Batteries!

But Were Too Afraid to Ask

When it comes to packing a bunch of free electrons around for use on the go, it's hard to beat the good, old battery. But what battery should you use? There are so many options, so many ways to make a plastic box imprison a bunch of angry pixies for later consumption, it can be hard to know where to begin. This guide is intended to explain the basics on different battery technologies as they apply to astromech droid building, so readers know where to start when it comes time to build their own solution.

Table of Contents

What is a Battery? – The Wonders of Electrochemistry

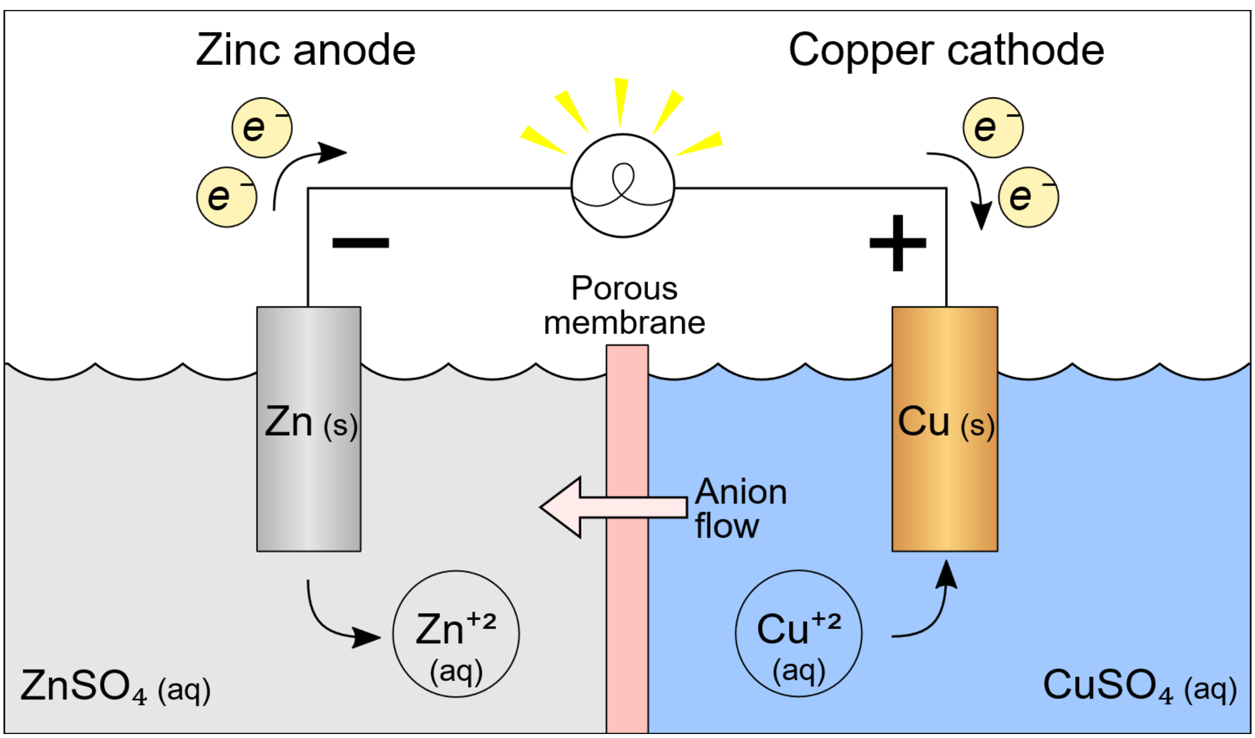
Battery
/ˈbat(ə)ri/
(noun)
a container consisting of one or more cells, in which chemical energy is converted into electricity and used as a source of power.

Batteries are boxes of metal (electrodes) and liquid (electrolyte) that, when connected to an electrical circuit, produce electricity via a chemical reaction. The ability to produce electricity by chemical reaction, and in turn to produce a chemical reaction by electricity, is called **Electrochemistry**. Some batteries can only produce a fixed amount of electricity, and then are depleted and must be discarded. However, some batteries have **Reversible Electrochemistry**, that is when they are discharged, applying a voltage to the battery causes the electricity-producing chemical reaction to reverse, enabling the battery to be reused over and over again. This is the fundamental difference between the battery in your car, and the battery in its key fob, and it all comes down to chemistry.

Battery Chemistry In Brief

In every battery, there are 2 main chemical components: electrodes and electrolytes. The electrodes are either positively charged (cathodes) or negatively charged (anodes) and they're submerged or coated in an electrolyte. The electrolyte is a chemical that reacts with the electrode, freeing electrons to flow from the anode to the cathode.

The following diagram details a galvanic cell, a type of electrochemical cell in which a current is generated when electrodes made of dissimilar metals immersed in electrolyte solution undergo oxidation-reduction reactions. Note how the anode donates electrons, which are absorbed by the cathode. By placing an electrical load between the electrodes, we can harness the energy released by the moving electrons.



Schematic of a voltaic (galvanic) cell – Wikipedia – Electrode

When we refer to common battery chemistries, we usually name them in terms of the electrode materials, for example Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), or Lithium Iron Phosphate ($LiFePO_4$). Sometimes, the composition of the electrolyte is part of the name, such as Lead-Acid or Lithium Polymer (LiPo).

Every battery chemistry has different properties. Some chemistries are reversible and some aren't, and every chemistry produces different cell voltages, with different discharge properties, and different charging requirements.

Charge! – A Primer on Battery Management

Obviously, we want to use rechargeable batteries for droids. Can you imagine how many D cells it would take to run a droid, and how expensive it would be to replace them every time they ran low? But charging batteries is tricky business. It's not enough to blindly throw electricity at a dead battery and expect it to come alive like some kind of Frankenstein's monster. In this section, we'll discuss the basics of battery management, both in terms of charging and discharging.

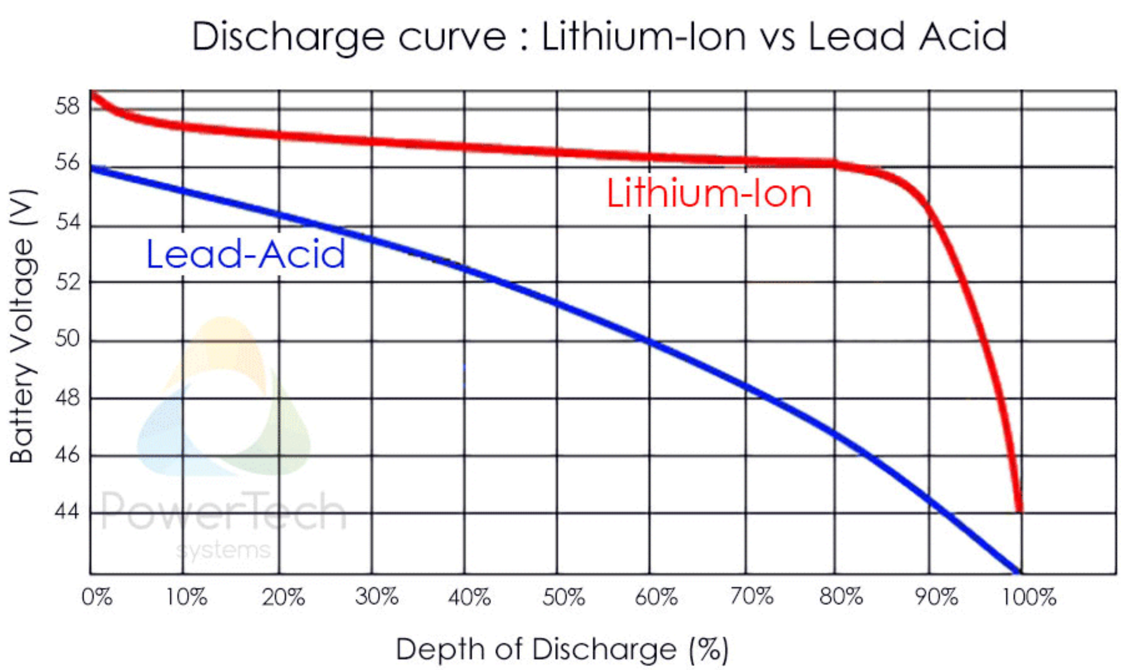
Discharging

We'll start with the easy part: **discharge**. You discharge a battery by placing a load on it, whether it's a light or a motor or a microcontroller. The load draws an electrical **current** which is supplied by the battery. As the battery discharges its electrical potential, its **voltage** will drop from its starting point, called **peak voltage**, falling through its **nominal voltage**, until eventually it reaches its **critical voltage**. When a battery reaches critical voltage, any further discharge will permanently damage the cells. This can occur due to various mechanisms, such as electrode sulfation or erosion, but in general the damage from excessive discharge is irreversible. Therefore, it is important to have a **low voltage cutoff** of some kind, which monitors battery voltage and disconnects the load.

