The Complete
Amateur Radio Operator

Theory, Technology, and Practice for the Modern Ham

A self-contained course in the physics, electronics, and operating practice of amateur ("ham") radio — written to prepare a motivated reader for *any* country's licensing examinations, from first principles to advanced RF engineering.

2026 Edition

Radio School Press

Preface

Amateur ("ham") radio sits at a rare intersection: it is simultaneously a hands-on engineering discipline, an experimental science, a public-service tradition, and a global community held together by little more than electromagnetic waves and a shared curiosity about how things work. Every licensed amateur, anywhere in the world, has had to learn the same underlying physics — Ohm's law does not change at a border, and a half-wave dipole behaves identically whether it is strung between two trees in Lisbon, Nairobi, or Auckland.

This book was written to teach that underlying physics and engineering as completely and rigorously as a motivated newcomer needs, independent of where they happen to live. National licensing authorities differ enormously in their exam formats, their band allocations, their power limits, and the paperwork required to get on the air — and this book intentionally does *not* try to teach any single country's regulations. Instead, it teaches the physics, mathematics, electronics, antenna theory, propagation, and operating practice that sit underneath *every* national exam syllabus, so that the material remains useful and accurate regardless of which administration issues your callsign. Where a topic is genuinely international — the ITU Region system, the Q-code, the NATO phonetic alphabet, Morse operating abbreviations — it is covered in full, because these are shared worldwide conventions rather than local law.

The book is organized in five parts of increasing sophistication, loosely mirroring the tiered structure used by most national licensing systems (an entry-level tier, an intermediate tier, and a full-privileges tier), so that a reader preparing for a foundation-level exam can stop after Part II with a solid, self-sufficient understanding, while a reader aiming for the highest available privileges can continue through the treatment of active devices, transmission line theory, antenna engineering, and propagation in Parts III and IV. Part V turns from theory to practice: operating procedure, radio etiquette, digital modes, and emergency communications, all described in terms general enough to apply to any amateur service worldwide.

Because exam questions ultimately test whether you can *use* a formula, not just recite it, every chapter includes worked examples, exam-style tips, and end-of-chapter review questions. A comprehensive formula appendix (Appendix A) collects every equation in the book in one place for quick reference and last-minute revision, alongside a table of physical constants, SI prefixes, and unit conversions (Appendix B) and a glossary of terms (Appendix C).

Before you use this book to sit a real examination, confirm the specific band plan, power limits, callsign format, and administrative procedure that apply in your own country with your national telecommunications regulator or IARU member society — those details are the one part of becoming a radio amateur that genuinely does depend on where you live.

Good luck, and 73.

How to Use This Book

Reading tiers. Chapters are grouped into five parts. Parts I and II correspond roughly to the depth expected of an entry-level ("foundation" or "novice"-class) license worldwide. Parts III and part of IV add the depth typically expected of an intermediate ("technician" or "general"-class) license. The remainder of Part IV and all of Part V, together with the full formula appendix, correspond to the depth expected of the highest license class most administrations offer (often called "advanced," "extra," or "full"). You do not need to read the parts in lockstep with a specific national syllabus — read as far as your target license requires, then treat the rest as a reference to return to. Part VI is different in kind from the rest of the book: it is not exam material at all, but an enrichment chapter applying the same radio science to aviation, maritime, and military signals now commonly explored with inexpensive SDR receivers.

Throughout the book you will find four recurring boxes:

Key Idea

A concept worth memorizing verbatim, because it recurs across many later chapters or is a favorite target of exam questions.

Worked Example

A fully worked numerical problem, solved step by step, in the style of a typical exam question.

Exam Tip

A practical hint about how a topic tends to be tested, or a common mistake to avoid.

Safety

A warning about a genuine electrical, RF-exposure, or mechanical hazard. Safety notes are not exam trivia — treat them as seriously as you would a warning label on a piece of test equipment.

Each chapter closes with a **Chapter Review** (a condensed list of the ideas you should be able to restate from memory) and a set of **Practice Problems** with the reasoning needed to solve them found in the chapter body. Appendix A gathers every formula in the book by topic; Appendix B gathers SI prefixes, unit conversions, and physical constants; Appendix C is a glossary. Bookmark all three — you will use them long after you pass an exam.

Contents

Part I

Mathematical and Physical Foundations

Chapter 1

Units and Measurement

Radio engineering spans an enormous numerical range: a weak-signal moonbounce contact may involve powers of 10^{-21} W at the receiver input, while a broadcast transmitter may radiate 10^{6} W. Working comfortably across eighteen or more orders of magnitude requires a disciplined system of units and prefixes. This chapter establishes that system before any circuit theory is introduced.

1.1 The International System of Units (SI)

Nearly all quantities used in electronics and radio are expressed in the **International System of Units (SI)**. SI defines seven base units, of which four are used constantly in this book:

Quantity	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A

Every other electrical quantity used in this book — voltage, resistance, capacitance, inductance, power, frequency — is a *derived* unit, built from these base units. For example, the volt is defined so that one ampere flowing through one ohm of resistance produces a potential difference of one volt; the ohm itself is defined in terms of volts and amperes. You do not need to memorize these base-unit derivations, but understanding that all electrical units are ultimately tied to the same consistent system explains why formulas in this book always balance: if you put SI units in, you get SI units out, with no hidden conversion factors.

Quantity	Unit	Symbol	In base SI units
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg \cdot m \cdot s^{-2}$
Energy	joule	J	$N \cdot m$
Power	watt	W	J/s
Charge	coulomb	C	$A \cdot s$
Potential difference	volt	V	J/C
Resistance	ohm	Ω	V/A
Capacitance	farad	F	C/V
Inductance	henry	H	$V \cdot s/A$
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	Wb/m^2

1.2 SI Prefixes

Rather than writing very large or very small numbers with long strings of zeros, SI defines a standard set of prefixes, each representing a power of ten. A radio amateur must be completely fluent with the prefixes from pico to giga; they appear on every data sheet, every dial, and in most exam numerical questions.

Prefix	Symbol	Factor	Example
tera	T	10^{12}	1 THz (far above amateur bands)
giga	G	10^{9}	2.4 GHz (Wi-Fi/amateur microwave)
mega	M	10^{6}	14.2 MHz (a 20 m band frequency)
kilo	k	10^{3}	3.5 kΩ resistor
—	—	10^{0}	base unit (V, A, Ω, Hz, F, H, W)
milli	m	10^{-3}	100 mA current
micro	μ	10^{-6}	100 μF capacitor
nano	n	10^{-9}	10 nH inductor
pico	p	10^{-12}	22 pF trimmer capacitor

Key Idea: Prefix arithmetic

To convert between prefixes, multiply or divide by the ratio of their powers of ten. For example, $2\,\text{mA} = 2 \times 10^{-3}\,\text{A} = 2000\,\mu\text{A}$. When in doubt, always convert back to the base unit (no prefix) before doing arithmetic, then convert the answer to a convenient prefix at the end.

Worked Example: Converting units

A capacitor is labeled 4700 pF. Express this value in microfarads and in farads.
Solution. $1\,\text{pF} = 10^{-12}\,\text{F}$ and $1\,\mu\text{F} = 10^{-6}\,\text{F}$, so $1\,\text{pF} = 10^{-6}\,\mu\text{F}$. Therefore

$$4700\,\text{pF} = 4700 \times 10^{-6}\,\mu\text{F} = 4.7 \times 10^{-3}\,\mu\text{F} = 0.0047\,\mu\text{F},$$

and in base units, $4700\,\text{pF} = 4.7 \times 10^{-9}\,\text{F} = 4.7\,\text{nF}$.

1.3 Scientific and Engineering Notation

Scientific notation writes a number as $a \times 10^n$ with $1 \leq a < 10$. **Engineering notation** is a variant that restricts n to multiples of 3, so the exponent always lines up with an SI prefix — this is the form used on virtually all electronic calculators and test equipment. For example, $47{,}000\,\Omega$ is $4.7 \times 10^4\,\Omega$ in scientific notation but $47 \times 10^3\,\Omega = 47\,\text{k}\Omega$ in engineering notation. Learn to think in engineering notation; it maps directly onto the prefix table above.

1.4 Significant Figures and Measurement Uncertainty

No physical measurement is perfectly exact. A digital multimeter reading of "14.235 MHz" implies a different precision than "14.2 MHz," even though both could describe the same signal. The number of **significant figures** in a stated value indicates how precisely it is known:

- All non-zero digits are significant.
- Zeros between non-zero digits are significant (1002 has four).
- Leading zeros are never significant (0.0042 has two).
- Trailing zeros after a decimal point are significant (3.50 has three).

When multiplying or dividing measured quantities, the result should be rounded to the same number of significant figures as the least precise input. This matters on exams that give component values "as measured" rather than as nominal (ideal) values, and it matters in the workshop when deciding how much precision a calculation actually deserves.

1.5 Logarithms: The Mathematics Behind the Decibel

Radio engineers constantly compare quantities that range over many orders of magnitude — transmitter power versus receiver sensitivity, for example. The tool for compressing such ratios into manageable numbers is the **logarithm**, formally introduced here because it underlies the decibel system developed in Chapter 15.

For a base-10 logarithm,

$$y = \log_{10}(x) \iff 10^y = x.$$

Three properties make logarithms indispensable for power and gain calculations:

$$\log(ab) = \log a + \log b, \qquad \log\left(\frac{a}{b}\right) = \log a - \log b, \qquad \log(a^n) = n \log a.$$

The first property is the reason decibels *add* when gains and losses are cascaded through a system (an amplifier followed by a length of lossy cable, for instance) instead of needing to be multiplied. This single fact is exploited throughout Chapters 15, 16, and 19.

1.6 Angles: Degrees and Radians

AC circuit analysis (Chapter 5 onward) uses *phase angles* extensively. Two units are used for angles: the familiar **degree**, where a full circle is 360°, and the **radian**, where a full circle is 2π radians. Radians are the natural unit inside trigonometric functions used in calculus-based derivations (such as $v(t) = V_{\text{pk}} \sin(\omega t)$), while degrees are more common in everyday circuit descriptions ("the current lags the voltage by 30°"). Conversion is direct:

$$\theta_{\text{rad}} = \theta_{\text{deg}} \times \frac{\pi}{180}, \qquad \theta_{\text{deg}} = \theta_{\text{rad}} \times \frac{180}{\pi}.$$

Chapter Review

- SI base units relevant to electronics: metre, kilogram, second, ampere; all other electrical units (volt, ohm, farad, henry, watt, ...) are derived from these.
- Memorize the prefix ladder from pico (10^{-12}) to giga (10^9); convert to base units before doing arithmetic.
- Engineering notation keeps exponents as multiples of 3, matching SI prefixes directly.

- Logarithms turn multiplication into addition — the mathematical basis of the decibel.
- $360° = 2\pi$ radians; both units appear throughout AC theory.

Practice Problems

1. Convert 0.000015 A into milliamperes and into microamperes.
2. A resistor is marked 2.2 kΩ. Express this value in ohms and in scientific notation.
3. Convert 47° to radians, keeping three significant figures.
4. Using the properties of logarithms, simplify $\log(1000) - \log(10)$ without a calculator.
5. A frequency counter displays 7.0300 MHz. How many significant figures does this reading have, and what does that imply about the counter's precision?

Chapter 2

Electricity Fundamentals

2.1 Charge, Current, and the Electron

All electrical phenomena trace back to **electric charge**, a fundamental property of matter carried by protons (positive) and electrons (negative). Charge is measured in **coulombs (C)**. In solid conductors, current flow is due almost entirely to the drift of free electrons through the material's crystal lattice; each electron carries a charge of

$$e = 1.602 \times 10^{-19}\,\text{C}.$$

Electric current, symbol I, is defined as the rate of flow of charge past a point:

$$I = \frac{Q}{t} \qquad \text{[amperes, A]}$$

where Q is the charge in coulombs that passes in time t (seconds). One ampere is one coulomb per second. Rearranged, this gives $Q = It$, used whenever you need to know how much charge (and hence how much battery capacity) a circuit consumes over time.

Key Idea: Conventional current vs. electron flow

By historical convention (fixed before the electron was discovered), current is defined as flowing from the positive terminal of a source, through the external circuit, to the negative terminal. Electrons actually drift the opposite way. Every formula and every schematic arrow in this book uses *conventional current*; keep this in mind if you ever reason from first-principles electron motion.

2.2 Voltage: Electromotive Force and Potential Difference

Voltage (potential difference), symbol U or V, is the energy per unit charge available to move charge between two points:

$$U = \frac{W}{Q} \qquad \text{[volts, V]}$$

where W is energy in joules and Q is charge in coulombs. A source that maintains a potential difference by chemical, mechanical, or photovoltaic means (a battery, generator, or solar cell) is said to supply an **electromotive force (EMF)**. Voltage is always measured *between two points* — it is meaningless to speak of "the voltage at a point" without an implied reference (commonly circuit ground, 0 V).

2.3 Resistance and Conductance

Resistance, symbol R, measured in **ohms (Ω)**, quantifies how strongly a material opposes current flow. Its reciprocal, **conductance** $G = 1/R$, is measured in **siemens (S)** and is occasionally more convenient when components are combined in parallel (Chapter 3).

The resistance of a uniform conductor depends on its physical dimensions and the material's intrinsic **resistivity** ρ (ohm-metres):

$$R = \rho \frac{\ell}{A}$$

where ℓ is the conductor's length and A its cross-sectional area. This equation explains several practical facts amateurs rely on: thicker wire has lower resistance (larger A), longer feedlines have more loss (larger ℓ), and different metals used for antenna elements or wire (copper, aluminum, steel) behave differently because of ρ.

Resistance also depends on temperature. For most conductors, resistance *increases* with temperature (a fact relevant to power resistors and antenna tuner components that heat up under load); for semiconductors, it typically *decreases*, a behavior exploited in some temperature sensors.

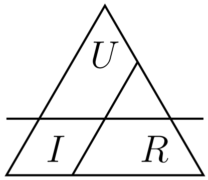
2.4 Ohm's Law

The single most-used relationship in all of electronics is **Ohm's law**, named for Georg Simon Ohm (1789–1854):

$$\boxed{U = IR}$$

Voltage equals current multiplied by resistance. Because it relates three quantities, knowing any two lets you solve for the third:

$$I = \frac{U}{R}, \qquad R = \frac{U}{I}.$$



The classic memory triangle above encodes all three rearrangements: cover the quantity you want to find, and the remaining two show whether to multiply or divide. Covering U leaves I beside R (multiply, $U = IR$); covering I leaves U over R (divide, $I = U/R$); covering R leaves U over I (divide, $R = U/I$).

Quantity	Symbol	Unit	Symbol for Unit
Voltage (potential difference)	U	volt	V
Current	I	ampere	A
Resistance	R	ohm	Ω

Worked Example: Applying Ohm's law

A 12 V battery is connected across a 470 Ω resistor. Find the current.

Solution.

$$I = \frac{U}{R} = \frac{12\,\mathrm{V}}{470\,\Omega} = 0.0255\,\mathrm{A} = 25.5\,\mathrm{mA}.$$

Exam Tip

Ohm's law questions on exams almost always require a prefix conversion as part of the arithmetic (mA, kΩ, etc.). Convert everything to base units (V, A, Ω) first, solve, then convert the final answer to a sensible prefix.

2.5 Electrical Power

Power is the rate of doing work (transferring energy), measured in **watts (W)**:

$$P = \frac{W}{t}.$$

In a DC circuit, electrical power delivered to a component is

$$\boxed{P = UI}$$

Combining this with Ohm's law gives two further useful forms, used whenever voltage or current (rather than both) is known:

$$P = I^2 R, \qquad P = \frac{U^2}{R}.$$

Worked Example: Power dissipation

The 470 Ω resistor from the previous example carries 25.5 mA. How much power does it dissipate, and could a standard $\frac{1}{4}$-W resistor be used safely?
Solution.

$$P = I^2 R = (0.0255\,\mathrm{A})^2 \times 470\,\Omega \approx 0.306\,\mathrm{W}.$$

This exceeds a $\frac{1}{4}$-W (0.25 W) resistor's rating, so a $\frac{1}{2}$-W or larger resistor should be used, ideally with margin for safety (Section 2.5).

Safety: Power rating margin

Never operate a resistor, or any dissipative component, right at its rated maximum. A common engineering rule of thumb is to keep steady-state dissipation below 50% of the component's rating, both because resistance itself drifts with temperature and because localized hot spots can exceed the average calculated value.

2.6 Energy

Energy is power sustained over time:

$$W = Pt.$$

When P is in watts and t is in seconds, W comes out in joules. Utility bills and battery capacities, however, are usually expressed in **watt-hours (Wh)** or **kilowatt-hours (kWh)**, where t is in hours instead of seconds; $1\,\mathrm{kWh} = 3.6 \times 10^6\,\mathrm{J}$. Battery amp-hour ratings, covered in Chapter 12, use the same underlying idea applied to charge instead of energy.

2.7 Conductors, Insulators, and Semiconductors

Materials are broadly classed by how easily their electrons can move under an applied field:

- **Conductors** (copper, aluminum, silver, gold) have a "sea" of loosely bound valence electrons that move freely, giving very low resistivity ($\rho \sim 10^{-8}\,\Omega \cdot \mathrm{m}$). Used for wire, antenna elements, PCB traces.
- **Insulators** (PVC, ceramic, glass, air under normal conditions) have tightly bound electrons and extremely high resistivity ($\rho \sim 10^{9}$–$10^{16}\,\Omega \cdot \mathrm{m}$). Used to prevent unwanted current paths — wire jacketing, standoff insulators, capacitor dielectrics.
- **Semiconductors** (silicon, germanium) have resistivity between the two, and — crucially — that resistivity can be controlled by doping, temperature, or an applied field. This tunability is what makes diodes, transistors, and integrated circuits possible (Chapter 13).

Chapter Review

- Current $I = Q/t$; voltage $U = W/Q$; resistance $R = U/I$ (Ohm's law, $U = IR$).
- Conventional current flows from + to − through the external circuit, opposite to actual electron drift.
- $R = \rho\ell/A$: resistance rises with length, falls with cross-sectional area, and depends on material resistivity.
- Power: $P = UI = I^2R = U^2/R$; energy $W = Pt$.
- Conductors, insulators, and semiconductors are distinguished by resistivity and by whether that resistivity can be externally controlled.

Practice Problems

1. A 9 V battery drives 300 mA through a resistor. Find the resistance.
2. Find the power dissipated by a 100 Ω resistor carrying 50 mA.
3. A device draws 2 A at 13.8 V for 3 hours. How much energy, in watt-hours, did it consume?
4. A wire's length is doubled and its cross-sectional area is halved. By what factor does its resistance change?

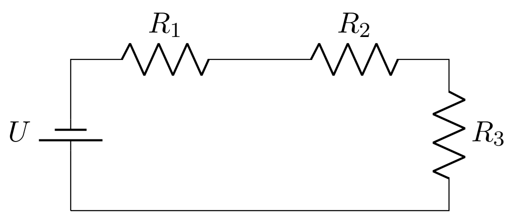
5. Explain, using the concept of resistivity, why thick antenna feedline conductors have less loss than thin ones of the same length.

Chapter 3

DC Circuits and the Resistor Color Code

3.1 Series Circuits

Components are in **series** when they are connected end-to-end so that the same current flows through each of them in turn, with no alternate path.



Key Idea: Series circuit rules

- Current is the *same* through every component: $I_1 = I_2 = I_3 = I$.
- Voltages *add* to equal the source voltage: $U = U_1 + U_2 + U_3$.
- Resistances *add*: $R_{\text{total}} = R_1 + R_2 + R_3 + \cdots$

Because the same current flows through every series resistor, and $U_n = IR_n$ for each one, the voltage across any single resistor in a series chain is a fraction of the source voltage proportional to that resistor's share of the total resistance — the **voltage divider** rule:

$$U_n = U \times \frac{R_n}{R_{\text{total}}}.$$

Worked Example: Voltage divider

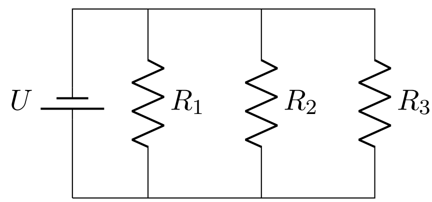
A $12\,\text{V}$ source drives a series circuit of $R_1 = 1\,\text{k}\Omega$ and $R_2 = 3\,\text{k}\Omega$. Find the voltage across R_2.

Solution. $R_{\text{total}} = 4\,\text{k}\Omega$, so

$$U_2 = 12\,\text{V} \times \frac{3\,\text{k}\Omega}{4\,\text{k}\Omega} = 9\,\text{V}.$$

3.2 Parallel Circuits

Components are in **parallel** when they share the same pair of nodes, so the same voltage appears across each of them.



Key Idea: Parallel circuit rules

- Voltage is the *same* across every branch: $U_1 = U_2 = U_3 = U$.
- Currents *add* to equal the total supplied current: $I = I_1 + I_2 + I_3$.
- Conductances add, so resistances combine by the reciprocal rule:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

For exactly two resistors in parallel, this simplifies to the frequently used **product-over-sum** shortcut:

$$R_{\text{total}} = \frac{R_1 R_2}{R_1 + R_2}.$$

A useful sanity check: the parallel combination of any set of resistors is always *smaller* than the smallest individual resistor, because adding a parallel path always gives current an easier route.

Worked Example: Parallel resistance

Find the total resistance of a $100\,\Omega$ and a $150\,\Omega$ resistor in parallel.
Solution.

$$R_{\text{total}} = \frac{100 \times 150}{100 + 150} = \frac{15000}{250} = 60\,\Omega.$$

Notice this is less than $100\,\Omega$, the smaller of the two, as expected.

Currents split between parallel branches in inverse proportion to resistance (the **current divider** rule); for two resistors,

$$I_1 = I_{\text{total}} \times \frac{R_2}{R_1 + R_2}, \qquad I_2 = I_{\text{total}} \times \frac{R_1}{R_1 + R_2}.$$

3.3 Series–Parallel Combinations

Real circuits usually combine both arrangements. The systematic method is to redraw the circuit in stages: identify a sub-group of resistors that are purely in series or purely in parallel, collapse that sub-group into a single equivalent resistor, and repeat until only one resistor remains. Work from the "furthest" part of the circuit from the source inward.

Worked Example: Series–parallel reduction

$R_1 = 2\,\text{k}\Omega$ is in series with the parallel combination of $R_2 = 4\,\text{k}\Omega$ and $R_3 = 4\,\text{k}\Omega$, all driven by a $10\,\text{V}$ source. Find the total current drawn from the source.
Solution. First collapse the parallel pair: $R_{23} = (4 \times 4)/(4 + 4) = 2\,\text{k}\Omega$. This is now in series with R_1: $R_{\text{total}} = 2 + 2 = 4\,\text{k}\Omega$. Then $I = U/R_{\text{total}} = 10\,\text{V}/4\,\text{k}\Omega = 2.5\,\text{mA}$.

3.4 Kirchhoff's Laws

The series and parallel rules above are special cases of two more general laws, published by Gustav Kirchhoff in 1845, which apply to *any* circuit topology, no matter how tangled.

Key Idea: Kirchhoff's Current Law (KCL)

The sum of currents entering a node equals the sum of currents leaving it — charge cannot accumulate at a node in steady state:

$$\sum I_{\text{in}} = \sum I_{\text{out}}.$$

Key Idea: Kirchhoff's Voltage Law (KVL)

The sum of voltage rises and drops around any closed loop is zero — energy gained from sources in a loop equals energy dissipated by components in that loop:

$$\sum U_{\text{loop}} = 0.$$

KCL and KVL are the foundation of general circuit analysis techniques (mesh and nodal analysis) taught in full electrical-engineering courses; for amateur radio purposes, it is enough to recognize that the series and parallel rules of this chapter are direct consequences of these two laws, and to be able to apply KVL/KCL qualitatively — for example, to recognize that the voltage across a shorted component must be zero, or that current from a source must ultimately return to that source.

3.5 Superposition and Thévenin Equivalents (Brief Introduction)

Two further techniques appear in more advanced treatments and occasionally in advanced-class exams:

- **Superposition**: in a linear circuit with multiple sources, the response (current or voltage) at any point equals the sum of the responses caused by each source acting alone, with all other independent voltage sources replaced by short circuits and all other independent current sources replaced by open circuits.
- **Thévenin's theorem**: any two-terminal network of linear sources and resistors can be replaced, from the point of view of an external load, by a single equivalent voltage source U_{Th} in series with a single equivalent resistance R_{Th}. This is extremely useful for analyzing how a source (such as a transmitter's final amplifier) will drive different loads, and reappears in Chapter 19 when discussing impedance matching.

3.6 The Resistor Color Code

Small fixed resistors are usually too small to print numeric values on, so their value and tolerance are encoded as a sequence of colored bands. The most common scheme uses four bands: two significant digits, a multiplier, and a tolerance.

Color	Digit	Multiplier	Tolerance
Black	0	$\times 10^0$	—
Brown	1	$\times 10^1$	$\pm 1\%$
Red	2	$\times 10^2$	$\pm 2\%$
Orange	3	$\times 10^3$	—
Yellow	4	$\times 10^4$	—
Green	5	$\times 10^5$	$\pm 0.5\%$
Blue	6	$\times 10^6$	$\pm 0.25\%$
Violet	7	$\times 10^7$	$\pm 0.1\%$
Grey	8	$\times 10^8$	—
White	9	$\times 10^9$	—
Gold	—	$\times 10^{-1}$	$\pm 5\%$
Silver	—	$\times 10^{-2}$	$\pm 10\%$
None	—	—	$\pm 20\%$

For a **4-band resistor**, read bands 1–2 as significant digits, band 3 as the power-of-ten multiplier, and band 4 as tolerance:

$$\text{Value} = (\text{digit}_1\, \text{digit}_2) \times 10^{\text{multiplier}}\, \Omega.$$

A **5-band resistor** (more common for precision, $\pm 1\%$ or better, resistors) uses three significant digits before the multiplier band.

Worked Example: Reading the color code

A resistor shows the bands Brown, Black, Red, Gold. Find its value and tolerance.

Solution. Brown = 1, Black = 0, so the significant digits are "10." Red is the multiplier, $\times 10^2 = \times 100$. So $R = 10 \times 100 = 1000\,\Omega = 1\,\text{k}\Omega$. Gold indicates $\pm 5\%$ tolerance, so the resistor's true value lies between $950\,\Omega$ and $1050\,\Omega$.

Exam Tip

A popular mnemonic for the digit sequence 0–9 (Black, Brown, Red, Orange, Yellow, Green, Blue, Violet, Grey, White) is: "*B*ad *B*oys *R*ob *O*ur *Y*oung *G*irls *B*ut *V*iolet *G*ives *W*illingly." Use whichever mnemonic sticks; what matters on an exam is speed and accuracy, not elegance.

3.7 Preferred Values (E-series)

Resistors (and capacitors) are not manufactured at every possible value; they follow standardized **preferred value** series (E6, E12, E24, E96, ...) where the number indicates how many values are spaced per decade. The E12 series, for instance, uses twelve values per decade spaced so that the maximum error between any achievable value and a desired value, given the series tolerance, stays small:

$$1.0,\ 1.2,\ 1.5,\ 1.8,\ 2.2,\ 2.7,\ 3.3,\ 3.9,\ 4.7,\ 5.6,\ 6.8,\ 8.2\ (\times 10^n).$$

This is why component catalogs list "4.7 kΩ" and "5.6 kΩ" resistors but not "5.0 kΩ" — the nearest E12 values are used instead, and circuit designs are built around whatever the nearest standard value achieves.

Chapter Review

- Series: same current, voltages add, resistances add.
- Parallel: same voltage, currents add, resistances combine by reciprocal sum (or product-over-sum for two resistors).
- Kirchhoff's Current Law and Voltage Law are the general principles underlying the series/parallel shortcuts.
- Resistor color bands encode two or three significant digits, a multiplier, and a tolerance.
- Component values follow standardized E-series preferred value tables, not arbitrary round numbers.

Practice Problems

1. Three resistors, 100 Ω, 220 Ω, and 330 Ω, are in series across a 9 V battery. Find the total resistance, the current, and the voltage across the 220 Ω resistor.
2. Find the equivalent resistance of 470 Ω, 470 Ω, and 1 kΩ in parallel.

3. A resistor's bands read Yellow, Violet, Orange, Gold. Find its value and tolerance range.
4. Explain, using KCL, why the total current entering a series–parallel network must equal the current leaving it, even though internal branch currents differ.
5. Two $100\,\Omega$ resistors and one $220\,\Omega$ resistor are connected so that the $220\,\Omega$ is in series with the parallel combination of the two $100\,\Omega$ units, across a $15\,\text{V}$ source. Find the total current.

