

VOL. 1.

Charles Platt

Encyclopedia of Electronic Components



Power Sources & Conversion

Resistors • Capacitors • Inductors
Switches • Encoders • Relays • Transistors

Free Sampler



O'REILLY®

Make:
makezine.com

Want to read more?

You can [buy this book](#) at [oreilly.com](#)
in print and ebook format.

Buy 2 books, get the 3rd FREE!

Use discount code: OPC10

All orders over \$29.95 qualify for **free shipping** within the US.

It's also available at your favorite book retailer,
including the iBookstore, the [Android Marketplace](#),
and [Amazon.com](#).



O'REILLY®

Spreading the knowledge of innovators

[oreilly.com](#)

Encyclopedia of Electronic Components Volume 1

Charles Platt

O'REILLY®

Beijing • Cambridge • Farnham • Köln • Sebastopol • Tokyo

Encyclopedia of Electronic Components Volume 1

by Charles Platt

Copyright © 2013 Helpful Corporation. All rights reserved.

Printed in the United States of America.

Published by O'Reilly Media, Inc., 1005 Gravenstein Highway North, Sebastopol, CA 95472.

O'Reilly books may be purchased for educational, business, or sales promotional use. Online editions are also available for most titles (<http://my.safaribooksonline.com>). For more information, contact our corporate/institutional sales department: 800-998-9938 or corporate@oreilly.com.

Editor: Brian Jepson

Production Editor: Melanie Yarbrough

Proofreader: Melanie Yarbrough

Indexer: Judy McConville

Cover Designer: Mark Paglietti

Interior Designer: Edie Freedman and Nellie McKesson

Illustrator: Charles Platt

Photographer: Charles Platt

Cover Production: Randy Comer

October 2012: First Edition

Revision History for the First Edition:

2012-10-03 First release

See <http://oreilly.com/catalog/errata.csp?isbn=9781449303181> for release details.

Nutshell Handbook, the Nutshell Handbook logo, and the O'Reilly logo are registered trademarks of O'Reilly Media, Inc. [Encyclopedia of Electronic Components Volume 1](#), the cover images, and related trade dress are trademarks of O'Reilly Media, Inc.

Many of the designations used by manufacturers and sellers to distinguish their products are claimed as trademarks. Where those designations appear in this book, and O'Reilly Media, Inc., was aware of a trademark claim, the designations have been printed in caps or initial caps.

While every precaution has been taken in the preparation of this book, the publisher and authors assume no responsibility for errors or omissions, or for damages resulting from the use of the information contained herein.

ISBN: 978-1-449-30318-1

[TI]

Table of Contents

Preface	xix
----------------------	------------

1. How to Use This Book	1
Reference vs. Tutorial	1
Theory and Practice	1
Organization	1
Subject Paths	2
Inclusions and Exclusions	2
Typographical Conventions	3
Volume Contents	3
Safari® Books Online	3
How to Contact Us	4

> POWER

> > SOURCE

2. Battery	5
What It Does	5
How It Works	6
Electrode Terminology	7
Variants	7
Disposable Batteries	8
Rechargeable Batteries	9
Values	11
Amperage	11
Capacity	11
Voltage	13
How To Use It	14

What Can Go Wrong	15
Short Circuits: Overheating And Fire	15
Diminished Performance Caused By Improper Recharging ..	15
Complete Discharge Of Lead-Acid Battery	15
Inadequate Current	15
Incorrect Polarity	15
Reverse Charging	16
Sulfurization	16
High Current Flow Between Parallel Batteries	16

> > CONNECTION

3. Jumper	17
What It Does	17
How It Works	17
Variants	18
Values	18
How To Use It	19
What Can Go Wrong	19
 4. Fuse	 21
What It Does	21
How It Works	21
Values	22
Variants	22
Small Cartridge Fuses	23
Automotive Fuses	23
Strip Fuses	24
Through-Hole Fuses	24
Resettable Fuses	24
Surface Mount Fuses	26
How To Use It	26
What Can Go Wrong	27
Repeated Failure	27
Soldering Damage	27
Placement	28
 5. Pushbutton	 29
What It Does	29
How It Works	29
Variants	30
Poles And Throws	30
On-Off Behavior	30
Slider	31
Styles	31
Termination And Contact Plating	32
Mounting Style	32
Sealed Or Unsealed	32

Latching	33
Foot Pedal	33
Keypad	33
Tactile Switch	34
Membrane Pad	34
Radio Buttons	35
Snap-Action Switches	35
Emergency Switch	35
Values	35
How To Use It	35
What Can Go Wrong	35
No Button	35
Mounting Problems	35
LED Issues	36
Other Problems	36
6. Switch	37
What It Does	37
How It Works	37
Variants	38
Terminology	38
Poles And Throws	38
On-Off Behavior	39
Snap-Action	39
Rocker	40
Slider	40
Toggle	41
DIP	43
SIP	44
Paddle	44
Vandal Resistant Switch	45
Tactile Switch	45
Mounting Options	45
Termination	45
Contact Plating Options	45
Values	45
How To Use It	46
Power Switches	46
Limit Switches	46
Logic Circuits	47
Alternatives	47
What Can Go Wrong	47
Arcing	47
Dry Joints	48
Short Circuits	48
Contact Contamination	48
Wrong Terminal Type	48
Contact Bounce	48

Mechanical Wear	48
Mounting Problems	48
Cryptic Schematics	49
7. Rotary Switch	51
What It Does	51
How It Works	52
Variants	52
Conventional	52
Rotary DIP	53
Gray Code	54
PC Board Rotary Switch	55
Mechanical Encoder	55
Pushwheel And Thumbwheel	55
Keylock	55
Values	56
How To Use It	56
What Can Go Wrong	57
Vulnerable Contacts	57
Contact Overload	57
Misalignment	57
Misidentified Shorting Switch	57
User Abuse	57
Wrong Shaft, Wrong Knobs, Nuts That Get Lost, Too Big To Fit	57
8. Rotational Encoder	59
What It Does	59
How It Works	59
Variants	60
Pulses And Detents	61
Format	61
Output	61
Rotational Resistance	61
Values	61
Contact Bounce	61
Sliding Noise	62
How To Use It	62
What Can Go Wrong	62
Switch Bounce	62
Contact Burnout	63
9. Relay	65
What It Does	65
How It Works	66
Variants	67
Latching	67
Polarity	67
Pinout Variations	67

Reed Relay	68
Small Signal Relay	68
Automotive Relays	69
General Purpose/Industrial	69
Time Delay Relay	69
Contactor	70
Values	70
How To Use It	71
What Can Go Wrong	72
Wrong Pinouts	72
Wrong Orientation	72
Wrong Type	72
Wrong Polarity	72
AC And DC	72
Chatter	72
Relay Coil Voltage Spike	72
Arcing	72
Magnetic Fields	72
Environmental Hazards	73

> > MODERATION

10. Resistor	75
What It Does	75
How It Works	76
Variants	76
Resistor Array	77
Values	79
Tolerance	79
Value Coding	81
Stability	82
Materials	82
How To Use It	84
In Series With LED	84
Current Limiting With A Transistor	84
Pullup And Pulldown Resistors	85
Audio Tone Control	85
RC Network	85
Voltage Divider	86
Resistors In Series	86
Resistors In Parallel	86
What Can Go Wrong	87
Heat	87
Noise	87
Inductance	87
Inaccuracy	87

