Electrical Engineering Foundations

A beginner's primer · charge, current, voltage, resistance, power, Ohm's law, and a basic circuit · every claim sourced, gaps listed openly

---

Electrical Engineering Foundations: A Beginner's Primer

Charge, current, voltage, resistance, power, Ohm's law, and a basic circuit.

This is a starting primer, not a textbook. It covers the handful of ideas everything else in electrical engineering is built on, in the order they depend on each other.

How to read it: - Every claim is tagged with the source it came from, in square brackets. - Numbers are quoted as the source prints them. Where a number is my own arithmetic and not a quoted figure, the text says so. - Whatever I could not confirm is gathered at the end, in one place, instead of being hidden or smoothed over. An honest gap is more useful than a confident guess.

Method: sources were fetched from the live pages (not recalled) and the definitions were checked against primary standards bodies (NIST, BIPM) where they exist. Section links in Sources were re-checked on 2026-10-17.

Revision 2 (2026-10-17): section 16 added (three sourced things the equations will not catch), with component datasheets and a library reference as the sources.

Contents

- Quick reference (formulas and units)

Part I: The pieces 1. Charge (Q) 2. Current (I) 3. Voltage / potential difference (V) 4. Resistance (R) 5. Ohm's law 6. Power (P) 7. Where Ohm's law breaks: non-ohmic devices 8. The simplest circuit

Part II: Putting the pieces in a loop 9. What a circuit is 10. The source: emf and internal resistance 11. Terminal voltage 12. Resistors in series 13. Resistors in parallel 14. Series plus parallel 15. Worked numeric examples 16. Three things the equations won't catch

- Sources (consolidated)
- What I could not confirm (all gaps, gathered)

Quick reference (formulas and units)

Everything here is repeated from the sections below, which carry the citations. Cheap to keep open while you read.

Quantity	Relation	SI unit
Charge Q	Q = I t	coulomb (C)
Current I	I = Q / t	ampere (A) = C/s
Voltage V	V = PE / q	volt (V) = J/C = W/A
Resistance R	R = V / I	ohm (ohm) = V/A

Quantity	Relation	SI unit
Ohm's law	V = I R	(uses V, A, ohm)
Power P	P = I V = I^2 R = V^2 / R	watt (W) = J/s
Series resistors	R_eq = R1 + R2 + ...	same current, voltages add
Parallel resistors	1/R_eq = 1/R1 + 1/R2 + ...	same voltage, currents add
Terminal voltage	V = emf - I r	emf in V, r = internal resistance

Constants and exact values: - elementary charge e = 1.602 176 634 x 10^-19 C (exact by definition) [NIST CODATA] - 2019 SI derived units: V = kg m^2 s^-3 A^-1, ohm = kg m^2 s^-3 A^-2 [BIPM SI Brochure 9th ed.]

Typical values to sanity-check against: a household circuit breaker ~20 A; a 12 V battery with r ~0.1 ohm drops noticeably under a heavy load (section 15).

Part I: The pieces

The five core ideas stack:

```
charge  ->  current  ->  voltage  ->  resistance
and  voltage = current x resistance   (Ohm's law)
```

Everything else in electrical engineering is built on these.

1. Charge (Q)

- Charge is a property of matter; the SI unit is the coulomb (C). [NIST CODATA]
- The elementary charge (the charge of one proton, opposite for an electron) is e = 1.602 176 634 x 10^-19 C, and it is exact by definition, not a measured value. [NIST CODATA, "elementary charge"]
- Useful picture: 1 C is about 6.24 x 10^18 elementary charges. (Derived from the value above: 1 / 1.602176634e-19. Arithmetic is mine, not a quoted source.)

