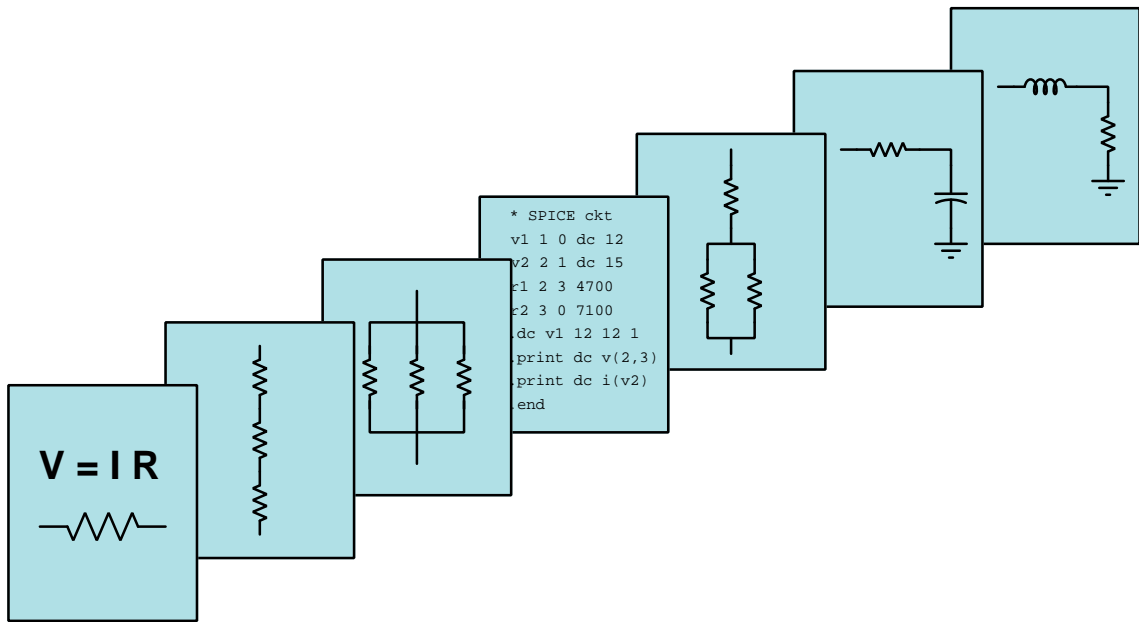


# MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



## INTERNET PROTOCOLS

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# Chapter 1

## Introduction

### 1.1 Recommendations for students

This module introduces the foundational protocols which make the *internet* possible as a world-wide network: Internet Protocol (IP) and Transmission Control Protocol (TCP). Together, these protocols provide an organizational framework within which many different lower-level communication protocols may exchange information, thus enabling a seamless network to be built from a patchwork of disparate data networks.

Important concepts related to these protocols include the **OSI Reference Model**, **data frames**, **encapsulation**, **IP addresses**, **masks**, **MAC addresses**, **subnetworks**, the **ping** utility, **routing** and **routing tables**, **IPv4** versus **IPv6**, **address resolution**, **TCP ports**, **flow control**, the **netstat** utility, and **TCP states**.

A useful reading strategy is to write your own summary page of important principles. This is useful with a topic such as network protocols, where you are faced with an array of different protocols handling different aspects of a complete communications link such as the case with IP and TCP/UDP. Your own summary describing what IP does, versus what TCP/UDP do, will help consolidate all the information you will read in the Tutorial.

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

- How might an experiment be designed and conducted to explore the concept of encapsulation for any given network protocol? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What exactly is a *protocol*?
- How are large data files communicated over networks capable only of transmitting short bursts of data?
- How do IP and TCP work together to achieve a larger goal?
- What is *encapsulation*, and why is this important to the operation of data networks?

- How is the function of IP distinct from the function of TCP or UDP?
- How and why might you use **ping** to troubleshoot a network?
- What purpose do subnetwork *masks* serve in IP networks?
- How are IP addresses specified, and how do these differ from other types of addresses such as Ethernet MAC addresses?
- What is *routing* as it applies to the internet?
- How do IP version 4 and IP version 6 compare with one another?
- What are some of the other protocols besides IP and TCP/UDP used in internet communication?
- How are errors detected in a TCP/IP network?
- How do TCP and UDP compare with one another? Why might one be used instead of the other?
- What software tools are available to help configure, test, and diagnose these networks?
- What is the purpose of a *state* in TCP?

## 1.2 Challenging concepts related to internet protocols

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

- **Encapsulation** – the notion of one protocol's data frame being contained as payload within another's is somewhat confusing, but is made clear by inspection of actual communications using packet-sniffing software (e.g. **Wireshark**).
- **Bitwise logical operations** – applying AND, OR, and XOR logical operations to respective bits of binary words is not a straight-forward concept, but is made more understandable by drawing out the binary word(s) in question and if necessary drawing small logic gates taking inputs from those bits to generate the respective bits of the output word. Another helpful perspective for understanding the purpose of bitwise operations is to view AND functions as *forcing* a 0 output if any input is 0, and OR functions as *forcing* a 1 output if any input is a 1. This is relevant to subnet masks in IP protocol.
- **Network arbitration** – the same is true for channel arbitration techniques such as CSMA/CD, master-slave, and others. It is helpful to imagine a set of devices all requiring access to a common channel of communication, and stepping through each of the protocols to see how they manage this access without having multiple devices “talk over” one another. This, like so many other things, simply takes time to digest and cannot be rushed.



### 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** – Demonstrate the concept of encapsulation by experimenting with packet-sniffing software

Assessment – Identify Ethernet, IP, and TCP/UDP message frames encapsulated within each other in packets intercepted using **Wireshark** software.

- **Outcome** – Diagnose a faulted network based on reported symptoms and testing

Assessment – Determine the probability of various component faults in a LAN given symptoms and “ping” test results; e.g. pose problems in the form of the “Possible faults in a network” Diagnostic Reasoning question.

Assessment – Determine the appropriateness of various diagnostic tests in identifying the location and nature of a fault in a LAN given symptoms and test results.

## Chapter 2

# Case Tutorial

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

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

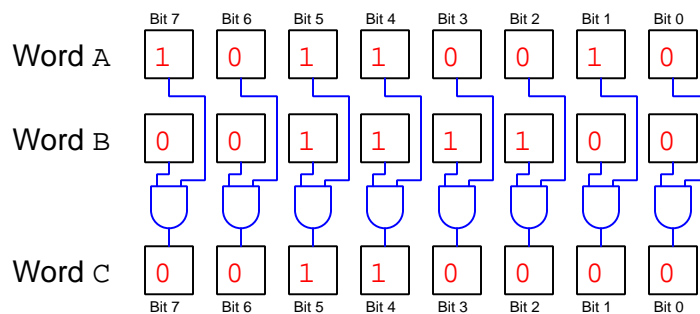
## 2.1 Example: bitwise logical operations

The following examples show bitwise operations being performed on 8-bit words (bytes).

### 2.1.1 Bitwise-AND

Bitwise-AND:  $A \& B \rightarrow C$

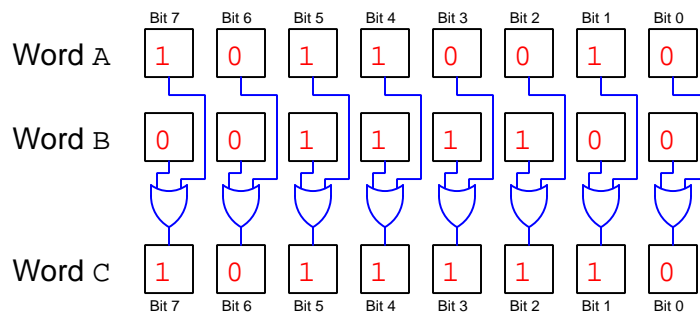
Example:  $0b10110010 \& 0b00111100 \rightarrow 0b00110000$



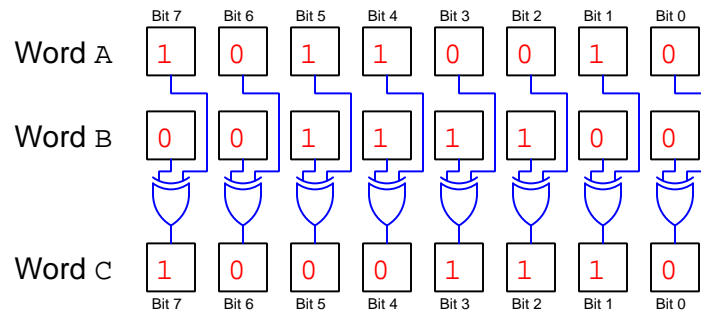
### 2.1.2 Bitwise-OR

Bitwise-OR:  $A | B \rightarrow C$

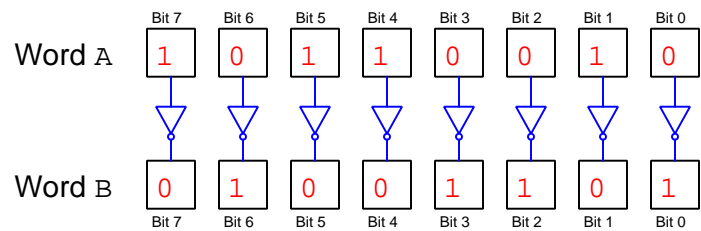
Example:  $0b10110010 | 0b00111100 \rightarrow 0b10111110$



## 2.1.3 Bitwise-XOR

Bitwise-XOR:  $A \wedge B \rightarrow C$ Example:  $0b10110010 \wedge 0b00111100 \rightarrow 0b10001110$ 

## 2.1.4 Bitwise-complement

Bitwise-complement:  $\sim A \rightarrow B$ Example:  $\sim 0b10110010 \rightarrow 0b01001101$ 

## 2.2 Example: simple TCP message analysis

Here we will use the Unix utility **netcat** to send simple ASCII text messages back and forth between two computers connected to a common Ethernet network, hereafter referred to as computer A and computer B. Our task will be to send a text message from computer A to computer B, and then to send a reply message from computer B back to computer A. Computer A's IPv4 address is 192.168.254.24, while computer B's IPv4 address is 192.168.254.18.

First we must invoke **netcat** on computer B to operate in “listen” mode. This opens up a specified TCP port on computer B, which computer A may then communicate to. For this exercise we will arbitrarily specify a TCP port number of 55555, using the following command-line instruction<sup>1</sup>:

```
nc -l -vv -p 55555
```

After doing this, we invoke **netcat** on computer A to prepare for sending the first message. Here we instruct **netcat** as to the IPv4 address and TCP port number of computer B, so the message we type on computer A will arrive at its intended destination. To do this, we will use the following command-line instruction<sup>2</sup>:

```
nc 192.168.254.18 55555
```

After invoking **netcat** on both computers, in this order, anything typed at the console of computer A (after pressing the Enter button) will be displayed on the console of computer B, and vice-versa.

Furthermore, we may use a “packet-sniffing” utility such as **Wireshark** to record this exchange for close analysis.

---

<sup>1</sup>In this mode, we use the `-l` argument to instruct **netcat** to *listen*, using the `-vv` option to specify “very verbose” operation, and lastly using the `-p` option to specify the TCP port number 55555 to open.

<sup>2</sup>In this mode, the two arguments to **netcat** are the IPv4 address and the TCP port number, in that order.

Using the filter string `tcp.port == 55555` in Wireshark to show only those network packets related to this exchange, we get the following summary of four packets:

Source	Destination	Pro.	Information
192.168.254.24	192.168.254.18	TCP	54171 -> 55555 [PSH, ACK] Seq=1 Ack=1 Win=1026 Len=38
192.168.254.18	192.168.254.24	TCP	55555 -> 54171 [ACK] Seq=1 Ack=39 Win=1026 Len=0
192.168.254.18	192.168.254.24	TCP	55555 -> 54171 [PSH, ACK] Seq=1 Ack=39 Win=1026 Len=36
192.168.254.24	192.168.254.18	TCP	54171 -> 55555 [ACK] Seq=39 Ack=37 Win=1026 Len=0

Note how computer B's TCP port number is 55555 as specified in our invocation of `netcat`, while computer A's TCP port is a value chosen by the computer (54171).

