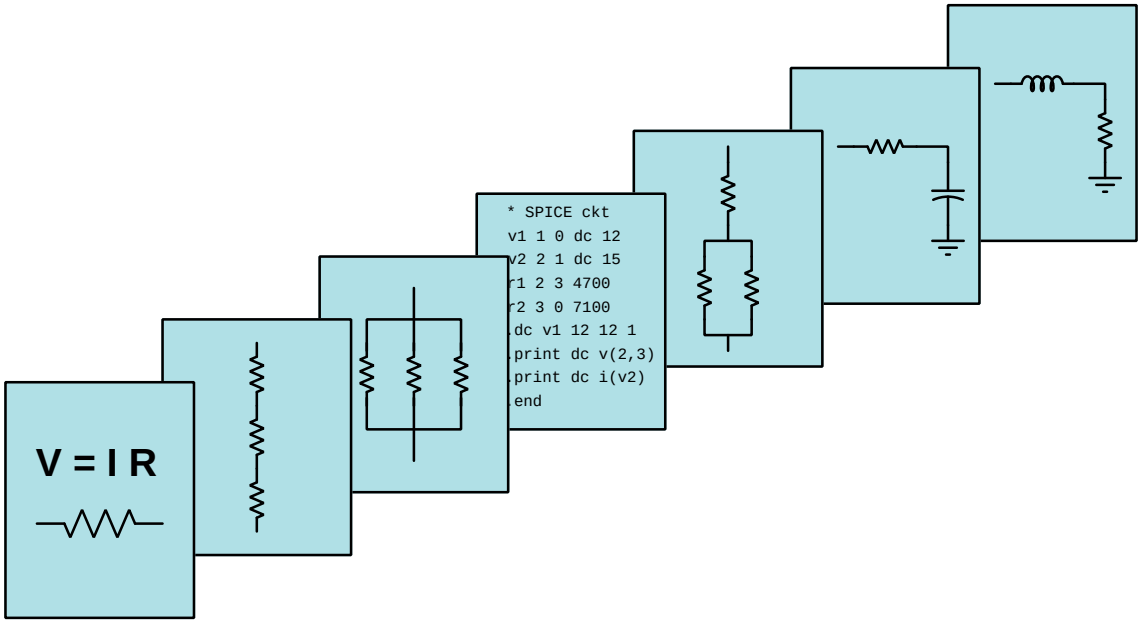
Modular Electronics Learning (ModEL) project



Amateur Radio

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Chapter 1

Introduction

Chapter 2

Tutorial

2.1 Amateur radio legalities

The *Federal Communications Commission* or *FCC* is the federal government agency within the United States tasked with regulating usage of the naturally-existing radio frequency spectrum. The terms and conditions of the *Amateur Radio Service* are defined by the FCC in the *Code of Federal Regulations* (CFR) Title 47, Chapter 1, Subchapter S, Part 97. Although inhabitants of the United States were using radio communications for amateur, business, and government purposes for decades prior to the establishment of any regulatory body[1], the rationale given for the creation of a recognized amateur radio service is stated explicitly in Subpart A of that document (97.1):

97.1 Basis and purpose

> The rules and regulations in this part are designed to provide an amateur radio service having a fundamental purpose as expressed in the following principles:
>
> (a) Recognition and enhancement of the value of the amateur service to the public as a voluntary noncommercial communication service, particularly with respect to providing emergency communications.
>
> (b) Continuation and extension of the amateur's proven ability to contribute to the advancement of the radio art.
>
> (c) Encouragement and improvement of the amateur service through rules which provide for advancing skills in both the communication and technical phases of the art.
>
> (d) Expansion of the existing reservoir within the amateur radio service of trained operators, technicians, and electronics experts.
>
> (e) Continuation and extension of the amateur's unique ability to enhance international goodwill.

In order to secure permission from the FCC to transmit radio waves as an amateur radio operator, one must first secure a *license* from the FCC. At the time of this writing, the FCC grants only the following classes of amateur radio licenses:

- Amateur Extra (greatest privileges)
- General
- Technician (least privileges)

All amateur radio licenses require passing a multiple-choice technical exam, provide transmitting privileges for a duration of ten years, and may be renewed without re-testing for up to two years after expiration. Question pools for all exams are public domain and may be freely studied prior to taking an exam. Increasing privilege from Technician to Amateur Extra class consists mostly of permitted frequency ranges and modulation types. Proficiency in Morse Code telegraphy was once required to become an amateur radio operator, but not anymore.

[1] In the United States, radio communications were first regulated by the *Radio Act of 1912* which created the *Federal Radio Commission*. Later, the *Radio Act of 1927* expanded the federal government's regulatory powers. Later yet, the *Communications Act of 1934* created the Federal Communications Commission as a new regulatory agency.

Some important concepts in amateur radio licensing include the following excerpted from CFR Title 47 Part 97 (in **bold-faced** and *italic* fonts, with commentary after each):

Control operator – *An amateur operator designated by the licensee of a station to be responsible for the transmissions from that station to assure compliance with the FCC Rules.*

Operator/primary station license grant – *One, but only one, operator/primary station license grant may be held by any one person. The primary station license is granted together with the amateur operator license. Except for a representative of a foreign government, any person who qualifies by examination is eligible to apply for an operator/primary station license grant.*

The distinction between operator license grants and station license grants is a subtle yet important one, though in the simplest use cases the two grants vest in the same person. In section 97.103(a) the FCC declares the station licensee as being *responsible for the proper operation of the station in accordance with the FCC Rules*, whereas in section 97.105(a) the control operator *must ensure the immediate proper operation of the station, regardless of the type of control*. To use the analogy of an automobile, the station licensee is the registered owner of the vehicle responsible for its maintenance and long-term care, while the control operator is the person sitting in the driver's seat actually driving the vehicle. In most cases the station licensee and the control operator are the exact same person. However, there are cases where the two roles may be held by different people. One important legal distinction between an operator license grant versus a station license grant is that any legal right to transmit radio energy is conferred by the former and not by the latter[2]. Another important distinction is that the alphanumeric call sign assigned by the FCC is technically linked to the station license and not to the operator license[3].

Section 97.105(b) states that *a station may only be operated in the manner and to the extent permitted by the privileges authorized for the class of operator license held by the control operator* which means operating privileges are limited by the control operator's license class and not the station licensee's license class. If a Technician-class operator borrows a transmitter from someone holding a General-class license, the Technician-class person may only transmit in ways permitted by *their* Technician class of operator license. The fact that the radio is owned and maintained by a General-class station licensee doesn't matter. It works the other way around, too: if a person holding a General-class operator license borrows a transmitter from a Technician-class ham that is capable of doing more than a Technician-class license will permit, that General-class ham will be free to use all of that radio's capabilities granted by their General-class privileges and will not be limited by the fact that the station licensee is only a Technician.

Another case illustrating these concepts is when a person of a lesser-class license (or even no license at all) is allowed to send a message using a higher-licensed person's transmitter under that owner's direct attention and care. This commonly happens during public events where an amateur radio club sets up a "Get On The Air" (GOTA) station for non-hams to use, in an effort to inspire people to become hams. In such cases the guest is allowed to press the push-to-talk (PTT) button

[2]In fact, for military recreation station license grants, the station licensee need not even be a licensed amateur radio operator! This is analogous to the legal owner of an automobile not possessing a current driver's license, but free to loan their vehicle to someone who does.

