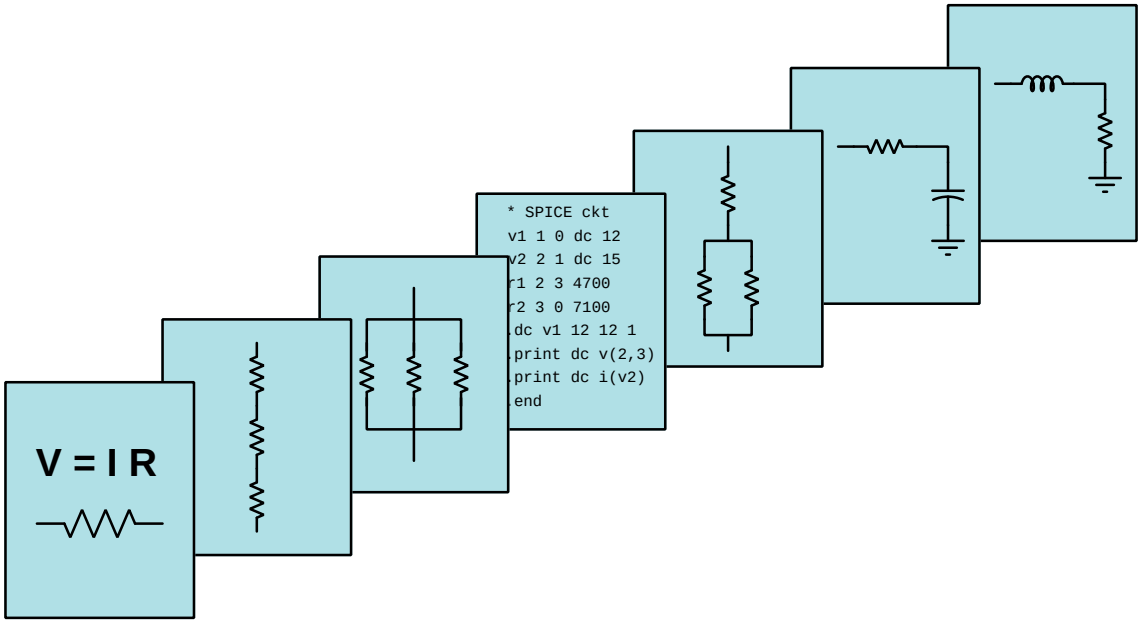
# Modular Electronics Learning (ModEL) project




## SPI Serial Networks



Last update = 10 February 2025

# Contents

# Chapter 1

# Introduction

## 1.1 Recommendations for students

One of the simplest types of digital communication networks used to connect integrated circuits together on a printed circuit board is *SPI*, which stands for *Serial Peripheral Interface*. This module explores the design and operation of SPI serial networks.

Important concepts related to SPI serial communication include **bit rate**, **synchronous** versus **asynchronous**, **tri-state logic**, **shift registers**, **flip-flops**, **clock** signals, **rising** versus **falling** edges, **master-slave** arbitation, and **full-duplex** communication.

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

- How might an experiment be designed and conducted to explore the operation of a shift register? 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 which operating mode (0, 1, 2, or 3) an existing SPI system was using? What hypotheses (i.e. predictions) might you pose for that experiment, and what result(s) would either support or disprove those hypotheses?
- What are some practical applications of SPI data communication?
- How does serial data communication differ from parallel data communication?
- How do synchrounous and asynchronous data communication methods differ?
- What is the purpose of a clock pulse signal in a digital circuit?
- How may a shift register be constructed from multiple flip-flops?
- What are the names and functions of the terminals on SPI devices?
- How does SPI achieve full-duplex communication?

- What are some different ways in which SPI may be used to communicate from one device to multiple other devices?
- How might you alter one of the example analyses shown in the text, and then determine the behavior of that altered circuit?
- Devise your own question based on the text, suitable for posing to someone encountering this subject for the first time

## 1.2 Challenging concepts related to SPI serial networks

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

- **Shift register modes** – the concepts of serial versus parallel data exchange for shift registers can be confusing, but experience has shown that likening these to the movement of packages on and off a conveyor belt is helpful in clarifying the concepts. In this analogy, the packages are data bits while the conveyor belt is the shift register.
- **Synchronous versus Asynchronous communication** – synchronous communication is when two or more digital devices communicate in lock-step with each other due to the simultaneous transmission of a clock signal. Asynchronous communication is when two or more digital devices use internal clocks to keep pace with each other, but rely on a "start" signal of some kind to synchronize themselves together at the start of each data frame. SPI is a synchronous communication standard.

## 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.

- **Outcome** – Apply the concepts of SPI clock and data signals to waveforms

  Assessment – Sketch proper SPI clock and data signal waveforms for given communicated byte values; e.g. pose problems in the form of the "Sketching SPI waveforms" Quantitative Reasoning question.

  Assessment – Properly interpret SPI clock/data waveform pairs for the data they convey.

- **Outcome** – Independent research

  Assessment – Locate datasheets for memory ICs utilizing SPI communication and properly interpret some of the information contained in those documents including minimum data set-up times, minimum data hold times, maximum clock frequency, data frame formats, etc.

  Assessment – Locate datasheets for analog-to-digital converter ICs utilizing SPI communication and properly interpret some of the information contained in those documents including minimum data set-up times, minimum data hold times, maximum clock frequency, data frame formats, etc.

# Chapter 2

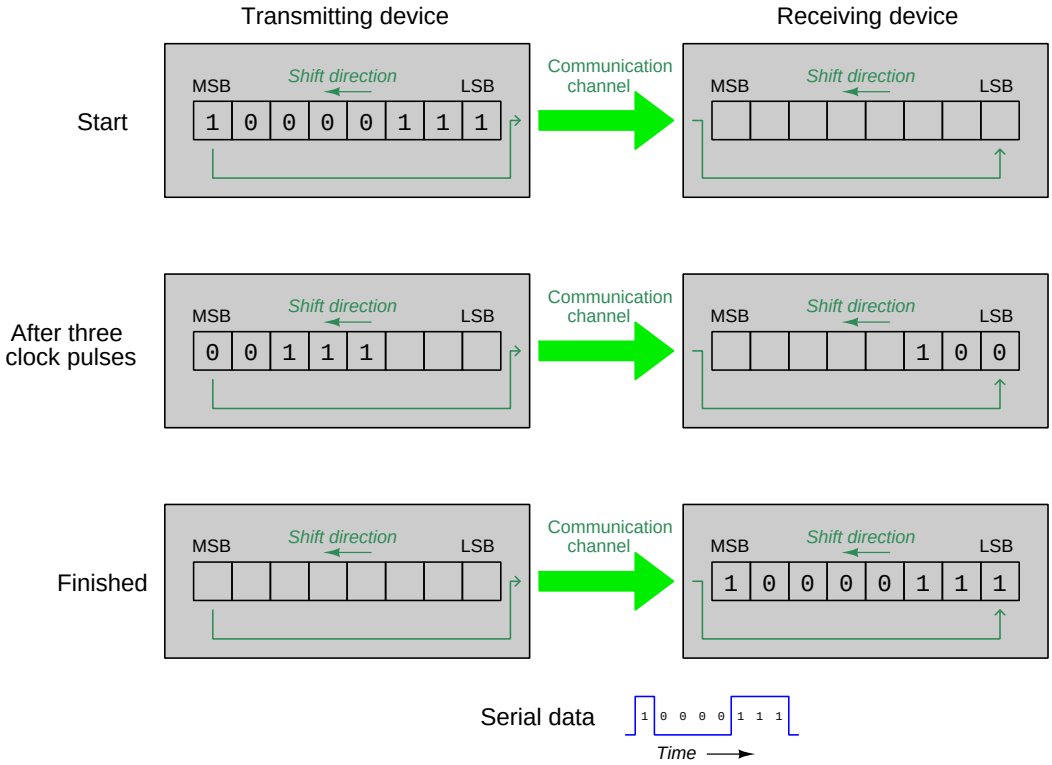
# Tutorial

## 2.1 Serial data communication and shift registers

Digital data is comprised of *bits* of information, each bit being either a 1 or a 0, a high or a low, a true or a false. Collections of bits are generally known as *words*, although some specific numbers of them have unique names, such as a *byte* for an 8-bit word, or a *nybble* for a 4-bit word.

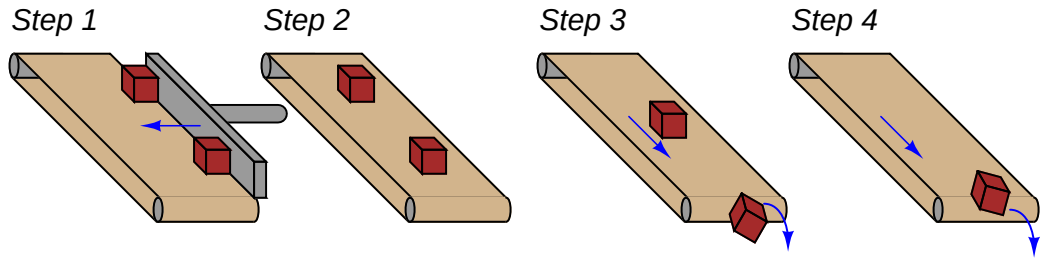
One way to communicate multi-bit digital words from one device to another is to do so one bit at a time over the same conductor(s), and this is known as *serial* communication because the bits are sent in a series over time rather than all at once using one conductor per bit (which is called *parallel* communication). Serial data communication is of course slower than parallel, but enjoys the decided advantage of using fewer conductors which is important in multiple contexts: for long-distance communication, fewer conductors means less expensive and less bulky cable; for communication between ICs on a circuit board, fewer conductors means fewer terminals (pins) necessary on the ICs to exchange that data which in turn means physically smaller devices are possible.

Multiple methods have been standardized for serial data communication, but fundamentally they all involve the use of digital devices known as *shift registers*. The following illustration shows a block diagram of a serial communication system where eight bits (one byte) are shifted out of the transmitting device's shift register, one bit at a time in sequence, and received at the receiving device's shift register to form a complete byte of data. This shifting of bits out of and in to the shift register circuits happens at the command of a signal called a *clock pulse*:

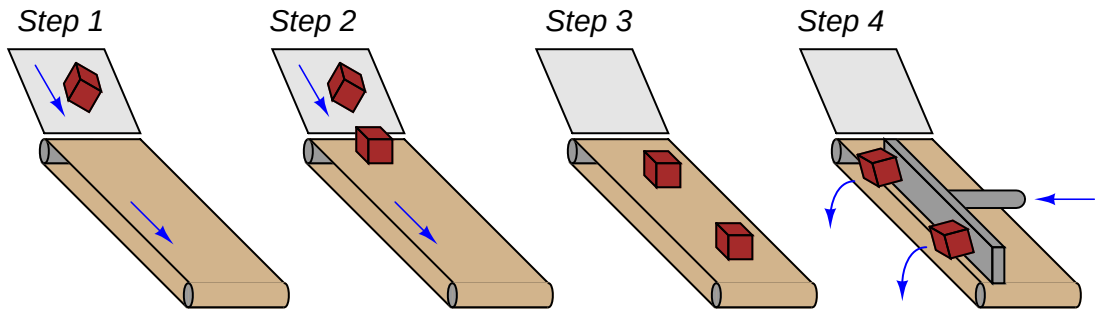


Shift registers are comprised of *flip-flops*, and are designed to move bits of data along from one flip-flop to another in sequence at the command of the clock pulse signal. The action of a shift register may be likened to a conveyor belt where packages move on to and off of the belt in various ways as shown below, the packages representing bits and the conveyor's motion representing the clock pulse:

