the input conditions; e.g. pose problems in the form of the "74HC154 decoder" Quantitative Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate IC multiplexer datasheets and properly interpret some of the information contained in those documents including truth tables, voltage levels, etc.

  Assessment – Locate IC demultiplexer datasheets and properly interpret some of the information contained in those documents including truth tables, voltage levels, etc.

Chapter 2

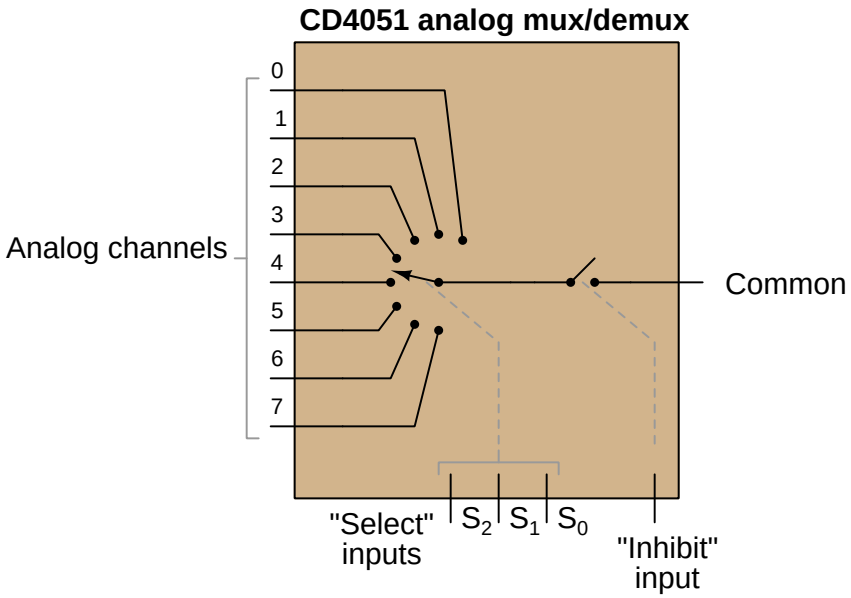
Case Tutorial

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: arbitrary waveform generator using an analog multiplexer

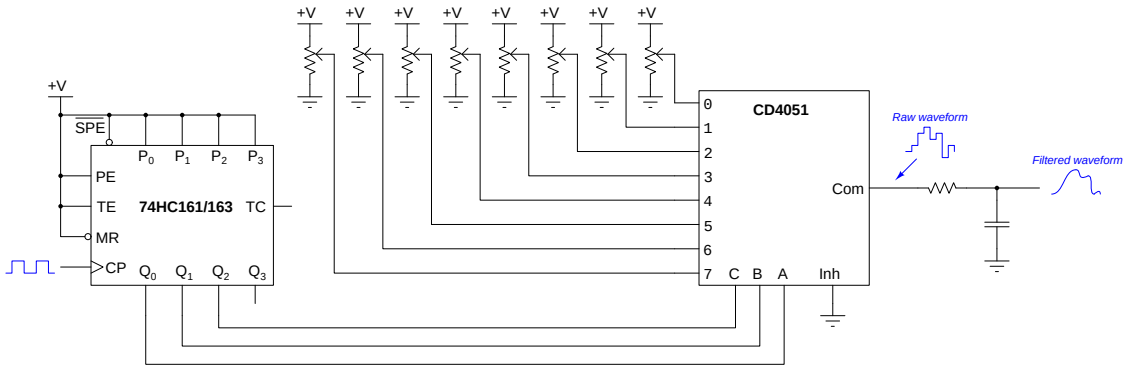
Multiplexer (mux) ICs are made for both digital (high/low) and analog (variable-voltage) signals. The model CD4051 and 74HC4051 integrated circuits are examples of analog multiplexers, which are also capable of functioning as demultiplexers since the inputs and output may both sink and source current. This particular analog mux/demux model also features an "inhibit" input which controls an internal MOSFET to either connect or disconnect the common terminal from the selected I/O pin. A functional diagram is shown below:



All digital inputs (the three select bits plus the inhibit) are active-high. Therefore, making the inhibit input pin high forces the internal MOSFET on the common terminal to turn off and places the device into an analog "high-impedance" mode where none of the eight analog channels connects to the common pin, while making the inhibit pin low connects the common pin to whichever analog channel is selected by the three select bits.

One useful circuit you can build with such an IC is a simple *arbitrary waveform generator* where a digital counter cycles through all the channel values for the mux, and the mux in turn sequentially connects eight adjustable DC voltage signals one at a time with the common signal to create a stepped waveform having whatever shape you desire using eight steps.

A schematic diagram of such a circuit appears below, DC power supply terminals omitted from the schematic for simplicity:

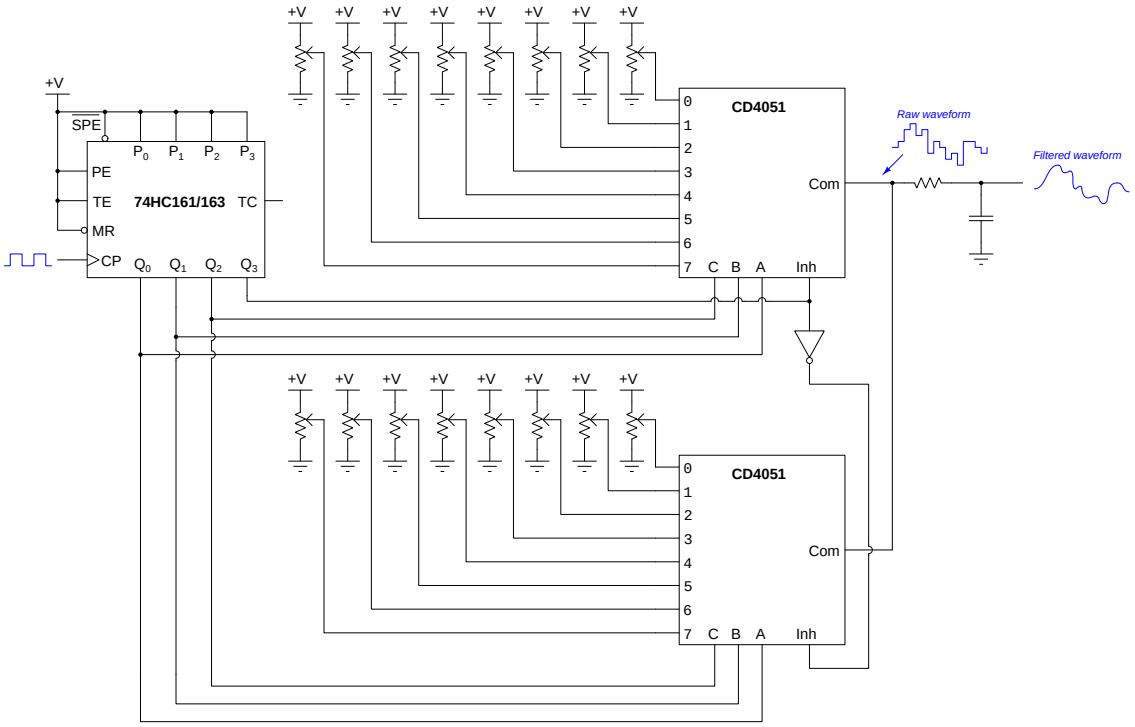


The clock signal may be supplied by a benchtop signal generator, by the output terminal of a 555 timer IC connected for astable operation, or any other suitable digital pulse signal source. Since the mux cycles through all its channels every *eight* counts of the counter IC, the final output signal will have a frequency one-eighth that of the digital clock pulse driving the counter.

Such a circuit is useful as a crude signal generator in its own right, as well as a source of interesting audio tones (for electronic music synthesis). The R and C values for the low-pass "smoothing" filter should be chosen to avoid loading down the eight signal-programming potentiometers; i.e. select a value for R that is at least ten times larger than the whole-resistance value of any single potentiometer, and select a suitable C value to provide a cutoff frequency that works well to soften the stair-step edges of the raw signal. This filter network's cutoff value, of course, depends on your intended analog signal frequency: the higher the signal frequency, the higher the cutoff needs to be in order to properly "smooth" the signal's wave-shape without attenuating it too much.

Note how the CD4051 IC's inhibit input is tied to ground, forcing it to be "low" all the time. This enables, rather than inhibits, the mux and allows the three select bits to choose which potentiometer signal gets passed along to the common output terminal and into the RC filter network. An alternative way to use this inhibit input is to connect it to a digital pulse waveform with a variable duty cycle (i.e. a pulse-width modulated or PWM signal). If this PWM pulse signal's frequency is substantially greater than the counter's clock frequency, the inhibit pin will be activated and de-activated multiple times during each of the eight "steps" of the arbitrary waveform, serving as an analog amplitude control for the arbitrary waveform. When the PWM duty cycle is low (i.e. "low" for more time each period than "high") the arbitrary waveform signal will largely pass through the 4051 mux unimpeded, but when the PWM signal is adjusted to a greater duty cycle value the mux will spend more and more time in its high-impedance mode which means the RC filter's capacitor won't be charged or discharged to as great a degree with each step of the eight-step cycle, resulting in a filtered output waveform with the same basic wave-shape but being smaller in peak-to-peak amplitude.

A more conventional use of the multiplexer's inhibit input is to permit multiple muxes to work together, allowing for more than eight analog signals to be sampled. Here we see two CD4051 analog mux ICs connected to the four-bit 74HC161/163[1] counter IC to allow a sixteen-step analog waveform to be synthesized:



In this circuit, the counter's most-significant bit (MSB) output Q_3 will be "low" during the first eight counts (0 through 7) and then "high" during the last eight counts (8 through 15), enabling the upper CD4051 mux for the first eight and the lower CD4051 mux for the latter eight count states. When each of these mux ICs are disabled, only the *other* mux will be able to send a potentiometer voltage value through to the RC filter.

Having a sixteen-step arbitrary waveform gives one the ability to generate a wave-shape with a "smoother" profile, having sixteen steps to work with rather than just eight. Of course, this means the synthesized analog signal will have a frequency that is now sixteen times slower than that of the digital clock.