Chapter 4

Electric, Magnetic, and Electromagnetic Fields

Everything a radio does — store energy in a capacitor, store energy in an inductor, radiate a signal from an antenna, propagate that signal across an ocean — is a manifestation of electric and magnetic fields. This chapter builds the field concepts needed to understand components (Part II) and antennas and propagation (Part IV).

4.1 The Electric Field

An **electric field** exists in the region around any electric charge; it is defined as the force per unit charge that a small positive "test charge" would experience at a given point:

$$E = \frac{F}{q} \qquad \text{[volts per metre, V/m]}$$

Field lines point away from positive charges and toward negative charges. Between two flat, oppositely charged parallel plates separated by distance d with potential difference U between them, the field is uniform and given by

$$E = \frac{U}{d}.$$

This is precisely the geometry inside a parallel-plate capacitor (Chapter 7): a capacitor is, at its core, a device for storing energy in an electric field confined between two conductors.

Key Idea

The electric field describes how strongly a charge distribution can push or pull on other charges. It is the mechanism by which a capacitor stores energy and by which a transmitting antenna's near field couples to nearby objects.

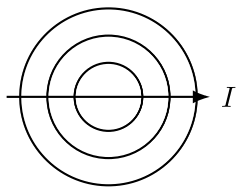
4.2 The Magnetic Field

A **magnetic field** is produced by moving charge (current) and is described by the flux density B, measured in **tesla (T)**. Unlike electric field lines, magnetic field lines have no starting or ending point; they form closed loops. For a long, straight conductor carrying current I, the field at perpendicular distance r is

$$B = \frac{\mu_0 I}{2\pi r}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the **permeability of free space**. The direction of the field circles the conductor according to the **right-hand rule**: point the thumb of your right hand in the direction of conventional current flow, and your fingers curl in the direction of the magnetic field.

Winding a conductor into a coil concentrates and reinforces this field inside the loops, which is precisely how an **inductor** (Chapter 8) stores energy in a magnetic field, and how a loop antenna couples to the magnetic component of a radio wave.



Field circles the conductor (right-hand rule)

4.3 Magnetic Flux and Faraday's Law

Magnetic flux, Φ, measured in **webers (Wb)**, is the total magnetic field passing through a given area:

$$\Phi = B \cdot A$$

for a uniform field B perpendicular to area A. **Faraday's law of induction** states that a changing magnetic flux through a loop induces an EMF around that loop:

$$\mathcal{E} = -N\frac{d\Phi}{dt}$$

where N is the number of turns of the loop and the negative sign (Lenz's law) indicates that the induced EMF always opposes the change that created it. Faraday's law is the working principle behind **inductors** (an inductor opposes changes in current because that current change causes a changing flux, which induces an opposing EMF), **transformers** (Chapter 11), and the reception of radio signals by any loop or wire antenna.

Key Idea: Lenz's law, intuitively

An induced current always flows in the direction that opposes the change that produced it. This is why inductors resist sudden changes in current, and why energy must be supplied to overcome this opposition when current is increased or decreased quickly.

4.4 The Electromagnetic Field and Maxwell's Insight

Electric and magnetic fields are not independent phenomena; they are two aspects of a single **electromagnetic field**. James Clerk Maxwell showed in the 1860s, through four coupled equations now called **Maxwell's equations**, that:

- A changing electric field produces a magnetic field (this completes the symmetry of Faraday's law, and was Maxwell's key addition — the "displacement current" term).
- A changing magnetic field produces an electric field (Faraday's law).

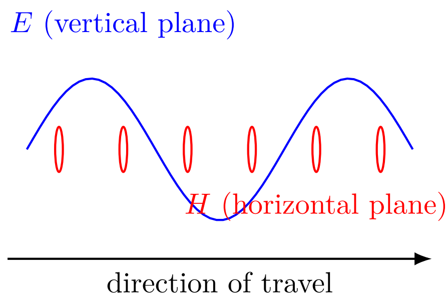
These two facts together mean that, once created, a time-varying electric field and a time-varying magnetic field can regenerate each other indefinitely, propagating outward from their source as a self-sustaining wave — an **electromagnetic wave** — without needing a material medium to carry them. Maxwell calculated the predicted speed of such a wave from purely electrical and magnetic constants,

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 2.998 \times 10^8 \text{ m/s},$$

and found it matched the already-measured speed of light — correctly concluding that light itself is an electromagnetic wave. Radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays are all electromagnetic waves, differing only in frequency (and hence wavelength); amateur radio operates in the radio-frequency portion of this same spectrum.

4.5 Properties of a Traveling EM Wave

In a radio wave traveling through free space, the electric field E and magnetic field H oscillate perpendicular to each other and to the direction of propagation, in phase, with a fixed ratio between them (the **impedance of free space**, $Z_0 = \sqrt{\mu_0/\varepsilon_0} \approx 377\,\Omega$).



The **wavelength** λ, **frequency** f, and **speed of light** c are related by

$$\boxed{c = f\lambda} \qquad \Longrightarrow \qquad \lambda = \frac{c}{f}, \quad f = \frac{c}{\lambda}.$$

This single relationship is one of the most exam-relevant formulas in the entire book: it converts between the two ways radio frequencies are described (as a frequency in Hz, or as a wavelength in metres, as in "the 20-metre band") and underlies antenna dimension calculations in Chapter 20.

Worked Example: Frequency–wavelength conversion

Find the wavelength corresponding to 14.200 MHz.
Solution.

$$\lambda = \frac{c}{f} = \frac{2.998 \times 10^8\,\text{m/s}}{14.200 \times 10^6\,\text{Hz}} \approx 21.1\,\text{m}.$$

This is why 14 MHz is colloquially called "the 20 m band" — 21.1 m rounds, by amateur radio band-naming convention, to the nearest traditional metre-band label.

4.6 Polarization

The **polarization** of an EM wave describes the orientation of its electric field vector. If E stays in a fixed plane as the wave travels (e.g., always vertical, or always horizontal), the wave is **linearly polarized**; a horizontal dipole radiates a horizontally polarized wave, a vertical antenna radiates a vertically polarized wave. If the E field instead rotates as the wave travels, tracing a helix, the wave is **circularly** (or, more generally, **elliptically**) polarized — used heavily in satellite work, where a spacecraft's orientation relative to a ground station is constantly changing, so neither pure horizontal nor pure vertical polarization stays aligned. Polarization mismatch between a transmitting and receiving antenna causes signal loss (Chapter 20), which is why matching polarization matters when choosing or orienting an antenna.

Chapter Review

- Electric field $E = F/q$ (V/m); magnetic flux density B (tesla); flux $\Phi = BA$ (weber).
- Faraday's law: a changing flux induces an EMF, $\mathcal{E} = -N\,d\Phi/dt$; Lenz's law fixes the sign (opposition to change).
- Maxwell's equations show that changing E and B fields sustain each other, propagating as an electromagnetic wave at $c \approx 3 \times 10^8$ m/s.
- $c = f\lambda$ links frequency and wavelength — essential for antenna design and band naming.
- Polarization describes the orientation of the wave's electric field; mismatched polarization causes signal loss.

Practice Problems

1. Find the magnetic field 5 cm from a straight wire carrying 2 A.
2. A single-turn loop of area $0.01\,\text{m}^2$ experiences a flux change from 0 to 5 mWb in 0.1 s. Find the induced EMF.
3. Calculate the wavelength for 145.500 MHz and for 433.500 MHz; identify the traditional amateur band name for each.
4. Explain, in terms of Maxwell's equations, why a radio wave can cross the vacuum of space with no medium to carry it, unlike a sound wave.
5. A satellite station uses circular polarization while a fixed home station uses a horizontal linear-polarized antenna. Explain qualitatively why using circular polarization at both ends often improves the link.

Chapter 5

Alternating Current and Sinusoidal Signals

Every radio signal is an alternating current (AC) waveform. This chapter develops the mathematics of sinusoidal AC — amplitude, frequency, phase, and the RMS value — that underlies every later chapter on reactance, resonance, and modulation.

5.1 Direct Current vs. Alternating Current

Direct current (DC) flows in one direction only in a circuit; its magnitude may be constant (a battery) or may vary, but its polarity does not reverse. **Alternating current (AC)** periodically reverses direction. The most important AC waveform, both because it is mathematically fundamental and because it is what oscillators naturally produce, is the **sine wave**.

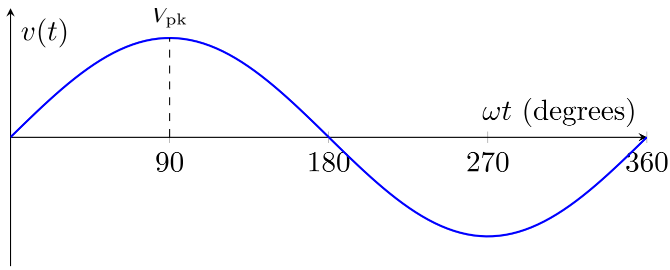
5.2 Describing a Sine Wave

A sinusoidal voltage varying with time t is written

$$\boxed{v(t) = V_{\text{pk}} \sin(\omega t + \phi)}$$

where:

- V_{pk} is the **peak amplitude** (maximum instantaneous value), in volts.
- $\omega = 2\pi f$ is the **angular frequency**, in radians per second, where f is the frequency in hertz.
- ϕ is the **phase angle**, describing a time offset relative to a reference, in radians or degrees.



5.2.1 Period and Frequency

The **period** T is the time for one complete cycle; frequency is its reciprocal:

$$\boxed{f = \frac{1}{T}} \qquad \text{[hertz, Hz = cycles per second]}$$

A 14 MHz signal completes 14×10^6 cycles every second, so its period is $T = 1/(14 \times 10^6) \approx 71.4\,\text{ns}$.

5.2.2 Amplitude Measures

A sine wave can be described by several different amplitude measures, and confusing them is one of the most common sources of error in AC calculations:

Measure	Meaning	Relation to V_{pk}
Peak (V_{pk})	Maximum instantaneous value	—
Peak-to-peak (V_{pp})	Total swing, trough to crest	$V_{pp} = 2V_{pk}$
RMS (V_{rms})	Effective (heating) value	$V_{rms} = V_{pk}/\sqrt{2}$
Average (V_{avg})	Mean of the rectified waveform	$V_{avg} = 2V_{pk}/\pi$

Key Idea: Why RMS matters

The **root-mean-square (RMS)** value of an AC waveform is defined so that it produces the *same heating effect* (the same average power dissipation in a resistor) as a DC voltage of the same numerical value. All of the DC power formulas from Chapter 2 ($P = UI$, $P = I^2R$, $P = U^2/R$) apply directly to AC *if* RMS values are used for U and I. Unless stated otherwise, voltages and currents quoted for AC mains, transmitter output, and test equipment readings are always RMS values.

For a pure sine wave, $V_{rms} = V_{pk}/\sqrt{2} \approx 0.707\,V_{pk}$. This factor of $1/\sqrt{2}$ comes from averaging $\sin^2(\theta)$ over a full cycle, which equals $\frac{1}{2}$.

Worked Example: RMS conversion

A sine wave has a peak voltage of 325 V (typical of 230 V AC mains). Find its RMS value.

Solution.

$$V_{\text{rms}} = \frac{V_{\text{pk}}}{\sqrt{2}} = \frac{325}{1.414} \approx 230\,\text{V}.$$

This confirms that "230 V mains" is quoted as an RMS value.

5.3 Phase

Phase describes the timing relationship between two waveforms of the same frequency. Two sine waves are **in phase** if their peaks and zero-crossings line up exactly ($\phi = 0$); they are **out of phase** by however many degrees (or radians) one is shifted relative to the other. A phase difference of 90° is described as **quadrature**; 180° means the waveforms are exact mirror images of each other (in **antiphase**).

Phase becomes critical once reactive components are introduced (Chapters 7–10): unlike a resistor, a capacitor or inductor shifts the phase between the voltage across it and the current through it, which is the origin of **reactance** and **impedance**.

5.4 The Rotating Phasor Picture

A sine wave can be visualized as the vertical projection of a vector (a **phasor**) of length V_{pk} rotating counterclockwise at angular velocity ω. This picture — formalized using complex numbers as $V_{\text{pk}}e^{j(\omega t+\phi)}$ — turns AC circuit analysis into algebra: instead of tracking a continuously varying instantaneous voltage, engineers track a fixed complex number (magnitude and phase) per frequency, and the differential-equation relationships between voltage and current across capacitors and inductors become simple multiplication by a complex impedance. This is the "j" notation used throughout Chapters 7–10.

5.5 Why Sine Waves Are Special

Sine waves are the natural output of resonant physical systems (a pendulum, a vibrating string, an LC oscillator) and, crucially, are the *only* waveform shape that a linear circuit (one built from resistors, capacitors, and inductors) cannot distort — passing a sine wave through a linear filter changes its amplitude and phase but never its fundamental shape. This property, combined with the mathematical fact that *any* periodic waveform can be built from a sum of sine waves at different frequencies (Fourier's theorem, Chapter 6), is why sinusoidal analysis is the foundation for understanding every other waveform used in radio.

Chapter Review

- $v(t) = V_{\text{pk}} \sin(\omega t + \phi)$, with $\omega = 2\pi f$ and $f = 1/T$.
- $V_{\text{pp}} = 2V_{\text{pk}}$; $V_{\text{rms}} = V_{\text{pk}}/\sqrt{2} \approx 0.707V_{\text{pk}}$; DC power formulas apply to AC when RMS values are used.
- Phase describes timing offset between waveforms; 90° is quadrature, 180° is antiphase.
- The rotating phasor (complex-exponential) picture turns AC analysis into algebra with complex numbers.
- Any periodic waveform is a sum of sine waves at different frequencies (previewing Fourier analysis, Chapter 6).

Practice Problems

1. A sine wave has $V_{\text{rms}} = 120\,\text{V}$. Find V_{pk} and V_{pp}.
2. Find the period of a 7.100 MHz signal.
3. Two sine waves of the same frequency have a phase difference of 90°. What term describes this relationship?
4. A signal generator is set to 1 kHz with a peak amplitude of 5 V. Write the instantaneous voltage $v(t)$ as an equation, assuming zero phase offset.
5. Explain why AC voltmeters are calibrated to read RMS rather than peak values.

Chapter 6

Non-Sinusoidal Signals and Fourier Analysis

Not every useful waveform is a sine wave. Square waves clock digital logic, sawtooth waves sweep oscilloscopes and older TV displays, and the keyed on/off waveform of Morse code is about as far from a sine wave as a signal can get. This chapter explains how such waveforms relate back to the sinusoidal theory of Chapter 5, and why that relationship matters for bandwidth and interference.

6.1 Common Non-Sinusoidal Waveforms

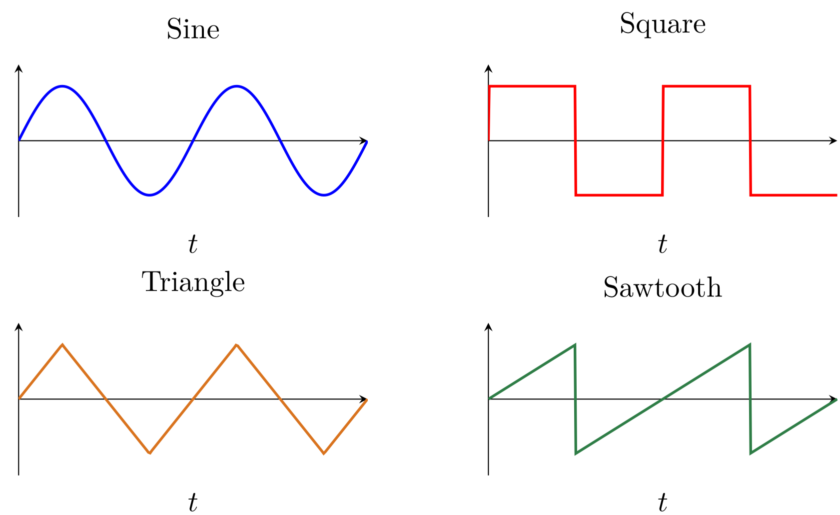


Figure 6.1: Common periodic waveforms: sine, square, triangle, and sawtooth, each shown over several cycles.

- **Square wave**: switches abruptly between two levels, spending equal time at each (50% duty cycle). Produced by digital logic gates, keyed CW (approximately), and switching-mode power supplies.

- **Triangle wave**: rises and falls linearly at a constant rate. Used in some function generators and as a building block for sweep and ramp circuits.
- **Sawtooth wave**: rises linearly then drops sharply (or vice versa). Classic use: the horizontal deflection sweep in a cathode-ray-tube display.
- **Pulse train**: a waveform that is at one level for a short time and at another level for the rest of the period, characterized by its **duty cycle** (fraction of the period spent "high"). Digital data and radar are naturally pulse-like.

6.2 Fourier's Theorem

The mathematician Joseph Fourier proved a result of enormous consequence for radio engineering: *any* periodic waveform, no matter its shape, can be expressed as a sum (in general, an infinite sum) of sine and cosine waves at the fundamental frequency and its integer multiples (**harmonics**):

$$x(t) = a_0 + \sum_{n=1}^{\infty} [a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t)]$$

where $\omega_0 = 2\pi f_0$ is the fundamental angular frequency and a_0, a_n, b_n are coefficients determined by the waveform's shape. This means a waveform's *shape* and its *frequency content* are two views of the same underlying signal, related by the **Fourier transform** (for non-periodic or more general signals) or the **Fourier series** (for periodic signals, as written above).

Key Idea

Every non-sinusoidal periodic signal occupies more than one frequency: a fundamental plus a ladder of harmonics. A signal's bandwidth — how much of the radio spectrum it actually occupies — is fundamentally a statement about its Fourier content, not just its nominal "frequency."

6.2.1 Square Wave Harmonics

A symmetric square wave of fundamental frequency f_0 and peak amplitude A contains *only odd* harmonics, with amplitude falling off as $1/n$:

$$x(t) = \frac{4A}{\pi} \left[\sin(\omega_0 t) + \frac{1}{3}\sin(3\omega_0 t) + \frac{1}{5}\sin(5\omega_0 t) + \cdots \right]$$

This is why a keyed CW signal or a switching power supply, even though it is nominally operating at one frequency, actually radiates energy at that frequency's odd multiples too — a real-world source of harmonic interference (Section 6.3) unless filtered.

Worked Example: Predicting a harmonic frequency

A square-wave clock oscillates at 7.023 MHz. At what frequency would you expect to find its strongest spurious harmonic, and in which amateur band might it fall?

Solution. The strongest harmonic of a square wave (after the fundamental) is the third harmonic: $3 \times 7.023 = 21.069$ MHz, which falls inside the 15 m amateur band (21.000–21.450 MHz in most IARU Region 1/2/3 allocations) — a classic real-world case for low-pass filtering a keyed oscillator or transmitter output.

6.3 Bandwidth and Rise Time

A perfectly square edge (instantaneous transition) requires *infinite* bandwidth to reproduce exactly, because it needs harmonics out to $n \to \infty$ to build the sharp corner. Real circuits have finite bandwidth, so real square waves always have a finite **rise time** t_r (time to transition, conventionally measured from 10% to 90% of full amplitude). A useful rule of thumb links rise time and the bandwidth B needed to reproduce it reasonably faithfully:

$$B \approx \frac{0.35}{t_r}.$$

This relationship explains why fast-keyed digital or CW signals, or poorly shaped keying waveforms, splatter energy into adjacent parts of the band — an important practical and courtesy consideration when operating, and the reason well-designed transmitters deliberately shape (“soften”) their keying edges.

Safety: Key clicks and splatter

Overly fast keying transitions (“hard keying”) generate broadband clicks that can interfere with stations operating hundreds of kilohertz away. Modern transmitters shape the CW envelope with a short rise/fall time (typically several milliseconds) specifically to keep the emitted bandwidth narrow. This is both good operating practice and, in most countries, a regulatory requirement on out-of-band emissions.

6.4 DC Offset and the Mean Value

The a_0 term in the Fourier series represents the waveform's **DC component** — its average value over a full cycle. A sine wave that swings symmetrically about zero has $a_0 = 0$; a keyed pulse train that is "on" more than it is "off" has a nonzero DC component equal to (peak value) $\times$ (duty cycle). This matters practically when a waveform passes through a transformer or capacitor-coupled stage, neither of which passes a DC component — the shape of the waveform will change (its average will be forced back to zero) even though its AC content is otherwise preserved.

6.5 Spectral (Frequency-Domain) View

Plotting a signal's amplitude at each frequency, rather than its instantaneous value over time, gives its **spectrum** — exactly what a spectrum analyzer or waterfall display shows. A pure sine wave appears as a single vertical line at its frequency; a square wave appears as a line at the fundamental plus progressively smaller lines at each odd harmonic; a burst of noise appears as energy spread continuously across a range of frequencies. Learning to think in both the **time domain** (a scope trace) and the **frequency domain** (a spectrum display) simultaneously is one of the most valuable skills a radio amateur can develop, and is essential for understanding modulation (Chapter 17).

Chapter Review

- Any periodic waveform is a sum of sine/cosine harmonics of its fundamental frequency (Fourier series).
- A symmetric square wave contains only odd harmonics, falling off as $1/n$ in amplitude.
- Sharper edges (shorter rise time) require more bandwidth, approximately $B \approx 0.35/t_r$.
- A waveform's DC component is its Fourier a_0 term — the average value over one cycle.
- Time-domain and frequency-domain views describe the same signal from two complementary perspectives.

Practice Problems

1. List the first three nonzero harmonics (as multiples of f_0) of a symmetric square wave.

2. A 3.573 MHz CW oscillator's third harmonic falls near which amateur band?
3. A digital keying circuit has a rise time of 1 ms. Estimate the bandwidth this implies, and comment on whether this is adequate for narrow, splatter-free CW.
4. Explain why a capacitor-coupled audio stage will not faithfully pass a waveform with a strong DC offset.
5. Sketch (in words) how the spectrum of a triangle wave would differ from that of a square wave of the same fundamental frequency.

Part II

Passive Components and Circuits

Chapter 7

Capacitors and Capacitive Reactance

7.1 The Capacitor

A **capacitor** stores energy in an electric field between two conductive plates separated by an insulating **dielectric**. Its defining property is **capacitance** C, measured in **farads (F)**:

$$\boxed{C = \frac{Q}{U}}$$

where Q is the charge stored (coulombs) and U is the voltage across the plates. One farad is a very large unit; practical capacitors are usually specified in microfarads (μF), nanofarads (nF), or picofarads (pF).

For a simple parallel-plate capacitor with plate area A, separation d, and a dielectric of permittivity $\varepsilon = \varepsilon_r \varepsilon_0$,

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

where $\varepsilon_0 = 8.854 \times 10^{-12}\,\mathrm{F/m}$ is the permittivity of free space and ε_r is the dielectric's **relative permittivity** (air ≈ 1, ceramic 5–10,000 depending on formulation, mica $\approx$ 5–7). This equation explains capacitor construction directly: more plate area or a thinner, higher-permittivity dielectric gives more capacitance in the same physical volume, which is why high-value capacitors use thin rolled or multilayer construction.

7.2 Charging and Discharging: the Capacitor's Defining Behavior

A capacitor opposes *changes* in voltage across it, just as an inductor (Chapter 8) opposes changes in current. The current into a capacitor is proportional to how fast its voltage is changing:

$$i(t) = C\,\frac{dU}{dt}.$$

Two consequences follow directly, and both are exam favorites:

- A capacitor blocks DC in steady state: once fully charged ($dU/dt = 0$), no current flows.
- A capacitor initially looks like a short circuit to a sudden voltage step (large dU/dt means large initial current), then charges toward the applied voltage.

The time-domain charge/discharge behavior (the **RC time constant**) is developed fully in Chapter 9.

7.3 Energy Stored in a Capacitor

The energy stored in a charged capacitor is

$$W = \frac{1}{2}CU^2 = \frac{1}{2}QU = \frac{Q^2}{2C}.$$

This stored energy is why capacitors are used for power-supply filtering (smoothing ripple by supplying current between rectifier pulses), timing circuits, and as the energy-storage element in an LC tank circuit (Chapter 10).

7.4 Capacitors in Series and Parallel

Unlike resistors, capacitor combination rules are "reversed":

Key Idea

Parallel capacitors add directly (more plate area, effectively):

$$C_{\text{total}} = C_1 + C_2 + C_3 + \cdots$$

Series capacitors combine by the reciprocal sum (effectively a thicker dielectric gap):

$$\frac{1}{C_{\text{total}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$$

For exactly two capacitors in series, $C_{\text{total}} = \dfrac{C_1 C_2}{C_1 + C_2}$ (product over sum, same shortcut form as parallel resistors).

Worked Example: Series capacitors

Find the total capacitance of a 100 pF and a 220 pF capacitor in series.
Solution.

$$C_{\text{total}} = \frac{100 \times 220}{100 + 220} = \frac{22000}{320} \approx 68.8\,\text{pF}.$$

As with parallel resistors, the series combination is always smaller than the smallest individual value.

7.5 Capacitive Reactance

When an AC voltage is applied to a capacitor, the current leads the voltage: current is largest exactly when voltage is changing fastest (at the zero-crossing) and zero when voltage is at its peak (momentarily not changing). This 90° phase relationship, combined with the frequency-dependent *magnitude* of opposition to current flow, is called **capacitive reactance**, X_C, measured in ohms:

$$\boxed{X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C}}$$

Key Idea: Reactance vs. resistance

Reactance, like resistance, is measured in ohms and limits current for a given voltage. Unlike resistance, reactance depends on frequency and does not dissipate energy as heat — it stores and returns energy each cycle. Capacitive reactance *decreases* as frequency increases (a capacitor looks increasingly like a short circuit at high frequency) and *increases* without bound as frequency approaches zero (a capacitor looks like an open circuit at DC, consistent with Section 7 above).

Worked Example: Calculating reactance

Find the reactance of a 100 pF capacitor at 14.2 MHz.
Solution.

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 14.2 \times 10^6 \times 100 \times 10^{-12}} \approx 112\,\Omega.$$

Because current leads voltage by exactly 90° in an ideal capacitor, the impedance of a capacitor is written as a purely imaginary number in the phasor (complex) notation introduced in Chapter 5:

$$Z_C = -jX_C = \frac{1}{j\omega C}.$$

This notation becomes essential once capacitors and resistors are combined (Chapter 9) or combined with inductors (Chapter 10), since it lets both magnitude and phase be tracked with ordinary complex-number arithmetic.

7.6 Capacitor Types and Practical Considerations

- **Ceramic**: small, cheap, low to moderate values (pF to low μF), widely used for RF bypass and coupling; some formulations (especially high-K types) have capacitance that varies with applied voltage and temperature.
- **Film** (polyester, polypropylene): good stability and low loss, common in filters and audio circuits.
- **Electrolytic**: large capacitance (µF to mF) in a small volume, but **polarized** — must be connected with correct polarity or they can fail catastrophically — and generally unsuitable for RF due to significant internal series resistance/inductance at high frequency.
- **Tantalum**: also polarized, more stable than aluminum electrolytics but historically less tolerant of voltage transients.
- **Variable (trimmer/tuning)**: mechanically adjustable capacitance, used for tuning and neutralization.

Safety: Electrolytic capacitor polarity and residual charge

Reverse-connecting a polarized capacitor, or exceeding its voltage rating, can cause it to vent or explode. Large electrolytic and film capacitors in power supplies can also retain a dangerous stored charge long after power is removed; always verify a capacitor is discharged (with an appropriate bleeder resistor or a meter check) before handling.

7.7 Real Capacitors: ESR and Tolerance

A real capacitor has a small **equivalent series resistance (ESR)** and series inductance, both of which become significant at high frequencies and ultimately give every capacitor a **self-resonant frequency** above which it behaves inductively rather than capacitively. Capacitor tolerance is typically wider than resistor tolerance (often ±10% or worse for ceramic types), a factor to keep in mind when designing or troubleshooting frequency-sensitive circuits such as filters and oscillators.

Chapter Review

- $C = Q/U$; parallel-plate capacitance $C = \varepsilon_r \varepsilon_0 A/d$.
- $i = C\,dU/dt$: capacitors block DC and initially pass sudden voltage steps as if shorted.
- Energy stored: $W = \frac{1}{2}CU^2$.
- Parallel capacitors add; series capacitors combine by reciprocal sum (opposite of resistors).
- $X_C = 1/(2\pi f C)$: reactance falls as frequency rises; current leads voltage by 90°; $Z_C = -jX_C$.