Let us begin with the first packet in this filtered capture of network traffic, where we typed a text message at computer A destined for computer B:

Source	Destination	Pro.	Information
192.168.254.24	192.168.254.18	TCP	54171 -> 55555 [PSH, ACK] Seq=1 Ack=1 Win=1026 Len=38

Here is Wireshark's analysis of that first packet:

```

92 bytes on wire (736 bits), 92 bytes captured (736 bits) on interface
  Interface id: 0 (\Device\NPF_{257A10A2-544E-4CD5-B1CB-CCEB5313B592})
    Interface name: \Device\NPF_{257A10A2-544E-4CD5-B1CB-CCEB5313B592}
    Interface description: Ethernet
  Encapsulation type: Ethernet (1)
  Arrival Time: Jun  5, 2022 19:57:51.418052000 Pacific Daylight Time
  [Time shift for this packet: 0.000000000 seconds]
  Epoch Time: 1654484271.418052000 seconds
  [Time delta from previous captured frame: 3.488957000 seconds]
  [Time delta from previous displayed frame: 0.000000000 seconds]
  [Time since reference or first frame: 20.408713000 seconds]
  Frame Number: 40
  Frame Length: 92 bytes (736 bits)
  Capture Length: 92 bytes (736 bits)
  [Frame is marked: False]
  [Frame is ignored: False]
  [Protocols in frame: eth:ethertype:ip:tcp:data]
  [Coloring Rule Name: TCP]
  [Coloring Rule String: tcp]
Ethernet II, Src: EliteGro_16:ec:cb, Dst: EliteGro_f8:16:06
  Destination: EliteGro_f8:16:06 (94:c6:91:f8:16:06)
    Address: EliteGro_f8:16:06 (94:c6:91:f8:16:06)
      .... ..0. .... = LG bit: Globally unique address (factory default)
      .... ...0 .... = IG bit: Individual address (unicast)
  Source: EliteGro_16:ec:cb (1c:69:7a:16:ec:cb)
    Address: EliteGro_16:ec:cb (1c:69:7a:16:ec:cb)
      .... ..0. .... = LG bit: Globally unique address (factory default)
      .... ...0 .... = IG bit: Individual address (unicast)
  Type: IPv4 (0x0800)
Internet Protocol Version 4, Src: 192.168.254.24, Dst: 192.168.254.18
  0100 .... = Version: 4
  .... 0101 = Header Length: 20 bytes (5)
  Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
    0000 00.. = Differentiated Services Codepoint: Default (0)
    .... ..00 = Explicit Congestion Notification: Not ECN-Capable Transport (0)
  Total Length: 78
  Identification: 0x54f3 (21747)
  Flags: 0x40, Don't fragment

```

```

    0... .. = Reserved bit: Not set
    .1... .. = Don't fragment: Set
    ..0. .... = More fragments: Not set
    ...0 0000 0000 0000 = Fragment Offset: 0
Time to Live: 128
Protocol: TCP (6)
Header Checksum: 0x0000 [validation disabled]
[Header checksum status: Unverified]
Source Address: 192.168.254.24
Destination Address: 192.168.254.18
Transmission Control Protocol, Src Port: 54171, Dst Port: 55555, Seq: 1, Ack: 1, Len: 38
Source Port: 54171
Destination Port: 55555
[Stream index: 5]
[Conversation completeness: Incomplete (12)]
[TCP Segment Len: 38]
Sequence Number: 1      (relative sequence number)
Sequence Number (raw): 2579253006
[Next Sequence Number: 39      (relative sequence number)]
Acknowledgment Number: 1      (relative ack number)
Acknowledgment number (raw): 3511748816
0101 .... = Header Length: 20 bytes (5)
Flags: 0x018 (PSH, ACK)
    000. .... = Reserved: Not set
    ...0 .... = Nonce: Not set
    .... 0... = Congestion Window Reduced (CWR): Not set
    .... .0.. = ECN-Echo: Not set
    .... ..0. = Urgent: Not set
    .... ...1 .... = Acknowledgment: Set
    .... .... 1... = Push: Set
    .... .... .0.. = Reset: Not set
    .... .... ..0. = Syn: Not set
    .... .... ...0 = Fin: Not set
    [TCP Flags: .....AP...]
Window: 1026
[Calculated window size: 1026]
[Window size scaling factor: -1 (unknown)]
Checksum: 0x7dbd [unverified]
[Checksum Status: Unverified]
Urgent Pointer: 0
[Timestamps]
    [Time since first frame in this TCP stream: 0.000000000 seconds]
    [Time since previous frame in this TCP stream: 0.000000000 seconds]
[SEQ/ACK analysis]
    [Bytes in flight: 38]
    [Bytes sent since last PSH flag: 38]

```



```

    TCP payload (38 bytes)
Data (38 bytes)
    Data: 546869732069732061206d65737361676520747970656420617420636f6d707574657220...
    [Length: 38]

```

A hexdump of this packet reveals the ASCII text message typed at computer A, as the data encapsulated by the TCP, IP, and Ethernet protocols:

```

0000  94 c6 91 f8 16 06 1c 69 7a 16 ec cb 08 00 45 00  ....iz....E.
0010  00 4e 54 f3 40 00 80 06 00 00 c0 a8 fe 18 c0 a8  .NT.@.....
0020  fe 12 d3 9b d9 03 99 bc 47 0e d1 51 08 d0 50 18  ....G..Q..P.
0030  04 02 7d bd 00 00 54 68 69 73 20 69 73 20 61 20  ..}...This is a
0040  6d 65 73 73 61 67 65 20 74 79 70 65 64 20 61 74  message typed at
0050  20 63 6f 6d 70 75 74 65 72 20 41 0a             computer A.

```

Next we will examine the other three packets in order of their capture. The second of the filtered packets is this acknowledgement from computer B as having received the transmission from computer A:

```

Source          Destination      Pro.  Information
192.168.254.18  192.168.254.24  TCP   55555 -> 54171 [ACK] Seq=1 Ack=39 Win=1026 Len=0

```

And here is Wireshark's analysis of the second packet:

```

60 bytes on wire (480 bits), 60 bytes captured (480 bits) on interface
  Interface id: 0 (\Device\NPF_{257A10A2-544E-4CD5-B1CB-CCEB5313B592})
    Interface name: \Device\NPF_{257A10A2-544E-4CD5-B1CB-CCEB5313B592}
    Interface description: Ethernet
  Encapsulation type: Ethernet (1)
  Arrival Time: Jun  5, 2022 19:57:51.462605000 Pacific Daylight Time
  [Time shift for this packet: 0.000000000 seconds]
  Epoch Time: 1654484271.462605000 seconds
  [Time delta from previous captured frame: 0.044553000 seconds]
  [Time delta from previous displayed frame: 0.044553000 seconds]
  [Time since reference or first frame: 20.453266000 seconds]
  Frame Number: 41
  Frame Length: 60 bytes (480 bits)
  Capture Length: 60 bytes (480 bits)
  [Frame is marked: False]
  [Frame is ignored: False]
  [Protocols in frame: eth:ethertype:ip:tcp]
  [Coloring Rule Name: TCP]
  [Coloring Rule String: tcp]
Ethernet II, Src: EliteGro_f8:16:06, Dst: EliteGro_16:ec:cb
  Destination: EliteGro_16:ec:cb (1c:69:7a:16:ec:cb)

```

```

    Address: EliteGro_16:ec:cb (1c:69:7a:16:ec:cb)
    .... ..0. .... = LG bit: Globally unique address (factory default)
    .... ...0 .... = IG bit: Individual address (unicast)
Source: EliteGro_f8:16:06 (94:c6:91:f8:16:06)
    Address: EliteGro_f8:16:06 (94:c6:91:f8:16:06)
    .... ..0. .... = LG bit: Globally unique address (factory default)
    .... ...0 .... = IG bit: Individual address (unicast)
Type: IPv4 (0x0800)
Padding: 000000000000
Internet Protocol Version 4, Src: 192.168.254.18, Dst: 192.168.254.24
0100 .... = Version: 4
.... 0101 = Header Length: 20 bytes (5)
Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
    0000 00.. = Differentiated Services Codepoint: Default (0)
    .... ..00 = Explicit Congestion Notification: Not ECN-Capable Transport (0)
Total Length: 40
Identification: 0x561d (22045)
Flags: 0x40, Don't fragment
    0... .... = Reserved bit: Not set
    .1.. .... = Don't fragment: Set
    ..0. .... = More fragments: Not set
...0 0000 0000 0000 = Fragment Offset: 0
Time to Live: 128
Protocol: TCP (6)
Header Checksum: 0x2736 [validation disabled]
[Header checksum status: Unverified]
Source Address: 192.168.254.18
Destination Address: 192.168.254.24
Transmission Control Protocol, Src Port: 55555, Dst Port: 54171, Seq: 1, Ack: 39, Len: 0
Source Port: 55555
Destination Port: 54171
[Stream index: 5]
[Conversation completeness: Incomplete (12)]
[TCP Segment Len: 0]
Sequence Number: 1      (relative sequence number)
Sequence Number (raw): 3511748816
[Next Sequence Number: 1      (relative sequence number)]
Acknowledgment Number: 39      (relative ack number)
Acknowledgment number (raw): 2579253044
0101 .... = Header Length: 20 bytes (5)
Flags: 0x010 (ACK)
    000. .... = Reserved: Not set
    ...0 .... = Nonce: Not set
    .... 0... = Congestion Window Reduced (CWR): Not set
    .... .0.. = ECN-Echo: Not set
    .... ..0. = Urgent: Not set

```

```

.... 1 = Acknowledgment: Set
.... 0... = Push: Not set
.... .0.. = Reset: Not set
.... ..0. = Syn: Not set
.... ...0 = Fin: Not set
[TCP Flags: .....A....]
Window: 1026
[Calculated window size: 1026]
[Window size scaling factor: -1 (unknown)]
Checksum: 0xc6a3 [unverified]
[Checksum Status: Unverified]
Urgent Pointer: 0
[Timestamps]
  [Time since first frame in this TCP stream: 0.044553000 seconds]
  [Time since previous frame in this TCP stream: 0.044553000 seconds]
[SEQ/ACK analysis]
  [This is an ACK to the segment in frame: 40]
  [The RTT to ACK the segment was: 0.044553000 seconds]

```

Here is the hexdump of this second packet:

```

0000  1c 69 7a 16 ec cb 94 c6 91 f8 16 06 08 00 45 00  .iz.....E.
0010  00 28 56 1d 40 00 80 06 27 36 c0 a8 fe 12 c0 a8  .(V.@...'6.....
0020  fe 18 d9 03 d3 9b d1 51 08 d0 99 bc 47 34 50 10  .....Q....G4P.
0030  04 02 c6 a3 00 00 00 00 00 00 00 00 00 00 00 00  .....

```

Next is the third packet, this one containing the text message typed at computer B in reply to the original message from computer A:

Source	Destination	Pro.	Information
192.168.254.18	192.168.254.24	TCP	55555 -> 54171 [PSH, ACK] Seq=1 Ack=39 Win=1026 Len=36

And here is Wireshark's analysis of the third packet:

```

90 bytes on wire (720 bits), 90 bytes captured (720 bits) on interface
  Interface id: 0 (\Device\NPF_{257A10A2-544E-4CD5-B1CB-CCEB5313B592})
    Interface name: \Device\NPF_{257A10A2-544E-4CD5-B1CB-CCEB5313B592}
    Interface description: Ethernet
  Encapsulation type: Ethernet (1)
  Arrival Time: Jun  5, 2022 19:58:33.805408000 Pacific Daylight Time
  [Time shift for this packet: 0.000000000 seconds]
  Epoch Time: 1654484313.805408000 seconds
  [Time delta from previous captured frame: 31.549835000 seconds]
  [Time delta from previous displayed frame: 42.342803000 seconds]
  [Time since reference or first frame: 62.796069000 seconds]
  Frame Number: 63
  Frame Length: 90 bytes (720 bits)
  Capture Length: 90 bytes (720 bits)
  [Frame is marked: False]
  [Frame is ignored: False]
  [Protocols in frame: eth:ethertype:ip:tcp:data]
  [Coloring Rule Name: TCP]
  [Coloring Rule String: tcp]
Ethernet II, Src: EliteGro_f8:16:06, Dst: EliteGro_16:ec:cb
  Destination: EliteGro_16:ec:cb (1c:69:7a:16:ec:cb)
    Address: EliteGro_16:ec:cb (1c:69:7a:16:ec:cb)
      .... ..0. .... = LG bit: Globally unique address (factory default)
      .... ...0 .... = IG bit: Individual address (unicast)
  Source: EliteGro_f8:16:06 (94:c6:91:f8:16:06)
    Address: EliteGro_f8:16:06 (94:c6:91:f8:16:06)
      .... ..0. .... = LG bit: Globally unique address (factory default)
      .... ...0 .... = IG bit: Individual address (unicast)
  Type: IPv4 (0x0800)
Internet Protocol Version 4, Src: 192.168.254.18, Dst: 192.168.254.24
  0100 .... = Version: 4
  .... 0101 = Header Length: 20 bytes (5)
  Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
    0000 00.. = Differentiated Services Codepoint: Default (0)
    .... ..00 = Explicit Congestion Notification: Not ECN-Capable Transport (0)
  Total Length: 76
  Identification: 0x561e (22046)
  Flags: 0x40, Don't fragment

