

5/12/2024

Coursera

* Algorithms for Battery Management Systems

- Dr. Gregory L. Plett

Batteries must be managed properly by electronics, software to:

- i Protect the application users
- ii Protect the battery pack itself
- iii maximize the performance (power and energy) delivered by the battery.
- iv maximize the service life of the battery pack itself

Algorithms are computer methods (codes) designed to accomplish a specific task.

Therefore, algorithms for BMS will about computer methods implemented in specialized electronics that protect the user and the battery pack, and optimize a tradeoff between performance and service life of the battery.

Course contents

1. Introduction to BMS
2. Equivalent-circuit cell model simulation
3. Battery state-of-charge (SOC) estimation
4. Battery state-of-health (SOH) estimation
5. Balancing and power estimation of battery pack.

* A BMS is an embedded system that comprises purpose-built electronics plus custom-designed software for the battery management task. The primary functions of a BMS are to:

- i protect human safety of device's operator; detect unsafe operating conditions and respond
- ii protect the cells of the battery from damage in abuse/failure cases
- iii prolong life of battery & high-level performance
- iv maintain battery in a state in which it can fulfill its functional design requirements.
- v provide information to the host controller regarding how best to use the battery pack. This including predicting energy & power limits estimates, charge control etc

N.B.: All lithium-ion battery packs require at least a minimal BMS for safety even in a simple application like a flashlight. Li-ion battery cells are extremely effluent. Lead acid or nickel metal hydride can withstand some level of overcharging and remain safe, but Li-ion cannot be safely overcharged, else it will explode.

Even with Li-ion batteries, we don't necessarily require a complicated BMS. It can be done with relatively inexpensive purpose-built electronics that integrated manufacturers have designed for that exact purpose.

"Your battery is "cheap enough" if you can't remember the last time you replaced it"

- Dr. Gregory

Large battery packs represent greater investment, and motivate better battery management.

- Vehicle Application of BMS

1. Hybrid-electric vehicle (HEV): motive power provided by battery plus at least one source (e.g. gasoline engine), essentially zero all-electric vehicle range e.g. Toyota Prius
 2. Plug-in hybrid-electric vehicle (PHEV): Larger battery than HEV allows some all-electric range under certain operating conditions. They operate in electric only mode only at low speed, then switch to gasoline engine at high speeds e.g. Ford C-Max Energi
 3. Extended-Range Electric Vehicle: Larger battery than PHEV allows some all-electric range under full-load condition. They have larger battery pack to store more energy unlike HEV & PHEV e.g. Chevrolet Volt
 4. Electric Vehicle (EV) aka Battery-Electric Vehicle (BEV): Battery provides only motive power. The gasoline engine is removed entirely. They have the largest battery packs because they must rely exclusively on the battery energy for range and for power. e.g. Tesla
- Vehicle Batteries between 250-600V or higher; Higher electrical current often over 1000A under peak load.

- Another large-scale application that justifies advanced battery management is for grid storage and backup.

- Another application is frequency regulation which deals with relatively small amounts of excess generation capacity or excess load and buffers the grid against large power swings over a relatively short time scale of the order of minutes rather than hours or days as the grid is often scheduled.

Week 1 : Battery Boot Camp

* Introducing Important Battery Terminology

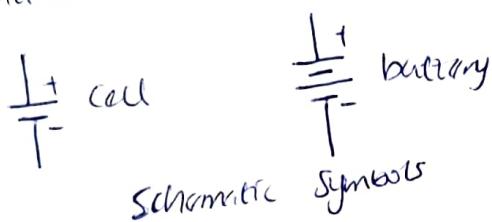
→ Cells: are the smallest individual electrochemical unit, and deliver a voltage that depends on the cell chemistry.

Primary (single use) and Secondary (rechargeable) cells

- Primary (single use) and Secondary (rechargeable) cells
- cell is different from battery, a battery comprises more than one cell, somehow connected together.

2.) Batteries and battery packs are made up from groups of cells. Those cells can be wired together in series or parallel, or in some combination of both.