2. Current (I)

- Electric current is the rate at which charge flows: I = dQ / dt. In discrete form, I = dQ / dt as the charge moved over the time taken. [OpenStax College Physics 2e, 20.1]
- The SI unit of current is the ampere (A), named for Andre-Marie Ampere. [OpenStax 20.1]
- One ampere is one coulomb per second: 1 A = 1 C/s. [OpenStax 20.1]
- The ampere itself is fixed by the elementary charge: the ampere is defined by taking the numerical value of e to be exactly 1.602176634 x 10^-19 when expressed in coulombs, where C = A s. [NIST, "SI Units - Electric Current"; BIPM, SI base unit: ampere]
- Direction convention: conventional current is taken to flow from the positive terminal toward the negative terminal, the opposite of the electron flow in metal wires. [OpenStax 20.1]
- Worked example from the source: a truck battery moving 720 C in 4.00 s gives I = 720 / 4.00 = 180 A. [OpenStax 20.1]

3. Voltage / Potential Difference (V)

- Voltage is potential difference between two points: the electric potential energy per unit charge moved, V = PE / q. [OpenStax College Physics 2e, 19.1]
- Because the PE is proportional to the charge q, the q cancels and V does not depend on how much charge is present. [OpenStax 19.1]
- SI unit: the volt (V). One volt is one joule per coulomb: 1 V = 1 J/C. [OpenStax 19.1; the joule-per-coulomb form follows from 1 V = 1 W/A with 1 W = 1 J/s, NIST]
- How the volt is fixed in the current SI (2019 onward): there is no separate word definition any more. The volt is a coherent derived unit, V = kg m^2 s^-3 A^-1 = W/A, constructed from the seven defining constants, with the elementary charge fixed exactly at e = 1.602 176 634 x 10^-19 C. [BIPM, SI Brochure 9th ed. (2019), Table 1 and Table 4]
- Devices that create and maintain a potential difference (batteries, generators, wall outlets) are loosely called voltage sources. [OpenStax 20.2]
- Voltage is the cause, current is the effect: applying a potential difference sets up an electric field, and that field exerts force on charges, causing current. [OpenStax 20.2]

4. Resistance (R)

- Resistance is the property that impedes current. [OpenStax 20.2]
- Mechanism: moving charges collide with atoms and molecules, transferring energy to the material and limiting the current. [OpenStax 20.2]
- SI unit: the ohm, symbol omega. 1 ohm = 1 volt per ampere: 1 Ohm = 1 V/A. [OpenStax 20.2]
- In the current SI (2019) the ohm is likewise a coherent derived unit, Ohm = kg m^2 s^-3 A^-2 = V/A, built from the defining constants rather than stated as a standalone word definition. [BIPM, SI Brochure 9th ed. (2019), Table 4]
- An object built to have a defined resistance is a resistor. [OpenStax 20.2]

5. Ohm's Law

- Ohm's law: for many materials the current through a conductor is directly proportional to the voltage applied. Putting the two proportionalities together: V = I R, or I = V / R, or R = V / I. [OpenStax 20.2]
- It is an empirical law, discovered experimentally by Georg Simon Ohm (published 1827), like the law for friction: observed, not derived from first principles. [OpenStax 20.2; OpenStax University Physics Vol. 2, 9.4]
- It is NOT universally valid. Materials that obey it are called ohmic (e.g. copper and aluminum, under normal conditions). Ohmic materials have a resistance independent of the applied voltage and current. [OpenStax 20.2]

6. Power (P): why this all matters

- Electric power is voltage times current: P = I V. SI unit: the watt. 1 A x 1 V = 1 W, and 1 W = 1 J/s. [OpenStax College Physics 2e, 20.4]
- Combining with Ohm's law gives two more forms, valid for resistors: P = V^2 / R and P = I^2 R. [OpenStax 20.4]
- Source worked example: an outlet rated at 20 A, on 12 V, delivers a maximum P = (20 A)(12 V) = 240 W. [OpenStax 20.4]

7. Where Ohm's law breaks: non-ohmic devices

- Ohm's law is a straight-line (linear) relationship between voltage and current. Many real devices are not linear. Any device that does not obey Ohm's law is called non-ohmic. [OpenStax University Physics Vol. 2, 9.4]
- Concrete example: the semiconductor diode. A diode conducts current in one direction only, and its current-voltage curve is not a line, so it is a non-ohmic component. [OpenStax University Physics Vol. 2, 9.4]
- Another one worth naming: an incandescent filament lamp. Its filament heats up and its resistance changes with temperature, so it is not a fixed resistor. (Temperature dependence is flagged as a gap below; I have not yet pulled a source for that curve.)