Practice Problems

1. Find the capacitance of a capacitor storing $5\,\mu$C at 12 V.
2. Two capacitors, 47 nF and 100 nF, are in parallel. Find the total capacitance.
3. Find the reactance of a 220 pF capacitor at 3.5 MHz and at 28 MHz. Comment on how reactance changes with frequency.
4. A $1000\,\mu$F electrolytic capacitor is charged to 25 V. Find the stored energy, and explain why this capacitor should be treated as a potential shock hazard even after the power supply is switched off.
5. Explain, using the $i = C\,dU/dt$ relationship, why a capacitor appears as a short circuit to a very fast voltage transient (such as a static discharge) even though it blocks steady DC.

Chapter 8

Inductors and Inductive Reactance

8.1 The Inductor

An **inductor** stores energy in a magnetic field, typically by winding a conductor into a coil. Its defining property is **inductance** L, measured in **henries (H)**, defined by how much EMF it develops in response to a changing current (a direct application of Faraday's law, Chapter 4):

$$\boxed{u(t) = L\,\frac{di}{dt}}$$

One henry is the inductance that produces one volt of induced EMF when current changes at one ampere per second. Practical RF inductors range from a few nanohenries (a short wire lead) to hundreds of microhenries or more (loading coils, RF chokes).

For a simple air-core solenoid of N turns, length ℓ, and cross-sectional area A (valid when ℓ is much greater than the coil's diameter),

$$L = \frac{\mu_0 N^2 A}{\ell}.$$

Inductance grows with the *square* of the number of turns — doubling the turns quadruples the inductance for the same core geometry, which is why small changes in winding count have a large effect when hand-winding RF coils. Wrapping the coil around a high-permeability magnetic core (ferrite or powdered iron, permeability $\mu = \mu_r\mu_0$) multiplies the inductance by roughly μ_r for the same winding, letting a physically small core-wound coil achieve inductance that would otherwise require many more turns of air-core wire.

8.2 Opposition to Changing Current

Just as a capacitor opposes changes in voltage, an inductor opposes changes in current, by Lenz's law (Chapter 4): any attempt to change the current through an inductor induces a back-EMF that resists the change. Two consequences follow, mirroring the capacitor behavior of the previous chapter:

- An inductor looks like a short circuit to steady DC (once current is constant, $di/dt = 0$, so no voltage drop develops).
- An inductor initially looks like an open circuit to a sudden current step (opposing the abrupt change), then allows current to build up gradually.

Safety: Inductive kick

Suddenly interrupting current through an inductor (switching off a relay coil, unplugging an energized transformer primary) forces di/dt to be very large for an instant, which can produce a large, damaging voltage spike ("inductive kick") and a visible spark at the switch contacts. Flyback diodes and snubber networks are used across relay coils and switching inductors specifically to control this spike.

8.3 Energy Stored in an Inductor

The energy stored in an inductor carrying current I is

$$W = \frac{1}{2}LI^2.$$

8.4 Inductors in Series and Parallel

Inductors, unlike capacitors, combine the same way resistors do (both describe direct opposition, whether resistive or reactive, without a reciprocal geometric relationship):

Figure 8.1: Inductors in series.

Key Idea

Series inductors add (assuming no mutual coupling between them):

$$L_{\text{total}} = L_1 + L_2 + L_3 + \cdots$$

Parallel inductors combine by reciprocal sum:

$$\frac{1}{L_{\text{total}}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots$$

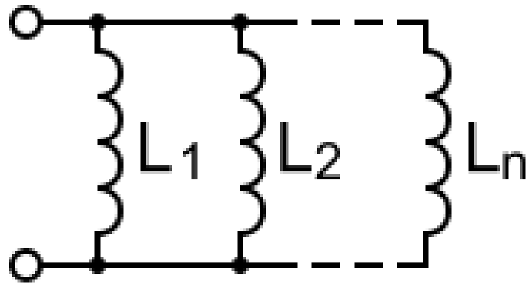


Figure 8.2: Inductors in parallel.

If two coils are wound close enough together that the magnetic field of one links with the other (**mutual inductance**, M), the series total becomes $L_{\text{total}} = L_1 + L_2 \pm 2M$, with the sign depending on whether the windings aid or oppose each other. This mutual-coupling effect is, in fact, the operating principle of the transformer (Chapter 11).

8.5 Inductive Reactance

Under AC excitation, an inductor's opposition to current is frequency-dependent, exactly as for a capacitor but with the opposite frequency trend and the opposite phase relationship. Voltage *leads* current by 90° in an ideal inductor (the mirror image of the capacitor case). The magnitude of this opposition is the **inductive reactance**, X_L, in ohms:

$$\boxed{X_L = 2\pi f L = \omega L}$$

Key Idea

Inductive reactance *increases* with frequency (an inductor looks increasingly like an open circuit at high frequency) and falls to zero as frequency approaches DC (an inductor looks like a plain wire, i.e. a short circuit, at DC) — the exact opposite frequency behavior of a capacitor's X_C.

Worked Example: Calculating reactance

Find the reactance of a $10\,\mu$H inductor at 14.2 MHz.
Solution.

$$X_L = 2\pi f L = 2\pi \times 14.2 \times 10^6 \times 10 \times 10^{-6} \approx 892\,\Omega.$$

In phasor notation, the inductor's impedance is

$$Z_L = jX_L = j\omega L,$$

a purely imaginary number with the opposite sign convention to the capacitor's $Z_C = -jX_C$ — the origin of the cancellation that occurs at resonance, developed fully in Chapter 10.

8.6 Practical Inductor Considerations

- **Air-core coils**: no core losses, highly linear, but need more turns (and more physical size) for a given inductance than a core-loaded equivalent; common in high-power or high-Q RF applications where core saturation or core loss would be problematic.
- **Ferrite/powdered-iron core coils**: much higher inductance per turn, widely used for RF chokes, transformers, and baluns, but subject to **core saturation** (inductance collapses if the core's magnetic flux density exceeds a material-specific limit) and core losses that increase with frequency.
- **Toroidal cores**: a closed magnetic loop (donut shape) that confines nearly all of the magnetic field within the core, minimizing stray coupling to nearby components — the standard choice for compact, well-shielded RF inductors, chokes, and transformers.

Real inductors also have parasitic series resistance (wire resistance, increased at RF by the **skin effect**, where high-frequency current crowds toward the conductor's surface) and parasitic parallel capacitance between windings, which together define the coil's quality factor Q (Chapter 10) and its self-resonant frequency, above which the coil behaves capacitively rather than inductively.

Chapter Review

- $u = L\,di/dt$; $L = \mu_0 N^2 A/\ell$ for an air-core solenoid — inductance scales with the square of turns.
- Inductors oppose current change: short circuit at DC, open circuit to a sudden current step; energy stored $W = \frac{1}{2}LI^2$.
- Series inductors add; parallel inductors combine by reciprocal sum.
- $X_L = 2\pi f L$: reactance rises with frequency; voltage leads current by 90°; $Z_L = j\omega L$.
- Magnetic cores boost inductance per turn but introduce saturation and core-loss limits; toroids confine the field for compact, low-stray designs.

Practice Problems

1. Find the reactance of a 4.7 μH inductor at 7.1 MHz and at 21.2 MHz.
2. Two inductors, 15 μH and 33 μH, are connected in series with negligible mutual coupling. Find the total inductance.
3. Find the energy stored in a 100 μH inductor carrying 2 A.
4. Explain why interrupting current through a relay coil abruptly can produce a damaging voltage spike, and name a common protective component used to prevent it.
5. A coil is wound on a ferrite toroid instead of air. Explain qualitatively why fewer turns are needed to reach the same inductance, and name one drawback of the ferrite-core approach at high power.

Chapter 9

RC and RL Circuits: Time Constants and AC Impedance

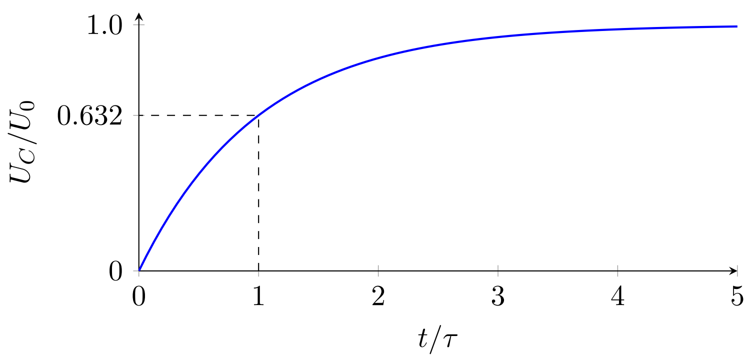
9.1 The RC Charging Transient

Connect a resistor and capacitor in series with a DC source (a step voltage U_0 applied at $t = 0$, capacitor initially uncharged). Solving $i = C\,dU/dt$ together with Kirchhoff's voltage law gives the classic exponential charging curve:

$$\boxed{U_C(t) = U_0\left(1 - e^{-t/\tau}\right)}, \qquad \tau = RC$$

where τ (tau), the **time constant**, has units of seconds when R is in ohms and C is in farads. The current, meanwhile, starts at its maximum value and decays exponentially:

$$i(t) = \frac{U_0}{R}\,e^{-t/\tau}.$$



Key Idea: Meaning of the time constant

After one time constant ($t = \tau$), the capacitor has charged to $1 - e^{-1} \approx 63.2\%$ of the final voltage. After five time constants ($t = 5\tau$), it is charged to $> 99\%$ and is conventionally considered "fully charged" for practical purposes. The same 63.2%/5-time-constant rule applies to discharge (in reverse) and to the analogous RL circuit below.

Worked Example: RC time constant

A $10\,\mathrm{k\Omega}$ resistor and a $100\,\mu\mathrm{F}$ capacitor are placed in series across a $9\,\mathrm{V}$ source. Find the time constant and the voltage across the capacitor after 2 seconds.
Solution. $\tau = RC = 10{,}000 \times 100 \times 10^{-6} = 1\,\mathrm{s}$. At $t = 2\,\mathrm{s} = 2\tau$:

$$U_C = 9\left(1 - e^{-2}\right) = 9 \times 0.865 \approx 7.79\,\mathrm{V}.$$

9.2 RC Discharge

If a charged capacitor is instead connected across a resistor (source removed), the voltage decays exponentially from its initial value U_0:

$$U_C(t) = U_0\, e^{-t/\tau}, \qquad \tau = RC.$$

This decaying-exponential shape, and its rising-exponential counterpart above, appear throughout electronics: power-supply filter ripple decay, the discharge of a defibrillator-style pulse capacitor, the decay of a keyed CW envelope shaped by an RC network, and the timing element of many oscillator and timer circuits.

9.3 The RL Transient

An inductor and resistor in series show the same mathematical shape, because the inductor's $u = L\,di/dt$ plays the same differential-equation role as the capacitor's $i = C\,dU/dt$, with current and voltage roles exchanged. For current building up through an inductor after a voltage step U_0 is applied:

$$i(t) = \frac{U_0}{R}\left(1 - e^{-t/\tau}\right), \qquad \tau = \frac{L}{R}$$

where now $\tau = L/R$ (seconds, when L is in henries and R is in ohms). Current rises toward its final DC value (U_0/R, since the inductor eventually looks like a plain wire) following the identical 63.2%-per-time-constant pattern as the RC charging curve.

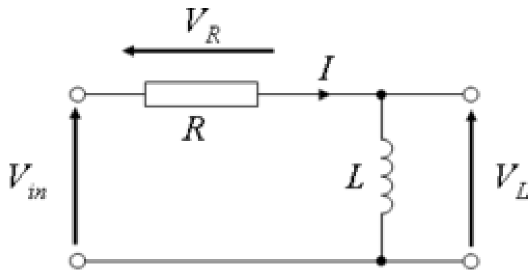


Figure 9.1: A series RL circuit driven by a step voltage.

Worked Example: RL time constant

A relay coil has $L = 200\,\mathrm{mH}$ and winding resistance $R = 50\,\Omega$. Find the time constant, and the time for current to reach 63.2% of its final value.
Solution. $\tau = L/R = 0.2/50 = 4\,\mathrm{ms}$. By definition, the current reaches 63.2% of its final value at exactly $t = \tau = 4\,\mathrm{ms}$.

9.4 Series RC and RL Circuits Under Sinusoidal AC

Under a sinusoidal (not step) drive, a series RC or RL network behaves as a frequency-dependent voltage divider between a real part (resistance) and an imaginary part (reactance). Using the complex impedances introduced in Chapters 7–8, the total impedance of a series RC network is

$$Z = R - jX_C, \qquad |Z| = \sqrt{R^2 + X_C^2}, \qquad \theta = -\arctan\left(\frac{X_C}{R}\right),$$

and of a series RL network,

$$Z = R + jX_L, \qquad |Z| = \sqrt{R^2 + X_L^2}, \qquad \theta = \arctan\left(\frac{X_L}{R}\right).$$

Here θ is the phase angle by which the total current lags (RL) or leads (RC) the applied voltage. Ohm's law generalizes directly to $U = IZ$, with U, I, and Z all treated as complex (magnitude and phase) quantities.

Worked Example: Series RC impedance

A $1\,\text{k}\Omega$ resistor is in series with a capacitor whose reactance at the operating frequency is $750\,\Omega$. Find the magnitude and phase angle of the total impedance.
Solution.

$$|Z| = \sqrt{1000^2 + 750^2} = \sqrt{1{,}000{,}000 + 562{,}500} \approx 1250\,\Omega,$$

$$\theta = -\arctan\left(\frac{750}{1000}\right) = -36.9^\circ.$$

The current leads the applied voltage by 36.9°.

9.5 RC and RL Circuits as Frequency-Selective Filters

Because X_C and X_L depend on frequency while R does not, a series RC or RL network divides voltage between its resistive and reactive parts differently at different frequencies — the basis of simple **filters**:

- An RC network, output taken across C, passes low frequencies and attenuates high frequencies (a **low-pass filter**): at low frequency X_C is large and most of the voltage appears across C; at high frequency $X_C \to 0$ and the output collapses.
- An RC network, output taken across R, does the opposite (a **high-pass filter**).
- An RL network, output taken across L, is a high-pass filter (at high frequency X_L dominates); output taken across R is a low-pass filter.

The frequency at which $X_C = R$ (RC) or $X_L = R$ (RL) is called the **cutoff (or corner) frequency** f_c, where the output power has fallen to half its low-frequency (or high-frequency) value, a $-3\,\text{dB}$ point in the language of Chapter 15:

$$f_c = \frac{1}{2\pi RC} \quad \text{(RC)}, \qquad f_c = \frac{R}{2\pi L} \quad \text{(RL)}.$$

These single-order RC/RL filters are gentle (attenuating at roughly 6 dB per octave beyond cutoff); sharper filtering requires combining reactive elements, covered next in Chapter 10.

Chapter Review

- RC time constant $\tau = RC$; RL time constant $\tau = L/R$; both in seconds when SI units are used.
- Charging/current-buildup: 63.2% of final value after one time constant; effectively complete after five time constants.
- Series impedance: $Z = R \mp jX$ (RC/RL), $|Z| = \sqrt{R^2 + X^2}$, phase $\theta = \arctan(X/R)$ (sign per RC or RL).
- RC/RL networks act as simple low-pass or high-pass filters depending on which element the output is taken across.
- Cutoff frequency f_c is where $X = R$; the response is down 3 dB (half power) at that point.

Practice Problems

1. An RC circuit has $R = 4.7\,\text{k}\Omega$ and $C = 10\,\mu\text{F}$. Find τ and the time to reach 99% of final charge.
2. Find the impedance magnitude and phase of a series RL circuit with $R = 220\,\Omega$ and $X_L = 330\,\Omega$.
3. Find the cutoff frequency of a low-pass RC filter with $R = 1\,\text{k}\Omega$ and $C = 470\,\text{pF}$.
4. A relay must fully release within 20 ms of power removal. If its coil resistance is $100\,\Omega$, what is the maximum inductance (assuming "fully released" means five time constants have elapsed)?
5. Explain, without equations, why an RC low-pass filter's output lags further and further behind the input as frequency increases.

Chapter 10

RLC Circuits, Resonance, and the Quality Factor

Combining an inductor and a capacitor in the same circuit produces one of the single most important phenomena in all of radio: **resonance**. Every tuned circuit, every antenna, every IF filter, and every transmitter's output network relies on the ideas in this chapter.

10.1 Why L and C Together Are Special

Recall from Chapters 7–8 that $X_C = 1/(\omega C)$ falls with frequency while $X_L = \omega L$ rises with frequency, and that they have opposite sign in complex impedance notation ($Z_C = -jX_C$, $Z_L = +jX_L$). This means there is always some frequency at which X_L and X_C are exactly equal in magnitude — and, because of their opposite signs, they *cancel* at that frequency. This special frequency is the circuit's **resonant frequency**, f_0.

10.2 Series Resonance

For a series RLC circuit, total impedance is

$$Z = R + j(X_L - X_C) = R + j\left(\omega L - \frac{1}{\omega C}\right).$$

At resonance, $X_L = X_C$, so the reactive part vanishes and $Z = R$ — the impedance is purely resistive and at its **minimum** possible value. This means current through a series RLC circuit is at its *maximum* at resonance, for a given applied voltage. Setting $X_L = X_C$ and solving for frequency gives the single most-used formula in RF circuit design:

$$\boxed{f_0 = \frac{1}{2\pi\sqrt{LC}}}$$

Worked Example: Resonant frequency

Find the resonant frequency of a 10 μH inductor and a 100 pF capacitor in series.
Solution.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{10 \times 10^{-6} \times 100 \times 10^{-12}}} \approx 5.03\,\text{MHz}.$$

Away from resonance, the series circuit's impedance rises (dominated by whichever reactance is larger), so current falls off on either side of f_0 — a series RLC circuit is inherently a **band-pass** response when current (or voltage across R) is the output of interest.

10.3 Parallel Resonance (the "Tank Circuit")

An inductor and capacitor in parallel (an **LC tank circuit**) show the complementary behavior. At resonance, the two branch currents (I_L through the inductor, I_C through the capacitor) are equal in magnitude and 180° out of phase, so they cancel in the external circuit — ideally, at resonance, a parallel LC combination draws *zero* net current from the source and presents an *infinite* impedance (limited in practice only by real-world losses, discussed below). This makes a parallel LC tank behave as a band-*reject* (notch) element as seen from outside, or, equivalently, as a very high-impedance load exactly at f_0 — the mechanism used to select one frequency in an oscillator or amplifier tank circuit while presenting low impedance to all other frequencies. The resonant frequency formula is identical: $f_0 = 1/(2\pi\sqrt{LC})$.

Key Idea: Energy exchange at resonance

At resonance, energy sloshes back and forth between the capacitor's electric field and the inductor's magnetic field every half-cycle, rather than being repeatedly drawn from (and returned to) the source. This is why a well-designed (low-loss) tank circuit, once excited, can "ring" at its resonant frequency for many cycles even with the drive removed — the same physical principle as a bell continuing to ring after being struck.

10.4 The Quality Factor, Q

Real inductors and capacitors have loss (mostly resistive: wire resistance, core loss, dielectric loss). The **quality factor** Q measures how "lossless" a resonant circuit is — the ratio of energy stored to energy dissipated per cycle:

$$Q = 2\pi \frac{\text{energy stored}}{\text{energy dissipated per cycle}}.$$

For a series RLC circuit,

$$\boxed{Q = \frac{X_L}{R} = \frac{X_C}{R} = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{2\pi f_0 L}{R}}$$

(evaluated at resonance, where $X_L = X_C$). For a parallel RLC circuit (loss modeled as a resistance in parallel with the tank),

$$Q = \frac{R}{X_L} = R\sqrt{\frac{C}{L}}.$$

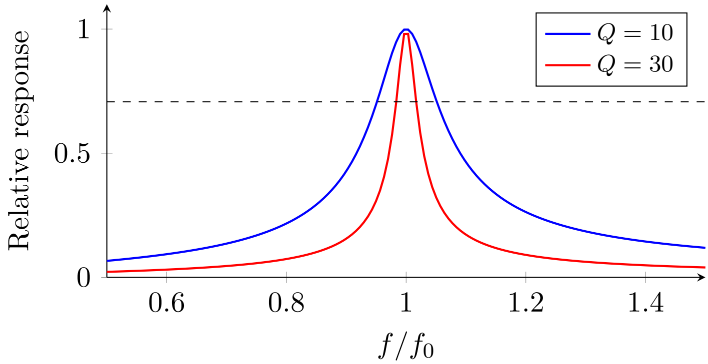
Key Idea: What Q buys you

A **high-Q** circuit has a narrow, sharply peaked resonance — excellent selectivity (able to separate closely spaced signals) but also unforgiving of small component drift and lossier to build. A **low-Q** circuit has a broad, gentle resonance — easier to build and more tolerant of component tolerance, but poorer at rejecting nearby unwanted signals. Receiver IF filters favor high Q; broadband matching networks often favor deliberately lower Q.

10.5 Bandwidth and the Resonance Curve

Q directly sets the **bandwidth** B of the resonance — the range of frequencies over which the response stays within 3 dB (half-power) of its peak value:

$$\boxed{B = \frac{f_0}{Q}}$$



Worked Example: Bandwidth from Q

A series-tuned circuit resonates at 7.1 MHz with $L = 2.5\,\mu$H, $C = 200$ pF, and series resistance $R = 3\,\Omega$. Find Q and the bandwidth.
Solution.

$$X_L = 2\pi f_0 L = 2\pi \times 7.1 \times 10^6 \times 2.5 \times 10^{-6} \approx 111.5\,\Omega,$$

$$Q = \frac{X_L}{R} = \frac{111.5}{3} \approx 37.2, \qquad B = \frac{f_0}{Q} = \frac{7.1\,\text{MHz}}{37.2} \approx 191\,\text{kHz}.$$

10.6 Applications of Resonance in Radio

- **Receiver front-end and IF selectivity**: tuned circuits select the wanted signal and reject adjacent ones (Chapter 16).
- **Transmitter output (tank) circuits**: convert an amplifying device's output into a clean sinusoidal RF signal while suppressing harmonics.
- **Antenna tuning units**: use variable L and C to present a resonant, well-matched impedance to a transmitter (Chapter 19).
- **Oscillators**: an LC tank sets the operating frequency of many RF oscillator designs.
- **Filters**: cascading multiple resonant sections builds the band-pass, low-pass, and high-pass filters used throughout receivers and transmitters (Chapter 18 and Chapter 16).

Chapter Review

- Resonance occurs where $X_L = X_C$; $f_0 = 1/(2\pi\sqrt{LC})$ for both series and parallel RLC circuits.
- Series resonance: minimum impedance, maximum current (band-pass behavior for current/output-across-R).
- Parallel resonance (tank): maximum impedance, minimum line current (band-reject as seen from outside; selects one frequency in a tank application).
- $Q = X/R$ at resonance; higher Q means narrower bandwidth, $B = f_0/Q$, and better selectivity but less tolerance and more loss sensitivity.

Practice Problems

1. Find the resonant frequency of $L = 4\,\mu\text{H}$, $C = 68\,\text{pF}$.
2. A parallel tank has $R = 10\,\text{k}\Omega$ (representing loss), $L = 1\,\mu\text{H}$, $C = 400\,\text{pF}$. Find f_0 and Q.
3. A series-tuned circuit has $Q = 50$ at $f_0 = 14.1\,\text{MHz}$. Find its bandwidth.
4. Explain why a high-Q circuit is more sensitive to small component value changes than a low-Q circuit.
5. A receiver needs to separate two signals 5 kHz apart at 7.05 MHz. Estimate the minimum Q needed for a single resonant circuit to provide meaningful separation (bandwidth on the order of the spacing).

Chapter 11

Transformers

11.1 Mutual Inductance and Transformer Action

A **transformer** consists of two (or more) coils — a **primary** and a **secondary** — wound so that they share a common magnetic flux, usually by winding both around the same core. A changing current in the primary produces a changing flux (Faraday's law, Chapter 4); that changing flux links the secondary winding and induces an EMF there. No direct electrical (galvanic) connection is required between primary and secondary — energy is transferred entirely through the shared magnetic field, which is why transformers are the standard way to provide **galvanic isolation**, in addition to voltage or impedance transformation.

11.2 The Ideal Transformer Equations

For an ideal transformer (no losses, all flux shared between windings), the ratio of secondary to primary voltage equals the ratio of secondary to primary turns, the **turns ratio**:

$$\boxed{\frac{U_2}{U_1} = \frac{N_2}{N_1} = n}$$

Conservation of power ($U_1 I_1 = U_2 I_2$ for an ideal, lossless transformer) then requires current to transform in the *inverse* ratio:

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} = \frac{1}{n}.$$

A **step-up** transformer ($N_2 > N_1$) raises voltage and lowers current; a **step-down** transformer ($N_2 < N_1$) does the opposite. Neither creates or destroys energy — power in equals power out for an ideal transformer.

Worked Example: Turns ratio

A transformer has 1000 turns on the primary and 50 turns on the secondary, with 230 V RMS applied to the primary. Find the secondary voltage, and the secondary current if the load draws 2 A on the primary side.
Solution. Turns ratio $n = 50/1000 = 0.05$, so $U_2 = 230 \times 0.05 = 11.5\,\text{V}$. Current transforms inversely: $I_2 = I_1/n = 2/0.05 = 40\,\text{A}$.

11.3 Impedance Transformation

Because a transformer changes the voltage-to-current ratio, it also changes the *impedance* seen looking into the primary for a given load impedance Z_2 on the secondary:

$$\boxed{Z_1 = n^2 Z_2}$$

This impedance-transforming property is exploited constantly in RF work: audio output transformers match a low-impedance speaker to a higher-impedance amplifier stage, and RF transformers (including **ferrite-core broadband transformers** wound with twisted or bifilar wire) match a transmitter's output impedance to an antenna system, or match one stage's impedance to the next, without the narrowband limitation of an LC matching network.

Worked Example: Impedance matching

Find the turns ratio needed to match a 50 Ω source to an 800 Ω load.
Solution. Require $Z_1 = n^2 Z_2 \Rightarrow n = \sqrt{Z_1/Z_2} = \sqrt{50/800} = \sqrt{1/16} = 0.25 =$ 1:4. A turns ratio of 1:4 (primary:secondary) steps the 800 Ω load down to an apparent 50 Ω at the primary.

11.4 Real Transformers: Losses and Efficiency

Real transformers depart from the ideal model in several ways:

- **Copper losses**: $I^2 R$ heating in the winding resistance, worse at high current (heavy secondary loading).
- **Core losses**: hysteresis loss (energy needed to repeatedly reverse the core material's magnetic domains) and eddy-current loss (circulating currents induced within the core itself), both of which increase with frequency — one

reason mains-frequency (50/60 Hz) power transformer cores cannot simply be reused, unmodified, at radio frequencies.

- **Leakage inductance**: flux produced by one winding that does *not* link the other winding, behaving as an unwanted series inductance.
- **Winding capacitance**: parasitic capacitance between turns and between windings, which becomes significant at high frequency.

Efficiency is defined the same way as for any energy-conversion device:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%.$$

Well-designed power transformers commonly exceed 95% efficiency at rated load; efficiency generally drops at light load (core losses become a larger fraction of a small output) and at heavy overload (copper losses dominate and the core may begin to saturate).

11.5 Autotransformers

An **autotransformer** uses a single tapped winding rather than electrically separate primary and secondary windings. It is smaller, cheaper, and more efficient than an equivalent two-winding transformer for a given power rating, but sacrifices galvanic isolation between input and output — an important safety distinction from a conventional isolation transformer. Variable autotransformers (e.g., the classic “Variac”-type device) are commonly used on the test bench to control AC line voltage.

11.6 RF Transformers and Baluns

At radio frequencies, transformers are frequently wound on ferrite toroid or binocular cores using twisted-pair or bifilar windings to achieve tight coupling (high efficiency) over a wide bandwidth. A particularly important RF application is the **balun** (“balanced-to-unbalanced” transformer), used to connect an unbalanced coaxial feedline to a balanced antenna element such as a dipole (Chapter 20) without upsetting the antenna’s current balance — a common source of feedline radiation and RF-in-the-shack problems if omitted or poorly chosen. A related device, the **unun** (“unbalanced-to-unbalanced”), transforms impedance between two unbalanced points, commonly used to match a random-wire or end-fed antenna to a 50 Ω coaxial feedline.

Chapter Review

- Transformer action relies on mutual inductance: a changing primary current induces an EMF in a magnetically coupled secondary.
- $U_2/U_1 = N_2/N_1 = n$; current transforms inversely, $I_2/I_1 = 1/n$; ideal power in equals power out.
- Impedance transforms as $Z_1 = n^2 Z_2$ — the basis of transformer impedance matching.
- Real transformers have copper loss, core loss (hysteresis and eddy current), leakage inductance, and winding capacitance, all limiting efficiency and bandwidth.
- RF baluns and ununs are specialized transformers for connecting balanced/unbalanced feedlines and antennas without disturbing current balance.

