

1. Batteries (By Lennon Rodgers)

This chapter discusses the history of batteries, how they work, ways of sizing batteries for particular applications, performance, limitations, and manufacturing methods.

1.1. Motivation

1.1.1. Historical context (the problem it solved)

In the late 1700s, Luigi Galvani was dissecting frogs, and noticed that static electricity made the legs twitch. Soon after he was able to make the legs twitch consistently using two different metals embedded in the leg tissue. The twitching of the legs acted as the first sensor to detect electrical flow! A few years later Alessandro Volta replaced the frog parts with cardboard and chemicals, and built instruments to sense the current. This is considered to be the first “battery”. Benjamin Franklin coined the term “battery”, since he thought some of the early glass-jar charge storage devices looked like an artillery battery (a grouping of weapons).

1.1.2. Modern context (a problem it solves)

With the discovery of electricity and its many uses came a realization that there is a need to store electricity for the later use of powering electronic devices. As inventions such as the light bulb (1878) electric motor (1837) and transistor (1954) gained broad adoption, electricity started to replace carbon-based fuels and became a dominant source of energy. Why has there been a dramatic shift towards electrifying everything, what are the limitations, and does it make sense from a technology perspective? This section will investigate these concepts further, and explain how batteries are an enabling technology for certain electronic devices.

Electricity has been widely adopted (and replaced carbon based fuels) because it has the following benefits¹:

1. **Transmission:** High voltage power lines make it easy to transfer energy over long distances with little losses. Liquid or solid (carbon-based) fuels require complex and costly piping systems.
2. **Efficiency in use:** Electricity is most commonly used to power motors and microelectronics, though there is a wide range of other applications. All of these devices have efficiencies of ~80% or better. Carbon-based fuels typically run heat engines (e.g. internal combustion) which have ~25% efficiencies.
3. **Versatility of use:** Nearly any mechanical device could be made to operate with some combination of motors and micro/power electronics. Carbon-

¹ Electricity is not typically a good source of energy for heating. The thermal energy available in carbon-based fuels make them much more attractive for these applications (e.g. household heating).

based fuels are mostly constrained to operate in a combustion-based heat engine.

4. **Versatility of generation:** Electricity is an energy that can be generated through many different methods (e.g. nuclear, natural gas, solar, wind). It has the potential to be a renewable energy if generated with pollution free methods (e.g. wind, solar). Also, electricity can be generated and consumed domestically. Carbon-based fuels can be generated from biomass, though they are more commonly obtained from non-renewable sources (e.g. petroleum).
5. **Performance:** Devices powered by electricity are often times very quiet (motors) or noiseless (microelectronics) and operate at relatively low temperatures. Carbon-based fuels typically power combustion-based heat engines, which are known to be louder and dangerously hot. There are many other performance-based advantages depending on the application (e.g. electric motors provide maximum torque at low speeds, which is very useful for certain applications).

Electricity is typically deemed the superior energy source for both high and lower powered *stationary* devices (Figure 1, e.g. alarm clock, washing machine), but faces more challenges and limitations for powering *mobile* devices (e.g. mobile phones, automobile). The main limitation has to do with batteries, and whether they can adequately store enough energy for a given application. Low-power mobile devices (e.g. mobile phones) already run on electricity, though there is a continuous demand for a longer operating life before charges, more cycles before failure, less weight, smaller volume and lower cost. High-power mobile devices (e.g. automobile) do not commonly run on electricity, and are the *last remaining category of devices to be fully converted to electricity*. Why?? To be useful for all applications, but especially for high-powered mobile devices, batteries need to store a sufficient amount of energy while being physically small, safe, lightweight and cost competitive. Scientist and engineers are working hard to tackle this challenge, and if successful, electricity may also fuel high-powered mobile devices such as automobiles.

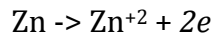
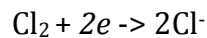
	Stationary	Mobile
Low Power (<100 Watts)	Alarm Clock	Mobile Phone
High Power (>100 Watts)	Washing Machine	Automobile

Figure 1: Powered devices can be categorized as either stationary or mobile, and as low or high power. Stationary electronic devices are those that receive their electricity by plugging directly into the wall outlet, and have no on-board energy storage. Mobile electronic devices are those that are powered exclusively by on-board energy storage. Certain devices have both stationary and mobile uses (e.g. laptop computer). Low powered devices are those that consume 100 Watts or less, while those consuming more are considered high power.

1.1.3. Function definitions (a more general view)

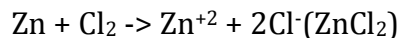
Overview

Batteries are used to store electrical energy for later use. They do this by storing the energy in chemical reactions, and thus they are often referred to as electrochemical batteries. The chemical reaction involves removing electrons from one material, and adding electrons to the other. This process is called a “**reduction-oxidation**” reaction (or in short a “redox reaction”). Reduction refers to adding electrons, while oxidation refers to removing electrons. During discharge, oxidation occurs at the “negative” or “anode” end of the battery, and reduction occurs at the “positive” or “cathode” end. Here is an example redox reaction to demonstrate the general concept of a battery:



In this case the two materials are Zinc (Zn) and Chlorine (Cl₂). Electrons are shown as *e*. During discharge, the Zinc metal is being oxidized to form Zn⁺² ions, and the Chlorine is being reduced to form Cl⁻ ions. The electrons are transferred in the process from the Zinc to the Chlorine through an external circuit. Energy is extracted as the electrons pass through a load (e.g. motor) from one side to another. As shown in Figure 2, the chemical reaction can only occur if ions are able to flow freely between the cathode and anode. To accomplish this, both electrodes are surrounded/soaked in a fluid called electrolyte. The electrolyte is unique in that it conducts ions but does not conduct electrons. Finally, physical separation is needed between the cathode and anode, and thus a “separator” is often needed. It’s also called a membrane because it prevents anything from passing through except ions². The lack of electron conductivity through the electrolyte and membrane is important, since otherwise the battery would have an alternative path for electrons to flow (which is referred to as “shunt current”), and this wasted energy (electron flow) would be converted to heat during an uncontrolled exothermic reaction.

The full chemical reaction during discharge can be written as:



² If two different electrolytes are used, the separator/membrane ensures that ions can pass through, but mixing does not occur between these two dissimilar electrolytes.

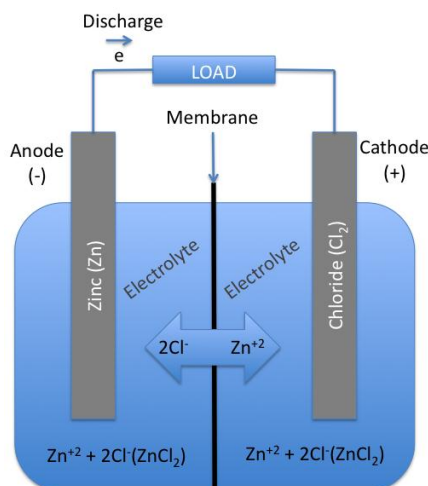


Figure 2: Schematic of a ZnCl₂ battery.

All batteries work under the same basic principle, and thus have (i) cathode and anode materials, (ii) electrolyte, (iii) a membrane (also known as a separator). A battery has a positive (cathode) and negative (anode) side, which are each called electrodes.

If a battery can be discharged and recharged multiple times, it is called a rechargeable (or “secondary”) battery. If it cannot be recharged, then it is called a disposable (or “primary”) battery. The ability to recharge the battery depends on the specific chemistry. Primary batteries use up the materials in one or both of their electrodes during discharging, while the reactions in a secondary battery are reversible.

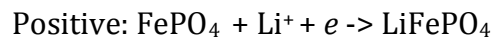
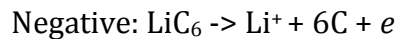
Common Battery Chemistries & Types

There are many different types of battery chemistries. Four of the most common chemistries are lead acid, alkaline, nickel metal hydride, and lithium ion. Lead acid batteries are most commonly used in gasoline cars for starting the engine and running the auxiliary electronics when the engine is off. Alkaline chemistries are used for disposable AA-sized batteries. Nickel metal hydride batteries are common in hybrid vehicles (e.g. Toyota Prius), and rechargeable AA-sized batteries. Lithium ion batteries are used in mobile electronic devices such as mobile phones and laptop computers. Rechargeable lithium ion batteries will be discussed in more detail in this section.