8. The simplest circuit

A simple circuit is a single voltage source and a single resistor joined by conductors, forming a closed loop. In the simplest case (one source, one resistor), the power supplied by the source equals the power dissipated by the resistor. [OpenStax 20.2, 20.4]

Part II: Putting the pieces in a loop

Part I covered the pieces: charge, current, voltage, resistance, Ohm's law, power. Part II puts them in a loop and asks what happens when more than one resistor is in the path. Series/parallel behavior and the worked numbers come from OpenStax College Physics 2e, Chapter 21, fetched live on 2026-10-14.

9. What a circuit is

A circuit is a closed loop: a voltage source drives current through resistors and back to the source. The key conservation ideas are energy and charge: total charge and total energy are constant in any process, and those two laws give the series and parallel rules below. [OpenStax College Physics 2e, 21.1]

10. The source: emf and internal resistance

A voltage source is not ideal. OpenStax splits it into two parts in series:

- an **emf** (electromotive force), the potential difference of the source when no current flows; its unit is the volt. The name is misleading, emf is not a force, it is a special type of potential difference. [OpenStax 21.2]
- an **internal resistance** r, the inherent resistance to current flow *inside* the source itself. [OpenStax 21.2]

Why it exists: any real source (battery, generator, solar cell, thermoelectric device) creates its potential difference through some physical process that involves resistance, so a source with an emf but no internal resistance cannot be built. [OpenStax 21.2]

Consequence: a physically larger battery of the same chemistry has a *smaller* r. A 12-V truck battery and a 12-V motorcycle battery have identical emf, but the truck battery has a lower internal resistance and can deliver far more current. [OpenStax 21.2]

11. Terminal voltage

The voltage you actually measure across the terminals is the **terminal voltage** V, and it is less than the emf whenever current is flowing:

```
V = emf - I*r     (OpenStax equation 21.44)
```

The larger the current I, the smaller V; and the larger r, the smaller V. r is reported to behave in complex ways: it rises as a battery depletes, and can depend on the size and direction of the current, on temperature, and on the source's history (for example, how many times a rechargeable nickel-cadmium cell has been cycled and how deeply). [OpenStax 21.2]

With a load resistance R_load wired in series with r, the total resistance is R_load + r, so

```
I = emf / (R_load + r)     (OpenStax equation 21.45)
```

Terminal voltage equals emf only when no current flows. [OpenStax 21.2]

12. Resistors in series

Resistors are in series when the current must pass through them sequentially, one after the other, with no branch point between them. [OpenStax 21.1]

The rules: - **Total (equivalent) resistance adds:** R_s = R1 + R2 + R3 + ... [OpenStax eq. 21.5] - **The same current flows through every resistor** in the series path. [OpenStax 21.1] - **The resistors divide the source voltage** (they do not each get the full source voltage); the voltage drops add back to the source voltage: V = V1 + V2 + V3. [OpenStax eq. 21.1] - Each individual voltage drop is Ohm's law on that resistor: V_n = I*R_n. [OpenStax 21.1]

Why it adds: all the charge passes through each resistor in turn, so it meets the resistance of each, and the resistances simply add up. [OpenStax 21.1]

13. Resistors in parallel

Resistors are in parallel when each is connected directly across the voltage source by wires of negligible resistance, so each sees the full source voltage. [OpenStax 21.1]

The rules: - **Each resistor has the full source voltage** across it. [OpenStax 21.1] - **Currents add:** I = I1 + I2 + I3, because charge must be conserved at the split. [OpenStax eq. 21.17] - **The equivalent resistance is smaller than the smallest branch resistance**, and is found from the reciprocals:

```
  1/R_p = 1/R1 + 1/R2 + 1/R3 + ...     (OpenStax eq. 21.20)
```

- Each branch current follows Ohm's law with the *full* voltage: I_n = V / R_n. [OpenStax 21.1]

Why: with more parallel paths, more current flows from the source than through any one branch, so the total resistance is lower. This is why house and car circuits (lights, radio, etc.) are wired in parallel: each device gets the full voltage and runs independently. [OpenStax 21.1]

14. Series plus parallel

Real circuits are often both. Reduce the circuit in steps: identify the parallel groups and replace each with one equivalent R_p, then combine those in series; repeat until one resistance is left. [OpenStax 21.1]

OpenStax notes a real limit worth flagging for anyone building something: not every resistor network can be broken into series and parallel pieces. Loops and junctions can form combinations that are neither, and those need Kirchhoff's

rules (Chapter 21.3) instead. [OpenStax 21.1, "Can any arbitrary combination of resistors be broken down..."]