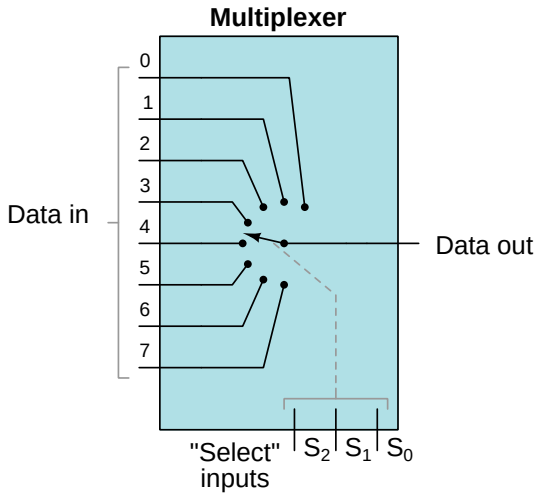
[1]The only functional difference between the model 74HC161 and 74HC163 counters is the behavior of their reset inputs, the '161 being asynchronous reset and the '163 being synchronous. Since we're not using the reset input at all, this distinction is irrelevant and therefore either model of counter will suffice. Both of these counter ICs happen to be *synchronous* in their counting, though, which is good for this application because otherwise a counter with asynchronous ("ripple") count bits might cause the mux to falsely select the wrong channel as it transitions from one count state to the next.

Chapter 3

Tutorial

3.1 Steering digital signals

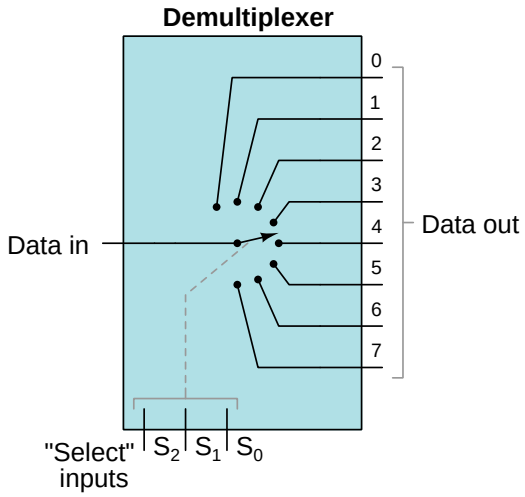
Many digital logic applications require signals to be "steered" in different directions, analogous to a *railroad switch* mechanism whereby railway trains may be steered from one set of tracks to another. A device that "steers" multiple incoming signals onto a single outgoing line is called a *multiplexer*, often abbreviated as *mux*. A functional[1] diagram of a mux appears below:



The three selector input lines accept a 3-bit binary number specifying which input channel's signal will be directed to the output (i.e. `000` selects input zero and `111` selects input seven).

[1] A functional diagram does not show electrical details like a schematic diagram, but rather attempts to convey the general purpose of the device or system. In this case, the multi-position switch represents combinational logic to direct one of the multiple input lines to the output line.

Conversely, a device built to "steer" a single incoming signal to one of multiple outgoing lines is called a *demultiplexer*, often abbreviated as *demux*, shown in the following functional diagram:



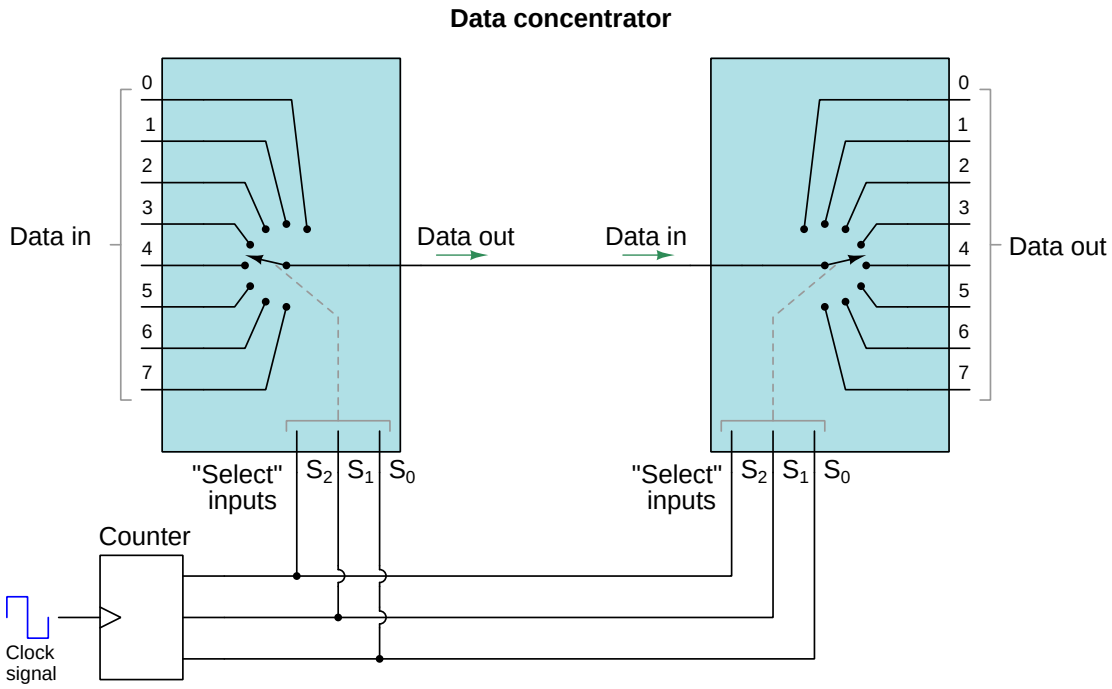
As with the mux, the demux's internal redirection logic is controlled by a binary word input, in this case a 3-bit binary value representing one of eight possible outputs.

Although most multiplexers and demultiplexers are strictly *digital* devices, directing the pathways for discrete voltage signals, *analog* muxes and demuxes also exist. An analog multiplexer or demultiplexer differs from its digital cousin in its redirection circuitry (typically field-effect transistors designed to present either a "shorted" or "open" series resistance to any analog signal passing through the device, much like a solid-state version of a mechanical switch)[2], but is still controlled by a digital binary word identifying the input or output line to be selected.

[2] In fact, a truly mechanical analog multiplexer or demultiplexer may be built using a decoder and a set of electromechanical relays: the digital decoder drives the coils of one-of-n relays, each relay dedicated to one of the non-multiplexed input or output lines. Sending a binary word to the decoder causes only one of the n relays to energize, closing its contact and allowing that particular analog signal through.

3.2 Data concentration

A very useful application for mux/demux pairs is to form a *data concentrator* circuit, the purpose of which is to "concentrate" multiple channels of digital data through the fewest possible wires. An example of this circuit appears below in functional-diagram form, showing how eight individual digital data streams may be sent – one at a time – through a single wire at the command of the binary counter's value (requiring three more wires):

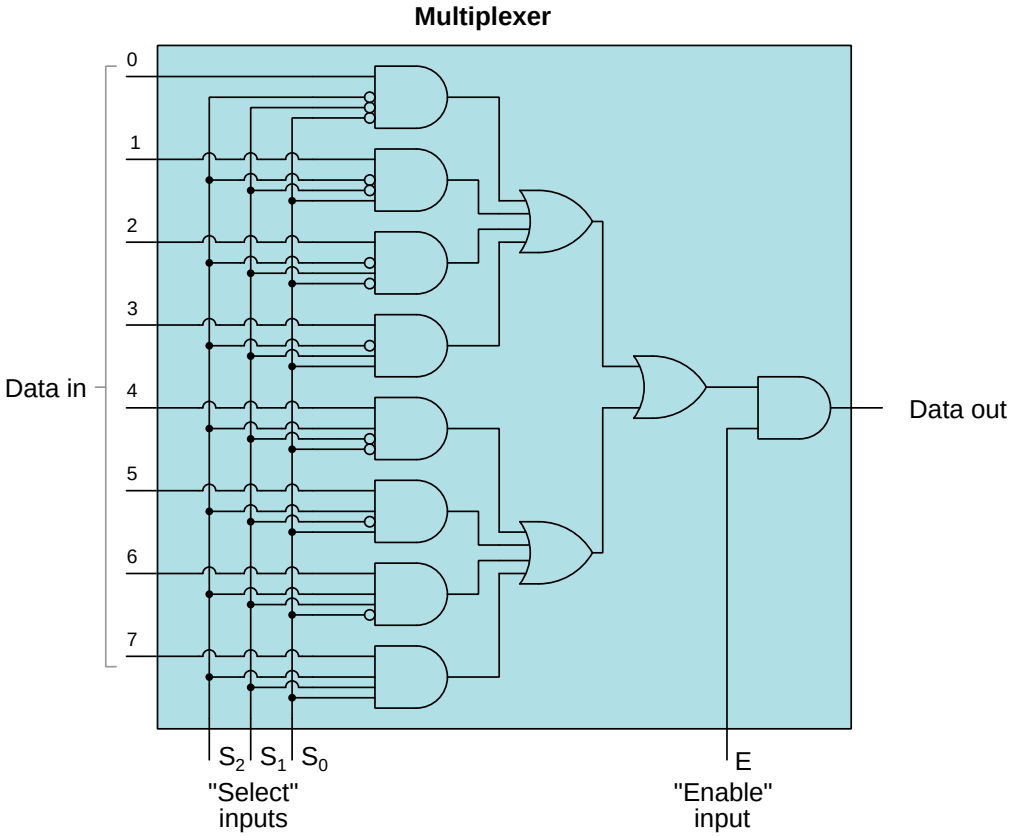


The three-bit counter increments from `000` to `001` to `010` and so on through to `111`, then "recycles" back to `000` in an endless sequence. If cycled fast enough, the data flow from inputs to outputs appears seamless, enabling eight distinct digital data streams to be communicated over four wires (plus a shared ground connection). Obviously, this circuit only makes sense for scenarios where wire count is extremely limited, as the obvious alternative of using eight wires to convey eight signals is far less complex.

The economy of a data concentrator grows with channel and selection-bit count. For example, a 4-bit-selected mux/demux pair could communicate *sixteen* distinct data channels using only *five* wires plus ground. With each additional bit in the binary selection word, the number of multiplexed data channels doubles while the conductor count merely increments by one.