A lithium-ion battery is a type of rechargeable battery in which the cathode is made of lithium and other metals, and the anode is made of a type of porous carbon (typically graphite). Secondary lithium ion batteries rely on the removal and insertion of lithium ions into both the cathode and anode (which is called “intercalation”). During discharge the electrons flow from the anode through an external circuit to the cathode. During this process the lithium ions (Li⁺) migrate

internally through the cell via a non-aqueous³ electrolyte, and finally embed themselves inside the cathode (Figure 3). During charging, external current is applied in the reverse direction, and the lithium ions separate from the cathode material and internally migrate via the electrolyte back to the anode. There are a few different types of lithium ion batteries, but typically they only vary on the cathode material (as mentioned previously, the anode is typically some form of porous carbon). Two common cathode materials are lithium iron phosphate (LiFePO₄), and lithium cobalt oxide (LiCoO₂). Below are the chemical reactions for discharging:

Lithium iron phosphate reaction (LiFePO₄):



Lithium cobalt oxide reaction (LiCoO₂).

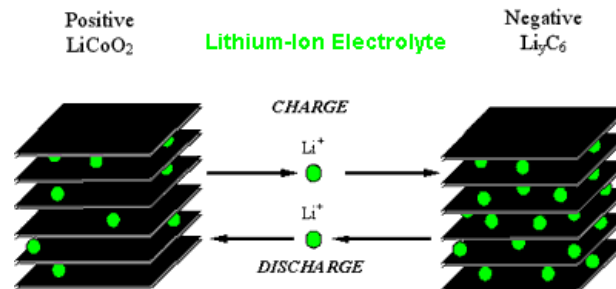
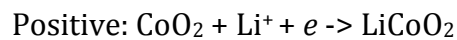
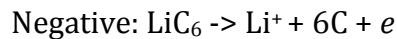


Figure 3: During charging and discharging, the lithium ions migrate between the anode and cathode. This process is called intercalation. Source: <http://www.mpoweruk.com/chemistries.htm>

1.2. Analysis

1.2.1. Definitions

Cell Voltages

The voltage of the battery depends on the particular materials used at both the cathode and anode. For example, LiCoO₂ (with a carbon-based anode) typically has a nominal voltage of 3.7V, while LiFePO₄ is 3.3V. Nickel metal hydride (NiMH)

³ Non-aqueous electrolytes are used in lithium ion batteries because lithium reacts violently with water, and above 2 Volts water disassociates to form oxygen and hydrogen (and lithium chemistries are above 2.7 V).

batteries have nominal voltages of 1.2V. Thus one of the many advantages of lithium chemistries is their inherent higher cell voltage. A higher cell voltage means fewer cells are needed when stacking cells in series to reach higher voltages (i.e. battery packs). But what exactly determines these voltages? The voltage of a battery is related to the theoretical amount of work that can be extracted during the actual redox reaction, which is called the Gibbs Free Energy, ΔG^0 :

$$\Delta G^0 = -nFE^0 \quad 1$$

Where n is the number of electrons involved in the stoichiometric reaction, F is a constant, and E^0 is called the potential measured in volts. The most important thing to know is that E^0 is a value determined experimentally and can be found in chemistry books. It is related to the number of valence electrons, and thus the reactive properties of the cathode/anode materials. If a material is very reactive, it will have a large E^0 . For example, elements on the far right and far left of the periodic table are considered reactive because their outer electron shell is nearly full (far right) or barely empty (far left). To determine the voltage of a battery, the E^0 for the anode should be subtracted from the E^0 of the cathode.

Quantifying Energy Capacity (Watt-hrs)

The capacity of a battery is specified by the amount of current (in amps) that it can output in one hour. For example, if a battery can output 3 Amps for 0.5 hours, then it would be rated as a $3 \times 0.5 = 1.5$ Amp-Hour battery (written as Ah or Amp-hr for short). The power (P) being provided by the battery during this discharge rate is generally (for LiFePO_4):

$$P = V \cdot I \quad 2$$

Thus if 3 Amps are being discharged:

$$P = 3.3V \cdot 3A = 9.9\text{Watts}$$

Since this occurred for 0.5 hours, the usable energy (Joules) stored in the battery is:

$$\text{Energy} = 9.9\text{Watts} \cdot 0.5\text{hours} = 9.9\text{Watts} \cdot 1800\text{seconds} = 17820 \text{ Joules}$$

The usable energy (E) stored in the battery is more commonly written in units of **Watt-hours**, which can be determined by simply multiplying the voltage (V) by amp-hour capacity (Ah). The energy in Joules can then be determined by converting hours to seconds:

$$E_{\text{battery}} = V \cdot \text{Ah} [\text{Watt-hrs}] = V \cdot \text{Ah} \cdot 3600 [\text{Joules}] \quad 3$$

It should be noted that some of this energy is converted to heat inside the battery, and thus cannot be used to do useful electrical work (this will be discussed later).

Energy Density (Watt-hrs/kg and Watt-hrs/liter)

Lead acid batteries weigh more and are volumetrically larger than lithium ion batteries for a given amount of energy stored inside a battery. This measurement is referred to as “energy density” and most commonly has units of

Watt-hrs per kg. Additionally, energy density can be specified on a volumetric basis, and thus has units of **Watt-hrs per liter**, which is a measurement of how much energy can be stored in a given volume. Each battery type (chemistry) has a theoretical energy density, though in practice the actual energy density of a battery cell is much lower. This is because a battery has many other components that add to the overall mass and volume (the enclosure/case, electrolyte, electrodes for example. See section 1.3 Manufacturing). Thus the energy density varies based on the specific chemistry and overall battery cell design. To measure the energy density, the energy capacity of the battery cell or pack in Watt-hrs should be divided by the total mass or volume. See Figure 4.

In general higher energy densities are obtained by using more reactive anode and cathode chemicals. The downside is that more reactive chemicals tend to be more unstable and may require special safety precautions. The energy density is also dependent on the quality of the active materials used in cell construction with impurities limiting the achievable cell capacities. This is why cells from different manufacturers with similar cell chemistries and similar construction may have a different energy content and discharge performance.

One might wonder if the energy density of batteries will follow “Moore’s Law”, and double every 18 months. Figure 5 shows that this will not occur since the upper limit is now being reached as most of the materials that are practical for use as active materials in batteries have already been investigated and the list of unexplored materials is being depleted [2]. Thus for a dramatic change in energy storage to occur, completely novel battery concepts will likely be needed.

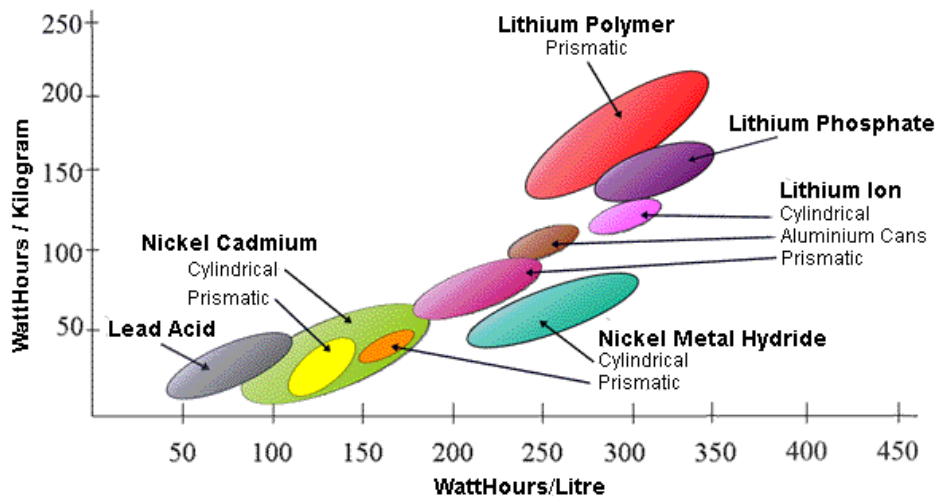


Figure 4: Mass and volumetric energy density of common batteries. Source: <http://www.mpoweruk.com/>