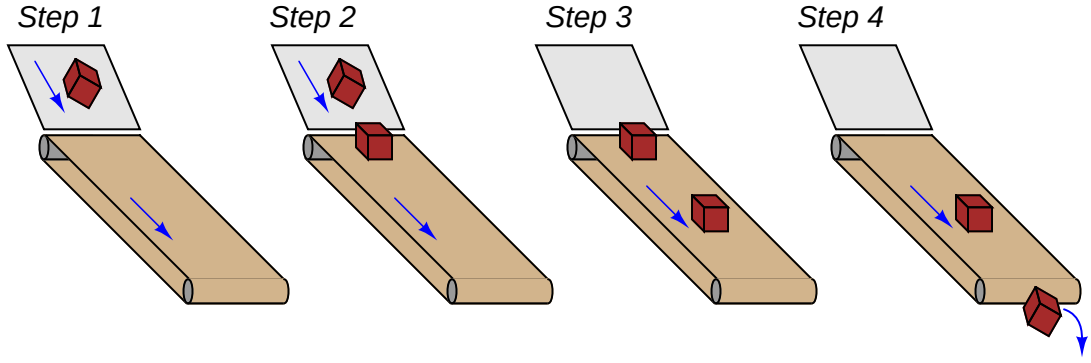
**Parallel-in, serial-out** (used by serial transmitting devices)



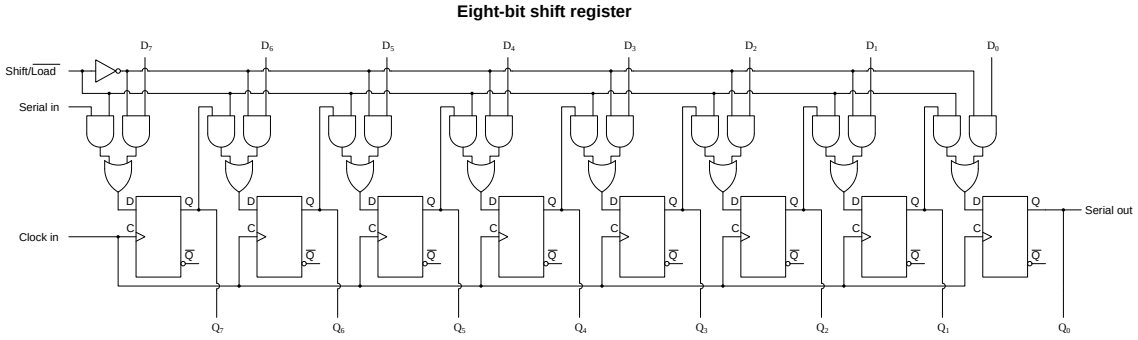

**Serial-in, parallel-out** (used by serial receiving devices)



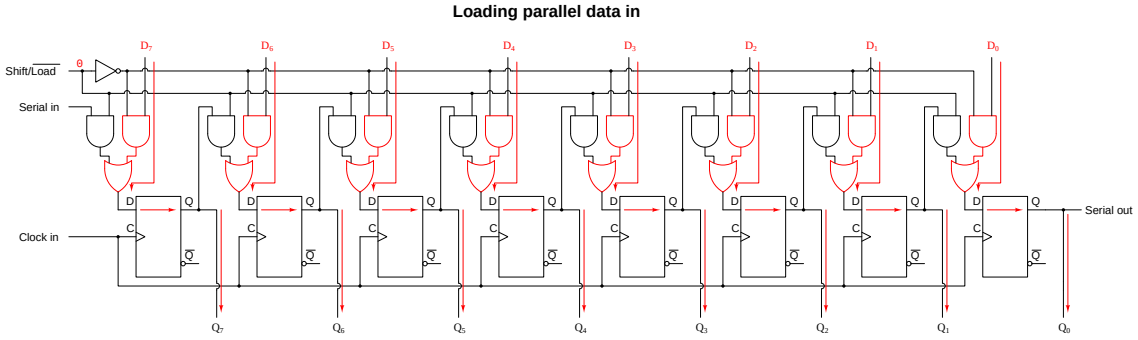

**Serial-in, serial-out**



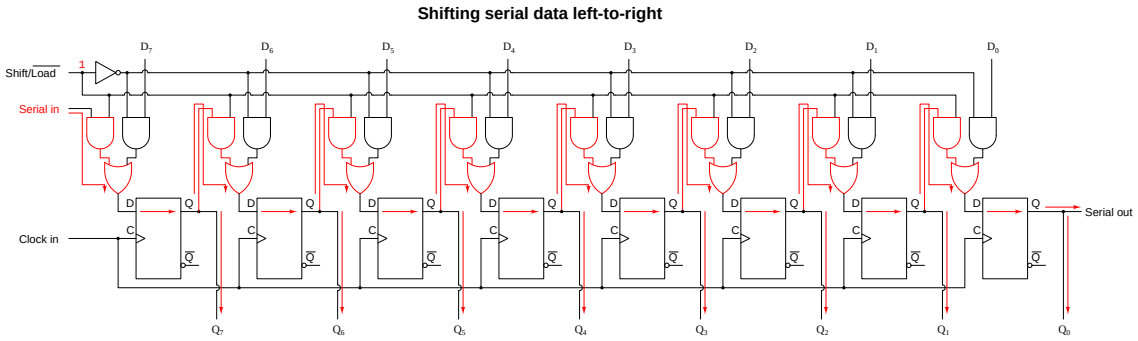
Shown below is a schematic diagram for an eight-bit (one-byte) shift register capable of all three modes of operation illustrated on the previous page. Lines $D_0$ through $D_7$ are for parallel data input, while lines $Q_0$ through $Q_7$ are for parallel data output. Serial data enters the shift register one bit at a time through the single "Serial in" line on the left, and exits the shift register one bit at a time through the single "Serial out" line on the right. A single "Clock" input receives a pulse signal causing parallel data to be fed into all the D-type flip-flops when the control line is in the Load state (i.e. "low"), and causing serial data to shift from left to right through all the D-type flip-flops when the control line is in the Shift state (i.e. "high"):




The AND/OR gate networks *steer* digital data to those flip-flops from different sources. In the "Load" mode of operation these steering gates route data from the parallel input terminals to the eight flip-flops as shown in red below:



In the "Shift" mode of operation these steering gates route data from one flip-flop stage to the next as shown in red below:




While all serial data communication systems employ shift registers at some level to convert between parallel and serial data formats, a range of different options distinguishes one standard from another. Some of this options include:

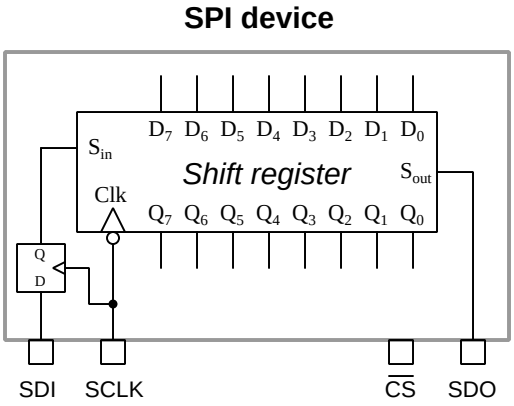
- The rate(s) at which the serial data may be communicated
- The manner in which clock pulses are synchronized between transmitter and receiver
- The exact voltage levels or other electrical characteristics of the serial data bits
- Properties of the communication channel connecting transmitter and receiver(s) together, for example the number of wires used and whether the signals are *single-ended* or *differential*

For example, a serial communication standard may specify certain allowable bit rates (i.e. bits per second), or let this be up to the end-user to decide. A serial communication standard may utilize a common clock pulse signal to drive both transmitter and receiver (called a *synchronous* network), or may use separate clock pulse generators at the transmitting and receiving ends which must be synchronized periodically to stay in-step with each other (called an *asynchronous* network). A serial communication standard may utilize common digital logic voltage levels to represent the 1 and 0 logical states of each bit, or it may use a much different set of voltage levels, or may even use some form of signal other than "high" and "low" voltage states to represent bits (e.g. using different audio-frequency tones). Many combinations exist on which to formulate a serial communications standard, which is why we have so many to choose from: EIA/TIA-232, EIA/TIA-485, SPI, I2C, 1-Wire, and Ethernet to name a few.

## 2.2 SPI device features

*Serial Peripheral Interface*, or *SPI*, is a loose standard for serial data communication primarily intended for IC-to-IC communication on a printed circuit board. It is a "loose" standard because no formal standard has been agreed upon by manufactures, but the simplicity of SPI hardware makes a formal standard *almost* unnecessary.

All SPI devices have (at least) four terminals (pins) used for communication, as shown in the partial schematic diagram below:



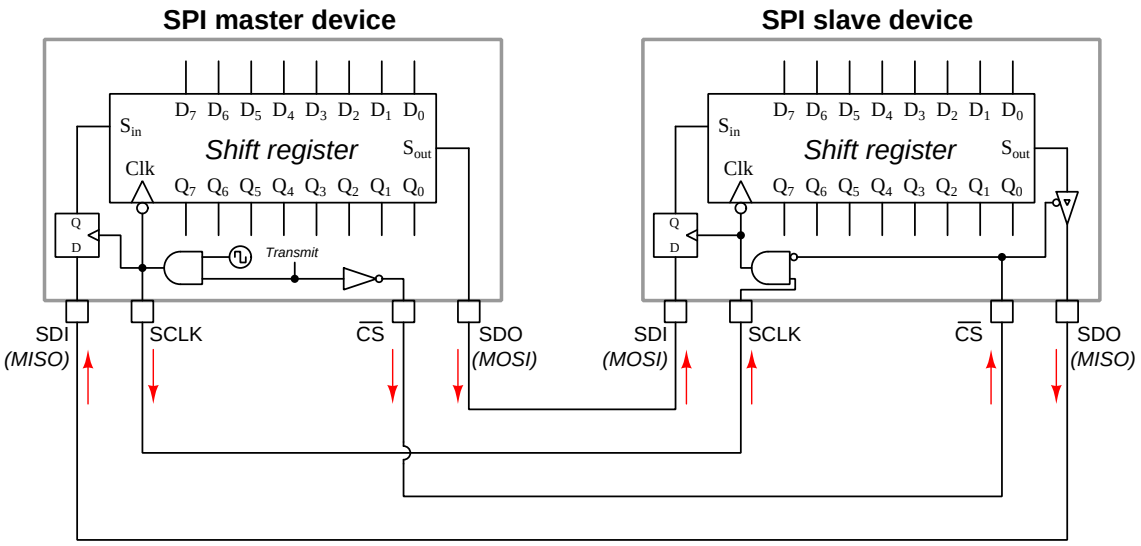

Serial data gets shifted into the first D-type flip-flop through the SDI (Serial Data In) terminal and shifted out of the register through the SDO (Serial Data Out) terminal at the command of a clock pulse signal on the SCLK (Serial CLocK) terminal. Note how the sampling D-type flip-flop and the shift register are each clocked on a different edge of the SCLK pulse: in this case, incoming serial data gets sampled from the SDI terminal on the pulse's rising edge and then shifted through the device's internal shift register on the pulse's falling edge.

In the example shown here that internal shift register stores eight bits of data, and so after eight clock pulses the last eight bits clocked serially into the shift register will be available for the device to read in parallel form. If and when the time comes for that device to write data onto the SPI network, it will load eight bits of data in parallel form into the shift register and then await eight clock pulses applied to its SCLK terminal to send those eight bits out in serial form at the SDO terminal.

An active-low CS (Chip Select) terminal determines if the device is active and ready to serially communicate. For a transmitting device, Chip Select is an output signal commanding a receiving device to prepare to receive data; for a receiving device, Chip Select is an input signal that acts not only to enable the clock signal input but also as a tri-state enable for its serial output line.