[3]This is association of call signs with stations and not operators is familiar to anyone who has ever tuned into a broadcast radio station with a four-letter commercial call sign such as "KROC". The station itself bears that call sign as a result of the licensee being permitted by the FCC, whereas the people employed to actually operate that station on a day to day basis (e.g. deejays) may come and go without the station changing its call sign.

and speak into the microphone, all under the watchful eye of a licensed ham who adjusts the radio equipment and ensures no FCC regulations are violated in the process, the superintending ham fulfilling the role of control operator. Note that because the control operator in this case is the licensed ham and not the guest, that (unlicensed) guest is allowed to transmit on any frequency and at any power and in any mode the licensed ham is privileged to use! Transmissions made from GOTA stations typically announce the call sign of the amateur radio club responsible for setting up the GOTA station. In non-GOTA applications where one person arbitrarily desires to transmit on another control operator's equipment, the identifying call sign will be that of the control operator supervising use of that equipment.

Another scenario is in the case of *automatic repeaters* which are transceiver stations designed to receive signals on one frequency and simultaneously re-transmit the received information on a slightly different frequency for the purpose of extending the effective range for radio operators. Repeaters are often advantageously located on mountaintops so as to best receive and transmit messages across a wide geographic range, and to provide radio communication to stations located in valleys and other challenging places. Every repeater has a station licensee responsible for its installation and maintenance, usually some designated member of an amateur radio club where membership dues fund the repeater. Every repeater must also have a control operator, which would be the individual person setting the frequencies it operates on, setting power levels, programming the tones or codes allowing other amateur radio operators to gain access so as to repeat their messages, and pre-configuring other features of the repeater necessary for automatic operation. If some other amateur radio operator transmits a signal to that repeater with intent to have the signal "repeated" to other radio users, that initial user is their own control operator and (most likely) the station licensee of whatever transmitting station they happen to be using, entirely distinct and separate from the control operator and station licensee of the automatic repeater. In order to shield the repeater control operator from legal exposure resulting from the misdeeds of random users, section 97.205(g) states *the control operator of a repeater that retransmits inadvertently communications that violate the rules in this part is not accountable for the violative communications.*

2.2 Amateur radio frequency allocations

The spectrum of frequencies comprising "RF" is quite broad, and commonly subdivided into different categories. Note that none of these categorical definitions is strict, and that the following ranges and lettered designations should be considered approximate only:

Frequency range	**Wavelength range**	**RF subcategory designation**
30 GHz to 300 GHz	1 cm to 0.1 cm	Extra High Frequency (EHF)
3 GHz to 30 GHz	10 cm to 1 cm	Super High Frequency (SHF)
300 MHz to 3 GHz	1 m to 10 cm	Ultra High Frequency (UHF)
30 MHz to 300 MHz	10 m to 1 m	Very High Frequency (VHF)
3 MHz to 30 MHz	100 m to 10 m	High Frequency (HF)
300 kHz to 3 MHz	1 km to 100 m	Medium Frequency (MF)
30 kHz to 300 kHz	10 km to 1 km	Low Frequency (LF)
3 kHz to 30 kHz	100 km to 10 km	Very Low Frequency (VLF)

These frequency ranges and associated subcategories are generally accepted throughout the electronics and radio professions.

In the United States, the Federal Communication Commission (FCC) allocates bands of frequencies for amateur radio use. Some of the more popular bands are shown in the following table:

Frequency range	**Nominal wavelength**
1.800 MHz to 2.000 MHz	160 meter band
3.500 MHz to 4.000 MHz	80 meter band
7.000 MHz to 7.300 MHz	40 meter band
10.100 MHz to 10.150 MHz	30 meter band
14.000 MHz to 14.350 MHz	20 meter band
18.068 MHz to 18.168 MHz	17 meter band
21.000 MHz to 21.450 MHz	15 meter band
24.890 MHz to 24.990 MHz	12 meter band
28.000 MHz to 29.700 MHz	10 meter band
50.000 MHz to 54.000 MHz	6 meter band
144.00 MHz to 148.00 MHz	2 meter band
420.00 MHz to 450.00 MHz	70 centimeter band

Furthermore, the FCC subdivides each of these bands by amateur license class, declaring which portion(s) of each band an amateur radio operator may legally transmit in. Transmitting a signal at a frequency not authorized by one's FCC license is a punishable violation, with fines potentially escalating into the tens of thousands of US dollars. Amateur radio band allocations are easily searched on the internet, and are subject to revision by the FCC.

The 40 meter and 20 meter "HF" bands are extremely popular among General and Amateur Extra class licensees for long-distance communication, but the 20 meter band is off limits to Technician licensees and only portions of the 40 meter band are allowed for Technicians and limited to CW[4] (on/off) mode at that.

The 2 meter (VHF) and 70 centimeter (UHF) bands are extremely popular among new amateur radio operators, as the entry-level Technician class license confers the same transmitting privileges in these VHF and UHF bands as enjoyed by General and Amateur Extra class operators. Entry-level 2 meter and 70 centimeter radio transceivers are also among the most affordable.

[4] This is the technically simplest form of radio transmission, where the carrier frequency is simply turned on and off in patterns. Radio operators using CW mode typically encode alphanumeric characters using Morse Code.

Band plans are sub-allocations of amateur radio frequencies for specific modes and purposes, but unlike FCC allocations are not legally binding. In the United States the *American Radio Relay League* (ARRL) subdivides each FCC-allocated frequency band into smaller frequency ranges with definite purposes amateur radio operators are expected to respect. For example, the 2 meter band allocated by the FCC from 144.000 to 148.000 MHz has an ARRL-defined band plan with over twenty different categories of use. To illustrate, 146.52 MHz is the National Simplex Calling Frequency, 144.275 MHz to 144.300 MHz is limited to propagation beacons, 144.000 MHz to 144.050 MHz is limited to Earth-Moon-Earth signal paths with CW mode, etc. Plans for each FCC-defined amateur radio band may be perused at the ARRL's website.

2.3 Amateur radio etiquette

- When calling another station, always begin with the other station's call sign, and end with yours. Never reverse this order!
- Avoid contentious topics of discussion. Keep it friendly and welcoming at all times.
- Wait and listen before transmitting. Check to see that the frequency is "clear" (no conversations) before transmitting.
- Don't forget that it may be possible you are not hearing *all* members of an ongoing conversation, given your position, antenna orientation, transmitting efficacy of the other stations, propagation modes, etc.! Again, wait and listen before transmitting and pay close attention to any "one-sided conversations" revealing such a scenario.
- Don't assume everyone can hear you as well (or as poorly) as you can hear them! This is why amateur radio operators exchange signal reports with each other.
- Include your call sign when terminating a radio conversation with others. If the conversation lasts a while, the FCC requires you to identify yourself using your call sign at least once every ten minutes. Note that some very brief exchanges may break this rule, such as Field Day exchanges.

2.4 Phonetic alphabet

Voice ("phone") communication, especially over HF bands where atmospheric noise can be severe, is often challenging. Attempting to spell out individual letters is especially susceptible to misinterpretation, as so many letters share common sounds (e.g. B, C, D, E, G, P, T, V, Z ; J and K ; M and N)[5]. A practical solution to this problem is the use of a *phonetic alphabet* where each letter of the alphabet is represented by a unique-sounding word. The phonetic alphabet adopted by NATO military personnel is most commonly used by amateur radio operators, and is easily understood by any listener familiar at all with the words.

- A = Alpha
- B = Bravo
- C = Charlie
- D = Delta
- E = Echo
- F = Foxtrot
- G = Golf
- H = Hotel
- I = India
- J = Juliet
- K = Kilo
- L = Lima
- M = Mike
- N = November
- O = Oscar
- P = Papa (emphasis on the *last* syllable)
- Q = Quebec (With the "Qu" enunciated as a "K" sound)
- R = Romeo
- S = Sierra
- T = Tango

[5] As a musician, I often see confusion in jam sessions when one person calls out the lettered key that the next song or tune is written in (A, B, C, D, E, F, or G), and that letter is misunderstood by other musicians across the stage or room.

- U = Uniform
- V = Victor
- W = Whiskey
- X = X-ray
- Y = Yankee
- Z = Zulu

Numbers are always voiced one digit at a time, pronounced normally with the exception of 9 which is spoken "niner" and 4 which is pronounced as though it had two syllables ("fo-wer"). For example, to speak "one hundred" you would say "One Zero Zero".