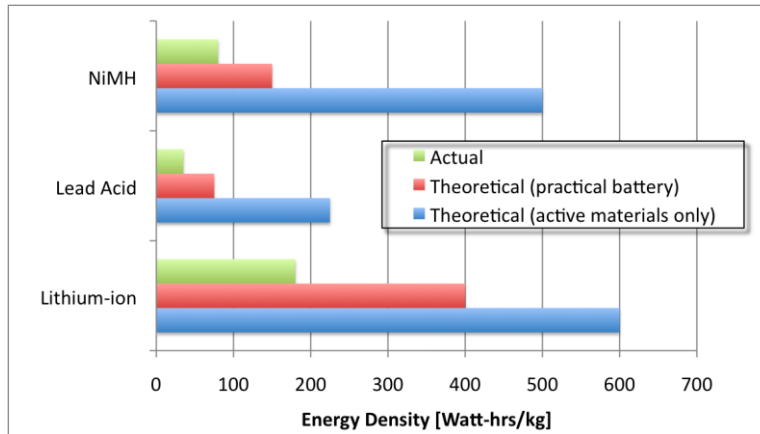


Figure 5: Theoretical and actual energy densities of common battery chemistries [2]. The “actual” column is energy densities for actual whole batteries that are currently commercially available. The “Theoretical (practical battery)” is the theoretical upper limit for a battery with electrodes, enclosure, electrolyte, etc. The “Theoretical (active materials only)” is the theoretical upper limit for only the active materials, thus no electrolyte, etc. is include.

Batteries Compared to Other Energy Storage Methods

Battery handbooks list the various *theoretical* limits of energy capacity, and it can be seen that most theoretical values are much less than 1,500 Watt-hrs/kg [2]. Compare this number with a nuclear reactor, which has 125,000 Watt-hrs/kg, gasoline with roughly 13,000 Watt-hrs/kg, and a hydrogen fuel cell that has 450 Watt-hrs/kg (see “Energy Density” at Wikipedia for more values).

But the usefulness of an energy storage method greatly depends on the application. Gasoline, for example is often used in internal combustion engines which are ~25% efficient, while the energy stored in batteries is used to power electronic devices which are 80%+ efficient. Thus the actual useful energy from gasoline (for certain applications) is approximately $0.25 \cdot 13,000$ Watt-hrs/kg = 3,250 Watt-hrs/kg.

1.2.2. Performance

Modeling a Battery:

Any electrical element that generates heat is said to have internal resistance. A battery feels warm after being discharged or charged, thus it must have an internal resistance. Assuming the resistance is a known measured quantity (actually measuring the internal resistance will be explained later), we can estimate the heat generated inside the battery for a given amount of charge or discharge current (Q_{battery}). Let’s first write Ohm’s law:

$$V = I \cdot R \quad 4$$

Combining with equation 2 yields

$$P = Q_{\text{IR}} = I^2 \cdot R_{\text{IR}} \quad 5$$

For example, if we have a battery cell that is specified as having an internal resistance of 10mΩ, and we are discharging it at 4 amps, the amount of heat generated can be estimated by:

$$Q_{IR} = 4^2 \cdot 10^{-3} = 0.16 \text{ Watts}$$

The total energy lost from the internal resistance of the battery can be estimated if constant current is assumed:

$$E_{IR} = Q_{IR} \cdot t_{\text{discharge}} = I^2 \cdot R \cdot t_{\text{discharge}} \quad 6$$

Thus a battery can be modeled as having an internal resistance in series with a voltage source (Figure 6). This resistance is often referred to as the battery's impedance, and is specified in the battery's datasheet.

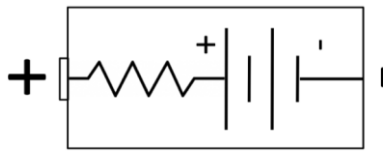


Figure 6: A battery can be modeled as a resistor and voltage source in series.

This “internal resistance”, which is often called the “internal impedance” is a lumped sum of multiple resistances within the cell. For example, there is resistance in the electrolyte, electrodes, etc. and at all the interfaces. As current passes through the various elements of the battery, and makes its way across the interfaces – resistance is experienced/generated.

Discharging a Battery

The simplest (and possibly most wasteful!) way of discharging a battery is to connect a high power resistor between the positive and negative terminals (Figure 7). The current can be determined using Ohm's law:

$$I = V/R_r \quad 7$$

Where V is the voltage of the battery (which is about 3.3V for a LiFePO₄, though it decreases with time), and R_r is the resistance of the power resistor. The amount of heat (Watts) generated from the resistor can be determined using equation 5.

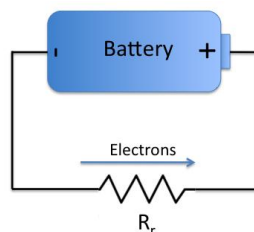


Figure 7: Discharging a battery by connecting the electrodes through a resistor.

As any battery is discharged, the voltage will slowly drop (Figure 8). If you let the battery drain without stopping it, then it would discharge all the way to zero volts. Most battery-powered electronics have circuit protection to avoid this condition, since this would permanently damage the battery (see the later discussion on Battery Management Systems, BMS).

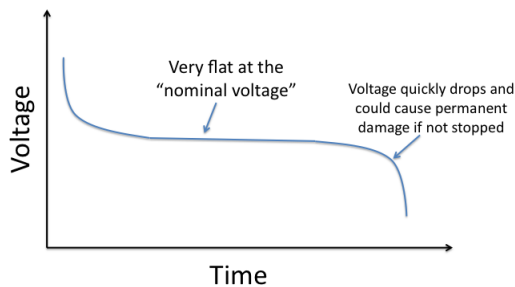


Figure 8: Discharge curve of a LiFePO₄ battery.

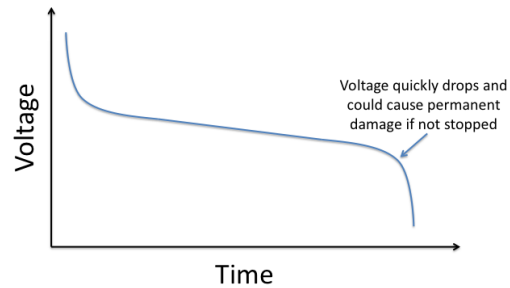


Figure 9: Discharge of a lead acid battery. Note that there is more of a slant when compared to lithium.

The discharge curve is unique to the cell chemistry. Lithium ion batteries tend to be nearly flat during most of the discharge. The discharge curve for lead acid, however, is not flat but instead has a non-zero slope (Figure 9). The discharge curve also changes based on the rate (Amps) of discharge. As shown in Figure 10, the curve shifts (or “sags”) down as the discharge current is increased. This can be explained using the battery model shown in Figure 6. According to this model, if 40 amps of current are discharged from a 3.3V (nominal) cell with 10mΩ of internal resistance, then the following voltage “sag” will occur during discharge:

$$V = I \bullet R = 40 \cdot 0.01 = 0.4 \text{ Volts.}$$

If discharging is stopped mid-way, then the voltage across the battery would return to the nominal value (3.3V if in the middle area of the discharge curve). It can be seen from Figure 10 that the model does not match reality perfectly, but does provide an estimate and an idea for the general behavior.

Battery sagging can be seen when starting a car, which uses a lead acid battery. When the driver stops cranking on the starter, the battery voltage will rise back up to some nominal value. Lead acid batteries have higher internal resistance when compared to lithium ion, thus voltage sag is even more of an issue.