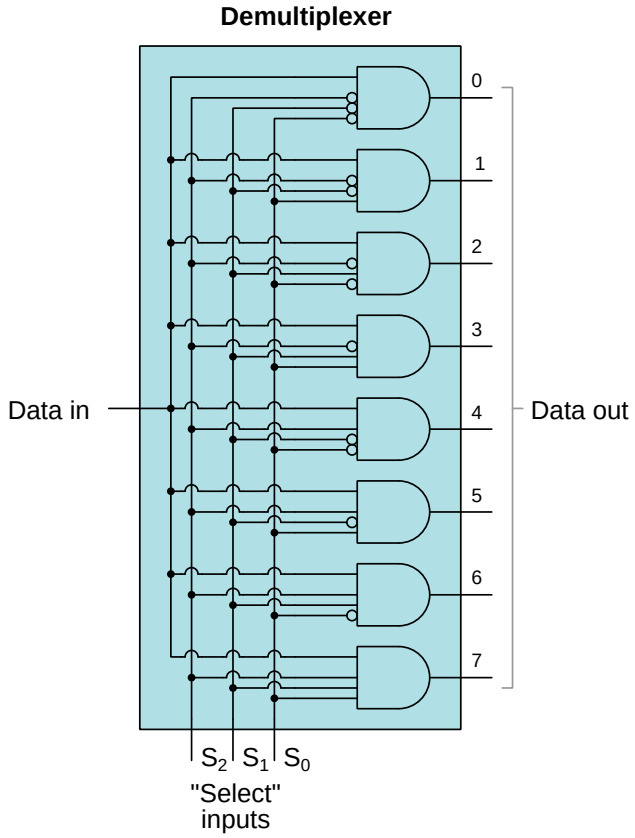
3.3 Multiplexer and demultiplexer construction

Multiplexer logic circuitry consists of AND gates, OR gates, and inverters (shown as complementation bubbles on some of the AND gate inputs). Recall that an AND gate outputs a high signal only if all inputs are high. Therefore, a "high" input signal becomes selected by a particular AND gate only if the other three inputs of that AND gate see the appropriate binary bit combination to satisfy the AND gate's requirement of all "high" inputs. Then, the cascaded OR gates route any AND gate's high output to the final output of the mux:



As with many combinational logic functions, multiplexers are often equipped with one or more *enable* or *strobe* inputs to override the output state regardless of channel or select line statuses. As you can see in the above diagram, the "enable" input allows data to pass through the multiplexer when active (high) but forces the output to a low state if inactive (low). Of course, you often find multiplexers with active-low enable inputs as well.

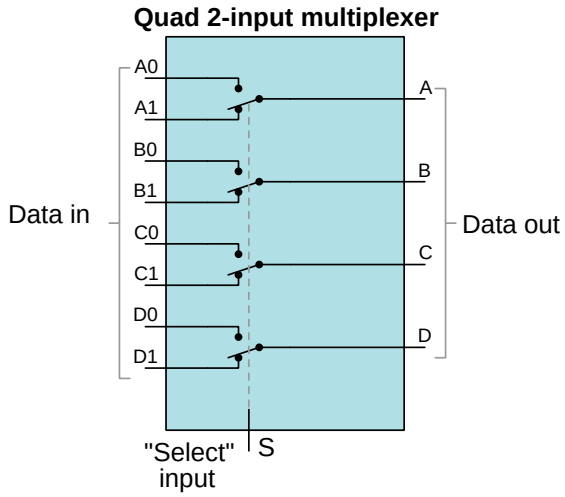
Demultiplexer logic is slightly simpler. Here, the OR gates are eliminated, while maintaining the same AND gate array. Each output line goes "high" only if the input line is high and the inverted/noninverted binary bits are such to satisfy that output's AND gate with all "high" inputs:



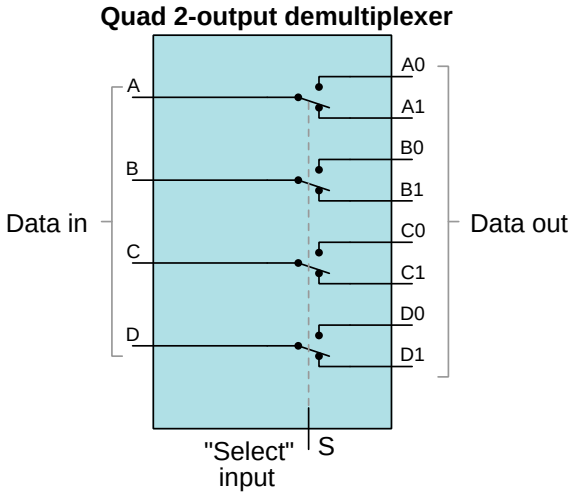
Interestingly, a demultiplexer is identical to a *binary decoder* equipped with an enable input. If you examine the demultiplexer circuit shown above and imagine re-labeling the "Data in" input as either "Enable" or "Strobe", you can see that by maintaining the newly-labeled "Enable/Strobe" line in an active state the circuit simply functions as a decoder: activating one out of n channels according to the binary value impressed at the "Select" input lines.

3.4 Multiplexing and demultiplexing words

So far all the multiplexer and demultiplexer designs we have explored handle single bits of data, but other versions exist as well. For example, a *quad 2-input* multiplexer consists of four multiplexers in one integrated circuit, each of those multiplexers selecting one of two inputs. A functional diagram of this appears in the following illustration:



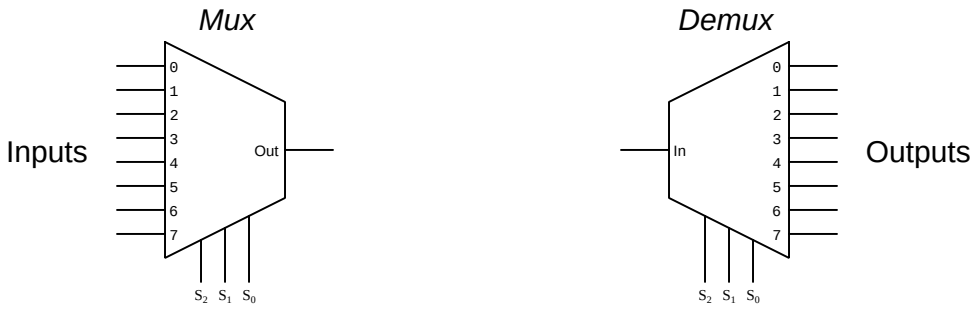
These multiplexers find popular use selecting between one of two four-bit digital *words*, in this case word 0 and word 1. Demultiplexers with similar formats also exist, directing a digital word to one of two banks of output lines.



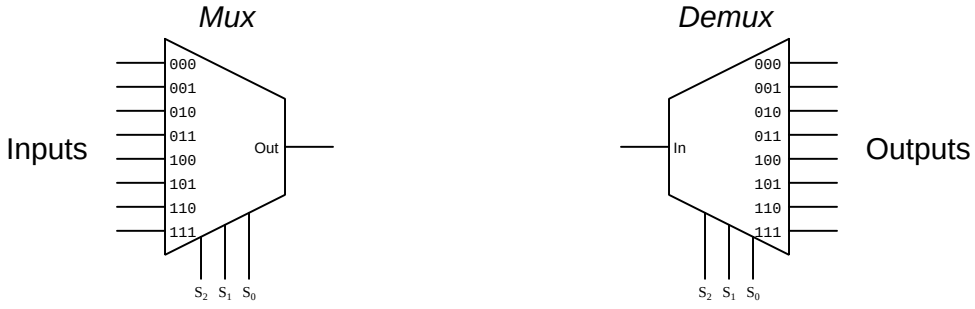
For both of these mux/demux units only one selection input line exists, since there are only *two* (2^1) switch states.

3.5 Common mux and demux symbols

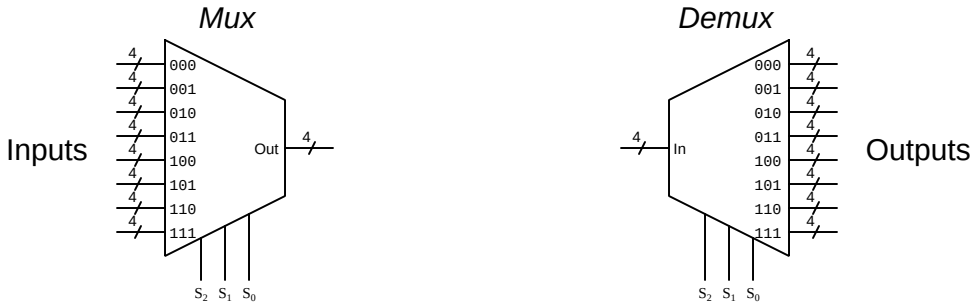
So far in this Tutorial we have illustrated the function of both multiplexers and demultiplexers using generic rectangular "box" symbols, but in many digital system documentation we see trapezoidal shapes used to denote these devices. The trapezoid shape is intended to evoke the image of data being either funneled into a single output channel (mux) or fanned out to a single output channel (demux):



In the above illustrations we see 8-channel mux and demux functions, each with 3-bit selector words. Note how each of the selected I/O lines is numbered in decimal form according to the binary value of the selector word, but that it is also appropriate to label in binary as well. This next example shows binary labeling of selectable I/O lines for both mux and demux devices:

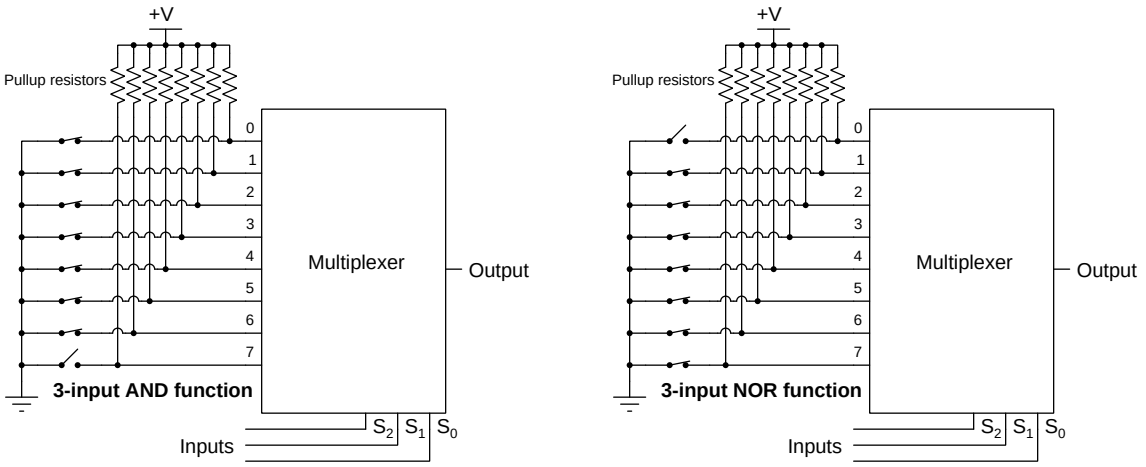


Multiplexers and demultiplexers operating on multi-bit words may also be represented using this same symbology. As an example of this, here we see both mux and demux units selecting one of eight four-bit words:



3.6 Arbitrary logic functions

One interesting application for a multiplexer is the generation of arbitrary logic functions. If we consider the "select" lines to be the input lines of a logic function, and the single mux output line to be the output line of that same logic function, the mux input lines serve as connection points for "programmable" output states. Consider these simple examples:

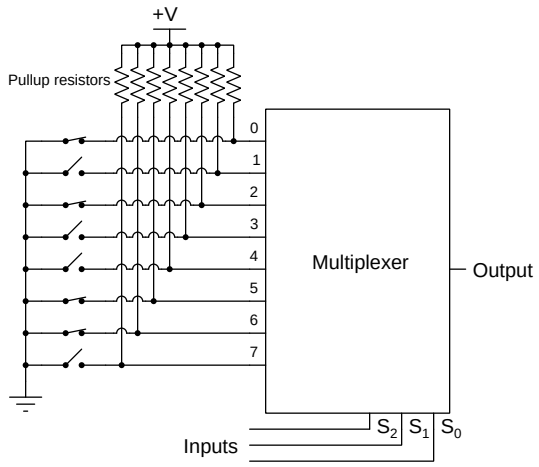


As we apply all possible high/low combinations to the three "select" input lines (S_2, S_1, and S_0) of these multiplexers, those binary values select one input channel at a time (e.g. when S_2 is low and S_1 is low, and S_0 is low, the mux selects the logic state applied to input terminal `0` to be "steered" to the output terminal.