2.5 Q codes, abbreviations, prosigns, and prowords

In the early days of radio communication when all conversations were literally spelled out letter-by-letter using Morse Code using a series of short and long audio tones ("dits" and "dahs" respectively), radio operators found various "shorthand" methods to communicate questions and statements using multi-letter codes, special words, and abbreviations. As radio technology expanded to include voice ("phone") communication, special words were adopted to help organize exchanges between operators. This section will explore some of these special codes, words, and abbreviations designed to make radio communication more efficient and less prone to error.

First, the terms "transmission" and "message" are used throughout the following subsections and should be clearly differentiated from one another in order to avoid confusion. In this tutorial I use the word "message" to mean the entire set of information conveyed from one radio operator to another, akin to a written letter sent from one person to another in the mail. By contrast, I use the word "transmission" to mean merely one portion of a message, akin to a sentence or a paragraph comprising part of a written letter, or an utterance in a verbal conversation. Most messages contain multiple transmissions.

2.5.1 Q codes

A large set of three-letter codes all beginning with the letter "Q" exist to encapsulate a variety of questions and statements commonly arising in radio communication. These were created to help streamline CW (Morse) communication by conserving on the number of characters required to convey a particular thought, and they all begin with the letter "Q" because that letter is seldom used in English and therefore makes these codes easier to identify from the very start. Widely used to this day in amateur radio for CW (Morse) conversations, Q codes are also used as slang within spoken and written/typed ham conversations.

Every Q code is usable as either a question or as a statement, the former when terminated by a question mark and the latter when unterminated. Modern parlance employs some Q codes even as nouns and/or adjectives though not all of these usages are common enough to be considered correct. This reference only lists *some* of the more common Q codes, certainly not all of them.

Q code	**As a question**	**As a statement**
`QRL`	Are you busy?	I am busy with . . .
`QRM`	Is there interference from another signal?	The interference is (*1-5 scale*) strong
`QRN`	Is there interference from natural noise?	The noise is (*1-5 scale*) strong
`QRO`	Shall I increase power?	Please increase power
`QRP`	Shall I decrease power?	Please decrease power
`QRQ`	Shall I send faster?	Please send faster
`QRS`	Shall I send slower?	Please send slower
`QRZ`	What's your name/call sign?	I am . . .
`QSB`	Is my signal fading?	Your signal is fading
`QSL`	Can you acknowledge?	I acknowledge
`QSO`	Can you send a message to . . .?	I can send a message to . . . via . . .
`QSY`	Can we change frequency to . . .?	I am changing my frequency to . . .
`QTH`	What's your location?	My location is . . .

A common example of using a Q code as a noun includes saying or keying `QSO` to simply mean "a conversation". A common example of using a Q code as an adjective includes saying or keying `QRP` to mean operating at a low power level (often 5 Watts peak or less).

The International Telecommunications Union (ITU) maintains the standard for all Q codes, making it a sort of international vocabulary. This is quite useful when communicating across national borders!

2.5.2 Abbreviations

In addition to Q codes, CW operators have their lettered abbreviations and codes for common words and phrases. Here are some of the more common abbreviations used in amateur radio:

Abbreviation	Meaning
AGN	Again
BK or BTU	Back to you
C	Affirmative (i.e. "Yes, that is correct")
CK	Check
CL	Closing station (i.e. "I'm signing off")
CQ	Calling any and all stations
CUAGN	"See You Again"
DE	This is from . . .
DX	[Long] Distance
ES	And
FB	Fine business (excellent)
FER	For
GA	Good afternoon
GM	Good morning
GN	Good night
HR	Hear, hear
HV	Have
HW	How? or How is my signal?
II	I say again (making a correction)
K	You are welcome to transmit (i.e. "over")
LID	An incompetent radio operator
MSG	Message
N	Negative (i.e. "no")
NIL	Nothing
NR	Number
NX	Noise or Noisy

Abbreviation	Meaning
OK	Okay
OO	Official observer
OP	Operator
PSE	Please
PX	Prefix
R	Received as transmitted (i.e. "roger")
RIG	Radio equipment/station
RST	Signal report (Readability, Strength, Tone)
RX	Receive or Receiver
SED / SEZ	Said / Says
SFR	So far
SN	Soon
SRI	Sorry
STN	Station
TT	That
TU	Thank you
TX	Transmit or Transmitter
U / UR / URS	You / Your / Yours
VX	Voice or Phone signal
VY	Very
W	Words
Z	Zulu time, i.e. UTC
ZX	Zero beat (right on-frequency)
72	Best regards (at low power QRP)
73	Best regards
88	Hugs and kisses

Interestingly, the numerical codes 73 and 88 had their origin with the Western Union "92 code" list adopted by the Western Union telegraph company in the year 1859. Other than 73, 72[6], and 88 these are not typically used in amateur radio anymore.

[6]The numerical code 72 is sometimes used by radio operators using low transmit power (QRP) to signify the end

For example, the following transmission shows how an amateur radio operator with the call sign `KW3XYZ` might put out a call to any other operators listening:

```
CQ CQ CQ KW3XYZ KW3XYZ
```

If operator `N5ABC` hears this call, they may answer like this:

```
KW3XYZ KW3XYZ DE N5ABC N5ABC K
```

The purpose of repeating call signs and certain abbreviations such as `CQ` stems from the typically poor quality of long-distance reception with amateur radio, especially when using ionospheric propagation where the noise floor is high and signals often fade in and out over the course of a transmission.

2.5.3 Prosigns

Next we have *procedural signs* which are often called *prosigns*. Unlike abbreviations which are combinations of individual letters with appropriate spaces (silence) in between those letters, prosigns are longer-than-usual combinations of CW (Morse-code) dits and dahs, each prosign intended to represent a whole thought or discrete message. Prosigns are often documented as combinations of letters from the Morse alphabet, but with an overhead bar added to denote the absence of spaces between the dits and dahs of the listed letters. For example, one of the most well-known prosigns is the distress call $\overline{SOS}$ which in Morse Code is represented by three dits followed by three dahs followed by three dits – equivalent to the sending of "S" (three dits), "O" (three dahs), and "S" (three dits), but without customary spaces between those letters.

Prosign	Meaning
$\overline{AR}$ or $\overline{EC}$	End of transmission
$\overline{AS}$	Must pause a few minutes, please wait!
$\overline{BT}$ or $=$	Pausing briefly (similar to a period)
$\overline{HH}$	Delete previous word/letter
$\overline{HH}\ \overline{AR}$	Ignore entire previous transmission
$\overline{KN}$	"Over" to a specified station
$\overline{CT}$ or $\overline{KA}$	"Attention!"
$\overline{SK}$ or $\overline{VA}$	End of entire conversation
$\overline{SOS}$	Distress call
$\overline{VE}$	Verified

A confusing property of prosign letter-representations is that there may be more than one combination of Morse symbols (with no spaces in-between) equivalent to a given prosign. For example, the prosigns $\overline{CT}$ and $\overline{KA}$ both represent the exact same sequence of dits and dahs, and bear the same meaning of "start of new message".

of the message. It's like 73, just one step lower.

2.5.4 Prowords

Lastly we have *procedural words* or *prowords*, which are special words with technical meaning in radio communication. These are never used in their full spelling when communicating CW (Morse Code) because abbreviations and prosigns already exist for the same meanings, but instead are used for phone communications and certain text-based digital modes.