In addition to voltage considerations, batteries have electrical **resistance** (**internal resistance**) which causes them to heat up as current passes through them during both charging and discharging. If the battery gets too hot, it can be damaged, and in some cases, even cause fires! In order to prevent this, it's important to have battery temperature monitoring, and to select batteries appropriately for the load that's going to be placed on them. A battery may be able to run a given load, but if it has high internal resistance, it will heat up and be damaged, whereas a different battery may support the same load with no issues.

This brings us to **current ratings**. Simply put, current is demanded by the load, regardless of what the supply can provide- and the supply will be compelled to provide that current, even if it's beyond its capabilities. Consider a short circuit: when positive and negative are directly connected with a wire, there's no resistance to limit current, so a massive current will start to flow. When this happens to an appliance in your house, a circuit breaker detects the massive current and turns off the circuit before anything bad can happen. When it happens to a lithium battery, the only thing limiting the current is the internal resistance, which is just high enough to turn the battery into a potent heater. Obviously, for this reason, it's important to install fuses between the battery and the load. However, a fuse can only protect you from abnormal current. That is, if your electronics draw 50 amps, a battery that can only safely supply 20 amps won't be protected by a 50 amp fuse- and a 20 amp fuse won't allow your electronics to run.

One way to ensure your battery has enough current capacity to safely power your droid is to double up. When multiple batteries are connected to a circuit in **parallel**, they provide more current at the same voltage, which means they also have a longer battery life. In order to do this safely, all the batteries in a parallel circuit must be of the same type and voltage rating. A 12-volt battery and a 9-volt battery aren't a good match- the 9-volt battery will be overloaded by the 12-volt battery, which can result in **overcharging**. You shouldn't mix and match battery types either, even if they have the same nominal voltage. A 12-volt lead-acid battery can have a voltage as high as 13.2v or as low as 10.8v, while a 12-volt lithium polymer battery's peak voltage is only 12.6v. A fully-charged lead-acid battery will overcharge a lipo battery on the same circuit. Moreover, since different chemistries have different **discharge curves**, if the lipo battery isn't damaged by overcharging, eventually it will begin to charge the lead-acid battery, which has a steeper rate of voltage drop.



Lithium LiFePO4 vs Lead discharge curve – PowerTech Systems

This principle actually applies not only to multiple batteries wired in parallel, but also all of the cells in each individual battery, which will be connected in some combination of **series** and parallel circuits, to raise the voltage and enable the battery to provide sufficient current. That 12-volt lead-acid battery is actually comprised of 6 cells in series, and a 12-volt lithium battery will have 3 cells in series- and potentially have multiple sets of 3 cells in parallel. It's up to the manufacturer of a battery to match the cells to each other, but when discharging and charging them, you have to be able to **balance** the cells. This is because small differences between two cells can affect their internal resistance or other factors, resulting in slightly different charge and discharge rates. Over time, this can result in cells having mismatched voltages.

A final note: all batteries have a tendency to **self-discharge**. That is, over time, the chemical energy stored in the battery will be released as the battery's chemical reaction occurs without a circuit connected. At high charge states, self-discharge occurs more quickly than at low charge states. In general, it is advisable to store batteries in a low charge state to minimize self-discharge. If you or your parents ever kept AAs in the refrigerator, it's because the cold temperatures slow down the chemical reaction, reducing the rate of self-discharge.

Charging

All of these considerations apply to charging as well as discharging. When a battery is connected to a voltage source, the electrochemical reaction reverses. The battery's internal resistance causes it to draw a current from the voltage source, until its internal voltage reaches the charging voltage. This causes the battery to heat up, and requires careful balancing to ensure each cell is at the same voltage. Different battery chemistries have different charging characteristics. Lithium batteries are charged by supplying a voltage that rises to ensure a **constant current** is supplied, until the peak cell voltage is achieved. Lead-acid batteries, conversely, are charged by supplying a **constant voltage** until the battery stops drawing a current, at peak voltage.

LiPo battery charger with balance connector and battery bag – airbuzz.one

Unlike discharging a battery, where all one needs to do is connect a load and let the electrons flow, successfully charging a battery requires specialized equipment that can provide electricity at varying rates to meet the battery's needs. Fortunately, you can take all of the guesswork out of designing your battery's charging system, by simply buying an appropriate charger for the kind of battery you choose. So even though I said discharging was the easy part, this is the much shorter section!

Battery Management Systems (BMS)

The tools and procedures used to safely charge and discharge a battery are collectively called a **Battery Management System**. A **BMS** factors in everything discussed in the previous sections and handles the battery's requirements. Your BMS might be a low-voltage cutoff switch, some fuses, and a benchtop charger with balancing capabilities. Or, it might be a sophisticated microcontroller built into your battery packs themselves.

An Important Note on Power Tool Batteries

Power tool batteries are a popular choice for droid builders, since they're easy to find and have easy to use chargers. However, most power tool batteries **do not** have integrated BMS. The majority of power tools integrate their discharge protection features into the tools themselves, with the chargers containing all of the charging protection features. Even batteries with built-in state-of-charge indicators usually do not have integrated BMS. **At the time of this writing, the only power tool batteries that reliably have integrated BMS are RYOBI 18V ONE+ and RYOBI 40V.** Any other power tool battery should be considered to have no integrated protection, and your droid should be designed accordingly.

Not to scale

Not to scale

Glossary

In this section, we covered a lot of technical terms. The following is an explanation of those terms:

- **Balance –** The state of all cells in a battery being at equal voltage
    - Related terms: cell balance, balance charging, balancing
- **Battery Management System –** A system of components, tools, and practices used to safely manage a battery's charge state, preventing irreversible damage and risk of fire or explosion during use and storage
- **Constant Current –** A method of power supply that monitors the electrical current being drawn by a load and lowers or raises voltage in order to maintain a consistent level of current flow, since current may raise as available voltage does
- **Constant Voltage –** A method of power supply that monitors the voltage drop induced by a load, and raises or lowers the voltage in order to maintain a consistent voltage, regardless of current draw
- **Critical Voltage –** The lowest safe voltage of a cell. Below the critical voltage, the cell can be permanently damaged by further discharge

- **Current –** The amount of electrons moving through a circuit. Current is set by the load, and must be provided by the source. Current can vary depending on voltage. Measured in **amperes** (**amps**; **a**)
- **Current Rating –** The amount of current a battery is rated to safely supply. In lithium batteries, this is the **C Rating**, and separate rates are provided for charge and discharge. More detail can be found in the respective battery chemistry sections
- **Discharge –** The process of drawing current from a battery, causing its voltage to drop as its chemical energy is depleted
- **Discharge Curve –** A graph plotting the relationship between the measured voltage of a cell and its remaining chemical energy. Different chemistries experience different rates of voltage change as their stored chemical energy is used up
- **Internal Resistance –** The electrical resistance provided by the internal structure of a battery
- **Low Voltage Cutoff –** A mechanism by which a circuit can be disconnected from a battery in the event the battery voltage falls below a set voltage, usually higher than the critical voltage to provide a safety margin
- **Nominal Voltage –** The standard reference voltage for a given battery technology. For example, a 6-cell lead-acid battery has a nominal voltage of 12 volts
- **Overcharging –** The state of causing a battery's voltage to exceed the safe peak voltage. This can be caused by having mismatched batteries in a parallel circuit. This should not be confused with the increased voltage of a circuit with multiple batteries in series, which does not cause overcharging
- **Parallel –** A method of electrical circuit design wherein electrons can take multiple paths from source to ground.
    - Related terms: parallel circuit, parallel wiring
- **Peak Voltage –** The highest safe voltage for a given battery technology. For example, a lead-acid battery's cells have a peak voltage of 2.2 volts
- **Resistance –** The tendency of the elements of a circuit to impede the flow of electrons. Measured in **ohms** (Ω)
- **Self-Discharge –** The tendency of a battery to discharge without a circuit connected, due to its chemical components reacting on their own
- **Series –** A method of electrical circuit design wherein multiple elements of a circuit are connected one after the other, such that electrons must flow through all of them concurrently in order to move from the source to the ground
    - Related terms: series circuit, series wiring
- **Voltage –** The difference in electrical potential between two elements in a circuit, such as between the positive and negative terminals of a battery, or the positive and negative sides of a resistor. Measured in **volts** (**v**)

Lead-Acid Batteries

Although lead-acid batteries are waning in popularity, they're still commonly used in droid building. There's also less to discuss when it comes to them, so we'll cover them now and save the long discussion on lithium for later in the guide.