The toggle switches connected to the multiplexer's input lines thus serve to *define* the logic function. Simply by setting these switches to different positions, we may specify any 3-input logic function desired.

To show just how arbitrary the logic function may be when implemented by a multiplexer, consider the following example. Here we see a truth table not adhering to any canonical logic function such as AND or NOR, but nevertheless implemented just as easily as any other logic function using the same multiplexer IC we saw in the two prior examples. The output states for each row of the truth table are "programmed" by the settings of the eight toggle switches connected to the multiplexer's input channel terminals:

S_2	S_1	S_0	Output
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1



A simple thought experiment works well to explore how this circuit functions. Just imagine setting the three "select" input lines to various high (1) and low (0) states, one combination at a time, and see for yourself which input channel the mux selects for each combination. Remember that the three "select" input line states constitute bits of a three-bit binary number, the value of that number determining which input channel gets "steered" to the output:

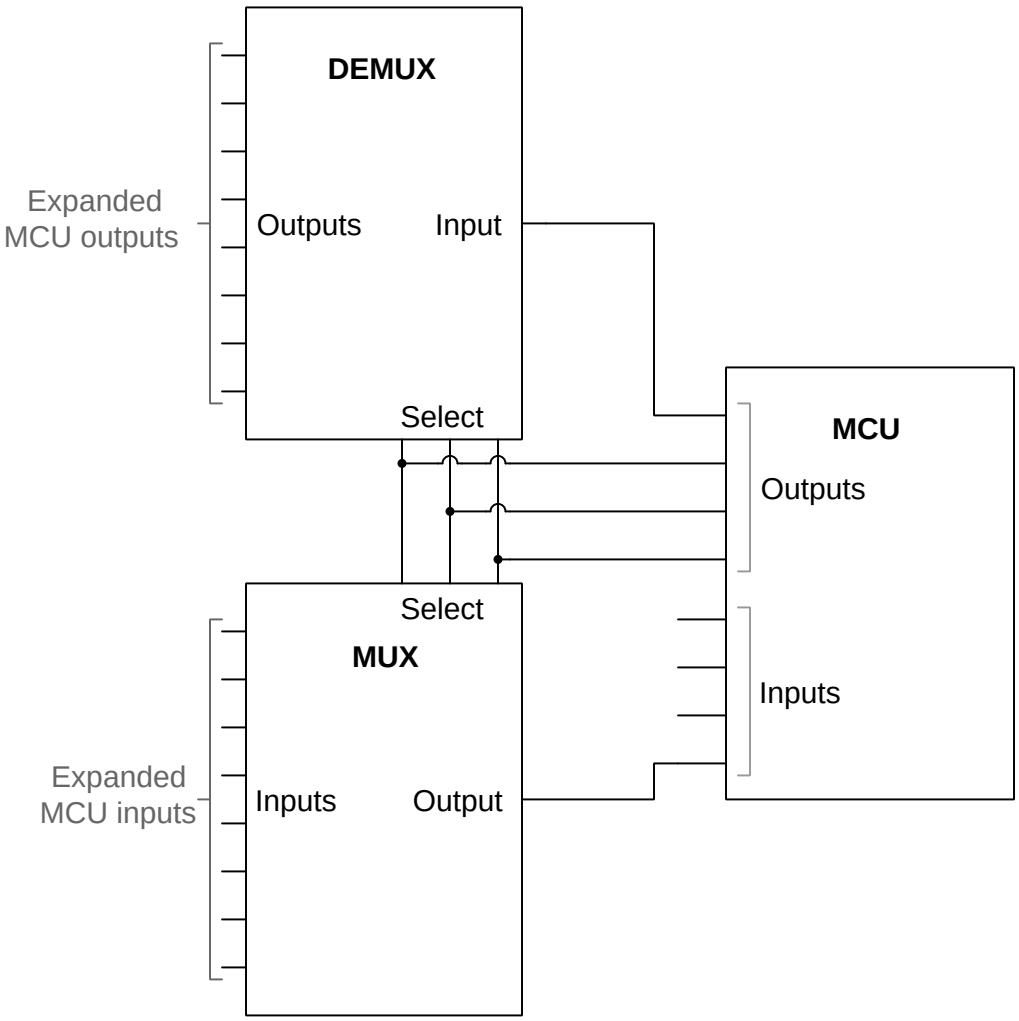
- $S_2 = 0 \quad S_1 = 0 \quad S_0 = 0$ Output = 0 because channel 0's toggle switch is closed
- $S_2 = 0 \quad S_1 = 0 \quad S_0 = 1$ Output = 1 because channel 1's toggle switch is open
- $S_2 = 0 \quad S_1 = 1 \quad S_0 = 0$ Output = 0 because channel 2's toggle switch is closed
- $S_2 = 0 \quad S_1 = 1 \quad S_0 = 1$ Output = 1 because channel 3's toggle switch is open
- $S_2 = 1 \quad S_1 = 0 \quad S_0 = 0$ Output = 1 because channel 4's toggle switch is open
- $S_2 = 1 \quad S_1 = 0 \quad S_0 = 1$ Output = 0 because channel 5's toggle switch is closed
- $S_2 = 1 \quad S_1 = 1 \quad S_0 = 0$ Output = 0 because channel 6's toggle switch is closed
- $S_2 = 1 \quad S_1 = 1 \quad S_0 = 1$ Output = 1 because channel 7's toggle switch is open

3.7 Microcontroller I/O expansion

Another practical use for multiplexers and demultiplexers is expanding the I/O capability of microcontrollers. This is similar in concept to the "data concentrator" examined earlier, where multiple digital signals could be routed, one at a time, through a single conductor. A *microcontroller* (often abbreviated *MCU*) is a functioning computer built on a single integrated circuit, useful for a great many practical tasks[3]. Due to their small physical size these small computers tend to be very limited in input and output (I/O) lines. Multiplexers may be used to effectively increase the number of input lines to the microcontroller by permitting a single input line to sequentially sample multiple inputs. Likewise, demultiplexers may be used to effectively expand the number of output lines on a microcontroller by permitting a single output line to sequentially drive multiple outputs.

[3] Most people reading this document actually own several microcontrollers without necessarily realizing their presence. Modern automobiles contain multiple microcontrollers, used for such tasks as airbag deployment, antilock brake modulation, engine management (e.g. air/fuel mixture control, ignition timing), and a host of "accessory" functions (e.g. sound system, seat adjustment, temperature control, etc.). Many residential appliances contain microcontrollers, too: digital thermostats, televisions, radios, remote control units, refrigerators, toasters, mixers, ovens, etc. Interestingly, most personal computers, besides containing their own microprocessor units, contain microcontrollers to handle peripheral tasks such as USB-networked devices (e.g. keyboard, mouse, printer). If you own an electric toothbrush, it most likely contains a microcontroller as well!

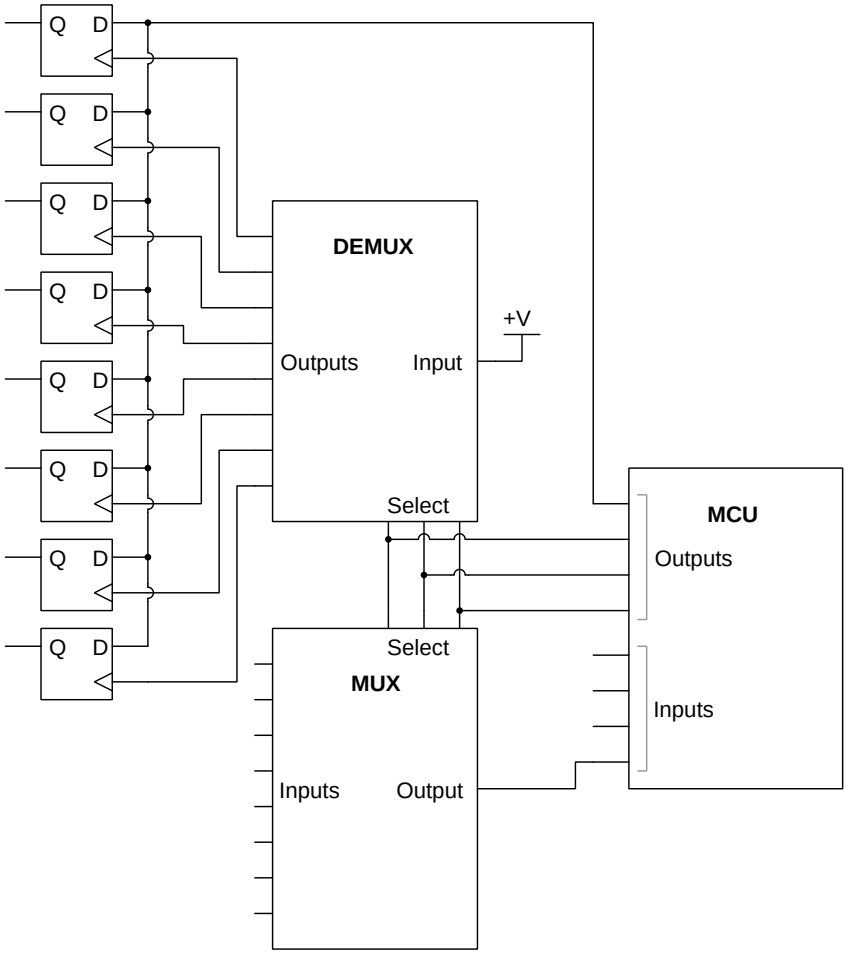
Examples of both applications appear in this diagram, where a microcontroller drives both a mux and a demux with three of its output lines, sampling the selected inputs with one input line and driving the selected outputs with an additional output line:



The microcontroller's program must instruct the three "select" output lines to periodically output binary values from `000` to `111` (a recirculating 3-bit binary count sequence is perhaps the easiest sequence to program), while other portion's of the MCU's program reads logic states at the one utilized input line and writes logic states to the remaining output line at the appropriate times (i.e. shortly following the output of each new count value). Given the necessary programming in the MCU, the multiplexer and demultiplexer have expanded the MCU's available I/O count from four inputs and four outputs to *eleven* inputs and *eight* outputs.