Proword	**Meaning**
`Affirmative`	Yes
`Initial(s)`	Precedes phonetic pronunciation of one or more letters
`Negative`	No
`Out`	End of transmission, with no reply expected
`Over`	End of transmission, welcome others to reply
`Roger`	Transmission received
`Wilco`	Will comply with received message (military)

2.5.5 Conversational turn-taking

When two or more people engage in a spoken conversation, a variety of cues help signal when one person has finished saying what they wish to say and is ready for another to begin, most of these cues being non-verbal. Radio operators must similarly signal when they are finished saying whatever they have to say, but are unable to do so non-verbally. This is why certain procedural words ("prowords") exist for phone communication, for example saying "over" at the conclusion of a thought inviting others to respond, and saying "out" when completing a thought not requiring a response.

Taking turns in a CW (Morse Code) exchange is more complicated, both as a result of Morse Code adding another layer of complexity to the task as well as the fact that operators often use different abbreviations and prosigns for similar purposes.

- `K` – "Over" (to anyone)
- `KN` – "Over to *you* specifically" (useful when there are multiple listeners to your transmission)
- `BK` – A quick "back to you" with no need to repeat call signs, common in brief exchanges such as POTA activations
- $\overline{BT}$ or = – A separator between thoughts (like a period), don't respond yet!
- $\overline{AR}$ or $\overline{EC}$ – End of transmission
- $\overline{SK}$ or $\overline{VA}$ – Ending the entire conversation
- `CL` – Shutting down my station now and will be unavailable

In phone transmissions, both the prowords "over" and "out" mark the end of a transmission, the former inviting a reply and the latter not. This is why the phrase ("over and out") makes no logical sense, because these two prowords contradict each other in terms of whether or not a reply is expected. In CW transmissions, however, it is acceptable to end a transmission with the prosign $\overline{AR}$ followed by one of the "over" abbreviations, as $\overline{AR}$ communicates nothing about a reply. In other words, while the phone proword "out" means *end of transmission with no reply expected*, the CW prosign $\overline{AR}$ merely means *end of transmission*.

An example of the prosign $\overline{AR}$ used both with and without a following K is found in this partial exchange:

CQ CQ CQ KW3XYZ KW3XYZ K

KW3XYZ KW3XYZ DE N5ABC N5ABC $\overline{AR}$

N5ABC DE KW3XYZ GM UR RST 599 599 HW? $\overline{AR}$ KW3XYZ DE N5ABC KN

(exchange continues)

This exchange began with KW3XYZ calling for anyone to respond. N5ABC responded, using $\overline{AR}$ to respectfully mark the end of the reply without assuming an established conversation with KW3XYZ. KW3XYZ then proceeded to reply with a signal report and then asked for one in return, marking the end of that transmission using $\overline{AR}$ before announcing both call signs and specifically asking N5ABC to reply.

For what it's worth, this degree of formality is becoming a thing of the past, as most modern CW operators simply terminate each transmission using K, KN, or BK without repeating both call signs.

2.6 Amateur radio repeaters and transponders

2.7 Amateur radio satellite operations

2.8 Amateur radio digital modes

2.9 Radio emission modulation codes

The following list is not exhaustive, but contains most of the commonly-encountered modulation modes:

Code	Description	Examples
A1A	Double-sideband 1-channel discrete data, manual	CW (Morse)
A1B	Double-sideband 1-channel discrete data, automatic	CW (Morse)
A1C	Double-sideband 1-channel discrete data, facsimile	Fax
A1D	Double-sideband 1-channel discrete data, telemetry	
A2A	Double-sideband 1-channel discrete data w/subcarrier, manual	CW (Morse)
A2B	Double-sideband 1-channel discrete data w/subcarrier, automatic	CW (Morse)
A2C	Double-sideband 1-channel discrete data w/subcarrier, facsimile	Fax
A2D	Double-sideband 1-channel discrete data w/subcarrier, telemetry	
A3C	Double-sideband 1-channel analog data, facsimile	Fax
A3E	Double-sideband 1-channel analog data, audio	AM phone
F1A	Frequency mod. 1-channel discrete data, manual	CW (Morse)
F1B	Frequency mod. 1-channel discrete data, automatic	RTTY
F1C	Frequency mod. 1-channel discrete data, facsimile	Fax
F2A	Frequency mod. 1-channel discrete data w/subcarrier, manual	CW (Morse)
F2C	Frequency mod. 1-channel discrete data w/subcarrier, facsimile	Fax
F2D	Frequency mod. 1-channel discrete data w/subcarrier, telemetry	
F3C	Frequency mod. 1-channel analog data, facsimile	Fax
F3E	Frequency mod. 1-channel analog data, audio	FM phone
F3F	Frequency mod. 1-channel analog data, video	SSTV
J2A	Single-sideband 1-channel discrete data w/subcarrier, manual	CW (Morse)
J2B	Single-sideband 1-channel discrete data w/subcarrier, automatic	PSK31
J2C	Single-sideband 1-channel discrete data w/subcarrier, facsimile	Fax
J2D	Single-sideband 1-channel discrete data w/subcarrier, telemetry	Fax
J3C	Single-sideband suppressed-carrier 1-channel analog data, facsimile	Fax
J3E	Single-sideband suppressed-carrier 1-channel analog data, audio	SSB phone
J3F	Single-sideband suppressed-carrier 1-channel analog data, video	

Breaking down the meanings of the letters and numbers used in these codes, including many not used in the previous table:

Modulation methods

- **A** = Amplitude modulation with full carrier and two sidebands
- B = Double-sideband where each sideband conveys different data
- C = Vestigial sideband
- D = Amplitude combined with either frequency or phase (e.g. Quadrature Amplitude Modulation, or QAM)
- **F** = Frequency modulation
- G = Phase modulation
- H = Single-sideband with full carrier
- **J** = Single-sideband with suppressed carrier
- K = Pulse-amplitude
- L = Pulse-width
- M = Pulse-position
- N = Unmodulated, steady signal
- P = Unmodulated sequence of pulses
- Q = Pulse-frequency modulation
- V = Combination of pulse-modulation methods
- W = Combination of any of the above
- X = None of these

Data formats

- 0 = No data
- 1 = Single channel of discrete data without using any subcarrier (e.g. CW)
- 2 = Single channel of discrete data using a subcarrier (e.g. audio-FSK impressed upon SSB AM)
- 3 = Single channel of analog data
- 7 = Multiple channels of discrete data
- 8 = Multiple channels of analog data (e.g. stereo FM phone broadcasting)
- 9 = Combination of digital and analog data
- X = None of these

Purpose of data

- A = Telegraphy, manually interpreted (e.g. CW Morse code)
- B = Telegraphy, automatically interpreted (e.g. "digital" modes such as RTTY, PSK31, PACTOR)
- C = Facsimile (single images)
- D = Telemetry or telecommand signals
- E = Telephony, manually interpreted (e.g. AM and FM phone)
- F = Video (rapid sequence of images)
- N = No transmitted information
- W = Combination of any of the above
- X = None of these

2.10 Radio wave propagation

2.10.1 Radio propagation in open space

2.10.2 Ground-based radio propagation

2.10.3 Atmospheric radio propagation

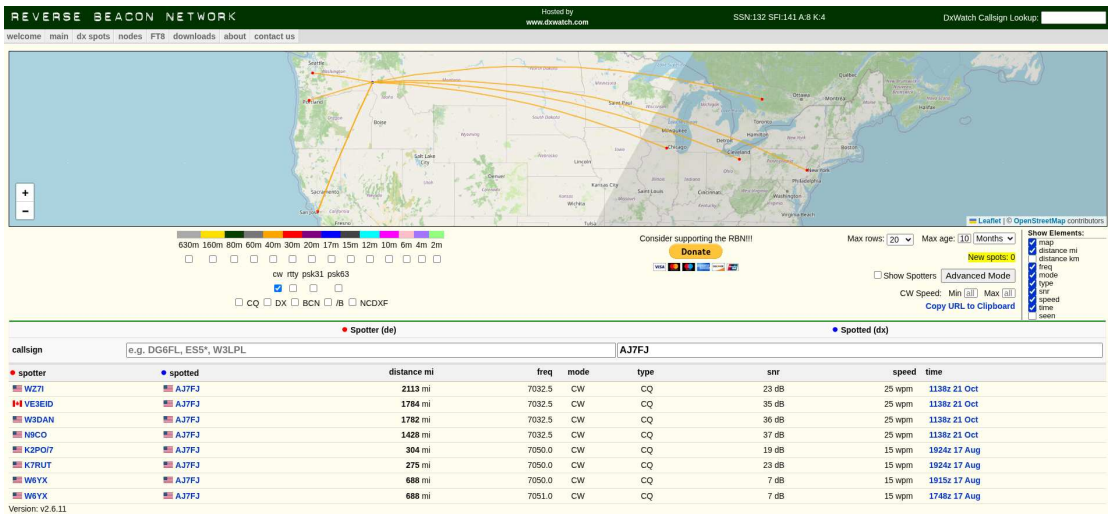
2.10.4 Propagation testing

Every amateur radio operator at one point in time or another wonders how far their signals reach. Here we will explore several methods to empirically test long-distance signal propagation.