```

```

    0... .... = Reserved bit: Not set
    .1... .... = Don't fragment: Set
    ..0. .... = More fragments: Not set
...0 0000 0000 0000 = Fragment Offset: 0
Time to Live: 128
Protocol: TCP (6)
Header Checksum: 0x2711 [validation disabled]
[Header checksum status: Unverified]
Source Address: 192.168.254.18
Destination Address: 192.168.254.24
Transmission Control Protocol, Src Port: 55555, Dst Port: 54171, Seq: 1, Ack: 39, Len: 36
Source Port: 55555
Destination Port: 54171
[Stream index: 5]
[Conversation completeness: Incomplete (12)]
[TCP Segment Len: 36]
Sequence Number: 1      (relative sequence number)
Sequence Number (raw): 3511748816
[Next Sequence Number: 37      (relative sequence number)]
Acknowledgment Number: 39      (relative ack number)
Acknowledgment number (raw): 2579253044
0101 .... = Header Length: 20 bytes (5)
Flags: 0x018 (PSH, ACK)
    000. .... .... = Reserved: Not set
    ...0 .... .... = Nonce: Not set
    .... 0... .... = Congestion Window Reduced (CWR): Not set
    .... .0.. .... = ECN-Echo: Not set
    .... ..0. .... = Urgent: Not set
    .... ...1 .... = Acknowledgment: Set
    .... .... 1... = Push: Set
    .... .... .0.. = Reset: Not set
    .... .... ..0. = Syn: Not set
    .... .... ...0 = Fin: Not set
    [TCP Flags: .....AP...]
Window: 1026
[Calculated window size: 1026]
[Window size scaling factor: -1 (unknown)]
Checksum: 0xe4b5 [unverified]
[Checksum Status: Unverified]
Urgent Pointer: 0
[Timestamps]
    [Time since first frame in this TCP stream: 42.387356000 seconds]
    [Time since previous frame in this TCP stream: 42.342803000 seconds]
[SEQ/ACK analysis]
    [Bytes in flight: 36]
    [Bytes sent since last PSH flag: 36]

```

```
TCP payload (36 bytes)
Data (36 bytes)
Data: 546869732069732061207265706c7920747970656420617420636f6d707574657220420a
[Length: 36]
```

Here is the hexdump of this third packet, where you can see the ASCII-encoded message:

```
0000  1c 69 7a 16 ec cb 94 c6 91 f8 16 06 08 00 45 00  .iz.....E.
0010  00 4c 56 1e 40 00 80 06 27 11 c0 a8 fe 12 c0 a8  .LV.@...'.
0020  fe 18 d9 03 d3 9b d1 51 08 d0 99 bc 47 34 50 18  .....Q....G4P.
0030  04 02 e4 b5 00 00 54 68 69 73 20 69 73 20 61 20  .....This is a
0040  72 65 70 6c 79 20 74 79 70 65 64 20 61 74 20 63  reply typed at c
0050  6f 6d 70 75 74 65 72 20 42 0a                   omputer B.
```

Lastly, we have the TCP acknowledgement from computer A upon receiving the response typed at computer B:

Source	Destination	Pro.	Information
192.168.254.24	192.168.254.18	TCP	54171 -> 55555 [ACK] Seq=39 Ack=37 Win=1026 Len=0

And here is Wireshark's analysis of this fourth packet:

```

54 bytes on wire (432 bits), 54 bytes captured (432 bits) on interface
  Interface id: 0 (\Device\NPF_{257A10A2-544E-4CD5-B1CB-CCEB5313B592})
    Interface name: \Device\NPF_{257A10A2-544E-4CD5-B1CB-CCEB5313B592}
    Interface description: Ethernet
  Encapsulation type: Ethernet (1)
  Arrival Time: Jun  5, 2022 19:58:33.849491000 Pacific Daylight Time
  [Time shift for this packet: 0.000000000 seconds]
  Epoch Time: 1654484313.849491000 seconds
  [Time delta from previous captured frame: 0.044083000 seconds]
  [Time delta from previous displayed frame: 0.044083000 seconds]
  [Time since reference or first frame: 62.840152000 seconds]
  Frame Number: 64
  Frame Length: 54 bytes (432 bits)
  Capture Length: 54 bytes (432 bits)
  [Frame is marked: False]
  [Frame is ignored: False]
  [Protocols in frame: eth:ethertype:ip:tcp]
  [Coloring Rule Name: TCP]
  [Coloring Rule String: tcp]
Ethernet II, Src: EliteGro_16:ec:cb, Dst: EliteGro_f8:16:06
  Destination: EliteGro_f8:16:06 (94:c6:91:f8:16:06)
    Address: EliteGro_f8:16:06 (94:c6:91:f8:16:06)
      .... ..0. .... = LG bit: Globally unique address (factory default)
      .... ...0 .... = IG bit: Individual address (unicast)
  Source: EliteGro_16:ec:cb (1c:69:7a:16:ec:cb)
    Address: EliteGro_16:ec:cb (1c:69:7a:16:ec:cb)
      .... ..0. .... = LG bit: Globally unique address (factory default)
      .... ...0 .... = IG bit: Individual address (unicast)
  Type: IPv4 (0x0800)
Internet Protocol Version 4, Src: 192.168.254.24, Dst: 192.168.254.18
  0100 .... = Version: 4
  .... 0101 = Header Length: 20 bytes (5)
  Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
    0000 00.. = Differentiated Services Codepoint: Default (0)
    .... ..00 = Explicit Congestion Notification: Not ECN-Capable Transport (0)
  Total Length: 40
  Identification: 0x54f4 (21748)
  Flags: 0x40, Don't fragment

```

```

    0... .... = Reserved bit: Not set
    .1... .... = Don't fragment: Set
    ..0. .... = More fragments: Not set
...0 0000 0000 0000 = Fragment Offset: 0
Time to Live: 128
Protocol: TCP (6)
Header Checksum: 0x0000 [validation disabled]
[Header checksum status: Unverified]
Source Address: 192.168.254.24
Destination Address: 192.168.254.18
Transmission Control Protocol, Src Port: 54171, Dst Port: 55555, Seq: 39, Ack: 37, Len: 0
Source Port: 54171
Destination Port: 55555
[Stream index: 5]
[Conversation completeness: Incomplete (12)]
[TCP Segment Len: 0]
Sequence Number: 39      (relative sequence number)
Sequence Number (raw): 2579253044
[Next Sequence Number: 39      (relative sequence number)]
Acknowledgment Number: 37      (relative ack number)
Acknowledgment number (raw): 3511748852
0101 .... = Header Length: 20 bytes (5)
Flags: 0x010 (ACK)
    000. .... .... = Reserved: Not set
    ...0 .... .... = Nonce: Not set
    .... 0... .... = Congestion Window Reduced (CWR): Not set
    .... .0.. .... = ECN-Echo: Not set
    .... ..0. .... = Urgent: Not set
    .... ...1 .... = Acknowledgment: Set
    .... .... 0... = Push: Not set
    .... .... .0.. = Reset: Not set
    .... .... ..0. = Syn: Not set
    .... .... ...0 = Fin: Not set
    [TCP Flags: .....A....]
Window: 1026
[Calculated window size: 1026]
[Window size scaling factor: -1 (unknown)]
Checksum: 0x7d97 [unverified]
[Checksum Status: Unverified]
Urgent Pointer: 0
[Timestamps]
    [Time since first frame in this TCP stream: 42.431439000 seconds]
    [Time since previous frame in this TCP stream: 0.044083000 seconds]
[SEQ/ACK analysis]
    [This is an ACK to the segment in frame: 63]
    [The RTT to ACK the segment was: 0.044083000 seconds]

```



Here is the hexdump of this fourth packet:

```
0000  94 c6 91 f8 16 06 1c 69 7a 16 ec cb 08 00 45 00  ....iz....E.
0010  00 28 54 f4 40 00 80 06 00 00 c0 a8 fe 18 c0 a8  .(T.@.....
0020  fe 12 d3 9b d9 03 99 bc 47 34 d1 51 08 f4 50 10  ....G4.Q..P.
0030  04 02 7d 97 00 00                                ...}...
```

## Chapter 3

## Tutorial

### 3.1 Encapsulation

I remember first learning about the world-wide Internet, and wondering what it actually *looked like*. The first vision entering my mind when people told me about a computer network spanning nearly all of the United States and many other parts of the world was that of a thick cable strung along telephone poles and buried underground, with a big sign on it saying “Internet.” I also remember well the shock of learning that although the Internet made use of several high-capacity networks (called *backbones*) connecting large data centers in different cities, the real “magic” of the Internet did not reside in any particular cable or link. Instead, what made the Internet so widespread and accessible was actually a series of *protocols* allowing free exchange of data along and between disparate systems. These “protocols” allowed digital data to be packaged in such a way that it could be sent along nearly any kind of communications link from copper wires to fiber-optic to radio waves – and indeed along multiple pathways between the same two points – while arriving at the destination intact. Thus, the Internet was akin to a random patchwork of existing communications pathways pressed into coordinated service by the sharing of a common “language.”

Physical network standards such as Ethernet only define aspects relevant to lower layers of the OSI Reference Model. While these details are essential for communication to occur, they are not enough on their own to support a wide-spread communications system. For this reason, network standards such as EIA/TIA-485 and Ethernet almost always comprise the lower layer(s) of a more complex communications protocol capable of managing higher-order addresses, message integrity, “sessions” between computers, and a host of other details.

Internet Protocol (IP) manages network addresses and data handling over a much larger physical domain than Ethernet (or any other layer 1/2 standard) is able. The basic principle of IP is that large digital messages may be broken down into smaller pieces, then each piece buffered with additional data bits to form *packets* specifying (among other things) how the pieces are to be directed to their proper destination(s). The completed packets are then transmitted individually and received individually, where they may be reassembled at the receiver to form the original message in its entirety. An analogy for this process is an author with a printed paper manuscript for a book, who needs to get her manuscript to a print shop across town. Unfortunately, the mail service in this town cannot transport the bulky manuscript in one piece, so the author divides the manuscript into 10-page bundles and mails each of these bundles in its own package to the print shop. The individual packages may not make it to the print shop on the same day, or even in the correct order, but the addressing on each package directs the postal service to deliver each of them to the proper location.

This strategy for transmitting large digital messages is at the heart of the Internet: data sent from one computer to another over the Internet is first broken down into packets, which are then routed over a variety of pathways to their destination. The packets need not take the same route to their destination, nor do they even need to travel along the same *kinds* of networks. The receiving computer must then reassemble those packets in the proper order to re-create the original data. This “packetization” of data allows multiple messages to be interleaved on a network (i.e. the network’s bandwidth being alternately used to convey pieces of completely different messages, rather than being reserved for one whole message at a time) as well as permitting alternate routes that the message may take in order to traverse large physical distances. In a web-shaped network where multiple pathways exist between any two points, the ability to direct packets of data along alternate

routes increases the reliability of that network: failure of any one routing node or communications pathway does not necessarily prevent data from reaching its final destination. This fault tolerance was one of the design criteria for what came to be the Internet when it was first developed by the United States' Department of Defense.

Interestingly, the task of portioning a large block of digital data into packet-sized pieces, and then re-assembling those pieces together in the proper order to form the original data block, is *not* the task of IP, but rather the task of some higher-level protocol such as TCP (Transmission Control Protocol). Internet Protocol (IP) merely specifies how the individual packets are to be marked and routed to their proper destination(s)<sup>1</sup>. To use the manuscript analogy again, IP is the postal service with its system of mailing addresses, postage stamps, and labeling conventions, while TCP (or some other higher-level protocol) is the author and publisher who divide the manuscript into smaller bundles and then reassemble those bundles into the original manuscript, respectively. For this reason, IP is not a complete solution for large-scale network communication on its own. This is why the Internet's central protocol is referred to as TCP/IP, the two protocols working together to ensure coordinated and reliable communication of packetized data over wide areas.