Of course, this multiplexed expansion of I/O lines comes at a price. First is the penalty in time delay: eight multiplexed inputs cannot read data as quickly as eight independent input lines, because time must be spent "cycling" through each one. Second is the inability for the microcontroller to *maintain* high states on the eight demultiplexed outputs, since all output lines on a demultiplexer default to their inactive states ("low" for an active-high output demux) when not selected. At best, all the MCU is able to do with the eight multiplexed outputs is *pulse* them one at a time.

There are ways to enable the MCU to "latch" its expanded output lines, but once again it carries a functional penalty. We may use the demux outputs not as expanded outputs for the MCU directly, but instead as *clock* inputs for eight D-type flip-flops. The demux's input line will be connected "high" so that each flip-flop receives a low-to-high pulse when that channel is selected, and it falls upon the MCU to output the desired state for that flip-flop just prior to and following the count transition (respecting the set-up time and hold time requirements of the flip-flops) in order to reliably "clock" that logic state through:



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.

[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 textitReading 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.

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[3]. 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.

[3] *Analytical* 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, journal their own 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 SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did 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.

Multiplexing

Demultiplexing

Binary number

Digital signal

Analog signal

Counter

OR function

AND function

Microcontroller

4.1.3 Oscilloscope alternate and chop modes

Most modern analog oscilloscopes have the ability to display multiple traces on their screens (dual-trace is the standard), even though the CRT itself used by the 'scope may only have one electron gun, and thus only be able to "paint" one flying dot on the screen at a time.

Oscilloscopes with single-gun display tubes achieve dual-trace capability by way of *multiplexing* the two input channels to the same CRT. There are usually two different modes for this multiplexing, though: **alternate** and **chop**.

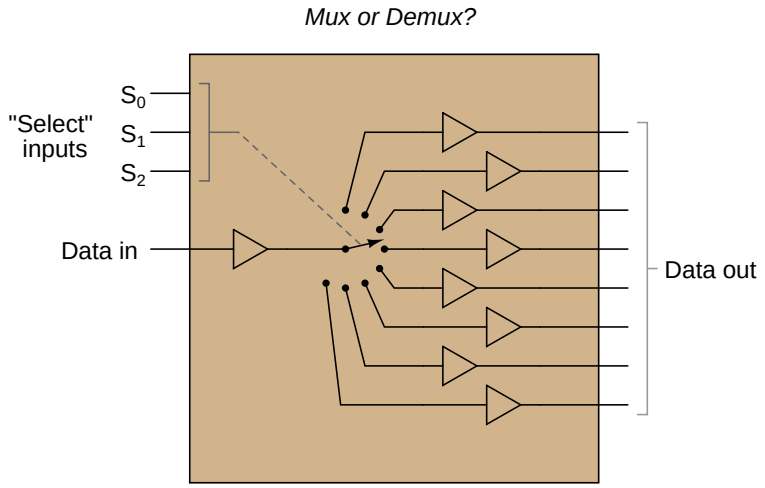
Explain how these multiplexing techniques work, and what conditions would prompt you to use the two different multiplexing modes. I *strongly* encourage you to experiment with displaying two different signals on one of these oscilloscopes as your research. You will likely learn far more from a hands-on exercise than if you were to read about it in a book!

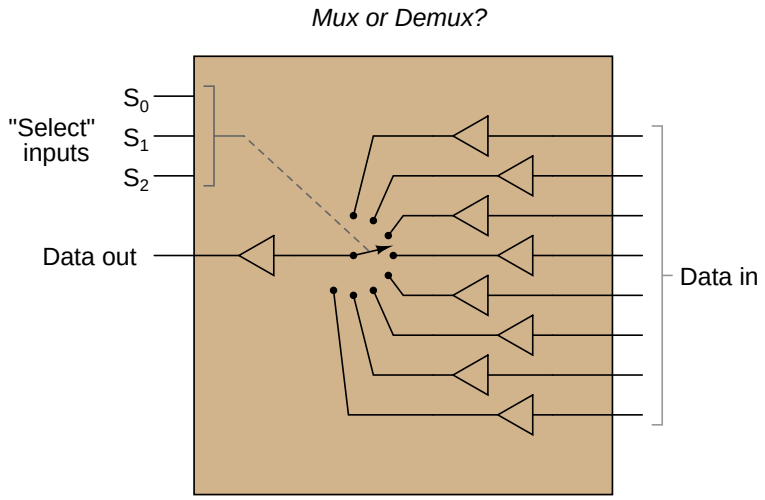
Challenges

- Describe what might happen if you have the oscilloscope set for the wrong multiplexing mode.

4.1.4 Mux versus demux

Multiplexers and *demultiplexers* are often confused with one another by students first learning about them. Although they appear similar, they certainly perform different functions. Shown here is a multiplexer and a demultiplexer, each using a multiple-position switch symbol to indicate the selection functions inside the respective circuits:





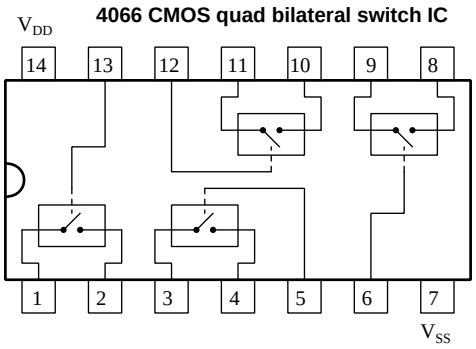
After identifying which is which, provide definitions for "multiplexer" and "demultiplexer" in your own words.

Challenges

- What do the triangle symbols represent, and why are those components included inside the mux and demux ICs?

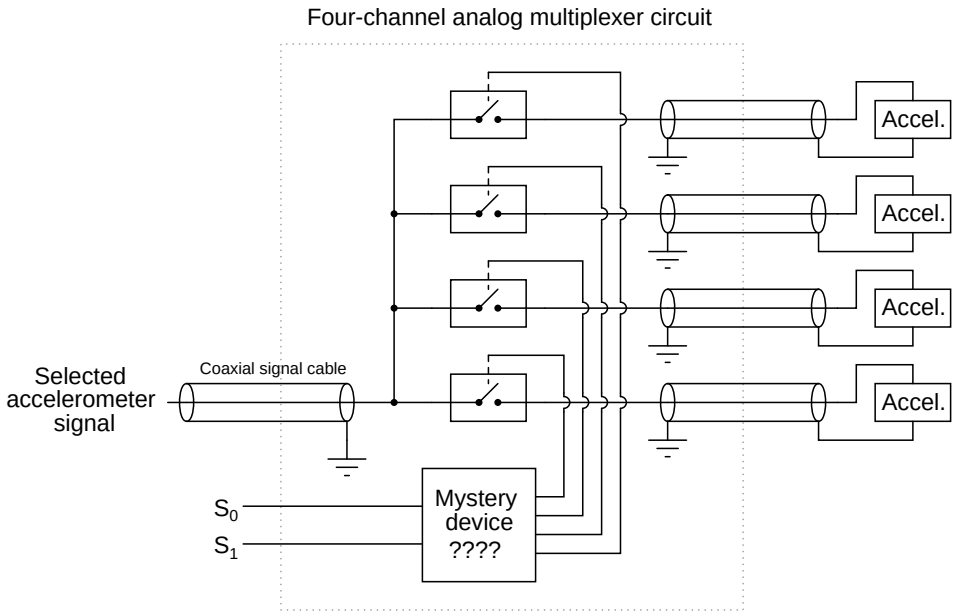
4.1.5 Multiplexed accelerometers

A variety of practical electronic applications require *multiplexing*, where several input signals are individually selected, one at a time but very rapidly, to be communicated through a single channel. In order to rapidly select (or switch) analog signals in these multiplexing applications, we need some form of semiconductor on/off switch capable of fast switching time, low pass-through ("on" state) impedance, and high blocking ("off" state) impedance. Thankfully, there is such a device commonly and inexpensively produced, called a *CMOS bilateral switch*:



This hybrid analog/digital device uses digital logic signals (high/low) to activate the gates of CMOS transistor assemblies to switch analog signals on and off. It is like having four low-current solid-state relays in a single integrated circuit. When the control line is made "high" (standard CMOS logic level), the respective switch goes into its conductive ("on") state. When the control line is made "low," the switch turns off. Because it is MOSFETs we are turning on and off, the control lines draw negligible current (just like CMOS logic gate inputs).

If we are to use such bilateral switches to multiplex analog signals along a common signal line, though, we must add some accessory components to control which switch (out of the four) is active at any given time. Take for instance this circuit where we use four bilateral switches to multiplex the voltage signals from four accelerometers (measuring acceleration on a vibration-testing jig):



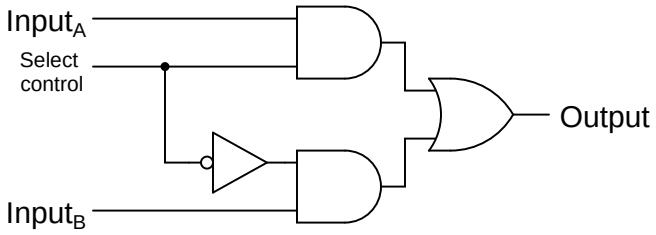
Identify the necessary "mystery device" shown in the schematic, which allows a binary input (S_0 and S_1 with four combinations of high/low states: `00`, `01`, `10`, and `11`) to activate just *one* bilateral switch at a time.

Challenges

- Propose a solution involving individual logic gates.

