Learn how to arrange batteries to increase voltage or gain higher capacity:

Batteries achieve the desired operating voltage by connecting several cells in series; each cell adds its voltage potential to derive at the total terminal voltage. Parallel connection attains higher capacity by adding up the total ampere-hour (Ah).

Some packs may consist of a combination of series and parallel connections. Laptop batteries commonly have four 3.6V Li-ion cells in series to achieve a nominal voltage 14.4V and two in parallel to boost the capacity from 2,400mAh to 4,800mAh. Such a configuration is called 4s2p, meaning four cells in series and two in parallel. Insulating foil between the cells prevents the conductive metallic skin from causing an electrical short.

Most battery chemistries lend themselves to series and parallel connection. It is important to use the same battery type with equal voltage and capacity (Ah) and never to mix different makes and sizes. A weaker cell would cause an imbalance. This is especially critical in a series configuration because a battery is only as strong as the weakest link in the chain. An analogy is a chain in which the links represent the cells of a battery connected in series (Figure 1).

Figure 1: Comparing a battery with a chain.
Chain links represent cells in series to increase voltage, doubling a link denotes parallel connection to boost current loading.

A weak cell may not fail immediately but will get exhausted more quickly than the strong ones when on a load. On charge, the low cell fills up before the strong ones because there is less to fill and it remains in over-charge longer than the others. On discharge, the weak cell empties first and gets hammered by the stronger brothers. Cells in multi-packs must be matched, especially when used under heavy loads.

Single Cell Applications

The single-cell configuration is the simplest battery pack; the cell does not need matching and the protection circuit on a small Li-ion cell can be kept simple. Typical examples are mobile phones and tablets with one 3.60V Li-ion cell. Other uses of a single cell are wall clocks, which typically use a 1.5V alkaline cell, wristwatches and memory backup, most of which are very low power applications.

The nominal cell voltage for a nickel-based battery is 1.2V, alkaline is 1.5V; silver-oxide is 1.6V and lead acid is 2.0V. Primary lithium batteries range between 3.0V and 3.9V. Li-ion is 3.6V; Li-phosphate is 3.2V and Li-titanate is 2.4V.
Li-manganese and other lithium-based systems often use cell voltages of 3.7V and higher. This has less to do with chemistry than promoting a higher watt-hour (Wh), which is made possible with a higher voltage. The argument goes that a low internal cell resistance keeps the voltage high under load. For operational purposes these cells go as 3.6V candidates.

Series Connection

Portable equipment needing higher voltages use battery packs with two or more cells connected in series. Figure 2 shows a battery pack with four 3.6V Li-ion cells in series, also known as 4S, to produce 14.4V nominal. In comparison, a six-cell lead acid string with 2V/cell will generate 12V, and four alkaline with 1.5V/cell will give 6V.

Figure2: Series connection of four cells (4s).
Adding cells in a string increases the voltage; the capacity remains the same.

If you need an odd voltage of, say, 9.50 volts, connect five lead acid, eight NiMH or NiCd, or three Li-ion in series. The end battery voltage does not need to be exact as long as it is higher than what the device specifies. A 12V supply might work in lieu of 9.50V. Most battery-operated devices can tolerate some over-voltage; the end-of-discharge voltage must be respected, however.

High voltage batteries keep the conductor size small. Cordless power tools run on 12V and 18V batteries; high-end models use 24V and 36V. Most e-bikes come with 36V Li-ion, some are 48V. The car industry wanted to increase the starter battery from 12V (14V) to 36V, better known as 42V, by placing 18 lead acid cells in series. Logistics of changing the electrical components and arcing problems on mechanical switches derailed the move.

High-voltage batteries require careful cell matching, especially when drawing heavy loads or when operating at cold temperatures. With multiple cells connected in a string, the possibility of one cell failing is real and this would cause a failure. To prevent this from happening, a solid state switch in some large packs bypasses the failing cell to allow continued current flow, albeit at a lower string voltage.