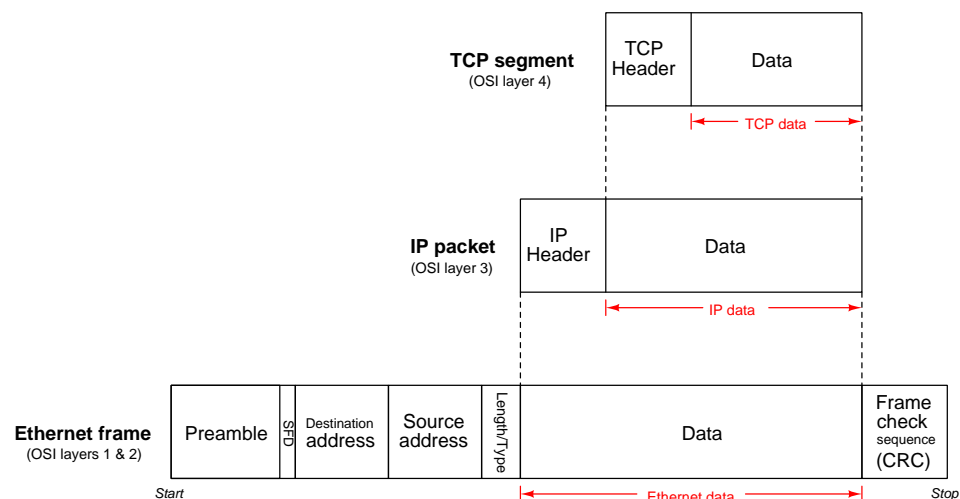
---

<sup>1</sup>When packets travel between different kinds of networks, the “gateway” devices at those transition points may need to *fragment* large IP packets into smaller IP packets and then re-assemble those fragments at the other end. This fragmentation and reassembly *is* a function of Internet Protocol, but it happens at the packet level. The task of portioning a large data block into packet-sized pieces at the very start and then reassembling those packets into a facsimile of the original data at the very end, however, is beyond the scope of IP.

This process of dividing up a data set and communicating it into “packets” must be performed by a computer following a program (code) instructing it how to follow these protocols. As an illustrative example, suppose a computer is tasked with sending a 500 kilobyte data file to another computer located some distance away and connected via Ethernet. A single Ethernet frame is only able to support a data message 1500 bytes *maximum*, and so sending this file within a single Ethernet frame is out of the question.

A common protocol *stack* uses TCP and IP to *encapsulate* portions of the data file for transport over Ethernet, using the following steps:

1. Execute the TCP protocol to subdivide the data file into manageably-sized pieces, prepending a TCP “header” containing identifying information to each of those pieces, creating a TCP *segment*
2. Execute the IP protocol to properly label each of those TCP segments for transport over the next lower-level protocol, prepending another “header” with identifying information, so that the TCP segment becomes the data payload for an IP *packet*
3. Each IP packet is now ready to be received as the data payload for Ethernet



In this example, TCP and IP are the “magic” that makes it possible to send the data file over the Internet to other computers. Any protocols above TCP (e.g. at the Application layer) merely send their messages to TCP for handling, and any protocols below IP (e.g. at the Physical and Data Link layers) handle all the details of message encoding and decoding, hardware-level addressing, logic level interpretation, etc. From the perspective of TCP and IP, both the *purpose* of the data and the *means of physical communication* are irrelevant, for their sole purpose is to form a reliable message-delivery service for *any* high-level application, working over *any* low-level physical network.

## 3.2 Internet Protocol (IP)

In this section, we will investigate the protocol at the heart of the Internet, appropriately called *Internet Protocol*, or *IP*. Again, IP is analogous to a postal system with its standards for labeling addresses, specifying package sizes, etc. It provides a structure necessary for organizing and routing data in volumes that would be too large and too complex for lower-level communication protocols to handle. We will discuss modern and legacy addressing schemes for IP as well as practical diagnostic tools useful for troubleshooting problems in IP-based communication systems.

### 3.2.1 IP addresses

IP is a “layer 3” technology, being concerned with network-wide addresses for routing information between two different locations. IP is not concerned with the details of communication along any particular wire or fiber-optic cable. It is not “aware” of how bits are represented electrically, or what kind of connectors are used to couple cables together. IP is only concerned with “networks” in the broad sense of the word, as abstract collections of computers that are *somehow* (it doesn’t care exactly how) connected to each other.

Networking equipment (DCE) designed to pay attention to IP addresses for routing purposes are called, not surprisingly, *routers*. Their purpose is to direct packets to their appropriate destinations in the shortest amount of time.

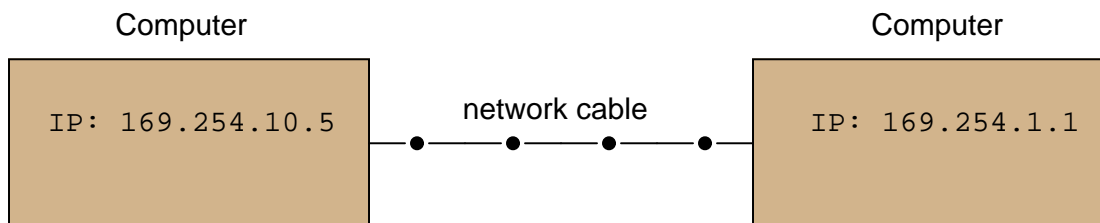
In order for the Internet Protocol to specify where packets are coming from and where they are going to, each source and destination must be marked with its own *IP address*. IP version 4 (IPv4) uses 32-bit addresses, usually expressed as four octets (four bytes) written using decimal numbers. For example:

IP address 00000000 00000000 00000000 00000000 is written as 0.0.0.0

IP address 11111111 11111111 11111111 11111111 is written as 255.255.255.255

IP address 10101001 11111010 00101101 00000011 is written as 169.250.45.3

In order for two inter-connected computers to exchange data using Internet Protocol, each one must have a unique IP address:



At first, this may seem redundant. Doesn’t each and every Ethernet device already have its own unique “MAC address” 48 bits in length to distinguish it from every other Ethernet device in existence? If so, why add *another* set of identifying addresses to the system?

This is true – Ethernet devices are already uniquely addressed – but those MAC addresses serve different purposes than IP addresses. Recall that Ethernet is a standard only at layers 1 and 2, and is not “aware” of any higher-level concerns. Ethernet MAC addresses are useful to switching hubs and other Ethernet DCE devices tasked with management of Ethernet data frames, but those MAC addresses – unique as they may be – have little relevance in the greater picture of IP where we must fragment and reassemble messages over very large-scale networks. More importantly, the reason we need IP addresses is to be able to use interconnecting networks other than Ethernet. For example, two computers may be connected to each other with a simple EIA/TIA-232 cable (or even using radio transceiver units for a “wireless” connection) instead of Ethernet, but still use Internet

Protocol to route packets to their destinations<sup>2</sup>. By having its own dedicated addressing scheme, IP ensures computers can send and receive data packets with no regard to *physical interconnection details, channel arbitration methods, or anything else in between*. In a sense, IP is the “glue” that holds disparate networks together, and makes something like a world-wide Internet possible when so many different network types exist to connect digital devices together. If we attempted to use Ethernet MAC addresses for the same purpose, *the entire Internet would have to consist solely of Ethernet networks!*

A helpful analogy is to think of Ethernet MAC addresses like Social Security numbers for United States citizens, while IP addresses are like street addresses used to route mail. Each US citizen should have their own unique Social Security number, shared by no one else. This number is used for many purposes, including identification on Federal tax documents, to help route specific information (such as income records and Social Security payments) to the proper people. Despite the uniqueness of these numbers, though, people still need separate mailing addresses in order to receive mail through the postal service and other package distribution agencies. The mailing address serves a different purpose than the Social Security “address” each US citizen possesses. Furthermore, the existence of separate mailing addresses ensures even non-citizens living in the United States (e.g. foreign students, ambassadors, etc.) who have no Social Security numbers still have a way to send and receive mail. The mapping of device MAC addresses to IP addresses is handled by a protocol called *ARP* (Address Resolution Protocol) discussed later in this chapter.

### The “ping” utility

Computers enabled to communicate using Internet Protocol (IP) are equipped with a utility program named **ping** useful for detecting the presence of other IP-enabled computers connected to the same network. The classic format of this program is execution by typing the word “ping” at the computer’s command-line interface followed by the IP address of the other computer you wish to detect the presence of. For example, if I wished to check for the presence of a computer on the network with an IP address of 133.82.201.5, I would type this command at my computer’s command line and press the “Enter” key:

```
ping 133.82.201.5
```

The **ping** utility works by sending a very short digital message<sup>3</sup> to the specified IP address, requesting a reply from that computer (usually with multiple attempts). The **ping** command as implemented on the Microsoft Windows operating system typically makes four attempts before quitting. Some other operating systems’ implementation of **ping** continue indefinitely until halted by the user with the “Control-C” keystroke interrupt combination.

---

<sup>2</sup>In fact, this is precisely the state of affairs if you use a *dial-up* telephone connection to link your personal computer with the Internet. If you use dial-up, your PC may not use Ethernet at all to make the connection to your telephone provider’s network, but rather it might use EIA/TIA-232 or USB to a modem (modulator/demodulator) device, which turns those bits into modulated waveforms transmittable over a voice-quality analog telephone line.

<sup>3</sup>The “ping” command is technically defined as an “Echo Request” command, which is part of the *Internet Control Message Protocol* (ICMP) suite.



When diagnosing problems with IP-enabled network devices, few utilities are as immediately useful as **ping**. Networking professionals commonly use the word “ping” as a verb, as in “I tried to *ping* that computer, but it gave no response.” There are many reasons why a computer might fail to respond to a **ping** query, but a successful **ping** attempt proves several things:

- The destination device is powered up and its IP functionality is working
- All network devices (DCE) between your computer and the destination device are communicating
- All cables necessary for the communication of data between your computer and the destination are functional
- Both your computer and the destination device are on the same *subnet* (this topic covered in more detail later)

Since **ping** requires the first three layers of the OSI model to properly function (Physical, Data Link, and Network layers), using this as a diagnostic test neatly identifies where in the OSI model a problem exists. If two computers are not communicating with each other as they should but the **ping** utility works between them, the communication fault must lie within one of the upper OSI layers (e.g. Transport, Session, Presentation, or Application). Thus, we see the **ping** utility as a tool for “divide-and-conquer” style troubleshooting, where we may prove good connections between certain devices and thereby narrow the scope of the problem by elimination.

### IPv4 address ranges

Given the addressing purpose of Internet Protocol (to designate addresses over an extremely large collection of digital communication devices), addresses must be chosen with care. IP version 4 uses a 32-bit field to designate addresses, limiting its address capacity to  $2^{32}$  unique addresses. As large as this number is, it is not enough to uniquely identify all Internet-capable devices worldwide. The inventors of IP did not dream their Internet would grow to the proportions it has today. Let this be a lesson to all those involved with computers: the future is usually bigger than you think! A variety of clever techniques has been developed to deal with this shortage of IP addresses. One of them is to dynamically assign addresses to Internet-connected computers *only when they are turned on*. This is how most personal Internet connections work: when you power up your personal computer to connect to the Internet, your service provider assigns you a temporary IP address through a protocol called DHCP (Dynamic Host Configuration Protocol). Your provider then forces you to relinquish this temporary IP address when you shut down your computer, so someone else may use it for theirs.

The *Internet Corporation for Assigned Names and Numbers*, or *ICANN*, is the organization responsible<sup>4</sup> for assigning IP addresses to Internet users worldwide (among other tasks). This group has designated certain IP address ranges specific to internal (i.e. *Local Area Network*, or *LAN*) network devices, which shall never be used “publicly” to address devices on the world-wide Internet. These specially-designated “private” LAN address ranges are as follows:

10.0.0.0 to 10.255.255.255

172.16.0.0 to 172.31.255.255

192.168.0.0 to 192.168.255.255

Additionally, all computers have their own special *loopback* IP address, used to send IP message packets to itself for certain purposes (including diagnostics): 127.0.0.1. This IP address is completely *virtual*, not associated with any network hardware at all<sup>5</sup>. Therefore, the `ping` command executed on any computer should *always* be able to detect address 127.0.0.1, regardless of the status or even existence of actual network hardware (cards or interfaces) on that computer. Failure of the `ping` command to detect the loopback address is a sign that the computer’s operating system is not configured to use Internet Protocol.

A computer’s loopback address may have uses other than diagnostic. Some computer applications are network-oriented by nature, and rely on IP addresses even if the application is performing some local function rather than a function between computers on an actual network. The *X-windows* graphic-user interface (GUI) system popularly used on UNIX operating systems is an example of this, referencing the loopback address to form a connection between client and server applications running on the same computer.

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<sup>4</sup>Prior to ICANN’s formation in 1999, the *Internet Assigned Numbers Authority*, or *IANA* was responsible for these functions. This effort was headed by a man named Jon Postel, who died in 1998.