## 2.3 Minimal SPI network

A minimal SPI network comprised of two devices would work like this:




The device generating the SCLK and Chip Select signals is called the *master* and the device receiving both those signals is called the *slave*, because the master is in full control of the communication process while the slave must do the master's bidding. For this reason, the SDI and SDO terminals whose labels refer to the direction of data flow relative to the device are often given the more absolute labels of MISO (Master In, Slave Out) and MOSI (Master Out, Slave In) as shown in the above diagram. In recent years (as of this writing in 2024) several manufacturers have re-named these functions with terms intended to be less politically offensive, resulting in *several* synonyms[1] for master and slave alike.

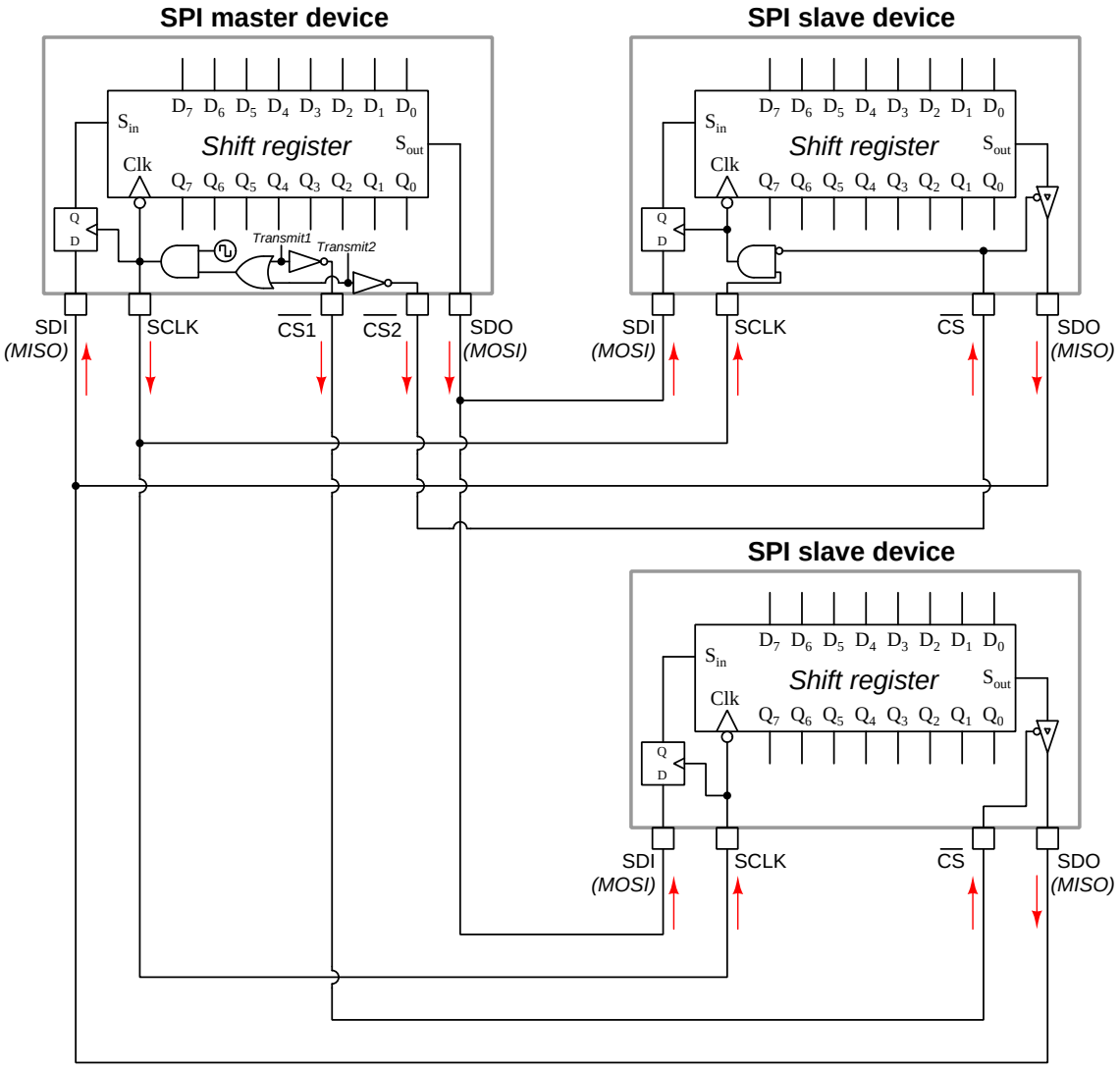
SPI networks are *synchronous* because a common clock signal line connects all the devices together to ensure synchronization of data flow at all times. This also means that the clock frequency (i.e. bit rate) is completely arbitrary. Given the short distances over which SPI is typically used to convey data between devices on a common circuit board, clock frequencies are typically in the megaHertz range.

An interesting characteristic of SPI networks is that the flow of information is full-duplex (i.e. data communicated both ways between the devices simultaneously). As bits serially output the master's shift register and enter the slave's shift register, any data that was previously loaded into the slave's register will output that register serially and be read by the master device.

[1] Some people view the words *master* and *slave* to be too reminiscent of the brutal slave regime that dominated much of early American economy and culture, especially in the southern states. They claim that modern use of these words, even in reference to inanimate objects such as digital logic circuits, perpetuates the generally poorer standard of living for black Americans by unnecessarily recalling this historical blight. Some of the alternative names proposed for master/slave include controller/peripheral, main/sub, primary/secondary, manager/subordinate, parent/child, etc.

## 2.4 Larger SPI networks

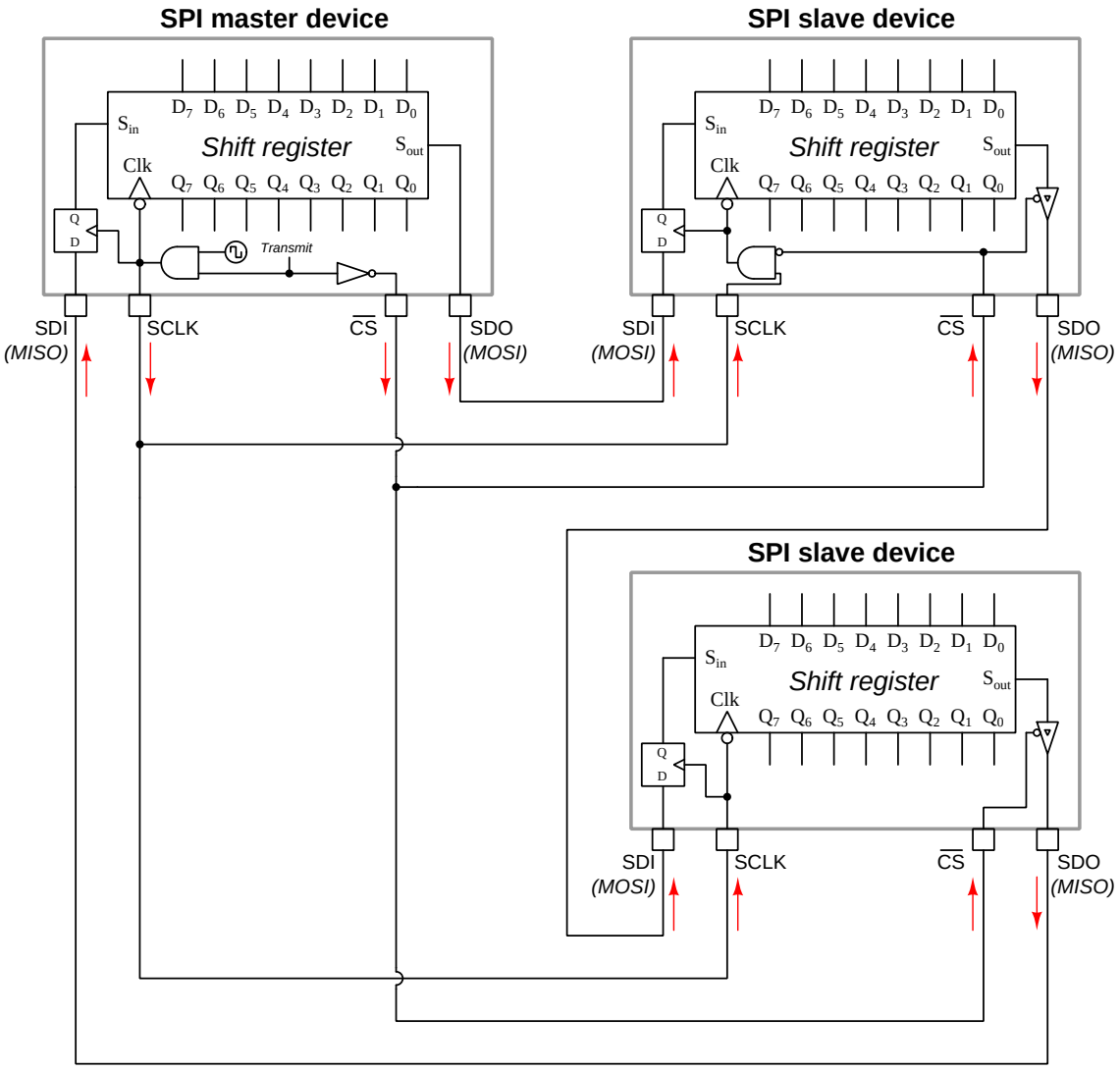
In SPI systems with multiple slave devices, more than one way exists to link them together. One method, shown below, equips the master device with multiple Chip Select output terminals, each one dedicated to enabling one slave device at a time:




Here we may clearly see the importance of the Chip Select inputs on each slave device. When the Chip Select input on a slave device is in the inactive ("high") state, that slave device's Serial Out terminal goes into high-impedance mode and essentially disconnects that output terminal of its shift register from the Serial Out terminal in order to avoid any conflicts with other slave devices

whose Serial Out terminals are electrically common.

Another method for an SPI master device to communicate to multiple slave devices is to form a large serial loop using the Serial Data In and Serial Data Out terminals of each, so that data pushed out of one flows through the next and eventually back to the master device's Serial Data In terminal:



## 2.5 SPI clock modes

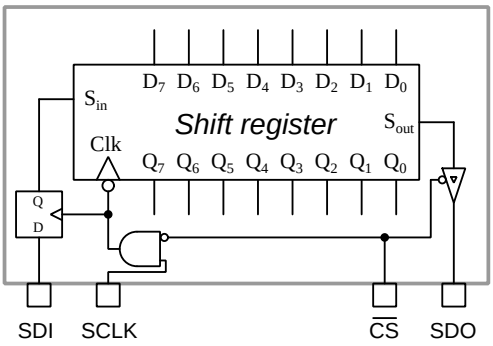
As was mentioned earlier, SPI is a fairly "loose" standard with few constraints on how signals must relate to each other, other than the characteristics essential for making shift registers function together to exchange data serially. One of the "loose" aspects of SPI is the clock signal's idle state and active edge, which may be any one of four combinations depending on the SPI device hardware used. These four combinations are known as *modes*, and are defined as follows:

- **Mode 0** – Data is sampled into the receiving device on the *rising* edge of the clock pulse, with the clock signal defaulting to a *"low"* state when the network is idle
- **Mode 1** – Data is sampled into the receiving device on the *falling* edge of the clock pulse, with the clock signal defaulting to a *"low"* state when the network is idle
- **Mode 2** – Data is sampled into the receiving device on the *falling* edge of the clock pulse, with the clock signal defaulting to a *"high"* state when the network is idle
- **Mode 3** – Data is sampled into the receiving device on the *rising* edge of the clock pulse, with the clock signal defaulting to a *"high"* state when the network is idle

As the master SPI device is typically a programmable IC such as a microcontroller or an FPGA, the SPI communication mode is typically something the engineer or technician sets as a device parameter in order to match the characteristics of non-programmable slave devices.