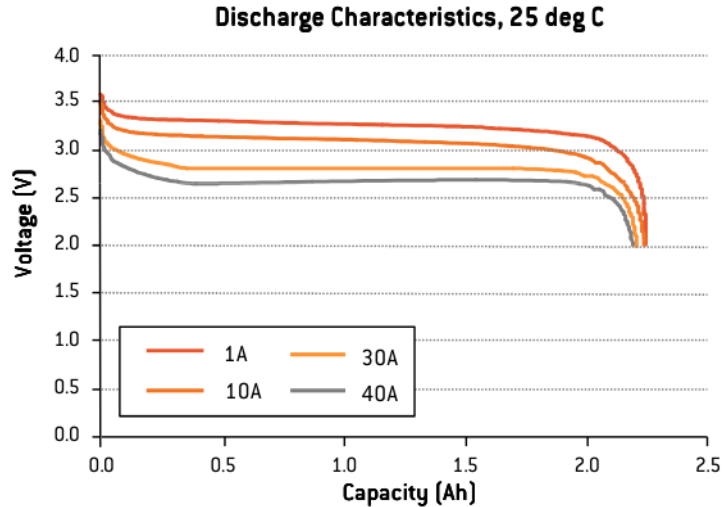


Figure 10: Discharge curve for A123 System's 26650 LiFePO₄ cell.

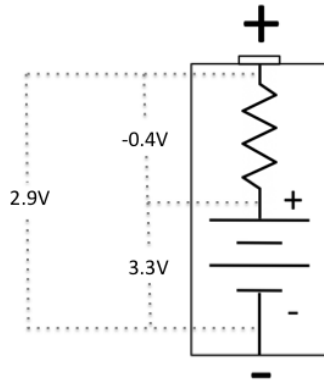


Figure 11: Using the battery model to explain the voltage "sag" during a discharge of 40 Amps.

As mentioned previously, some of the energy stored in the battery (Equation 3) is lost to heat dissipated through the internal resistance of the battery (E_{IR} , Equation 7). Thus the usable energy (E_{usable}) that can be used to power a motor, etc. can be written as:

$$E_{usable} = E_{battery} - E_{IR} \quad 8$$

It's important to note that the usable energy decreases as the internal resistance and rate of discharge increases. Thus lead acid batteries (which have a higher internal resistance) are less energy efficient than lithium ion. Also, a battery produces less energy when discharged rapidly.

Charging a Battery

When a battery is being charged, the voltage vs. time (charge curve) looks like a mirrored image of the discharge curve, though it is shifted slightly upwards (Figure 12). It's shifted upwards because the charger has to apply a higher voltage to overcome the internal resistance to flow a charging current (Figure 13). The

charging current can be estimated by knowing the difference in voltage between the charger and battery. In the case depicted in Figure 13, the difference in voltage is:

$$\Delta V = 4V - 3.3V = 0.7V$$

The charging current can be determined using Ohm's law and the known internal resistance. See the next section for more information.

All the same concepts from discharging apply for charging; the internal resistance produces losses, thus more energy is required from the charger than will go into the battery. The energy is lost via heat generated within the battery, and the amount of heat limits the rate at which a battery can be charged. If a battery has very low internal resistance, it can be charged very quickly.

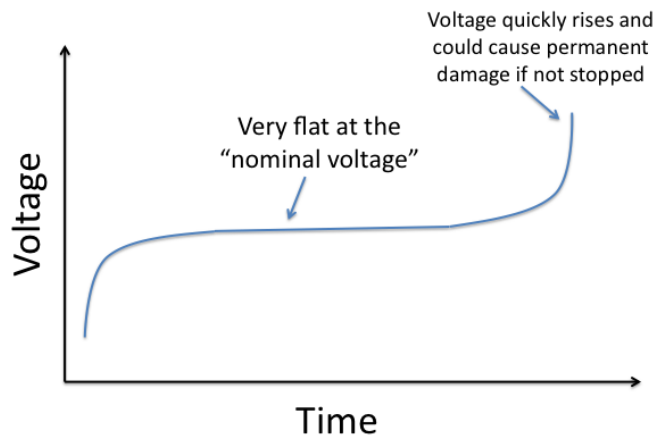


Figure 12: Charge curve for a generic lithium ion battery.

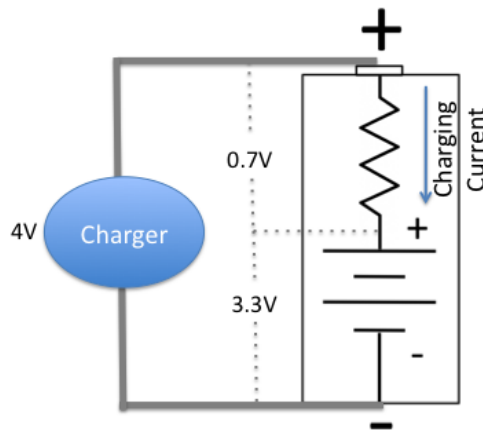


Figure 13: A charger has to apply a higher voltage to overcome the internal resistance and produce a charging current.

Modeling a Battery (advanced version)

As discussed in the previous section, a battery has losses during charge and discharge, which results in battery heating and a voltage sag (discharge) or rise (charging). Internal resistance was used to explain these, but there are two other contributing factors: (1) activation polarization and (2) concentration polarization. These are slightly more complex to measure, and are explained in terms of the specific electrochemical kinetics. Activation polarization can be thought of losses associated with the actual chemical reaction (removal of electrons, etc.). Concentration polarization is associated with the diffusion process at the electrode surface, which is where the chemical reaction is actually occurring. It can be seen from Figure 14 that all of these losses contribute to the total resistance of the battery, which produces a voltage sag/rise that depends on the current through the battery.

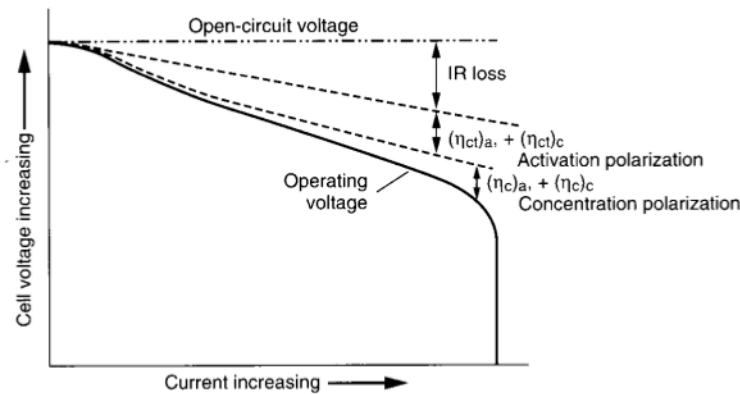


Figure 14: The losses of a battery are caused by a sum of these losses (1) Ohmic "internal resistance" (shown as "IR loss"), (2) activation polarization, and (3) concentration polarization. The most significant loss is the

Battery Chargers

Imagine having two different hypothetical batteries: one that needs charged and has a voltage of 5V and another that is fully charged and has a voltage of 8V. They each have an internal resistance of 20 m Ω . A (dangerous) way of charging the depleted battery is to connect the two batteries in parallel (Figure 15). The voltage difference is:

$$\Delta V = 8V - 5V = 3V$$

The higher voltage battery would drive current into the lower voltage battery according to Ohm's law (Figure 16):

$$I = \Delta V / (R_{IR1} + R_{IR1}) = 3 / 0.04 = 75 \text{ Amps!}$$

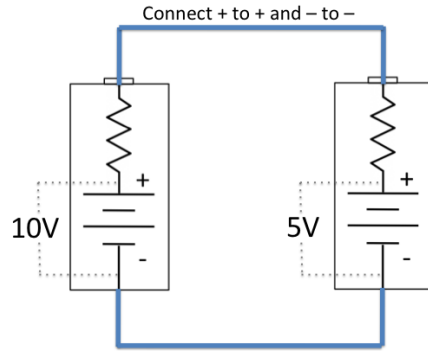


Figure 15: A very bad / dangerous way of charging a battery (but good for understanding the principle of charging a battery).

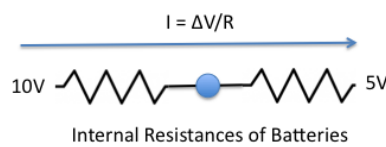


Figure 16: Current flows from one battery to another because there is a difference in voltage.

This is not typically how batteries are charged since it's very uncontrolled and typically would charge the battery very quickly (75 amps!), thus generating a lot of internal heat and damaging the battery. The current might be high enough to melt the wires used to connect the battery! We need a charger to control the current.