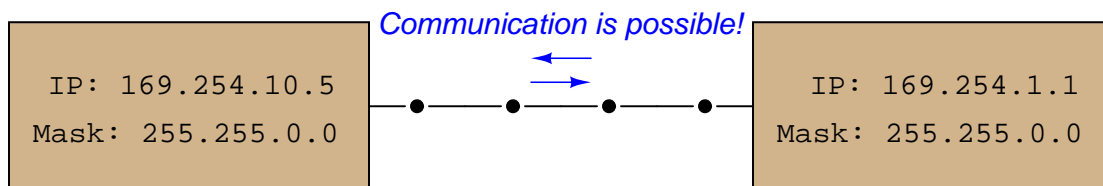
<sup>5</sup>The term “loopback” refers to an old trick used by network technicians to diagnose suspect serial port connections on a computer. Using a short piece of copper wire (or even a paperclip) to “jumper” pins 2 and 3 on an EIA/TIA-232 serial port, any serial data transmitted (out of pin 3) would be immediately received (in pin 2), allowing the serial data to “loop back” to the computer where it could be read. This simple test, if passed, would prove the computer’s low-level communication software and hardware was working properly and that any networking problems must lie elsewhere.

### 3.2.2 Subnetworks and subnet masks

IP (version 4) addresses are used in conjunction with something called *subnet masks*<sup>6</sup> to divide IP networks into “subnetworks.” A “subnetwork” is a range of IP-addressed devices allowed to communicate with each other. You may think of the subnet mask to be a sort of “filter” used to identify IP addresses belonging to the proper range.

The subnet mask works as a bitwise-AND filter, identifying those bits in the IP address defining the subnetwork. For example, if the subnet mask on a computer is set to 255.0.0.0 (binary 11111111 00000000 00000000 00000000), it means the first 8 bits of the IP address define the subnetwork, and thus the computer is only allowed to communicate with another computer belonging to the same subnetwork (i.e. having the same first octet in its IP address).

A set of examples showing two interconnected computers with differing IP addresses (and in some cases, different masks) illustrates how this works<sup>7</sup>. In the first example, two computers with IP addresses differing in the last two octets are able to communicate because their subnets are the same (169.254):



We may check to see the IP addresses and subnet masks are correct by using the `ping` command. A screenshot of `ping` being used on a personal computer running the Microsoft Windows XP operating system is shown here:

```

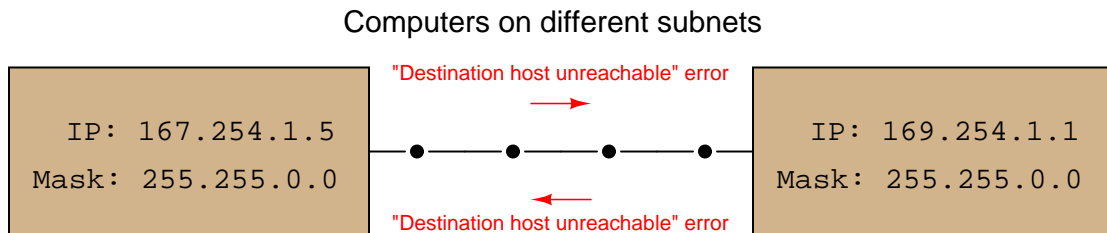
C:\Documents and Settings\btc>ping 169.254.1.1
Pinging 169.254.1.1 with 32 bytes of data:
Reply from 169.254.1.1: bytes=32 time<1ms TTL=128
Reply from 169.254.1.1: bytes=32 time<1ms TTL=128
Reply from 169.254.1.1: bytes=32 time<1ms TTL=128
Reply from 169.254.1.1: bytes=32 time<1ms TTL=128
Ping statistics for 169.254.1.1:
    Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
    Approximate round trip times in milli-seconds:
        Minimum = 0ms, Maximum = 0ms, Average = 0ms
C:\Documents and Settings\btc>

```

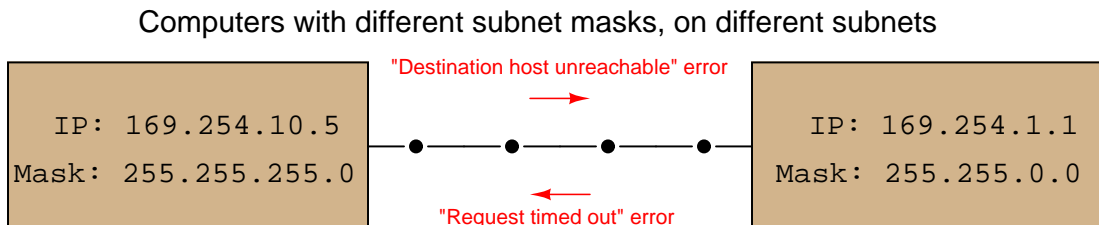
<sup>6</sup>Also called “netmasks” or simply “masks.”

<sup>7</sup>These are real test cases I performed between two computers connected on a 10 Mbps Ethernet network. The error messages are those generated by the `ping` utility when communication was attempted between mis-matched computers.

In the next example, we see two computers with the same mask value, but with different address values in the octets designated by their masks. In other words, these two computers belong to different subnets: one to 167.254 and the other to 169.254, and as a result they are not allowed to communicate with each other using Internet Protocol. The resulting error messages generated by the `ping` utility are shown in this diagram:



In the last example, we see two computers having different mask values as well as different IP addresses. The subnet of the left-hand computer is 169.254.10 while the subnet of the right-hand computer is 169.254:



The computer on the left may only communicate with IP addresses matching in the first three octets (169.254.10). Seeing that the destination address for the second computer does not match in its third octet, **ping** returns a “Destination host unreachable” error message when executed from the left-hand computer.

When the computer on the right attempts to communicate with (“ping”) the computer on the left, it is allowed to transmit to that computer because its mask only screens for agreement in the first two octets (169.254), which happen to match. However, the computer on the left is not allowed to transmit to the computer on the right because of its more restrictive subnet, and so **ping** running on the right-hand computer returns a “Request timed out” error message because it never receives a reply from the left-hand computer to any of its queries.

With just two computers connected by a single cable, the concept of subnetworks and masks seems useless, and indeed it is on this small of a scale. However, “subnetting” is a useful technique for managing high traffic loads on large networked systems using IP addresses, and so it is commonly seen in many local area networks (LANs) such as those found at industry and commercial sites.

While many IPv4-compliant computers designate both the IP address and the subnet mask values as sets of “dotted-decimal” numbers with each decimal (0-255) representing an “octet” of eight bits in the 32-bit IPv4 address space (e.g. IP = 169.254.5.1 and Mask = 255.255.0.0), a more modern designation for subnets is to append the device’s IP address with a forward slash character and a decimal number specifying how many bits are used to specify the subnet.

To illustrate by example, consider a computer having the IP address 169.254.5.1 and a mask value of 255.255.0.0 (thus specifying that it belongs to the subnetwork 169.254), we could alternatively state that computer’s IP address as 169.254.5.1/16. The “16” means that the first sixteen bits of its IP address define its subnet. To cite another example, a computer with an IP address of 192.168.35.100 and a subnet mask of 255.255.255.0 could have its address alternatively written as 192.168.35.100/24. The “24” tells us the first 24 bits (first three octets) of the IP address define its subnetwork: this computer belongs to the subnetwork 192.168.35.

The `ping` diagnostic utility program may be used to search for unknown IP addresses on a known subnet. This may be done by “pinging” to the *broadcast address* for that subnet: an IP address formed by the known subnet numbers, followed by all binary 1’s filling the unknown bit spaces. For example, you could use `ping` to search for devices on the subnet `156.71` (subnet mask `255.255.0.0`) by using the following command:

```
ping 156.71.255.255
```

### 3.2.3 Routing tables

Devices on an IP-compliant network need to know how to best route IP data packets from one location to another. In the case of special *router* devices managing traffic on the Internet, optimum packet routes are determined by a number of different criteria (e.g. degree of congestion in a route, the fewest number of “hops” from one router to another, geographical distance, etc.), updated continually by sophisticated algorithms operating within the routers. Data for these optimum routes are stored in lists called *routing tables*.

Personal computers also have routing tables, which may be modified by the user. An application where you may need to modify the routing table of a personal computer is the case of enabling that computer to communicate with a brand-new device installed on the industrial network, whose subnetwork ID differs from the other devices on that network. Many network-ready devices ship from the manufacturer with default subnets of 192.168.1. It is quite possible that the subnet of the industrial network you intend to have the device operate on is different from this default factory-configuration. This in itself is not necessarily a problem, as IP addresses and subnet mask values of IP-enabled devices are always user-configurable. However, if the only method of configuring this new device is by communicating to it through an IP network connection, you are faced with a Catch-22: how do you communicate with it to alter its subnet, when its subnet prevents you from communicating with it?

One solution to this Catch-22 dilemma is to temporarily use a personal computer with a subnet matching the new device to configure that new device, then disconnecting the device from the personal computer after it has been configured for the new subnetwork, and subsequently plugging the device into the industrial network where it will function.

Another solution is to use one of the personal computers already residing on the industrial network to configure the new device, and specially enabling that one computer to talk to the device’s default subnet. In this way, the new device may be plugged into the industrial network, configured for a new IP address and subnet while on that network, where it will subsequently communicate with existing devices on the proper subnet. This may be done through the `route` command-line utility. At a command prompt (just like when using the `ping` command), type “route” followed by arguments telling it to add the device’s default address and subnet mask to the computer’s routing table. Supposing our new device has a default IP address of 192.168.1.10 and a default mask of 255.255.255.0, our `route` command would need to be entered as follows:

```
route add 192.168.1.10 mask 255.255.255.0
```

After issuing this command to the personal computer, it may be used to communicate with the new device to change its IP address and subnet mask values to match devices on the industrial network.

### 3.2.4 IP version 6

The next version of IP (version 6, or IPv6) uses 128-bit addresses, giving  $2^{128}$  address possibilities (in excess of  $3.4 \times 10^{38}$ ), in stark contrast to IPv4's paltry  $2^{32}$  address space. To put this enormous quantity into perspective, there are enough IPv6 addresses to designate nearly 57 *billion* of them for each and every gram of the Earth's mass<sup>8</sup>. While IPv4 addresses are typically written as four octets in decimal form (e.g. 169.254.10.5), this notation would be very cumbersome for writing IPv6 addresses. Thus, IPv6 addresses are written as a set of eight hexadecimal numbers (up to four characters per number) separated by colons, such as 4ffd:522:c441:d2:93b2:f5a:8:101f. The phase-in of IPv6 to replace IPv4 has already started for certain portions of the Internet, but the full transition to IPv6 is expected to take many years. The IPv6 "loopback" virtual address for computers is 0:0:0:0:0:0:0:1, or more simply<sup>9</sup> written as ::1.

Note the "shorthand" notation used in the previous IPv6 addresses to eliminate extra characters: some of the 16-bit segments are truncated to less than four hexadecimal characters if the preceding (more-significant) characters are zero. Thus, you see :522: instead of :0522:, and :d2: instead of :00d2:. The loopback address of ::1 is the ultimate shorthand notation, collapsing all prior segments (which are all zero) into a pair of back-to-back colons.

IP version 6 supports subnetworks just as IPv4 does, but instead of denoting subnet masks in the same colon-delimited fashion as IPv6 addresses, IPv6 subnet masks are simply specified by the number of "1" bits beginning from the first (MSB). The rationale here is that subnet mask bits should be contiguous<sup>10</sup>, with no zero bits separating one bits. This being the case, the subnet mask for any practical IP range may be specified as a simple number of 1's from the MSB down to the LSB<sup>11</sup>.

For example, an IPv6 address written as 4ffd:522:c441:d2:93b2:f5a:8:101f/48 means that the first 48 bits of that address must match the first 48 bits of another address in order to be within the same subnetwork as the other address. In other words, any other address existing within the same subnetwork would also have to begin with 4ffd:522:c441.

It should be noted that an updated version of the ping command (called ping6) is available to help diagnose IPv6 systems.

---

<sup>8</sup>According to Douglas Giancoli's *Physics for Scientists and Engineers* textbook, the mass of the Earth is  $5.98 \times 10^{24}$  kg, or  $5.98 \times 10^{27}$  grams. Dividing  $2^{128}$  (the number of unique IPv6 addresses) by the Earth's mass in grams yields the number of available IPv6 address per gram of Earth mass. Furthermore, if we assume a grain of sand has a mass of about 1 milligram, and that the Earth is modeled as a very large collection of sand grains (not quite the truth, but good enough for a dramatic illustration!), we arrive at 57 *million* IPv6 addresses per grain of sand on Earth.