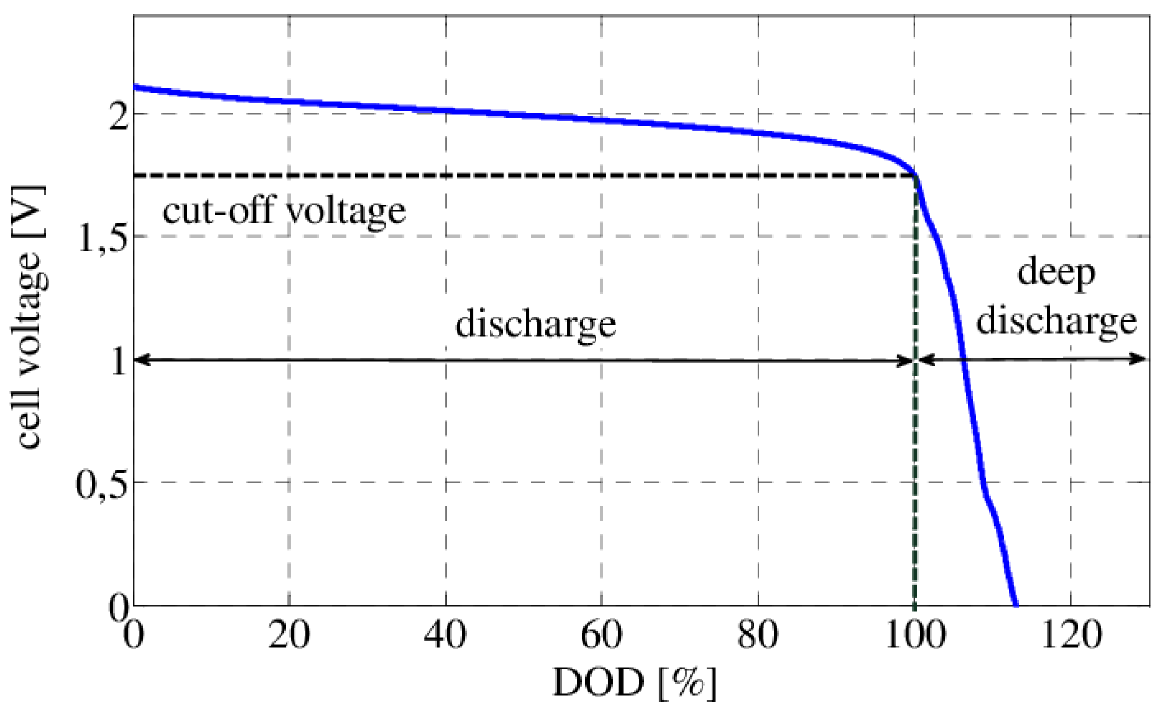
Chemistry

The cells of a lead-acid battery are comprised of lead electrodes (commonly called plates) immersed or coated in sulfuric acid. In a lead-acid battery, two chemical reactions occur during discharge: at the negative plate, lead reacts with sulfuric acid to form lead sulfate, hydrogen ions, and free electrons; at the positive plate, lead dioxide reacts with the sulfuric acid, hydrogen ions, and free electrons to form lead sulfate and water. The chemical formulae are as follows:

Negative Plate:
$Pb(s) + HSO^{-}_{4}(aq) \rightarrow PbSO_4(s) + H^{+}(aq) + 2e^{-}$

Positive Plate:
$PbO_2(s) + HSO^{-}_{4}(aq) + 3H^{+}(aq) + 2e^{-} \rightarrow PbSO_4(s) + 2H_2O(l)$

The electrons released produce 2.05 volts per cell at full charge. As the cell discharges, the sulfuric acid electrolyte becomes dilute, which reduces the rate of the reaction, resulting in lower voltage. When fully discharged, the cell only produces 1.8 volts. Charging reverses the chemical reaction, though specifics of charging differ based on battery construction.

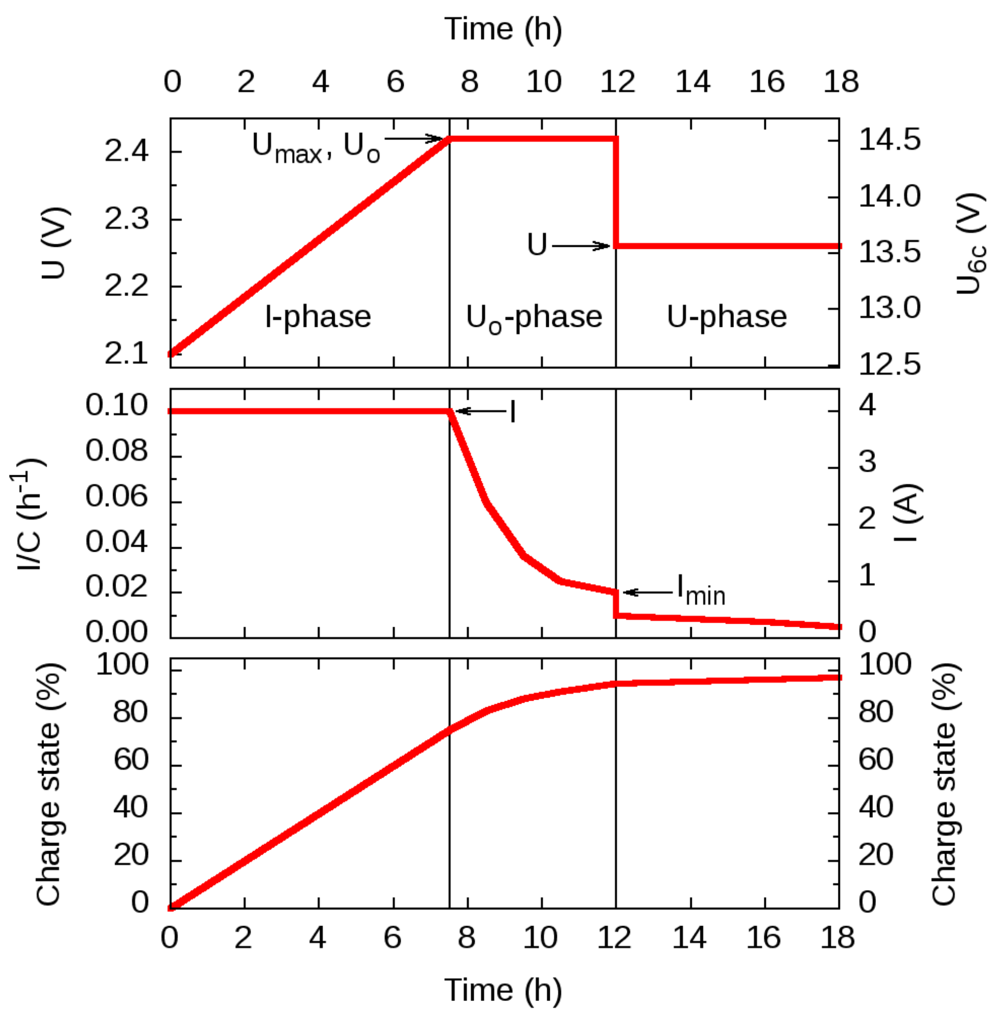


Voltage curve of lead-acid battery cell with deep discharge – Dirk Uwe Sauer (2012)

General Charging Information

In general, lead-acid batteries are charged in 3 stages: *I-phase*, *Uo-phase*, and *U-phase*, a process known as IUoU Charging.

1. In the I-Phase, also called the Constant Current Stage or Bulk Charge Stage, the charger provides a constant current, with voltage rising from around 2.1v to around 2.4v per cell. When the U_{max} voltage (typically 2.4v) is reached, the charger enters Uo-Phase.
2. The Uo-Phase is a constant voltage phase, with current dropping over time as the battery becomes unable to accept further charge at the Uo voltage. The Uo voltage is an over-voltage, which cannot be applied indefinitely, but allows quicker charging. Applied correctly, this over-voltage condition does not damage the battery. When current drops below a set threshold, the charger enters U-phase.
3. During U-Phase, also known as the Float Charge State, the charger's voltage drops to a safe value that can be applied to the battery for long periods of time without damaging or reducing the battery's lifetime. During this phase, charge current drops to a small value that compensates for the battery's self-discharge rate.