- Some batteries are packaged in a single physical unit e.g. automotive 12V lead-acid batteries comprise six 2V cells in series.



Schematic Symbols

3. Nominal voltage and capacity

- cell (nominal) voltage depends on the combination of active chemicals used in the cell. Nominal voltage is typical voltage or average voltage of a battery cell (labelled voltage).

→ 1.5V (e.g. $\text{M}\text{i}(\text{Cl})$, $\text{M}\text{i}(\text{OH})$) nickel metal hydride

- for many nickel-based cells, it is 1.2V (e.g. $\text{M}\text{i}(\text{Cl})$, $\text{M}\text{i}(\text{OH})$)

→ for many lithium-based cells, this is over 3V

- nominal voltage is often printed on the cell package

→ nominal voltage is different from cell voltage under load - it is more of an average or typical voltage.

- cell (nominal) capacity specifies the quantity of charge, in ampere hours (Ah) or milliampere hours (mAh), that the cell is rated to hold.

N.B.: If a battery cell has a capacity of 1Ah, then a fully charged cell can deliver 1A per hour of current before fully discharged.

- i) metric unit of charge is "coulombs" but they are very awkward units to work with when analysing circuit and also very small unit of charge.

- ii) the labelled cell nominal voltage and capacity are most likely not the true voltage and capacity. A new battery may exceed the value while the value degrades over time.

- 4. C rate

The C-rate is a relative measure of cell electrical current. 1A is a small current but it is quite different from the impact of 1A of current to a large battery cell.

- the C-rate of a battery cell is the level of constant current charge or discharge that the cell can sustain for one hour of time.
 - A 20Ah cell should be able to deliver 20A ("1C") for 1h or 2A ("C/10") for about 10h (but, the relationship is not strictly linear)
 - If the cell is discharged at a 10C rate, it will be completely discharged in about six (6) minutes.
e.g. the 1C rate of 1.9Ah is 1.9A

5. Energy and Power

A cell stores energy in electrochemical form, which it can later release to do work.

- the total energy storage capacity of a cell is roughly its nominal voltage \times its nominal capacity (mWh, Wh, or kWh)

e.g.: The normal energy storage capacity
 $= 3.7V \times 1.9Ah = 7036mWh$

The energy release rate is the cell's instantaneous power (mW, W, or kW)

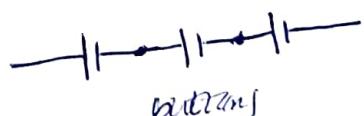
6. Cells connected in series

When cells are connected in series, the battery voltage is the sum of the individual cell voltage. However, battery capacity is equal to individual cell capacity since the same electrical current passes through all of the cells (charging and discharging all cells at the same rate).

e.g.: A battery constructed from three 3V, 20Ah cells in

series will have

- nominal voltage $= 3 \times 3V$
 $= 9V$



- nominal capacity $= 1 \times 20Ah$
 $= 20Ah$

- nominal energy $= 3 \times 3V \times 20Ah$
 $= 180Wh$

7 Cells connected in parallel

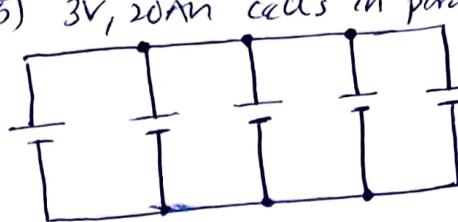
When cells are connected in parallel, the battery voltage is equal to the cell's voltage. However, battery capacity is the sum of the cell's capacities, since the battery current is the sum of all the cell currents.

e.g. A battery constructed from (5) 3V, 20Ah cells in parallel will have:

$$\begin{aligned}- \text{nominal voltage} &= 1 \times 3V \\ &= 3V\end{aligned}$$

$$\begin{aligned}- \text{nominal capacity} &= 5 \times 20\text{Ah} = 100\text{Ah}\end{aligned}$$