<sup>9</sup>The fully-written loopback address is actually 0000:0000:0000:0000:0000:0000:0000:0001.

<sup>10</sup>While it is possible to use non-contiguous subnet mask values, the practice is frowned upon by most system administrators.

<sup>11</sup>Indeed, subnet masks for IPv4 can be specified in this manner as well, not just IPv6 subnet masks.



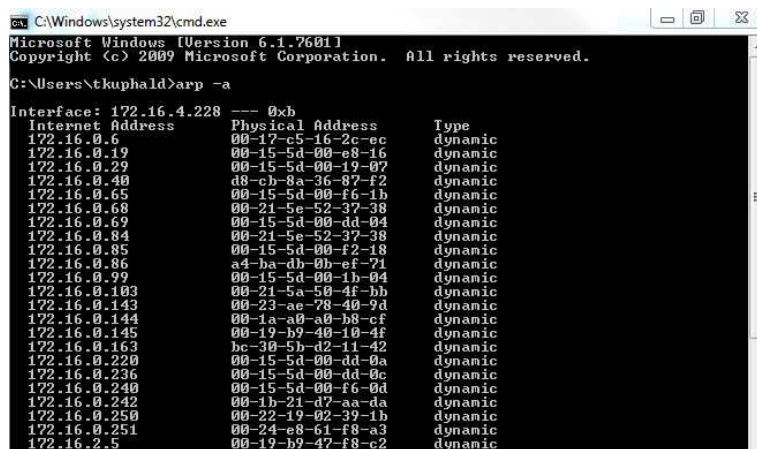
### 3.2.5 ARP

While Internet Protocol (IP) provides a universal addressing standard for devices operating on large-scale digital networks, individual devices usually possess MAC addresses unique to each device. As mentioned in a previous section, IP addresses are to MAC addresses as mailing addresses are to Social Security numbers: the IP address serves to route information sent over the network, while MAC addresses identify the individual devices themselves. Any digital network system dealing with both types of addresses must somehow “map” each MAC address to a corresponding IP address, and this is handled by a protocol called *Address Resolution Protocol*, or *ARP*.

Every node running the ARP protocol on a digital network maintains a table of equivalent addresses, MAC to IP. This table is called the *ARP cache*, the contents of which may be displayed by running the following command on the device’s command-line interface:

```
arp -a
```

The `arp -a` command instructs the machine to print *all* (-a) ARP cache entries to the screen for your viewing. This, of course, only displays what that machine happens to know at that time. If the ARP cache has not been updated recently, addressing data found in the ARP cache may be out of date or even missing. Here is a partial screenshot of the `arp -a` command run on a Microsoft Windows computer, showing each IP (“internet”) address in the ARP cache and its corresponding MAC (“physical”) address:



```

C:\Windows\system32\cmd.exe
Microsoft Windows [Version 6.1.7601]
Copyright (c) 2009 Microsoft Corporation. All rights reserved.

C:\Users\tkuphal>arp -a

Interface: 172.16.4.228 --- 0xb
Internet Address      Physical Address      Type
172.16.0.6             00-17-c5-16-2c-ec     dynamic
172.16.0.19            00-15-5d-00-e8-16     dynamic
172.16.0.29            00-15-5d-00-19-07     dynamic
172.16.0.40            d8-cb-8a-36-87-f2     dynamic
172.16.0.65            00-15-5d-00-f6-1b     dynamic
172.16.0.68            00-21-5e-52-37-38     dynamic
172.16.0.69            00-15-5d-00-dd-04     dynamic
172.16.0.84            00-21-5e-52-37-38     dynamic
172.16.0.85            00-15-5d-00-f2-18     dynamic
172.16.0.86            a4-ba-db-0b-ef-71     dynamic
172.16.0.99            00-15-5d-00-1b-04     dynamic
172.16.0.103           00-21-5a-50-4f-bb     dynamic
172.16.0.143           00-23-ae-78-40-9d     dynamic
172.16.0.144           00-1a-a0-a0-b8-cf     dynamic
172.16.0.145           00-19-b9-40-10-4f     dynamic
172.16.0.163           bc-30-5b-d2-11-42     dynamic
172.16.0.220           00-15-5d-00-dd-0a     dynamic
172.16.0.236           00-15-5d-00-dd-0c     dynamic
172.16.0.240           00-15-5d-00-f6-0d     dynamic
172.16.0.242           00-1b-21-d7-aa-da     dynamic
172.16.0.250           00-22-19-02-39-1b     dynamic
172.16.0.251           00-24-e8-61-f8-a3     dynamic
172.16.2.5             00-19-b9-47-f8-c2     dynamic

```

One way to update the ARP cache on a machine with a command-line interface is to first issue a broadcast<sup>12</sup> ping request. Responses from active nodes on the network will populate the machine’s ARP cache with address information, after which you may run the `arp -a` command to display those cache entries.

<sup>12</sup>The “ping” command is often used to test the response of a single IP node on a network, by issuing the command followed by the IP address of interest (e.g. `ping 192.168.35.70`). By contrast, a “broadcast” ping request attempts to contact a range of IP addresses within a subnet. For example, if we wished to ping all the IP addresses beginning with 192.168.35, we would issue the command with all 1’s in the last octet of the IP address field (e.g. `ping 192.168.35.255`).

### 3.2.6 DNS

The acronym *DNS* actually stands for two related things: *Domain Name System* and *Domain Name Server*. The first meaning of “DNS” refers to the system of exchanging numerical IP addresses with alphanumeric *Uniform Resource Locators (URLs)* which are easier for human beings to remember. When you use web browser software to navigate to a web site on the Internet, you have the option of entering the URL *name* of that site (e.g. `www.google.com`) or a numerical IP address (e.g. `75.125.53.104`). Special computers connected to the Internet called *Domain Name Servers*, and *Domain Name Resolvers (DNRs)* use the *Address Resolution Protocol (ARP)* to convert your target web site name to its actual IP address so that a connection may be made between that computer and yours.

ICANN, the same organization responsible for allotting IP addresses, also maintains databases for all registered domain names.

### 3.3 Transmission Control Protocol (TCP) and User Datagram Protocol (UDP)

At the next OSI Reference Model layer (layer 4) is a set of protocols specifying how reliable communication “connections” should be established between devices on a digital network. Rather than specifying addresses for routing data packets on a large network (OSI layer 3), layer 4 works on the level of virtual data “ports” at the transmitting and receiving devices. The purpose of these virtual ports is to manage multiple types of data transactions to and from the same IP address, such as in the case of a personal computer accessing a web page (using HTTP) and sending an email message (using SMTP) at the same time. An analogy to help understand the role of ports is to think of multiple packages delivered to different people at a common address such as a business office. The mailing address for the office is analogous to the IP address of a computer exchanging data over a network: it is how other computers on the network “find” that computer. The personal or department names written on the different packages are analogous to virtual ports on the computer: “places” within that node where specific messages are directed once they arrive.

*Transmission Control Protocol (TCP)* and *User Datagram Protocol (UDP)* are two methods used to manage data flow through “ports” on a DTE device, with TCP being the more complex and robust of the two. Both TCP and UDP rely on IP addressing to specify which devices send and receive data, which is why you will often see these protocols listed in conjunction with IP (e.g. TCP/IP and UDP/IP). TCP and UDP are both useless on their own: a protocol specifying port locations without an IP address would be as meaningless as a package placed in the general mail system with just a name but with no street address. The combination of an IP address and a TCP or UDP port number is called a *socket*. Conversely, IP anticipates the presence of a higher-level protocol such as TCP or UDP by reserving a portion of its “datagram” (packet) bit space for a “protocol” field<sup>13</sup> to specify which high-level protocol generated the data in the IP packet.

TCP is a complex protocol specifying not only which virtual “ports” will be used at the sending and receiving devices, but also how data integrity will be guaranteed. Data communicated via TCP are sent in blocks of bits called *segments*. In the same way that the IP algorithm encapsulates data into self-contained “packets” with the necessary routing data to ensure proper delivery to the destination, the TCP algorithm encapsulates data with “header” bits specifying such details as sequence number, acknowledgment identification, checksum (for error-detection), urgency of the message, and optional data. TCP takes responsibility for ensuring both devices on the network are ready to exchange data, breaks the data block into segments of an appropriate size to be encapsulated inside IP packets on the transmitting end, checks each segment for corruption (using the CRC method) upon receipt, reassembles those segments into the whole data block at the receiving end, and terminates the connection between devices upon completion. If a TCP segment successfully arrives at the receiving device, the TCP protocol running at the receiving device acknowledges this to the transmitting device. If the transmitting device fails to receive an acknowledgment within a specified time, it automatically re-sends the segment. If a TCP segment arrives corrupted, the TCP protocol running at the receiving device requests a re-send from the transmitting device. TCP thus fulfills the task of the author and publisher in the manuscript analogy, handling the disassembly and reassembly of the manuscript. In rigorously checking the integrity of the data transfer, TCP’s

---

<sup>13</sup>Both IPv4 and IPv6 reserve eight bits for this purpose.

### 3.3. TRANSMISSION CONTROL PROTOCOL (TCP) AND USER DATAGRAM PROTOCOL (UDP)41

functionality is akin to sending each manuscript package via *certified mail* where the author may track the successful delivery of each and every package.

Another feature of TCP is end-to-end *flow control*, enabling the receiving device to halt the incoming data stream for any reason, for example if its buffer memory becomes full. This is analogous to the XON/XOFF control signals used in simple serial communication protocols such as EIA/TIA-232. In the case of large networks, TCP flow control manages the flow of data segments even when the communication paths are dynamic and liable to change.

If IP (Internet Protocol) is the “glue” that holds the Internet together, TCP (Transmission Control Protocol) is what makes that glue strong enough to be practically useful. Without TCP, data communication over the wildly disparate physical networks that comprise the world-wide Internet would be far less reliable.

UDP is a much simpler protocol for managing data ports, lacking not only the segment sequencing of TCP but also lacking many of the data-integrity features of TCP. Unlike TCP, the UDP algorithm does not sequence the data block into numbered segments at the transmitting end or reassemble those numbered segments at the receiving end, instead relegating this task to whatever application software is responsible for generating and using the data. Likewise, UDP does not error-check each segment and request re-transmissions for corrupted or lost segments, once again relegating these tasks to the application software running in the receiving computer. It is quite common to see UDP applied in industrial settings, where communication takes place over much smaller networks than the world-wide Internet, and where the IP data packets themselves tend to be much smaller as well. Another reason UDP is more common in industrial applications is that it is easier to implement in the “embedded” computer hardware at the heart of many industrial devices. The TCP algorithm requires greater computational power and memory capacity than the UDP algorithm, and so it is much easier to engineer a single-chip computer (i.e. microcontroller<sup>14</sup>) to implement UDP than it would be to implement TCP.

Information-technology professionals accustomed to the world of the Internet may find the use of UDP rather than TCP in industrial networks alarming. However, there are good reasons why industrial data networks do not necessarily need all the data-integrity features of TCP. For example, many industrial control networks consist of seamless Ethernet networks, with no routers (only hubs and/or switches) between source and destination devices. With no routers to go through, all IP packets communicated between any two specified devices are guaranteed to take the exact same data path rather than being directed along alternate, dynamic routes. The relative stability and consistency of communication paths in such industrial networks greatly simplifies the task of packet-reassembly at the receiving end, and makes packet corruption less likely. In fact, many industrial device messages are short enough to be communicated as single IP packets, with no need for data segmentation or sequencing at all!

---

<sup>14</sup>This limitation is fast becoming obsolete as microcontroller designs continue to advance in memory capacity and computational power.