Practice Problems

1. A transformer steps 120 V down to 12 V. If the primary turns count is 600, find the secondary turns count.
2. Find the primary current if the secondary of the above transformer delivers 3 A to a load (assume ideal, lossless transformer).
3. Find the turns ratio needed to match a 50 Ω transmitter output to a 200 Ω antenna feedpoint impedance.
4. A transformer delivers 90 W output while consuming 100 W input. Find its efficiency, and name two loss mechanisms that could account for the difference.
5. Explain why a balun is typically used where a coaxial feedline connects to a dipole antenna, in terms of balanced vs. unbalanced currents.

Chapter 12

Power Sources and Batteries

12.1 Ideal and Real Sources

An **ideal voltage source** maintains a fixed voltage regardless of load current; an **ideal current source** maintains a fixed current regardless of load voltage. Real sources (batteries, power supplies, generators) approximate the ideal voltage source but have a small **internal resistance** R_{int} in series, which causes the terminal voltage to sag under load:

$$\boxed{U_{\text{terminal}} = \text{EMF} - IR_{\text{int}}}$$

This single equation explains why a weak or discharged battery's voltage recovers somewhat when a load is removed (the IR_{int} drop disappears) and why a heavily loaded supply's voltage is lower than its open-circuit (no-load) rating.

Worked Example: Voltage sag under load

A 12 V battery with internal resistance 0.2 Ω supplies 8 A to a transceiver. Find the terminal voltage.

Solution.

$$U_{\text{terminal}} = 12 - (8 \times 0.2) = 12 - 1.6 = 10.4\,\text{V}.$$

This sag is one reason mobile/portable radio equipment often specifies a minimum operating voltage below the nominal 12 V or 13.8 V rating.

12.2 Maximum Power Transfer

For a source with fixed internal resistance R_{int} driving a variable load R_L, the power delivered *to the load* is maximized when $R_L = R_{\text{int}}$ (the **maximum power transfer theorem**) — at that point exactly half the source's total generated power is delivered to the load and half is dissipated internally, so this condition maximizes load power but not overall efficiency. This principle underlies impedance-matching practice throughout RF systems (Chapter 19): matching source and load impedance maximizes power transfer, though in power-supply and battery contexts, efficiency (minimizing R_{int} relative to the load) is usually the more relevant goal instead.

12.3 Cells and Batteries

A single electrochemical **cell** converts stored chemical energy into electrical energy; a **battery** is one or more cells combined (in series for higher voltage, in parallel for higher capacity, or both).

Chemistry	Cell V	Rechg.?	Energy density	Notes
Alkaline (Zn-MnO_2)	1.5 V	No	Low	Cheap, common, poor at high current
NiMH	1.2 V	Yes	Moderate	Low self-discharge (LSD) types common
Lead-acid	2.0 V/cell	Yes	Low–mod.	High current capable; heavy
Li-ion	3.6–3.7 V	Yes	High	Requires protection circuitry
$LiFePO_4$	3.2 V	Yes	High	Safer chemistry, flatter discharge curve

12.3.1 Series and Parallel Battery Combinations

Key Idea

Cells in series add voltage; capacity (in amp-hours) stays the same as a single cell. **Cells in parallel** add capacity; voltage stays the same as a single cell. A common 12 V lead-acid battery is internally six 2 V cells in series.

Safety: Mixing cells

Never combine cells of different chemistry, capacity, or state of charge in the same series or parallel string. Mismatched cells can be forced into reverse charge, over-discharge, or unequal current sharing, any of which can cause overheating, venting, or fire — especially with lithium-based chemistries, which additionally require dedicated protection/balancing circuitry in multi-cell packs.

12.4 Amp-Hour Capacity and Runtime

Battery capacity is rated in **amp-hours (Ah)** or milliamp-hours (mAh) — a direct application of $Q = It$ from Chapter 2, expressed with t in hours instead of seconds. Approximate runtime for a given load current is

$$t \approx \frac{\text{Capacity (Ah)}}{I_{\text{load}}(\text{A})}$$

(approximate because usable capacity typically falls at high discharge current, a behavior described empirically by **Peukert's law** for lead-acid batteries, and because most chemistries should not be discharged to 0% without damage or reduced cycle life).

Worked Example: Estimating runtime

A handheld transceiver draws 300 mA average on receive and is powered by a 2000 mAh battery. Estimate the receive-only runtime.

Solution.

$$t \approx \frac{2000\,\text{mAh}}{300\,\text{mA}} \approx 6.7\,\text{hours.}$$

Real-world runtime will be shorter due to periods of transmit current (much higher than receive current) and capacity derating at higher discharge rates.

Energy capacity in watt-hours (useful for comparing different battery voltages on an equal footing) is

$$W_h = \text{Ah} \times U_{\text{nominal}}.$$

12.5 Charging Considerations

Different chemistries require different charge algorithms (constant current then constant voltage for Li-ion; different profiles for NiMH and lead-acid), and using the wrong charger or charge rate can permanently damage capacity, or in the case of lithium chemistries, create a serious fire hazard. **C-rate** notation describes charge or discharge current relative to capacity: a "1C" rate for a 2 Ah battery is 2 A; a "0.5C" rate is 1 A.

12.6 DC Power Supplies

A mains-powered DC **power supply** typically consists of a transformer (Chapter 11) to change AC mains voltage to a convenient level, a rectifier (diodes, Chapter 13) to convert AC to pulsating DC, a filter capacitor to smooth the pulsations into a nearly steady DC voltage, and a voltage regulator to hold the output constant despite input ripple and load changes. A **linear regulator** dissipates the voltage difference between input and output as heat (simple, low-noise, but inefficient at large voltage drops); a **switching regulator** rapidly switches a storage inductor or capacitor to convert voltage with much higher efficiency, at the cost of potential RF noise/interference that must be filtered — a genuine concern for a radio amateur choosing a supply to sit next to a sensitive receiver.

Chapter Review

- Real sources sag under load: $U_{\text{terminal}} = \text{EMF} - IR_{\text{int}}$.
- Maximum power transfer occurs when load resistance equals source internal resistance.
- Series cells add voltage; parallel cells add capacity; never mix chemistries, capacities, or states of charge in a pack.
- Capacity (Ah) combined with load current gives approximate runtime, $t \approx \text{Ah}/I$; watt-hours allow comparison across voltages.
- Linear regulators are simple and quiet but lossy; switching regulators are efficient but can generate RF interference.

Practice Problems

1. A power supply has an open-circuit voltage of 13.8 V and internal resistance 0.05 Ω. Find the terminal voltage at a 20 A load.
2. Four 1.2 V, 2000 mAh NiMH cells are connected in series. Find the resulting pack voltage and capacity.
3. Estimate the runtime of a 7 Ah battery supplying a constant 1.4 A load.
4. Explain, using $Q = It$, why amp-hours (not just amps) are the correct way to compare battery "size."
5. A radio amateur reports RF hash/noise across several bands after switching from a linear to a switching power supply. Explain a likely cause and one practical mitigation.

Part III

Active Devices and RF Systems

Chapter 13

Semiconductors, Diodes, and Transistors

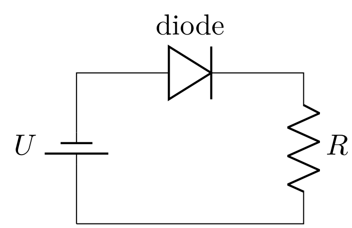
13.1 Doping and the p-n Junction

Pure (**intrinsic**) silicon is a poor conductor. Deliberately introducing trace impurities (**doping**) transforms its conductivity in a controllable way: adding an element with one more valence electron than silicon (phosphorus, arsenic) creates **n-type** material with an excess of free electrons; adding an element with one fewer valence electron (boron) creates **p-type** material with an excess of "holes" (missing-electron sites that behave as mobile positive charge carriers).

Where p-type and n-type materials meet, a **p-n junction** forms. Electrons and holes diffuse across the junction and recombine near the boundary, leaving a thin **depletion region** depleted of free carriers and building a small internal electric field that opposes further diffusion. This junction is the foundation of essentially every semiconductor device in electronics.

13.2 The Diode

A **diode** is a single p-n junction packaged with two terminals, the **anode** (p-side) and **cathode** (n-side). It conducts current easily in one direction (**forward bias**, anode positive relative to cathode) once the applied voltage exceeds a threshold — about 0.6–0.7 V for silicon, 0.2–0.3 V for germanium, and roughly 1.8–3.3 V (varying by color/wavelength) for light-emitting diodes — and blocks current almost completely in the opposite direction (**reverse bias**), up to a maximum reverse voltage rating beyond which it breaks down.



13.2.1 Diode Types and RF/Amateur Applications

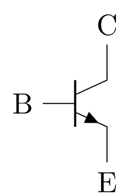
- **Rectifier diodes**: convert AC to pulsating DC in power supplies (Chapter 12).
- **Zener diodes**: designed to operate safely in reverse breakdown at a well-defined voltage, used as simple voltage references or shunt regulators.
- **Varactor (varicap) diodes**: reverse-biased junction capacitance varies with applied voltage, used for electronic tuning in VFOs and PLL synthesizers.
- **Schottky diodes**: metal-semiconductor junction with a lower forward voltage drop and much faster switching than a standard silicon junction diode, widely used in RF detectors and mixers.
- **PIN diodes**: behave as a variable resistor at RF when forward-biased with varying DC current, used as RF switches and attenuators (e.g., for T/R switching).
- **Light-emitting diodes (LEDs)**: emit light when forward biased, used for indicators and, in laser diode form, for optical communication experiments.

13.3 Bipolar Junction Transistors (BJTs)

A **bipolar junction transistor** adds a second junction, forming either an **NPN** or **PNP** sandwich of doped regions — **emitter**, **base**, and **collector**. A BJT is a **current-controlled current source**: a small current flowing into the base controls a much larger current flowing from collector to emitter (NPN), with the ratio between them called **current gain**, β (or h_{FE}):

$$\boxed{I_C = \beta I_B}, \qquad I_E = I_B + I_C.$$

Typical small-signal transistors have β in the range of roughly 50–300. This current-controlled amplification is the basic mechanism behind BJT amplifier and switching circuits.



13.3.1 Common Amplifier Configurations

- **Common-emitter**: input at base, output at collector, emitter grounded (often through a small resistor). High voltage and current gain, inverts the signal (180° phase shift), moderate input/output impedance — the most common general-purpose amplifier configuration.
- **Common-base**: input at emitter, output at collector, base grounded (at AC). Low input impedance, high output impedance, no phase inversion, good high-frequency performance — often used in RF amplifier and mixer stages.
- **Common-collector** (**emitter follower**): input at base, output at emitter, collector grounded (at AC). Voltage gain near unity, but high current gain and impedance transformation (high input impedance, low output impedance) — widely used as a buffer stage.

13.4 Field-Effect Transistors (FETs)

A **field-effect transistor** is a **voltage-controlled current source**: a voltage applied to the **gate** controls current flowing between **drain** and **source**, with (ideally) no gate current at all — giving FETs an extremely high input impedance, in contrast to the current-driven BJT.

- **JFET** (junction FET): gate forms a reverse-biased junction with the channel; normally "on," with gate voltage used to pinch the channel off.
- **MOSFET** (metal-oxide-semiconductor FET): gate is insulated from the channel by a thin oxide layer, giving even higher input impedance than a JFET; available in **enhancement mode** (normally off, turned on by gate voltage — the dominant type in digital logic and switching power supplies) and **depletion mode** (normally on).

MOSFETs, particularly power MOSFETs, are widely used in RF power amplifiers and switching applications for amateur equipment because of their high input impedance, ease of biasing, and good high-frequency switching behavior.

Safety: Static sensitivity

MOSFET gates are separated from the channel by an extremely thin insulating layer that can be punctured by static discharge well below the voltage a person can even feel. Handle MOSFETs and other static-sensitive devices using proper ESD precautions (grounded workstation, anti-static packaging) until they are soldered into a circuit.

13.5 The Transistor as a Switch

Beyond linear amplification, both BJTs and FETs are used as electronic **switches**: driven fully "on" (**saturation** for a BJT, low on-resistance for a MOSFET) or fully "off" (**cutoff**), a transistor can control power to a load (a relay, a keying line, a transmitter's PTT circuit) with a small control signal, forming the building block of digital logic gates and switch-mode power circuits.

13.6 Integrated Circuits

An **integrated circuit (IC)** fabricates many transistors (from a handful to billions), along with diodes, resistors, and sometimes small capacitors, on a single piece of semiconductor material. This allows complex functions — operational amplifiers (Chapter 14), digital logic, microcontrollers, RF mixers, phase-locked loop synthesizers, and entire radio transceivers — to be built far more compactly, reliably, and cheaply than from discrete components, and underlies essentially all modern amateur radio equipment design.

Chapter Review

- Doping creates n-type (excess electrons) and p-type (excess holes) semiconductor material; a p-n junction is the basic building block.
- Diodes conduct in one direction above a forward-voltage threshold and block in reverse, up to a breakdown limit; many specialized diode types (Zener, varactor, Schottky, PIN, LED) exploit particular junction behaviors.
- BJTs are current-controlled ($I_C = \beta I_B$); FETs are voltage-controlled with very high input impedance.
- Common-emitter, common-base, and common-collector configurations trade off gain, impedance, and phase behavior differently.
- Transistors are used both as linear amplifiers and as switches; ICs integrate many transistors and other components on one chip.

Practice Problems

1. A BJT has $\beta = 100$ and $I_B = 50\,\mu\text{A}$. Find I_C and I_E.
2. Explain why a MOSFET's gate current is essentially zero in normal operation, in terms of its construction.

3. Name one diode type suited to (a) voltage regulation, (b) electronic tuning, (c) fast RF detection, and briefly justify each choice.
4. Explain why an emitter-follower stage, despite having voltage gain near 1, is still a useful amplifier configuration.
5. A technician reports a MOSFET failed immediately upon handling before installation, with no circuit fault found. Suggest a likely cause and a preventive measure.

Chapter 14

Operational Amplifiers

14.1 The Ideal Op-Amp

An **operational amplifier (op-amp)** is a high-gain differential voltage amplifier IC, so widely used as a building block that it is treated as a component in its own right rather than analyzed transistor-by-transistor. It has two inputs — the **non-inverting input** (+) and the **inverting input** (−) — and one output, and amplifies the *difference* between its two inputs by an enormous open-loop gain (typically 10^5 or more).

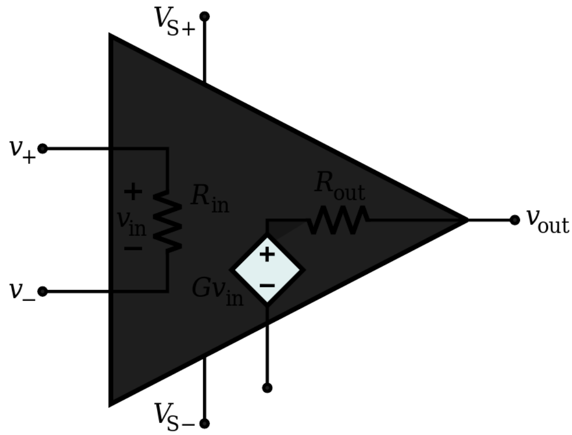


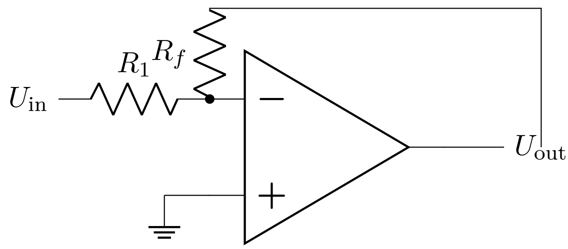
Figure 14.1: A simplified internal structure of an operational amplifier: differential input stage, gain stage, and output stage.

Key Idea: The two golden rules of ideal op-amp analysis

When an op-amp is used with **negative feedback** (a path from the output back to the inverting input), two simplifying assumptions make hand analysis of nearly any op-amp circuit tractable:

1. **No current flows into either input** (the inputs have essentially infinite impedance).
2. **The output adjusts itself so that the voltage difference between the two inputs is zero** (“virtual short”), provided the feedback loop is intact and the output is not saturated.

14.2 The Inverting Amplifier



With the input applied through R_1 to the inverting input and feedback resistor R_f from output back to that same node, the “virtual short” rule forces the inverting input to sit at 0 V (since the non-inverting input is grounded), so the same current flows through R_1 and R_f. The result is the widely used **inverting amplifier** gain formula:

$$\boxed{A_v = \frac{U_{\text{out}}}{U_{\text{in}}} = -\frac{R_f}{R_1}}$$

The negative sign indicates 180° phase inversion. Gain is set purely by the ratio of two resistors, independent (to a good approximation) of the op-amp’s own large and imprecisely specified open-loop gain — the central practical benefit of negative feedback.

Worked Example: Inverting amplifier gain

$R_1 = 10\,\mathrm{k\Omega}$, $R_f = 100\,\mathrm{k\Omega}$. Find the gain, and the output voltage for a $-0.2\,\mathrm{V}$ input.

Solution.

$$A_v = -\frac{R_f}{R_1} = -\frac{100}{10} = -10, \qquad U_{\text{out}} = A_v \times U_{\text{in}} = -10 \times (-0.2) = 2\,\mathrm{V}.$$

14.3 The Non-Inverting Amplifier

Applying the input directly to the non-inverting input, with a feedback network (R_f and R_1 to ground) setting the inverting input to a fraction of the output, gives:

$$\boxed{A_v = 1 + \frac{R_f}{R_1}}$$

Gain is always ≥ 1 and the output is *in phase* with the input (no inversion). Setting $R_f = 0$ (or removing it and connecting output directly to the inverting input) gives $A_v = 1$: the **voltage follower** (buffer), used purely for its extremely high input impedance and low output impedance, without adding voltage gain.

14.4 Other Common Op-Amp Circuits

- **Summing amplifier**: multiple input resistors into the inverting node combine several input voltages with individually weighted gains, output being the (inverted, scaled) sum — used in audio mixing and analog computation.
- **Differential amplifier**: amplifies the difference between two input signals while rejecting any voltage common to both (**common-mode rejection**) — useful for extracting a small signal riding on a larger common noise voltage.
- **Integrator / differentiator**: replacing a resistor with a capacitor in the feedback or input path produces a circuit whose output is proportional to the time-integral or time-derivative of the input, used in filter, waveform-shaping, and control applications.
- **Active filters**: op-amps combined with RC networks implement precise low-pass, high-pass, and band-pass filters (audio CW and SSB filtering in receivers is a direct amateur radio application) without the bulky inductors that a purely passive filter would need at audio frequencies.

- **Comparator**: an op-amp used without negative feedback (or with positive feedback for hysteresis) simply drives its output to one supply rail or the other depending on which input is higher — used for squelch circuits, threshold detection, and simple ADC building blocks.

14.5 Real Op-Amp Limitations

- **Finite open-loop gain and bandwidth**: gain is not literally infinite, and it falls off with frequency (the **gain-bandwidth product**, GBW, is a key datasheet specification — a 1 MHz GBW device configured for a gain of 100 will only be usable up to roughly 10 kHz).
- **Slew rate**: a maximum rate of change the output can follow, in V/μs — limits large-signal high-frequency performance even within the small-signal bandwidth.
- **Input offset voltage and bias current**: small imperfections that cause a nonzero output even with both inputs grounded, of particular concern in high-precision or high-gain DC applications.
- **Output swing and current limits**: the output cannot exceed the supply rails (often not quite reaching them either, unless the device is specifically a "rail-to-rail" design) and can only supply a limited current before distorting or current-limiting.

Standard general-purpose op-amps (with gain-bandwidth products in the single-digit MHz) are used extensively in amateur radio audio stages — receiver audio filtering, AGC (automatic gain control) generation, CW sidetone oscillators, and microphone amplifiers — but are generally unsuitable as direct RF amplifiers at HF and above without specialized high-speed devices, for which dedicated RF amplifier ICs or discrete transistor stages (Chapter 13) are typically used instead.

Chapter Review

- Ideal op-amp analysis: no current into either input; feedback forces the two inputs to the same voltage (virtual short).
- Inverting amplifier: $A_v = -R_f/R_1$ (inverted, gain set by resistor ratio).
- Non-inverting amplifier: $A_v = 1 + R_f/R_1$ (in phase, gain ≥ 1); $R_f = 0$ gives a unity-gain buffer.
- Summing, differential, integrator/differentiator, active filter, and comparator circuits all build on the same two golden rules.

- Real op-amps have finite gain-bandwidth product, slew rate, offset errors, and output swing/current limits.

Practice Problems

1. Design an inverting amplifier with gain -20 using $R_1 = 1\,\mathrm{k\Omega}$; find the required R_f.
2. A non-inverting amplifier uses $R_1 = 2\,\mathrm{k\Omega}$, $R_f = 18\,\mathrm{k\Omega}$. Find the gain and the output for a $0.1\,\mathrm{V}$ input.
3. An op-amp has a gain-bandwidth product of $3\,\mathrm{MHz}$. Estimate the maximum usable frequency at a closed-loop gain of 50.
4. Explain, using the golden rules, why the inverting input of an inverting amplifier is called a "virtual ground" even though it is not physically connected to ground.
5. Explain why a voltage-follower (buffer) stage is useful even though its voltage gain is only 1.

Chapter 15

Decibels, Gain, and Loss

15.1 Why Use a Logarithmic Unit?

A radio signal chain often includes many stages, each multiplying power by some factor: an antenna's gain, a length of feedline's loss, a preamplifier's gain, a filter's loss, a receiver's sensitivity. Multiplying many such ratios together by hand is tedious and error-prone; expressed logarithmically (Chapter 1), those same ratios simply *add*. This is the entire motivation for the **decibel (dB)**, one-tenth of a **bel** (named for Alexander Graham Bell), and the single most-used unit in RF system-level work.

15.2 Defining the Decibel

For **power** ratios,

$$\boxed{dB = 10\log_{10}\left(\frac{P_2}{P_1}\right)}$$

For **voltage** (or current) ratios measured across the *same* impedance, since power is proportional to voltage squared ($P = U^2/R$), the factor of 2 from squaring moves in front of the log:

$$\boxed{dB = 20\log_{10}\left(\frac{U_2}{U_1}\right)}$$

Key Idea: Values worth memorizing

Ratio	Power (dB)	Voltage (dB)
$\times 1$	0 dB	0 dB
$\times 2$	3 dB	6 dB
$\times 4$	6 dB	12 dB
$\times 10$	10 dB	20 dB
$\times 100$	20 dB	40 dB
$\div 2$	-3 dB	-6 dB
$\div 10$	-10 dB	-20 dB

"3 dB" meaning a doubling (or, negative, a halving) *of power* is one of the most exam-relevant and practically useful facts in this entire book — it is the basis for the -3 dB (half-power) bandwidth points used to define filter and resonance bandwidth (Chapter 10).

Worked Example: Cascaded gains and losses

A signal passes through a preamplifier (+12 dB), a length of coaxial cable (-2 dB), and a filter (-1.5 dB). Find the net gain or loss.
Solution. Because decibels represent logarithms of ratios, they simply add along a cascade:

$$12 + (-2) + (-1.5) = 8.5\,\text{dB (net gain)}.$$

Multiplying the equivalent linear power ratios directly ($10^{1.2} \times 10^{-0.2} \times 10^{-0.15} \approx 15.85 \times 0.631 \times 0.708 \approx 7.08$, i.e. $10 \log_{10}(7.08) \approx 8.5$ dB) confirms the same result — but the addition is far faster.

15.3 Converting Between dB and Linear Ratios

To go the other direction, from a dB value back to a plain ratio:

$$\frac{P_2}{P_1} = 10^{(dB/10)}, \qquad \frac{U_2}{U_1} = 10^{(dB/20)}.$$

Worked Example: dB to linear

An amplifier is specified with 20 dB of gain. Find the power ratio and the voltage ratio it represents.
Solution.

$$\frac{P_2}{P_1} = 10^{20/10} = 10^2 = 100, \qquad \frac{U_2}{U_1} = 10^{20/20} = 10^1 = 10.$$

15.4 Absolute Levels: dBm, dBW, and dBi

The decibel itself is always a *ratio* (dimensionless); appending a reference to the unit turns it into an absolute level:

- **dBm**: power relative to 1 milliwatt.

$$P(\text{dBm}) = 10 \log_{10}\left(\frac{P(\text{mW})}{1\,\text{mW}}\right).$$

  0 dBm = 1 mW; 30 dBm = 1 W; 60 dBm = 1 kW. dBm is the standard unit for receiver sensitivity specifications, signal levels at a mixer or amplifier input, and RF test equipment readouts.

- **dBW**: power relative to 1 watt; 0 dBW = 30 dBm, used for higher-power figures such as transmitter output or effective radiated power.
- **dBi**: antenna gain relative to a theoretical **isotropic radiator** (a point source radiating equally in all directions) — the standard way antenna gain is specified (Chapter 20).
- **dBd**: antenna gain relative to a reference half-wave dipole; dBi = dBd + 2.15, since a dipole itself has 2.15 dBi of gain over an isotropic radiator.

Worked Example: dBm arithmetic

A transmitter delivers 100 W to a feedline with 3 dB of loss, feeding an antenna with 6 dBi of gain. Find the effective radiated power (ERP, referenced to a dipole, or EIRP referenced to isotropic).
Solution. Convert 100 W to dBW: $10\log_{10}(100) = 20\,\text{dBW}$. Apply cascade addition:

$$20\,\text{dBW} - 3\,\text{dB} + 6\,\text{dBi} = 23\,\text{dBW (EIRP)}.$$

Converting back: $10^{23/10} \approx 200\,\text{W}$ EIRP — twice the transmitter's output power, because the antenna gain ($6\,\text{dB} \approx \times 4$) outweighs the feedline loss ($3\,\text{dB} \approx \div 2$).

15.5 Signal-to-Noise Ratio

Signal-to-noise ratio (SNR), expressed in dB, compares wanted signal power to unwanted noise power at the same point in a system:

$$\text{SNR (dB)} = 10\log_{10}\left(\frac{P_{\text{signal}}}{P_{\text{noise}}}\right).$$

SNR is the single most important figure of merit for whether a communication link will be intelligible; it reappears throughout Chapters 16 (receiver noise figure) and 21 (link budgets), and is a core concept behind digital mode weak-signal performance (Chapter 26).

Chapter Review

- Power ratio in dB: $10\log_{10}(P_2/P_1)$; voltage ratio in dB: $20\log_{10}(U_2/U_1)$.
- Cascaded gains/losses simply add in dB (versus multiplying as linear ratios).
- Memorize: $+3\,\text{dB} \approx \times 2$ power, $+10\,\text{dB} = \times 10$ power, $+6\,\text{dB} \approx \times 2$ voltage/current, $+20\,\text{dB} = \times 10$ voltage/current.
- dBm (ref. 1 mW), dBW (ref. 1 W), dBi (ref. isotropic antenna), dBd (ref. dipole, $=$ dBi $- 2.15$) are absolute levels built on the relative dB unit.
- SNR in dB compares signal to noise power and is the key determinant of link intelligibility.

Practice Problems

1. Convert a power ratio of 500 into dB.
2. Convert −6 dB into a linear voltage ratio.
3. A receiver preamplifier has 15 dB gain; a following filter has 2.5 dB loss. Find the net dB and the equivalent linear power ratio.
4. Convert 5 W to dBm.
5. An antenna is rated at 9 dBd. Express this gain in dBi.

Chapter 16

Receiver Architectures

A radio receiver's job is to select one wanted signal from among the enormous number of other signals and noise present at its antenna, convert it to a usable form, and produce audio (or digital data) with adequate signal-to-noise ratio and freedom from interference. This chapter surveys the major receiver architectures used from the earliest days of radio to the present.

16.1 Key Receiver Performance Concepts

- **Sensitivity**: the weakest signal a receiver can usefully detect, limited ultimately by internally generated noise (thermal noise in resistive elements and semiconductor devices), quantified by the receiver's **noise figure** (how much noisier the receiver is than an ideal noiseless one, in dB).
- **Selectivity**: the receiver's ability to reject signals on frequencies close to the wanted one, set largely by its filter bandwidth and shape (Chapter 10).
- **Dynamic range**: the span, in dB, between the weakest signal the receiver can detect and the strongest signal it can handle without unacceptable distortion (**overload** or **intermodulation distortion**, where two or more strong nearby signals mix together inside a nonlinear stage to create spurious "phantom" signals).
- **Image rejection**: the ability to reject an unwanted frequency that a mixing stage would otherwise convert to the same output frequency as the wanted signal (Section 16.4 below).