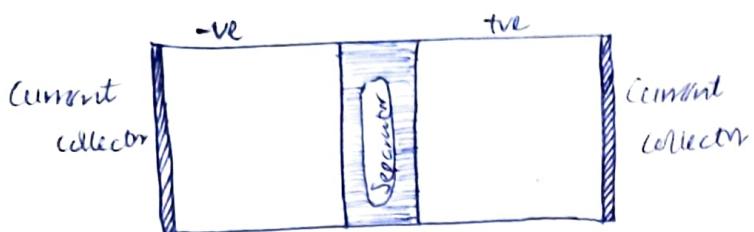
$$\begin{aligned}- \text{nominal energy} &= 5 \times 3V \times 20\text{Ah} = 300\text{Wh}\end{aligned}$$



* Summary

1. A cell is the smallest electrochemical storage unit
2. Primary cells are not rechargeable; secondary cells are rechargeable
3. Cells have nominal (i.e. typical) voltage and charge-storage capacities
4. The C-rate is a way of normalizing electrical current to cell nominal capacity
5. Cells store energy (that can be released to do work); rate of energy release is power.
6. Batteries are made by connecting cells in series and/or parallel
7. We can compute battery nominal voltage, nominal capacity, and nominal energy ratings by knowing how the cells are connected.

* Electrochemical Cell



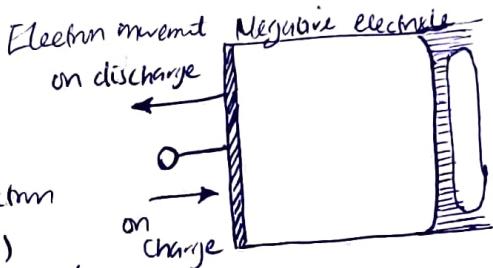
- the drawing shows a schematic cross-section of an electrochemical cell (the structure of a lithium-ion cell is similar, all electrochemical cells have the same components):
 - Negative electrode
 - Positive electrode
 - Electrolyte
 - Separator
 - Current collectors

- Negative Electrode

In an electrochemical cell, the negative electrode is often a metal or an alloy or hydrogen (lead metal or paste for PbA)

Pb Lead And

- during discharge, the negative electrode gives up electrons to external circuit, is oxidized (OIL: "Oxidation is Loss (of electrons)")
- during charge, accepts electrons from external circuit, is reduced (RIG: Reduction is Gain (g electrons))
- during discharge, it is the anode (-ve)
- during charge (the negative electrode is the cathode (+ve) charged)

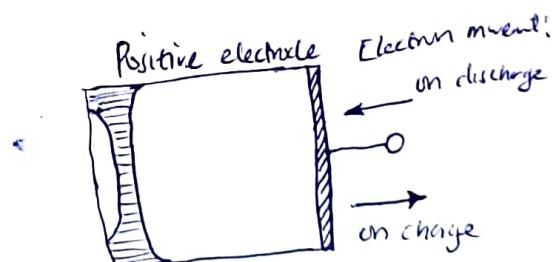


- Positive Electrode

In an electrochemical cell, the positive electrode is often a metallic oxide, sulphide, or oxygen (lead oxide for PbA)

- during discharge, accepts electrons from circuit, is reduced.
- during charge, gives up electrons to external circuit, is oxidized.

- during discharge, it is the cathode
- technically, during charge it is the anode, but most people still call it the cathode.



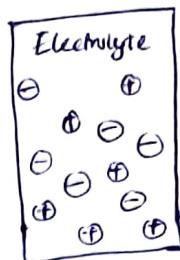
- Electrolyte

- As electrons move in the external circuit, compensation ions must move internal to the cell.
- Cations are ions with net positive charge: during discharge may move through the electrolyte toward the positive electrode.
 - Anions: like ions with net negative charge: during discharge may move through the electrolyte toward the negative electrode
 - The electrolyte provides the medium for internal ion charge transfer between the electrodes (Sulfuric acid for PbA)

The sulfuric acid is diluted by water. In general, the electrolyte has some kind of solvent that contains dissolved chemicals that have balanced positive and negative charges.

When the solvent that's used in the battery cell is water, then it is said that the battery cell has an aqueous electrolyte. In Li-ion, organic solvent are used.