A charger is analogous to a dimming light switch. The intensity of the light from a dimmer switch is controlled by an internal automatic switch that turns the light on/off so quickly that it is unnoticed to the eye. A charger works similarly by switching the charging current on/off very quickly, such that the charging current can be controlled and varied as needed. This general concept is illustrated in Figure 17. This is not the full explanation of how a charger actually works, but is the most basic concept behind a charger (see the "more detailed explanation" for the full story).

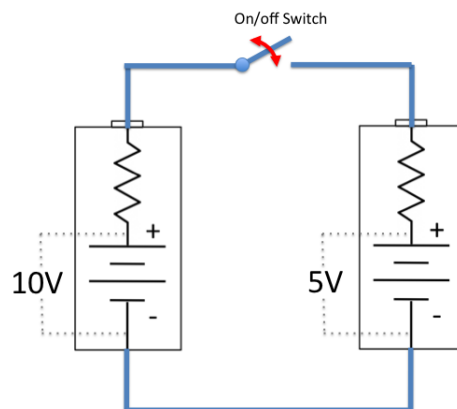


Figure 17: The basic concept behind a charger. It's like a dimmer light switch in the way it controls the charging current.

A charger has “Current” and “Voltage” knobs/adjustments and a display(s) (Figure 18). The current adjustment sets the maximum amount of current, and the voltage adjustment sets the maximum voltage. When the charger is turned on, the charger adjusts the on/off switching to ensure neither of the current and voltage limits are exceeded. The switching is the only internal adjustment made by the charger (single input system). Many power supplies found in labs/workshops can act as a charger, *though care must be taken and the battery datasheet should be checked for the proper current limits and voltage cut-offs*. It is also important that the voltage measurement is made through a high impedance pair of wires, and not through the current carrying wires. Thus chargers commonly have a second set of wires specially intended for voltage measuring (they are called “sense leads”).

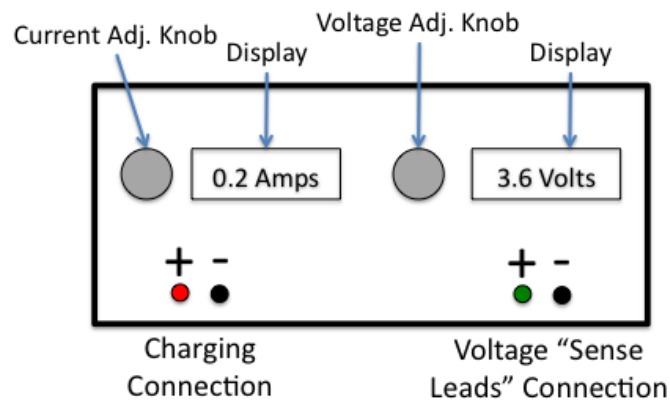


Figure 18: Schematic of a lab power supply that can be used to charge a battery.

Typically the current limit is reached first, thus the charger goes into a constant current mode (called “CC” mode) where the maximum current is maintained. During the CC mode, the voltage on the battery will slowly increase as the battery is charged. When the maximum voltage has been reached, the charger will maintain that constant voltage (“CV” mode) while the current slowly decreases to zero. This type of charging is called CC-CV charging (see Figure 22).

Battery Chargers (advanced version)

The “switch” in a charger is called a transistor (a MOSFET or IGBT to be specific), and it is able to turn on/off quickly and handle a large amount of current. The on/off switching of the power causes a ripple in the current, which can be harmful to the batteries being charged. An inductor is used to smooth out this current ripple. Also, capacitors are needed as a buffer for the energy supply side. This provides an instantaneous energy source when the transistor is turned on. Thus the capacitors are continuously being charged by the energy source, while simultaneously being drained by the charging batteries. A schematic of a charger is shown in Figure 19. As previously explained, the main components of a charger are the (1) energy source i.e. electrical outlet, (2) capacitor(s), (3) inductor, (4) transistor(s).

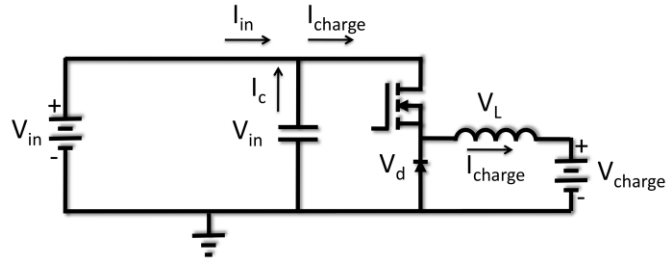


Figure 19: A schematic of a battery-to-battery charger. This is called a DC-to-DC buck converter.

Batteries are not typically used to charge other batteries. Instead there is an alternating current (AC) supply of power coming from a wall-outlet that is converted to direct current (DC). This DC power supply acts as the power supply and the concept is exactly the same as the battery-to-battery example described above.

A charger is a single input system (i.e. only one internal setting to adjust), and the amount of energy transferred to the charging battery is controlled by the amount of time the transistor is on versus off. This ratio of on/off time is referred to as the Duty Cycle, and is controlled via a Pulse Width Modulation (PWM) signal that comes from a microcontroller. The PWM function is built into most microcontrollers. The Switching Frequency is the rate at which the on/off occurs (Figure 20). A high Switching Frequency is desirable because it reduces the current and voltage ripples. In this specific case, a switching frequency of ~ 30 kHz was used.

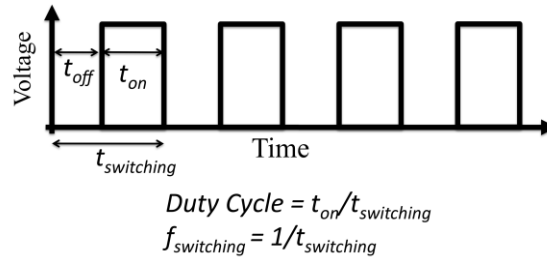


Figure 20: Pulse Width Modulation (PWM) signal from a microcontroller. The PWM function is built into most controllers.

As the Duty Cycle is increased, effectively more energy is transferred. When charging batteries, it is common to adjust the Duty Cycle to initially maintain a constant electrical current flowing into the batteries (i.e. Constant Current (CC) mode). Thus the microcontroller is programmed with a PI-feedback loop that uses a sensor to measure the electrical current, and then adjusts the Duty Cycle to maintain a prescribed value of electrical current (Figure 21). Once the voltage on the battery reaches a maximum value (V_{max}), the feedback loop begins adjusting the Duty Cycle so that a constant voltage is maintained. This is referred to as the Constant Voltage (CV) mode (Figure 22).

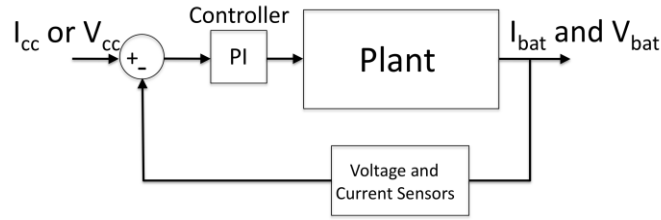


Figure 21: Proportional-Integration (PI) controller used to regulate the energy going to the charged battery.

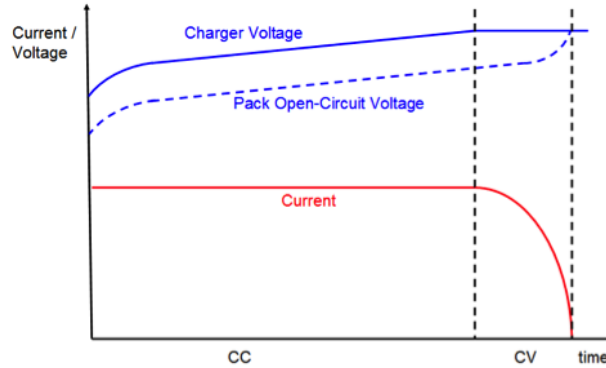


Figure 22: Example of a CC/CV charging profile. The charger voltage and pack open-circuit voltage differ due to the internal resistance of the pack itself.