Cell matching is a challenge when replacing a faulty cell in an aging pack. A new cell has a higher capacity than the others, causing an imbalance. Welded construction adds to the complexity of the repair, and this is why battery packs are commonly replaced as a unit.

High-voltage batteries in electric vehicles, in which a full replacement would be prohibitive, divide the pack into modules, each consisting of a specific number of cells. If one cell fails, only the affected module is replaced. A slight imbalance might occur if the new module is fitted with new cells. Figure 3 illustrates a battery pack in which “cell 3” produces only 2.8V instead of the full nominal 3.6V. With depressed operating voltage, this battery reaches the end-of-discharge point sooner than a normal pack. The voltage collapses and the device turns off with a “Low Battery” message.

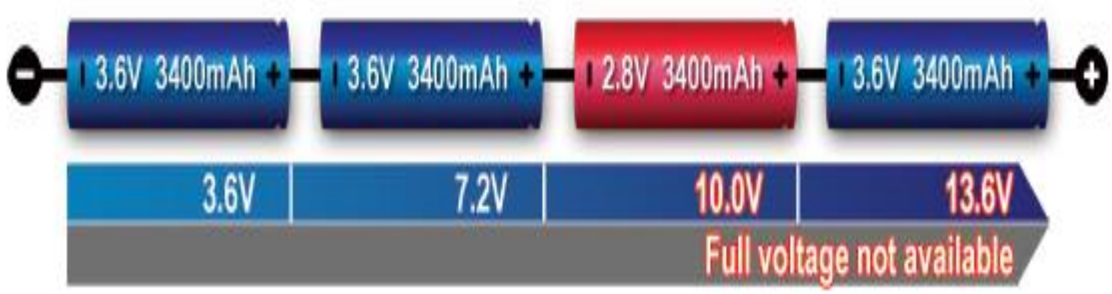

Figure 3: Series connection with a faulty cell.
Faulty cell 3 lowers the voltage and cuts the equipment off prematurely.

Batteries in drones and remote controls for hobbyist requiring high load current often exhibit an unexpected voltage drop if one cell in a string is weak. Drawing maximum current stresses frail cells, leading to a possible crash. Reading the voltage after a charge does not identify this anomaly; examining the cell-balance or checking the capacity with a battery analyzer will.

Parallel Connection

If higher currents are needed and larger cells are not available or do not fit the design constraint, one or more cells can be connected in parallel. Most battery chemistries allow parallel configurations with little side effect. Figure 4 illustrates four cells connected in parallel in a P4 arrangement. The nominal voltage of the illustrated pack remains at 3.60V, but the capacity (Ah) and runtime are increased fourfold.

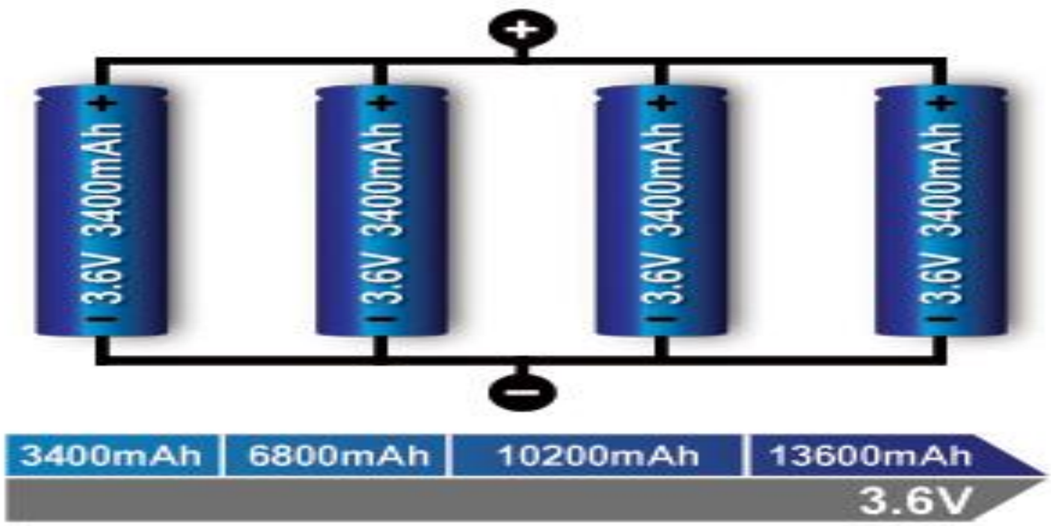

Figure 4: Parallel connection of four cells (4p).
With parallel cells, capacity in Ah and runtime increases while the voltage stays the same.