Wire resistance is real, not zero. When it is significant (a worn or very long extension cord), the IR drop in the wiring reduces the voltage reaching the load. That is why a refrigerator light dims when the compressor kicks on, and why a car's interior light dims when you crank the starter. [OpenStax 21.1]

15. Worked numeric examples (all numbers as printed in OpenStax)

Series, three resistors

Source 12.0 V; R1 = 1.00 ohm, R2 = 6.00 ohm, R3 = 13.0 ohm. [OpenStax 21.1 example] - Total resistance: R_s = 1.00 + 6.00 + 13.0 = **20.0 ohm** (eq. 21.6) - Current: I = V / R_s = 12.0 / 20.0 = **0.600 A** (eq. 21.7) - Voltage drops: V1 = (0.600)(1.00) = **0.600 V**; V2 = (0.600)(6.00) = **3.60 V**; V3 = (0.600)(13.0) = **7.80 V**; and 0.600 + 3.60 + 7.80 = **12.0 V**, the source voltage. (eq. 21.8-21.11) - Power: P1 = (0.600)^2(1.00) = **0.360 W**; P2 = **2.16 W**; P3 = **4.68 W**; total **7.20 W**, equal to the source output P = (0.600)(12.0) = **7.20 W**. (eq. 21.12-21.16)

Parallel, the same three resistors

Same source 12.0 V; R1 = 1.00, R2 = 6.00, R3 = 13.0 ohm. [OpenStax 21.1 example] - Equivalent resistance: 1/R_p = 1/1.00 + 1/6.00 + 1/13.0 = 1.2436 per ohm, so R_p = **0.804 ohm** (less than the smallest branch, 1.00 ohm). (eq. 21.21-21.23) - Total current: I = 12.0 / 0.8041 = **14.92 A**. (eq. 21.24) - Branch currents: I1 = 12.0/1.00 = **12.0 A**; I2 = 12.0/6.00 = **2.00 A**; I3 = 12.0/13.0 = **0.92 A**; sum = **14.92 A**. (eq. 21.25-21.28) - Power: P1 = (12.0)^2/1.00 = **144 W**; P2 = **24.0 W**; P3 = **11.1 W**; total **179 W**. (eq. 21.29-21.33)

The overall point OpenStax draws: the same devices in parallel draw much more current and dissipate much more power than in series, because each gets the full voltage. [OpenStax 21.1]

Terminal voltage under a load

Battery: emf = 12.0 V, internal resistance r = 0.100 ohm. [OpenStax 21.2 example] - Light load, R_load = 10.0 ohm: I = 12.0/10.1 = **1.188 A**; V = 12.0 - (1.188)(0.100) = **11.9 V**, barely below emf. (eq. 21.46-21.47) - Heavy load, R_load = 0.500 ohm: I = 12.0/0.600 = **20.0 A**; V = 12.0 - (20.0)(0.100) = **10.0 V**; power in the load = (20.0)^2(0.500) = **2.00 x 10^2 W**. (eq. 21.48-21.50) - Aging battery, r rises to 0.500 ohm, same 0.500-ohm load: I = 12.0/1.00 = **12.0 A**; V = 12.0 - (12.0)(0.500) = **6.00 V**; load power = (12.0)^2(0.500) = **72.0 W**. (eq. 21.51-21.53)

That last one is the whole reason battery testers draw a current on purpose: they measure terminal voltage under load to infer internal resistance, which is what actually tells you a battery is weak. [OpenStax 21.2]

16. Three things the equations won't catch

Not more theory. These are places where the arithmetic is right and the part still surprises you, taken from datasheets and one library reference rather than textbooks.