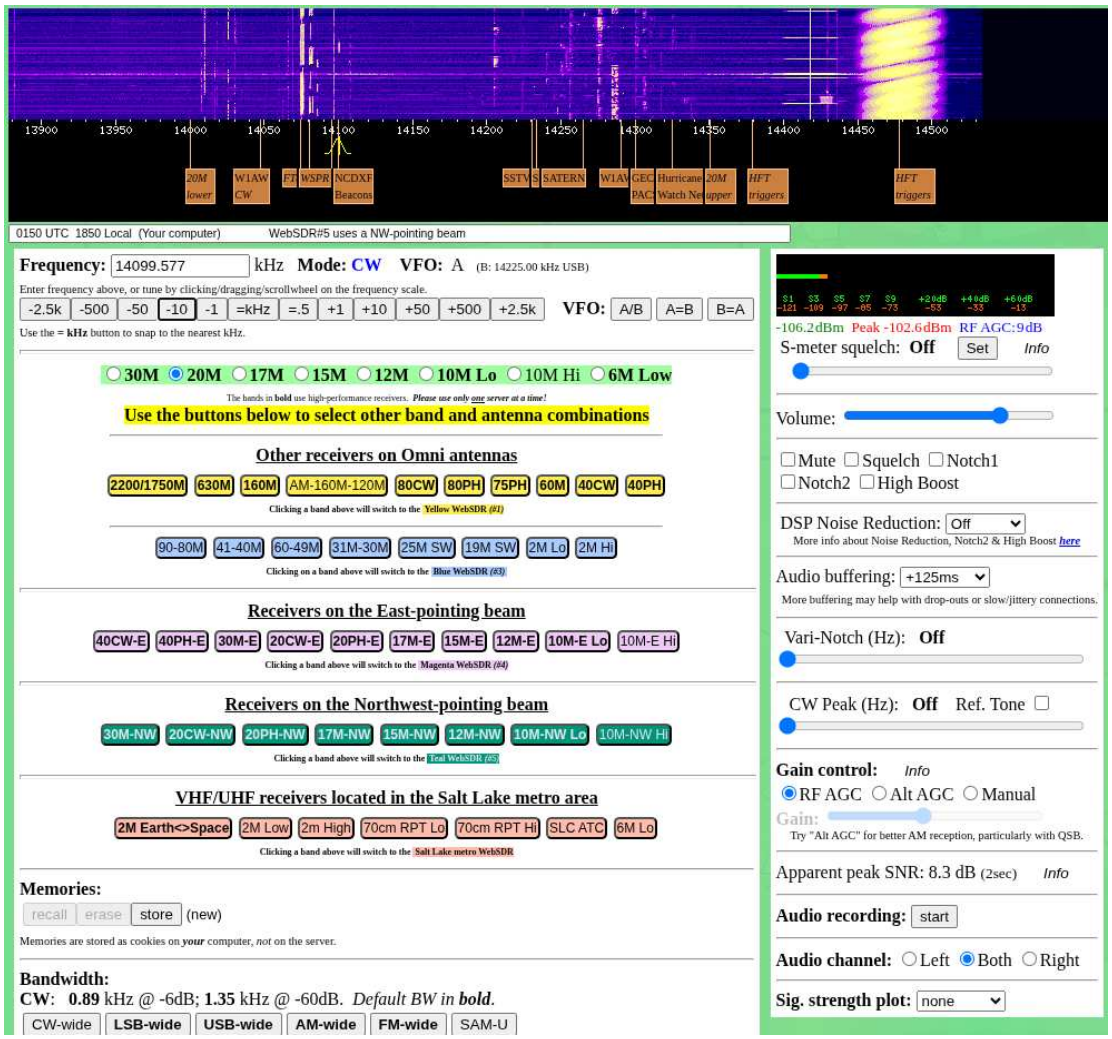
The first method is a world-wide array of HF beacon transmitters called the *International Beacon Project* created and maintained by the Northern California DX Foundation (NCDXF) and the International Amateur Radio Union (IARU). These are automated transmitting stations periodically broadcasting their call signs in Morse Code (CW) followed by a series of four pulses at decreasing power levels: 100 Watts, 10 Watts, 1 Watt, and 0.1 Watt. Each transmitter broadcasts on a specific frequency every three minutes, with transmitters sharing common frequencies and time-staggered from each other by ten-second intervals so as not to overlap. At the time of this writing (2026) there are eighteen of these beacons in service, with their broadcast schedules published on a live-updating webpage for all to view. By tuning in to those specific frequencies with an HR receiver while consulting the live webpage, one can see just how strongly the signal reaches them from those locations around the globe.

Frequencies broadcast by these beacons include 14.100 MHz, 18.110 MHz, 21.150 MHz, 24.930 MHZ, and 28.200 MHz.

A second method is a world-wide array of HF receivers called the *Reverse Beacon Network* using computers to monitor wide ranges of amateur frequencies for CW and digital mode transmissions, automatically logging them by call sign, date, time, etc. and placing them on a website where one may search for call signs. Below is a screenshot showing several "spots" of my own CW test signals:



A third method is to use the internet to log into any number of networked software-defined radio (SDR) receivers around the world and then try transmitting on a frequency heard by one of them, checking that you can hear yourself received over the internet. This method is similar to the Reverse Beacon Network except in most cases there is no automatic logging of detected transmissions. When logged into a remote SDR receiver, your computer's web browser will display a set of controls along with a spectrum and waterfall display, your computer's speaker(s) making the signal audible. The screenshot appearing below is for the Northern Utah WebSDR server #2 located near Corrine, Utah using omnidirectional antennas:



Chapter 3

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

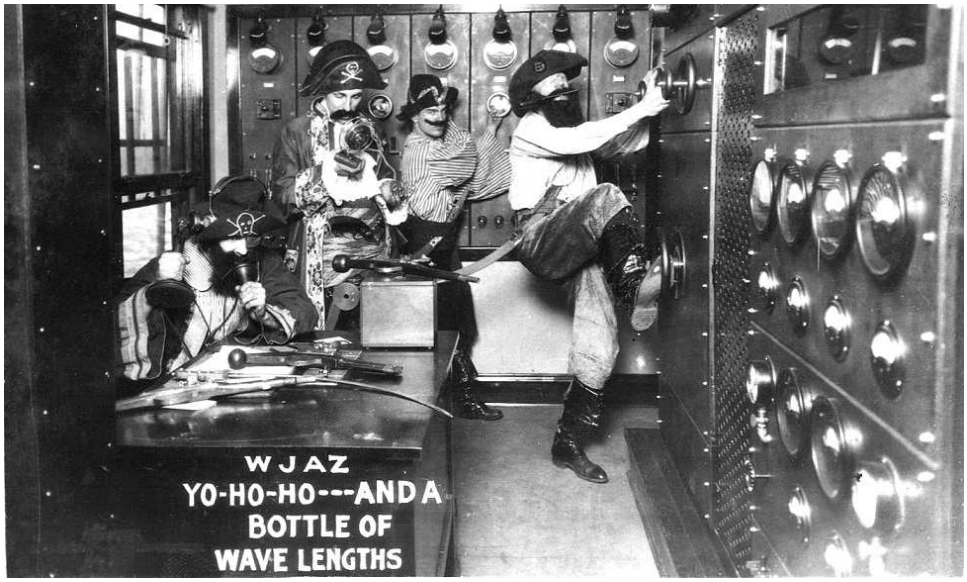
Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