Using another utility program on a personal computer called **netstat** (available for both Microsoft Windows and UNIX operating systems) to check active connections<sup>15</sup>, we see the various IP addresses and their respective port numbers (shown by the digits following the colon after the IP address) as a list, organized by TCP connections and UDP connections:

```
C:\Documents and Settings\htc>netstat -an
Active Connections

```

Proto	Local Address	Foreign Address	State
TCP	0.0.0.0:135	0.0.0.0:0	LISTENING
TCP	0.0.0.0:445	0.0.0.0:0	LISTENING
TCP	0.0.0.0:2869	0.0.0.0:0	LISTENING
TCP	127.0.0.1:1025	0.0.0.0:0	LISTENING
TCP	127.0.0.1:5152	0.0.0.0:0	LISTENING
TCP	169.254.1.2:23	169.254.1.1:1116	ESTABLISHED
TCP	169.254.1.2:139	0.0.0.0:0	LISTENING
UDP	0.0.0.0:445	**:	
UDP	0.0.0.0:500	**:	
UDP	0.0.0.0:1062	**:	
UDP	0.0.0.0:4500	**:	
UDP	0.0.0.0:7725	**:	
UDP	127.0.0.1:123	**:	
UDP	127.0.0.1:1063	**:	
UDP	127.0.0.1:1066	**:	
UDP	127.0.0.1:1900	**:	
UDP	169.254.1.2:123	**:	
UDP	169.254.1.2:137	**:	
UDP	169.254.1.2:138	**:	
UDP	169.254.1.2:1900	**:	

```
C:\Documents and Settings\htc>
```

An interesting distinction between TCP and UDP is evident in this screenshot. Note how each of the TCP connections has an associated “state” (either LISTENING or ESTABLISHED), while none of the UDP connections has any state associated with it. Recall that TCP is responsible for initiating and terminating the connection between network devices, and as such each TCP connection must have a descriptive state. UDP, on the other hand, is nowhere near as formal as TCP in establishing connections or ensuring data transfer integrity, and so there are no “states” to associate with any of the UDP connections shown. Data arriving over a UDP connection simply shows up unannounced, like an impolite guest. Data arriving over a TCP connection is more like a guest who announces in advance when they will arrive, and also says “good bye” to the host as they depart.

Many different port numbers have been standardized for different applications at OSI Reference Model layers above 4 (above that of TCP or UDP). Port 25, for example, is always used for SMTP (Simple Mail Transfer Protocol) applications. Port 80 is used by HTTP (HyperText Transport Protocol), a layer-7 protocol used to view Internet “web” pages. Port 443 is used by HTTPS, an encrypted (secure) version of HTTP. Port 107 is used by TELNET applications, a protocol whose purpose it is to establish command-line connections between computers for remote administrative work. Port 22 is used by SSH, a protocol similar to TELNET but with significantly enhanced security. Port 502 is designated for use with Modbus messages communicated over TCP/IP.

<sup>15</sup>In this particular case, I typed **netstat -an** to specify *all* (a) ports with *numerical* (n) IP addresses and port numbers shown.

## Chapter 4

# 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.

## 4.1 The OSI Reference Model

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

## 4.2 Command-line diagnostic utilities

In addition to `ping` and `arp`, another utility program useful for troubleshooting network connections from a Microsoft Windows computer's command line interface<sup>1</sup> is `ipconfig`. When executed, `ipconfig` returns a listing of all available (configured and operating) network interfaces on that computer:

```
C:\Documents and Settings\btc>ipconfig

Windows IP Configuration

Ethernet adapter Local Area Connection:

    Connection-specific DNS Suffix  . : 
    IP Address. . . . .               : 169.254.1.2
    Subnet Mask . . . . .             : 255.255.0.0
    Default Gateway . . . . .         : 

Ethernet adapter Wireless Network Connection:

    Media State . . . . .             : Media disconnected

C:\Documents and Settings\btc>
```

---

<sup>1</sup>In UNIX-based operating systems the program used to access the command line is often called `terminal` or `xterm`. In Microsoft Windows systems it is simply called `cmd`.



The equivalent command for UNIX operating systems is `ifconfig`, shown in this screenshot:

```

root@Renegade2:/home# ifconfig
eth0      Link encap:Ethernet  HWaddr 00:13:20:08:ec:e6
          inet addr:192.168.0.64  Bcast:192.168.0.255  Mask:255.255.255.0
          inet6 addr: fe80::213:20ff:fe08:ece6/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:170901 errors:0 dropped:0 overruns:0 frame:0
          TX packets:107550 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:212178154 (212.1 MB)  TX bytes:14005068 (14.0 MB)

eth1      Link encap:Ethernet  HWaddr 00:0e:35:a2:1b:7f
          inet6 addr: fe80::20e:35ff:fea2:1b7f/64 Scope:Link
          UP BROADCAST MULTICAST  MTU:1500  Metric:1
          RX packets:441 errors:0 dropped:0 overruns:0 frame:0
          TX packets:570 errors:0 dropped:6 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:0 (0.0 B)  TX bytes:0 (0.0 B)
          Interrupt:18 Base address:0x2000 Memory:48005000-48005fff

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING  MTU:16436  Metric:1
          RX packets:8 errors:0 dropped:0 overruns:0 frame:0
          TX packets:8 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:516 (516.0 B)  TX bytes:516 (516.0 B)

root@Renegade2:/home#

```

Some of the more interesting details contained in the output from `ifconfig` are the IPv6 addresses (in addition to IPv4 addresses), Ethernet MAC addresses (listed as “hardware addresses” or *HWaddr*), Ethernet performance data (e.g. number of collisions), IP performance data (e.g. number of IP packets received and transmitted), and details on the “loopback” address (IPv4 127.0.0.1 or IPv6 ::1).

A utility intended to reveal the DNS name of a computer given its IP address, or visa versa, is `nslookup`. The same command works on Microsoft Windows and UNIX operating systems alike. Here, we see the UNIX version used to identify four IP addresses of the popular Google search engine web site, followed by the Microsoft Windows version:

```
root@Renegade2:/home# nslookup www.google.com
Server:          192.168.0.1
Address:         192.168.0.1#53

Non-authoritative answer:
www.google.com canonical name = www.l.google.com.
Name:   www.l.google.com
Address: 74.125.53.103
Name:   www.l.google.com
Address: 74.125.53.147
Name:   www.l.google.com
Address: 74.125.53.99
Name:   www.l.google.com
Address: 74.125.53.104
```

```
Microsoft Windows [Version 5.2.3790]
(C) Copyright 1985-2003 Microsoft Corp.

U:\>nslookup www.google.com
Server:   htc2000-dc1.bellingham-tech.edu
Address:  172.16.0.240

Non-authoritative answer:
Name:     www.l.google.com
Addresses: 209.85.173.104, 209.85.173.103, 209.85.173.147, 209.85.173.99
Aliases:  www.google.com

U:\>_
```

Another utility used to explore network connections is **traceroute** (spelled **tracert** on Microsoft Windows operating systems). This utility sends a test packet to the designated destination address, returning information on all the “hops” the IP packet takes between computers along the network to reach its destination and the amount of time taken to make the trip. Execution of **traceroute** on a UNIX computer and **tracert** on a Microsoft Windows computer are shown here:

```
root@Renegade2:/home# traceroute www.google.com
traceroute to www.google.com (74.125.53.147), 30 hops max, 40 byte packets
 1 home [192.168.0.1] 4.763 ms 4.803 ms 4.784 ms
 2 tukw-dsl-gw22-214.tukw.qwest.net (63.231.10.214) 57.927 ms 59.993 ms 61.916 ms
 3 tukw-agw1.inet.qwest.net (71.217.184.169) 63.924 ms 65.905 ms 67.882 ms
 4 sea-core-01.inet.qwest.net (67.14.1.194) 71.775 ms 71.784 ms 73.609 ms
 5 sea-brdr-01.inet.qwest.net (205.171.26.54) 75.642 ms 77.442 ms 79.421 ms
 6 63.146.26.198 (63.146.26.198) 81.438 ms 67.052 ms 68.856 ms
 7 sl-gw20-sea-0-0-0.sprintlink.net (144.232.6.8) 70.633 ms 56.617 ms 60.219 ms
 8 sl-googl13-199181-0.sprintlink.net (144.224.13.138) 62.133 ms 64.301 ms 66.162
 9 209.85.249.32 (209.85.249.32) 68.140 ms 209.85.249.34 (209.85.249.34) 70.028 ms
10 216.239.46.204 (216.239.46.204) 79.865 ms 81.739 ms 85.587 ms
11 64.233.174.121 (64.233.174.121) 249.193 ms 64.233.174.129 (64.233.174.129) 113.
12 72.14.232.70 (72.14.232.70) 93.458 ms 72.14.232.10 (72.14.232.10) 99.574 ms 72.
13 72.14.232.6 (72.14.232.6) 68.876 ms 72.14.232.2 (72.14.232.2) 70.251 ms pw-in-f
root@Renegade2:/home#
```

```
U:\>tracert www.google.com

Tracing route to www.l.google.com [209.85.173.99]
over a maximum of 30 hops:
  1  4294964928 ms  4294964927 ms  4294964927 ms  134.39.250.1
  2  4294964927 ms  4294964927 ms  4294964927 ms  bellingham-2691.ctc.edu [192.6
4.1.105]
  3  4294964931 ms  4294964931 ms  4294964930 ms  ge-0-1-0--941.seawescarl.infra
.wa-k20.net [68.179.207.210]
  4  4294964931 ms  4294964931 ms  4294964930 ms  ge-3-0-3--0.seawescor1.infra.
wa-k20.net [68.179.203.26]
  5  4294964931 ms  4294964931 ms  4294964931 ms  ge-2-2-0--311.iccr-sttlwa01-02
.infra.pnw-gigapop.net [209.124.188.182]
  6  4294964931 ms  4294964930 ms  4294964931 ms  pnwgp-cust.tr01-sttlwa01.trans
itrail.net [137.164.131.186]
  7  4294964931 ms  4294964931 ms  4294964931 ms  te4-3--301.tr01-sttlwa01.trans
itrail.net [137.164.131.185]
  8  4294964931 ms  4294964931 ms  4294964931 ms  137.164.130.158
  9  4294964931 ms  4294964931 ms  4294964931 ms  209.85.249.32
 10  4294964935 ms  4294964938 ms  4294964938 ms  216.239.46.208
 11  4294964936 ms  4294964937 ms  4294964937 ms  64.233.174.127
 12  4294964937 ms  4294964936 ms  4294964937 ms  209.85.251.149
 13  4294964943 ms  4294964937 ms  4294964941 ms  209.85.251.145
 14  4294964941 ms  4294964944 ms  4294964937 ms  mh-in-f99.google.com [209.85.1
73.99]

Trace complete.

U:\>
```

## 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<sup>1</sup> the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture<sup>2</sup>, the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

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

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

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

<sup>2</sup>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<sup>3</sup>. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

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

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

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

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

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<sup>3</sup>*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.

Packet

Encapsulation

Ethernet

Internet Protocol (IP)

Transmission Control Protocol (TCP)

User Datagram Protocol (UDP)

Router

IP address

MAC address

Ping

Loopback address

Broadcast address

Subnetwork

Mask

Routing table

Address Resolution Protocol (ARP)

DNS

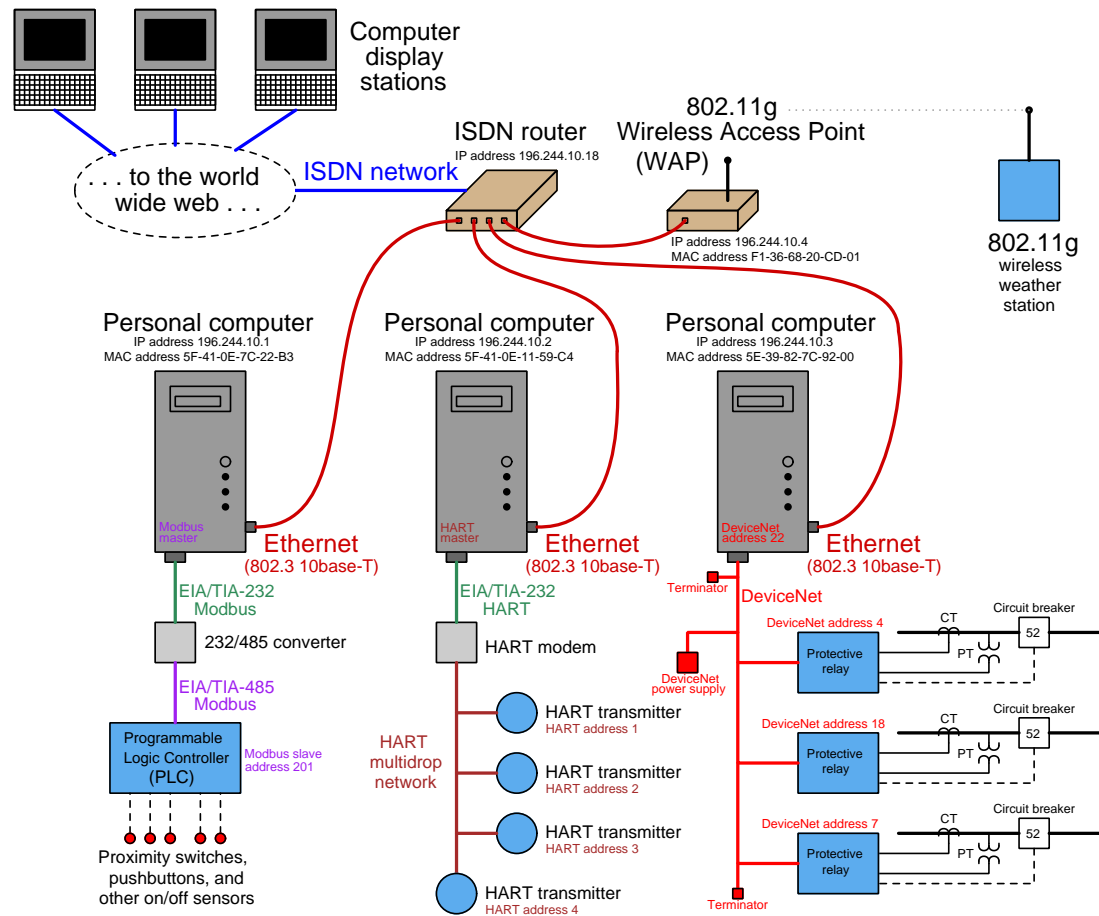
Netstat

Port

Unix

### 5.1.3 Industrial SCADA system

Examine this network diagram of an industrial SCADA (Supervisory Control And Data Acquisition) system, comprised of different technologies for acquiring the data, but ultimately communicating to computer display stations located somewhere on the Internet (world wide web):



Identify some of the different OSI layer 1 (physical) network standards you see in this system, as well as OSI layer 2 (data link) addressing schemes. Then, explain how all this data, in all its different forms, gets shuttled over the same ISDN cable to the Internet using TCP/IP packets.