Wrong Values	88
11. Potentiometer	89
What It Does	89
How It Works	90
Variants	90
Linear And Log Taper	90
Classic-Style Potentiometer	91
Multiple-Turn Potentiometer	92
Ganged Potentiometer	93
Switched Potentiometer	93
Slider Potentiometer	93
Trimmer Potentiometer	93
How To Use It	94
What Can Go Wrong	95
Wear And Tear	95
Knobs That Don't Fit	95
Nuts That Get Lost	95
A Shaft That Isn't Long Enough	96
Sliders With No Finger Grip	96
Too Big To Fit	96
Overheating	96
The Wrong Taper	96
12. Capacitor	97
What It Does	97
How It Works	97
Variants	99
Format	99
Principal Types	101
Dielectrics	103
Values	104
Farads	104
Commonly Used Values	104
Dielectric Constant	105
The Time Constant	105
Multiple Capacitors	106
Alternating Current And Capacitive Reactance	106
Equivalent Series Resistance	106
How To Use It	107
Bypass Capacitor	107
Coupling Capacitor	107
High-Pass Filter	107
Low-Pass Filter	107
Smoothing Capacitor	108
Snubber	108
Capacitor As A Battery Substitute	109
What Can Go Wrong	109

Wrong Polarity	110
Voltage Overload	110
Leakage	110
Dielectric Memory	110
Specific Electrolytic Issues	110
Heat	110
Vibration	110
Misleading Nomenclature	111
13. Variable Capacitor	113
What It Does	113
How It Works	113
Variants	114
Values	115
Formats	115
How To Use It	115
What Can Go Wrong	117
Failure To Ground Trimmer Capacitor While Adjusting It ...	117
Application Of Overcoat Material Or “Lock Paint”	117
Lack Of Shielding	117
14. Inductor	119
What It Does	119
How It Works	120
DC Through A Coil	121
Magnetic Core	122
EMF And Back-EMF	122
Electrical And Magnetic Polarity	123
Variants	124
Magnetic Cores	124
Nonmagnetic Cores	125
Variable Inductors	125
Ferrite Beads	126
Toroidal Cores	126
Gyrator	127
Values	128
Calculating Inductance	128
Calculating Reactance	128
Calculating Reluctance	129
Datasheet Terminology	129
Series And Parallel Configurations	129
Time Constant	129
How To Use It	130
Core Choices	132
Miniaturization	132
What Can Go Wrong	132
Real-World Defects	132
Saturation	132

RF Problems	133
-------------------	-----

> > CONVERSION

15. AC-AC Transformer 135

What It Does	135
How It Works	136
The Core	137
Taps	137
Variants	138
Core Shapes	138
Power Transformer	138
Plug-In Transformer	139
Isolation Transformer	139
Autotransformer	140
Variable Transformer	140
Audio Transformer	140
Split-Bobbin Transformer	141
Surface-Mount Transformer	141
Values	141
How To Use It	142
What Can Go Wrong	142
Reversal Of Input And Output	142
Shock Hazard From Common Ground	142
Accidental DC Input	142
Overload	142
Incorrect AC Frequency	142

16. AC-DC Power Supply 143

What It Does	143
Variants	143
Linear Regulated Power Supply	143
Switching Power Supply	144
Unregulated Power Supply	146
Adjustable Power Supply	146
Voltage Multiplier	146
Formats	146
How To Use It	147
What Can Go Wrong	147
High Voltage Shock	147
Capacitor Failure	147
Electrical Noise	147
Peak Inrush	147

17. DC-DC Converter 149

What It Does	149
How It Works	149
Variants	150

Buck Converter	150
Boost Converter	151
Flyback Converter With Inductor	151
Flyback Converter With Transformer	151
Formats	151
Values	152
Nominal Input Voltage And Frequency	152
Output Voltage	153
Input Current And Output Current	153
Load Regulation	153
Efficiency	153
Ripple And Noise	154
Isolated Or Non-Isolated	154
How To Use It	154
What Can Go Wrong	155
Electrical Noise In Output	155
Excess Heat With No Load	155
Inaccurate Voltage Output With Low Load	155
18. DC-AC Inverter	157
What It Does	157
How It Works	157
Variants	158
Values	158
How To Use It	159
What Can Go Wrong	160
> > REGULATION	
19. Voltage Regulator	161
What It Does	161
How It Works	161
Variants	163
Packaging	163
Popular Varieties	163
Adjustable Regulators	163
Negative And Positive Regulators	164
Low-Dropout Linear Regulators	164
Quasi-Low-Dropout Linear Regulators	165
Additional Pin Functions	165
Values	165
How To Use It	165
What Can Go Wrong	166
Inadequate Heat Management	166
Transient Response	166
Misidentified Parts	166
Misidentified Pins	167
Dropout Caused By Low Battery	167

Inaccurate Delivered Voltage	167
------------------------------------	-----

> ELECTROMAGNETISM

> > LINEAR

20. Electromagnet	169
What It Does	169
How It Works	169
Variants	170
Values	171
How To Use It	171
What Can Go Wrong	172
 21. Solenoid	 173
What It Does	173
How It Works	174
Variants	176
Low Profile	176
Latching	176
Rotary	176
Hinged Clapper	176
Values	176
Coil Size Vs. Power	177
How To Use It	177
What Can Go Wrong	177
Heat	177
AC Inrush	177
Unwanted EMF	177
Loose Plunger	177

> > ROTATIONAL

22. DC Motor	179
What It Does	179
How It Works	179
Variants	181
Coil Configurations	181
Gearhead Motor	181
Brushless DC Motor	183
Linear Actuator	184
Values	184
How To Use It	185
Speed Control	186
Direction Control	186
Limit Switches	187
What Can Go Wrong	187

Brushes And Commutator	187
Electrical Noise	187
Heat Effects	188
Ambient Conditions	188
Wrong Shaft Type Or Diameter	188
Incompatible Motor Mounts	188
Backlash	188
Bearings	188
Audible Noise	189
23. AC Motor	191
What It Does	191
How It Works	191
Stator Design	191
Rotor Design	192
Variants	195
Single-Phase Induction Motor	195
Three-Phase Induction Motor	196
Synchronous Motor	196
Reluctance Motor	197
Variable Frequency Drive	198
Wound-Rotor AC Induction Motor	198
Universal Motor	198
Inverted AC Motors	199
Values	199
How To Use It	199
What Can Go Wrong	200
Premature Restart	200
Frequent Restart	200
Undervoltage Or Voltage Imbalance	200
Stalled Motor	200
Protective Relays	200
Excess Torque	200
Internal Breakage	200
24. Servo Motor	201
What It Does	201
How It Works	201
Variants	203
Values	204
How To Use It	205
Modification For Continuous Rotation	206
What Can Go Wrong	206
Incorrect Wiring	206
Shaft/Horn Mismatch	206
Unrealistically Rapid Software Commands	207
Jitter	207
Motor Overload	207