Example charging graph – Wikipedia – IuoU battery charging

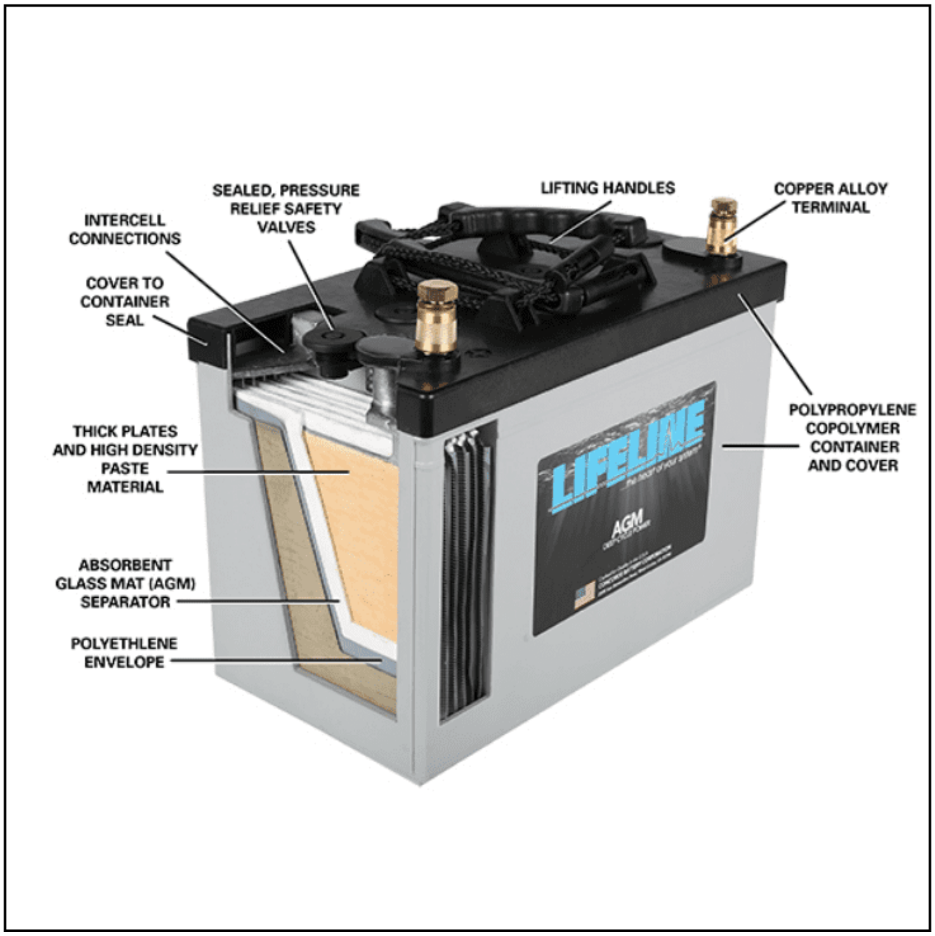
The voltages and current thresholds for different types of lead-acid batteries will differ. Therefore, it's important to use a charger that's appropriate to your type of battery.

Finally, note that unlike other battery chemistries, lead-acid batteries are generally safer and last longer when stored fully charged. When stored in a discharged state, sulfation of the lead plates can occur, which reduces effectiveness and lifespan of the battery.

Common Constructions

Sealed Lead-Acid Battery

The most common type of lead-acid battery is the Sealed Lead-Acid Battery, also called a Valve-Regulated Lead-Acid Battery. This style of battery consists of lead plates immersed in a solution of sulfuric acid and water, contained in a sealed plastic case. The primary benefit of this type of battery is its cheap construction, being made of common materials. SLA batteries can be broken down into two categories: Gel Batteries, and Absorbent Glass Mat Batteries. A gel battery uses silica dust to thicken the electrolyte into a gel, whereas an absorbent glass mat (or AGM) battery uses glass fiber mats to soak up the electrolyte. Generally, this type of battery can be installed in any orientation, as the sealed construction prevents leakage of the electrolyte. However, SLA batteries cannot be serviced as they age, since the sealed case prevents replacing the electrolyte as it depletes.



What is an AGM battery? – Lifeline Batteries

All lead-acid batteries suffer electrolyte depletion over time, due to the hydrogen gas produced as the battery discharges. No matter how well sealed, some of the hydrogen leaks out*, which prevents some of the lead sulfate from reducing back to lead and sulfuric acid when the battery is recharged. Over time, this reduces the battery's capacity.

With all lead-acid batteries, the primary disadvantage is weight. The lead plates are extremely dense, and lead-acid batteries provide only around 30-40 watt-hours per kilogram as a result. In order to provide enough power to drive a droid for several hours, a very heavy lead-acid battery is required. Also, no matter how well-sealed, SLA batteries may leak highly corrosive sulfuric acid, which can be hazardous to human health and wiring. Under high temperatures or electrical loads, gaseous sulfuric acid can be vented, which is corrosive, and gaseous hydrogen can be vented, which can potentially be explosive. The risk of fire or explosion is low, but non-zero, with any lead-acid battery chemistry.

Apart from weight and corrosion danger, lead-acid batteries are prone to damage due to significant discharging, known as deep-cycle discharge. When a lead-acid battery is deeply discharged, the layer of electrically-resistive lead sulfate that builds up on the surface of the lead plate can become so thick that it becomes impossible to recharge the battery at a safe voltage. Additionally, the loss of hydrogen during deep cycle discharge can prevent the sulfate from reducing back to sulfuric acid, even when sufficient voltage can be provided to pass through the sulfate layer. The same resistance sulfated plates cause during charging, reduces the current the battery can provide during discharge. **They may also experience thermal runaway during charging if inappropriately charged, which can cause fires.**

Sulfated plates from a 12-V 5-Ah battery – Wikipedia – Lead-acid battery

In general, SLA batteries should only be discharged to a 50% or higher state of charge. Ideally, they should not be allowed to drop below 60-80% charge. Some high-end SLA batteries can handle deep discharge cycles, to as low as 20% on occasion, but they will still lose effective life when discharged this deeply. With careful charging and discharging practices, an SLA battery may last as long as 1000 charge cycles. If allowed to deeply discharge frequently, it may only last 100 cycles.

Typical SLA batteries are available in 3-cell and 6-cell constructions, providing nominal voltages of 6v or 12v respectively.

*This is generally by design. Sealed lead-acid batteries have a ventilation port, which allows gas to escape, in order to prevent excessive pressure inside the battery. Without these vents, an SLA battery could explode under the pressure generated by the electrochemical reaction in extreme circumstances.

Car lead-acid battery after explosion showing brittle fracture in casing ends – Wikipedia – Lead-acid battery

Flooded Lead-Acid Battery

Similar to sealed lead-acid batteries, flooded (or wet) batteries immerse lead plates in an aqueous electrolyte of sulfuric acid. However, flooded batteries don't use gelling agents or absorbents to prevent spilling, and the battery is simply full of liquid. This type of battery is the cheapest by far, but it can only be safely installed in one orientation, as the liquid electrolyte can leak if the battery is installed on its side or upside down. Additionally, flooded batteries tend to have poorer deep cycle performance and take longer to charge. Some flooded batteries are serviceable, with removable caps that allow the electrolyte in each cell to be topped up or replaced. This type of battery has an extremely long effective service life, as electrolyte depletion is manageable. However, serviceable options are becoming rarer as the industry continues to phase out serviceable batteries in favor of non-serviceable batteries with shorter lifespans.

In general, flooded batteries are inadvisable for droid use, due to installation constraints, poor cycle performance, excessive weight, and diminishing options for appropriately sized batteries. Like SLA batteries, they are generally available in 3 and 6 cell configurations providing 6 and 12 volt nominal voltages.

Lithium-Ion Batteries

Lithium-ion batteries use the reversible intercalation of positively-charged Lithium ions into electrically conductive solids to store energy. Lithium-ion batteries are characterized by their high specific energy, energy density, energy efficiency, long cycle life, and long shelf life. There are numerous lithium-ion battery chemistries, but in general, a Li-ion battery consists of a lithium-containing cathode, a graphite* anode, and a gel electrolyte to provide anywhere from 3 to 10 times as much energy per kilogram as lead-acid batteries.

