

Why does a battery run out?

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QUE · Article 008 · Simple Questions, Deep Answers · Version 0.1 EN

A battery can stop powering a device while still containing electrons, atoms and chemical energy. What has diminished is its ability to sustain the required electrical output under the particular conditions. “Empty” is therefore a practical description that can conceal several different physical states: reversible discharge, temporary voltage loss under load, or lasting degradation.

The distinction explains why resting a battery can sometimes change its measured voltage without restoring its original chemical state, and why recharging a rechargeable cell does not make it permanently new. The question is about a coupled chemical and electrical system, not a container from which individual electrons are gradually used up.

1. A reaction organized into a circuit

An electrochemical cell separates oxidation and reduction so that electron transfer can support current through an external circuit. Ions move within the cell to maintain the necessary charge balance. The materials and interfaces make these linked paths possible. A battery can contain one cell or an arrangement of cells [1].

In a lithium-ion cell, for example, lithium ions move between electrode materials during charge and discharge [1]. Electrons follow the external conducting path. These distinct ionic and electronic paths are essential to cell operation.

Electrons delivered to the external circuit are not destroyed in the device. Electrical energy is transferred as charges move through potential differences. If charge vanished at the load, a different conservation problem would arise. The battery's operation instead changes the chemical and physical states that sustain its voltage.

2. Voltage is connected to free-energy change

For a reversible electrochemical reaction transferring n moles of electrons per mole of reaction, the relation $\Delta G = -nFE$ connects the molar Gibbs free-energy change for the stated reaction to the equilibrium cell potential E . F is the Faraday constant. The signs refer to a specified reaction direction. A positive equilibrium voltage for discharge corresponds to a negative free-energy change in that direction [2].

The chemical potentials entering ΔG depend on composition and conditions. As discharge changes the cell, the equilibrium voltage can change. The exact curve is chemistry-dependent: phase behaviour can produce relatively flat regions, and the voltage need not decline smoothly in proportion to the remaining charge. A voltage reading therefore cannot universally serve as a linear fuel gauge.

Equilibrium voltage is also not identical to the terminal voltage while the device draws current. Electrode kinetics, transport limitations and electrical resistance introduce differences. A practical circuit can stop operating because the terminal voltage falls below its required threshold even though some further reaction would be possible under a different load.

3. Charge capacity and energy are not the same number

Charge delivered during discharge is $q = \int I \, dt$. An ampere-hour is a charge unit: $1 \text{ Ah} = 3600 \text{ C}$. Electrical energy delivered is $W = \int VI \, dt$, which depends on the changing terminal voltage as well as current. Two cells with the same charge capacity can therefore deliver different amounts of energy.

For an intentionally simplified example, suppose a hypothetical cell delivers 2 Ah at a constant 3 V . Its delivered charge is 7200 C and its delivered electrical energy is 6 Wh , or 21.6 kJ . This arithmetic assumes constant voltage and does not describe a measured discharge curve. If voltage changes during discharge, the integral must replace that multiplication.

The example also shows why a capacity rating needs test conditions. Current, temperature, discharge endpoint and prior history influence the usable result. A label alone cannot establish the energy available to every conceivable device, and an energy calculation cannot predict the internal temperature without a separate thermal account.

4. Why a load can make the battery seem empty earlier

A simple circuit approximation writes $V_{\text{terminal}} = E - IR$, where R represents an effective internal resistance. For an illustrative $E = 3 \text{ V}$ and $R = 0.2 \, \Omega$, a 1 A load gives 2.8 V , while a 3 A load gives 2.4 V . These are chosen values that isolate one effect, not specifications for a commercial battery.

Actual cells can also develop concentration gradients and kinetic overpotentials. Removing the load allows some non-equilibrium gradients to relax, so the terminal voltage can recover. That recovery does not mean that the discharge reaction has spontaneously reversed in full. A state variable measured after relaxation and a loaded operating voltage are different observations.

This is why identifying the cause of shutdown requires more than noting that the screen went dark. A cell may reach a permitted operating limit, a reaction or transport limitation, or a voltage threshold set by the device. The relevant question is what output remains available under specified conditions, rather than whether literally every reactive species has disappeared.

5. Discharge differs from degradation

A rechargeable cell is designed so that an imposed electrical input can drive much of the useful electrochemical change in the reverse direction. Recharging requires energy. It is not the replacement of electrons that have been consumed, and not every primary-cell chemistry or construction is designed for reversible cycling [1].

Degradation changes the cell's ability to carry out later cycles. Edge and colleagues distinguish underlying degradation mechanisms, their observable effects at cell level and the resulting loss of capacity or power. Their review emphasizes interactions among mechanisms [3]. These mechanisms must not be collapsed into one universal cause. Which processes dominate depends on chemistry, construction and operating history.

A lower measured capacity can consequently have more than one explanation. A cell may possess less reversible reaction capacity, or it may encounter the discharge cutoff earlier because polarization has increased. Distinguishing those possibilities takes controlled measurements. Merely observing reduced runtime does not identify a unique microscopic failure mode.

6. What measurements can distinguish the possibilities?

A discharge test can record current, terminal voltage, time and temperature under a defined protocol. An open-circuit measurement after a specified rest probes a different state. Comparing several loads helps separate some rate-dependent effects from a simple inventory picture. None of these measurements should be called an equilibrium result without checking the relevant relaxation assumptions.

To investigate degradation, the same test conditions must be maintained across comparisons. Otherwise a change in temperature or cutoff can imitate a change in cell health. Additional electrochemical or structural measurements can constrain mechanisms, but a detailed diagnostic argument lies beyond an everyday explanation of why a battery stops delivering useful output.

The well-established answer is that a battery runs down as its electrochemical state and operating losses limit the voltage and charge it can deliver. Lasting ageing is a related but distinct process. The useful energy was associated with a chemical free-energy difference, not with a finite stock of disposable electrons. Keeping those ideas separate explains both ordinary discharge and the limits of recharge without turning the article into a purchasing or operating guide.

Related reading: PIO-061, on the history of the electric pile; IDE-001, on energy and its availability.

References

- [1] OpenStax. Chemistry 2e, §17.5, Batteries and Fuel Cells.
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<https://openstax.org/books/chemistry-2e/pages/17-4-potential-free-energy-and-equilibrium>
- [3] Edge, J. S. et al. Lithium ion battery degradation: what you need to know. Physical Chemistry Chemical Physics 23, 8200–8221 (2021). <https://doi.org/10.1039/D1CP00359C> (abstract and bibliographic record consulted through the University of Bristol repository).