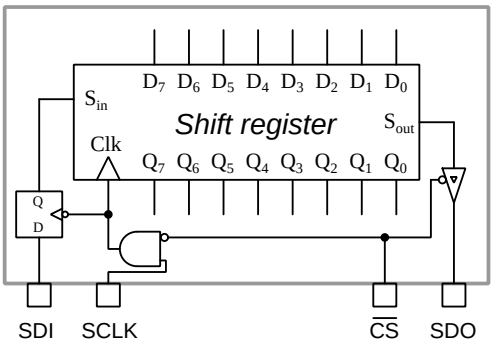
From a hardware perspective, the distinction between these four modes is a matter of clock signal inversion for the sampling flip-flop and shift register, respectively, as well as the inhibiting action of the Chip Select input on that clock signal. Shown below are internal schematic diagrams of SPI slave devices designed to operate in one of these four modes:

**Mode 0 SPI device**



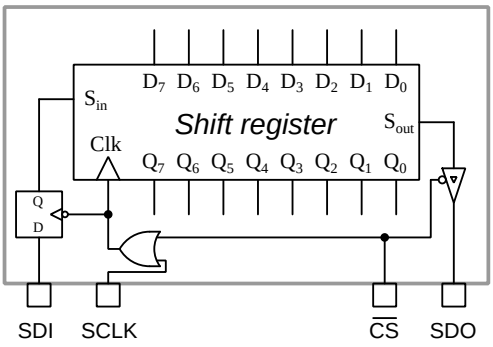

*Samples on SCLK rising edge*
*Shifts on SCLK falling edge*
*Idle state of SCLK is low*

**Mode 1 SPI device**



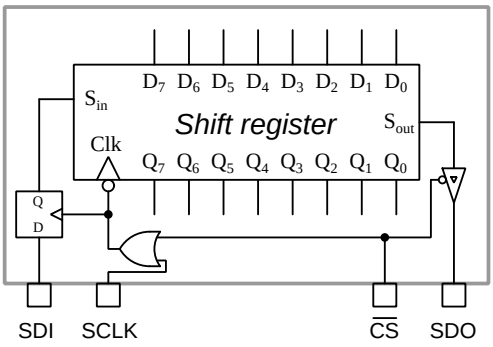

*Samples on SCLK falling edge*
*Shifts on SCLK rising edge*
*Idle state of SCLK is low*

**Mode 2 SPI device**




*Samples on SCLK falling edge*
*Shifts on SCLK rising edge*
*Idle state of SCLK is high*

**Mode 3 SPI device**




*Samples on SCLK rising edge*
*Shifts on SCLK falling edge*
*Idle state of SCLK is high*

Note how the AND gates contained within the mode 0 and 1 devices effectively disable clocking of the D-type flip-flop and the shift register if either SCLK is idle (low) or Chip Select is high. Similarly, the OR gates contained within the mode 2 and 3 devices disable clocking of the flip-flop and shift register if either SCLK is idle (high) or Chip Select is high. In all four modes the SDO output is forced into high-impedance (floating) mode whenever the Chip Select signal is high.

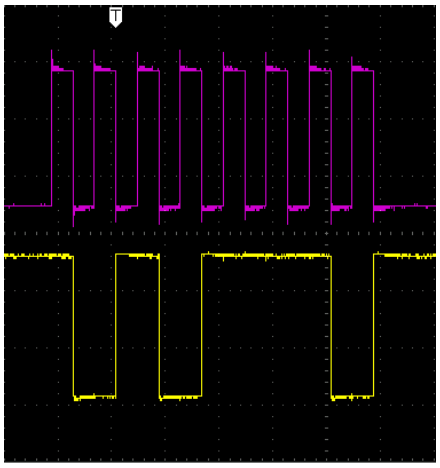
Just to make things confusing, some SPI devices specify mode using a pair of binary bits that together equal the mode number: the most-significant of these being CPOL (Clock POLarity) and the least-significant of these being CPHA (Clock PHAse). The Clock Phase bit value is fairly simple to understand: a CPOL value of 0 refers to the clock signal's idle state being "low" while a CPOL value of 1 means the clock defaults to a "high" idle state. The Clock Phase bit value's meaning is not quite as clear: here, a CPHA value of 0 means the data gets sampled as the clock signal transitions from its idle state toward its other state while a CPHA value of 1 means the data gets sampled as the clock signal transitions toward its idle state:

| | CPOL | CPHA |
|---|---|---|
| Mode 0 | 0 =  | 0 =  |
| Mode 1 | 0 =  | 1 =  |
| Mode 2 | 1 =  | 0 =  |
| Mode 3 | 1 =  | 1 =  |

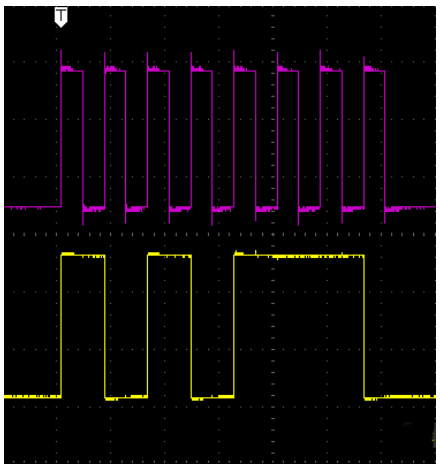
Again, these settings are typically found only in SPI master-capable devices which are almost universally *programmable* and therefore support such customization.

To illustrate, we will now examine four different oscillographs of the same 8-bit word being communicated via SPI, each image representing one of the four modes. In each example the binary word is `0b10101110` with the most-significant bit transmitted first and the least-significant bit transmitted last. The violet trace is the SCLK (Clock) signal while the yellow trace is the data signal measured at the SDO (Serial Data Out) output of the microcontroller, which of course would be connected to the SDI input of the slave device(s):

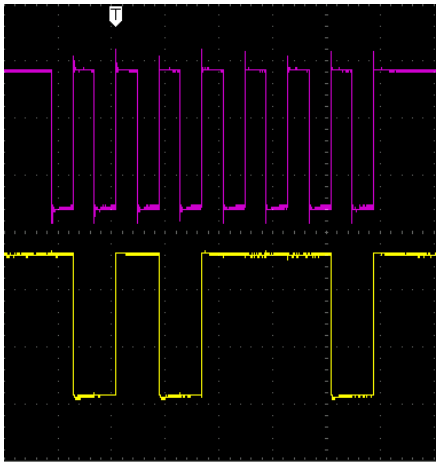
**SPI clock mode 0** – data sampled on rising edge and shifted on falling edge of SCLK, idle state of SCLK is low:



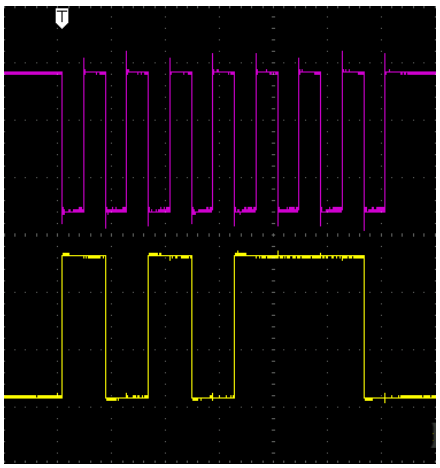
**SPI clock mode 1** – data sampled on falling edge and shifted on rising edge of SCLK, idle state of SCLK is low:



**SPI clock mode 2** – data sampled on falling edge and shifted on rising edge of SCLK, idle state of SCLK is high:



**SPI clock mode 3** – data sampled on rising edge and shifted on falling edge of SCLK, idle state of SCLK is high:



# Chapter 3

# Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

## 3.1 ASCII character codes

ASCII characters consist of seven-bit digital words. The following table shows all 128 possible combinations of these seven bits, from 0000000 (ASCII "NUL" character) to 1111111 (ASCII "DEL" character). For ease of organization, this table's columns represent the most-significant three bits of the seven-bit word, while the table's rows represent the least-significant four bits. For example, the capital letter "C" would be encoded as 1000011 in the ASCII standard.

| ↓ LSB / MSB → | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
|---|---|---|---|---|---|---|---|---|
| 0000 | NUL | DLE | SP | 0 | @ | P | ‘ | p |
| 0001 | SOH | DC1 | ! | 1 | A | Q | a | q |
| 0010 | STX | DC2 | ” | 2 | B | R | b | r |
| 0011 | ETX | DC3 | # | 3 | C | S | c | s |
| 0100 | EOT | DC4 | $ | 4 | D | T | d | t |
| 0101 | ENQ | NAK | % | 5 | E | U | e | u |
| 0110 | ACK | SYN | & | 6 | F | V | f | v |
| 0111 | BEL | ETB | ’ | 7 | G | W | g | w |
| 1000 | BS | CAN | ( | 8 | H | X | h | x |
| 1001 | HT | EM | ) | 9 | I | Y | i | y |
| 1010 | LF | SUB | * | : | J | Z | j | z |
| 1011 | VT | ESC | + | ; | K | [ | k | { |
| 1100 | FF | FS | , | < | L | \ | l | \| |
| 1101 | CR | GS | − | = | M | ] | m | } |
| 1110 | SO | RS | . | > | N | ˆ | n | ˜ |
| 1111 | SI | US | / | ? | O | _ | o | DEL |

It is worth noting that the ASCII codes for the Arabic numerals 0 through 9 are simply the four-bit binary representation of those numbers preceded by 011. For example, the number six (0110) is represented in ASCII as 0110110; the number three (0011) in ASCII as 0110011; etc. This is useful to know, for example, if you need to program a computer to convert single decimal digits to their corresponding ASCII codes: just take each four-bit numerical value and add forty-eight (0x30 in hexadecimal) to it.

## 3.2 The OSI Reference Model

| | |
|---|---|
| Layer 7<br>**Application** | This is where digital data takes on practical meaning in the context of some human or overall system function.<br>*Examples: HTTP, FTP, HART, Modbus* |
| Layer 6<br>**Presentation** | This is where data gets converted between different formats.<br>*Examples: ASCII, EBCDIC, MPEG, JPG, MP3* |
| Layer 5<br>**Session** | This is where "conversations" between digital devices are opened, closed, and otherwise managed for reliable data flow.<br>*Examples: Sockets, NetBIOS* |
| Layer 4<br>**Transport** | This is where complete data transfer is handled, ensuring all data gets put together and error-checked before use.<br>*Examples: TCP, UDP* |
| Layer 3<br>**Network** | This is where the system determines network-wide addresses, ensuring a means for data to get from one node to another.<br>*Examples: IP, ARP* |
| Layer 2<br>**Data link** | This is where basic data transfer methods and sequences (frames) are defined within the smallest segment(s) of a network.<br>*Examples: CSMA/CD, Token passing, Master/Slave* |
| Layer 1<br>**Physical** | This is where data bits are equated to electrical, optical, or other signals. Other physical details such as cable and connector types are also specified here.<br>*Examples: EIA/TIA-232, 422, 485, Bell 202* |

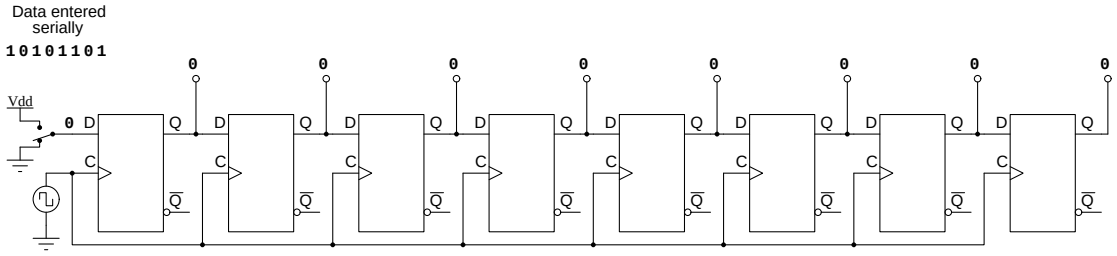
# Chapter 4

# Animations

Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed to be viewed by paging forward (and/or back) with the document-reading software application, watching it frame-by-frame. Unlike video which may be difficult to pause at certain moments, "flip-book" animations lend themselves very well to individual frame viewing.