Unrealistic Duty Cycle	207
Electrical Noise	207
25. Stepper Motor	209
What It Does	209
How It Works	209
Reluctance Stepper Motors	210
Permanent Magnet Stepper Motors	211
Bipolar Stepper Motors	213
Unipolar Motors	213
Variants	214
High Phase Count	214
Hybrid	216
Bifilar	216
Multiphase	216
Microstepping	217
Sensing And Feedback	217
Voltage Control	217
Values	218
How To Use It	218
Protection Diodes	218
Positional Control	219
What Can Go Wrong	219
Incorrect Wiring	219
Step Loss	219
Excessive Torque	219
Hysteresis	220
Resonance	220
Hunting	220
Saturation	220
Rotor Demagnetization	220

> DISCRETE SEMICONDUCTOR

> > SINGLE JUNCTION

26. Diode	221
What It Does	221
How It Works	223
Variants	224
Packaging	224
Signal Diodes	224
Rectifier Diodes	224
Zener Diode	224
Transient Voltage Suppressor (TVS)	225
Schottky Diode	225
Varactor Diode	225

Tunnel Diode, Gunn Diode, PIN Diode	226
Diode Array	226
Bridge Rectifier	226
Values	226
How To Use It	227
Rectification	227
Back-EMF Suppression	228
Voltage Selection	229
Voltage Clamping	230
Logic Gate	230
DC Voltage Regulation And Noise Suppression	230
AC Voltage Control And Signal Clipping	231
Voltage Sensing	231
What Can Go Wrong	232
Overload	232
Reversed Polarity	233
Wrong Type Of Diode	233
27. Unijunction Transistor	235
What It Does	235
How It Works	236
Variants	238
Values	238
How To Use It	239
What Can Go Wrong	239
Name Confusion	239
Incorrect Bias	239
Overload	240
 > > MULTI-JUNCTION	
28. Bipolar Transistor	241
What It Does	241
How It Works	241
Current Gain	244
Terminology	245
Variants	245
Packaging	245
Connections	246
How To Use It	246
Darlington Pairs	248
Amplifiers	250
What Can Go Wrong	251
Wrong Connections On A Bipolar Transistor	251
Wrong Connections On A Darlington Pair Chip	251
Soldering Damage	252
Excessive Current Or Voltage	252

Excessive Leakage	252
29. Field Effect Transistor	253
What It Does	253
How It Works	253
JFETs	253
JFET Behavior	255
MOSFETs	256
The Substrate Connection	261
Variants	262
MESFET	262
V-Channel MOSFET	262
Trench MOS	262
Values	262
How To Use It	263
P-Channel Disadvantage	263
Bipolar Substitution	263
Amplifier Front Ends	263
Voltage-Controlled Resistor	263
Compatibility With Digital Devices	263
What Can Go Wrong	263
Static Electricity	263
Heat	263
Wrong Bias	264
Appendix A. Schematic Symbols	265
Index	269

battery

2

This entry covers electrochemical power sources. Electricity is most often generated electromagnetically, but since these sources cannot be classified as components, they are outside the scope of the encyclopedia. Electrostatic sources are excluded for similar reasons.

A battery is sometimes referred to as a *cell* or *power cell*, but can actually contain multiple cells, as defined in this entry. It used to be called an *accumulator* or a *pile*, but those terms are now archaic.

OTHER RELATED COMPONENTS

- **capacitor** (see [Chapter 12](#))

What It Does

A battery contains one or more *electrochemical cells* in which chemical reactions create an electrical potential between two immersed terminals. This potential can be discharged as *current* passing through a *load*.

An electrochemical cell should not be confused with an *electrolytic cell*, which is powered by an external source of electricity to promote *electrolysis*, whereby chemical compounds are broken down to their constituent elements. An electrolytic cell thus consumes electricity, while an electrochemical cell produces electricity.

Batteries range in size from *button cells* to large *lead-acid* units that store power generated by solar panels or windmills in locations that can be off the grid. Arrays of large batteries can provide bridging power for businesses or even small communities where conventional power is unreliable. [Figure 2-1](#) shows a 60KW, 480VDC self-watering battery array installed in a corporate data center, supplementing wind and solar sources

and providing time-of-day peak shaving of energy usage. Each lead-acid battery in this array measures approximately 28" × 24" × 12" and weighs about 1,000 lb.



Figure 2-1. A battery array providing 60KW at 480VDC as backup for a corporate data center. (Photo by permission of Hybridyne Power Systems, Canada, Inc., and the Hybridyne group of companies. Copyright by Hybridyne, an internationally registered trademark of Hybridyne Power Systems Canada Inc. No right of further reproduction unless specifically granted by Hybridyne.)

Schematic symbols for a battery are shown in [Figure 2-2](#). The longer of the two lines represents the positive side of the battery, in each case. One way to remember this is by imagining that the longer line can be snipped in half so that the two segments can combine to form a + sign. Traditionally, multiple connected battery symbols indicate multiple cells inside a battery; thus the center symbols in the figure could indicate a 3V battery, while those on the right would indicate a voltage greater than 3V. In practice, this convention is not followed conscientiously.

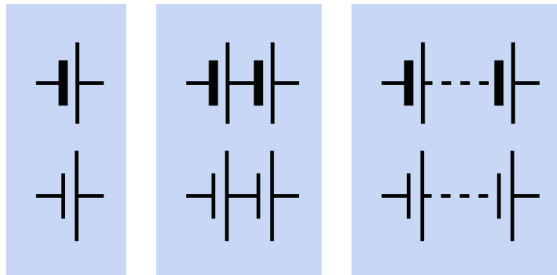


Figure 2-2. Schematic symbols for a battery. Each pair of symbols within a blue rectangle is functionally identical.

How It Works

In a basic battery design often used for demonstration purposes, a piece of copper serves as an *electrode*, partially immersed in a solution of copper sulfate, while a piece of zinc forms a second electrode, partially immersed in a solution of zinc sulfate. Each sulfate solution is known as an *electrolyte*, the complete battery may be referred to as a *cell*, and each half of it may be termed a *half-cell*.

A simplified cross-section view is shown in [Figure 2-3](#). Blue arrows show the movement of electrons from the zinc terminal (the *anode*), through an external load, and into a copper terminal (the *cathode*). A *membrane separator* allows the electrons to circulate back through the battery, while preventing electrolyte mixing.

Orange arrows represent positive copper *ions*. White arrows represent positive zinc ions. (An ion

is an atom with an excess or deficit of electrons.) The zinc ions are attracted into the zinc sulfate electrolyte, resulting in a net loss of mass from the zinc electrode.

Meanwhile, electrons passing into the copper electrode tend to attract positive copper ions, shown as orange arrows in the diagram. The copper ions are drawn out of the copper sulfate electrolyte, and result in a net accumulation of copper atoms on the copper electrode.

This process is energized partially by the fact that zinc tends to lose electrons more easily than copper.