3.1 WJAZ pirate radio

In the year 1926 a broadcast radio station owned and operated by the Zenith Radio Corporation in Chicago, Illinois under the call sign WJAZ began transmitting broadcasts on a frequency different from the one it was previously permitted to operate on by the Department of Commerce. The new frequency they chose was one previously reserved for Canadian broadcasters. Personnel at the WJAZ station knew they were flouting the Commerce department's allocation, and even went to the length of photographing their engineering crew dressed as pirates. The following publicity photo from WJAZ appeared in volume 10 (May-December 1926) of *Popular Radio and Television* magazine:



During that time the US Department of Commerce assigned radio frequencies to broadcasting stations under the authority of the *Radio Act of 1912*. In the particular case of station WJAZ the allocated frequency was 930 kHz, shared with a General Electric broadcast station located in Denver, Colorado under the call sign KOA. The Department of Commerce gave station KOA priority access to the 930 kHz frequency, allowing it to transmit on that frequency for 166 hours per week and station WJAZ to transmit for the remaining 2 hours per week, and even that small amount of time could be revoked at KOA's discretion.

Eugene F. McDonald, president of Zenith, wrote in *Radio Age* magazine in March of 1926 that his action of "wave band piracy" was intended to challenge the law as it stood. Legal analysis revealed the US government had insufficient regulatory power under the *Radio Act of 1912* to curb such behaviors, leading to a formal expansion of regulatory powers in the form of the *Radio Act of 1927*.

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 International Morse Code

The following shows a subset of the International Morse Code, the full version containing many non-English characters and other punctuation marks. The full standard for International Morse Code is Recommendation ITU-R M.1677-1 published by the Radiocommunication Sector of the International Telecommunications Union (ITU-R).

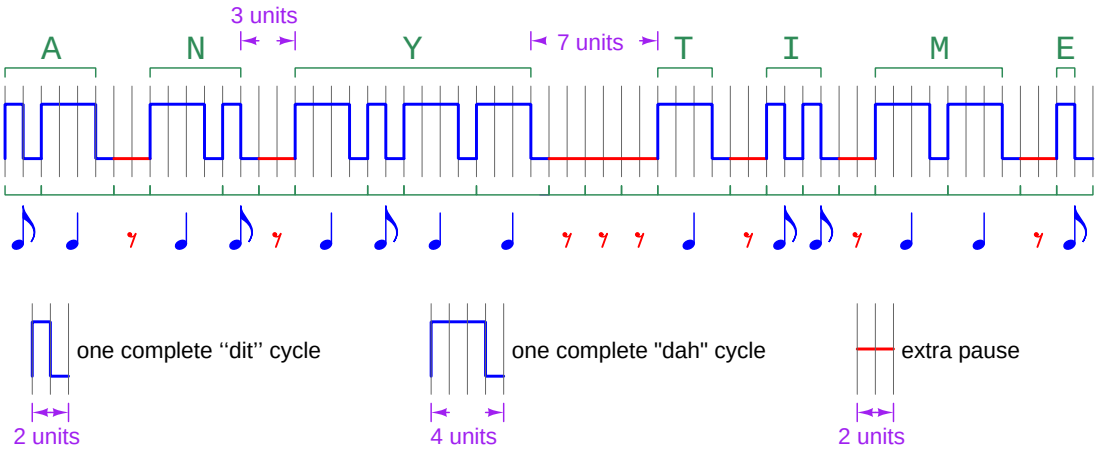
International Morse Code (English letters, Arabic numerals, some symbols)

A •—	J •———	S •••	0 —————
B —•••	K —•—	T —	1 •————
C —•—•	L •—••	U ••—	2 ••———
D —••	M ——	V •••—	3 •••——
E •	N —•	W •——	4 ••••—
F ••—•	O ———	X —••—	5 •••••
G ——•	P •——•	Y —•——	6 —••••
H ••••	Q ——•—	Z ——••	7 ——•••
I ••	R •—•		8 ———••
			9 ————•

? ••——•• *(Question mark)*	, ——••—— *(Comma)*	/ —••—• *(Slash)*	- —••••— *(Hyphen)*
& •—••• *(Ampersand)*	: ———••• *(Colon)*	. •—•—•— *(Period)*	" •—••— *(Quotation mark)*
× —••— *(Multiplication)*	+ •—•—• *(Addition)*	= —•••— *(Equals)*	•••—•— *(End of work)*
(—•——• *(Left parenthesis)*	) —•——•— *(Right parenthesis)*	′ •————• *(Apostrophe)*	•••••••• *(Backspace delete)*

According to Recommendation ITU-R M.1677 from the ITU Radiocommunication Assembly in 2004, a dash (sounded as "dah") should have a tone duration three times that of a dot (sounded as "dit"), the time delay between dits and dahs within the same character should last as long as the audible duration of a single dit, the time delay between characters should last as long as the audible duration of a dah (three dits), and the space between two words should last as long as the audible duration of seven dits.

If we model each dit as a pulse with a 50% duty cycle (on as long as it is off) and a dah as a pulse with a 75% duty cycle (on three times as long as it is off), we see that the total on/off cycle time of a dah is exactly *twice* the duration of the total on/off cycle time of a dit. As such, we may model dits and dahs and the extra pauses demarcating letters and words using standard musical notations of eighth- and quarter-notes. Consider the following example of the phrase `ANY TIME`, where the smallest subdivision of time (marked by the thin grey vertical lines) is the audible duration of a single dit:



With practice, one's sending of Morse words and phrases will have an almost musical feel. In fact, it is possible to practice sending Morse Code transmissions to the beat of a metronome in order to help learn these precise timing relationships. Getting the pause (rest) durations correct is the most challenging part of this. In real-world practice, if one must compromise on timing accuracy while sending Morse Code, it is better to err on the side of having too much silence between letters and words than too little! The intentional practice of lengthening pause times for easier decoding of individual characters is called *Farnsworth timing*.

Lest anyone think that Morse Code is obsolete, know that this form of communication still enjoys a vibrant following within the amateur radio community for its elegant simplicity as well as for its readability even with low signal-to-noise ratios[1]. Morse Code (or "CW" as amateur radio operators refer to it) is without a doubt the most robust and bandwidth-efficient modulation mode

[1] I have personally experienced the difference between single-sideband telephony (SSB phone) and CW in applications where a voice signal was completely unintelligible but CW pulses sent on the same frequency by the same transmitter were clear and unmistakable. Also, it is routine for low-power (QRP) radio operators to communicate with other people thousands of kilometers away on HF bands using CW mode on transmitters having just 5 Watts of output power, sent through makeshift long-wire antennas!

that human beings are able to directly interpret. Transmitter and receiver hardware for CW radio communication is also far simpler than for any other modulation mode, a crude CW transmitter being little more than an RF oscillator combined with an on/off switch.

If you are interested in learning Morse Code, expect to spend about a week's worth of time learning to send all the alphanumeric characters. Beware that learning to *receive* Morse Code, especially at speed, takes longer than this!