## 4.1 Animation of serial-in, parallel-out shift register

The following animation shows an eight-bit serial-in, parallel-out shift register accepting a serial stream of eight bits and one-by-one shifting them to its eight output lines for parallel reading.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Vdd
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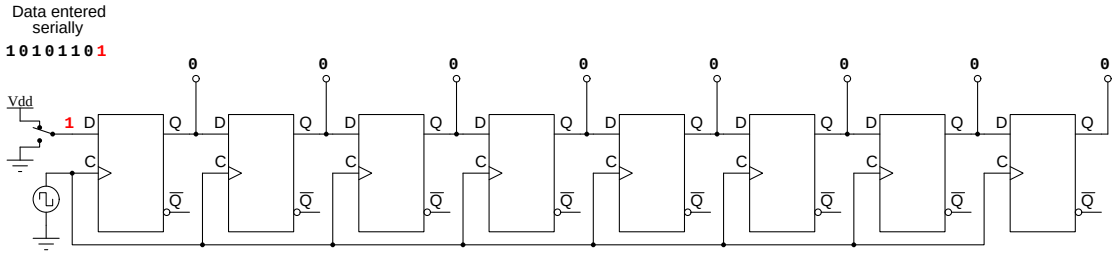
D
C
Q
$\overline{Q}$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D
Q
C
Q
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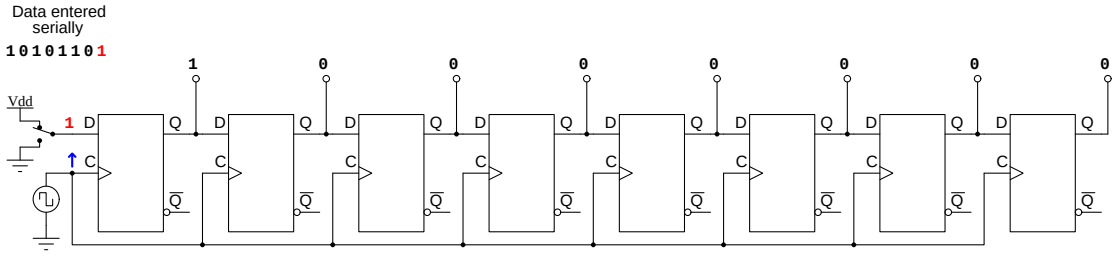
Data entered serially
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Vdd
1
D
C
Q
$\overline{Q}$
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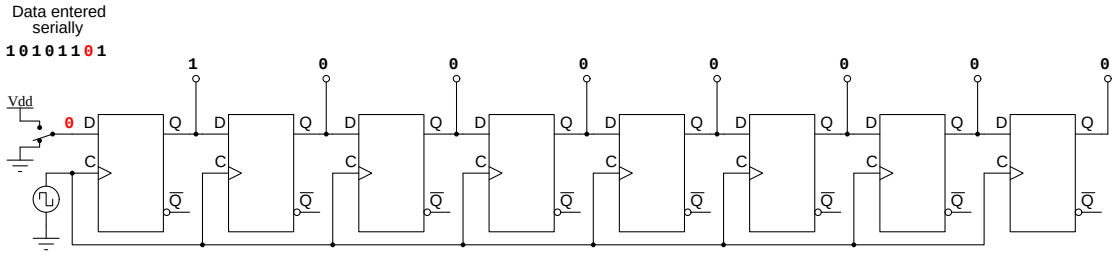
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Vdd
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D
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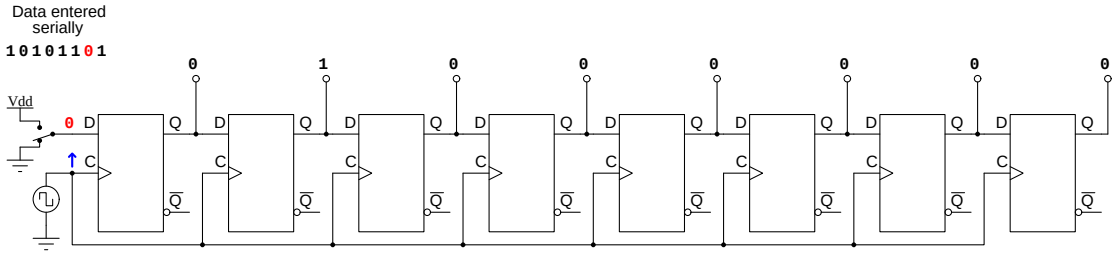
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Vdd
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D
C
Q
$\overline{Q}$
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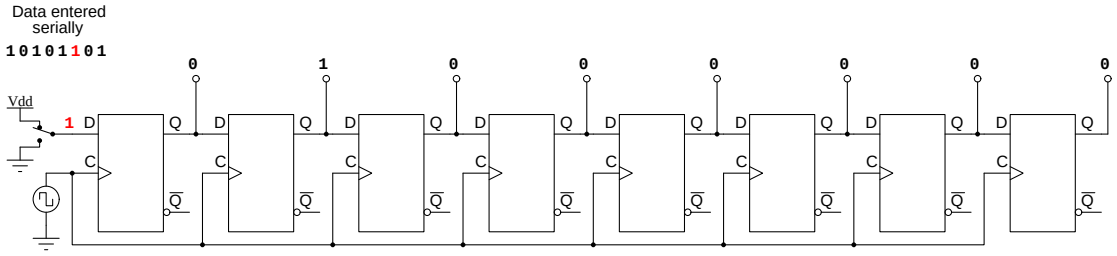
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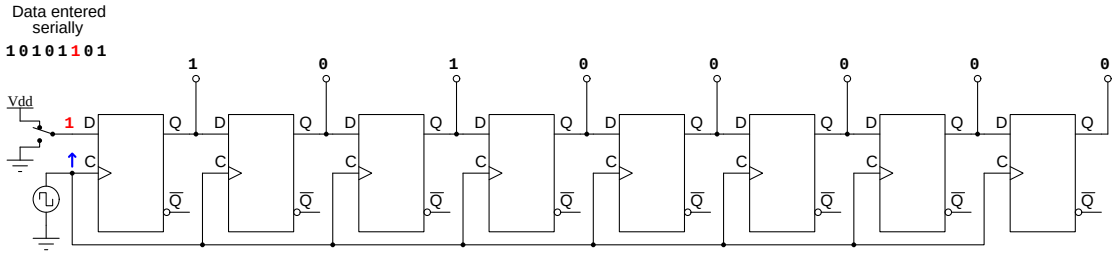
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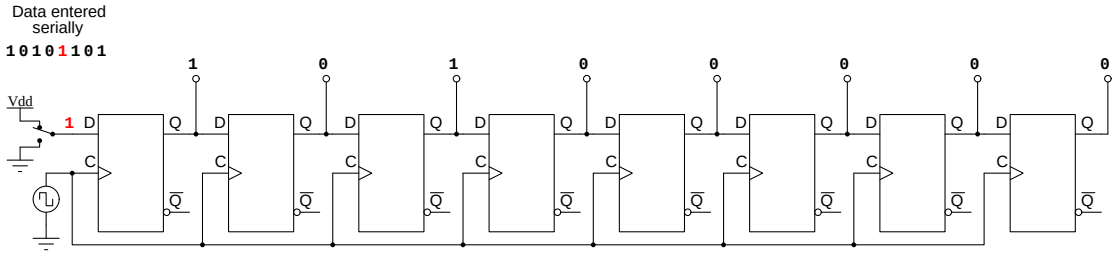
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Q
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Q
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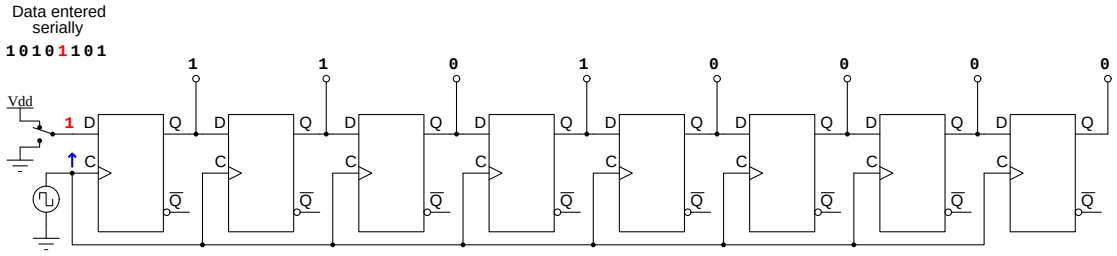
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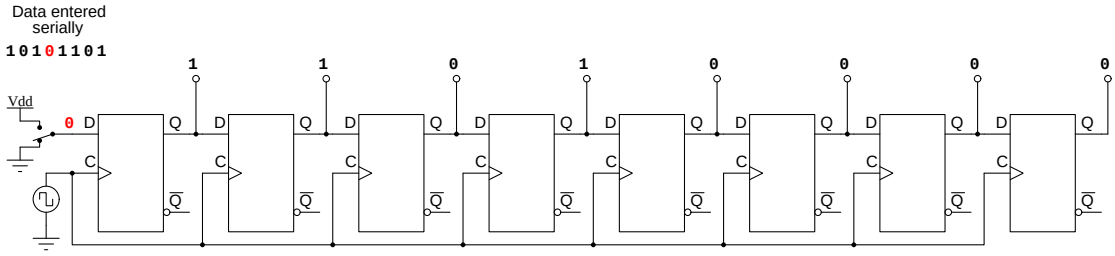
Vdd
1
D
C
Q
$\overline{Q}$
1
1
0
1
0
0
0
0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Vdd
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Q
C
Q
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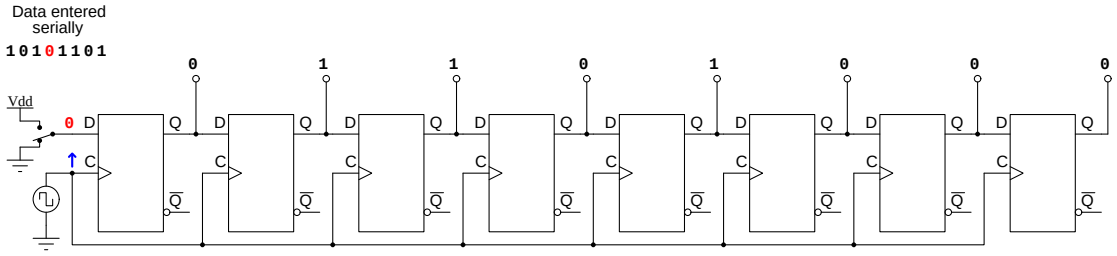
0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Vdd
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D
C
Q
$\overline{Q}$
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1
1
0
1
0
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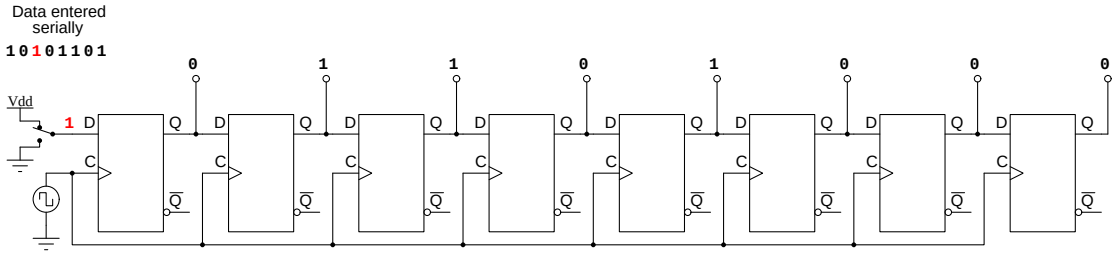
0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Vdd
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Q
C
Q
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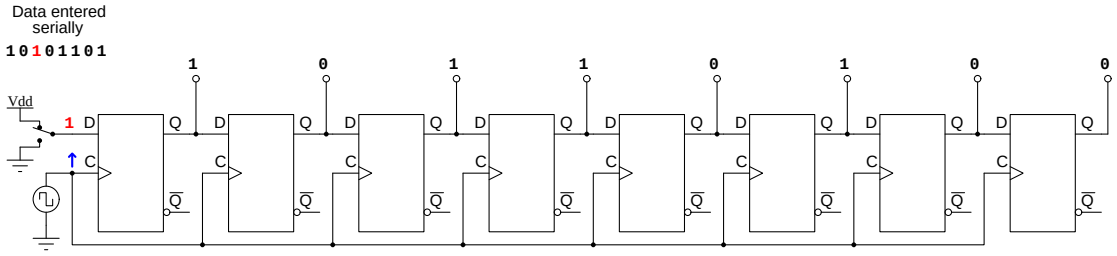
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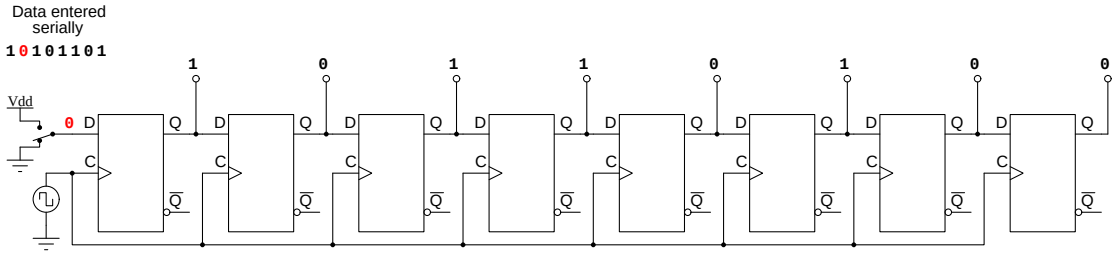
Vdd
1
D
C
Q
Q
1
0
1
1
0
1
0
0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Vdd
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Q
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Q
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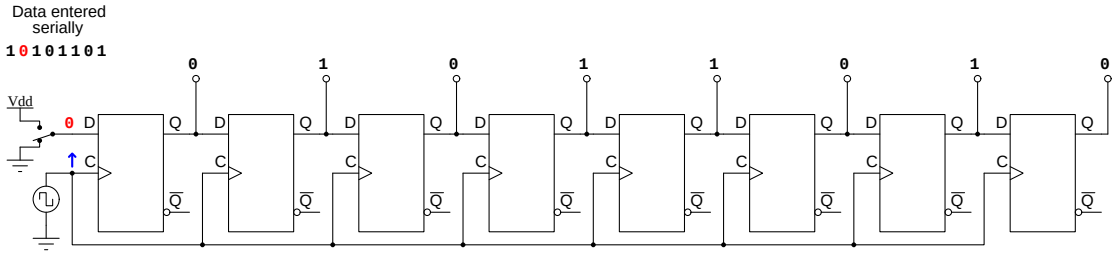
Data entered serially
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Vdd
0
D
C
Q
$\overline{Q}$
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1
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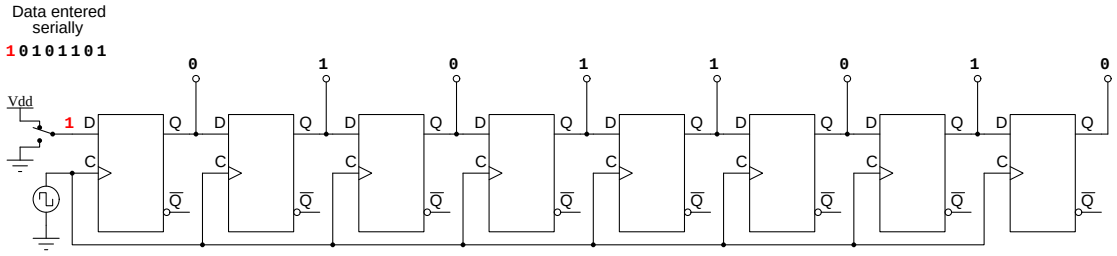
1
1
0
1
0