#### Challenges

- Identify where the diagnostic utility `ping` could be used to test nodes in this heterogeneous network.

- Identify where the diagnostic utility `ping` could *not* be used to test nodes in this heterogeneous network.

#### 5.1.4 Different protocols

One day an industrial electrician goes to connect a PLC (programmable logic controller) to an operator display panel and notices the communication ports on both the PLC and on the display panel are labeled *Modbus*, which the electrician figures is some sort of networking standard. Upon inspection of the screw terminals the electrician also notices the wiring is similar to RS-485 (EIA/TIA-485), with TD(+), TD(-), RD(+), and RD(-) terminals. Later on, when reading the user manuals for both devices, the electrician notices the ports described as being “RS-485” as well as being “Modbus.”

Asking a more experienced electrician about this, the answer is that the ports are *both* EIA/TIA-485 and Modbus. These two network standards are not exclusive, but complementary.

Elsewhere in the world, a new computer network technician is going to download some software from a website, and notices it is possible to use either *HTTP* (Hyper-Text Transfer Protocol) or *FTP* (File Transfer Protocol) to do the job. Looking behind the computer, the technician notices a regular Ethernet cable (twisted-pair) plugged into the network port. Later, the technician asks someone more experienced, “Which network standard am I using when I download files, HTTP, FTP, or Ethernet?” The answer is similar to that given to the instrument technician: HTTP and FTP are alternatives to each other, both being complementary to Ethernet as parts of a complete protocol “pathway” from file to user. It is never a question of HTTP *or* Ethernet, just as it is never a question of Modbus *or* RS-485.

How would you explain either situation, using the OSI seven-layer model as a guide?

#### Challenges

- A commonly-heard criticism of the OSI model is that “no communications standard fully agrees with it,” i.e. no single standard has specifications in all seven layers of the model. Explain why this is not really a problem at all, and how it represents a fundamental misunderstanding of the OSI model.
- *ASCII* is a layer-6 standard for encoding alphanumeric text in digital form. Give an example where this standard works in conjunction with lower-level standards to communicate text data between two computers.
- *S-HTTP* is a layer-7 standard used for encrypting and decrypting digital data over networks. This is what you are using when you access a web page beginning with `https://`. Give an example where this standard works in conjunction with ASCII and other lower-level standards to securely communicate a credit card number between two computers during an online purchase transaction.

## 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<sup>4</sup>” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely<sup>5</sup> on an answer key!

---

<sup>4</sup>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.

<sup>5</sup>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<sup>-1</sup>)

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<sup>3</sup>/kg-s<sup>2</sup>)

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**<sup>4</sup> (W/m<sup>2</sup>·K<sup>4</sup>)

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*<sup>6</sup> 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.

---

<sup>6</sup>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<sup>7</sup> 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<sup>8</sup> 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<sup>9</sup> 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.

<sup>7</sup>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.

<sup>8</sup>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.

<sup>9</sup>Reviewing some algebra here, a *root* is a value for  $x$  that yields an overall value of zero for the polynomial. For this polynomial ( $9x^2 + 5x - 2$ ) the two roots happen to be  $x = 0.269381$  and  $x = -0.82494$ , with these values displayed in cells B1 and B2, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

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

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

	A	B	C
<b>1</b>	x_1	= ( -B4 + C1 ) / C2	= sqrt ( (B4^2) - (4*B3*B5) )
<b>2</b>	x_2	= ( -B4 - C1 ) / C2	= 2*B3
<b>3</b>	a =	9	
<b>4</b>	b =	5	
<b>5</b>	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<sup>10</sup> – 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.

<sup>10</sup>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 IP address space

The fourth version of the *IP* (Internet Protocol) standard, known as IPv4, specifies an address that is 32 bits wide. The address is usually expressed in the form of four “octets” translated into decimal form and separated by periods. Here is an example of an IPv4 address:

196.252.70.183

What are the largest and the smallest IPv4 addresses possible in this format? How many total unique addresses does this work out to be?

The next version of IP is version 6 (version 5 was experimental). IPv6 uses a 128-bit wide address. How many “octets” does it take to express an IPv6 address? How many unique addresses can be represented in the IPv6 field?

Challenges
------------

- Are there any special IP addresses reserved for specific purposes?
- How do the address spaces of IPv4 and IPv6 compare to that of Ethernet MAC address space?
- Why are IP addresses required in addition to Ethernet MAC addresses in a network where most devices are Ethernet-based?
- Explain what 192.168.25.7/24 means as an IP address.
- Explain what 192.168.25.7/8 means as an IP address.

## 5.3 Diagnostic reasoning

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

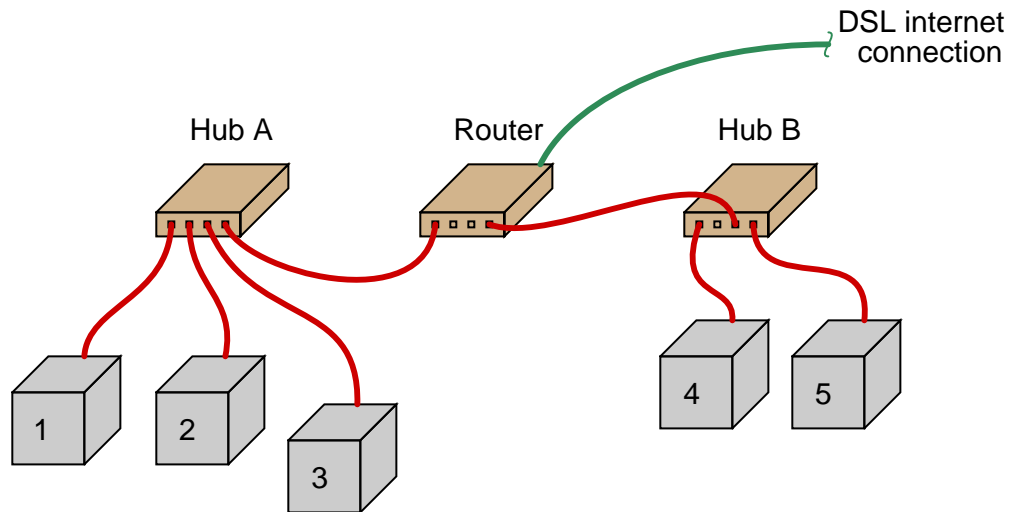
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

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

### 5.3.1 Tracing message routes

This Ethernet network has a problem in it somewhere:



- 1 can “ping” 3
- 4 can “ping” `www.google.com`
- 4 can “ping” 5
- 2 cannot “ping” `www.google.com`

An excellent diagnostic strategy is to trace paths of data flow in a complex system, looking for places of intersection. Successful paths prove all points along the pathway are functioning. Places of overlap between unsuccessful paths prove that section is suspect.

Apply this strategy to the problem at hand, and use the results to narrow the field of possible faults.

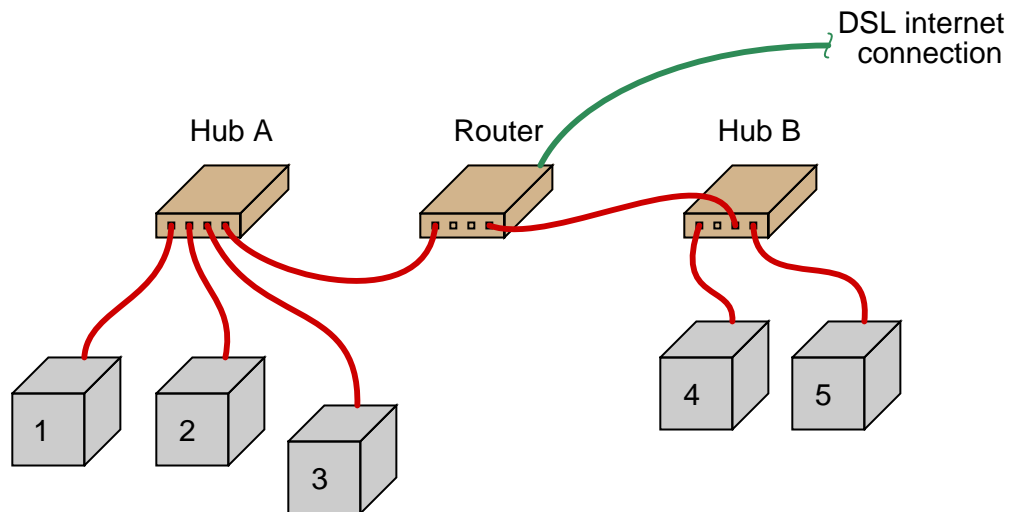
Finally, identify a good “next ping” test to do.

#### Challenges

- Suppose you were to swap hubs A and B, and repeat these same tests. What would this demonstrate, if anything?

### 5.3.2 Possible faults in a network

The following Ethernet network has a problem. Someone trying to access the Internet from personal computer #4 cannot do so, and has called you to troubleshoot the problem:



Your first diagnostic test is to “ping” computer #4 from computer #5, and you find that this test is successful. Your next test is to check Internet connectivity at computer #5 by “pinging” <http://www.google.com>, and you find that test is successful as well.

Identify the likelihood of each specified fault for this network. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with *all* measurements and symptoms in this network.

- Hub A failed =
- Hub B failed =
- Router failed =
- Internet service provider failed =
- Cable failed between computer #4 and Hub B =
- Cable failed between Hub A and Router =
- Cable failed between Hub B and Router =
- Security settings (e.g. firewall) in computer #4 =

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

Challenges
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- Identify a case where **ping** would fail even though two computers connect to each other using proper cabling and non-faulted DCE devices.

## 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<sup>1</sup> 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<sup>2</sup> 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<sup>3</sup> through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

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

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<sup>1</sup>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.

<sup>2</sup>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.

<sup>3</sup>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<sup>4</sup> 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<sup>5</sup> one another.

To high standards of education,

Tony R. Kuphaldt

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<sup>4</sup>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.

<sup>5</sup>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 $\text{\TeX}$ 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.  $\text{\TeX}$  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,  *$\text{\TeX}$  is a programmer's approach to word processing*. Since  $\text{\TeX}$  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  $\text{\TeX}$  makes it relatively easy to learn how other people have created their own  $\text{\TeX}$  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 $\text{\LaTeX}$ extensions to $\text{\TeX}$

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

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# 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.

**13 February 2025** – added some comments to the Tutorial about OSI layers 3 and 4.

**16-19 September 2024** – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors. Also added some details on subnetting for IPv6.

**15 February 2024** – minor edits to the text in the “Encapsulation” section of the Tutorial for clarity, and minor edits to the “Internet Protocol (IP)” section on subnet masks.

**27 March 2023** – fixed a very simple typographical error in the Case Tutorial chapter, where I forgot a closing parenthesis.

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

**5 June 2022** – added a Case Tutorial chapter.

**10 May 2021** – commented out or deleted empty chapters.

**5 October 2020** – added to the Introduction chapter.

**5 September 2020** – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading “inverted” teaching sessions.

**27 June 2020** – added another Foundational Concept.

**25 June 2020** – added a Technical Reference section on the OSI Reference Model.

**22 June 2020** – document first created.

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