A cell that develops high resistance or opens is less critical in a parallel circuit than in a series configuration, but a failing cell will reduce the total load capability. It's like an engine only firing on three cylinders instead of on all four. An electrical short, on the other hand, is more serious as the faulty cell drains energy from the other cells, causing a fire hazard. Most so-called electrical shorts are mild and manifest themselves as elevated self-discharge.

A total short can occur through reverse polarization or dendrite growth. Large packs often include a fuse that disconnects the failing cell from the parallel circuit if it were to short. Figure 5 illustrates a parallel configuration with one faulty cell.

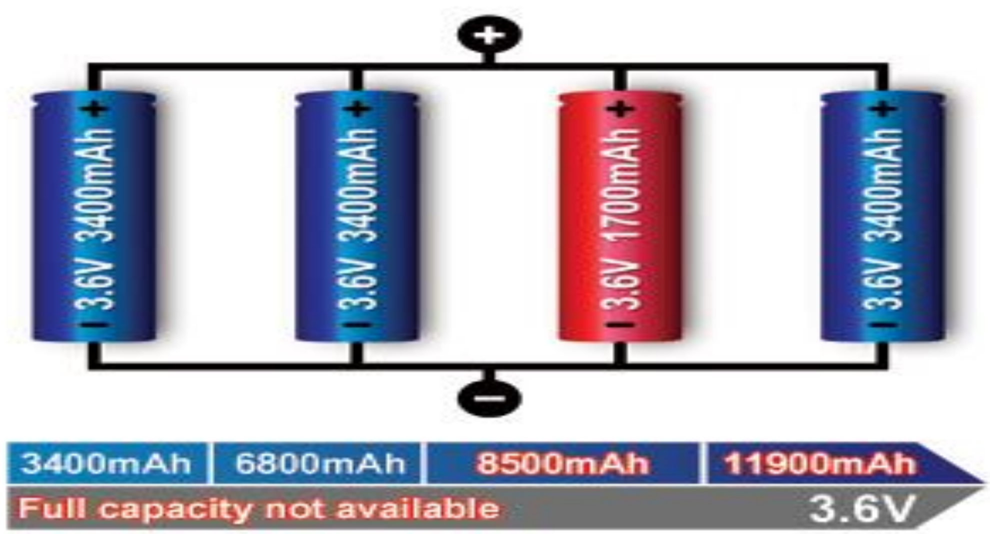

Figure 5: Parallel/connection with one faulty cell.
A weak cell will not affect the voltage but provide a low runtime due to reduced capacity. A shorted cell could cause excessive heat and become a fire hazard.
On larger packs a fuse prevents high current by isolating the cell.
Courtesy of Cadex

Series/parallel Connection

The series/parallel configuration shown in Figure 6 enables design flexibility and achieves the desired voltage and current ratings with a standard cell size. The total power is the product of voltage-times-current; four 3.6V (nominal) cells multiplied by 3,400mAh produce 12.24Wh. Four 18650 Energy Cells of 3,400mAh each can be connected in series and parallel as shown to get 7.2V nominal and 12.24Wh. The slim cell allows flexible pack design but a protection circuit is needed.