As there are numerous battery chemistries and constructions in the lithium-ion family, this guide will focus solely on commonly-available options suitable for droid building. As a result, exotic chemistries such as lithium manganese oxide and LTO spinel, as well as user-unfriendly constructions such as loose cylindrical cells, will be omitted.

Each lithium-ion battery chemistry has different characteristics, from voltage, to cycle durability, to charging parameters, and safety considerations.

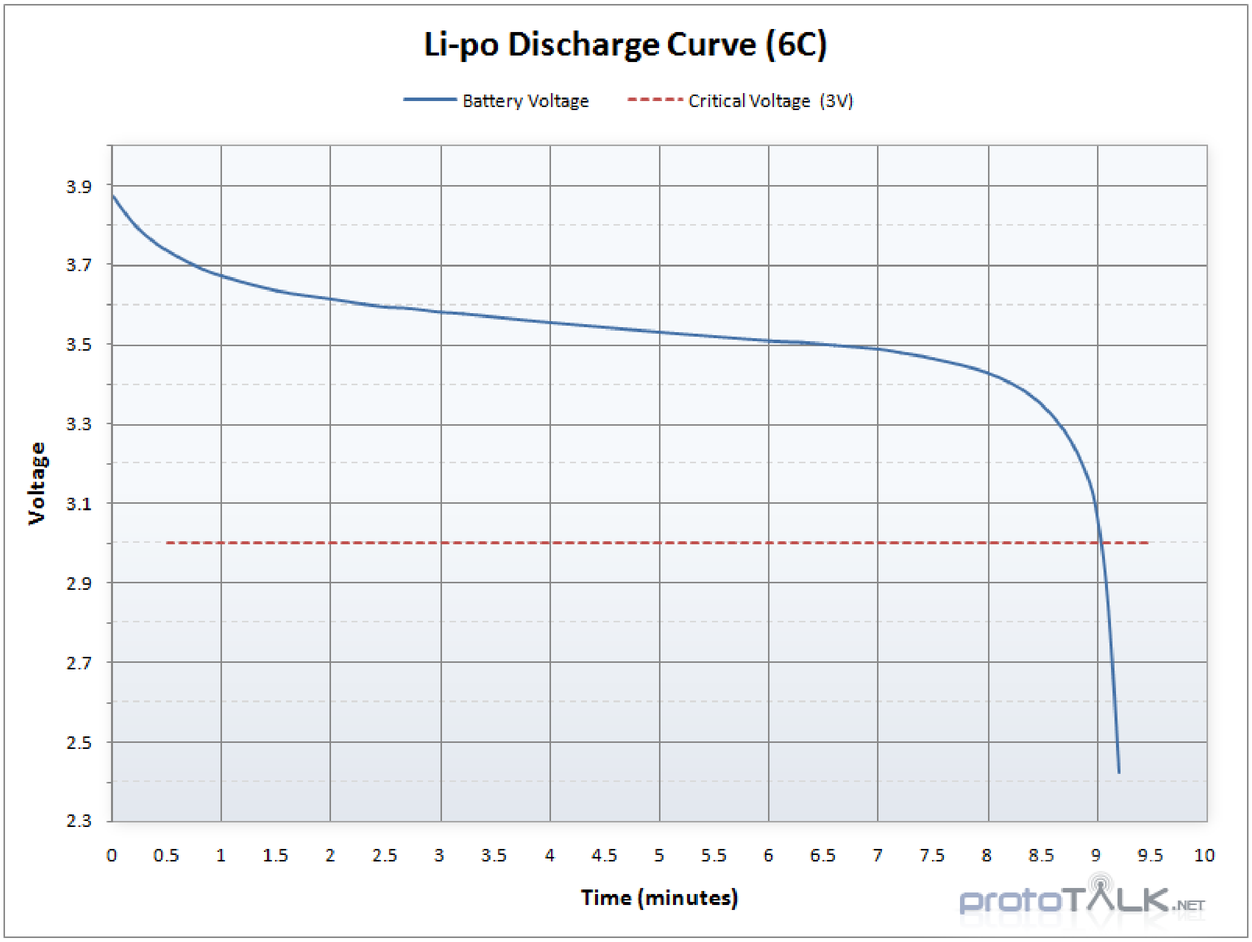
*Over 95% of the time anyway. Other materials are more rarely used.

Lithium Polymer (LiPo)

Lithium Polymer, or LiPo, batteries use a semi-solid polymer electrolyte instead of a conventional gel electrolyte. A typical lithium-ion battery uses an electrolyte comprised of a lithium salt suspended in an organic solvent, but a LiPo battery uses a polymer, such as polyethylene glycol, in its electrolyte. The result is a battery where every internal component is a solid. Since there are no liquids to contain, and every part of the battery will hold its shape independently, a strong, sealed case is not needed, so LiPo batteries have reduced weight and size compared to other battery constructions of equivalent stored energy. This has led to their ubiquity in mobile electronics, and in R/C vehicles.

Chemistry

There are numerous lithium polymer chemistries, but in general a single LiPo cell will have a nominal voltage of 3.7v, with a peak of 4.2v and a critical voltage of around 3.0v. Datasheets for specific batteries will contain the statistics for that battery. It is critical that LiPo batteries be protected from over-charging and over-discharging, as these conditions can quickly cause damage, and in the case of overcharging, it can cause fires. If a battery does not have available specifications, you shouldn't buy that battery.



Lithium Polymer discharge curve (6C) – Sparkfun - uncredited

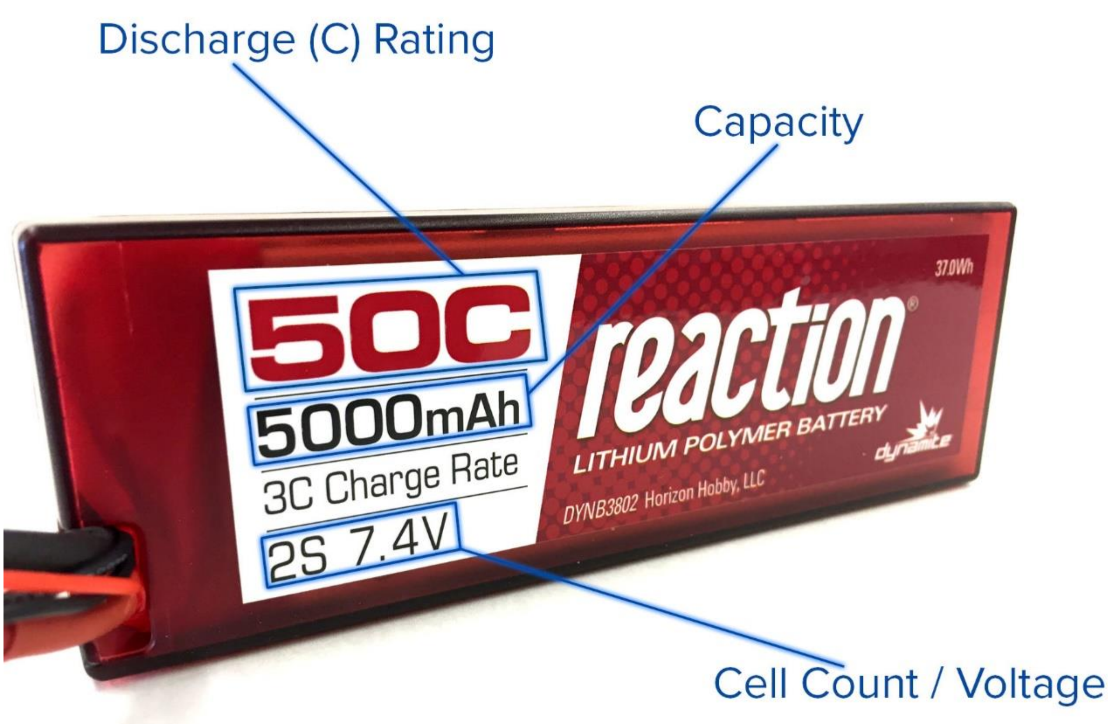
Construction and Terminology

LiPo batteries are composed of one or more LiPo cells arranged in series and parallel. Using multiple cells in series allows the battery to supply a greater nominal voltage than the single-cell rating of 3.7v. Hobby R/C batteries are the most common type of LiPo battery for droid building use, and these are designed with an **S-rating** that defines the number of cells in series. A **1S** battery has no cells connected in series, and provides 3.7v nominal, where a **2S** battery has 2 cells (or 2 groups of parallel cells) connected in series to provide 7.4v nominal. Refer to the following table for generally available S-ratings and their corresponding peak and nominal voltages.