Data entered
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Vdd
1
D
Q
C
Q
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1
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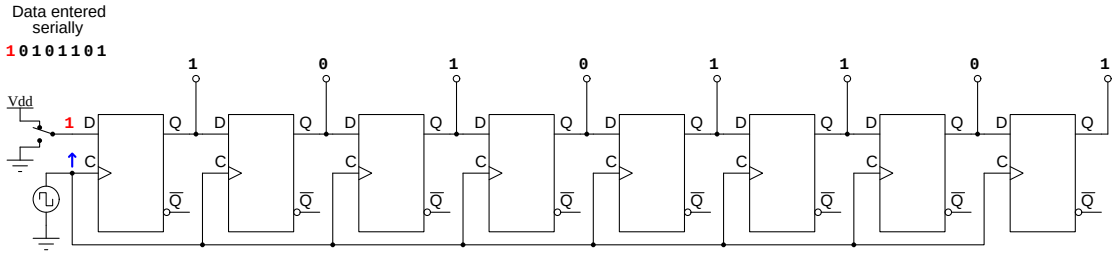
1
0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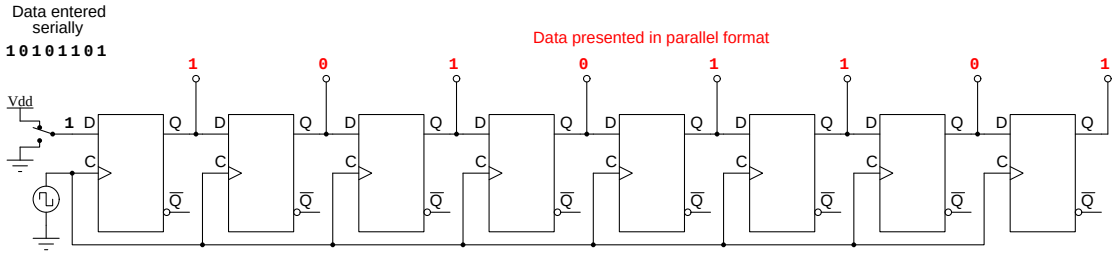
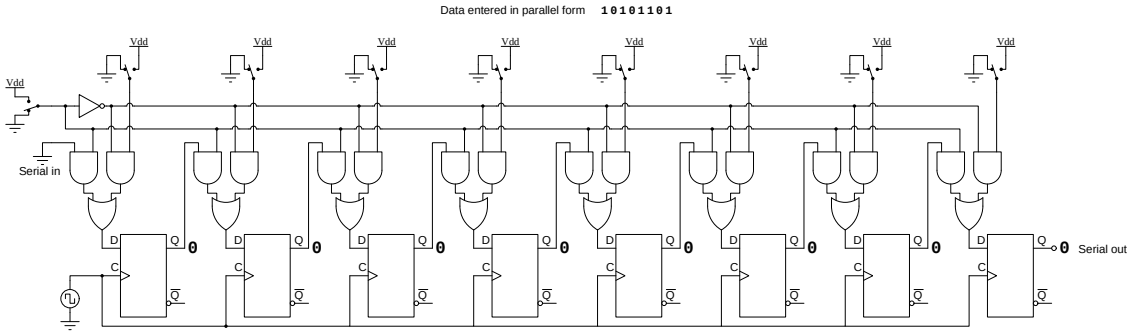
Vdd
1
D
C
Q
$\overline{Q}$
1
0
1
0
1
1
0
1


Data entered serially
10101101
Data presented in parallel format
1 0 1 0 1 1 0 1
Vdd
1
D
Q
C
Q̄

