1.1 Naming Conventions

1.1.1 Cells, Batteries, and Packs

There is some confusion in the terms used to describe the various components of a battery pack, probably due to the fact that we say “batteries” when referring to alkaline cells, and that we tend to forget that a car starter battery is really made up of six cells.

In this book we use the following terms:

- **Cell**: the most basic element of a battery [providing 3V to 4V in the case of lithium-ion (Li-Ion)];
- **Block**: a collection of cells wired directly in parallel, also providing 3V to 4V;
- **Battery**: a collection of cells (or blocks) wired in series, and constituting a single physical module, providing a higher voltage (for example, a battery module that uses four cells in series to provide 12V nominally);
- **Pack** (or battery pack): a collection of batteries, arranged in any series and/or parallel combination.

1.1.2 Resistance

When cell manufacturers list resistance in their specs, they usually are talking about AC impedance (see Section 1.2.7). What the user needs to know is the DC series resistance, not AC impedance, because DC is what flows through the cells. Therefore, throughout this book, the term resistance refers specifically to the internal DC series resistance of a cell or battery.

1.2 Li-Ion Cells

Li-Ion rechargeable cells have the highest energy density, and among the highest power densities, of any cell commercially available today. They are capable of amazing performance (Figure 1.1), and are the standard choice for many consumer
electronic products, such as laptop computers and cell phones. They are also fast becoming the choice for traction packs in vehicles.

1.2.1 Formats

Li-Ion cells are available in four basic formats (Figure 1.2 and Table 1.1): cylindrical (small and large), prismatic, and pouch.

Some of these formats are far easier to use than others, making them more appropriate for small projects. Cylindrical cells inherently retain their shape against expansion due to chemical processes when fully charged, while, with the other formats, you must provide an overall battery enclosure to retain their expansion.

Additionally, K2 Energy assembles a set of small cylindrical cells in a prismatic case, forming a battery that has the mechanical and thermal advantages of small cylindrical cells and the convenience of prismatic cells.

![Figure 1.1](image1)  The KillaCycle, the world’s quickest electric motorcycle, burning rubber. (Courtesy of Bill Dubé.)

![Figure 1.2](image2)  Li-Ion cell formats: small and large cylindrical, pouch, and prismatic.
1.2.2 Chemistry

Lithium-Ion is the name given to a class of rechargeable cells that use lithium intercalation reactions in both electrodes; lithium ions travel between the two electrodes in a so-called rocking chair framework.

Among Li-Ion cells, lithium polymer (LiPo) cells use a polymer or gel electrolyte, while all other cells use a nonaqueous, liquid electrolyte.

Many Li-Ion chemistries are available. They are usually named according to the composition of the cathode. They include:

- LiCoO$_2$: Standard lithium-cobalt-oxide;
- LiMnNiCo: Lithium-manganese-nickel-cobalt;
- LiFePO$_4$ and Li$_2$FePO$_4$F: Nano-phosphate/lithium-iron-phosphate/lithium-ferro-phosphate;
- LiMnO$_2$: Lithium-manganese-oxide;
- Li$_4$Ti$_5$O$_{12}$: Lithium-titanate;
- LiMn$_2$O$_4$: Lithium-manganese-oxide;
- LiNiO$_2$: Lithium-nickel-oxide.

The nominal voltage, energy, and power density of these cells varies with their chemistry. Some are considered safer and are more appropriate for large traction

<table>
<thead>
<tr>
<th>Table 1.1 Comparison of Cell Formats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Small Cylindrical</strong></td>
</tr>
<tr>
<td><strong>Large Cylindrical</strong></td>
</tr>
<tr>
<td><strong>Prismatic</strong></td>
</tr>
<tr>
<td><strong>Pouch</strong></td>
</tr>
<tr>
<td>Shape: Encased in a metal cylinder, usually 65-mm long</td>
</tr>
<tr>
<td>Connections: Welded nickel or copper strips or plates</td>
</tr>
<tr>
<td>Retention against expansion when fully charged: Inherent from cylindrical shape</td>
</tr>
<tr>
<td>Appropriateness for mall projects: Poor: high design effort, requires welding, labor intensive</td>
</tr>
<tr>
<td>Appropriateness for production runs: Good: welded connections are reliable</td>
</tr>
<tr>
<td>Field replacement: Not possible</td>
</tr>
<tr>
<td>Notes: Best for retrofits, as small shape can be fit in all available space</td>
</tr>
</tbody>
</table>
packs (especially LiFePO$_4$ and lithium-titanate) compared to standard (LiCoO$_2$) Li-Ion cells.