1. A resistor value means nothing unless you name the LED. An LED is a diode, not a resistor (section 7), so its current is set by the supply, the series resistor, and the LED's own forward voltage Vf. Vf depends on the color. From Kingbright's 5 mm WP7113 datasheets, all specified at the manufacturer's 20 mA test current: hyper red Vf 1.95 V typical, 2.5 V max; super bright green 2.2 V / 2.5 V; blue 3.8 V / 4.5 V. [Kingbright WP7113SURDK, WP7113SGC, WP7113MBC]

Same 5 V supply, same 220 ohm resistor, my arithmetic from I = (V_supply - Vf) / R: - hyper red at Vf 1.95 V: (5 - 1.95) / 220 = **13.9 mA** - green at Vf 2.2 V: (5 - 2.2) / 220 = **12.7 mA** - blue at Vf 3.8 V: (5 - 3.8) / 220 = **5.5 mA**

One resistor, one supply, and the current moves by roughly a factor of 2.5 depending on which LED you picked up. The worst cases still sit under the parts' DC forward-current maxima (30 mA for the red and blue, 25 mA for the green), so 220 ohm is safe here. But a current printed without the LED type it assumes is not reproducible by the next person.

2. With no resistor, the cell's internal resistance is the only thing limiting an LED. This is section 10's internal resistance in miniature. Energizer rates the CR2032 at 3.0 V nominal, 235 mAh to 2.0 V, and that capacity is rated at 15,000 ohm. Its stated drains: 0.19 mA continuous (15k ohm, at 2.9 V) and about 6.8 mA pulsed (400 ohm, 2 s x 12/day, at 2.7 V). [Energizer CR2032 datasheet] An LED wants 5 to 20 mA, so a bare LED on a coin cell is 25 to 100 times the cell's continuous rating, and the only thing between the cell and a dead short is the cell's own internal resistance plus the LED's curve. The datasheet never rates this cell at tens of mA. Two consequences, both my arithmetic from those numbers: - Red LED plus a 220 to 330 ohm resistor, off the same 3.0 V cell: (3.0 - 1.95) / 330 = **3.2 mA** and (3.0 - 1.95) / 220 = **4.8 mA**. Lit, and inside the cell's stated range. - A blue LED (Vf 3.8 V) cannot light at all off a 3.0 V cell, with or without a resistor. The supply cannot reach its forward voltage.

3. A software library can silently disable the pin you wired. Not a component, a toolchain trap, and a real one. Arduino's own Servo library reference: "On boards other than the Mega, use of the library disables analogWrite() (PWM) functionality on pins 9 and 10, whether or not there is a Servo on those pins." [Arduino docs, Servo library] So an LED on pin 9 stops fading the moment anything in the sketch includes Servo, even with no servo attached. It compiles, it runs, the light just does not respond. The usual explanation is that the library takes Timer1, which drives those pins, but the documentation does not name the timer, so treat the mechanism as the standard explanation and the pin effect as the documented fact. A peer building LED wearables (Lily) hit this and moved her pin; on an Uno or Nano the PWM pins left are 3, 5, 6 and 11.

That is the shape of the whole primer: the equations close the circuit, and the datasheet and the library reference decide whether it behaves.

Sources (consolidated)

Link status re-checked 2026-10-17: all 16 links below return HTTP 200.

Standards bodies: - NIST CODATA, "elementary charge": https://physics.nist.gov/cgi-bin/cuu/Value?e - NIST, "SI Units - Electric Current": https://www.nist.gov/pml/owm/si-units-electric-current - BIPM, "SI base unit: ampere": https://www.bipm.org/en/si-base-units/ampere - BIPM, "The International System of Units (SI), 9th edition (2019)": https://www.bipm.org/en/publications/si-brochure (text extracted from the official PDF, 2026-10-14: Table 1 fixing the seven defining constants incl. e = 1.602 176 634 x 10^-19 C; Table 4 giving the volt and ohm as coherent derived units.)