16.2 Tuned Radio Frequency (TRF) Receivers

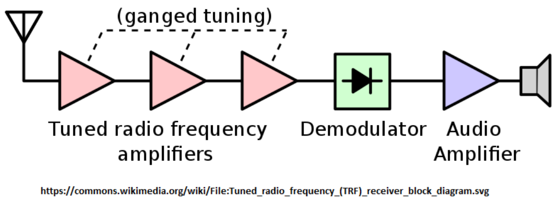


Figure 16.1: Block diagram of a tuned radio frequency (TRF) receiver.

The earliest practical receiver architecture amplifies the incoming signal directly at its original (radio) frequency through one or more stages of RF amplification, each individually tuned to the wanted frequency, before demodulating it. TRF receivers are conceptually simple but have a fundamental weakness: keeping several separate tuned stages aligned to exactly the same frequency as the operator tunes across the band is mechanically difficult, and selectivity (which depends on Q, Chapter 10) is hard to make uniformly good across a wide tuning range, since a fixed-Q circuit's absolute bandwidth changes with frequency.

16.3 Direct Conversion Receivers

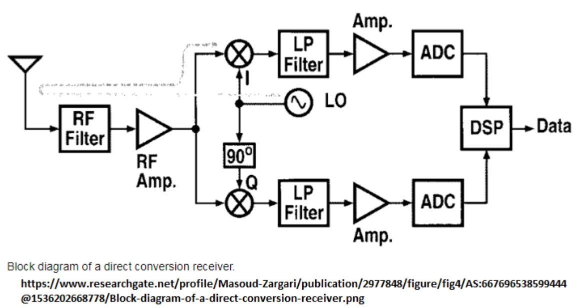


Figure 16.2: Block diagram of a direct conversion receiver.

A **direct conversion** receiver mixes the incoming RF signal directly with a local oscillator (LO) set to (nearly) the same frequency as the wanted signal, producing an output directly at audio frequency (the mixing process is developed fully in Chapter 17). This is simpler than a superheterodyne design (fewer stages, no

IF filter needed) and is popular in simple and homebrew equipment, but suffers from being susceptible to **audio-frequency image response** (signals above and below the LO frequency both fold into the same audio output, requiring phasing techniques to separate sidebands) and generally offers less overall selectivity than a well-designed superheterodyne.

16.4 The Superheterodyne Receiver

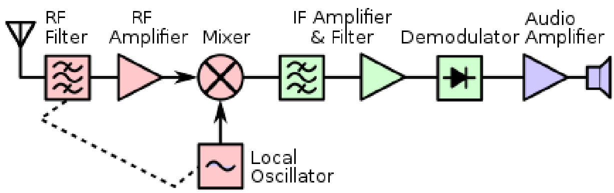


Figure 16.3: Block diagram of a superheterodyne receiver.

The **superheterodyne** ("superhet"), developed by Edwin Armstrong and still the dominant architecture (now often implemented digitally rather than with discrete analog stages), solves the TRF alignment problem by converting every incoming signal to a fixed **intermediate frequency (IF)**, regardless of the tuned frequency, using a mixer and a tunable local oscillator:

$$\boxed{f_{\text{IF}} = |f_{\text{signal}} - f_{\text{LO}}|}$$

Because the IF is fixed, the bulk of the receiver's gain and selectivity can be built once, at a single frequency, using well-optimized fixed-tuned filters (often crystal or ceramic filters) — giving consistently good, easily reproducible selectivity across the entire tuning range, the key advantage over a TRF design.

16.4.1 The Image Frequency Problem

Because the mixer output depends only on the *difference* between signal and LO frequency, *two* input frequencies produce the same IF output: the wanted signal at $f_{\text{LO}} + f_{\text{IF}}$ (or $f_{\text{LO}} - f_{\text{IF}}$) and an unwanted **image frequency** on the opposite side of the LO, offset by exactly $2f_{\text{IF}}$ from the wanted signal:

$$f_{\text{image}} = f_{\text{signal}} \pm 2f_{\text{IF}}.$$

Worked Example: Finding an image frequency

A receiver tuned to 14.200 MHz uses a 9.000 MHz IF and high-side injection ($f_{\mathrm{LO}} = f_{\mathrm{signal}} + f_{\mathrm{IF}} = 23.200$ MHz). Find the image frequency.
Solution.

$$f_{\mathrm{image}} = f_{\mathrm{LO}} + f_{\mathrm{IF}} = 23.200 + 9.000 = 32.200\,\mathrm{MHz}.$$

(Equivalently, $f_{\mathrm{signal}} + 2f_{\mathrm{IF}} = 14.200 + 18.000 = 32.200$ MHz.) A signal at 32.200 MHz, if not rejected before the mixer, would appear at the same 9.000 MHz IF as the wanted 14.200 MHz signal.

Key Idea: Fighting the image

Image rejection is provided by front-end filtering *before* the mixer. A *higher* IF pushes the image frequency further away from the wanted signal (easier to filter with a simple front-end filter), but makes it harder to build a narrow, high-selectivity IF filter at that higher frequency (Chapter 10: absolute bandwidth for a given Q grows with frequency). This trade-off is why many modern receivers use a high first IF for good image rejection, followed by conversion to a lower second IF for good adjacent-channel selectivity — a **dual (or multiple) conversion** superheterodyne.

16.5 The Superregenerative Receiver

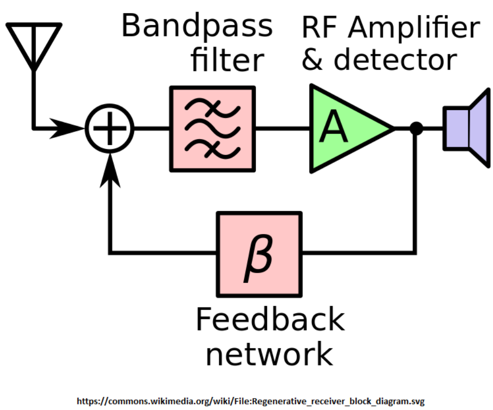


Figure 16.4: A simplified superregenerative detector.

A **superregenerative** receiver deliberately drives a single RF amplifier stage into and out of oscillation at a rapid (typically ultrasonic) rate, exploiting the huge effective gain available right at the threshold of oscillation to achieve remarkable sensitivity from a very small number of components. It trades selectivity and linearity for extreme simplicity and low cost, and remains common in inexpensive, short-range devices (some remote controls and simple telemetry receivers) despite being essentially obsolete for general-purpose amateur communication receivers.

16.6 Software-Defined Radio (SDR)

A **software-defined radio** performs some or all of the traditional analog stages — filtering, mixing, demodulation — in digital signal processing after an analog-to-digital converter (ADC) samples the incoming RF (or an early IF) directly. Modern amateur SDR receivers commonly use a **direct sampling** or **quadrature-sampling-detector (QSD)** front end feeding a general-purpose or dedicated digital signal processor, implementing all subsequent filtering, mixing, AGC, and demodulation as software algorithms rather than discrete analog circuit stages. This gives extraordinary flexibility (mode, bandwidth, and filter shape can be changed instantly in software) and, in modern designs, performance that matches or exceeds the best conventional analog superheterodynes, at the cost of requiring fast, high-dynamic-range ADCs and significant digital processing power. SDR concepts underlie most currently manufactured amateur transceivers, whether marketed as "SDR" or built with a more conventional-looking analog front panel.

16.7 Automatic Gain Control (AGC)

Because received signal strength can vary over many orders of magnitude (weak DX signals to strong local stations), nearly all practical receivers include **automatic gain control**: a feedback loop that senses the receiver's output level and automatically reduces gain for strong signals (and restores it for weak ones), keeping the audio output level roughly constant and protecting later stages from overload. AGC response speed (fast vs. slow "attack" and "release" times) is usually adjustable and matters for how comfortably different modes — CW, SSB voice, or the sudden noise bursts common on HF — sound to the operator.

Chapter Review

- Receiver quality is described by sensitivity (noise figure), selectivity, dynamic range, and image rejection.

- TRF receivers amplify directly at RF; hard to align across a wide tuning range.
- Direct conversion mixes straight to audio; simple, but prone to image response unless phasing techniques are used.
- Superheterodyne receivers convert every signal to a fixed IF for consistent selectivity; the trade-off is the image frequency, $f_{\text{image}} = f_{\text{signal}} \pm 2f_{\text{IF}}$.
- SDR performs filtering/demodulation digitally after early analog-to-digital conversion, offering great flexibility and, in modern designs, top-tier performance.
- AGC automatically adjusts receiver gain to keep output level manageable across widely varying signal strengths.

Practice Problems

1. A superhet uses a 455 kHz IF to receive 7.150 MHz with high-side injection. Find the LO frequency and the image frequency.
2. Explain why a higher IF improves image rejection but can worsen adjacent-channel selectivity for a fixed filter Q.
3. Explain, conceptually, why a direct conversion receiver needs a phasing technique to reject one sideband, while a superheterodyne typically does not for the same purpose.
4. A receiver's noise floor is -130 dBm and the strongest signal it can handle without unacceptable distortion is -10 dBm. Find its dynamic range in dB.
5. Explain, in your own words, one practical advantage SDR receivers have over fixed analog-filter superheterodynes.

Chapter 17

Modulation

A steady, unmodulated sine wave — a **carrier** — conveys no information beyond its own presence. **Modulation** is the process of varying some property of a carrier (its amplitude, frequency, or phase) in a way that encodes information, so it can be recovered at a receiver by the inverse process, **demodulation**.

17.1 Why Modulate at All?

Two practical facts force the use of modulation rather than transmitting audio (or data) directly: efficient radiation requires an antenna comparable in size to a wavelength (Chapter 20), and audio frequencies (tens of Hz to a few kHz) would need impossibly large antennas; and multiple simultaneous users need to occupy different parts of the spectrum without interfering, which is only possible if each signal is shifted to its own radio-frequency "slot."

17.2 Amplitude Modulation (AM)

In **amplitude modulation**, the carrier's amplitude is varied in proportion to the modulating (information) signal, while its frequency stays fixed:

$$v(t) = [V_c + V_m \sin(\omega_m t)] \sin(\omega_c t)$$

The ratio $m = V_m/V_c$ is the **modulation index** (or percentage, $\times 100\%$); $m = 1$ (100%) is the maximum before the envelope is driven to zero and distortion (**overmodulation**) begins.

Expanding the AM equation trigonometrically reveals that AM actually produces *three* components: the original carrier, plus two new frequencies — an **upper sideband (USB)** at $f_c + f_m$ and a **lower sideband (LSB)** at $f_c - f_m$:

$$v(t) = V_c \sin(\omega_c t) + \frac{mV_c}{2} \cos[(\omega_c - \omega_m)t] - \frac{mV_c}{2} \cos[(\omega_c + \omega_m)t] \,.$$

Key Idea: AM occupies twice the information bandwidth

Both sidebands carry the *same* information (each is a complete, redundant copy), and the carrier itself carries no information at all — yet standard AM transmits both sidebands plus the carrier, using roughly twice the bandwidth actually needed and wasting most of the transmitted power in the informationless carrier. This inefficiency is the direct motivation for single-sideband transmission, below.

17.3 Single-Sideband (SSB)

Single-sideband modulation removes the carrier (using a **balanced modulator**) and one of the two redundant sidebands (using a sharp filter or a phasing technique), transmitting only USB or LSB. This roughly halves the occupied bandwidth compared to full AM and concentrates all transmitted power into the one sideband that actually carries information, making SSB dramatically more efficient than AM for a given transmitter power — the reason SSB (not AM) is the dominant analog voice mode on amateur HF bands today. The receiver must supply its own locally generated carrier (a **beat frequency oscillator**, BFO, or product detector reference) to recover audio, and any error in that reconstructed carrier's frequency shifts the recovered audio pitch — the reason SSB signals sound garbled when a receiver is mistuned even slightly.

Exam Tip

By long-standing convention, most amateur voice operation uses lower sideband (LSB) below 10 MHz and upper sideband (USB) at 10 MHz and above. This is a convention, not a law of physics — either sideband can technically carry a voice signal — but following it is essential for interoperability with other stations.

17.4 Frequency Modulation (FM)

In **frequency modulation**, the carrier's *frequency* is varied in proportion to the modulating signal, while amplitude stays constant:

$$v(t) = V_c \sin[\omega_c t + \beta \sin(\omega_m t)]$$

where β is the **modulation index**, related to **deviation** Δf (the peak frequency shift from the carrier) by $\beta = \Delta f / f_m$. Because the information rides on frequency rather than amplitude, FM is largely immune to amplitude-varying noise and interference (most natural and man-made electrical noise is amplitude noise) — the **FM capture effect** and superior noise-rejection are why FM is preferred for local VHF/UHF voice repeater and simplex operation, at the cost of requiring more bandwidth than AM or SSB for a given audio quality (**Carson's rule** estimates occupied bandwidth as $B \approx 2(\Delta f + f_m)$).

17.5 Phase Modulation (PM)

Phase modulation varies the carrier's instantaneous phase in proportion to the modulating signal. PM and FM are closely related — mathematically, FM is what results from phase-modulating a carrier with the *integral* of the audio signal, and PM is what results from frequency-modulating a carrier with the *derivative* of the audio signal — and in practice many "FM" transmitters actually generate their signal using phase modulation of a crystal-referenced oscillator, which is easier to keep frequency-stable than direct FM of a free-running oscillator.

17.6 Digital Modulation Concepts

Digital modes (developed further in Chapter 26) apply the same three basic parameters — amplitude, frequency, phase — to a carrier, but switch between a finite set of discrete states rather than varying continuously:

- **On-off keying (OOK)**: the simplest digital amplitude modulation, the carrier is simply switched on and off — the basis of traditional CW (Morse code) transmission.
- **Frequency-shift keying (FSK)**: the carrier is switched between two (or more) discrete frequencies representing binary states — used by RTTY and many amateur digital modes.
- **Phase-shift keying (PSK)**: the carrier's phase is switched between discrete states (e.g., 0° and 180° for binary PSK) — used by PSK31 and as a building block within more complex modes.
- **Quadrature amplitude modulation (QAM)**: combines discrete amplitude *and* phase states to encode multiple bits per symbol, packing more data into the same bandwidth at the cost of requiring higher signal-to-noise ratio to distinguish the closely spaced states — used in modern high-data-rate digital modes.

17.7 Demodulation

Recovering the original information requires the inverse operation:

- **Envelope/diode detection**: rectifying and low-pass filtering an AM signal recovers its envelope (the original audio) — extremely simple, the basis of the classic "crystal set."
- **Product detection**: mixing the received signal with a locally generated reference at (or near) the carrier frequency, then low-pass filtering, recovers audio from SSB and CW signals; this is the receive-side counterpart of the balanced modulator used to generate SSB.
- **FM discrimination**: circuits (classically, a frequency-to-voltage converter such as a ratio detector or quadrature detector; in modern receivers, often a digital phase-locked loop or DSP algorithm) that convert instantaneous frequency deviation directly into an output voltage proportional to the original modulating signal.

Chapter Review

- Modulation shifts information onto a radio-frequency carrier, enabling practical antenna sizes and shared spectrum use.
- AM varies amplitude, producing a carrier plus two redundant sidebands; SSB removes the carrier and one sideband for much higher power/bandwidth efficiency.
- FM varies frequency (deviation Δf, index $\beta = \Delta f / f_m$); it trades bandwidth for strong noise immunity via the capture effect.
- PM varies phase and is closely mathematically related to FM.
- Digital modes apply amplitude/frequency/phase switching between discrete states (OOK, FSK, PSK, QAM); demodulation reverses the original modulation process.

Practice Problems

1. An AM signal has $V_c = 10\,\text{V}$ and $V_m = 4\,\text{V}$. Find the modulation index and percentage.
2. Explain why SSB uses roughly half the bandwidth of full-carrier double-sideband AM for the same audio content.

3. An FM signal has a peak deviation of 5 kHz and a maximum audio frequency of 3 kHz. Estimate its occupied bandwidth using Carson's rule.
4. Explain, conceptually, why a mistuned SSB receiver produces garbled, "Donald Duck"-like audio rather than just a change in pitch alone.
5. Name the digital modulation scheme used by classic on/off-keyed Morse code, and explain why it is considered the simplest possible digital modulation.

Chapter 18

Error Detection and Correction: CRC and FEC

Every digital signal traveling over a radio link is exposed to noise, fading, and interference that can flip received bits. This chapter covers the two complementary families of techniques used to deal with that reality: detecting that an error occurred, and, where possible, correcting it without needing a retransmission.

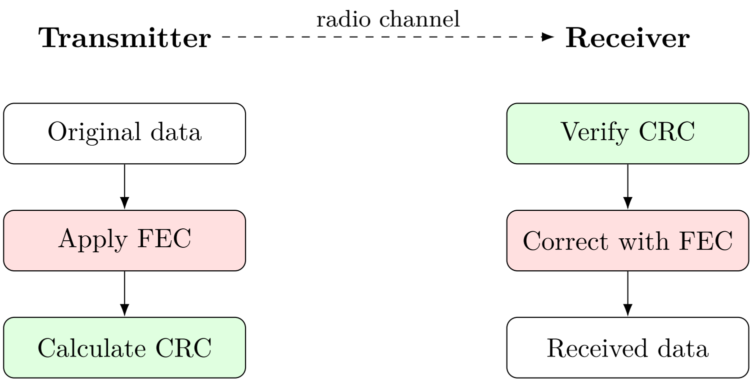


Figure 18.1: Error detection (CRC) vs. forward error correction (FEC) in a digital transmission chain.

18.1 The Basic Problem

A block of k information bits, transmitted over a noisy channel, may arrive with one or more bits flipped. Without any additional structure, the receiver has no way to know this happened — an altered but still-valid-looking bit pattern is simply accepted as correct. Error control techniques add carefully structured **redundant** bits to the transmitted data specifically so the receiver can recognize (and, in some schemes, correct) errors.

18.2 Cyclic Redundancy Check (CRC)

A **cyclic redundancy check** is an error-*detection* (not correction) scheme. The transmitter treats the data block as a large binary number, divides it (using a special binary polynomial division, modulo 2) by a fixed **generator polynomial**, and appends the remainder — the **CRC checksum** — to the transmitted data. The receiver performs the same division on the received data (including the appended checksum) and checks whether the remainder is zero: if not, at least one bit was altered in transit, and the receiver knows to discard the block or request retransmission.

Key Idea

CRC is extremely effective at *detecting* that an error occurred (essentially guaranteed to catch any single-bit or short burst error, and to catch the vast majority of longer or multiple-bit error patterns, depending on the generator polynomial's length), but on its own gives no way to determine *which* bit was wrong, and therefore no way to fix it. CRC-protected protocols typically respond to a failed check by requesting a retransmission (an **automatic repeat request**, ARQ) rather than attempting a repair.

CRC is used throughout amateur digital communications: packet radio (AX.25) frames include a CRC (technically an FCS, frame check sequence) to catch corrupted packets; many file transfer and digital mode protocols use CRC in a similar role.

18.3 Forward Error Correction (FEC)

Forward error correction takes a different, more ambitious approach: it adds redundancy structured so that the receiver can *correct* at least some error patterns without needing any retransmission at all — valuable on links (satellite, weak-signal HF, one-way beacon or telemetry transmissions) where requesting a repeat is slow, expensive, or simply impossible.

18.3.1 A Simple Example: The Repetition Code

The simplest possible FEC scheme repeats each bit multiple times (e.g., three times: $0 \to 000$, $1 \to 111$) and uses **majority voting** at the receiver to decide the original bit, correcting any single-bit error within each group of three at the cost of tripling the transmitted data. This illustrates the fundamental FEC trade-off in its simplest form: **more redundancy buys more error-correcting capability, at**

the direct cost of reduced information throughput for a given channel bandwidth.

18.3.2 Practical FEC Codes

Real FEC systems use far more efficient (less redundant, for the same correcting power) mathematical structures than simple repetition:

- **Block codes** (Hamming, Reed–Solomon, BCH): operate on fixed-size blocks of data, adding a calculated set of parity/check symbols; Reed–Solomon codes are particularly good at correcting **burst errors** (many consecutive bits corrupted together, typical of fading and impulse noise) and are used in satellite telemetry and digital broadcast standards.
- **Convolutional codes**: encode a continuous stream of data using a sliding-window structure, decoded with algorithms such as the **Viterbi algorithm**; well suited to the continuously varying noise conditions typical of a real radio channel, and long used in satellite and deep-space communication.
- **Low-density parity-check (LDPC) codes** and modern **turbo codes**: iteratively decoded codes that approach the theoretical (Shannon) limit of channel capacity very closely; used in recent weak-signal amateur digital modes and modern satellite/deep-space links.

Key Idea: Why weak-signal digital modes decode below the noise floor

Modern weak-signal amateur digital modes (Chapter 26) combine strong FEC coding with narrow bandwidth and long averaging (integration) times to reliably decode signals that are, by ear, completely inaudible in the noise — often 10–20 dB below the noise floor. The FEC code does not create information out of nothing; rather, it lets the decoder use redundancy spread across the whole transmitted block to statistically reconstruct the most likely original message even when individual symbols are severely corrupted by noise.

18.4 Combining CRC and FEC

Many real protocols use both techniques together: FEC coding to correct the errors it can, followed by a CRC check on the FEC-decoded output to catch (and flag or reject) any errors that were too severe for the FEC to fix. This layered approach — correct what you can, detect what you cannot correct so bad data is never silently accepted as good — is the standard architecture for robust digital data links, including many amateur satellite and digital-mode protocols.

18.5 Automatic Repeat Request (ARQ)

Where a return channel exists, error *detection* (CRC) can be combined with automatic retransmission: the receiver acknowledges correctly received blocks and requests retransmission of blocks that fail their CRC check. **ARQ** protocols (used in amateur packet radio, Winlink, and many other bidirectional digital modes) trade throughput and latency (a corrupted block must be resent, taking extra time) for a very high assurance of eventually delivering error-free data, in contrast to pure FEC, which trades bandwidth for correcting errors without any retransmission delay but cannot guarantee a perfect result on a very poor link.

Chapter Review

- CRC detects (but does not correct) errors by comparing a transmitted and recomputed checksum; failed checks typically trigger a retransmission request (ARQ).
- FEC adds structured redundancy that lets the receiver correct certain error patterns without retransmission, at the cost of reduced raw throughput.
- Block codes (Reed–Solomon, Hamming), convolutional codes, and modern LDPC/turbo codes are the main practical FEC families, each suited to different error patterns (burst vs. random) and decoding complexity budgets.
- Strong FEC plus narrow bandwidth and long integration time lets modern digital modes decode signals well below the audible noise floor.
- CRC and FEC are frequently combined: FEC corrects what it can, CRC flags what remains uncorrected.

Practice Problems

1. Explain the key functional difference between error *detection* and error *correction*.
2. A simple triple-repetition FEC code receives the group “101” for a transmitted single bit. Using majority voting, what was the original bit most likely to have been, and can you be certain?
3. Explain why Reed–Solomon-style codes are particularly well suited to correcting burst errors caused by fading, compared to a code optimized only for isolated single-bit errors.

4. Explain why a protocol might use both FEC and CRC together rather than relying on FEC alone.
5. Explain, at a conceptual level (no equations required), how combining strong FEC with a very narrow receive bandwidth and long averaging time allows some digital modes to decode signals inaudible to the human ear.

Part IV

Antennas, Transmission Lines, and Propagation

Chapter 19

Transmission Lines and Standing Wave Ratio

A **transmission line** (coaxial cable, open-wire ladder line, twisted pair) carries RF energy from a transmitter to an antenna, or from an antenna to a receiver, with as little loss and distortion as possible. Unlike the DC and low-frequency AC circuits of earlier chapters, a transmission line's physical length is often a significant fraction of the signal's wavelength, and its behavior must be analyzed as a distributed, wave-carrying system rather than a simple two-terminal lumped circuit.

19.1 Characteristic Impedance

Every transmission line has a **characteristic impedance** Z_0, determined entirely by its physical geometry (conductor spacing, diameter, dielectric) and, for an ideal lossless line, independent of its length or the frequency of the signal on it:

$$Z_0 = \sqrt{\frac{L'}{C'}}$$

where L' and C' are the line's inductance and capacitance *per unit length*. Common amateur coaxial cable is manufactured to standard values of $50\,\Omega$ (the overwhelming standard for amateur HF/VHF/UHF work) or $75\,\Omega$ (common in broadcast and video applications); open-wire ladder line is typically 300–600 Ω.

Key Idea

Z_0 is *not* something you measure with an ohmmeter across a disconnected line's ends (a long line will simply read as an open or short circuit depending on its length relative to a wavelength) — it describes the impedance a wave experiences while traveling *along* the line, and only becomes directly relevant once the line is driving a load and carrying a traveling wave.

19.2 Matched vs. Mismatched Loads

When a transmission line is terminated in a load whose impedance exactly equals Z_0, all of the power traveling down the line is absorbed by the load; no energy is reflected. This is a **matched** condition. If the load impedance Z_L differs from Z_0, some of the incident power is reflected back toward the source, creating a second wave traveling in the opposite direction. The interference between the forward (incident) and reflected waves creates a **standing wave** pattern of voltage and current along the line.

19.3 Reflection Coefficient and SWR

The fraction of voltage reflected is the **reflection coefficient**, Γ (Greek capital gamma), a complex number in general but often quoted by magnitude:

$$\boxed{\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}}$$

$\Gamma = 0$ for a perfectly matched load; $|\Gamma| = 1$ for a completely reactive/open/short load (total reflection, no power absorbed).

The **standing wave ratio (SWR)**, the ratio of the standing wave pattern's maximum voltage to its minimum voltage along the line, is related directly to $|\Gamma|$:

$$\boxed{\text{SWR} = \frac{V_{\text{max}}}{V_{\text{min}}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}}$$

SWR is always ≥ 1, with 1:1 representing a perfect match. Because it depends only on $|\Gamma|$, SWR (unlike Γ itself) carries no information about the *phase* of the mismatch — only its severity.

Worked Example: SWR from a load mismatch

A $50\,\Omega$ line is terminated in a $75\,\Omega$ resistive load. Find Γ and the SWR.
Solution.

$$\Gamma = \frac{75 - 50}{75 + 50} = \frac{25}{125} = 0.2, \qquad \text{SWR} = \frac{1 + 0.2}{1 - 0.2} = \frac{1.2}{0.8} = 1.5.$$

A 1.5:1 SWR, generally considered a mild, acceptable mismatch.

19.4 Power Reflected

The fraction of incident power that is reflected (rather than delivered to the load) is $|\Gamma|^2$:

$$\frac{P_{\text{reflected}}}{P_{\text{forward}}} = |\Gamma|^2.$$

Worked Example: Power lost to reflection

For the 1.5:1 SWR example above ($|\Gamma| = 0.2$), find the fraction of power reflected and the fraction delivered to the load.

Solution.

$$\frac{P_{\text{reflected}}}{P_{\text{forward}}} = 0.2^2 = 0.04\ (4\%), \qquad \text{delivered} = 96\%.$$

This illustrates why a modest 1.5:1 SWR is rarely a practical problem: the actual power lost to reflection is small. Very high SWR (5:1 or worse) reflects a much larger fraction of power and can additionally stress transmitter output stages and increase line loss significantly.

19.5 Why High SWR Matters

- **Transmitter stress**: many solid-state transmitters automatically reduce power ("foldback") or shut down when SWR exceeds a safe limit, since a severely mismatched load can present the final amplifier stage with voltage or current levels well outside its safe operating range.
- **Increased line loss**: standing waves increase the peak current and voltage on the line relative to a matched condition, increasing I^2R and dielectric losses beyond the line's already frequency-dependent matched-line loss — the mismatch loss adds on top of, and interacts with, the line's intrinsic loss.
- **Voltage/current peaks**: at high SWR, the standing wave's voltage and current maxima can be large enough to cause arcing or component stress at those points along the line, even if the average power is modest.

Safety

Very high SWR at significant power levels can generate dangerously high RF voltages at points along a feedline or at an antenna feedpoint, particularly with unterminated or badly damaged coaxial lines. Address high SWR readings before operating at higher power levels.