1.2.3 Safety

Li-Ion cells perform magnificently, but are rather unforgiving if operated outside a rather tight safe operating area (SOA), with consequences ranging from the annoying to the dangerous.

In most cases the only effect is simply that the life of the cell is reduced, or that the cells are damaged, with no safety issues. However, abusing a Li-Ion cell in particular ways can be extremely dangerous and can result in physical damage (piercing, crushing) and/or overheating (from over-voltage, over-current, or external heat).

I have witnessed in horror the result of making a short circuit across a “safe” LiFePO$_4$ battery: the cells expelled their contents very violently, in succession, like firecrackers (Figures 1.3 and 1.4). Thanks to safety procedures in place at the time, the battery was on a cart and next to an exit, which allowed the technicians to quickly wheel it outside.

I also have performed a forensic analysis on a Prius converted to PHEV (Figure 1.5), which caught on fire due to arcing inside it Li-Ion traction pack (see Section 6.1.1.5).

No one got hurt in either event. In both cases, human error was at fault: poor mechanical design and bad manufacturing processes (no quality control and distractions present in the manufacturing area). In neither case was a BMS to blame.

Those are extreme examples. However unlikely such events may be, let them serve as a warning of how dangerous large Li-Ion batteries can be. Be safe when working on such a battery.

Figure 1.3 Putting out a Li-Ion battery on fire after a direct short circuit across it.
Think clearly, and categorically tell people nearby to be quiet—chitchat and Li-Ion do not mix.

Wear proper safety equipment: goggles and insulated gloves for working with batteries above 40V.

Do not place metal objects on a plane that is higher than unprotected cells, as gravity will invariably cause those objects to fall on the cells. This means no screwdrivers, no meter probes, no socket wrenches, no paint cans, no calipers. If it is not firmly in your hand, place it beneath the battery.

Design batteries properly, and build them according to the design, using tight quality control.

Prepare a procedure to follow in case a battery should ignite (cable cutters, quick ejection out of the building, fire suppression); before you work on a bat-
tery, know that procedure by heart, and be prepared to complete it within 10 seconds of the starting event.

1.2.4 Safe Operating Area
The SOA of Li-Ion cells is bound by current, temperature, and voltage.

- Li-Ion cells will be quickly damaged and may burst into flames if overcharged above a certain voltage.
- Most Li-Ion cells will be damaged if allowed to be discharged below a certain voltage.
- The lifetime of Li-Ion cells will be drastically reduced if discharged outside a certain temperature range, or charged outside an even tighter temperature range.
- Li-Ion cells can experience a thermal runaway and ignite if allowed to exceed a safe temperature; even cells that are not prone to thermal runaway may contain an organic electrolyte, which will fuel flames.
- Li-Ion cells’ lifetime will be reduced if discharged at too high a current, or charged too fast.
- Li-Ion cells may be damaged if operated at high pulse currents for more than a few seconds.

These limits vary considerably with the chemistry of the cell. For example, standard Li-Ion cells (LiC₂) without any additional protection mechanisms will go into thermal runaway at a relatively low temperature, while LiFePO₄ cells are intrinsically immune to thermal runaway. These limits vary to a certain extend with the manufacturer. For example, A123 and K2 manufacture very similar small cylindrical cells, yet the A123 cells can be discharged down to 0V with no ill effects, while the K2 cells may not be discharged below 1.8V (Figure 1.6).

1.2.5 Efficiency
A significant advantage of Li-Ion cells compared to other chemistries is that they are particularly efficient in energy and charge.