4.1.6 Two-input selector logic

The following schematic diagram is for a *two-input selector* circuit, which (as the name implies) selects one of two inputs to be sent to the output:



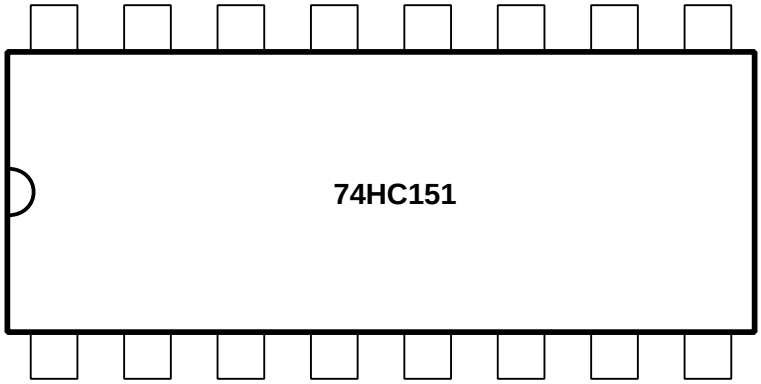
Determine which state the "select control" input line has to be in to select Input$_A$ to be sent to the output, and which state it has to be in to select Input$_B$ to go to the output.

Challenges

- Why is the inverter gate necessary for proper function?

4.1.7 74HC151 mux

The 74HC151 is a high-speed CMOS (TTL-compatible) integrated circuit multiplexer, also known as a *data selector*. It is commonly available as a 16 pin DIP "chip." Identify the terminals of a 74HC151, and label them here:



In particular, note the locations and functions of the "select" terminals, as well as the output terminal.

What types of electrical "data" may be "selected" by this particular integrated circuit? For example, can it select an analog waveform, such as human speech from a microphone? Is it limited to discrete TTL logic levels? How can you tell?

Challenges

- How will this IC behave if its enable line is left unconnected?

4.1.8 Address latching

The 74HC137 and 74HC237 decoder/demultiplexer integrated circuits have a feature that some other decoder/demultiplexers do not: *address latching*. Explain what this additional feature is, how it works, and how you would disable the feature if you needed to use one of these integrated circuits in an application not requiring address latching.

Challenges

- What is the functional difference between the 74HC137 and the 74HC237? How would the respective schematic symbols for these two decoder/demux ICs differ?
- Devise a practical application where you might need the feature of address latching.

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[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] 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.

4.2.1 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, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_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) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

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:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

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.

Common[7] 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[8] 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 $ax^2 + bx + c$:

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

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] 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.

[7] 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.

[8] 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.

[9] 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:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

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[10] – all that matters is that they properly reference each other in the formulae.

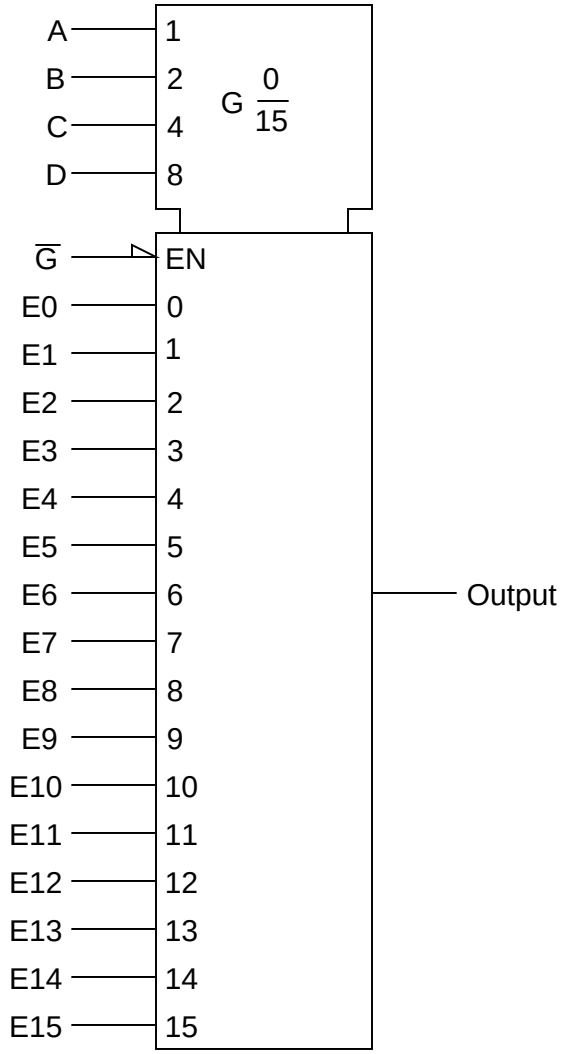
Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application 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.*

4.2.3 Arbitrary truth table

Multiplexers, or data selectors, may be used to generate arbitrary truth table functions. Take for example this truth table, shown beside a symbol for a 16-channel multiplexer:

D	C	B	A	Out
0	0	0	0	0
0	0	0	1	1
0	0	1	0	0
0	0	1	1	0
0	1	0	0	0
0	1	0	1	1
0	1	1	0	1
0	1	1	1	1
1	0	0	0	0
1	0	0	1	1
1	0	1	0	0
1	0	1	1	1
1	1	0	0	1
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1



Show the wire connections necessary to make the multiplexer output the specified logic states in response to the data select (A, B, C, and D) inputs.

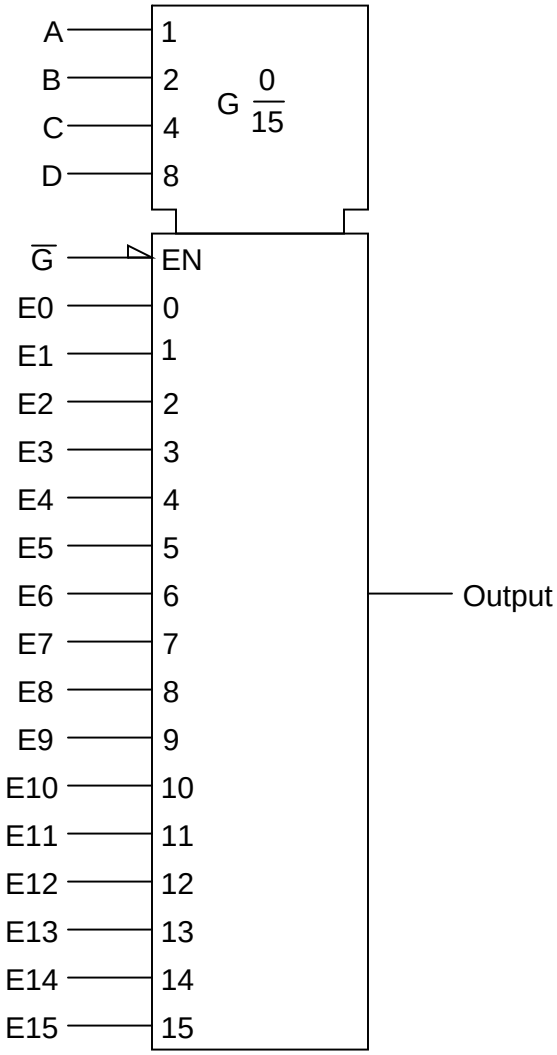
Challenges

- What should be done with the $\overline{G}$ line?

4.2.4 Arbitrary SOP expression

Multiplexers, or data selectors, may be used to generate arbitrary truth table functions. Take for example this Boolean SOP expression, shown beside a symbol for a 16-channel multiplexer:

$A\overline{B}CD + AB\overline{C}D + \overline{A}BC\overline{D}$



Show the wire connections necessary to make the multiplexer implement the specified Boolean expression.

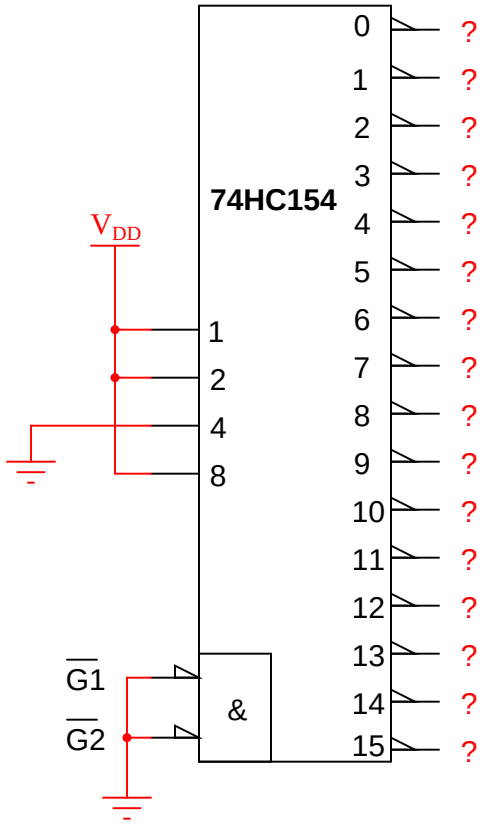
Challenges

- What should be done with the $\overline{G}$ line?

- Complete a truth table describing this same SOP expression.

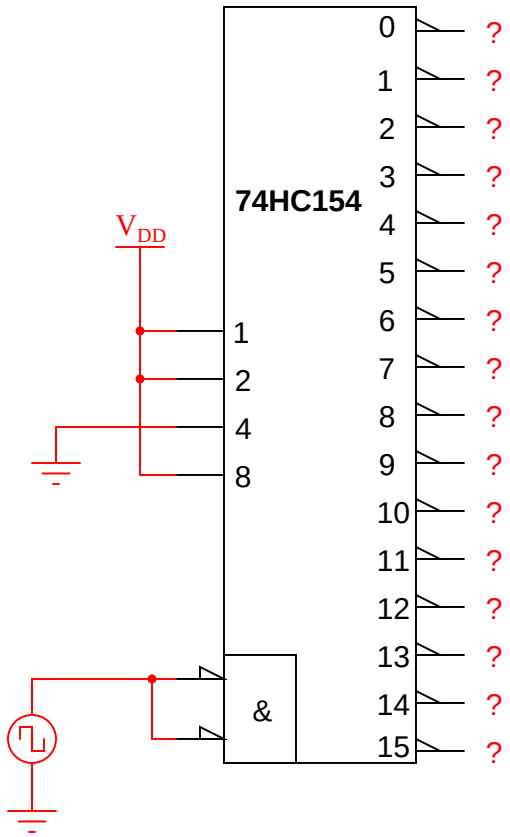
4.2.5 74HC154 decoder

The 74HC154 is a high-speed CMOS (TTL-compatible) integrated circuit decoder with four input lines and sixteen output lines:



Identify the logic states of all output terminals given the input conditions shown.