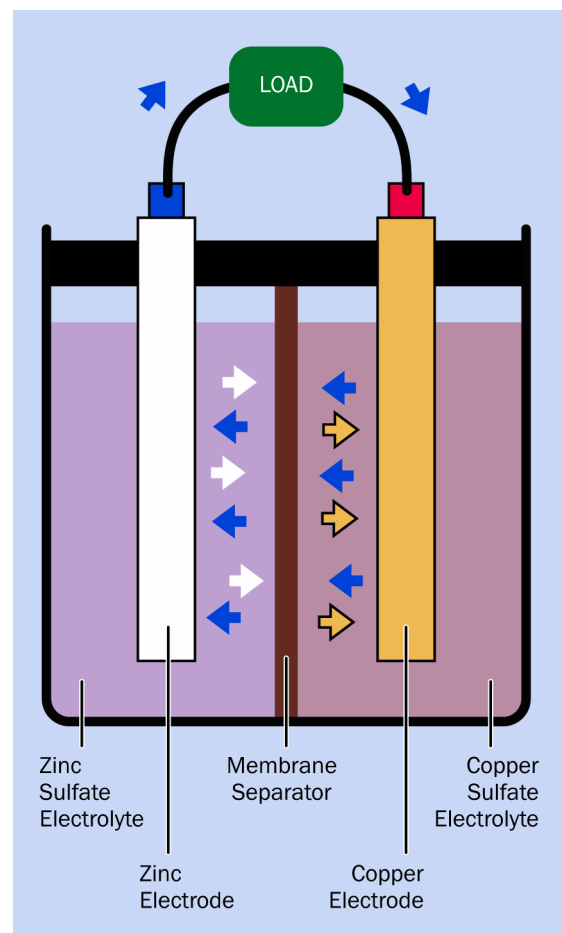


Figure 2-3. A classically simple electrochemical cell. See text for additional details.

Batteries for use in consumer electronics typically use a paste instead of a liquid as an electrolyte, and have been referred to as *dry cells*, although this term is becoming obsolete. The two half-cells may be combined concentrically, as in a typical 1.5-volt C, D, AA, or AAA alkaline battery (see Figure 2-4).

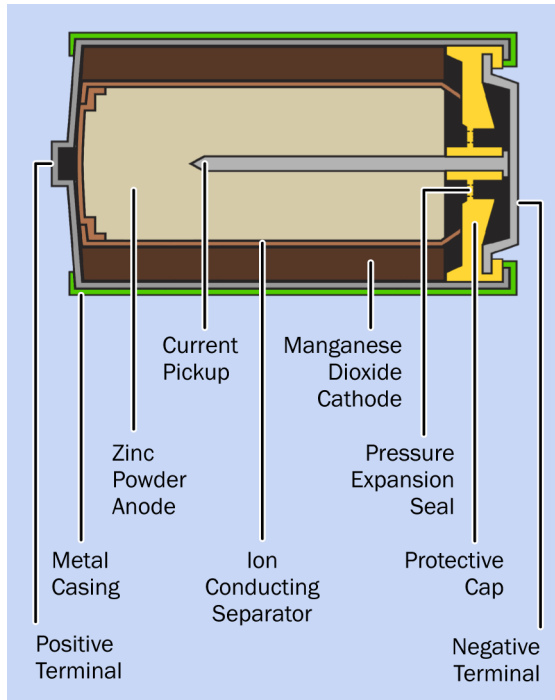


Figure 2-4. Cross-section view of a typical 1.5-volt alkaline battery.

A 1.5V battery contains one cell, while a 6V or 9V battery will contain multiple cells connected in series. The total voltage of the battery is the sum of the voltages of its cells.

Electrode Terminology

The electrodes of a cell are often referred to as the *anode* and the *cathode*. These terms are confusing because the electrons enter the anode inside the cell and leave it outside the cell, while electrons enter the cathode from outside the cell

and leave it inside the cell. Thus, the anode is an electron emitter if you look at it externally, but the cathode is an electron emitter if you look at it internally.

Conventional current is imagined to flow in the opposite direction to electrons, and therefore, outside the cell, this current flows from the cathode to the anode, and from this perspective, the cathode can be thought of as being “more positive” than the anode. To remember this, think of the letter t in “cathode” as being a + sign, thus: ca+hode. In larger batteries, the cathode is often painted or tagged red, while the anode may be painted or tagged black or blue.

When a reusable battery is recharged, the flow of electrons reverses and the anode and the cathode effectively trade places. Recognizing this, the manufacturers of rechargeable batteries may refer to the more-positive terminal as the anode. This creates additional confusion, exacerbated further still by electronics manufacturers using the term “cathode” to identify the end of a **diode** which must be “more negative” (i.e., at a lower potential) than the opposite end.

To minimize the risk of errors, it is easiest to avoid the terms “anode” and “cathode” when referring to batteries, and speak instead of the negative and positive terminals. This encyclopedia uses the common convention of reserving the term “cathode” to identify the “more negative” end of any type of diode.

Variants

Three types of batteries exist.

1. *Disposable batteries*, properly (but infrequently) referred to as *primary cells*. They are not reliably rechargeable because their chemical reactions are not easily reversible.
2. *Rechargeable batteries*, properly (but infrequently) known as *secondary cells*. They can be recharged by applying a voltage between

the terminals from an external source such as a [battery charger](#). The materials used in the battery, and the care with which the battery is maintained, will affect the rate at which chemical degradation of the electrodes gradually occurs as it is recharged repeatedly. Either way, the number of charge/discharge cycles is limited.

3. [Fuel Cells](#) require an inflow of a reactive gas such as hydrogen to maintain an electrochemical reaction over a long period. They are beyond the scope of this encyclopedia.

A large **capacitor** may be substituted for a battery for some applications, although it has a lower energy density and will be more expensive to manufacture than a battery of equivalent power storage. A capacitor charges and discharges much more rapidly than a battery because no chemical reactions are involved, but a battery sustains its voltage much more successfully during the discharge cycle. See [Figure 2-5](#).

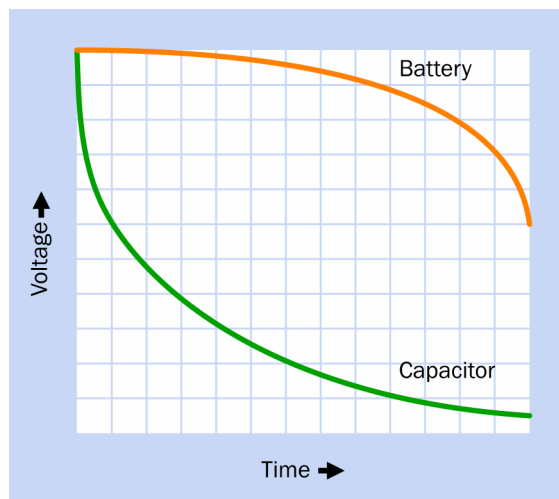


Figure 2-5. The voltage drop of a discharging capacitor is much steeper initially than that of a battery, making capacitors unsuitable as a battery substitute in many applications. However, the ability of a capacitor to discharge very rapidly at high amperage can sometimes be a significant advantage.

Capacitors that can store a very large amount of energy are often referred to as [supercapacitors](#).