19.6 Impedance Along a Mismatched Line

For a lossless line of length ℓ and characteristic impedance Z_0, terminated in load Z_L, the impedance seen looking into the line varies periodically with distance from the load, repeating every half wavelength:

$$Z_{\text{in}} = Z_0 \frac{Z_L + jZ_0 \tan(\beta\ell)}{Z_0 + jZ_L \tan(\beta\ell)}, \qquad \beta = \frac{2\pi}{\lambda}.$$

Two special cases are worth knowing without the full formula:

- A line exactly **one-half wavelength** (or any integer multiple) long repeats the load impedance at its input, regardless of Z_0 — useful for relocating a matched (or known) impedance to a more convenient physical location.
- A line exactly **one-quarter wavelength** long acts as an impedance **inverter/transformer**: $Z_{\text{in}} = Z_0^2/Z_L$. This **quarter-wave transformer** principle is widely used to match a real, resistive antenna feedpoint impedance to a different feedline impedance using a length of line with an intermediate characteristic impedance, $Z_0 = \sqrt{Z_{\text{in}} Z_L}$.

19.7 Line Loss

Real transmission lines dissipate some power even when perfectly matched, due to conductor resistance (worse at higher frequency because of the **skin effect**, Chapter 8) and dielectric loss in the insulating material. Manufacturers publish matched-line loss in dB per 100 m (or 100 ft) at various frequencies; loss increases with frequency and, for a fixed cable type, with distance. Mismatch (SWR > 1) adds additional loss on top of this intrinsic matched-line loss, an effect that becomes more significant as intrinsic cable loss increases (which is one reason high SWR is more consequential on a long run of lossy cable than on a short run of low-loss line).

Chapter Review

- Characteristic impedance $Z_0 = \sqrt{L'/C'}$ depends on line geometry, not length or (ideally) frequency.
- $\Gamma = (Z_L - Z_0)/(Z_L + Z_0)$; SWR $= (1 + |\Gamma|)/(1 - |\Gamma|)$; reflected power fraction $= |\Gamma|^2$.
- High SWR can stress transmitters, increase line loss, and produce dangerous voltage/current peaks at significant power.
- A half-wavelength line repeats the load impedance; a quarter-wavelength line transforms impedance as $Z_{\text{in}} = Z_0^2/Z_L$.
- Real lines have intrinsic matched loss (worse at higher frequency); mismatch adds further loss on top of this.

Practice Problems

1. A $50\,\Omega$ line feeds a purely resistive $100\,\Omega$ load. Find Γ and SWR.
2. For an SWR of 3:1, find $|\Gamma|$ and the fraction of power reflected.
3. Find the characteristic impedance of a quarter-wave matching section needed to match a $50\,\Omega$ line to a $200\,\Omega$ antenna feedpoint.
4. Explain why a transmitter's automatic power foldback at high SWR is a protective feature rather than a fault.
5. A 1:1 SWR is measured at the transmitter end of a long, lossy feedline. Does this guarantee the antenna itself is well matched? Explain, considering line loss.

Chapter 20

Antenna Fundamentals and Common Designs

An antenna is the transducer between guided energy on a transmission line and free-space electromagnetic waves (Chapter 4), working identically (by reciprocity) whether transmitting or receiving. This chapter covers the core parameters used to describe any antenna, then surveys the designs an amateur is most likely to build or use.

20.1 Radiation: Why an Oscillating Charge Radiates

An accelerating (including oscillating) electric charge radiates electromagnetic energy. A current-carrying conductor driven at radio frequency has continuously accelerating charge carriers, and therefore radiates — but efficient radiation requires the conductor's length to be comparable to the signal's wavelength (Chapter 4, $c = f\lambda$); a conductor much shorter than a wavelength radiates very inefficiently, which is why antenna dimensions scale directly with operating wavelength.

20.2 The Half-Wave Dipole

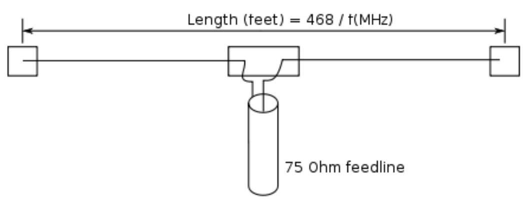


Figure 20.1: A center-fed half-wave dipole antenna.

The **half-wave dipole** — two straight conductors, each approximately a quarter-wavelength long, fed at the center — is the fundamental reference antenna against which most others are compared. Its resonant length, accounting for the practical fact that RF propagates slightly slower along a real (finite-diameter) wire than in free space (the **velocity factor** or “end effect”), is approximately

$$\boxed{\ell_{\text{ft}} = \frac{468}{f_{\text{MHz}}}} \qquad \text{or equivalently} \qquad \ell_{\text{m}} \approx \frac{143}{f_{\text{MHz}}}$$

for total dipole length. (The free-space half-wavelength would be $\ell = c/(2f) = 150/f_{\text{MHz}}$ metres; the shortening factor, roughly 0.95, accounts for end effect in typical thin-wire construction.)

Worked Example: Dipole length

Find the total length of a half-wave dipole for 7.100 MHz.
Solution.

$$\ell_{\text{m}} \approx \frac{143}{7.100} \approx 20.1\,\text{m}.$$

Each leg is therefore approximately 10.1 m.

A resonant half-wave dipole in free space presents a feedpoint impedance of approximately 73 Ω (resistive, at resonance), reasonably close to standard 50 Ω coax, though height above ground and surroundings shift this value somewhat in practice. A dipole fed at its center is inherently a **balanced** load and should be fed through a balun (Chapter 11) if connected to unbalanced coaxial cable, to avoid feedline radiation and pattern distortion.

20.3 Radiation Pattern, Gain, and Directivity

An antenna’s **radiation pattern** describes how strongly it radiates as a function of direction. Even the simplest dipole is not omnidirectional in three dimensions: it radiates a figure-eight pattern broadside to the wire (maximum) and radiates essentially nothing off the ends of the wire (nulls).

Directivity and **gain** quantify how much an antenna concentrates radiation in its favored direction(s) compared to a reference. Gain, expressed in **dBi** (relative to a theoretical isotropic radiator) or **dBd** (relative to a reference dipole), was defined precisely in Chapter 15; a real dipole has about 2.15 dBi (0 dBd) of gain in its favored broadside directions, simply from concentrating energy away from the (nulled) end directions rather than spreading it equally in all directions like a true isotropic source.

Key Idea: Gain is a trade, not free energy

An antenna cannot amplify signal power — gain in one direction is always achieved by concentrating radiation that would otherwise have gone elsewhere, not by adding energy. A high-gain directional antenna therefore radiates *less* in directions away from its main lobe than an isotropic radiator would, even as it radiates significantly *more* in its favored direction.

20.4 Antenna Efficiency and Losses

$$\eta = \frac{P_{rad}}{P_{in}}$$

Figure 20.2: Antenna efficiency: radiated power vs. power lost to resistive and ground losses.

Real antennas dissipate some power as heat rather than radiating it all, due to conductor resistance, loading-coil losses, and losses in nearby lossy ground or objects. **Radiation efficiency** is

$$\eta = \frac{R_{\text{rad}}}{R_{\text{rad}} + R_{\text{loss}}} \times 100\%$$

where R_{rad} is the antenna's **radiation resistance** (the equivalent resistance that would dissipate the same power as is actually radiated) and R_{loss} lumps together all real resistive losses. Electrically short antennas (loaded verticals and mobile whips well under a quarter-wavelength, for instance) tend to have low radiation resistance, making loss resistance a proportionally larger fraction of the total and efficiency correspondingly poorer — a key reason full-size or close-to-full-size antennas generally outperform heavily shortened/loaded designs when space permits.

20.5 Polarization and Ground Effects

An antenna's orientation sets its **polarization** (Chapter 4): a horizontal dipole radiates horizontally polarized waves; a vertical antenna radiates vertically polarized waves. Ground reflections interact strongly with a nearby antenna, modifying both its feedpoint impedance and its radiation pattern (particularly the low-angle performance important for long-distance HF propagation, Chapter 21); antenna height above ground, in wavelengths, is therefore a major practical design variable, not just an installation convenience.

20.6 The Yagi–Uda Antenna

Figure 20.3: A Yagi–Uda beam antenna: driven element, reflector, and directors.

The **Yagi–Uda** antenna (commonly just "Yagi"), invented by Shintaro Uda and popularized by Hidetsugu Yagi in the 1920s, achieves significant directional gain from a single driven half-wave dipole element by adding nearby **parasitic elements**: a slightly longer **reflector** behind the driven element and one or more slightly shorter **directors** in front of it. These parasitic elements are not directly fed; they are excited by mutual coupling with the driven element's near field, and their carefully tuned length and spacing cause constructive interference in the forward direction and destructive interference to the rear, producing a directional beam pattern with useful gain (typically 6–15 dBi depending on the number of elements and boom length) and a front-to-back ratio that helps reject interference and noise arriving from behind the antenna.

20.7 Ground-Plane and Vertical Antennas

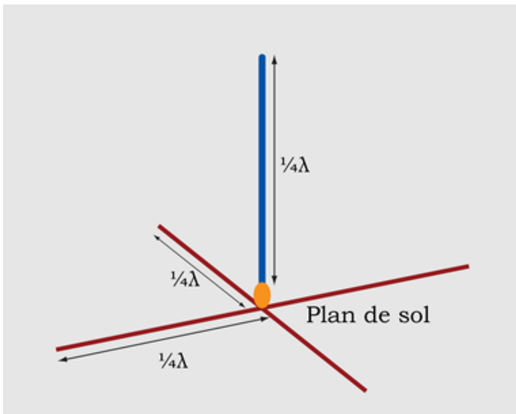


Figure 20.4: A quarter-wave ground-plane vertical antenna with radial elements.

A **ground-plane vertical** uses a quarter-wave vertical radiator fed against a set of radial elements (or an actual conductive ground plane) that serve as the antenna's "other half," effectively forming half of a dipole with an electrical mirror image below the feedpoint. Feedpoint impedance for an ideal quarter-wave vertical over a perfect ground plane is approximately 36 Ω (roughly half the dipole's 73 Ω, consistent with the mirror-image picture). Verticals radiate omnidirectionally in azimuth (all compass directions equally) with vertical polarization, and — with a low radiation angle particularly useful for DX contacts — are popular where a horizontal antenna large enough for the operating band is impractical, at the cost of typically needing an effective radial/ground system to perform well.

20.8 Loop Antennas

Figure 20.5: A small transmitting magnetic loop antenna.

A **loop antenna** forms a closed (or nearly closed) conductive loop. **Full-size loops** (a wavelength or more in circumference) behave broadly like a folded dipole variant with useful gain and different polarization/pattern characteristics depending on orientation. **Small (magnetic) loops**, with circumference well under a wavelength, are physically compact and couple predominantly to the magnetic near-field component; they achieve resonance using a high-voltage tuning capacitor across the loop and, despite modest radiation efficiency for their small size, are valued for space-constrained installations and for a naturally narrow bandwidth that provides useful front-end selectivity even before a receiver's own filtering.

20.9 Multiband and Wire Antenna Techniques

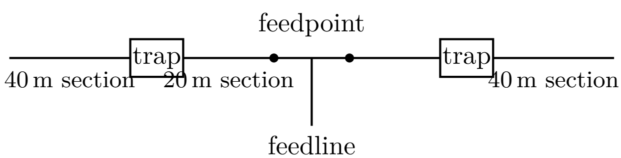


Figure 20.6: A trap dipole: LC traps present a high impedance at their design frequency, electrically shortening the antenna so a single wire resonates on more than one band.

- **Trap dipoles/verticals**: parallel LC resonant circuits (**traps**, Chapter 10) inserted along the antenna element present a high impedance (effectively an open circuit, electrically shortening the antenna) at their design frequency, letting a single physical antenna present resonant electrical lengths on several different bands.
- **End-fed half-wave (EFHW) antennas**: a half-wave wire fed at (or very near) one end, where feedpoint impedance is very high (thousands of ohms) rather than the ~73 Ω of a center-fed dipole; a purpose-built impedance-matching transformer converts this high impedance down to 50 Ω, letting the antenna be fed conveniently from one end rather than requiring center support.
- **Folded dipoles**: a dipole with a second parallel conductor connecting its two ends, raising feedpoint impedance (approximately 4× a plain dipole's, or about 280–300 Ω for a simple two-wire fold) and providing a somewhat broader bandwidth — the classic feed for 300 Ω balanced television ribbon line and folded-element Yagi driven elements.

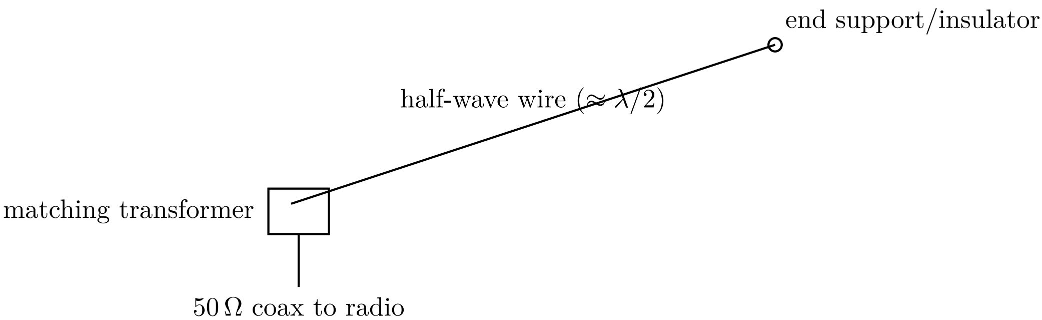


Figure 20.7: An end-fed half-wave (EFHW) antenna. A step-up impedance transformer (typically 49:1 or 64:1) matches the wire's high end-feed impedance down to 50 Ω.

20.10 Antenna Bandwidth

Figure 20.8: Typical amateur HF antenna bandwidth across several bands.

An antenna's usable **bandwidth** (the frequency range over which its feedpoint impedance stays reasonably close to the feedline's characteristic impedance, typically judged by SWR) depends on the antenna's own effective Q (Chapter 10): thicker conductors and lower operating Q generally give wider bandwidth, which is why a fan dipole, thick aluminum Yagi element, or cage dipole often covers more of a band comfortably than a thin, single wire of the same nominal design.

Chapter Review

- An antenna radiates because it carries oscillating (accelerating) charge; efficient radiation needs dimensions comparable to a wavelength.
- Half-wave dipole length (m) $\approx 143/f_{\text{MHz}}$; free-space feedpoint impedance $\approx 73\,\Omega$.
- Gain (dBi/dBd) describes concentration of radiation in a favored direction, not added total power; efficiency $\eta = R_{\text{rad}}/(R_{\text{rad}} + R_{\text{loss}})$.

- Yagi–Uda antennas use parasitic reflector/director elements around one driven element to achieve directional gain.
- Verticals/ground-planes give omnidirectional, low-angle, vertically polarized radiation; loops, traps, EFHW, and folded-dipole techniques address space, multiband, and feed-impedance needs.

Practice Problems

1. Find the total length of a half-wave dipole for 21.200 MHz.
2. A Yagi has 10 dBi of gain. Express this in dBd.
3. Explain why an electrically short, heavily loaded mobile whip antenna typically has lower efficiency than a full-size dipole on the same band.
4. Explain, in terms of the mirror-image picture, why a quarter-wave ground-plane vertical's feedpoint impedance is roughly half that of a half-wave dipole.
5. Explain the practical purpose of a matching transformer on an end-fed half-wave antenna, given that a half-wave wire's end-fed impedance is very high rather than close to 50 Ω.

Chapter 21

Radio Wave Propagation

How a radio signal gets from a transmitting antenna to a receiving antenna, hundreds or thousands of kilometres away, depends on frequency, time of day, season, solar activity, and geography. This chapter surveys the main propagation mechanisms an amateur exploits across the HF, VHF, UHF, and microwave amateur bands.

21.1 The Ground Wave

At lower frequencies (roughly below a few MHz), a vertically polarized wave can travel along the Earth's curved surface for a considerable distance as a **ground wave** (or **surface wave**), guided partly by the interaction between the wave and the conductive ground. Ground-wave range is limited by ground conductivity (seawater performs far better than dry rocky or sandy soil) and increases at lower frequency; it is a minor factor for most HF amateur bands but is the dominant propagation mode for AM broadcast and some maritime/beacon services at lower frequencies.

21.2 Line-of-Sight and the Radio Horizon

At VHF, UHF, and microwave frequencies, propagation is normally **line-of-sight**: the direct wave travels essentially in a straight line, blocked by the curvature of the Earth and by terrain obstructions. Because the atmosphere's refractive index normally decreases slightly with height, radio waves bend (**refract**) gently downward, extending the effective **radio horizon** somewhat beyond the optical horizon — a commonly used approximation for the radio horizon distance (in kilometres, with antenna height h in metres) is

$$d_{\mathrm{km}} \approx 4.12\sqrt{h_{\mathrm{m}}}$$

applied to each end of the path and summed, which is why raising a VHF/UHF antenna (or operating from a hilltop) so directly and dramatically increases usable range.

21.2.1 Tropospheric Effects

Under certain weather conditions, temperature and humidity gradients in the lower atmosphere (**troposphere**) create layers where the refractive index changes more sharply than usual, bending (**tropospheric ducting** or simple **tropo enhancement**) VHF and UHF signals well beyond the normal radio horizon — sometimes hundreds of kilometres — along stable high-pressure weather boundaries or temperature inversions. **Tropospheric scatter**, a weaker but more consistently available mechanism, allows some signal energy to scatter forward off small-scale turbulence in the troposphere even without a defined duct.

21.3 The Ionosphere and Skywave Propagation

The **ionosphere** is a region of the upper atmosphere (approximately 60–1000 km altitude) where solar ultraviolet and X-ray radiation ionizes atmospheric gases, creating layers of free electrons capable of refracting (and, at a steep enough angle or low enough frequency, fully reflecting) radio waves back toward Earth. This **skywave** propagation is what makes long-distance ("DX") HF communication possible without a chain of relay stations, by bouncing a signal off the ionosphere and back down to a distant receiver – potentially over several successive "hops."

21.3.1 Ionospheric Layers

- **D layer** (∼60–90 km): forms only in daylight; does not refract HF signals back to Earth but does *absorb* them, particularly at lower HF frequencies — the main reason low HF bands (80 m, 40 m) are noticeably "quieter" but shorter-range for DX during the day and open up dramatically for longer-distance propagation after D-layer ionization decays at night.
- **E layer** (∼90–150 km): present mainly in daylight, refracts lower/mid HF frequencies and supports the anomalous, short-lived **sporadic-E** propagation discussed below.
- **F layer** (splitting into **F1** and **F2** in daylight, recombining into a single F layer at night, roughly 150–500 km): the primary layer responsible for long-distance HF skywave propagation, with the F2 layer's height and ionization density — strongly dependent on solar activity — setting the **maximum usable frequency (MUF)** for a given path on a given day.

21.3.2 Critical Frequency and MUF

For a signal transmitted straight up, the highest frequency the ionosphere will still reflect back down is the **critical frequency**, f_c. For a signal transmitted at an oblique angle (the normal case for a real communication path), a higher frequency can still be refracted back to Earth — the **maximum usable frequency** for that specific path, related to the critical frequency and the wave's incidence angle θ (measured from vertical) by the **secant law**:

$$\boxed{\text{MUF} = f_c \sec(\theta)}$$

Operating above the MUF for a given path, the signal passes through the ionosphere into space rather than being returned to Earth. Because lower launch angles (more oblique, larger θ) permit a higher MUF, DX contacts over very long paths are often possible at frequencies that would not support shorter, steeper-angle paths at the same time.

Key Idea: LUF, MUF, and the usable window

Below a **lowest usable frequency (LUF)**, D-layer absorption (and increasing atmospheric/man-made noise at lower frequencies) makes a signal too weak to be useful even if the ionosphere would otherwise support the path; above the MUF, the signal is not returned to Earth at all. Real-world HF operation lives in the changing window between these two limits, which is why band selection "for the conditions" is such a core operating skill — and why real-time MUF/LUF prediction tools and propagation beacons are widely used by serious HF operators.

21.4 The Solar Cycle and Space Weather

Ionization of the F2 layer depends strongly on solar ultraviolet output, which varies on an approximately **11-year solar cycle** of rising and falling sunspot activity. Higher sunspot numbers generally mean a denser, higher F2 layer and a correspondingly higher MUF, supporting DX propagation on higher HF bands (15 m, 12 m, 10 m) that may be largely closed during solar minimum. Solar flares and coronal mass ejections can also cause sudden, disruptive space-weather events:

- A **sudden ionospheric disturbance (SID)**, triggered by a solar flare's X-ray flux, causes a rapid increase in D-layer ionization and a corresponding **HF radio blackout** on the sunlit side of Earth, lasting from minutes to a few hours.

- A **geomagnetic storm**, triggered by a coronal mass ejection reaching Earth's magnetosphere, disturbs the ionosphere over a longer period (a day or more), variably degrading HF propagation while sometimes *enhancing* high-latitude VHF/UHF propagation via aurora.

21.5 Sporadic-E

Sporadic-E propagation results from dense, patchy, short-lived clouds of ionization in the E layer (mechanism not fully understood, but statistically linked to season — most common in late spring/early summer in each hemisphere — and to wind shear in the upper atmosphere). It can support surprisingly strong single- or multi-hop propagation on the upper HF bands and, notably, on the lower VHF bands (6 m and, less commonly, 2 m) that are normally limited to line-of-sight — producing some of the most exciting unpredictable VHF DX openings available to an amateur.

21.6 Meteor Scatter and Auroral Propagation

- **Meteor scatter**: the brief ionized trail left by a meteor burning up in the upper atmosphere can reflect VHF signals for a fraction of a second to a few seconds, long enough (especially with digital modes designed for very short contacts) to complete brief contacts over 1000–2000 km paths, enhanced during annual meteor showers.
- **Auroral propagation**: during geomagnetic disturbances, VHF/UHF signals can scatter off ionization associated with the aurora, typically producing a characteristic rasping, Doppler-smeared signal quality, mainly usable for paths oriented toward the auroral region at higher latitudes.

21.7 Greyline Propagation

The **greyline** (or **terminator**) is the band of twilight circling the Earth between day and night. Along the greyline, the D layer on the sunset/sunrise side has largely decayed (reducing absorption) while the F layer, which decays more slowly after sunset, remains sufficiently ionized to support propagation — a favorable combination that experienced HF operators specifically exploit for long-path and unusual DX openings around their local sunrise and sunset.

21.8 Multipath, Fading, and Doppler Effects

A received signal often arrives via more than one path simultaneously (different ionospheric hops, ground wave plus skywave, or multiple ionospheric layers at once), each with a slightly different path length and therefore a different arrival phase. The combination of these paths, constantly shifting as the ionosphere changes, produces **fading** — and, over sufficiently different path lengths, measurable time-domain echo or **Doppler**-related frequency smearing, both of particular relevance to digital mode performance (Chapter 26) and to precise frequency measurement.

Chapter Review

- Ground wave (low HF/MF, vertical polarization) and line-of-sight plus tropospheric effects (VHF/UHF/microwave) dominate at those frequency extremes; skywave dominates general-purpose HF DX.
- Ionospheric D, E, and F layers absorb (D) or refract (E, F) HF signals; the F2 layer sets the MUF for long-distance skywave paths, MUF $= f_c \sec\theta$.
- The solar cycle and space-weather events (SIDs, geomagnetic storms) drive large day-to-day and year-to-year variation in HF propagation.
- Sporadic-E, meteor scatter, and auroral propagation are anomalous mechanisms that can open otherwise line-of-sight-limited VHF bands over much longer paths.
- Greyline propagation exploits the favorable D-layer/F-layer balance found along the day/night terminator.

Practice Problems

1. Estimate the radio horizon distance for a VHF station with a 30 m antenna height, communicating with a station whose antenna is 10 m high (sum both contributions).
2. A path has a critical frequency of 4 MHz and an incidence angle of 70° from vertical. Estimate the MUF for this path.
3. Explain why the 80 m and 40 m amateur bands are typically much better for long-distance contacts at night than during the day.
4. Explain, qualitatively, why higher sunspot activity tends to improve propagation on the higher HF bands (e.g., 10 m) specifically.
5. Explain why meteor scatter contacts are typically brief and rely on specialized digital modes rather than sustained voice conversation.

Part V

Operating Practice and the Amateur Service Worldwide

Chapter 22

Becoming a Licensed Amateur: An International Overview

Every country that permits amateur radio operates its own licensing system, but nearly all of them share a common shape, because nearly all of them are built around the same international framework. This chapter explains that shared shape without attempting to describe any single country's specific rules — for those, always consult your own national telecommunications regulator or IARU member society.

22.1 Why Licensing Exists at All

Amateur radio operators are granted access to shared, finite radio spectrum and are permitted to transmit at power levels that can cause real interference to other services (aviation, marine, emergency communications, other amateurs) if used carelessly. Licensing exists to verify, before granting that access, that an operator understands enough electronics, radio theory, and operating procedure to use the privilege responsibly — which is precisely the material this book is designed to teach.

22.2 The International Framework

Key Idea

Nearly every national licensing system sits underneath the same international structure: the **International Telecommunication Union (ITU)** allocates radio spectrum globally and divides the world into three **ITU Regions** for band-planning purposes; the **International Amateur Radio Union (IARU)** coordinates amateur band planning and operating practice within that framework; and **CEPT** (in Europe) and similar regional bodies elsewhere facilitate reciprocal license recognition between member countries. These bodies are covered in full in Chapter 23.

22.3 Typical License Tiers

Although the exact names, requirements, and privileges differ by country, most administrations offer licensing in **progressive tiers**, each unlocking greater operating privileges (more bands, higher power, more modes) in exchange for demonstrating greater technical knowledge. A common three-tier pattern, which this book's five parts are loosely organized around, looks approximately like this:

Typical tier	Typical exam scope	Typical privileges
Entry-level ("Foundation," "Novice," "Technician")	Basic safety, regulations, and simple operating procedure; limited electronics theory	Limited bands and/or power, often VHF/UHF-focused; sometimes CW-only or supervised HF access
Intermediate ("General," "Class 2")	Adds AC theory, components, antennas, and propagation basics	Wider HF band access, higher power limits
Full/Advanced ("Extra," "Class 1," "Full")	Adds active devices, filters, transmission line theory, and deeper technical detail	Full amateur band and power privileges available in that country

Some countries use two tiers, some four or five; some require a period of experience or a practical assessment between tiers; some (though a shrinking number worldwide) still require a Morse code proficiency test for HF privileges. Always check your own regulator's current requirements rather than assuming any particular country's structure.

22.4 What Exams Actually Test

Despite wide variation in format (multiple choice is most common worldwide; some countries use written or oral components), amateur radio exams overwhelmingly test the same underlying knowledge areas, each of which maps directly onto a part of this book:

- **Basic electricity and electronics** (Ohm's law, power, components, AC theory) — Parts I and II of this book.
- **RF theory** (resonance, filters, semiconductors, receivers, modulation) — Part III.
- **Antennas, feedlines, and propagation** — Part IV.

- **Operating procedure and radio safety** — Part V.
- **National regulations specific to your country**: band plans, power limits, callsign format, station identification requirements, and the administrative process for obtaining and renewing a license. *This last category is intentionally not covered in this book* and must be learned from your national regulator's own official study materials.

22.5 Practical Exam Preparation Advice

Exam Tip

Most national exam question pools are published in advance, often with the exact wording of every possible question. Working through the official question pool for your specific country, alongside (not instead of) understanding the underlying theory in this book, is by far the most efficient way to prepare — memorizing a question pool without understanding the theory behind it leaves gaps that show up the moment a real operating or troubleshooting situation differs even slightly from a memorized question.

- Work practice questions from your own country's official or widely used question pool.
- Revisit the worked examples and practice problems in each chapter of this book until the underlying calculation (not just the final number) feels routine.
- Use Appendix A (formula reference) for rapid last-minute review, but make sure you can also derive or explain *why* each formula works, not just recite it.
- If your target license requires a practical or oral assessment, practice the specific skills involved (correct phonetic alphabet use, proper procedure, safe equipment operation) well before the assessment date, not just the written theory.

22.6 After Licensing: Reciprocal Operation and Ongoing Learning

Many countries recognize licenses issued by other administrations under reciprocal agreements (within CEPT in Europe, under IARU-facilitated arrangements elsewhere, or through bilateral agreements) — but the specific rules, required paperwork, and permitted privileges when operating in a foreign country vary considerably and must always be checked with the *visited* country's regulator before transmitting there. Licensing is also only the beginning: amateur radio rewards continued learning, and operators are encouraged to keep building technical knowledge, try new modes and bands, and, in many countries, progress toward higher license tiers as experience grows.

Chapter Review

- Licensing verifies enough technical and procedural knowledge to use shared spectrum responsibly.
- Nearly all national systems sit under the shared international framework of ITU, IARU, and regional bodies like CEPT.
- Most countries use progressive license tiers granting increasing privileges for increasing demonstrated knowledge, though exact structures vary widely.
- Exams test electricity/electronics, RF theory, antennas/propagation, operating procedure, and country-specific regulations — the first four are universal and are this book's focus; the last is not.
- Reciprocal operating privileges between countries exist but must always be verified with the visited country's own regulator.