Next, identify the logic states for the same circuit, this time with a square wave (on/off pulse) logic signal applied to the enable terminals:



Challenges

- In the square-wave application of this decoder, is it functioning as a mux or as a demux?
- Explain why it is necessary to use both $\overline{G1}$ and $\overline{G2}$, and not just one of them.

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.

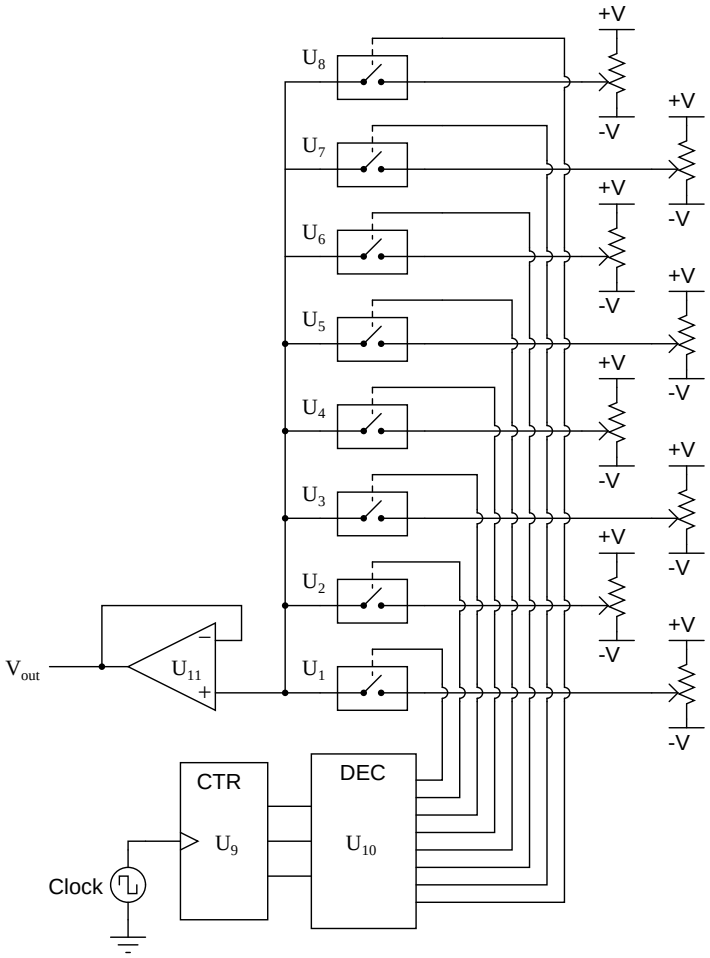
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of 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 Faulted AWG circuit

The following schematic diagram shows an eight-step arbitrary waveform generator (AWG). The analog multiplexer selects one of the eight potentiometer signals at a time, stepping from one to the next at the pace of the clock pulse:



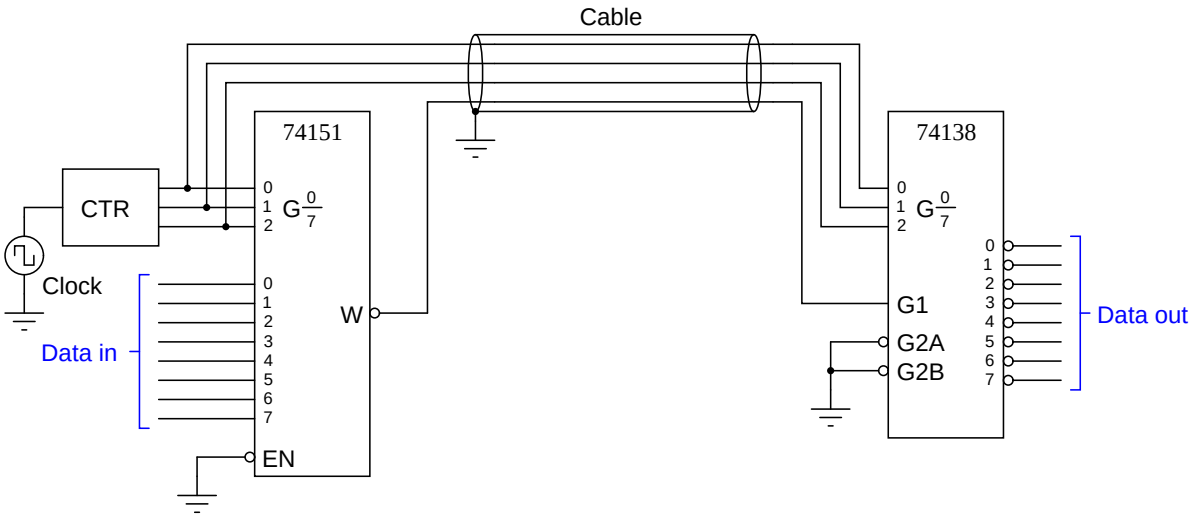
Explain what effect a *shorted* bilateral switch would have on the output waveform. Be as specific as possible.

Challenges

- Why is it important that all the potentiometers connect to both +V and −V?
- Identify how to increase or decrease the frequency output by the AWG.
- Identify the function of U_{11}.

4.3.2 Faulted concentrator circuit

Predict how the operation of this "concentrator" circuit (taking eight digital inputs and "concentrating" them into a single, multiplexed, communication line to be expanded into eight outputs at the receiving end) will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no coincidental faults):



- Clock pulse generator stops pulsing:
- Pin breaks on the W output of 74151 chip, leaving that wire floating:
- Pin breaks on G2A input of 74138 chip, leaving it floating:
- Enable pin breaks on 74151 chip, leaving it floating:

For each of these conditions, explain *why* the resulting effects will occur.

Challenges

- What factors influence the appropriate choice of clock frequency for a circuit such as this?

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

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- 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.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- 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. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- 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 equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[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.

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.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- 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. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- 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.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- 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! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **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[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] 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.

B.4 Design of these learning modules

"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. Every effort has been made to embed the following instructional and assessment philosophies within:

- 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[4] 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[5] 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[6] 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

[4] In 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.

[5] Socrates 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.

[6] This 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 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.

To high standards of education,

Tony R. Kuphaldt

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 TEX 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. TEX 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, TEX *is a programmer's approach to word processing*. Since TEX 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 TEX makes it relatively easy to learn how other people have created their own TEX 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 LATEX extensions to TEX

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

Creative Commons License

Creative Commons Attribution 4.0 International Public License

By exercising the Licensed Rights (defined below), You accept and agree to be bound by the terms and conditions of this Creative Commons Attribution 4.0 International Public License ("Public License"). To the extent this Public License may be interpreted as a contract, You are granted the Licensed Rights in consideration of Your acceptance of these terms and conditions, and the Licensor grants You such rights in consideration of benefits the Licensor receives from making the Licensed Material available under these terms and conditions.

Section 1 – Definitions.

a. **Adapted Material** means material subject to Copyright and Similar Rights that is derived from or based upon the Licensed Material and in which the Licensed Material is translated, altered, arranged, transformed, or otherwise modified in a manner requiring permission under the Copyright and Similar Rights held by the Licensor. For purposes of this Public License, where the Licensed Material is a musical work, performance, or sound recording, Adapted Material is always produced where the Licensed Material is synched in timed relation with a moving image.

b. **Adapter's License** means the license You apply to Your Copyright and Similar Rights in Your contributions to Adapted Material in accordance with the terms and conditions of this Public License.

c. **Copyright and Similar Rights** means copyright and/or similar rights closely related to copyright including, without limitation, performance, broadcast, sound recording, and Sui Generis Database Rights, without regard to how the rights are labeled or categorized. For purposes of this Public License, the rights specified in Section 2(b)(1)-(2) are not Copyright and Similar Rights.

d. **Effective Technological Measures** means those measures that, in the absence of proper authority, may not be circumvented under laws fulfilling obligations under Article 11 of the WIPO Copyright Treaty adopted on December 20, 1996, and/or similar international agreements.

e. **Exceptions and Limitations** means fair use, fair dealing, and/or any other exception or

limitation to Copyright and Similar Rights that applies to Your use of the Licensed Material.

f. **Licensed Material** means the artistic or literary work, database, or other material to which the Licensor applied this Public License.

g. **Licensed Rights** means the rights granted to You subject to the terms and conditions of this Public License, which are limited to all Copyright and Similar Rights that apply to Your use of the Licensed Material and that the Licensor has authority to license.

h. **Licensor** means the individual(s) or entity(ies) granting rights under this Public License.

i. **Share** means to provide material to the public by any means or process that requires permission under the Licensed Rights, such as reproduction, public display, public performance, distribution, dissemination, communication, or importation, and to make material available to the public including in ways that members of the public may access the material from a place and at a time individually chosen by them.

j. **Sui Generis Database Rights** means rights other than copyright resulting from Directive 96/9/EC of the European Parliament and of the Council of 11 March 1996 on the legal protection of databases, as amended and/or succeeded, as well as other essentially equivalent rights anywhere in the world.

k. **You** means the individual or entity exercising the Licensed Rights under this Public License. **Your** has a corresponding meaning.

Section 2 – Scope.

a. License grant.

1. Subject to the terms and conditions of this Public License, the Licensor hereby grants You a worldwide, royalty-free, non-sublicensable, non-exclusive, irrevocable license to exercise the Licensed Rights in the Licensed Material to:

A. reproduce and Share the Licensed Material, in whole or in part; and

B. produce, reproduce, and Share Adapted Material.

2. Exceptions and Limitations. For the avoidance of doubt, where Exceptions and Limitations apply to Your use, this Public License does not apply, and You do not need to comply with its terms and conditions.

3. Term. The term of this Public License is specified in Section 6(a).

4. Media and formats; technical modifications allowed. The Licensor authorizes You to exercise the Licensed Rights in all media and formats whether now known or hereafter created, and to make technical modifications necessary to do so. The Licensor waives and/or agrees not to assert any right or authority to forbid You from making technical modifications necessary to exercise the Licensed Rights, including technical modifications necessary to circumvent Effective Technological Measures.

For purposes of this Public License, simply making modifications authorized by this Section 2(a)(4) never produces Adapted Material.

5. Downstream recipients.

A. Offer from the Licensor – Licensed Material. Every recipient of the Licensed Material automatically receives an offer from the Licensor to exercise the Licensed Rights under the terms and conditions of this Public License.