Disposable Batteries

The energy density of any disposable battery is higher than that of any type of rechargeable battery, and it will have a much longer shelf life because it loses its charge more slowly during storage (this is known as the [self-discharge rate](#)). Disposable batteries may have a useful life of five years or more, making them ideal for applications such as smoke detectors, handheld remotes for consumer electronics, or emergency flashlights.

Disposable batteries are not well suited to delivering high currents through loads below 75Ω. Rechargeable batteries are preferable for higher-current applications. The bar chart in [Figure 2-6](#) shows the rated and actual capabilities of an alkaline battery relative to the three most commonly used rechargeable types, when the battery is connected with a resistance that is low enough to assure complete discharge in 1 hour.

The manufacturer's rating of watt hours per kilo is typically established by testing a battery with a relatively high-resistance load and slow rate of discharge. This rating will not apply in practice if a battery is discharged with a C-rate of 1, meaning complete discharge during 1 hour.

Common types of disposable batteries are [zinc-carbon cells](#) and [alkaline cells](#). In a zinc-carbon cell, the negative electrode is made of zinc while the positive electrode is made of carbon. The limited power capacity of this type of battery has reduced its popularity, but because it is the cheapest to manufacture, it may still be found where a company sells a product with "batteries included." The electrolyte is usually ammonium chloride or zinc chloride. The 9V battery in [Figure 2-7](#) is actually a zinc-carbon battery according to its supplier, while the smaller one beside it is a 12V alkaline battery designed for use in burglar alarms. These examples show that batteries cannot always be identified correctly by a casual assessment of their appearance.

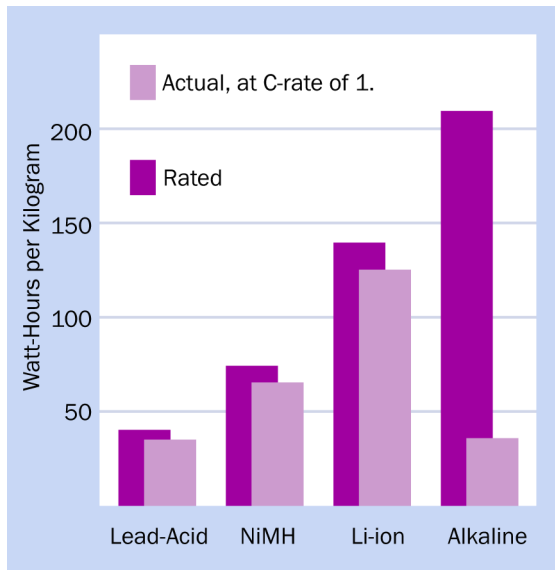


Figure 2-6. Because of their relatively high internal resistance, alkaline batteries are especially unsuited to high discharge rates, and should be reserved for applications where a small current is required over a long period. (Chart derived from <http://batteryuniversity.com>.)



Figure 2-7. At left, a cheap carbon-zinc battery; at right, a 12V alkaline burglar-alarm battery. See text for additional details.

In an alkaline cell, the negative electrode is made of zinc powder, the positive electrode is manganese dioxide, and the electrolyte is potassium hydroxide. An alkaline cell may provide between three to five times the power capacity of an equal size of zinc-carbon cell and is less susceptible to voltage drop during the discharge cycle.

Extremely long shelf life is necessary in some military applications. This may be achieved by using a *reserve battery*, in which the internal chemical compounds are separated from each other but can be recombined prior to use.

Rechargeable Batteries

Commonly used types are *lead-acid*, *nickel cadmium* (abbreviated *NiCad* or *NiCd*), *nickel-metal hydride* (abbreviated *NiMH*), *lithium-ion* (abbreviated *Li-ion*), and *lithium-ion polymer*.

Lead-acid batteries have existed for more than a century and are still widely used in vehicles, burglar alarms, emergency lighting, and large power backup systems. The early design was described as *flooded*; it used a solution of sulfuric acid (generically referred to as *battery acid*) as its electrolyte, required the addition of distilled water periodically, and was vented to allow gas to escape. The venting also allowed acid to spill if the battery was tipped over.

The *valve-regulated lead-acid* battery (*VRLA*) has become widely used, requiring no addition of water to the cells. A pressure relief valve is included, but will not leak electrolyte, regardless of the position of the battery. VRLA batteries are preferred for *uninterruptible power supplies* for data-processing equipment, and are found in automobiles and in electric wheelchairs, as their low gas output and security from spillage increases their safety factor.

VRLA batteries can be divided into two types: absorbed glass mat (AGM) and gel batteries. The electrolyte in an AGM is absorbed in a fiber-glass mat separator. In a gel cell, the electrolyte is mixed with silica dust to form an immobilized gel.

The term *deep cycle battery* may be applied to a lead-acid battery and indicates that it should be more tolerant of discharge to a low level—perhaps 20 percent of its full charge (although manufacturers may claim a lower number). The plates in a standard lead-acid battery are composed of a lead *sponge*, which maximizes the surface area available to acid in the battery but can be phys-

ically abraded by deep discharge. In a deep cycle battery, the plates are solid. This means they are more robust, but are less able to supply high amperage. If a deep-discharge battery is used to start an internal combustion engine, the battery should be larger than a regular lead-acid battery used for this purpose.

A sealed lead-acid battery intended to power an external light activated by a motion detector is shown in [Figure 2-8](#). This unit weighs several pounds and is trickle-charged during the day-time by a 6" × 6" solar panel.



Figure 2-8. A lead-acid battery from an external light activated by a motion sensor.

Nickel-cadmium (*NiCad*) batteries can withstand extremely high currents, but have been banned in Europe because of the toxicity of metallic cadmium. They are being replaced in the United States by *nickel-metal hydride* (*NiMH*) types, which are free from the *memory effect* that can prevent a NiCad cell from fully recharging if it has been left for weeks or months in a partially discharged state.

Lithium-ion and lithium-ion polymer batteries have a better energy-to-mass ratio than NiMH batteries, and are widely used with electronic devices such as laptop computers, media players, digital cameras, and cellular phones. Large arrays of lithium batteries have also been used in some electric vehicles.

Various small rechargeable batteries are shown in [Figure 2-9](#). The NiCad pack at top-left was manufactured for a cordless phone and is rapidly becoming obsolete. The 3V lithium battery at top-right was intended for a digital camera. The three batteries in the lower half of the photograph are all rechargeable NiMH substitutes for 9V, AA, and AAA batteries. The NiMH chemistry results in the AA and AAA single-cell batteries being rated for 1.2V rather than 1.5V, but the manufacturer claims they can be substituted for 1.5V alkaline cells because NiMH units sustain their rated voltage more consistently over time. Thus, the output from a fresh NiMH battery may be comparable to that of an alkaline battery that is part-way through its discharge cycle.



Figure 2-9. Top left: NiCad battery pack for a cordless phone. Top right: Lithium battery for a digital camera. The other batteries are rechargeable NiMH substitutes for everyday alkaline cells.

NiMH battery packs are available to deliver substantial power while being smaller and lighter than lead-acid equivalents. The NiMH package in [Figure 2-10](#) is rated for 10Ah, and consists of ten

D-size NiMH batteries wired in series to deliver 12VDC. This type of battery pack is useful in robotics and other applications where a small motor-driven device must have free mobility.