## 4.2 Animation of parallel-in, serial-out shift register

The following animation shows an eight-bit parallel-in, serial-out shift register accepting a parallel batch of of eight bits and one-by-one shifting them to its eight output lines for serial transmission to some other digital circuit.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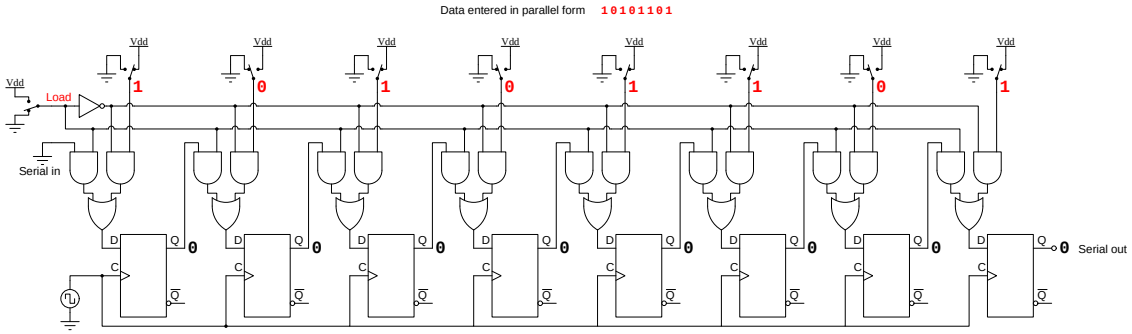
Vdd
Serial in
D
Q
C
Q
0
Serial out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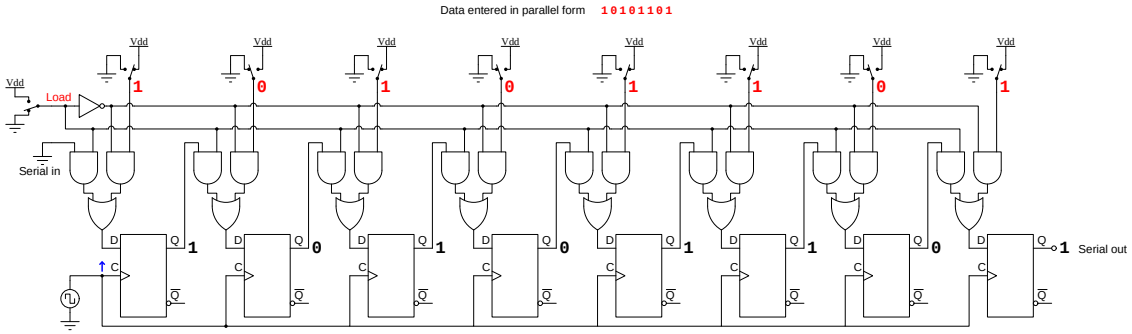
Vdd
Load
Serial in
Serial out
D
Q
C
1
0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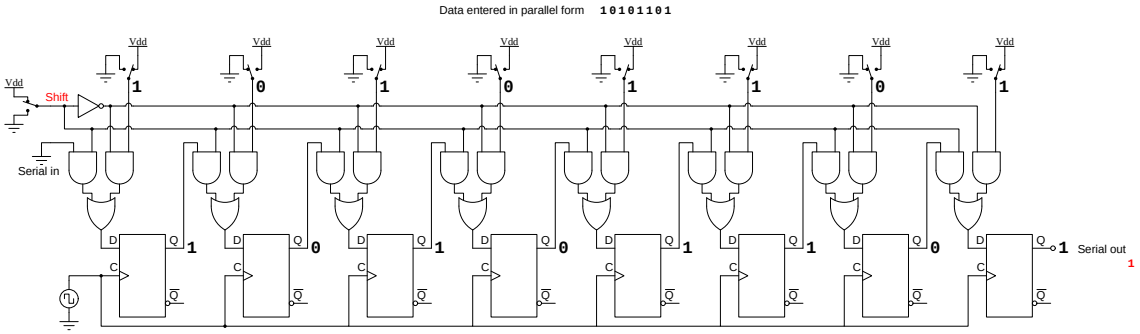
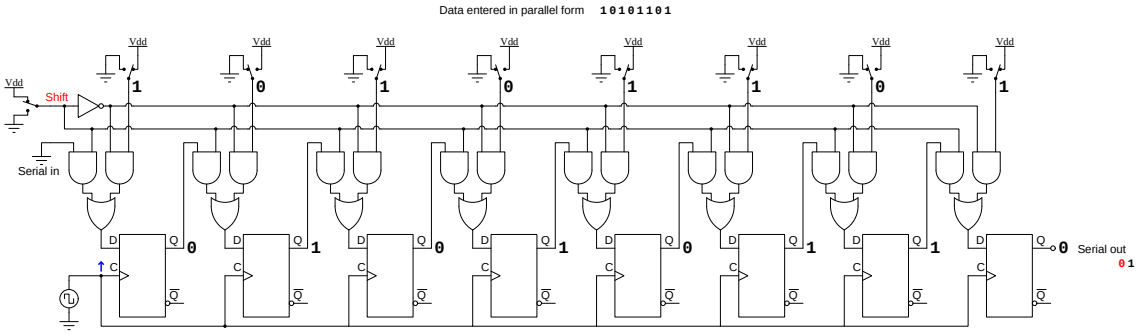
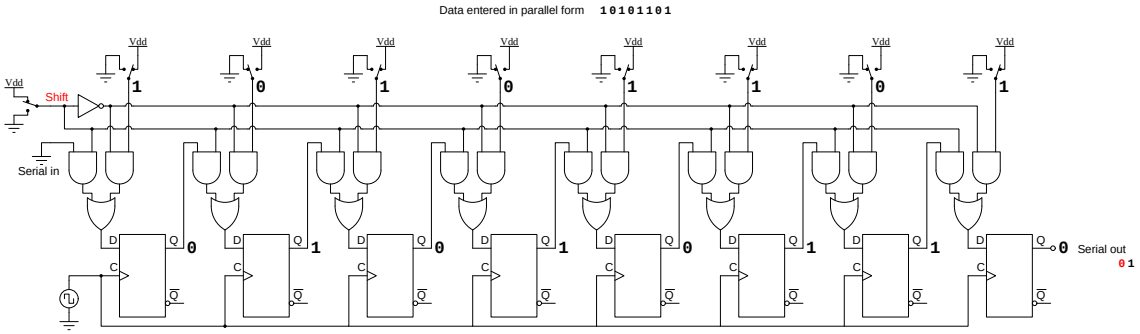
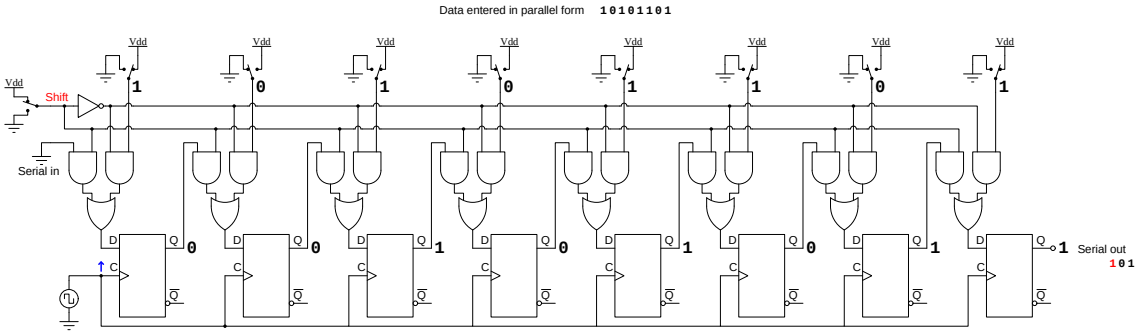
Vdd
Load
Serial in
Serial out
D
Q
C
1
0


Data entered in parallel form 10101101
Vdd
Shift
Serial in
1
0
1
0
1
1
0
1
D
Q
C
Q
1
0
1
0
1
1
0
1
Serial out
1


Data entered in parallel form 10101101
Vdd
Shift
Serial in
Serial out
01
D
Q
C
Q̄


Data entered in parallel form 10101101
Vdd
Shift
Serial in
1
0
1
0
1
1
0
1
D
Q
C
Q
0
1
0
1
0
1
1
0
Serial out
01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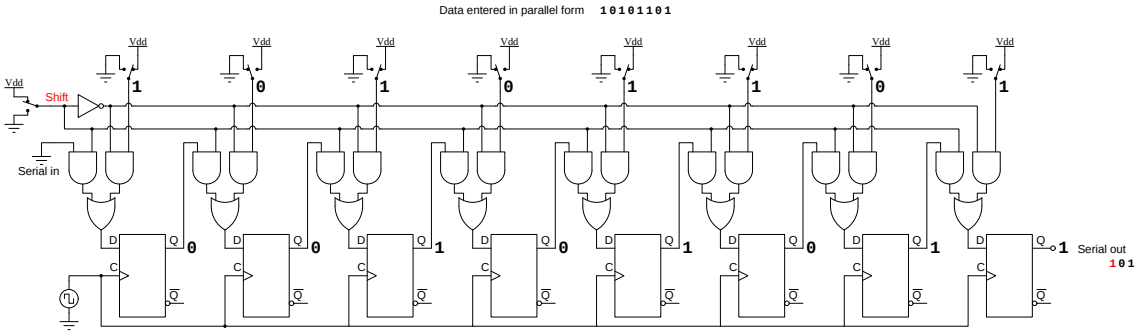
Vdd
Shift
Serial in
Serial out
101
D
Q
C
Q̄


Data entered in parallel form 10101101
Vdd
Shift
Serial in
1
0
1
0
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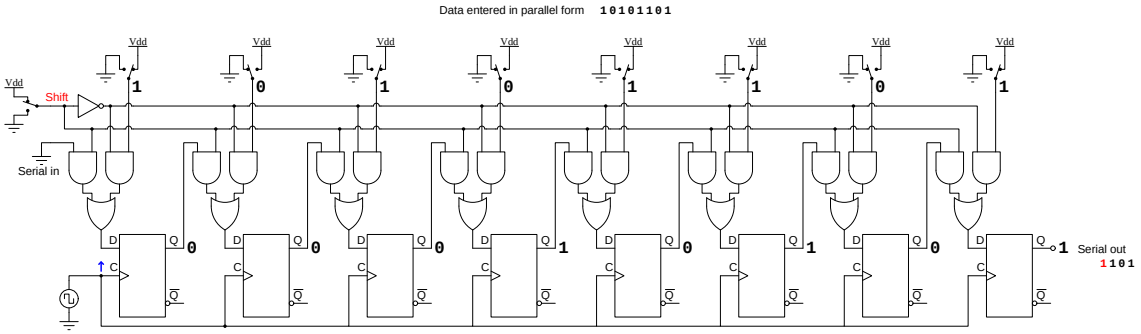
0
1
D
Q
C
Q
0
0
1
0
1
0
1
1
Serial out
101


Data entered in parallel form 10101101
Vdd
Shift
Serial in
1
0
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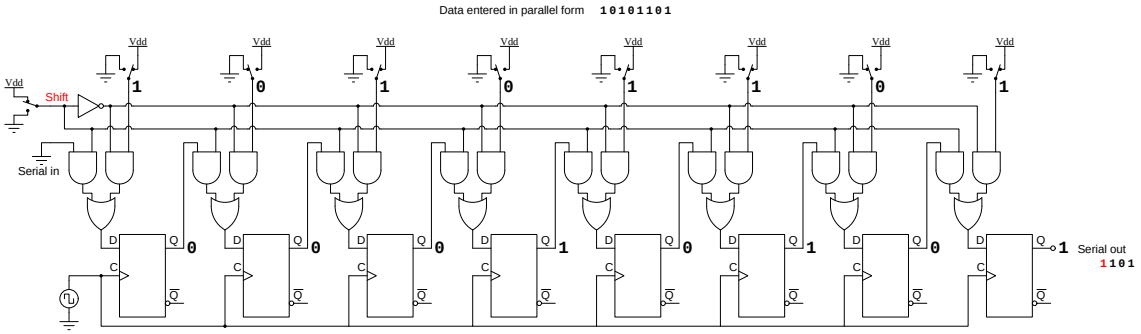
1
D
Q
C
Q
0
0
0
1
0
1
0
1
Serial out
1101