1.2.5.1 Energy
The resistance of a Li-Ion cells is quite low (especially in a so-called power cell), which means that little $I^2R$ power is wasted in heat inside of them. For example, the M1 26,650 cells from A123 (used in power tools and PHEV conversion), have a typical resistance of 10 mΩ; when loaded at 1C (2.3A), they waste $P = 2.3^2 \times 10 \text{ mΩ} = 53 \text{ mW}$, while delivering $P = 2.3A \times 3.2V = 7.6W$, which is an efficiency of 99.3% (98.6% round trip when considering both charging and discharging).

At higher currents the energy efficiency of a cell goes down. More energy is wasted in heat inside the cell (across its resistance) leaving less energy available to do work outside the cell.
Maximum power can be extracted from a cell when the load’s resistance is equal to the cell’s resistance. Half the power will be wasted in heat inside the cell, and half of the power will do work outside the cell.

An M1 26,650 cell from A123 can generate 150A and 500W this way, 250W of which is in heat inside the cells. This can only be sustained for a very short time (less than 10 seconds), as the heat in the cell will quickly degrade it and increase its temperature to dangerous levels. Still, that is something to consider for a race vehicle, for which breaking records is more important than saving the life of the cells, and for which the occasional fire is acceptable.

1.2.5.2 Charge

From a charge standpoint, Li-Ion cells are practically 100% efficient (as long as a charge and discharge cycle is completed within a time that is short enough that self leakage is not an issue). That is, essentially every electron that goes into a cell while charging from completely empty to completely full is available to come back out while discharging back down to completely empty, regardless of the rate of charge or discharge. Note that I didn’t say that all the energy can be recovered; I said that all the charge can be recovered. The cell voltage during discharge is lower than during charge, so the energy discharged is lower than the energy during charging, even though the charge in and out is the same.

If you take exception to this statement, because a specification sheet shows a reduced charge out of a cell at higher current, I would like to point out that I specified complete charge and discharge, while the curves in specification sheet are at constant current, and stop when the cell voltage under load drops down to a certain
level. At that point the cell is not yet fully discharged. You can still extract the remaining charge by discharging the cell at a lower current, for example by discharging it at a constant voltage equal to the cutoff voltage (Figure 1.7). By the time the current drops to zero, the total charge from the cell adds up to essentially the same value, regardless of the rate of discharge (whether the discharge was at a low current or at a high current finished off at a low current).

Of course, in many applications (such as backup power), the load must operate at a high current, and will not be able to extract the last bit of charge out of the cell. For these applications, the fact that all the charge could be extracted at lower current is purely academic.

Some applications do have some flexibility. For example, an EV can go to a “valet” mode at reduced torque, to let the driver “limp home.” Such applications are able to use the entire charge from a battery.

---

1. To those of you familiar with lead acid batteries and the Peukert constant concept, it may be interesting to know that Li-Ion cells have a Peukert constant of about 1.05 (compared to lead acid batteries, which have a Peukert constant between 1.1 and 1.3).
1.2.6 Aging

Li-Ion cells have a longer life than other chemistries, but still have a limited cycle life and may have a limited calendar life.

1.2.6.1 Calendar Life

Standard Li-Ion cells have a relatively short calendar life (Figure 1.8). Whether or not they are cycled, they lose capacity (as users of cell phones and laptops can attest). This is due to a chemical process that occurs when the cells sit fully charged at a voltage above 4.0V. Other Li-Ion chemistries (notably LiFePO4 cells) operate at a lower voltage so that a chemical effect does not take place, and therefore they do not appear to have any calendar life limitations.

1.2.6.2 Cycle Life

You have certainly seen plots of Li-Ion cell capacity versus number of cycles; the capacity decreases linearly with the number of charge and discharge cycles, at a rate that depends on the discharge current used. You may have not seen plots of resistance increase versus cycles, which drops a little after a few cycles, then increases until a few hundreds of cycles, and then continues increasing, though more rapidly.

Figure 1.8 Calendar life of Li-Ion cells.

2. Note the spelling of calendar, which is often misspelled “calender.” A calendar is a device used to mark the passage of time, very different from a calender, which is a device used in paper making.
What only a few people realize [1] is that these two plots are related. While a portion of the capacity loss is indeed due to a loss of active material inside the cell, the rest is not really lost, but is just simply unused; the cell is undercharged and underdischarged due to the increase of resistance and the fixed cutoff voltages specified by the cell manufacturers. By using fixed cutoff voltages, the cell manufacturer’s test equipment charges and discharges cells less and less each time as their resistance increases, resulting in an apparent loss of capacity; it’s not just that cells lose some capacity as they are used (which they do), it’s also that the cell manufacturer’s test algorithm is limited in such a way that the cells appear to be losing even more capacity than they really are.