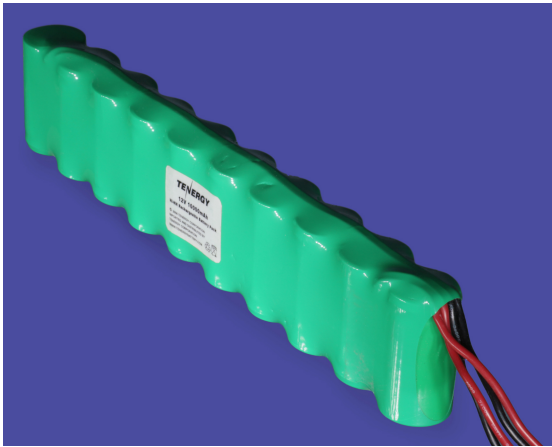


Figure 2-10. This NiMH battery pack is rated at 10Ah and delivers 12 volts from ten D-size cells wired in series.

Values

Amperage

The current delivered by a battery will be largely determined by the resistance of the external load placed between its terminals. However, because ion transfer must occur inside the battery to complete the circuit, the current will also be limited by the *internal resistance* of the battery. This should be thought of as an active part of the circuit.

Since a battery will deliver no current if there is no load, current must be measured while a load is attached, and cannot be measured by a meter alone. The meter will be immediately overloaded, with destructive results, if it is connected directly between the terminals of a battery, or in parallel with the load. Current must always be measured with the meter in series with the load, and the polarity of the meter must correspond with the polarity of the battery. See [Figure 2-11](#).

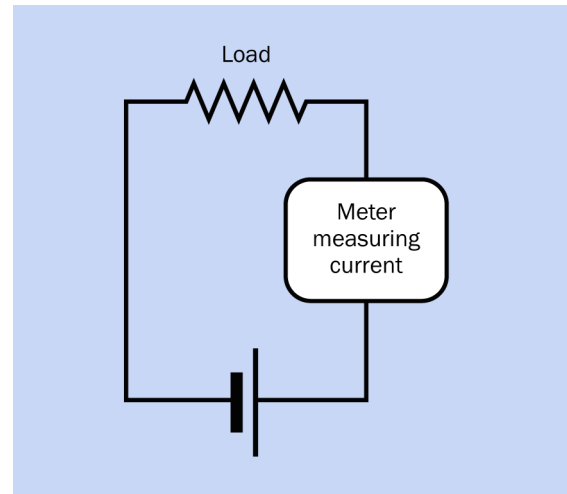


Figure 2-11. When measuring current using an ammeter (or a multimeter configured to measure amps), the meter must be placed in series with the battery and a load. To avoid damaging the meter, it must never be applied directly across the terminals of the battery, or in parallel with a load. Be careful to observe the polarity of the meter.

Capacity

The *electrical capacity* of a battery is measured in *amp-hours*, abbreviated *Ah*, *AH*, or (rarely) *A/H*. Smaller values are measured in *milliamp-hours*, usually abbreviated *mAh*. If *I* is the current being drawn from a battery (in amps) and *T* is the time for which the battery can deliver that current (in hours), the amp-hour capacity is given by the formula:

$$\text{Ah} = I * T$$

By turning the formula around, if we know the amp-hour rating that a manufacturer has determined for a battery, we can calculate the time in hours for which a battery can deliver a particular current:

$$T = \text{Ah} / I$$

Theoretically, Ah is a constant value for any given battery. Thus a battery rated for 4Ah should provide 1 amp for 4 hours, 4 amps for 1 hour, 5 amps for 0.8 hours (48 minutes), and so on.

In reality, this conveniently linear relationship does not exist. It quickly breaks down as the

current rises, especially when using lead-acid batteries, which do not perform well when required to deliver high current. Some of the current is lost as heat, and the battery may be electrochemically incapable of keeping up with demand.

The *Peukert number* (named after its German originator in 1897) is a fudge factor to obtain a more realistic value for T at higher currents. If n is the Peukert number for a particular battery, then the previous formula can be modified thus:

$$T = Ah / I^n$$

Manufacturers usually (but not always) supply Peukert's number in their specification for a battery. So, if a battery has been rated at 4Ah, and its Peukert number is 1.2 (which is typical for lead-acid batteries), and I=5 (in other words, we want to know for how long a time, T, the battery can deliver 5 amps):

$$T = 4 / 5^{1.2} = \text{approximately } 4 / 6.9$$

This is about 0.58 hours, or 35 minutes—much less than the 48 minutes that the original formula suggested.

Unfortunately, there is a major problem with this calculation. In Peukert's era, the amp-hour rating for a battery was established by a manufacturer by drawing 1A and measuring the time during which the battery was capable of delivering that current. If it took 4 hours, the battery was rated at 4Ah.

Today, this measurement process is reversed. Instead of specifying the current to be drawn from the battery, a manufacturer specifies the time for which the test will run, then finds the maximum current the battery can deliver for that time. Often, the time period is 20 hours. Therefore, if a battery has a modern 4Ah rating, testing has probably determined that it delivered 0.2A for 20 hours, not 1A for 4 hours, which would have been the case in Peukert's era.

This is a significant distinction, because the same battery that can deliver 0.2A for 20 hours will not

be able to satisfy the greater demand of 1A for 4 hours. Therefore the old amp-hour rating and the modern amp-hour rating mean different things and are incompatible. If the modern Ah rating is inserted into the old Peukert formula (as it was above), the answer will be misleadingly optimistic. Unfortunately, this fact is widely disregarded. Peukert's formula is still being used, and the performance of many batteries is being evaluated incorrectly.

The formula has been revised (initially by Chris Gibson of SmartGauge Electronics) to take into account the way in which Ah ratings are established today. Suppose that AhM is the modern rating for the battery's capacity in amp-hours, H is the duration in hours for which the battery was tested when the manufacturer calibrated it, n is Peukert's number (supplied by the manufacturer) as before, and I is the current you hope to draw from the battery. This is the revised formula to determine T:

$$T = H * (AhM / (I * H)^n)$$

How do we know the value for H? Most (not all) manufacturers will supply this number in their battery specification. Alternatively, and confusingly, they may use the term *C-rate*, which can be defined as 1/H. This means you can easily get the value for H if you know the C-rate:

$$H = 1 / \text{C-rate}$$

We can now use the revised formula to rework the original calculation. Going back to the example, if the battery was rated for 4Ah using the modern system, in a discharge test that lasted 20 hours (which is the same as a C-rate of 0.05), and the manufacturer still states that it has a Peukert number of 1.2, and we want to know for how long we can draw 5A from it:

$$T = 20 * (4 / (5 * 20)^{1.2}) = \text{approximately } 20 * 0.021$$

This is about 0.42 hours, or 25 minutes—quite different from the 35 minutes obtained with the old version of the formula, which should never be used when calculating the probable dis-

charge time based on a modern Ah rating. These issues may seem arcane, but they are of great importance when assessing the likely performance of battery-powered equipment such as electric vehicles.