Data entered in parallel form 10101101
Vdd
Shift
Serial in
1
0
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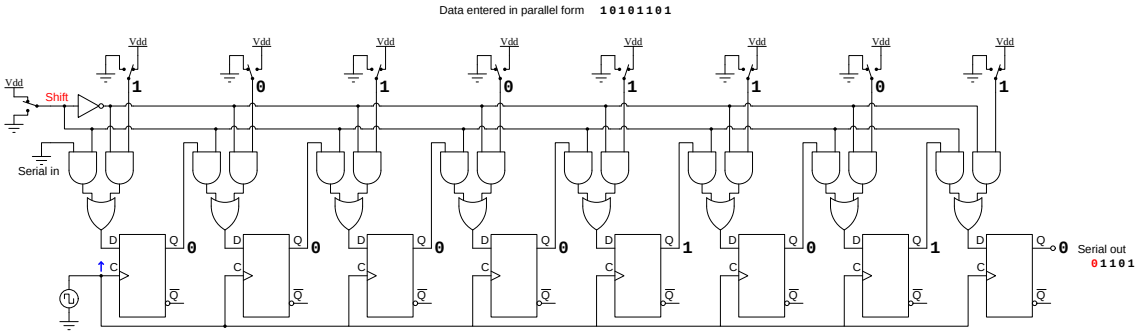
D
Q
C
Q
0
1
Serial out
1101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Vdd
Shift
Serial in
1
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D
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1
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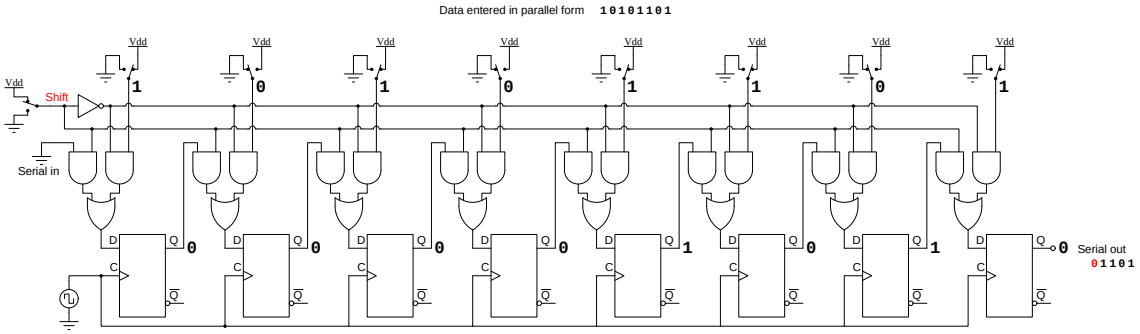
1
0
Serial out
01101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Vdd
Shift
Serial in
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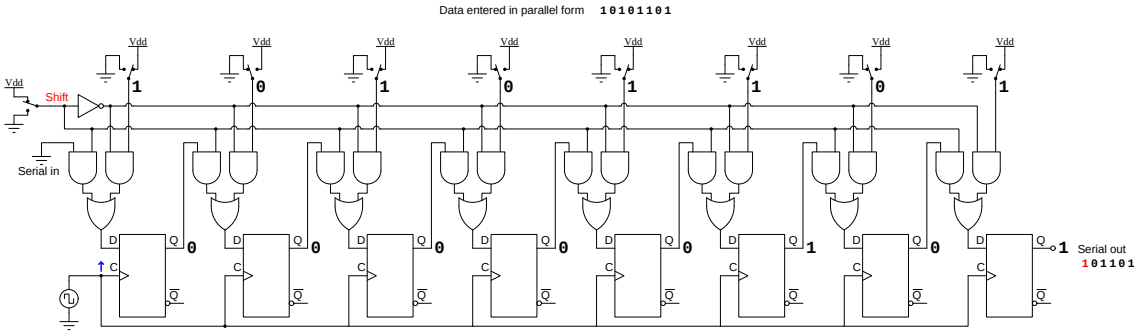
Serial out
01101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Vdd
Shift
Serial in
1
0
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1
D
Q
C
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1
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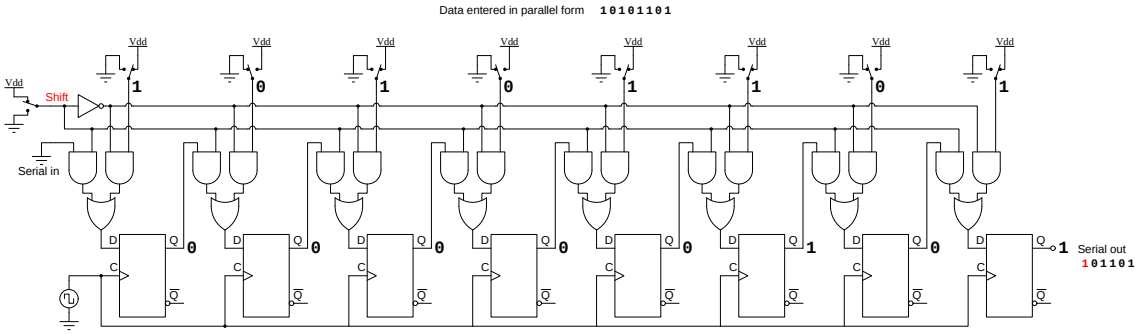
Serial out
101101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Serial in
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Q
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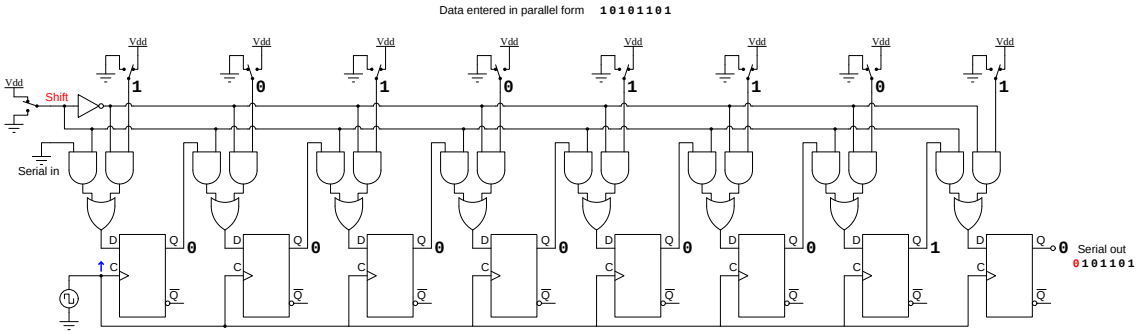
Serial out
101101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Shift
Serial in
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Serial out
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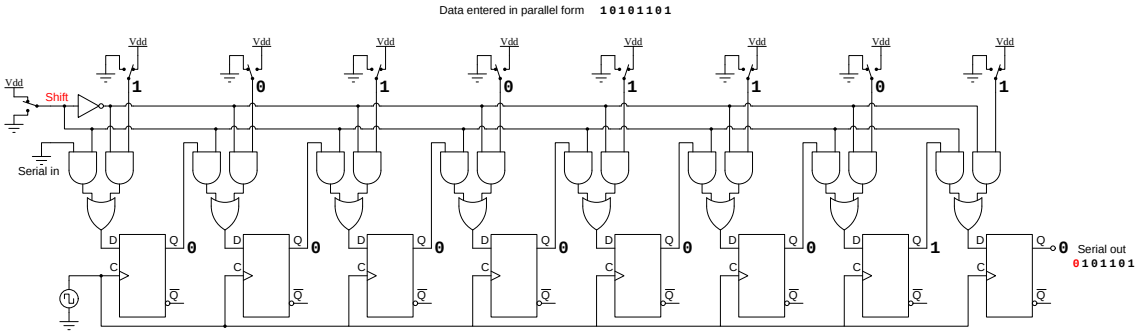
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Serial in
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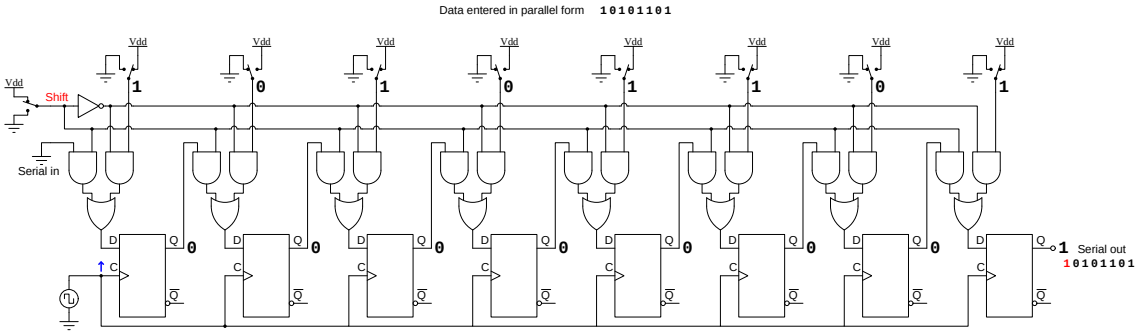
1
Serial out
0101101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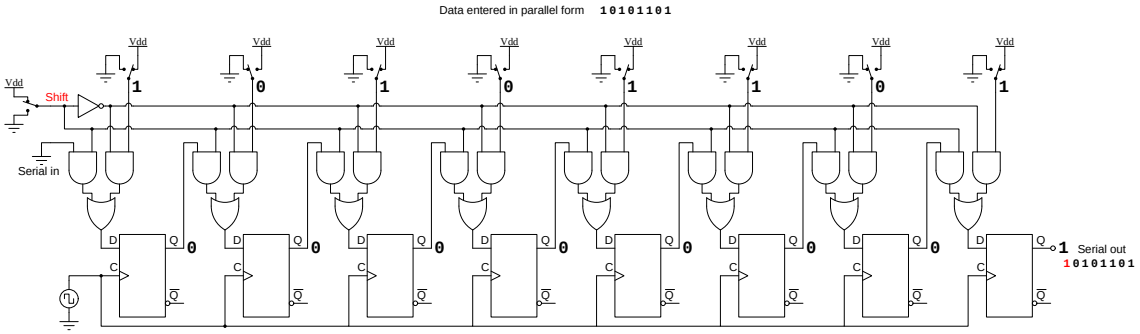
Serial out
10101101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Vdd
Shift
Serial in
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D
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Serial out
10101101

# Chapter 5

# 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?

## 5.1 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.

### 5.1.1 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.

### 5.1.2 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.

Energy

Conservation of Energy

Simplification as a problem-solving strategy

Thought experiments as a problem-solving strategy

Limiting cases as a problem-solving strategy

Annotating diagrams as a problem-solving strategy

Interpreting intermediate results as a problem-solving strategy

Graphing as a problem-solving strategy

Converting a qualitative problem into a quantitative problem

Converting a quantitative problem into a qualitative problem

Working "backwards" to validate calculated results

*Reductio ad absurdum*

Re-drawing schematics as a problem-solving strategy

Cut-and-try problem-solving strategy

Algebraic substitution

???

### 5.1.3 TI CC113L Value Line Receiver datasheet

Locate a datasheet for the Texas Instruments model CC113L "value line" RF receiver IC and answer the following questions using information gleaned from that document:

How are the SPI-related pins identified on this particular IC?

What are some of the configurable parameters of this particular IC, programmed using the SPI interface?

Explain the purpose of the FIFO shift register contained within this radio receiver IC, as well as the significance of "overflow" and "underflow" for this register.

Explain how SPI is used to read from and/or write to registers within this particular IC.

Explain the importance of set-up and hold times for SPI data, citing these minimum durations from the datasheet.

Are binary values communicated with MSB-first or LSB-first in these SPI transactions? What are the minimum and maximum clock rates for this IC?

Challenges

- Is the RF input to this receiver IC single-ended or differential in nature?

## 5.2 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.

### 5.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation ($\sigma$) 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 ($\mu_0$) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space ($\epsilon_0$) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

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

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 ($\sigma$) = **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.

### 5.2.2 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.*

### 5.2.3 Sketching SPI waveforms

Sketch clock and data pulse waveforms appropriate for SPI frames, assuming MSB-first bit ordering in each case:

**SPI Clock Mode 0, data = 0xC6**

Clock mode 0 is where the clock signal idles in a low state, and where data is clocked in on the rising edge of the clock signal.

**SPI Clock Mode 1, data = 0x2E**

Clock mode 1 is where the clock signal idles in a low state, and where data is clocked in on the falling edge of the clock signal.

**SPI Clock Mode 2, data = 0x71**

Clock mode 2 is where the clock signal idles in a high state, and where data is clocked in on the falling edge of the clock signal.

**SPI Clock Mode 3, data = 0xAF**

Clock mode 3 is where the clock signal idles in a high state, and where data is clocked in on the rising edge of the clock signal.

Challenges

- Is SPI limited to one-byte data payloads in the frame?

# Appendix A

# Problem-Solving Strategies

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

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

# Appendix B

# Instructional philosophy

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

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

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

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[1] 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[2] 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[3] 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

[1] 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.

[2] 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.

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

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

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

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

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

To this end, instructors managing courses based on these modules should adhere to the following principles:

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

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

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

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

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

- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done "live" before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.

Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea *in your own words, using your own examples.*
- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.
- Never take the easy path of highlighting or underlining important text. Instead, *summarize* and/or *comment* on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.
- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least *imagine* yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.
- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of *circuit simulation software*, checking to see if your simulated results agree with the results shown in the text.
- Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[4] effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge[5] one another.

To high standards of education,

Tony R. Kuphaldt

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

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

# Appendix C

# Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's 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

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# Appendix E

# References

# 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.

**10 February 2025** – minor edits to the Tutorial, and also removed the Diagnostic Reasoning section because it lacked content.

**15-17 September 2024** – added questions to the module, as well as a fuller Introduction chapter.

**2-4 June 2024** – document first created.

# Index