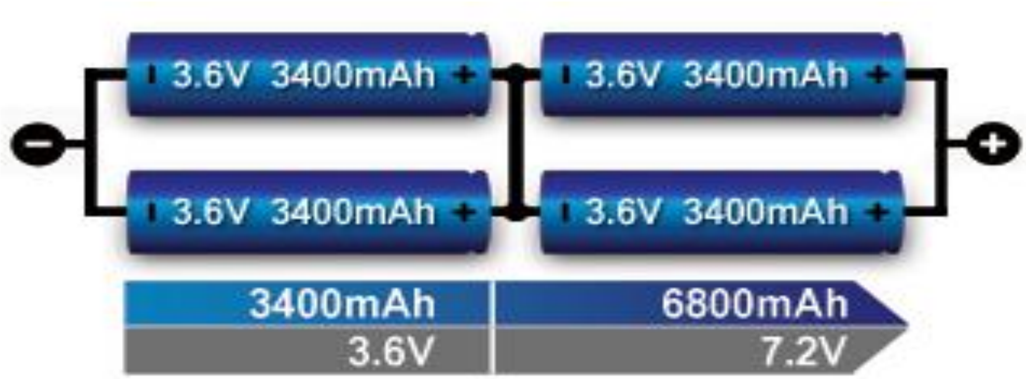

Figure 6: Series/ parallel connection of four cells (2s2p).
This configuration provides maximum design flexibility. Paralleling the cells helps in voltage management.

Li-ion lends itself well to series/parallel configurations but the cells need monitoring to stay within voltage and current limits. Integrated circuits (ICs) for various cell combinations are available to supervise up to 13 Li-ion cells. Larger packs need custom circuits, and this applies to e-bike batteries, hybrid cars and the Tesla Model 85 that devours over 7000 18650 cells to make up the 90kWh pack.

Terminology to describe Series and Parallel Connection

The battery industry specifies the number of sells in series' first, followed by the cells placed in parallel. An example is 2s2p. With Li-ion, the parallel strings are always made first; the completed parallel units are then placed in series. Li-ion is a voltage based system that lends itself well for parallel formation. Combining several cells into a parallel and then adding the units serially reduces complexity in terms of voltages control for pack protection.

Building series strings first and then placing them in in parallel may be more common with NiCd packs to satisfy the chemical shuttle mechanism that balances charge at the top of charge. "2s2p" is common; white papers have been issued that refer to 2p2s when a serial string is paralleled.

Safety devices in Series and Parallel Connection

Positive Temperature Coefficient Switches (PTC) and Charge Interrupt Devices (CID) protect the battery from overcurrent and excessive pressure. While recommended for safety in a smaller 2- or 3-cell pack with serial and parallel configuration, these protection devices are often being omitted in larger multi-cell batteries, such as those for power tool. The PTC and CID work as expected to switch of the cell on excessive current and internal cell pressure; however the shutdown occurs in cascade format. While some cells may go offline early, the load current causes excess current on the remaining cells. Such overload condition could lead to a thermal runaway before the remaining safety devices activate.

Some cells have built-in PCT and CID; these protection devices can also be added retroactively. The design engineer must be aware than any safety device is subject to failure. In addition, the PTC induces a small internal resistance that reduces the load current.

Simple Guidelines for Using Household Primary Batteries

- Keep the battery contacts clean. A four-cell configuration has eight contacts and each contact adds resistance (cell to holder and holder to next cell).
- Never mix batteries; replace all cells when weak. The overall performance is only as good as the weakest link in the chain.
- Observe polarity. A reversed cell subtracts rather than adds to the cell voltage.
- Remove batteries from the equipment when no longer in use to prevent leakage and corrosion. This is especially important with zinc-carbon primary cells.
- Do not store loose cells in a metal box. Place individual cells in small plastic bags to prevent an electrical short. Do not carry loose cells in your pockets.
- Keep batteries away from small children. In addition to being a choking hazard, the current-flow of the battery can ulcerate the stomach wall if swallowed. The battery can also rupture and cause poisoning. Do not recharge non-rechargeable batteries; hydrogen buildup can lead to an explosion. Perform experimental charging only under supervision.

Simple Guidelines for Using Secondary Batteries

- Observe polarity when charging a secondary cell. Reversed polarity can cause an electrical short, leading to a hazardous condition.
- Remove fully charged batteries from the charger. A consumer charger may not apply the correct trickle charge when fully charged and the cell can overheat.
- Charge only at room temperature.