The portion of that capacity that is unavailable due to increased resistance can be recovered by raising the top cutoff voltage during charge and lowering the bottom cutoff voltage during discharge, using IR \( (V = I \cdot R) \) compensation (Figure 1.9). The very same cell that has “lost 10% of its capacity,” in actuality may still have much of its original capacity; to access it, the charge cutoff voltage must be increased and the discharge cutoff must be decreased, to make up for the additional IR voltage drop due to its increased resistance.

A BMS that is able to measure each cell’s resistance and compensate its cutoff voltages accordingly can make better use of a battery’s capacity.

1.2.7 Modeling

A chemist thinks of a cell in terms of its processes, while an electrical engineer finds it more useful to view a cell in terms of an electrical circuit; this is called the electrical equivalent model. The simplest model of an Li-Ion cell, yet a very effective one when used at a constant current, is as a voltage source and series resistance \[ \text{Figure 1.10(a)} \]. This is indeed the resistance that we are talking about when we use the term “resistance” in the remainder of this book.
In a typical Li-Ion cell, the resistance is on the order of few milliohms (10 to 50 mΩ for a 26,650 LiFePO4 power cell, 0.5 to 5 mΩ for a prismatic cell). That resistance results from the series combination of the effective resistance due to the chemical processes and the bulk metal resistance in the current collectors and terminals. The voltage drop due to this resistance and the cell’s current (IR drop) is what chemists call the polarization potential.

Here we are not talking about simple resistance (which is something you can measure with an ohm meter, or calculate as $R = \frac{V}{I}$). We are actually talking about a dynamic resistance, which is different because of the presence of a voltage source in series with that resistance. Dynamic resistance is defined as the ratio of delta voltage over delta current:

$$ R = \frac{\Delta V}{\Delta I} $$

Therefore, in order to calculate dynamic resistance, there must be a delta in the current (i.e., the pack current cannot be constant), which results in a delta in the voltage. This resistance varies with (Figure 1.11):

- **SOC**: its value is higher at both low and high SOC levels;
- **Temperature**: its value is higher at colder temperatures;
- **Current**: its value is higher at higher currents and when charging (compared to the same current discharging);
- **Usage**: its value increases over time as the cell is used.
From the point of view of the cell user, the next level of complexity is achieved by splitting the resistance into two resistors and adding a large capacitor in parallel with one of the resistors [Figure 1.10(b)]. This allows the model to correctly emulate the actual behavior of a cell when suddenly loaded. The initial drop in cell voltage is small (just due to $R_1$), only to drop further, exponentially, down to the level due to both resistances, with a time constant $T = R_2 \times C_2$, which is on the order of 1 minute. This effect is what chemists call relaxation.

Unfortunately, cell manufacturers, use a different model [Figure 1.10(c)], which at first may look the same, but instead uses an RC circuit ($R_3$ and $C_3$) whose time constant is on the order of 1 ms. This allows the model to correctly emulate the AC impedance (at frequencies of the order of 1 kHz) seen by the test equipment available to the cell manufacturers. Cell manufacturers measure this parameter at no load, on a brand new cell, and at 1 kHz, which is a set of conditions that is very different from how the cells are used in the real world. Manufacturers use that measurement method because test equipment to measure 1-kHz impedance is readily available, impedance at 1 kHz remains pretty constant over the life of the cell, and, frankly, their chemists may not be very clear on the concept of DC resistance under load. However, this model is useless to the cell user. If this model were accurate, the voltage drop when a cell was initially loaded would be practically instantaneous and would be much more shallow. Cell manufacturers report the real part of the AC impedance at 1 kHz as the cell’s resistance. This is entirely misleading to the user who mistakes that value as the value of the cell’s DC resistance. Combining the two models results in a more accurate model with two RC circuits [Figure 1.10(d)], which serves both the cell manufacturer and the user [2].