B. No downstream restrictions. You may not offer or impose any additional or different terms or conditions on, or apply any Effective Technological Measures to, the Licensed Material if doing so restricts exercise of the Licensed Rights by any recipient of the Licensed Material.

6. No endorsement. Nothing in this Public License constitutes or may be construed as permission to assert or imply that You are, or that Your use of the Licensed Material is, connected with, or sponsored, endorsed, or granted official status by, the Licensor or others designated to receive attribution as provided in Section 3(a)(1)(A)(i).

b. Other rights.

1. Moral rights, such as the right of integrity, are not licensed under this Public License, nor are publicity, privacy, and/or other similar personality rights; however, to the extent possible, the Licensor waives and/or agrees not to assert any such rights held by the Licensor to the limited extent necessary to allow You to exercise the Licensed Rights, but not otherwise.

2. Patent and trademark rights are not licensed under this Public License.

3. To the extent possible, the Licensor waives any right to collect royalties from You for the exercise of the Licensed Rights, whether directly or through a collecting society under any voluntary or waivable statutory or compulsory licensing scheme. In all other cases the Licensor expressly reserves any right to collect such royalties.

Section 3 – License Conditions.

Your exercise of the Licensed Rights is expressly made subject to the following conditions.

a. Attribution.

1. If You Share the Licensed Material (including in modified form), You must:

A. retain the following if it is supplied by the Licensor with the Licensed Material:

i. identification of the creator(s) of the Licensed Material and any others designated to receive attribution, in any reasonable manner requested by the Licensor (including by pseudonym if designated);

ii. a copyright notice;

iii. a notice that refers to this Public License;

iv. a notice that refers to the disclaimer of warranties;

v. a URI or hyperlink to the Licensed Material to the extent reasonably practicable;

B. indicate if You modified the Licensed Material and retain an indication of any previous modifications; and

C. indicate the Licensed Material is licensed under this Public License, and include the text of, or the URI or hyperlink to, this Public License.

2. You may satisfy the conditions in Section 3(a)(1) in any reasonable manner based on the medium, means, and context in which You Share the Licensed Material. For example, it may be reasonable to satisfy the conditions by providing a URI or hyperlink to a resource that includes the required information.

3. If requested by the Licensor, You must remove any of the information required by Section 3(a)(1)(A) to the extent reasonably practicable.

4. If You Share Adapted Material You produce, the Adapter's License You apply must not prevent recipients of the Adapted Material from complying with this Public License.

Section 4 – Sui Generis Database Rights.

Where the Licensed Rights include Sui Generis Database Rights that apply to Your use of the Licensed Material:

a. for the avoidance of doubt, Section 2(a)(1) grants You the right to extract, reuse, reproduce, and Share all or a substantial portion of the contents of the database;

b. if You include all or a substantial portion of the database contents in a database in which You have Sui Generis Database Rights, then the database in which You have Sui Generis Database Rights (but not its individual contents) is Adapted Material; and

c. You must comply with the conditions in Section 3(a) if You Share all or a substantial portion of the contents of the database.

For the avoidance of doubt, this Section 4 supplements and does not replace Your obligations under this Public License where the Licensed Rights include other Copyright and Similar Rights.

Section 5 – Disclaimer of Warranties and Limitation of Liability.

a. Unless otherwise separately undertaken by the Licensor, to the extent possible, the Licensor offers the Licensed Material as-is and as-available, and makes no representations or warranties of any kind concerning the Licensed Material, whether express, implied, statutory, or other. This includes, without limitation, warranties of title, merchantability, fitness for a particular purpose, non-infringement, absence of latent or other defects, accuracy, or the presence or absence of errors,

whether or not known or discoverable. Where disclaimers of warranties are not allowed in full or in part, this disclaimer may not apply to You.

b. To the extent possible, in no event will the Licensor be liable to You on any legal theory (including, without limitation, negligence) or otherwise for any direct, special, indirect, incidental, consequential, punitive, exemplary, or other losses, costs, expenses, or damages arising out of this Public License or use of the Licensed Material, even if the Licensor has been advised of the possibility of such losses, costs, expenses, or damages. Where a limitation of liability is not allowed in full or in part, this limitation may not apply to You.

c. The disclaimer of warranties and limitation of liability provided above shall be interpreted in a manner that, to the extent possible, most closely approximates an absolute disclaimer and waiver of all liability.

Section 6 – Term and Termination.

a. This Public License applies for the term of the Copyright and Similar Rights licensed here. However, if You fail to comply with this Public License, then Your rights under this Public License terminate automatically.

b. Where Your right to use the Licensed Material has terminated under Section 6(a), it reinstates:

1. automatically as of the date the violation is cured, provided it is cured within 30 days of Your discovery of the violation; or

2. upon express reinstatement by the Licensor.

For the avoidance of doubt, this Section 6(b) does not affect any right the Licensor may have to seek remedies for Your violations of this Public License.

c. For the avoidance of doubt, the Licensor may also offer the Licensed Material under separate terms or conditions or stop distributing the Licensed Material at any time; however, doing so will not terminate this Public License.

d. Sections 1, 5, 6, 7, and 8 survive termination of this Public License.

Section 7 – Other Terms and Conditions.

a. The Licensor shall not be bound by any additional or different terms or conditions communicated by You unless expressly agreed.

b. Any arrangements, understandings, or agreements regarding the Licensed Material not stated herein are separate from and independent of the terms and conditions of this Public License.

Section 8 – Interpretation.

a. For the avoidance of doubt, this Public License does not, and shall not be interpreted to, reduce, limit, restrict, or impose conditions on any use of the Licensed Material that could lawfully

be made without permission under this Public License.

b. To the extent possible, if any provision of this Public License is deemed unenforceable, it shall be automatically reformed to the minimum extent necessary to make it enforceable. If the provision cannot be reformed, it shall be severed from this Public License without affecting the enforceability of the remaining terms and conditions.

c. No term or condition of this Public License will be waived and no failure to comply consented to unless expressly agreed to by the Licensor.

d. Nothing in this Public License constitutes or may be interpreted as a limitation upon, or waiver of, any privileges and immunities that apply to the Licensor or You, including from the legal processes of any jurisdiction or authority.

Creative Commons is not a party to its public licenses. Notwithstanding, Creative Commons may elect to apply one of its public licenses to material it publishes and in those instances will be considered the "Licensor." Except for the limited purpose of indicating that material is shared under a Creative Commons public license or as otherwise permitted by the Creative Commons policies published at `creativecommons.org/policies`, Creative Commons does not authorize the use of the trademark "Creative Commons" or any other trademark or logo of Creative Commons without its prior written consent including, without limitation, in connection with any unauthorized modifications to any of its public licenses or any other arrangements, understandings, or agreements concerning use of licensed material. For the avoidance of doubt, this paragraph does not form part of the public licenses.

Creative Commons may be contacted at `creativecommons.org`.

Appendix E

References

Bogart, Theodore F. Jr., *Introduction to Digital Circuits*, Glencoe division of Macmillan/McGraw-Hill, 1992.

Appendix F

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.

27 April 2026 – typographical error corrections courtesy of Wyatt Gleason.

9 January 2025 – added a new Case Tutorial chapter with a section showing an analog multiplexer used to create an arbitrary waveform generator circuit.

19 November 2024 – corrected an error in image_2530 courtesy of Daniel Renshaw.

9 November 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors.

26-27 November 2023 – added a new Tutorial section describing trapezoidal mux and demux symbols. Also added some instructor notes to Challenge questions.

24 April 2023 – improvement to Tutorial text regarding switching between different binary words, referring to them as words 0 and 1 rather than words A and B. This improvement courtesy of Joe Archer.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

26 July 2022 – added more explanatory text on forming arbitrary logic functions using a mux.

25 May 2022 – divided the Tutorial into sections. Also, corrected minor illustration error in image_2530 and added some more questions to the Introduction chapter.

2 December 2021 – added Challenge questions.

10 May 2021 – commented out or deleted empty chapters.

2 October 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

11 Mar 2020 – minor error corrections: wrong type of quotation marks used in a problem, and also had "encoder" written in a footnote where it should have said "decoder". Also expanded on some of the instructor-version answers, and added discussion of enable/strobe inputs to the tutorial.

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

18 December 2019 – minor edits to diagnostic questions, replacing "no multiple faults" with "no coincidental faults".

22 November 2019 – began writing Tutorial.

21 November 2019 – document first created.

Index

Adding quantities to a qualitative problem, 54
Annotating diagrams, 53

Checking for exceptions, 54
Checking your work, 54
Code, computer, 63

Demultiplexer, 3, 12
Demux, 3, 12
Dimensional analysis, 53

Edwards, Tim, 64
Enable, 14, 15

Graph values to solve a problem, 54
Greenleaf, Cynthia, 25

Hold time, 23
How to teach with these modules, 61
Hwang, Andrew D., 65

I/O, 21
Identify given data, 53
Identify relevant principles, 53
Input/Output, 21
Intermediate results, 53
Inverted instruction, 61

Knuth, Donald, 64

Lamport, Leslie, 64
Limiting cases, 54

MCU, 21
Metacognition, 30
Microcontroller, 21
Moolenaar, Bram, 63
Multiplexer, 3, 11
Murphy, Lynn, 25
Mux, 3, 11

Open-source, 63

Problem-solving: annotate diagrams, 53
Problem-solving: check for exceptions, 54
Problem-solving: checking work, 54
Problem-solving: dimensional analysis, 53
Problem-solving: graph values, 54
Problem-solving: identify given data, 53
Problem-solving: identify relevant principles, 53
Problem-solving: interpret intermediate results, 53
Problem-solving: limiting cases, 54
Problem-solving: qualitative to quantitative, 54
Problem-solving: quantitative to qualitative, 54
Problem-solving: reductio ad absurdum, 54
Problem-solving: simplify the system, 53
Problem-solving: thought experiment, 53
Problem-solving: track units of measurement, 53
Problem-solving: visually represent the system, 53
Problem-solving: work in reverse, 54
Pulse width modulation, 9
PWM, 9

Qualitatively approaching a quantitative problem, 54

Reading Apprenticeship, 25
Reductio ad absurdum, 54, 60, 61

Schoenbach, Ruth, 25
Scientific method, 30
Set-up time, 23
Simplifying a system, 53
Socrates, 60

Socratic dialogue, 61
SPICE, 25
Stallman, Richard, 63
Strobe, 14, 15

Thought experiment, 53
Torvalds, Linus, 63

Units of measurement, 53

Visualizing a system, 53

Work in reverse to solve a problem, 54
WYSIWYG, 63, 64