4.2 CW script for general exchanges

Learning to communicate with other radio operators using Morse Code (i.e. *Continuous Wave*, or *CW*) can feel daunting because not only must one learn an entirely new alphabet consisting of "beep" sounds, but there are numerous abbreviations and prosigns commonly used by CW operators to make conversations more efficient, as well as typical exchange formats intended to make each type of conversation more predictable. An important detail to note is that just as in ordinary spoken conversation, *more than one acceptable format exists with some being more formal than others*. FCC regulations require the use of call signs for station identification, but the rest is merely convention and not law.

Beginners in CW benefit from having a "script" to guide their initial exchanges. The following shows how two CW radio operators *might* conduct a brief conversation. In this example I (AJ7FJ) will be the one responding to another operator's (Z5ZZZ) initiation:

CQ CQ CQ DE Z5ZZZ PSE K
Calling all stations, from Z5ZZZ, please (respond) over

Z5ZZZ Z5ZZZ DE AJ7FJ AJ7FJ $\overline{KN}$
Z5ZZZ from AJ7FJ, over to you

AJ7FJ DE Z5ZZZ TU GM/GA/GE UR 599 599 OP MARY MARY QTH OK OK K
AJ7FJ from Z5ZZZ, thank you, good morning/afternoon/evening, your readability/strength/tone (RST) is 599, my name is Mary, my location is Oklahoma, over

Z5ZZZ DE AJ7FJ TU GM/GA/GE UR 579 579 OP TONY TONY QTH ID ID K
Z5ZZZ from AJ7FJ, thank you, good morning/afternoon/evening, your readability/strength/tone (RST) is 579, my name is Tony, my location is Idaho, over

AJ7FJ DE Z5ZZZ TU RIG IC705 100W ANT DIPOLE WX COLD WET K
AJ7FJ from Z5ZZZ, thank you, my rig is an ICOM IC-705 running 100 Watts through a dipole antenna, weather is cold and wet, over

Z5ZZZ DE AJ7FJ TU RIG IC7300 80W ANT EFHW WX WARM SUNNY K
Z5ZZZ from AJ7FJ, thank you, my rig is an ICOM IC-7300 running 80 Watts through an end-fed-half-wave antenna, weather is warm and sunny, over

AJ7FJ DE Z5ZZZ FB TONY TU FER QSO 73 $\overline{SK}$
AJ7FJ from Z5ZZZ, fine business (good job) Tony, thank you for the conversation (QSO), best regards (73), signing out

Z5ZZZ DE AJ7FJ TNX MARY 73 $\overline{SK}$
Z5ZZZ from AJ7FJ, thanks Mary, best regards (73), signing out

Note that many CW exchanges are not this rigid or formal. For example, FCC regulations only require station identification by call sign once every 10 minutes (which is a *long* CW exchange!) and at the end of the exchange, not with every message in the exchange as is shown here. Some

CW exchanges may be even more formal and verbose than this one, for example ending every line with the prosign $\overline{AR}$ ("out") followed immediately by a repeat of the call signs and the prosign $\overline{KN}$ ("over to you"). Experienced CW operators spell out full words that read almost like a verbal conversation, and at intimidating speeds.

When amateur radio operators have conversations with each other for the first time, it is customary for them to exchange (at minimum) these three pieces of information:

1. **Signal report** using the Readability/Strength/Tone (RST) convention for CW and Readability/Strength (RS) convention for phone
2. **Location** giving context to the signal report, at minimum the state for US operators but often the city as well
3. **First name** (making the exchange more personal than just call signs)

4.3 CW script for contesting

A "contest" is a competition among amateur radio operators to make the greatest number of contacts within a specified time frame. For this reason, contest exchanges are extremely minimalistic. Here is an example where once again I (AJ7FJ) am responding to another operator's (Z5ZZZ) initiation during a CW contest known as the "Slow Speed Test" (SST):

CQ CQ SST Z5ZZZ Z5ZZZ
Calling all stations, Slow Speed Test (contest name), from Z5ZZZ

AJ7FJ
I am AJ7FJ

AJ7FJ MARY OK
AJ7FJ, this is Mary from Oklahoma

Z5ZZZ TONY ID
Z5ZZZ, this is Tony from Idaho

TU Z5ZZZ
Thank you from Z5ZZZ

Short-form, prescriptive exchanges like this lend themselves well to pre-programmed CW sequences within a modern transceiver. For example, Mary could have `CQ CQ SST Z5ZZZ Z5ZZZ` stored in her radio as a CW sequence ready to transmit at the press of a button, as well as `TU Z5ZZZ`. Other sequences could be pre-programmed to form the ending of various statements, for example Mary could have `MARY OK` stored as a sequence to which she would prepend the other operator's call sign when that time comes.

4.4 CW script for POTA

A fun activity many amateur radio operators participate in is called *Parks On The Air* or *POTA* where they set up transceiver and antenna equipment in some public park and then make contacts from that park. A sample exchange between `Z5ZZZ` (the "activator" located in a park) and myself (`AJ7FJ`) serving as the "hunter" is as follows:

`CQ CQ POTA DE Z5ZZZ Z5ZZZ K`
Calling all stations, Parks On The Air from Z5ZZZ, over

`AJ7FJ`
This is AJ7FJ responding

`AJ7FJ GM/GA/GE UR 599 599 BK`
AJ7FJ, good morning/afternoon/evening, your readability/strength/tone (RST) is 599, break

`BK RR UR 439 439 ID ID BK`
Break, roger roger (received), your readability/strength/tone (RST) is 439, my state is Idaho, break

`BK TU ID 73 DE Z5ZZZ E E`
Break, thank you, Idaho, best regards from Z5ZZZ (dit, dit)

`E E`
(dit, dit)

A noteworthy feature of POTA exchanges is that the hunter need not transmit their call sign, just the activator. Also note how once the hunter replies to the activator's `CQ` call and an exchange begins, each line of CW code begins and ends with a "break" (`BK`) until the last sign-off lines!

4.5 CW script for summer Field Day

Field Day is an annual event held on the fourth weekend in June intended to give amateur radio operators practice making contacts "in the field", ostensibly to prepare for emergency situations where outdoor setups may be required. Each station has a designated alphanumeric *operating class*, with extra points assigned on the basis of restricted power sources, more challenging operating modes (e.g. CW), etc. One commonly finds groups of people belonging to specific amateur radio clubs gathered in parks and other public areas setting up portable antennas, with barbeque grills on hand for food preparation.

A sample CW exchange for Field Day resembles that of contesting, where the exchange is minimal:

`CQ CQ FD DE Z5ZZZ Z5ZZZ`
Calling all stations, Field Day, from Z5ZZZ

`AJ7FJ`
I am AJ7FJ

`AJ7FJ 1E OK 1E OK`
AJ7FJ, I'm operating class 1E from ARRL Section OK (Oklahoma)

`RR 1C ID 1C ID`
Roger, I'm operating class 1C from ARRL Section ID (Idaho)

`RR TU 73`
Acknowledged, thank you, best regards

`73`
Best regards

At minimum, all Field Day exchanges must contain both call signs, each person's operating class, and their ARRL/RAC sections (geographical areas). Sections are typically state abbreviations within the United States, but more populous states will have multiple sections (e.g. California has several, including `SF` for the San Francisco area, `SCV` for Santa Clara Valley, etc.).

Operating class designators for Field Day in June consist of a number followed by a letter, the number representing the maximum number of transmitters on the air at any given time for that site, and the letter representing different scenarios:

- **Class A** = either an amateur radio club station or a portable station with three or more operators
- **Class B** = a portable station with one or two operators
- **Class C** = a mobile (vehicle-mounted) station
- **Class D** = a home station running on utility power

- **Class E** = a home station running on emergency power
- **Class F** = a station operating from an established Emergency Operation Center (EOC)

4.6 CW script for Winter Field Day

Winter Field Day is another annual event intended to give amateur radio operators practice making contacts "in the field", this one scheduled every year on the last full weekend in January. Given the generally poorer outdoor conditions in January compared to June, Winter Field Day is more of a serious emergency preparation event than regular (summer) Field Day. Each station has a designated alphanumeric *operating class* just as in summer Field Day, but the alphanumeric codes are not the same.