Battery Packs

As mentioned previously, a single battery cell has a relatively low cell voltage (~1 to 4 Volts). Applications often required much higher voltage, and thus individual batteries must be put in series to increase the overall voltage. To increase the capacity (Amp-hours), an identical string of series-connected batteries can be added in parallel (Figure 23). The entire series/parallel set is referred to as a “battery pack”.

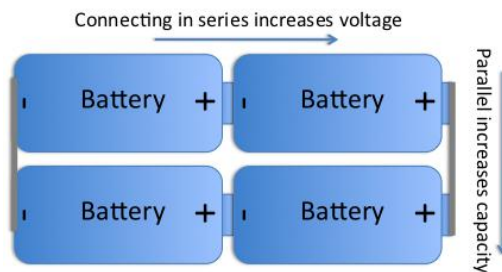


Figure 23: Adding battery cells in series increases voltage, and connecting in parallel adds capacity.

An example of a battery pack designed by members of the MIT EVT is shown in Figure 24. This module has 10 cells connected in parallel (called “cell groups”) and then 6 of these cell groups are put in series to generate a total of 19.8V.

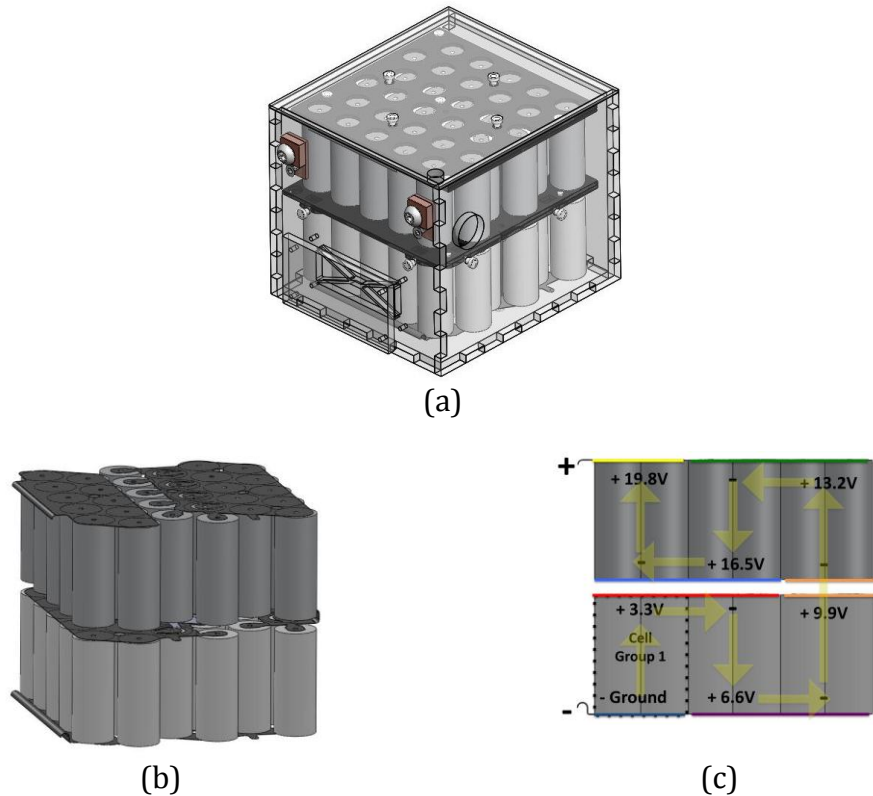


Figure 24: (a) a battery module with case. (b) The core of a single module (courtesy of Radu Gogoana). There are 6 cell groups (parallel members), each with 10 cells. (c) A schematic showing how the 6 cells groups are connected with sheets of nickel. Each color represents a different voltage. The yellow arrows represent the current flow.

Battery Management Systems

As shown in the discharge and charge curves (Figure 8 and Figure 12) the voltage quickly increases or decreases at the very end of a discharge or charge. If the cell voltage rapidly increases or decreases beyond a limit, the battery will be damaged. Thus there is a need to measure the voltage of each cell group and ensure that discharging and charging is halted before the cell reaches a critically low or high value. This is the job of a “**Battery Management System**” or BMS. The BMS also needs to measure the amount of energy remaining in the battery (ex. a laptop battery is able to predict how many hours of usage are remaining). This is called the “State of Charge” (SOC) measurement. Typically the BMS is an integrate circuit with the appropriate measuring circuits and cut-off switches.

1.2.3. Failure mechanisms

The main failure modes of a battery are: (1) external shorting, (2) puncture, (3) over charging, (4) over discharging, (5) capacity fading, and (6) over heating. The following sections will explain each of these.

External Shorting

A “short” occurs when the positive and negative electrodes come in contact through a low resistance path (for example, accidentally connecting the + and – together, or having them touch through a tool, piece of conductive metal, etc.). This will discharge the battery very rapidly. Ohm’s law states that a low resistance means a high current, thus current is rapidly transferred through the short and often times a large amount of heat is generated within the battery (because of its internal resistance). A high voltage short will generate a bright and hot arc flash. This flash is bright enough to cause permanent eye or skin damage (through burning). A member of the MIT EVT experienced arc flash when a loose connection accidentally touched the chassis of an electric vehicle. It was a high voltage short that caused a bright arc flash, which burned a significant amount of her arm skin. Her face was sunburned everywhere around her safety glasses.

The battery is often damaged during a short. If it’s a fast short, then the battery might overheat (see the Thermal section for more information). If it’s a slow short that goes unnoticed, the battery could be over discharged (see the over discharging section for more information).

Puncture

A puncture occurs if a battery’s outer enclosure is penetrated by a sharp object (ex. nail). Due to the way a typical battery is manufactured, a puncture creates an internal short if the damage cuts across multiple anode/cathode layers. This would generate heat and gas and has the risk of explosion (if pressure builds up). Internal shorts can cause “run away” – meaning the process is uncontrolled and becomes progressively worse. This is because the heat from the internal short can melt the membrane (separator) material, which makes the internal short even more severe. Also, increasing the temperature increases the rate of the reaction.

Over Charging

Over charging can occur if a charger malfunctions, or if the incorrect charger is used (ex. a LiCoO_2 charger is used to charge a LiFePO_4 battery). When a battery is overcharged, the battery voltage rapidly increases above safe levels (Figure 12). The excessive amount of current causes a buildup of lithium ions on the anode. The build-up forms lithium metal, which is called “lithium plating”. The plating consumes lithium, is an irreversible process, and thus causes a decrease in capacity. Also, the plating has a pointy shape, and thus could cause an internal short by poking through / penetrating multiple layers of anode/cathode layers (see the section on how a battery is manufactured). Finally, the excessive amount of current also causes an increase in temperature (see the Thermal section).

Over Discharging

Over discharging can occur if a battery is drained below a specified low-voltage value (typically 2V for lithium ion). If this occurs, the electrode (current collector) material is broken down and permanently damaged. For example, if the anode electrode is made of copper, an over discharge would cause the copper to

break down, which would lead to an increase in internal resistance and thus a faster self discharge, etc. Note that the electrode is not the same as the anode or cathode.

Capacity Fading

The capacity of a battery will reduce/fade as it is cycled multiple times. For modern lithium ion batteries, capacity fade is not significant until after 1000+ cycles. Figure 25 shows an example of how capacity fade depends on the number of cycles, and also on the temperature during discharge. Capacity fade is mainly caused by a chemical reaction that occurs between the anode and electrolyte, which forms a layer on the anode called the Solid Electrolyte Interface/Interphase (SEI). The SEI is partially composed of active material (lithium), and thus the capacity of the battery decreases as the SEI thickens with cycles. There is also a risk that the SEI could build up large enough that pieces break loose. The removal of SEI would cause a rapid reformation of the SEI where it was broken off, which could generate a significant amount of heat. This heating could cause thermal runaway (see Thermal section).