Series	Peak Voltage	Nominal Voltage
1S	4.2V	3.7V
2S	8.4V	7.4V
3S	12.6V	11.1V
4S	16.8V	14.8V
5S	21V	18.5V
6S	25.2V	22.2V
7S	29.4V	25.9V
8S	33.6V	29.6V
9S	37.8V	33.3V
10S	42V	37V

Note: this table only goes as high as 10S. In practice, even this voltage is too high for droid use, but LiPo batteries are available in much higher voltage configurations, all the way into the hundreds of volts. As a general rule, using batteries rated higher than 7S will cause commonly available 24-volt components to exceed their maximum voltage ratings.

In addition to the S-rating, hobby batteries will have a designated **C-rating**, which refers to the maximum safe discharge current. The C-rating is more complicated than the S-rating, as it's tied to the battery's rated storage capacity. For any battery, capacity is rated in ampere-hours (**amp-hours; Ah**) which refers to the number of amps of current a battery could theoretically supply for 1 hour before being fully discharged. In practice, most LiPo batteries will use **milliamp-hours** (**mAh**) instead, because 1000 looks better than 1 on a label.



Common battery ratings – Roger's HobbyCenter

In principle, maximum safe current is equal to storage capacity times C-rating. That is, a battery with a capacity of 10Ah and a C-rating of 10C can supply 100 amps continuously. A more realistic example would be 5000mAh (5Ah) at 30C, for a maximum safe discharge current of 150 amps. C-ratings can be as low as 1C, or as high as 150C or even higher. LiPo batteries generally have excellent discharge characteristics, owing to low internal resistance and comparatively large surface area allowing the chemical reaction to occur quickly.

Caution: LiPo batteries have a separate C-rating for charging, which is generally much lower than the discharge rating. Most batteries will display their charge rate separately. A battery rated to 50C in discharge may only be able to safely charge at 3C. For that same 5000mAh (5Ah) battery, the maximum safe charge current would be only 15 amps. Exceeding the C-rating in either discharge or during charging can cause the battery to heat up, which can lead to fires.

Some batteries may be labeled with a P-rating, for example 2S1P or 2S2P. This refers to the number of cells connected in parallel. A 2S1P battery has 2 cells connected in series, and paradoxically no cells in parallel, while a 2S2P battery has a total of 4 cells: 2 sets of 2 parallel-connected cells, where the sets are connected to each other in series. Not all batteries use this labeling, so always refer to the manufacturer's specifications.

Safety

Lithium Polymer batteries offer extremely high performance at ever-more-affordable prices, however they must be treated with some caution for the sake of safety. Fundamentally, a battery is a means of storing large amounts of chemical energy to be released on demand, and LiPo batteries store a lot of energy in a very small space. This is also how bombs work, and if mistreated, a LiPo battery can respond by becoming one. Safe handling of LiPo batteries is not difficult or expensive, and when treated appropriately, they're so safe, you can sleep with the LiPo batteries in your phone sitting unattended on a fast charger.

There are 4 relevant states that have their own considerations for safe handling of lithium polymer batteries: charging, discharging, storage, and disposal.

Charging

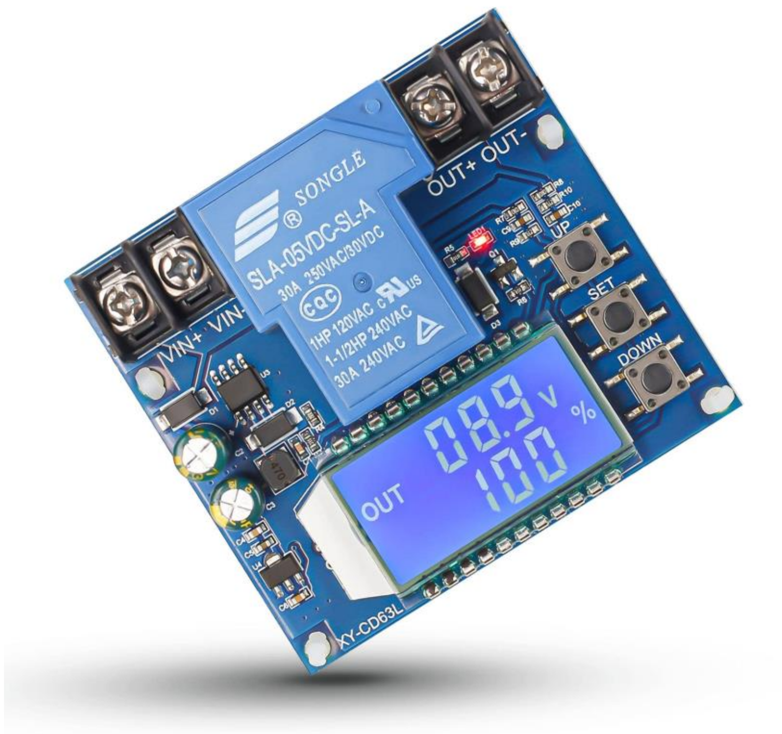
Lithium polymer batteries large enough for droid use should never be charged unattended. This is an inviolable rule of safe LiPo ownership. No matter how advanced your charger is, you should never leave a battery connected to it without an adult attending to it. In the event something goes wrong, the battery can go from the first signs of trouble to being an unextinguishable fire in seconds. To prevent potential lithium fires from spreading, lithium batteries should always be charged in a special fire-resistant bag made specifically for the charging of such batteries.

LiPo Guard LiPo Safe Bag – Amazon

Always follow the recommendations of the battery manufacturer when setting charging parameters. In the event of fire during charging, disconnect the leads from the charger and immediately get the bag containing the damaged batteries away from any flammable materials, to a well-ventilated area outside, unless you are at an event with designated alternate procedures for handling lithium fires. Follow the instructions of designated safety personnel where applicable.

Discharging

Care should be taken during discharging to ensure LiPo batteries are not allowed to discharge below their critical voltage. The use of low-voltage cutoff circuits is advised, to prevent over-discharge. These work by monitoring battery voltage and disconnecting the batteries from the load in the event the voltage drops below a safe threshold. In addition to a hard cutoff, user-observable voltage monitoring is also useful, as it can give you an idea of your remaining charge, and allow you to swap or recharge batteries before your droid simply stops working in the middle of an event.



Low Voltage Disconnect – Amazon

More importantly, your batteries should always be connected to the rest of the droid through a fuse sized no greater than the maximum safe discharge current for your batteries. In the event of a short circuit, a LiPo battery can supply many hundreds of amps of current, even if it isn't rated for it. This will cause the battery to rapidly heat up, which increases the amount of current the battery can supply. This can cause a positive feedback loop called **thermal runaway** where the battery eventually gets so hot, it self-ignites. To reiterate: lithium battery fires cannot be extinguished until all the chemical energy in the battery has been converted into heat. Prevent this from occurring by using fuses and protecting wiring between your batteries and your fuses from damage.

Storage

In general, LiPo batteries should be stored at a low state of charge (usually 3.6-3.7v*) in fire-resistant charging bags, in a cool, dry area. Keep them away from children and pets, and anything that could fall and crush or puncture them. Storing the batteries in a spare refrigerator can add a safety margin, as the low temperature slows the chemical reaction in the batteries, though they generally should not be allowed to drop below 0°C*, and should always be allowed to warm to room temperature before charging.

*Refer to the specifications for your specific batteries, as they may differ from the numbers given here. Always follow manufacturer recommendations.

Disposal

When it comes time to dispose of lithium polymer batteries, they should be discharged and taken to an appropriate waste disposal facility in accordance with local regulations. Consult your local authorities for advice on how to dispose of LiPo batteries in your area.

Lithium Iron Phosphate ($LiFePO_4$)

Lithium Iron Phosphate batteries ($LiFePO_4$, LFP, or LiFe) are a type of lithium-ion battery that uses lithium iron phosphate as their cathode material. LFP batteries have dramatically long cycle life, low toxicity, low cost, and in hobby use, they're mostly known for being safer than conventional lithium-ion chemistries. Conversely, they offer lower energy density than conventional lithium-ion chemistries, and operate at lower voltage. In spite of this, their improved safety and lack of cobalt in their construction have led to them becoming the predominant chemistry used in electric vehicles, and they are becoming more popular in hobby use.