1.2.8 Unequal Voltages in Series Strings

In a small battery with just a few cells in series, the charger voltage is divided nearly equally among the cells. For example (Figure 1.12), when charging a standard lead-acid starter battery for a car, a constant voltage of 13.5V is applied to it, and each of the six cells within it sees about 2.25V. If any cell is charged more, its voltage
will be a bit higher, taking away some voltage from the other cells. For example, if one cell is at 2.5V, the other cells will be, on the average, at 2.20V. That delta voltage among cells is perfectly acceptable; lead acid cells are much more tolerant to variances in their voltage.

For another example (Figure 1.13), a small LiPo battery for a consumer product may have two cells in series. When charging with 8.4V, if the cells are balanced, each cell sees 4.2V. If the cells are out of balance, in the worst case the most discharged cell will be at 3.3V, leaving 4.9V on the most charged one. 4.9V is above the maximum rating for a LiPo cell (4.2V), but it is still low enough that it is not going to go in the thermal runaway and catch fire.

Figure 1.12  A lead acid starter battery: (a) balanced and (b) unbalanced.

Figure 1.13  Cells in series in a two-cell LiPo battery: (a) balanced and (b) unbalanced.
In a high-voltage battery with many cells in series, though, there is a much greater chance that the overall pack voltage is not evenly divided among its cells. (This is true for any chemistry.)

Consider a four-cell LiPo battery, charged up to 16.8V. If the cells are perfectly balanced, the total voltage will be equally divided into 4.2V per cell [Figure 1.14(a)]. In practice, the cells will be unbalanced, and one will be the first to be fully charged and then be overcharged. Li-Ion cells do not deal well with overcharging. Once charged, they cannot take more current as the other cells in series get their needed charge. Instead, their voltage rises rapidly, possibly to dangerous levels. In this example [Figure 1.14(b)], the second cell is overcharged to 6.3V, while the other ones are around 3.5V. Despite the fact that the total voltage is 16.8V, three of the cells in this battery are not fully charged, and one of its cell is in danger of thermal runaway. Therefore, a system that relies on the total battery voltage to determine when to stop charging the battery (such as a CCCV charger) gives the user a false sense of security; that system will overcharge some cells, and will create a safety issue as some cells with be overcharged to dangerous levels. It is therefore essential that a BMS monitor such a battery, first and foremost to prevent any cell from being overcharged, and optionally to balance the battery to maximize its performance.

Now consider the same battery, after it has been discharged down to 12.0V. If the cells are perfectly balanced, the total voltage will be equally divided into 3.0V per cell [Figure 1.15(a)]. In practice, the cells will be unbalanced, and one will be the first to be fully discharged, and then be overdischarged. To varying degrees, Li-Ion cells do not deal well with overdischarging. If their voltage is allowed to drop below a certain threshold, irreversible damage may occur. In this example [Figure 1.15(b)].

![Figure 1.14](image)

**Figure 1.14** Four-cell battery, charged: (a) balanced and (b) unbalanced. One cell is in danger of thermal runaway.
[Image: Four-cell battery, discharged: (a) balanced and (b) unbalanced.]

1.15(b)], one cell is overdischarged down to 1.5V, while the other ones are around 3.5V. Despite the fact that the total voltage is 12V, three of the cells in this battery are not fully discharged, and one of its cells is being damaged. Therefore, a system that relies on the total battery voltage to determine when to stop discharging the battery (such as a motor controller with a low voltage cutoff) gives the user a false sense of security; that system *will* overdischarge some cells, damaging them. It is therefore essential that a BMS monitor such a battery to prevent any cell from being overdischarged and damaged.

### 1.3 Li-Ion BMSs

In the previous sections we saw how abusing Li-Ion cells may reduce their life, result in damage, and can even be a safety issue. Having analyzed the problems with Li-Ion cells, let us look at Li-Ion BMSs for solutions. It is the job of a BMS to ensure that the cells in a battery are operated within their SOA. This is particularly important for large Li-Ion battery packs because:

- Li-Ion cells are so much more unforgiving of abuse than other chemistries.
- Large battery packs, with many cells in series, are more prone to be charged and discharged unevenly due to unbalance among cells. Li-Ion cells must not be overcharged or overdischarged.