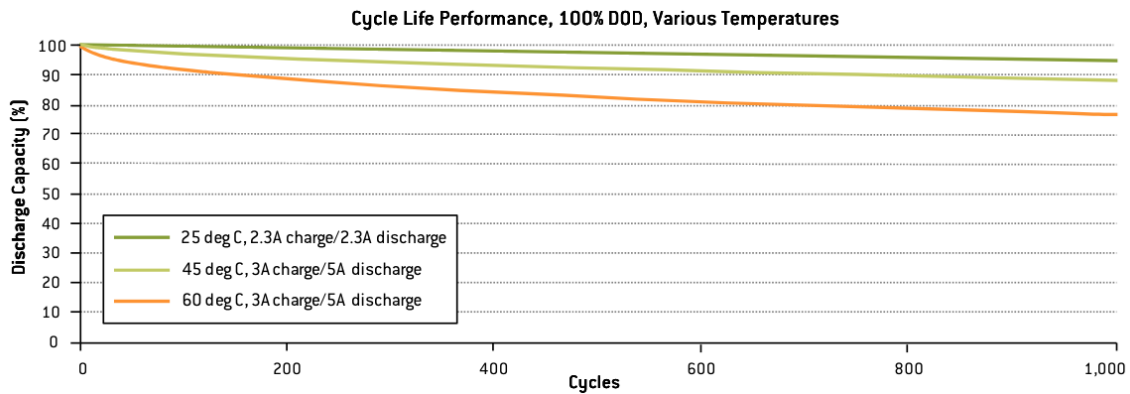


Figure 25: Batteries experience a significant capacity reduction after multiple cycles.

Thermal

Batteries can fail by either being too hot or too cold. There is a range of temperatures for which a battery should operate. For example, A123's 26650 battery is specified to operate within -30°C- to +60 °C.

If the battery is too cold, then the lithium ions are unable to properly insert themselves into the cathode/anode (intercalation process). This causes lithium plating, which was described in the "Over Charging" section. Also, since chemical reaction rates are proportional to temperature, the actual chemical reaction is slowed down. This greatly degrades the performance, and thus less current can be charged or discharged from the battery.

If the battery is too hot, the internal resistance increases, which generates even more heat. Also, reaction rates increase with temperature. Both of these create a very undesirable "positive feedback" scenario. As the temperature continues to increase, one possibility is that part of the SEI layer could break off from the anode. The consequences of this were described in the Capacity Fading section. As heat

builds up, the electrolyte starts to break down and form flammable gasses. The gasses will increase the internal pressure, which can be explosive if not properly vented. Typically batteries have a pressure sensitive cap that blows a specified pressure. At extremely high temperatures the separator (which is plastic) can melt, which would cause an internal short (see the Puncture section for a discussion on internal shorts). “Thermal Runaway” occurs when these thermal effects become unstoppable and the battery self-destructs.

Summary of Possible Failures

A summary of the resulting failure mechanisms is shown in Figure 26.

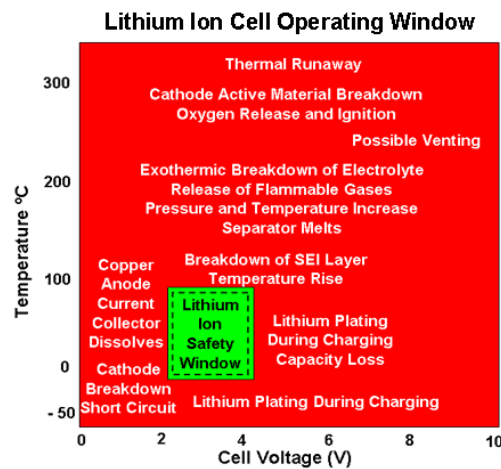


Figure 26: Summary of the various failure mechanisms for lithium ion batteries. Source: <http://www.mpoweruk.com/>

Safety

Battery failures are typically caused by human error. Below are some common errors, which could cause serious safety issues:

1. Plugging the battery into the charger backwards.
2. Using the incorrect charger, and thus over voltage occurs.
3. Not using a battery management system, and thus having under voltage.
4. Leaving the battery in a very hot or cold environment.
5. Discharging the battery too quickly.
6. External short (dropping a tool across the +/- of the battery, touching the +/- wires together, etc.)

1.3. Manufacturing

Batteries typically have a cylindrical or prismatic shape (Figure 27). Both types have the same generic layered construction (Figure 28) though they differ in that one is rolled and one is folded. The layers consist of metal foil coated on both sides with cathode or anode powder material. The anode and cathode powders are mixed

with a conductive slurry that also acts as a binder for it to adhere to the foil. It is desirable that the powders have smooth round shapes to maximize the surface area (which is good for conduction). The metal foil acts as a current collector to transfer the charge to/from the +/- electrodes. A plastic "separator" is soaked in electrolyte is used to insulate the anode from the cathode. The entire battery is filled with electrolyte.

A cylindrical cell has a metal enclosure to maintain a necessary positive pressure within the cell. This is because the battery swells when fully charged, which could result in delimitation of the battery if not constrained. Since a prismatic cell does not have a (heavy) metal enclosure, the energy density is better (mass savings), but there is still the need to apply pressure to the cells in some way. Two common ways of accomplishing this are illustrated Figure 30.

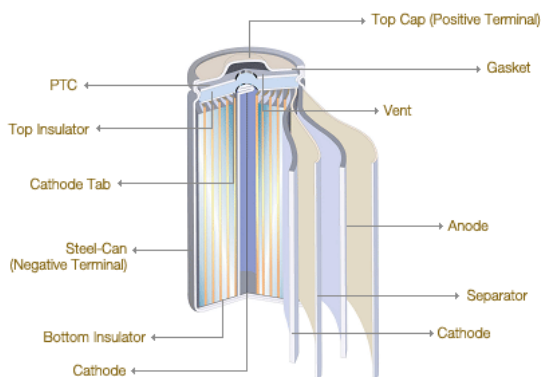
The energy of a cell can be increased by adding more electrolyte. But, assuming a constant volume, this reduces the available space for cathode/anode material. This means there's less surface area for charge carriers, and thus the intercalation process is slower. This means a reduction in the power capability of the cell (and an increase in internal resistance). Thus there is a fundamental tradeoff between energy and power density. Typically very high energy density cells have worse power performance, etc.



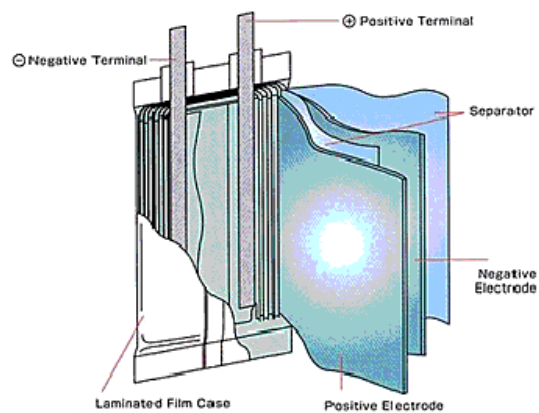
Source: A123systems.com



Source: A123systems.com



Source: <http://www.mpoweruk.com/>



Source: <http://www.mpoweruk.com/>

(a) (b)
 Figure 27: Cylindrical (a) and prismatic (b) battery cells. Not to scale. The schematics don't necessary correspond exactly to the actual A123system batteries shown above.

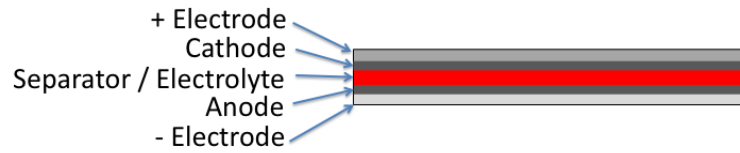


Figure 28: The multiple layers of a battery.