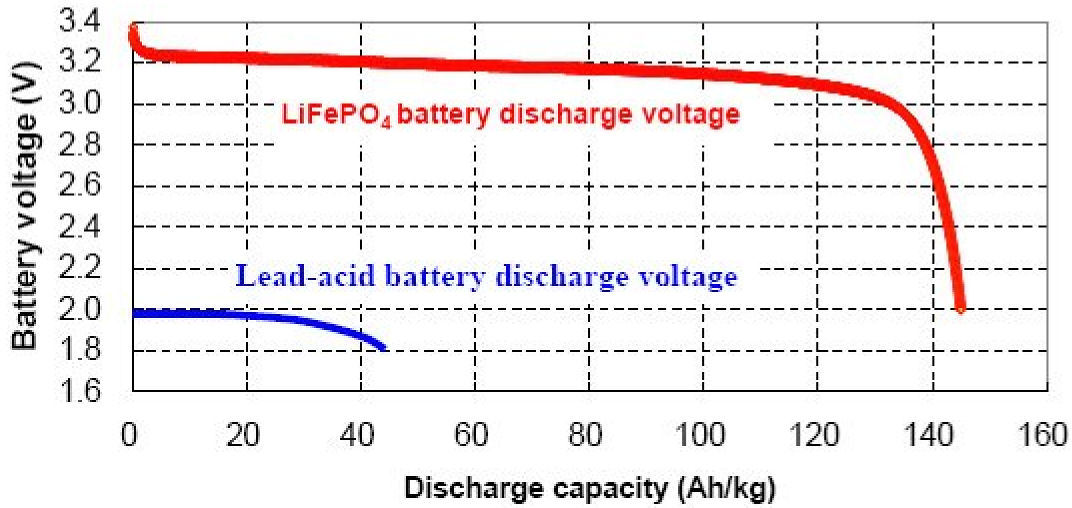
Chemistry

An LFP battery differs from other lithium-ion chemistries in their use of lithium iron phosphate as the cathode material. Like other Li-ion chemistries, they use a graphite anode, with an electrolyte consisting of a conductive salt suspended in an organic solvent or polymer. Unlike most Li-ion chemistries, they do not use cobalt, nickel, or manganese. This has positive implications for environmental friendliness during manufacturing and disposal, but also helps to tame lithium's reputation for safety issues.

A contributing factor to lithium batteries' propensity for thermal runaway is the negative temperature coefficient of cobalt used in their cathodes. As a conventional Li-ion battery becomes hotter, it becomes more conductive internally, which allows more current to flow, making it get hotter. By omitting cobalt, LFP batteries have a positive temperature coefficient. As they warm up, they become less conductive, reducing the current that can flow through the battery, resisting further heating. Other factors, such as lithium migration during charge and discharge, and stability of oxygen bonds in the phosphate also contribute to reduced risk of fire.

LFP cells exhibit a peak voltage of 3.6v and a nominal voltage of 3.2v. Critical voltage can vary widely, from 2.0-2.8v depending on cell and manufacturer. They have exceptionally long cycle life, surviving anywhere from 3,000 to 10,000 or more charge-discharge cycles, and their chemistry and construction make them more resistant to damage from overcharging and overdischarging than other lithium chemistries.

Since there is significant variability in the specifications for individual batteries, always refer to the manufacturer's spec sheets. If they are not available for a given battery, do not buy that battery.



LiFePO$_4$ battery discharge voltage – CloudyNights.com – Uncredited

Construction

LFP batteries are usually made with cylindrical cells connected by spot-welded tabs. The cells contain a gel electrolyte, with tightly coiled electrodes to maximize surface area. Polymer-electrolyte cells are also available.

Two main constructions are available for main droid power: hobby-style and lead-acid replacement type.

ZIPPY Compact 8400mAh LiFePO$_4$ Pack – HobbyKing

$LiFePO_4$ Battery for Motorcycle Starting – Casil Batteries USA

Hobby R/C style batteries are generally available in similar form factors as hobby R/C LiPo batteries, and they use the same terminology for series connection, discharge rating, and capacity. Remember that LFP batteries operate at different voltages from LiPo batteries, however. The following table correlates LFP S ratings to peak and nominal voltages:

Series	Peak Voltage	Nominal Voltage
1S	3.6V	3.2V
2S	7.2V	6.4V
3S	10.8V	9.6V
4S	14.4V	12.8V
5S	18V	16V
6S	21.6V	19.2V
7S	25.2V	22.4V
8S	28.8V	25.6V
9S	32.4V	28.8V
10S	36V	32V

Note: Similar to LiPo batteries, LFP batteries can be manufactured in much higher voltages than are listed here. Additionally, due to different manufacturing methods, some LFP batteries have slightly higher peak and nominal voltages (typically 3.65v peak, 3.3v nominal) and may be advertised using these different voltages. Critical voltages vary widely depending on manufacturer. As always, refer to manufacturer specifications, and be cautious when mixing different batteries.

Lead-acid replacement batteries are generally only available in a limited number of form factors and cell counts. They are invariably larger than hobby-style batteries for a given capacity, and almost always more expensive. Some have built-in battery management systems, but most do not. They are most commonly available in a 4S, or 12.8v nominal, configuration for replacing 12v nominal lead-acid batteries, and are meant to be used primarily in the 30-70% state of charge range. This type of battery is generally only a good option for builders replacing existing lead-acid batteries in order to save weight. Unless you have a specific reason to use them, I would not advise using this type of battery in a new build.

Power Tool Batteries

Modern power tools are most frequently powered by lithium-ion batteries, contained in convenient, modular shells, with matching chargers. Aftermarket taps exist for all manner of power tool batteries, allowing them to supply power to anything that accepts a positive and negative wire. As a result, power tool batteries have become very popular among builders of all manner of projects, and droids are no exception.

Nearly all power tool batteries are based on common cylindrical-cell lithium-ion chemistries, providing 3.7v nominal per cell, with multiple cells in series and parallel within a plastic case. Many of these batteries contain additional circuitry used to display the state of charge. Broadly, power tool batteries are manufactured in “12V” and “18V” specifications, with some manufacturers advertising “20V” or some other number. In fact, none of these batteries are voltage-regulated as the advertising would lead consumers to believe, and effectively all such tool batteries are either 3S or 5S Li-ion batteries, providing 11.1V and 18.5V nominal voltages respectively. Some batteries are marketed as 24V, and these are typically 6S batteries. More rarely, batteries may use higher voltages, such as Ryobi’s 40V line of high-intensity tool batteries. (Which are actually 10S batteries providing 37V nominal)

The following table correlates branding to actual nominal and peak voltages:

Brand	Series	Peak Voltage	Nominal Voltage
Bauer 20V	5S	21V	18.5V
Black + Decker 20v	5S	21V	18.5V
Dewalt 20V	5S	21V	18.5V
Earthquake XT 12V	3S	12.6V	11.1V
Earthquake XT 20V	5S	21V	18.5V
Hercules 20V	5S	21V	18.5V
Kobalt 24v	6S	25.2V	22.2V
Kobalt 40v	10S	42V	37V
Makita 18v	5S	21V	18.5V
Milwaukee M12	3S	12.6V	11.1V
Milwaukee M18	5S	21V	18.5V
Ridgid 18V	5S	21V	18.5V
Ryobi 18V	5S	21V	18.5V
Ryobi 40V	10S	42V	37V
Stanley V20	5S	21V	18.5V

An overwhelmingly common myth is that power tool batteries have built-in battery management systems. Overwhelmingly, this is not the case. The vast majority of power tool systems integrate their BMS into their chargers and tools, with the batteries being little more than dumb collections of tab-welded cells connected to proprietary terminals. Even batteries with state-of-charge indicators typically only have a simple voltage sensing circuit in line with the LEDs on the indicator- and nothing preventing over-discharge of the cells. Some batteries do have temperature sensing- which they pass on to the tool via a data connection- but ultimately most batteries rely on circuitry in the tool itself to prevent over-discharge, and limit current. A key exception is Ryobi batteries. These all integrate BMS into the batteries themselves. Ryobi batteries will reliably prevent over-discharge and limit output current to safe levels without additional hardware. Some specific batteries produced by other manufacturers may have integrated BMS, but only Ryobi batteries are guaranteed to.

If you use any other battery, assume it does not have the ability to prevent damage due to excess discharge.