A sample CW exchange for Winter Field Day resembles that of contesting, where the exchange is minimal:

CQ CQ WFD DE Z5ZZZ Z5ZZZ
Calling all stations, Field Day, from Z5ZZZ

AJ7FJ
I am AJ7FJ

AJ7FJ 1O OK 1O OK
AJ7FJ, I'm operating class 1O from ARRL Section OK (Oklahoma)

RR 1C ID 1M ID
Roger, I'm operating class 1M from ARRL Section ID (Idaho)

RR TU 73
Acknowledged, thank you, best regards

73
Best regards

Operating class designators for Winter Field Day in January consist of a number followed by a letter, the number representing the maximum number of transmitters on the air at any given time for that site, and the letter representing different scenarios (but different from summer Field Day):

- **Class H** = a station located inside a permanent, livable residence
- **Class I** = a station located inside a permanent, weather-protected building
- **Class O** = a station located inside a temporary shelter or a crude permanent building lacking plumbing and heating
- **Class M** = a mobile (vehicle-mounted) station

As in summer Field Day, all Winter Field Day exchanges must include call signs, operating class, and ARRL/RAC section (geographical area) at minimum.

4.7 NCDXF/IARU beacons

Eighteen HF-band radio transmitters called *beacons* regularly broadcast from different locations in the world and on several frequencies: 14.100 MHz, 18.110 MHz, 21.150 MHz, 24.930 MHZ, and 28.200 MHz for the purpose of sensing propagation conditions around the globe. Each beacon transmission consists of the beacon's call sign in Morse Code at 22 words per minute and at full power, followed by four 1-second tones each at descending power levels (100 W, 10 W, 1 W, and 100 mW in that order).

Timeslot	**Call sign**	**Location**
1	`4U1UN`	New York City, New York, USA
2	`VE8AT`	Inuvik, Northern Territories, Canada
3	`W6WX`	Mount Umunhum, California, USA
4	`KH6RS`	Maui, HI, USA
5	`ZL6B`	Masterton, New Zealand
6	`VK6RBP`	Rolystone, Australia
7	`JA2IG`	Mount Asama, Japan
8	`RR9O`	Novosibirsk, Russia
9	`VR2B`	Hong Kong
10	`4S7B`	Colombo, Sri Lanka
11	`ZS6DN`	Pretoria, South Africa
12	`5Z4B`	Kikuyu, Kenya
13	`4X6TU`	Tel Aviv, Israel
14	`OH2B`	Lohja, Finland
15	`CS3B`	São Jorge, Madeira
16	`LU4AA`	Buenos Aires, Argentina
17	`OA4B`	Lima, Peru
18	`YV5B`	Caracas, Venezuela

All beacon transmissions are offset by ten seconds of time to avoid multiple beacons transmitting simultaneously on the same frequency.

Chapter 5

Questions

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

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

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

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

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

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

5.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

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

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

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

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

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

5.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

5.1.2 Foundational concepts

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

Energy

Conservation of Energy

Simplification as a problem-solving strategy

Thought experiments as a problem-solving strategy

Limiting cases as a problem-solving strategy

Annotating diagrams as a problem-solving strategy

Interpreting intermediate results as a problem-solving strategy

Graphing as a problem-solving strategy

Converting a qualitative problem into a quantitative problem

Converting a quantitative problem into a qualitative problem

Working "backwards" to validate calculated results

Reductio ad absurdum

Re-drawing schematics as a problem-solving strategy

Cut-and-try problem-solving strategy

Algebraic substitution

???

5.1.3 First conceptual question

Challenges

- ???.
- ???.
- ???.

5.1.4 Second conceptual question

Challenges

- ???.
- ???.
- ???.

5.1.5 Applying foundational concepts to ???

Identify which foundational concept(s) apply to each of the declarations shown below regarding the following circuit. If a declaration is true, then identify it as such and note which concept supports that declaration; if a declaration is false, then identify it as such and note which concept is violated by that declaration:

(Under development)

- ???
- ???
- ???
- ???

Here is a list of foundational concepts for your reference: **Conservation of Energy**, **Conservation of Electric Charge**, **behavior of sources vs. loads**, **Ohm's Law**, **Joule's Law**, **effects of open faults**, **effect of shorted faults**, **properties of series networks**, **properties of parallel networks**, **Kirchhoff's Voltage Law**, **Kirchhoff's Current Law**. More than one of these concepts may apply to a declaration, and some concepts may not apply to any listed declaration at all. Also, feel free to include foundational concepts not listed here.

Challenges

- ???.
- ???.
- ???.

5.1.6 Explaining the meaning of calculations

Below is a quantitative problem where all the calculations have been performed for you, but all variable labels, units, and other identifying data are unrevealed. *Assign proper meaning* to each of the numerical values, identify the correct unit of measurement for each value as well as any appropriate metric prefix(es), explain the significance of each value by describing where it "fits" into the circuit being analyzed, and identify the general principle employed at each step:

Schematic diagram of the ??? circuit:

(Under development)

Calculations performed in order from first to last:

1. $x + y = z$
2. $x + y = z$
3. $x + y = z$
4. $x + y = z$
5. $x + y = z$
6. $x + y = z$

Challenges

- ???.
- ???.
- ???.

5.1.7 Explaining the meaning of code

Shown below is a schematic diagram for a ??? circuit, and after that a source-code listing of a computer program written in the ??? language simulating that circuit. Explain the purpose of each line of code relating to the circuit being simulated, identify the correct unit of measurement for each computed value, and identify all foundational concepts of electric circuits (e.g. Ohm's Law, Kirchhoff's Laws, etc.) employed in the program:

Schematic diagram of the ??? circuit:

(Under development)

Code listing:

```
#include <stdio.h>

int main (void)
{

  return 0;
}
```

Challenges

- ???.
- ???.
- ???.

5.2 Quantitative reasoning

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

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

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

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

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

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

5.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

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

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

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

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

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

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

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

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

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

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

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

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

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

5.2.2 Introduction to spreadsheets

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

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

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

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

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

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

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

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

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2.3 First quantitative problem

Challenges

- ???.
- ???.
- ???.

5.2.4 Second quantitative problem

Challenges

- ???.
- ???.
- ???.

5.2.5 ??? simulation program

Write a text-based computer program (e.g. C, C++, Python) to calculate ???

Challenges

- ???.
- ???.
- ???.

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 First diagnostic scenario

Challenges

- ???.
- ???.
- ???.

5.3.2 Second diagnostic scenario

Challenges

- ???.
- ???.
- ???.

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

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

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

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

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

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

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

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

To high standards of education,

Tony R. Kuphaldt
AJ7FJ

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

Andrew D. Hwang's `ePiX` mathematical visualization programming library

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

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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.

22 June 2026 – expanded upon the "Amateur radio frequency allocations" section of the Tutorial chapter, discussing FCC-allocated frequency bands for amateur radio operators. Also added some information about GOTA stations and people borrowing others' radios in the "Amateur radio legalities" section.

23 May through 4 June 2026 – added multiple Technical Reference sections showing example CW scripts for various scenarios such as general CQ calls and responding to POTA activations. Made minor edits to the CW abbreviations and prosigns tables. Also added another Technical References section on NCDXF/IARU transmitting beacons. Also added a new Tutorial subsection discussing turn-taking in CW exchanges. Also changed all instances of "dot" and "dash" to "dit" and "dah" respectively when referencing Morse Code.

26 April 2026 – elaborated on CW prosigns and abbreviations for "over" and "out".

9 March 2026 – minor edits regarding abbreviations and prosigns.

15 May to 8 August 2025 – document first created.

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