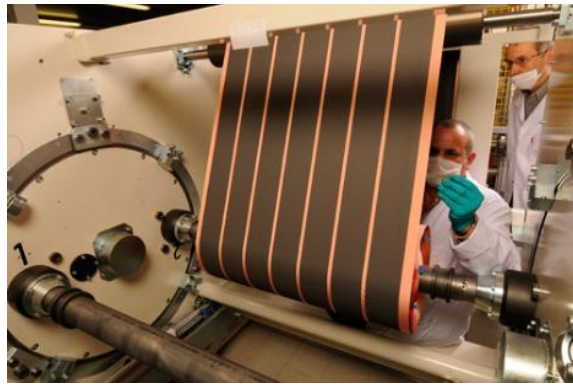
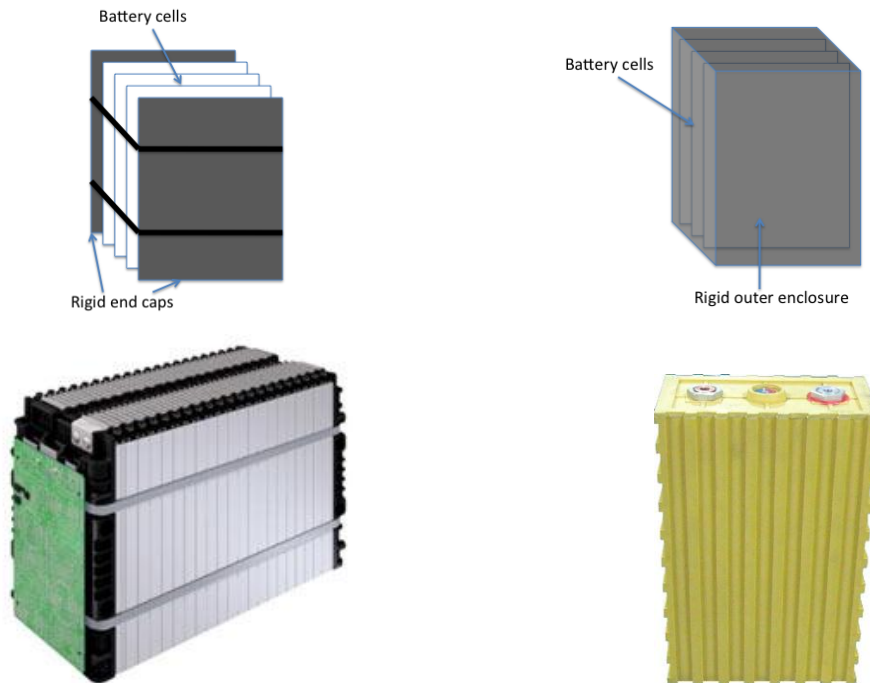


Figure 29: Fabricating a lithium ion battery: the active material is being deposited on the metal foil.
 Source: www.johnsoncontrols.com



Source: www.technologyreview.com

(a)

(b)

Figure 30: Since prismatic cells do not have a metal enclosure like the cylindrical cells, prismatic modules are made to provide positive pressure to the individual cells by either metal bands + rigid end caps (a) or an outer plastic enclosure (b).

1.4. Selection

Type

Lead acid, nickel metal hydride (NiMH), and lithium ion are the most common. Lead acid is not typically used for mobile applications because of their poor energy density and cycle life. The main advantages to lithium ion over NiMH are mass and volumetric energy density, and performance. However, lithium ion tends to be the most expensive battery (see Table 1). Also, NiMH cells have a lower voltage (1.2V) compared to lithium ion (3.3 to 3.7V), which is disadvantageous for certain applications.

The most common lithium ion battery chemistries are lithium cobalt oxide (LiCoO₂) and lithium iron phosphate (LiFePO₄). LiCoO₂ are most commonly used, and are found in laptops, mobile phones, etc. LiFePO₄ is gaining popularity since they are known to be safer, and A123 Systems has produced very high power cells using this chemistry.

Lithium polymer batteries (often written as LiPo, and pronounced “Lie-po”) have a polymer-based electrolyte instead of liquid, and have a prismatic construction (see Figure 30). LiPo’s have LiCoO₂ or LiMn₂O₄ chemistries. The extremely high power density makes them very dangerous when shorted, if thermal runaway occurs, etc.

Cost

The cost of batteries is usually stated in units of \$/Watt-hrs (or \$/kWatt-hrs). The cost will largely depend on the capacity of the battery. It is recommended to compare the \$/Watt-hrs for various suppliers and chemistries. The cost should be weighed with the other selection criteria to make a final decision.

Mass/Volume

The important metric for the mass and volume of batteries is Watt-hrs/kg and Watt-hrs/liter, respectively. The importance of mass and volume depends on the application.

Safety

If all of the failure mechanisms are considered, and the proper thermal system and BMS are implemented, batteries are typically very safe.

Performance

A battery datasheet will state the maximum amount of current that can be safely discharged and charged from the battery as a “C-Rating” (e.g. Maximum discharge is 4C), which is a multiple of the rated Capacity (C). For example, if a

battery has a 3 Ah Capacity, and the maximum discharge rate is specified as 5C, then this would mean the maximum current that can be safely discharged from the battery is $5 \times 3 = 15$ Amps. The same idea is used to specify the fastest charging rate. For a 3 Ah battery, a 2C charge means that the maximum charging current is $3 \times 2 = 6$ Amps.

Table 1: Estimates of various performance metrics (from wikipedia.org). Exact values are extremely difficult to generalize.

Battery Chemistry	Cost [\$/kWatt-hrs]	Mass Energy Density [Watt-hrs/kg]	Vol. Energy Density [Watt-hrs/L]	Cycle Life
Lead-acid	<400	30-40	60-75	500-800
NiMH	<400	30-80	140-300	<1000
Lithium-ion	400	100-250	250-360	1000+

1.5. Hands-on understanding / exercise

2.007 Battery

The battery used in 2.007 is a lithium polymer battery (Figure 31). The specifications of the battery are listed in Table 2.



Figure 31: The lithium polymer battery used for 2.007

Table 2: Specifications for the battery used for 2.007.

Specification	Value
Chemistry	LiCoO ₂
Type	LiPo / prismatic
Voltage (2 cells in series)	7.4V
Discharge Rate	15C constant 25C bursts
Charge Rate	2C
Capacity	500 mAh
Weight	31 g

Exercise: Create a hypothetical set (at least three) of robot maneuvers (e.g. lift a ball, go up a ramp, etc.), calculate the necessary energy required to complete these

maneuvers, and compare this with the battery capacity available in the kit. Include all your assumptions, calculations and references.

Case Studies: iPhone and Electric Vehicles

So the question remains – are the projections for energy density good enough to feed the technological demand? Or are we faced with a great challenge for powering mobile electronics? Let's take two extreme examples to investigate: (1) cell phone batteries and (2) electric vehicles. Assume you are an engineer/consultant and asked to evaluate the current battery technology for both smart phones and electric vehicles.

iPhone:

Use the information discussed in this chapter and from online to evaluate the future prospects of batteries for iPhones and similar devices. What is the best we can expect in terms of talk time, web browsing, etc.? Safety considerations? Weight? State all assumptions and references.

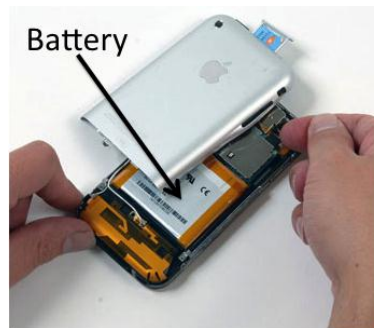


Figure 32: iPhone battery.

Table 3: iPhone's battery specifications.

Specification	Value
Chemistry	LiCoO ₂
Type	LiPo / prismatic
Voltage (single cell)	3.7V
Capacity	1400 mAh
Rated operation (per charge)	40 hours (audio only)

Nissan Leaf, Electric Vehicle:

Use the information discussed in this chapter and from online to evaluate the future prospects of batteries for electric vehicles and similar devices. What is the

best we can expect in terms of driving range, weight, cost, etc.? Safety considerations? Weight? Include all assumptions, calculations, and references.



Nissan Leaf

Vehicle Name	Battery Pack Size	Vehicle Electric Range
Nissan Leaf	24 kWh	100 miles
Chevy Volt	16 kWh	40 miles



Chevy Volt

1.6. Reading References

Online:

[1] <http://www.mpoweruk.com/>

e-Book:

[2] Handbook of Batteries (3rd Edition), Edited by: Linden, D.; Reddy, T.B. © 2002 McGraw-Hill

Must be on the MIT network to access (for free):

<http://goo.gl/MPgOG>