Figure 2-12 shows the probable actual performance of batteries with Peukert numbers of 1.1, 1.2, and 1.3. The curves were derived from the revised version of Peukert's formula and show how the number of amp-hours that you can expect diminishes for each battery as the current increases. For example, if a battery that the manufacturer has assigned a Peukert number of 1.2 is rated at 100Ah using the modern 20-hour test, but we draw 30A from it, the battery can actually deliver only 70Ah.

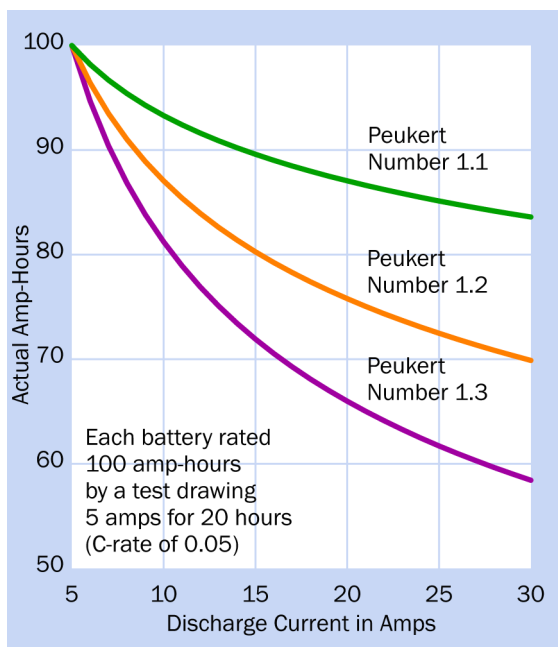


Figure 2-12. Actual amp-hour performance that should be expected from three batteries of Peukert numbers 1.1, 1.2, and 1.3 when they discharge currents ranging from 5 to 30 amps, assuming that the manufacturer has rated each battery at 100Ah using the modern system, which usually entails a 20-hour test (a C-rate of 0.05).

One additional factor: For any rechargeable battery, the Peukert number gradually increases with age, as the battery deteriorates chemically.

Voltage

The rated voltage of a fully charged battery is known as the *open circuit voltage* (abbreviated *OCV* or V_{oc}), defined as the potential that exists when no load is imposed between the terminals. Because the internal resistance of a volt meter (or a multimeter, when it is used to measure DC volts) is very high, it can be connected directly between the battery terminals with no other load present, and will show the OCV quite accurately, without risk of damage to the meter. A fully charged 12-volt car battery may have an OCV of about 12.6 volts, while a fresh 9-volt alkaline battery typically has an OCV of about 9.5 volts. Be extremely careful to set a multimeter to measure DC volts before connecting it across the battery. Usually this entails plugging the wire from the red probe into a socket separately reserved for measuring voltage, not amperage.

The voltage delivered by a battery will be pulled down significantly when a load is applied to it, and will decrease further as time passes during a discharge cycle. For these reasons, a **voltage regulator** is required when a battery powers components such as digital integrated circuit chips, which do not tolerate a wide variation in voltage.

To measure voltage while a load is applied to the battery, the meter must be connected in parallel with the load. See Figure 2-13. This type of measurement will give a reasonably accurate reading for the potential applied to the load, so long as the resistance of the load is relatively low compared with the internal resistance of the meter.

Figure 2-14 shows the performance of five commonly used sizes of alkaline batteries. The ratings in this chart were derived for alkaline batteries under favorable conditions, passing a small current through a relatively high-ohm load for long periods (40 to 400 hours, depending on battery type). The test continued until the final voltage for each 1.5V battery was 0.8V, and the final voltage for the 9V battery was a mere 4.8V. These voltages were considered acceptable when the

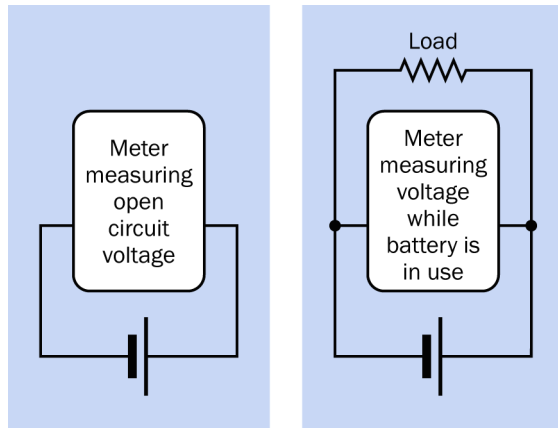


Figure 2-13. When using a volt meter (or a multimeter configured to measure voltage), the meter can be applied directly between the battery terminals to determine the open-circuit voltage (OCV), or in parallel with a load to determine the voltage actually supplied during use. A multimeter must be set to measure DC volts before connecting it across a battery. Any other setting may damage the meter.

Ah ratings for the batteries were calculated by the manufacturer, but in real-world situations, a final voltage of 4.8V from a 9V battery is likely to be unacceptable in many electronics applications.

Battery type	Rating (Ah)	Final voltage	Load (ohms)	Current (mA)
AAA	1.15	0.8	75	20
AA	2.87	0.8	75	20
C	7.8	0.8	39	40
D	17	0.8	39	40
9V	0.57	4.8	620	14

Figure 2-14. The voltage delivered by a battery may drop to a low level while a manufacturer is establishing an amp-hour rating. Values for current, shown in the chart, were calculated subsequently as estimated averages, and should be considered approximate. (Derived from a chart published by Panasonic.)

As a general rule of thumb, if an application does not tolerate a significant voltage drop, the manufacturer's amp-hour rating for a small battery may be divided by 2 to obtain a realistic number.

How to Use it

When choosing a battery to power a circuit, considerations will include the intended shelf life, maximum and typical current drain, and battery weight. The amp-hour rating of a battery can be used as a very approximate guide to determine its suitability. For 5V circuits that impose a drain of 100mA or less, it is common to use a 9V battery, or six 1.5V batteries in series, passing current through a **voltage regulator** such as the LM7805. Note that the voltage regulator requires energy to function, and thus it imposes a voltage drop that will be dissipated as heat. The minimum drop will vary depending on the type of regulator used.

Batteries or cells may be used in series or in parallel. In series, the total voltage of the chain of cells is found by summing their individual voltages, while their amp-hour rating remains the same as for a single cell, assuming that all the cells are identical. Wired in parallel, the total voltage of the cells remains the same as for a single cell, while the combined amp-hour value is found by summing their individual amp-hour ratings, assuming that all the batteries are identical. See [Figure 2-15](#).

In addition to their obvious advantage of portability, batteries have an additional advantage of being generally free from power spikes and noise that can cause sensitive components to misbehave. Consequently, the need for smoothing will depend only on possible noise created by other components in the circuit.

Motors or other inductive loads draw an initial surge that can be many times the current that they use after they start running. A battery must be chosen that will tolerate this surge without damage.