Practice Problems

1. List the five knowledge areas most amateur radio exams cover, and identify which one this book intentionally does not attempt to teach.
2. Explain why a three-tier (or similar) progressive licensing structure is common internationally, even though exact names and requirements differ by country.
3. Explain the practical risk of preparing for an exam purely by memorizing a published question pool without understanding the underlying theory.
4. Explain why reciprocal license recognition between countries still requires checking the visited country's specific rules, even when a reciprocal agreement broadly exists.
5. Identify which parts of this book you would need to study for an entry-level license in a hypothetical country that requires only basic electronics and operating procedure, versus a full-privilege license requiring the entire syllabus.

Chapter 23

International Regulatory Bodies

23.1 The International Telecommunication Union (ITU)

The **International Telecommunication Union**, founded in 1865 (making it one of the oldest international organizations in existence) and now a specialized agency of the United Nations, is the global body responsible for coordinating use of the radio spectrum, satellite orbits, and international telecommunications standards among its member states. Its **Radio Regulations**, revised periodically at World Radiocommunication Conferences (WRCs), form the international treaty-level framework within which every national regulator allocates spectrum — including the frequency bands available to the amateur and amateur-satellite services.

23.1.1 ITU Regions

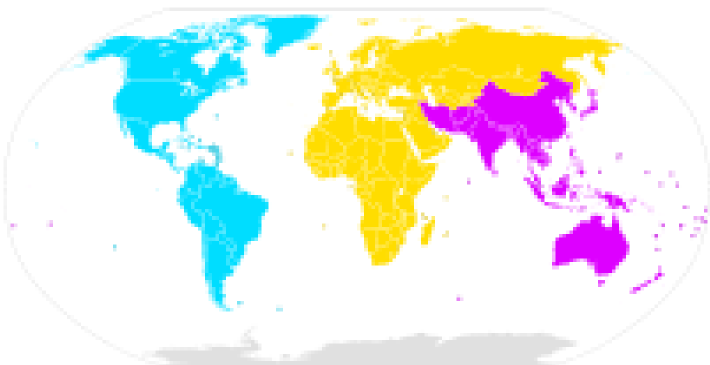


Figure 23.1: The three ITU Regions used for international frequency allocation.

For frequency-allocation purposes, the ITU divides the world into three **Regions**:

- **Region 1**: Europe, Africa, the Middle East, and the former Soviet Union.
- **Region 2**: the Americas.

- **Region 3**: Asia and Oceania (most of the Asia-Pacific area).

Amateur band allocations are broadly similar across all three Regions but differ in some specific frequency ranges — this is why, for example, the amateur 40 m band's exact upper edge and the presence or absence of certain segments can differ between Regions, and why operators should always confirm current allocations for their own Region and country rather than assuming a foreign band plan applies locally.

23.2 The International Amateur Radio Union (IARU)

The **International Amateur Radio Union**, founded in 1925, is a federation of national amateur radio societies (one per country or territory, in general) that represents the interests of the amateur and amateur-satellite services at the ITU and other international forums, and coordinates voluntary **band plans** that go beyond the ITU's own (broader) allocations. IARU is itself organized into three regional bodies (**IARU Region 1, 2, and 3**, mirroring the ITU Region structure) that publish detailed recommended band plans — for example, recommending which segments of a band should be used for CW, for digital modes, or for satellite operation — which member societies then work to have adopted, in whole or in part, by their national regulators. Because IARU band plans are *voluntary gentlemen's agreements* among amateurs rather than binding law in most countries, following them is a matter of good operating practice and courtesy toward the wider amateur community, even where a national regulator's own legal allocation would technically permit different use.

Key Idea

The distinction between an ITU *allocation* (the legally binding international/-national assignment of a frequency band to the amateur service), an IARU *band plan* (a voluntary, community-coordinated convention for how amateurs use that allocated band), and a national regulator's own specific *rules* (legally binding requirements particular to one country) is worth keeping straight: all three matter, but only the first and third carry direct legal weight, while the band plan is what keeps the global amateur community usably organized within that legal space.

23.3 CEPT and Regional Reciprocal Licensing Arrangements

In Europe, the **European Conference of Postal and Telecommunications Administrations (CEPT)** maintains recommendations (most notably CEPT Recommendation T/R 61-01) that allow amateurs licensed in one CEPT member (or CEPT-recognized) country to operate temporarily in another member country without obtaining a separate local license, provided their home license meets the recommendation's minimum requirements. Similar reciprocal frameworks, with their own specific rules and participating countries, exist in other parts of the world, often facilitated by IARU member societies and bilateral or regional agreements between national regulators.

Exam Tip

Reciprocal operating arrangements are a genuine convenience for traveling amateurs, but the specific requirements — which license classes qualify, what identification format to use while operating under reciprocal privileges, which bands and power levels apply, and whether advance notification or registration is required — vary by the *visited* country and by which reciprocal framework applies. Always verify current requirements with the visited country's regulator or the relevant IARU member society before operating there; this information changes over time and is beyond the scope of any general-purpose textbook.

23.4 National Telecommunications Regulators

Beneath this international structure, each country designates its own **national regulator** (sometimes a dedicated telecommunications authority, sometimes a broader communications or spectrum agency) that implements ITU allocations into binding national law, administers the license examination and issuance process, assigns callsigns according to the country's internationally allocated **callsign prefix block** (itself an ITU-administered allocation), and enforces compliance. Because this is precisely the layer of the system that differs from country to country, this book deliberately does not attempt to describe any specific national regulator's procedures, forms, fees, or current rules — consult your own national regulator's official published materials for that information, ideally at the time you are actually preparing to sit an exam or apply for a license, since administrative requirements can change.

Chapter Review

- The ITU sets the binding international framework for spectrum allocation, divided into three Regions for allocation purposes.
- IARU (itself divided into three matching Regions) coordinates voluntary band plans that organize amateur use within ITU allocations.
- CEPT and similar regional frameworks enable reciprocal operating privileges between member countries, subject to specific, changeable requirements.
- National regulators implement international allocations as binding domestic law, administer licensing, and assign callsigns from their country's allocated prefix block.
- Allocation (legal), band plan (voluntary convention), and national rules (legal, country-specific) are three distinct layers, only the first two of which are meaningfully universal.

Practice Problems

1. Name the three ITU Regions and, in general terms, which part of the world each covers.
2. Explain the difference between an ITU frequency allocation and an IARU band plan, and why following a band plan matters even though it is voluntary.
3. Explain why an amateur planning to operate temporarily from a foreign country should check that country's specific reciprocal licensing rules rather than assuming their home license is automatically valid everywhere.
4. Explain the role of a national telecommunications regulator in relation to the international ITU framework.
5. Explain why this textbook covers ITU, IARU, and CEPT in detail but does not cover any single country's specific licensing procedure.

Chapter 24

Operating Procedure and Radio Terminology

Good operating practice is what makes a shared, crowded radio spectrum usable by everyone. This chapter defines the core vocabulary and procedural concepts used universally across amateur radio operating, independent of any particular country's specific rules.

24.1 Core Definitions

- **Station**: one or more transmitters, receivers, or transceivers, together with any associated equipment, necessary at one location to carry out a radiocommunication service.
- **Emission**: the radiation produced by a transmitting station — the actual radio energy sent out, as distinct from the information it may carry.
- **Radio spectrum**: the range of electromagnetic frequencies used for radiocommunication, allocated internationally by the ITU (Chapter 23) and subdivided nationally among different services.
- **Interference**: the effect of unwanted energy, from one or more emissions or from other sources, on the reception of a wanted signal — ranging from mild degradation to complete disruption.

24.2 Emission Classification (Emission Designators)

Internationally, radio emissions are described using a standardized alphanumeric code (an **emission designator**) capturing bandwidth, modulation type, nature of the modulating signal, and type of information transmitted. The general structure, defined by the ITU Radio Regulations, is:

$$\underbrace{\text{Bandwidth}}_{\text{e.g., 2K80}}\quad\underbrace{\text{Letter}}_{\text{modulation type}}\quad\underbrace{\text{Digit}}_{\text{modulating signal}}\quad\underbrace{\text{Letter}}_{\text{information type}}$$

Symbol (1st letter, modulation)	Meaning
N	Unmodulated carrier
A	Double-sideband AM
J	Single-sideband, suppressed carrier (SSB)
F	Frequency modulation
G	Phase modulation

Symbol (3rd, information)	Meaning
A	Telegraphy, aural (Morse by ear)
B	Telegraphy, automatic reception
E	Telephony (voice)
F	Television/video
W	Combination of the above

Worked Example: Reading an emission designator

Interpret the emission designator `J3E`.
Solution. J = single-sideband, suppressed carrier; 3 = a single analog channel containing quantized or digital information... (for voice, simply a single analog channel); E = telephony. `J3E` is the standard designator for an SSB voice signal — exactly what most amateur SSB voice operation uses.

Exam Tip

You do not need to memorize every possible emission designator combination, but recognizing the common ones — `A1A` (CW, on-off keyed Morse), `J3E` (SSB voice), `F3E` (FM voice), `F1B`/`J2B` (common digital mode designators) — appears frequently on exams worldwide, since this designator system is one of the genuinely universal, non-country-specific pieces of amateur radio terminology.

24.3 Simplex and Duplex Operation

- **Simplex**: both stations transmit and receive on the same frequency, taking turns (one station transmits while the other listens, then they swap) — the default mode for most HF and casual VHF/UHF contacts.
- **Half-duplex**: communication can occur in both directions, but not simultaneously; a push-to-talk (PTT) transceiver used with separate transmit and

receive frequencies (as on many VHF/UHF repeaters) is technically half-duplex from the human operator's perspective, even though the underlying repeater itself transmits and receives simultaneously on different frequencies.

- **Full duplex**: both directions of communication happen simultaneously, each on its own frequency, with both parties able to transmit and receive at the same time (as in a telephone call) — less common in amateur voice operation but used in some satellite and repeater-linking contexts, and by the repeater itself even when users experience it as half-duplex.

24.4 Repeater Operation

A **repeater** receives a signal on one frequency (the **input**) and simultaneously retransmits it, usually with higher power and from an elevated, well-sited antenna, on a different frequency (the **output**), extending the effective range of low-power mobile and handheld stations well beyond normal line-of-sight limits. The frequency difference between input and output is the **offset** (a fixed, band-dependent value in most regions, occasionally requiring a specific value that differs by country or region). Many repeaters use a sub-audible tone or digital code (**CTCSS** or **DCS**) transmitted alongside the voice signal to selectively open the repeater only for users sending the correct tone/code, reducing accidental keying from unrelated signals on the input frequency.

24.5 Standard Operating Conventions

- **Calling frequency / calling channel**: a widely recognized frequency used to establish initial contact before moving to a working frequency, common in VHF/UHF simplex and in some HF sub-bands.
- **CQ call**: a general call inviting any station to respond ("CQ, CQ, CQ, this is . . . "), as opposed to calling a specific station directly.
- **Break-in / QSK**: full break-in CW operation, where the transmitter momentarily mutes between individual Morse elements so the operator can hear (and, if needed, immediately interrupt) the other station even while their own signal is going out.
- **Roger, over, out**: procedural words indicating, respectively, that a transmission was received and understood, that the operator is finished transmitting and awaiting a reply, and that the contact (or that operator's part of it) is complete and no reply is expected.

Exam Tip

Standard procedural words and Q-codes (Chapter 25) exist precisely because they are unambiguous across languages and accents, unlike improvised phrasing — using them correctly is both good practice and frequently tested on exams.

24.6 Interference and Good Spectrum Citizenship

Because spectrum is shared, every operator has a responsibility to minimize unnecessary interference: listening before transmitting (especially before calling CQ or joining a frequency already in use), using no more power than needed for reliable communication, keeping transmitted bandwidth as narrow as the mode reasonably requires (Chapter 6), and promptly addressing any equipment problem (spurious emissions, excessive splatter, an unstable signal) brought to their attention by other operators.

Chapter Review

- Emission designators (e.g., J3E, F3E, A1A) internationally describe bandwidth, modulation, and information type in a standardized, country-independent code.
- Simplex (shared frequency, taking turns), half-duplex (both directions possible, not simultaneous from the operator's side), and full duplex (simultaneous both ways) describe communication timing structure.
- Repeaters extend range by receiving on one frequency and retransmitting on another (the offset), often gated by CTCSS/DCS tones.
- Standard procedural conventions (CQ, roger/over/out, break-in) exist to keep communication unambiguous across languages and conditions.
- Minimizing interference through good operating habits is a universal amateur responsibility, independent of any specific national rule.

Practice Problems

1. Identify the modulation type, and information type, encoded in the emission designator `F3E`.
2. Explain the difference between half-duplex and full-duplex operation, using a repeater as an example.
3. Explain the purpose of CTCSS tone squelch on a repeater.

4. Explain why listening before transmitting (particularly before calling CQ) is considered good operating practice.
5. Explain why standardized procedural words like “roger” and “over” are preferred over improvised phrasing during radio contacts.

Chapter 25

The Phonetic Alphabet, Morse Code, and the Q-Code

Three shared international conventions let amateurs of any nationality communicate unambiguously, often across significant language barriers: a standard way to spell letters aloud, a standard code for sending text as sound, and a standard shorthand for common operating phrases. All three are examined constantly by licensing exams worldwide, because all three are genuinely universal.

25.1 The Phonetic Alphabet

Individual letters (especially in callsigns) are easily confused when spoken plainly, particularly over a noisy or weak radio link, or between speakers of different native languages. The **NATO phonetic alphabet** (formally the International Radiotelephony Spelling Alphabet) assigns each letter a distinct, unambiguous keyword chosen so that no two words sound alike even under poor conditions.

Ltr	Word	Ltr	Word	Ltr	Word
A	Alfa	J	Juliett	S	Sierra
B	Bravo	K	Kilo	T	Tango
C	Charlie	L	Lima	U	Uniform
D	Delta	M	Mike	V	Victor
E	Echo	N	November	W	Whiskey
F	Foxtrot	O	Oscar	X	X-ray
G	Golf	P	Papa	Y	Yankee
H	Hotel	Q	Quebec	Z	Zulu
I	India	R	Romeo		

Exam Tip

Note the standardized spellings *Alfa* (not "Alpha") and *Juliett* (with a double T) — deliberately chosen so the words are pronounced consistently by speakers of many different languages, none of whom necessarily share English spelling conventions. Exams occasionally test this exact spelling detail.

Numbers are spoken as their normal names in most amateur usage ("one," "two," . . . , "nine," "zero"), though some formal aviation/maritime contexts use modified pronunciations ("niner" for 9) to avoid confusion with similar-sounding words; check your local convention if operating in a formal net or emergency-communications context.

25.2 Morse Code (CW)

Morse code, still widely used on amateur HF bands under the name **CW** (continuous wave, referring to the on-off keyed carrier used to send it, Chapter 17), represents each letter, digit, and punctuation mark as a sequence of short (**dits**) and long (**dahs**) elements, conventionally in a 3:1 duration ratio, with defined spacing between elements, letters, and words.

Ltr	Code	Ltr	Code	Ltr	Code
A	.–	J	.– – –	S	...
B	–...	K	–.–	T	–
C	–.–.	L	.–..	U	..–
D	–..	M	––	V	...–
E	.	N	–.	W	.––
F	..–.	O	– – –	X	–..–
G	––.	P	.––.	Y	–.––
H	....	Q	––.–	Z	––..
I	..	R	.–.		

Numerals follow a regular pattern: 1 is `.--`, 2 is `..--`, counting down one dit at a time to 5 (`.....`), then counting up one dah at a time to 0 (`---`).

Key Idea: Timing, not just symbols

Morse code proficiency is fundamentally about *timing* recognition — a skilled operator hears whole letter and word *sounds* (the rhythm of "dah-dit-dah-dit" as "C," not four separately counted elements) rather than consciously decoding dits and dahs one at a time. Standard spacing is one unit between elements of the same letter, three units between letters, and seven units between words, all scaled by the sending speed (measured in words per minute, WPM).

25.3 CW Operating Abbreviations

To speed up telegraphy communication, standardized abbreviations (many predating amateur radio, originating in commercial and military telegraphy) shorten common words and phrases. A representative sample of the most frequently used:

Abbr.	Meaning	Abbr.	Meaning
AGN	Again	OM	Old man (fellow amateur)
BTU	Back to you	PSE	Please
CUL	See you later	RIG	Radio equipment
FB	Fine business (good/great)	RST	Signal report (R/S/Tone)
GA	Go ahead / Good afternoon	TNX/TKS	Thanks
GE	Good evening	UR	Your / You're
GM	Good morning	WX	Weather
HI	Laughter ("hi hi")	73	Best regards
HR	Here	88	Love and kisses (sparingly)
HW	How (copy)?		

25.4 The Q-Code

The **Q-code**, standardized by the ITU, is a set of three-letter groups (always beginning with Q) originally developed for commercial Morse telegraphy to compress common phrases into a fixed, language-independent shorthand. Each Q-code can function either as a question or a statement depending on context (with or without a question mark), and, while designed for CW, many have carried over into everyday voice operating slang worldwide.

Code	Meaning
QRG	What is my exact frequency? / Your exact frequency is ...
QRL	Is this frequency in use? / This frequency is in use, please do not interfere.
QRM	Are you being interfered with? / I am being interfered with (man-made interference).
QRN	Are you troubled by static? / I am troubled by static (natural/atmospheric noise).
QRO	Shall I increase power? / Increase power.
QRP	Shall I decrease power? / Decrease power (also used as a noun: "QRP operating," meaning low-power operation).
QRT	Shall I stop transmitting? / Stop transmitting.
QRV	Are you ready? / I am ready.
QRX	When will you call again? / I will call you again at ...
QRZ	Who is calling me?
QSB	Is my signal fading? / Your signal is fading.
QSL	Can you acknowledge receipt? / I acknowledge receipt (also used as a noun: a "QSL card" confirms a contact).
QSO	Can you communicate with ... directly? / I can communicate with ... (also used as a noun: "a QSO" means a contact/conversation).
QSY	Shall I change frequency? / Change frequency to ...
QTH	What is your location? / My location is ...

Exam Tip

QTH, QSL, QRP, QSO, and QRM/QRN are used so pervasively — even in casual English-language voice conversation among amateurs worldwide — that they function almost as ordinary vocabulary within the hobby. Learn these five thoroughly even before memorizing the rest of the list.

25.5 The RST Signal Report

Signal reports are conventionally given using the **RST** system: **R**eadability (1–5, from unreadable to perfectly readable), **S**trength (1–9, from faint to extremely strong), and **T**one (1–9, CW only, describing the purity/quality of the received tone; commonly omitted or given as "9" for voice modes, where it does not apply in the same way). A report of "59" (voice) or "599" (CW) — perfectly readable, very strong, perfectly pure tone — represents an excellent signal.

Chapter Review

- The NATO phonetic alphabet (Alfa, Bravo, Charlie, ...) gives unambiguous letter spelling across languages and conditions.
- Morse code represents letters as dit/dah patterns in fixed timing ratios; proficiency means recognizing rhythm, not counting symbols.
- Standardized CW abbreviations (FB, GA, TNX, 73, ...) speed up telegraphy and remain common in general amateur slang.
- The Q-code (QTH, QSL, QRM, QSY, ...) is an ITU-standardized, language-independent operating shorthand usable on both CW and voice.
- RST reports (Readability/Strength/Tone) give a standardized way to describe received signal quality.

Practice Problems

1. Spell your own callsign (or a hypothetical one) using the NATO phonetic alphabet.
2. Write the Morse code for the letters composing "CQ."
3. Explain the meaning of QRZ, QSY, and QRT.
4. A CW operator sends "UR RST 599 HR, TNX FER CALL, 73." Translate this into plain English.
5. Explain why a language-independent code system like the Q-code is particularly valuable in amateur radio, compared to using plain national-language phrases.

Chapter 26

Digital Modes and Modern Radio

Amateur radio has always adopted new technology quickly, and the past two decades have brought a wave of digital modes and software-defined techniques that meaningfully extend what a modest station can achieve. This chapter surveys the modern digital operating landscape, building on the modulation (Chapter 17) and error-control (Chapter 18) foundations already covered.

26.1 Why Digital Modes

Compared to analog voice, digital modes can be engineered for specific, quantifiable goals: minimum bandwidth for a given data rate, maximum robustness to noise and fading at a given signal level, or maximum throughput for file/data transfer. Because a digital signal's information content is a defined, known set of discrete states, its processing gain (Chapter 18) can be pushed far beyond what human hearing achieves decoding analog voice or even CW by ear, letting well-designed digital modes complete contacts at signal levels where a voice or CW signal would be completely inaudible.

26.2 Keyboard-to-Keyboard Text Modes

- **RTTY (radioteletype)**: one of the oldest amateur digital modes, using frequency-shift keying (Chapter 17) between two audio tones to send Baudot-coded text, historically implemented with electromechanical teleprinters and now almost universally via a computer sound card.
- **PSK31**: a narrowband phase-shift-keyed mode designed specifically for real-time keyboard-to-keyboard conversation, using a variable-length coding scheme (shorter codes for more common letters) that keeps typical typing speeds within an extremely narrow bandwidth (around 31 Hz, hence the name) — allowing many simultaneous PSK31 conversations within the bandwidth a single SSB voice signal would occupy.

26.3 Weak-Signal and Low-Rate Modes

A newer generation of modes, largely built around combining strong forward error correction (Chapter 18) with narrow bandwidth and computer-controlled precise timing, trades data rate for extreme sensitivity:

- **FT8** and related modes (part of the WSJT-X/MSHV software family): structured, computer-synchronized exchanges (typically 15 seconds per transmission, tightly time-aligned to UTC) carrying a minimal, highly compressed message set (callsigns, grid locators, signal reports) using strong FEC coding, able to complete a logged contact with signals well below the audible noise floor. The constrained message format is a deliberate trade-off: extreme sensitivity and speed of exchange, at the cost of the free-form conversation possible on voice, CW, or PSK31.
- **WSPR (Weak Signal Propagation Reporter)**: a very low-rate, beacon-style mode designed not for two-way conversation but for automatically probing and mapping propagation conditions, with receiving stations automatically reporting decoded signals (including estimated signal strength) to a shared online database.
- **JT65 and related legacy modes**: earlier members of the same weak-signal design family as FT8, historically important for enabling reliable Earth-Moon-Earth (moonbounce) and other extreme-path contacts that were previously impractical with analog modes.

26.4 Digital Voice

Digital voice modes encode speech as compressed digital data (using a **vocoder**) and transmit it much as any other digital data stream, typically over FM. Several competing amateur digital voice systems exist (differing in vocoder technology, network architecture, and whether they are open or proprietary standards), generally offering improved noise immunity and, where linked over the internet, wide-area or global connectivity between repeaters and hotspots — extending local VHF/UHF coverage far beyond a single repeater's radio footprint, though at the cost of a hard failure mode (digital signals tend to either decode cleanly or not at all, rather than degrading gracefully like analog FM near the noise floor).

26.5 Packet Radio and Data Networking

Packet radio, built on the amateur **AX.25** protocol (itself derived from a wired data-networking standard, adapted for radio), packages data into discrete, individually addressed and checksummed packets (Chapter 18), enabling store-and-forward messaging, position/status broadcasting (as used by **APRS**, the Automatic Packet Reporting System, which continuously broadcasts station location, weather, and status data over a shared network of digipeaters and internet gateways), and email-like messaging over radio-only paths (as used by systems such as Winlink, particularly valuable for emergency and remote/maritime communication where internet access is unavailable).

26.6 Software-Defined Radio in Practice

Building on the SDR receiver concepts introduced in Chapter 16, modern amateur transceivers increasingly implement transmit signal generation the same way: digital signal processing generates the desired waveform (SSB, FM, digital mode audio, or a fully digital signal) which is then converted to analog and upconverted to the operating frequency, rather than being built up through a chain of discrete analog mixer and filter stages. This architecture makes it practical for a single piece of hardware to support an enormous and continually growing range of modes purely through software updates, and has made computer-controlled digital modes far more accessible than in the era of dedicated hardware modems for each individual mode.

26.7 Choosing a Mode

Key Idea

No single mode is universally "best"; the right choice depends on the goal. Voice (SSB/FM) suits real-time conversation and is the most accessible to newcomers. CW remains highly effective in poor conditions with minimal bandwidth and equipment. Weak-signal digital modes (FT8 and similar) excel at making contacts under marginal propagation but support only minimal, structured exchanges. Packet-based data modes (APRS, Winlink) suit position reporting and message delivery rather than conversation at all. A well-rounded operator learns enough about each family to select the right tool for a given goal and set of band conditions.

Chapter Review

- Digital modes trade among bandwidth, data rate, and sensitivity in ways that can be engineered far more precisely than analog voice or manual CW.
- RTTY and PSK31 support real-time keyboard-to-keyboard text conversation with modest bandwidth.
- FT8, WSPR, and related weak-signal modes use strong FEC, narrow bandwidth, and precise timing to decode signals below the audible noise floor, at the cost of a constrained message format.
- Digital voice modes offer noise-immune audio and, when linked, wide-area connectivity, with a more abrupt (rather than gradual) failure mode than analog FM.
- Packet radio (AX.25), APRS, and Winlink extend amateur radio into automated data networking, position reporting, and message delivery.

Practice Problems

1. Explain why FT8 can complete a contact when a voice signal at the same power and antenna would be inaudible.
2. Explain the practical trade-off between FT8's extreme sensitivity and its very limited message format.
3. Explain the purpose of APRS, and name one practical use beyond simple vehicle tracking.
4. Explain why digital voice modes are described as having a more "abrupt" failure mode than analog FM as signal strength decreases.
5. Given a goal of making a contact under very poor HF propagation conditions with a modest antenna, which mode family from this chapter would you choose, and why?

Chapter 27

Emergency Communications and Safety

One of amateur radio's most valued roles, recognized by the ITU Radio Regulations and by disaster-response organizations worldwide, is serving as an independent, resilient communications resource when normal infrastructure fails. This closing chapter covers the operating and safety knowledge specific to that role, along with a summary of the electrical and RF safety principles referenced throughout the book.

27.1 Why Amateur Radio Matters in Emergencies

Commercial communication systems — cellular networks, internet service, even commercial broadcast — depend on infrastructure (power, switching centers, network links) that can fail during earthquakes, hurricanes, wildfires, floods, and other large-scale disasters, often precisely when communication is needed most. Amateur radio stations, particularly battery- or generator-powered portable and mobile stations, can remain operational independent of commercial infrastructure, and the amateur service's worldwide network of trained, licensed, self-equipped operators represents a substantial standing capability that many national and local emergency management organizations formally incorporate into their planning.

27.2 Priority for Emergency Communications

Key Idea

The ITU Radio Regulations recognize that normal band-planning and operating conventions may reasonably be set aside during a genuine emergency: a station in distress, or relaying safety-of-life traffic, generally takes priority over routine communications, and many national regulators grant amateurs specific latitude (for example, to operate outside normal amateur allocations, or with otherwise non-compliant equipment, in a genuine life-safety emergency) precisely because saving life takes priority over routine spectrum discipline. The exact scope of this latitude is defined by national law and should be understood *before* an emergency, not improvised during one.

27.3 Distress and Priority Calling

- **Mayday** (from the French *m'aidez*, "help me"): the internationally recognized voice distress call, used only for a genuine grave and imminent threat to life or a vessel/aircraft, repeated three times to open a distress transmission and avoid confusion with similar-sounding routine traffic.
- **SOS**: the equivalent distress signal in Morse code (... -- ..., sent as a single continuous string without inter-letter spacing), historically the maritime radiotelegraph distress call and still recognized internationally.
- **Pan-pan**: an urgency call, one level below a full distress call — used for a situation that is serious and requires assistance but does not yet pose an immediate threat to life.

Safety

Distress and urgency calls (Mayday, SOS, Pan-pan) are reserved exclusively for genuine emergencies. Misuse — even as a joke or test without clearly identifying it as a drill — is taken extremely seriously by regulators worldwide and can trigger a real emergency response, waste critical resources, and carries serious legal consequences in virtually every jurisdiction.

27.4 Emergency Communications Organizations and Nets

Many countries have formal or informal amateur emergency communications organizations (structured around IARU member societies or independent of them) that train volunteer operators, maintain rosters, and liaise with local government and disaster-response agencies; specific organization names and structures vary by country. A common operational tool across virtually all of these organizations is the **net**: a structured, moderated on-air session with a designated **net control station (NCS)** managing who transmits when, used both for routine training/practice and for actual incident response, where its structure prevents the chaos of many stations trying to communicate urgent information simultaneously.