Regarding Ryobi batteries, another myth is that the BMS in these batteries prevents connecting them in either series or parallel with other batteries, depending on who's retelling the myth. The reality is, the BMS in these batteries does not prevent connection of multiple batteries. The BMS monitors the voltage of each cell in an individual battery, not the overall battery voltage, and has no way to become aware of other batteries in a circuit. In fact, Ryobi sell tools that use multiple batteries in parallel, to provide sufficient current or life for their highest-intensity tools.

Safety

Power tool batteries offer several advantages in terms of safety, whether or not they include onboard BMS. They use rigid enclosures, which prevent damage from impact or punctures. They have foolproof chargers, which are very conservative and unlikely to cause charging fires. Their construction is generally good and reliable, since tool companies have reputations to uphold. However, they should still be treated with care. Always follow manufacturer recommendations for charging and discharging power tool batteries. And remember, you are using the battery in a way it was not designed to be used, so take appropriate precautions.

Always protect your circuits with appropriately-sized fuses, and be mindful of protecting your batteries from excessive discharge. Always remove batteries from your droid to charge with a manufacturer-approved charger.

Disadvantages of Power Tool Batteries

While power tool batteries are an attractive option for many builders for the reasons discussed above, they do have several disadvantages when compared to more generic batteries. In general, for a given capacity, they're bulky and expensive. They're available in very limited options for voltage and generally have low C-ratings, which frequently aren't made publicly available. (Making it hard to design safe circuits) They have limited options for capacity as well.

Turnigy nano-tech 4000mah 5S 35-70C Lipo Pack w/XT-60 – Hobbyking.com

Ryobi 18V ONE+ 4AH LITHIUM BATTERY – Ryobitools.com

In addition to the limitations of the batteries themselves, power tool battery chargers tend to be very conservative and limited in their ability to charge batteries quickly, or to charge batteries that have fallen below critical voltage, but may still be recoverable. The options for battery connectors are also often bulky and use sub-standard wiring, and frequently have poor fitment with the batteries themselves.

A perceived advantage of power tool batteries is, they offer a simple alternative to other battery types, due to their simplified ecosystem of batteries and chargers, with all the considerations relevant to safety already taken care of. However, as previously mentioned, most batteries are “dumb” with no built-in protection for any kind of fault condition, as they’re meant to rely on the tools they power to provide that protection. The false sense of security this perception can create, can lead to significant problems and expenses down the line. Unless you are using Ryobi batteries, which are among the bulkiest for a given capacity, you will still need to take all the same precautions you would need for generic hobby batteries.

Closing Notes

Power tool batteries are a perfectly viable way to power droids. Ultimately, they do offer sufficient performance, reliability, and availability for droid building, and many builders have successfully used them. They do have several disadvantages and considerations that builders should be aware of, but provided that awareness, they may be a good option for your build.

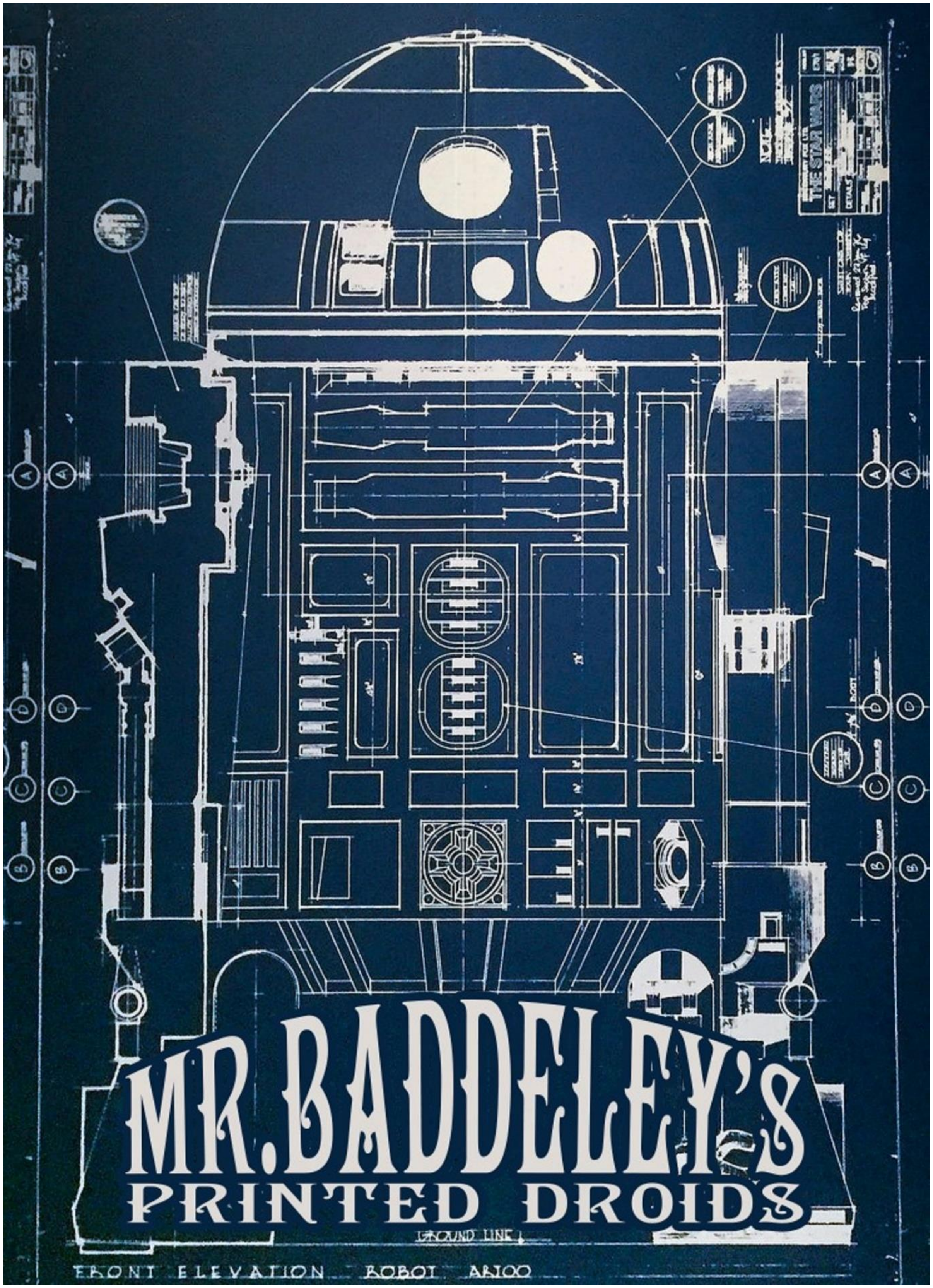
Nickel-Based Batteries

The final category of batteries this guide will cover is Nickel-based chemistries, specifically a brief look at Nickel-Cadmium (NiCd) and Nickel-Metal Hydride (NiMH) batteries. These batteries are generally considered to be obsolete, as the price of generally-superior lithium chemistries have come down in recent years. While they shouldn't be your first choice for a new build, an older droid may use these for drive, and they're still fairly common for peripheral controls, such as dedicated receiver power in droids using conventional R/C controls.

In general, Nickel chemistries provide a nominal cell voltage of 1.2v, with peak voltage in the area of 1.25-1.3v. This has led to their continued popularity as rechargeable alternatives to disposable 1.5v alkaline batteries, as many devices that run on 1.5v (or some multiple) can run on 1.2v (or the equivalent multiple). NiCd and NiMH batteries are available in multi-cell configurations providing greater voltage, such as so-called "Receiver Batteries" which are typically 4 or 5 cell batteries supplying 4.8 or 6.0v respectively. If you've ever wondered why the standard voltage for servos is 4.8v, it's because of their origin in Nickel battery days.

Ultimately, Nickel batteries have much lower energy density than Lithium batteries, and are less and less available in capacities or voltage offerings that are appropriate for droid power. As Battery Eliminator Circuits, or BECs, have become more common, their use for dedicated R/C receiver power supplies has also diminished. For those using R/C receivers with dedicated power, many options now support lithium ion voltages, making it easier to use a single type of charger for all of an R/C droid builder's batteries. And, as many droids use alternatives to R/C in the first place, the need for this class of battery is even lower than ever.

However, Nickel-based AA alternatives may be a good option if your control solution runs on AA batteries, like Xbox 360 controllers do. (Though Li-ion options are becoming more available in this space as well)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