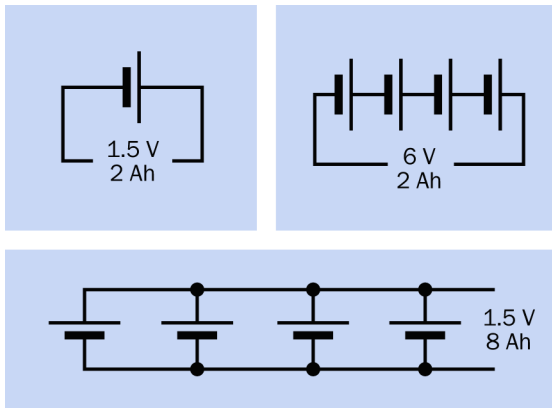


Figure 2-15. Theoretical results of using 1.5V cells in series or in parallel, assuming a 2Ah rating for one cell.

Because of the risk of fire, United States airline regulations limit the amp-hour capacity of lithium-ion batteries in any electronic device in carry-on or checked passenger baggage. If a device may be carried frequently as passenger baggage (for example, emergency medical equipment), NiMH batteries are preferred.

What Can Go Wrong

Short Circuits: Overheating and Fire

A battery capable of delivering significant current can overheat, catch fire, or even explode if it is short-circuited. Dropping a wrench across the terminals of a car battery will result in a bright flash, a loud noise, and some molten metal. Even a 1.5-volt alkaline AA battery can become too hot to touch if its terminals are shorted together. (Never try this with a rechargeable battery, which has a much lower internal resistance, allowing much higher flow of current.) Lithium-ion batteries are particularly dangerous, and almost always are packaged with a current-limiting component that should not be disabled. A short-circuited lithium battery can explode.

If a battery pack is used as a cheap and simple workbench DC power supply, a **fuse** or circuit breaker should be included. Any device that uses significant battery power should be fused.

Diminished Performance Caused by Improper Recharging

Many types of batteries require a precisely measured charging voltage and a cycle that ends automatically when the battery is fully charged. Failure to observe this protocol can result in chemical damage that may not be reversible. A charger should be used that is specifically intended for the type of battery. A detailed comparison of chargers and batteries is outside the scope of this encyclopedia.

Complete Discharge of Lead-Acid Battery

Complete or near-complete discharge of a lead-acid battery will significantly shorten its life (unless it is specifically designed for deep-cycle use—although even then, more than an 80% discharge is not generally recommended).

Inadequate Current

Chemical reactions inside a battery occur more slowly at low temperatures. Consequently, a cold battery cannot deliver as much current as a warm battery. For this reason, in winter weather, a car battery is less able to deliver high current. At the same time, because engine oil becomes more viscous as the temperature falls, the starter motor will demand more current to turn the engine. This combination of factors explains the tendency of car batteries to fail on cold winter mornings.

Incorrect Polarity

If a battery charger or generator is connected with a battery with incorrect polarity, the battery may experience permanent damage. The **fuse** or **circuit breaker** in a charger may prevent this from occurring and may also prevent damage to the charger, but this cannot be guaranteed.

If two high-capacity batteries are connected with opposite polarity (as may happen when a clumsy attempt is made to start a stalled car with jumper cables), the results may be explosive. Never lean over a car battery when attaching cables to it, and ideally, wear eye protection.

Reverse Charging

Reverse charging can occur when a battery becomes completely discharged while it is wired (correctly) in series with other batteries that are still delivering current. In the upper section of the schematic at [Figure 2-16](#) two healthy 6V batteries, in series, are powering a resistive load. The battery on the left applies a potential of 6 volts to the battery on the right, which adds its own 6 volts to create a full 12 volts across the load. The red and blue lines indicate volt meter leads, and the numbers show the reading that should be observed on the meter.

In the second schematic, the battery on the left has become exhausted and is now a “dead weight” in the circuit, indicated by its gray color. The battery on the right still sustains a 6-volt potential. If the internal resistance of the dead battery is approximately 1 ohm and the resistance of the load is approximately 20 ohms, the potential across the dead battery will be about 0.3 volts, in the opposite direction to its normal charged voltage. Reverse charging will result and can damage the battery. To avoid this problem, a battery pack containing multiple cells should never be fully discharged.

Sulfurization

When a lead-acid battery is partially or completely discharged and is allowed to remain in that state, sulfur tends to build up on its metal plates. The sulfur gradually tends to harden, forming a barrier against the electrochemical reactions that are necessary to recharge the battery. For this reason, lead-acid batteries should not be allowed to sit for long periods in a discharged condition. Anecdotal evidence suggests that even a very small trickle-charging current can prevent sulfurization, which is why some people recommend attaching a small solar panel to a battery that is seldom used—for example, on a sail boat, where the sole function of the battery is to start an auxiliary engine when there is insufficient wind.

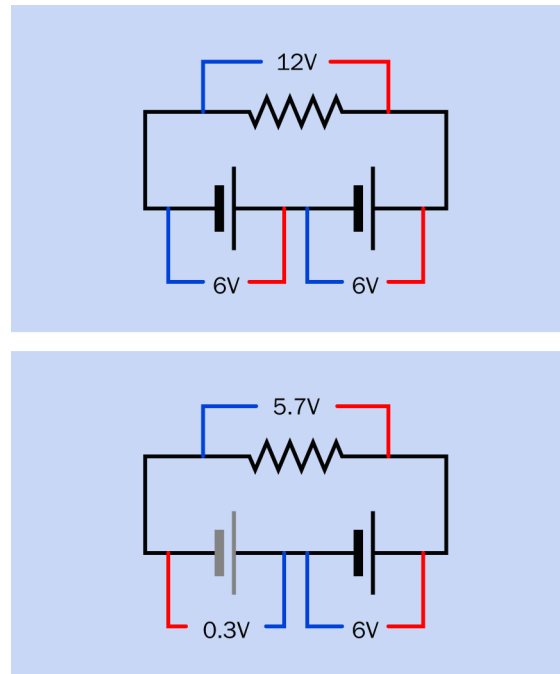


Figure 2-16. When a pair of 6V batteries is placed in series to power a resistive load, if one of the batteries discharges completely, it becomes a load instead of a power source, and will be subjected to reverse charging, which may cause permanent damage.

High Current Flow Between Parallel Batteries

If two batteries are connected in parallel, with correct polarity, but one of them is fully charged while the other is not, the charged battery will attempt to recharge its neighbor. Because the batteries are wired directly together, the current will be limited only by their internal resistance and the resistance of the cables connecting them. This may lead to overheating and possible damage. The risk becomes more significant when linking batteries that have high Ah ratings. Ideally they should be protected from one another by high-current **fuses**.

O'Reilly Ebooks—Your bookshelf on your devices!



When you buy an ebook through oreilly.com you get lifetime access to the book, and whenever possible we provide it to you in five, DRM-free file formats—PDF, .epub, Kindle-compatible .mobi, Android .apk, and DAISY—that you can use on the devices of your choice. Our ebook files are fully searchable, and you can cut-and-paste and print them. We also alert you when we've updated the files with corrections and additions.

Learn more at ebooks.oreilly.com

You can also purchase O'Reilly ebooks through the iBookstore, the [Android Marketplace](http://AndroidMarketplace), and Amazon.com.

O'REILLY®

Spreading the knowledge of innovators

oreilly.com