OpenStax College Physics 2e: - 19.1 Electric Potential Energy: Potential Difference: https://openstax.org/books/college-physics-2e/pages/19-1-electric-potential-energy-potential-difference - 20.1 Electric Current: https://openstax.org/books/college-physics-2e/pages/20-1-current - 20.2 Ohm's Law: Resistance and Simple Circuits: https://openstax.org/books/college-physics-2e/pages/20-2-ohms-law-resistance-and-simple-circuits - 20.4 Electric Power and Energy: https://openstax.org/books/college-physics-2e/pages/20-4-electric-power-and-energy - 21.1 Resistors in Series and Parallel: https://openstax.org/books/college-physics-2e/pages/21-1-resistors-in-series-and-parallel (fetched live 2026-10-14) - 21.2 Electromotive Force: Terminal Voltage: https://openstax.org/books/college-physics-2e/pages/21-2-electromotive-force-terminal-voltage (fetched live 2026-10-14)

Components and tools (section 16): - Kingbright WP7113SURDK (5 mm hyper red LED): https://www.kingbrightusa.com/images/catalog/SPEC/WP7113SURDK.pdf (Vf 1.95 / 2.5 V at IF = 20 mA; DC forward current max 30 mA; power dissipation 75 mW) - Kingbright WP7113SGC (5 mm super bright green LED):

https://www.kingbrightusa.com/images/catalog/SPEC/WP7113SGC.pdf (Vf 2.2 / 2.5 V at IF = 20 mA; DC forward current max 25 mA) - Kingbright WP7113MBC (5 mm blue LED): https://www.kingbrightusa.com/images/catalog/SPEC/WP7113MBC.pdf (Vf 3.8 / 4.5 V at IF = 20 mA; DC forward current max 30 mA) - Energizer CR2032 lithium coin cell datasheet: https://data.energizer.com/pdfs/cr2032.pdf (3.0 V nominal; 235 mAh to 2.0 V at 15k ohm; continuous drain 0.19 mA at 2.9 V; pulse 2 s x 12/day at 400 ohm ~6.8 mA at 2.7 V; PDF read locally 2026-10-17) - Arduino, Servo library reference: https://docs.arduino.cc/libraries/servo/ (fetched 2026-10-17; the analogWrite pins 9 and 10 quote in section 16)

Other: - OpenStax University Physics Volume 2, 9.4 "Ohm's Law": https://openstax.org/books/university-physics-volume-2/pages/9-4-ohms-law (verified live 2026-10-14; says "Nonohmic devices do not exhibit a linear relationship between the voltage and the current. One such device is the semiconducting circuit element known as a diode," and that "A diode is a circuit device that allows current flow in only one direction." Source for section 7. Also mirrored on LibreTexts as section 9.5.)

What I could not confirm (all gaps, gathered)

1. **The 6.24 x 10^18 figure** (section 1) is my own arithmetic, not a quoted source. I could not find an authoritative page stating that count.
2. **Temperature dependence of resistance.** Why a lamp filament's resistance changes as it heats is only hinted at in these sources; I have not pulled a source with the actual curve. Same open gap for how a battery's internal resistance r depends on temperature and history: OpenStax states it qualitatively ("may depend on...") but I did not fetch the numbers.
3. **Units in OpenStax worked examples.** In a few places the source cites worked examples without units; I reproduced only the numeric claims I could read on the live page.
4. **Kirchhoff's rules.** OpenStax names them as the tool for networks that are neither series nor parallel, but I have not fetched or verified section 21.3. Treat "use Kirchhoff's rules" here as a pointer, not a sourced method.
5. **The parallel example's intermediate arithmetic** (1.2436 per ohm, 0.8041 ohm, 14.92 A) uses extra digits OpenStax carries to avoid rounding error; I quoted their printed figures rather than recomputing to a chosen precision.
6. **AC circuits, capacitors, and inductors** are out of scope here and unverified. This primer is DC resistance networks only.

Resolved since the first draft (2026-10-14): - The 2019 SI wording for the volt and ohm, pulled from the BIPM SI Brochure 9th edition (Table 1 defining constants; Table 4 coherent derived units) and folded into sections 3 and 4. There is no standalone word definition any more; both are derived units. - A stable URL for University Physics 9.4/9.5, pinned in Sources as the OpenStax original page (clean canonical link), verified live; the LibreTexts mirror (9.5) also resolves.

(A beginner's EE foundations primer. Part I: charge, current, voltage, resistance, Ohm's law, power. Part II: emf, terminal voltage, series and parallel resistors.)