27.5 Traffic Handling

Formal **message (traffic) handling** — relaying a structured message accurately from an origin station, potentially through one or more intermediate relay stations, to a final destination — is a distinct operating skill from casual conversation, built around standardized message formats and strict accuracy (reading back critical details, spelling names and numbers phonetically) precisely because an error introduced during relay can have real consequences in a genuine emergency message.

27.6 Preparing a Station for Emergency Readiness

- **Independent power**: batteries, solar, or generator capability sufficient to operate for the expected duration of a communications-infrastructure outage, sized using the amp-hour and runtime concepts of Chapter 12.
- **Portable, field-deployable antennas**: capability to erect an effective antenna away from a station's normal fixed installation, should that installation be damaged or inaccessible.
- **Multi-band, multi-mode capability**: the ability to fall back to whatever band and mode (voice, CW, digital) actually propagates under the specific conditions present during an event, rather than depending on a single favored combination.
- **Practiced procedure**: familiarity with local net structure, message formats, and any specific emergency-communications role an operator has trained for, built through regular participation in practice nets and drills *before* a real event.

27.7 General Electrical and RF Safety Review

This closing section consolidates safety principles introduced throughout the book:

Safety: Electrical safety

Mains voltage and high-voltage supplies (found in some transmitter final amplifier stages) can be lethal. Always verify power is removed and capacitors are discharged (Chapter 7) before working inside equipment; use proper grounding and, where required, ground-fault protection; never work on energized equipment alone.

Safety: RF exposure

RF energy at sufficient power density can cause tissue heating; most national regulators define maximum permissible exposure limits and, at higher power levels, may require an RF exposure evaluation of a specific antenna installation. Maintain appropriate separation from antennas while transmitting at significant power, be aware that handheld and mobile antennas are typically operated very close to the body, and consult your national regulator's specific RF exposure requirements and calculation methods.

Safety: Antenna and tower safety

Antenna installation work, particularly at height or near power lines, carries serious fall and electrocution risk. Maintain safe clearance from all power lines (a falling or wind-blown antenna or mast contacting a power line is a leading cause of serious amateur radio accidents and fatalities worldwide), use proper fall-protection equipment when working at height, and never work alone on tower or mast installations.

Safety: Lightning and grounding

A station's antenna system should include appropriate lightning protection and grounding, and antenna feedlines should be disconnected and, ideally, grounded, during electrical storms. Station and antenna grounding also reduces RF interference and stray voltage issues even outside of storm conditions.

Chapter Review

- Amateur radio's independence from commercial infrastructure makes it a valued emergency communications resource worldwide, formally recognized by the ITU and incorporated into many national/local emergency plans.

- Mayday/SOS (distress) and Pan-pan (urgency) are internationally recognized priority calls reserved strictly for genuine emergencies.
- Nets, with a net control station, provide the structure needed to manage many stations during incident response; formal traffic handling demands strict accuracy.
- Emergency readiness combines independent power, portable antennas, multimode capability, and practiced procedure developed before an actual event.
- Electrical, RF exposure, tower/antenna, and lightning/grounding safety are cross-cutting concerns that apply to every chapter's technical content in real-world practice.

Practice Problems

1. Explain the difference between a Mayday call and a Pan-pan call, and give an example situation appropriate to each.
2. Explain why amateur radio is often specifically valued during large-scale natural disasters, in terms of infrastructure independence.
3. Explain the role of a net control station during an emergency net, and why unstructured simultaneous transmission would be problematic.
4. List three components of a well-prepared emergency-ready amateur station, and briefly justify each.
5. Explain why antenna and mast installation work near power lines is considered one of the more serious safety risks in amateur radio.

Part VI

Beyond the Amateur Bands: Enrichment

Chapter 28

Beyond the Amateur Bands: Aviation, Maritime, and Military Radio

The radio spectrum an amateur studies for exams is one neighborhood in a much larger city. Cheap, wideband software-defined radio hardware — a USB dongle costing little more than a cable, paired with free decoding software — has made it trivial for anyone with a computer to *listen* across aviation, maritime, and other services that once required specialized, expensive receivers. This chapter is a broadening excursion outside the amateur allocations: it will not be on your license exam, but it uses exactly the same physics (modulation, propagation, antennas) developed everywhere else in this book, and it is one of the most popular on-ramps into the hobby for newcomers arriving via SDR rather than via a first callsign.

28.1 A Note on Legality Before You Start

Safety: Receiving is not the same everywhere

Whether it is legal to *receive* (listen to) transmissions outside the amateur bands — and whether it is legal to *disclose* the content of what you hear — varies enormously by country, and sometimes by the specific service involved. Many countries permit receive-only monitoring of aviation and maritime traffic freely; others restrict it; several restrict listening to cellular telephone traffic specifically even where other monitoring is permitted; a smaller number restrict radio scanning broadly. **Transmitting** on any frequency outside your license privileges is illegal essentially everywhere and is not discussed in this chapter. Before monitoring any service described here, confirm the specific rules in your own country. This chapter describes what these signals *are* and how they work, purely as radio science and engineering education — it is not guidance on where such monitoring is or is not legally permitted.

28.2 The SDR Monitoring Ecosystem

The same direct-sampling and quadrature-sampling architectures described in Chapter 16 underpin an entire hobby ecosystem built around inexpensive wideband receivers (commonly covering roughly 24 MHz to 1.7 GHz or wider on the least expensive devices, extended further with upconverters or purpose-built HF-capable units) feeding open-source decoding software. Because these receivers present raw digitized RF to a host computer rather than a single fixed demodulator, one piece of hardware can be retargeted from one service to another purely by changing software — the same receiver that tracks aircraft one moment can decode marine safety broadcasts the next. Antenna choice matters considerably: a simple dipole cut for one amateur band performs poorly far outside that band, so serious multi-service monitoring typically uses a wideband discone, log-periodic, or service-specific antenna (an airband-optimized vertical, for instance) rather than a repurposed amateur antenna.

28.3 Aviation

28.3.1 VHF Air-Band Voice

Civil aviation voice communication (air traffic control, pilot position reports) uses AM voice — notably *not* FM — in the roughly 118–137 MHz band, internationally, with 25 kHz or (in some regions) narrower 8.33 kHz channel spacing. AM was retained for aviation long after FM became dominant elsewhere in VHF land mobile use for a specific safety reason: when two aircraft transmit AM signals on the same channel simultaneously, both are typically still at least partially intelligible (a heterodyne tone is heard, but speech often remains readable); simultaneous FM transmissions on the same channel instead tend to produce the FM capture effect (Chapter 17), where only the stronger signal is heard and the weaker one is suppressed entirely — far more dangerous if the suppressed transmission was a safety-critical call.

28.3.2 ACARS and VDL

ACARS (Aircraft Communications Addressing and Reporting System) is a digital datalink that airliners use to exchange short, structured messages with airline operations centers — position reports, weather requests, maintenance data, gate information — largely automatically, without a pilot manually keying a microphone. Classic ACARS uses a relatively simple 2400-baud audio-frequency-shift-keyed signal on VHF frequencies around 131 MHz, decodable with widely available free software directly from an SDR's audio output; a modern successor, **VDL Mode 2**, uses a more spectrally efficient D8PSK-modulated signal carrying substantially more traffic and is now the dominant form on the primary international ACARS frequency. Decoded ACARS traffic is largely operational/administrative rather than safety-of-life air traffic control communication, but it offers a vivid, approachable illustration of a real-world FSK/PSK digital data link (Chapter 17) running continuously overhead.

28.3.3 Mode S, ADS-B, and Aircraft Tracking

Modern aircraft transponders reply to ground radar interrogation, and increasingly broadcast unprompted, on **1090 MHz** using a pulse-position-modulated format. **ADS-B** (Automatic Dependent Surveillance–Broadcast) extends this into a self-announced digital message containing an aircraft's GPS-derived position, altitude, velocity, and identity, transmitted roughly once per second without requiring any ground interrogation. Because 1090 MHz ADS-B messages are unencrypted and specifically designed for wide reception, decoding them with an inexpensive SDR dongle and free software is one of the most popular and beginner-friendly SDR projects, commonly used to build real-time aircraft tracking maps and to contribute data to crowd-sourced flight-tracking networks.

28.3.4 HF Aviation

Over oceans and remote regions beyond VHF line-of-sight range, aviation falls back to HF skywave propagation (Chapter 21), using dedicated internationally coordinated frequencies for long-range air traffic control voice and, increasingly, the digital **HFDL** (HF Data Link) datalink — functionally an HF-band counterpart to VHF ACARS/VDL, using multiple simplex ground-station frequencies with the aircraft selecting whichever currently propagates best. **SELCAL** (selective calling) tones allow a ground station to silently alert a specific aircraft's flight deck on an otherwise-monitored HF voice channel without requiring continuous crew listening.

28.4 Maritime

28.4.1 VHF Marine Band and Digital Selective Calling

Maritime VHF (approximately 156–174 MHz, internationally standardized into numbered channels) carries ship-to-ship and ship-to-shore voice traffic, with specific channels reserved by international agreement for distress, safety, and calling purposes. **Digital Selective Calling (DSC)**, a burst digital signal on a dedicated calling channel, allows a vessel to transmit an automated, GPS-tagged distress alert

— identifying the vessel and its position — at the press of a single guarded button, then directs other stations to a working voice channel, substantially speeding up distress response compared to voice alerting alone.

28.4.2 NAVTEX

NAVTEX broadcasts maritime safety information — navigational warnings, weather forecasts and warnings, search-and-rescue notices — as narrow-band direct-printing (digital text) transmissions on standardized frequencies (internationally, principally 518 kHz), automatically received and printed or displayed by dedicated shipboard receivers without requiring an operator to be actively listening, extending the same store-and-forward safety philosophy amateur emergency nets rely on (Chapter 27) into routine commercial and leisure maritime operation.

28.4.3 AIS: Automatic Identification System

AIS is the maritime counterpart to aviation's ADS-B: vessels above a certain size (and many smaller ones voluntarily) broadcast position, course, speed, and identity using a GMSK-modulated digital signal on two dedicated VHF channels (161.975 and 162.025 MHz), enabling both collision avoidance between nearby vessels and shore-based or satellite-based global vessel tracking. Like ADS-B, AIS is unencrypted by design and is a popular, approachable SDR decoding project.

28.4.4 The GMDSS Framework

These maritime systems — VHF DSC, NAVTEX, and additional HF/satellite components not detailed here — fit within the international **Global Maritime Distress and Safety System (GMDSS)**, a layered, largely automated framework designed so that a vessel in distress has multiple independent, largely automatic paths to alert rescue authorities even if a radio operator cannot personally send a manual distress call — a philosophy directly comparable to the redundancy and priority-of-life-safety-traffic principles discussed for amateur emergency communications in Chapter 27.

28.5 Military and Government Radio

Military and government radio use spans the same physics as every other service in this book, generally with three practical differences from civil use: greater use of encryption and specialized waveforms (which SDR monitoring cannot and should not attempt to defeat), greater use of frequency-hopping and other anti-jam/anti-intercept techniques, and, for what remains observable, a strong tradition of extremely disciplined, standardized procedure.

28.5.1 HF Global Communications

Long-range military HF communication, like civil aviation and maritime HF, relies on ionospheric skywave propagation (Chapter 21). Some military HF networks (for example, the United States Air Force's High Frequency Global Communications System, historically monitored under callsigns beginning "Skyking" for certain emergency-action traffic) use plain, highly standardized voice procedure specifically so that the format itself, not secrecy of the channel, provides authentication — an interesting contrast to the assumption that "military" automatically means "encrypted."

28.5.2 Numbers Stations

Numbers stations — shortwave broadcasts reading strings of spoken digits, letters, or coded phrases, often preceded by a distinctive interval signal or melody — have been observed on HF for decades and are widely believed (though rarely officially acknowledged by any government) to transmit one-time-pad-encrypted messages to field intelligence operatives, since a correctly used one-time pad is theoretically unbreakable regardless of how many people listen to the broadcast. Whatever their true purpose, numbers stations are a freely and legally receivable, genuinely strange corner of the HF spectrum, and a favorite target for SDR hobbyists purely as a listening curiosity.

28.5.3 Trunked and Digital Land Mobile Radio

Public safety and some military land-mobile users increasingly use **trunked radio** systems (where a pool of frequencies is shared dynamically among many talkgroups under computer control, rather than each group having a permanently dedicated channel) built on digital standards such as P25 or DMR (Chapter 26 covers the general digital voice/vocoder concepts these systems share with amateur digital voice). Many such systems are receivable in the clear with appropriate SDR software; increasingly many others are encrypted, which SDR software can identify (the traffic is present and structured) without being able to decode the actual content.

28.6 Why This Matters Even If You Never Transmit Here

Key Idea

Every signal in this chapter is built from the same building blocks covered earlier in this book: a carrier, a modulation scheme (Chapter 17), a propagation path (Chapter 21), and, for the digital ones, an error-control scheme (Chapter 18). Listening to AM aviation voice next to FM amateur repeater traffic, or watching an ADS-B decoder plot aircraft in real time next to an APRS map (Chapter 26), is one of the fastest ways to make those chapters feel like real, observable physics rather than abstract formulas — which is exactly why this material, though absent from any license exam, belongs in a book about understanding radio deeply rather than just passing a test.

Chapter Review

- Legality of receive-only monitoring, and of disclosing what is received, varies by country and by service — verify local rules before monitoring; transmitting outside your license privileges is illegal essentially everywhere.
- Cheap wideband SDR hardware plus free software lets one receiver retarget across aviation, maritime, and other services entirely in software.
- Aviation uses AM voice (deliberately, for graceful co-channel degradation), ACARS/VDL digital datalink, and unencrypted 1090 MHz ADS-B position broadcasts; HF extends aviation communication beyond VHF range with HFDL and SELCAL.
- Maritime uses VHF voice with DSC digital distress alerting, NAVTEX safety broadcasts, and AIS vessel tracking, all coordinated under the GMDSS framework.
- Military/government use spans the same physics with more encryption, frequency-hopping, and standardized procedure; numbers stations and observable-but-encrypted trunked systems are notable SDR curiosities.

Practice Problems

1. Explain why civil aviation retained AM voice rather than switching to FM, in terms of co-channel interference behavior.

2. Explain the functional difference between classic ACARS and VDL Mode 2, referencing the modulation concepts of Chapter 17.
3. Explain why ADS-B and AIS are described as "unencrypted by design," and why that design choice makes sense given their safety purpose.
4. Explain the role of DSC in maritime distress alerting, and how it differs from a traditional spoken Mayday call.
5. Before monitoring any service in this chapter, what should you personally verify first, and why does this book decline to state a single universal answer?

Appendix A

Formula Reference

This appendix collects every major formula developed in the book, organized by topic and cross-referenced to the chapter where it is derived and explained. Use it for rapid review and problem-solving — but remember that recognizing *when* and *why* to apply a formula matters as much as recalling it.

Units and Basic Math (Chapter 1)

$$f_{\mathrm{Hz}} = \frac{1}{T_{\mathrm{s}}} \qquad \text{frequency–period}$$

$$\log(ab) = \log a + \log b, \quad \log(a/b) = \log a - \log b, \quad \log(a^n) = n \log a$$

$$\theta_{\mathrm{rad}} = \theta_{\mathrm{deg}} \times \frac{\pi}{180}$$

Electricity Fundamentals (Chapter 2)

$$I = \frac{Q}{t} \qquad U = \frac{W}{Q}$$

$$U = IR \qquad \text{(Ohm's law)}$$

$$R = \rho \frac{\ell}{A}$$

$$P = UI = I^2 R = \frac{U^2}{R}$$

$$W = Pt$$

DC Circuits (Chapter 3)

$$\text{Series: } R_{\text{total}} = R_1 + R_2 + \cdots \qquad U_n = U\frac{R_n}{R_{\text{total}}}$$

$$\text{Parallel: } \frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots \qquad R_{\text{total}} = \frac{R_1 R_2}{R_1 + R_2} \text{ (two resistors)}$$

$$I_1 = I_{\text{total}}\frac{R_2}{R_1 + R_2} \qquad \text{(current divider, two branches)}$$

Fields (Chapter 4)

$$E = \frac{F}{q} = \frac{U}{d} \qquad B = \frac{\mu_0 I}{2\pi r}$$

$$\Phi = BA \qquad \mathcal{E} = -N\frac{d\Phi}{dt} \quad \text{(Faraday's law)}$$

$$c = f\lambda = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 2.998 \times 10^8 \text{ m/s}$$

AC Theory (Chapter 5)

$$v(t) = V_{\text{pk}} \sin(\omega t + \phi), \quad \omega = 2\pi f$$

$$V_{\text{pp}} = 2V_{\text{pk}} \qquad V_{\text{rms}} = \frac{V_{\text{pk}}}{\sqrt{2}} \approx 0.707 V_{\text{pk}}$$

$$V_{\text{avg}} = \frac{2V_{\text{pk}}}{\pi}$$

Capacitors (Chapter 7)

$$C = \frac{Q}{U} \qquad C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

$$i = C\frac{dU}{dt} \qquad W = \frac{1}{2}CU^2$$

$$\text{Parallel: } C_{\text{total}} = C_1 + C_2 + \cdots \qquad \text{Series: } \frac{1}{C_{\text{total}}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots$$

$$X_C = \frac{1}{2\pi f C} \qquad Z_C = -jX_C$$

Inductors (Chapter 8)

$$u = L\frac{di}{dt} \qquad L = \frac{\mu_0 N^2 A}{\ell}$$

$$W = \frac{1}{2}LI^2$$

$$\text{Series: } L_{\text{total}} = L_1 + L_2 + \cdots \qquad \text{Parallel: } \frac{1}{L_{\text{total}}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots$$

$$X_L = 2\pi f L \qquad Z_L = jX_L$$

RC/RL Transients and AC Impedance (Chapter 9)

$$U_C(t) = U_0(1 - e^{-t/\tau}), \quad \tau = RC \qquad \text{(RC charging)}$$

$$U_C(t) = U_0 e^{-t/\tau} \qquad \text{(RC discharge)}$$

$$i(t) = \frac{U_0}{R}(1 - e^{-t/\tau}), \quad \tau = \frac{L}{R} \qquad \text{(RL current buildup)}$$

$$Z = R \mp jX, \quad |Z| = \sqrt{R^2 + X^2}, \quad \theta = \arctan\left(\frac{X}{R}\right)$$

$$f_c = \frac{1}{2\pi RC} \text{ (RC)} \qquad f_c = \frac{R}{2\pi L} \text{ (RL)}$$

RLC Resonance and Q (Chapter 10)

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$Q = \frac{X_L}{R} = \frac{X_C}{R} = \frac{1}{R}\sqrt{\frac{L}{C}} \text{ (series)} \qquad Q = \frac{R}{X_L} = R\sqrt{\frac{C}{L}} \text{ (parallel)}$$

$$B = \frac{f_0}{Q}$$

Transformers (Chapter 11)

$$\frac{U_2}{U_1} = \frac{N_2}{N_1} = n \qquad \frac{I_2}{I_1} = \frac{1}{n}$$

$$Z_1 = n^2 Z_2 \qquad \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

Power Sources (Chapter 12)

$$U_{\text{terminal}} = \text{EMF} - IR_{\text{int}}$$

$$t \approx \frac{\text{Capacity (Ah)}}{I_{\text{load}}} \qquad W_h = \text{Ah} \times U_{\text{nominal}}$$

Transistors (Chapter 13)

$$I_C = \beta I_B \qquad I_E = I_B + I_C$$

Op-Amps (Chapter 14)

$$A_v = -\frac{R_f}{R_1} \text{ (inverting)} \qquad A_v = 1 + \frac{R_f}{R_1} \text{ (non-inverting)}$$

Decibels (Chapter 15)

$$dB = 10\log_{10}\left(\frac{P_2}{P_1}\right) \qquad dB = 20\log_{10}\left(\frac{U_2}{U_1}\right)$$

$$P(\text{dBm}) = 10\log_{10}\left(\frac{P(\text{mW})}{1\,\text{mW}}\right) \qquad \text{dBi} = \text{dBd} + 2.15$$

$$\text{SNR (dB)} = 10\log_{10}\left(\frac{P_{\text{signal}}}{P_{\text{noise}}}\right)$$

Receivers (Chapter 16)

$$f_{\text{IF}} = |f_{\text{signal}} - f_{\text{LO}}| \qquad f_{\text{image}} = f_{\text{signal}} \pm 2f_{\text{IF}}$$

Modulation (Chapter 17)

$$m = \frac{V_m}{V_c} \text{ (AM modulation index)}$$

$$\beta = \frac{\Delta f}{f_m} \text{ (FM modulation index)} \qquad B \approx 2(\Delta f + f_m) \text{ (Carson's rule)}$$

Transmission Lines and SWR (Chapter 19)

$$Z_0 = \sqrt{\frac{L'}{C'}} \qquad \Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$$\text{SWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \qquad \frac{P_\text{reflected}}{P_\text{forward}} = |\Gamma|^2$$

$$Z_\text{in} = \frac{Z_0^2}{Z_L} \text{ (quarter-wave transformer)}$$

Antennas (Chapter 20)

$$\ell_\text{dipole,m} \approx \frac{143}{f_\text{MHz}} \qquad \ell_\text{dipole,ft} \approx \frac{468}{f_\text{MHz}}$$

$$\eta = \frac{R_\text{rad}}{R_\text{rad} + R_\text{loss}} \times 100\%$$

Propagation (Chapter 21)

$$d_\text{km} \approx 4.12\sqrt{h_\text{m}} \text{ (radio horizon, per antenna)}$$

$$\text{MUF} = f_c \sec(\theta) \text{ (secant law)}$$

Physical Constants Used Throughout

$c = 2.998 \times 10^8$ m/s	speed of light
$e = 1.602 \times 10^{-19}$ C	elementary charge
$\mu_0 = 4\pi \times 10^{-7}$ H/m	permeability of free space
$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m	permittivity of free space
Z_0 (free space) $\approx 377\,\Omega$	impedance of free space

Appendix B

Units, Prefixes, and Physical Constants

SI Prefixes

Prefix	Symbol	Factor
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
—	—	10^{0}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

Electrical Units

Quantity	Symbol	Unit	Unit symbol
Charge	Q	coulomb	C
Current	I	ampere	A
Voltage	U	volt	V
Resistance	R	ohm	Ω
Conductance	G	siemens	S
Capacitance	C	farad	F
Inductance	L	henry	H
Power	P	watt	W
Energy	W	joule	J
Frequency	f	hertz	Hz
Magnetic flux	Φ	weber	Wb
Flux density	B	tesla	T

Physical Constants

Constant	Symbol	Value
Speed of light (vacuum)	c	$2.998 \times 10^{8}\,\mathrm{m/s}$
Elementary charge	e	$1.602 \times 10^{-19}\,\mathrm{C}$
Permeability of free space	μ_0	$4\pi \times 10^{-7}\,\mathrm{H/m}$
Permittivity of free space	ε_0	$8.854 \times 10^{-12}\,\mathrm{F/m}$
Impedance of free space	Z_0	$\approx 377\,\Omega$
Boltzmann constant	k	$1.381 \times 10^{-23}\,\mathrm{J/K}$

Common Unit Conversions

Conversion	Relation
Wavelength/frequency	$\lambda(\text{m}) = 300/f(\text{MHz})$
Degrees to radians	$\theta_{\text{rad}} = \theta_{\text{deg}} \times \pi/180$
Power ratio to dB	$dB = 10\log_{10}(P_2/P_1)$
Watt-hours to joules	$1\,\text{Wh} = 3600\,\text{J}$
Inches to metres	$1\,\text{in} = 0.0254\,\text{m}$
Feet to metres	$1\,\text{ft} = 0.3048\,\text{m}$

Resistor Color Code Quick Reference

Color	Digit	Multiplier
Black	0	$\times 10^0$
Brown	1	$\times 10^1$
Red	2	$\times 10^2$
Orange	3	$\times 10^3$
Yellow	4	$\times 10^4$
Green	5	$\times 10^5$
Blue	6	$\times 10^6$
Violet	7	$\times 10^7$
Grey	8	$\times 10^8$
White	9	$\times 10^9$
Gold	—	$\times 10^{-1}$ ($\pm 5\%$)
Silver	—	$\times 10^{-2}$ ($\pm 10\%$)

Amateur HF Band Wavelength/Frequency Correspondence

The traditional metre-band names used throughout the amateur service are derived from approximate free-space wavelength, $\lambda \approx 300/f_{\text{MHz}}$, and are consistent across ITU Regions even though exact band edges can differ regionally (Chapter 23):

Band name	Approximate frequency range
160 m	1.8–2.0 MHz
80 m	3.5–4.0 MHz
40 m	7.0–7.3 MHz
20 m	14.0–14.35 MHz
17 m	18.068–18.168 MHz
15 m	21.0–21.45 MHz
12 m	24.89–24.99 MHz
10 m	28.0–29.7 MHz
6 m	50–54 MHz (Region 2/3; narrower/absent in parts of Region 1)
2 m	144–148 MHz (varies by Region/country)
70 cm	420–450 MHz (varies by Region/country)

Always confirm exact current band edges and any sub-band restrictions with your own national regulator — these figures are approximate and change over time and by jurisdiction.

Appendix C

Glossary

AGC Automatic gain control; a receiver feedback loop that reduces gain for strong signals and restores it for weak ones.

AGN, BTU, FB, . . . see CW operating abbreviations, Chapter 25.

AM Amplitude modulation.

APRS Automatic Packet Reporting System; packet-radio-based position and status broadcasting network.

ARQ Automatic repeat request; retransmission triggered by a failed error-detection check.

Balun Balanced-to-unbalanced transformer.

Bandwidth The range of frequencies a signal or filter occupies.

BJT Bipolar junction transistor.

CEPT European Conference of Postal and Telecommunications Administrations; facilitates reciprocal amateur licensing in Europe.

Critical frequency Highest frequency reflected by the ionosphere for a vertically transmitted signal.

CRC Cyclic redundancy check; an error-detection scheme.

CTCSS Continuous tone-coded squelch system; sub-audible repeater access tone.

CW Continuous wave; on-off keyed Morse code telegraphy.

dB, dBm, dBi, dBd Decibel and its absolute-reference variants; see Chapter 15.

Deviation Peak frequency shift in FM, Δf.

Dipole A two-element antenna fed at its center.

Directivity Concentration of an antenna's radiation in particular directions.

Duplex Simultaneous two-way communication (full duplex) or alternating two-way communication (half-duplex).

EMF Electromotive force; the source-side driving potential of a circuit.

FEC Forward error correction.

FM Frequency modulation.

FSK Frequency-shift keying.

Greyline The twilight band circling Earth between day and night, favorable for certain HF propagation.

IARU International Amateur Radio Union.

Impedance The total (resistive plus reactive) opposition to AC current flow, $Z = R \pm jX$.

Ionosphere The ionized upper-atmosphere region responsible for HF skywave propagation.

ITU International Telecommunication Union.

LO Local oscillator.

LUF Lowest usable frequency for a given ionospheric path.

MOSFET Metal-oxide-semiconductor field-effect transistor.

MUF Maximum usable frequency for a given ionospheric path.

Op-amp Operational amplifier.

PM Phase modulation.

PSK Phase-shift keying.

Q (quality factor) Ratio of energy stored to energy dissipated per cycle in a resonant circuit; sets resonance sharpness.

QAM Quadrature amplitude modulation.

Q-code Standardized three-letter operating shorthand beginning with Q (QTH, QSL, QRM, . . .); see Chapter 25.

Reactance Frequency-dependent opposition to AC current from a capacitor (X_C) or inductor (X_L), without energy dissipation.

Repeater A station that receives on one frequency and retransmits on another to extend range.

Resonance The frequency at which inductive and capacitive reactance cancel, $f_0 = 1/(2\pi\sqrt{LC})$.

RF Radio frequency.

RMS Root-mean-square; the AC amplitude measure equivalent to DC heating effect.

RST Readability/Strength/Tone signal report system.

RTTY Radioteletype.

Sensitivity The weakest signal a receiver can usefully detect.

Simplex Two stations sharing one frequency, transmitting in turn.

Skin effect The tendency of high-frequency current to crowd toward a conductor's surface, raising effective AC resistance.

Skywave Propagation via reflection/refraction from the ionosphere.

Sporadic-E Anomalous, patchy E-layer ionization supporting unusual VHF/upper-HF propagation.

SSB Single-sideband modulation.

SWR Standing wave ratio.

Transceiver A combined transmitter and receiver.

Yagi–Uda A directional antenna using a driven element plus parasitic reflector and director elements.