- The electrolyte is typically a solvent containing dissolved chemicals, an acid/base or salt - providing ionic conductivity.
- Another feature of the electrolyte is that while it must be a conductor of ions (ionic conductor), it also must be an electronic insulator to avoid self discharge. We don't want electrons moving from one side of the cell to the other side through the electrolyte



- Separator

The separator electrically isolates the positive and negative electrodes to avoid short circuit and self discharge of the cell. If the negative electrode were to come into contact with a positive electrode, there would be an immediate short circuit where electrons from one electrode would flow into the other electrode and very quickly discharge the battery cell.

The separator provides electrical and mechanical isolation of the two sides of the battery cell. It's often made from some kind of a porous glass mat or a fibrous mat or a polyethylene or a polymer with micro pores. It really only keeps the two electrodes separated from each other but it still has pores or openings inside of it that are large enough to let the electrolyte through, so ions can flow from one side of the cell to the other with very little ionic impedance.

- Current Collectors

If the electrode is made up of some kind of metal, then we can attach the external terminal of the battery cell directly to the electrode. But often, electrodes are made from some kind of a powder and we cannot attach the external terminals of the battery directly to a powder.

So instead, we attach the external terminals of the battery cell to metallic foils that are called current collectors. The electrode powders are somehow adhered to the current collectors to allow the electrons to flow from the electrode to the current collector to the outside circuit.

Often lithium battery cells have negative electrode current collectors that are almost always made from a copper foil, positive electrode current collectors that are made from aluminium.

- Example of Electrochemical Cells

The table below shows components for commonly used electrochemical cells:

Electrochemistry	Negative electrode	Positive electrode	Electrolyte	Standard voltage
Lead acid	Pb	PbO ₂	H ₂ SO ₄	2.1V
Dry cell	Zn	MnO ₂	ZnCl ₂	1.6V
Alkaline	Zn	MnO ₂	KOH	1.5V
Nickel Cadmium	Cd	Ni(OH) ₂	KOH	1.35V
Nickel Zinc	Zn	Ni(OH) ₂	KOH	1.73V
Zinc air	Zn	O ₂ air	KOH	1.65V

We often use alkaline battery cells for high power applications whereas dry cell might be used for low power applications. Usually, dry cells or alkaline cells are not considered rechargeable.

Nickel Cadmium are rechargeable open used as a replacement for dry cells and alkaline cells.

Zinc air battery weight is less (no positive electrode) and can have quite high energy storage for a particular volume or weight and make very interesting rechargeable batteries.

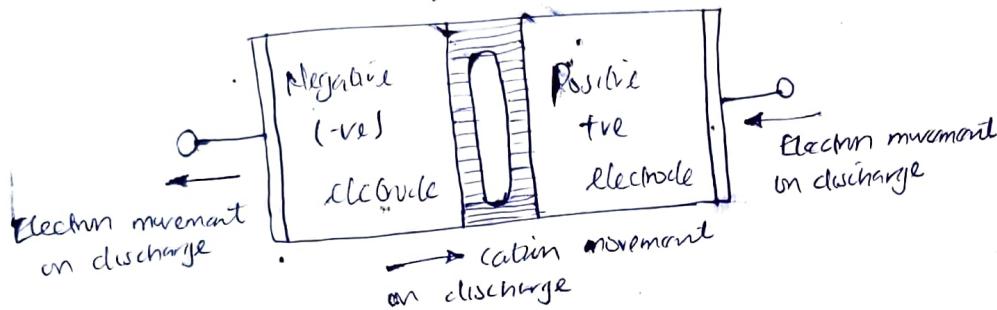
* How does an Electrochemical cell store & release Energy

- Potential Energy

To understand how electrochemical cells store and release energy, we need to understand the idea of potential energy.

Electrochemical potential energy at negative electrode favours a chemical process that releases electrons into external circuit and cations into electrolyte.

Electrochemical potential energy at positive electrode favours a chemical process that accepts cation electrons from external circuit and cations from electrolyte.



- Voltage & Work

Resulting electrical pressure (potential difference) between terminals is cell voltage. There is an electrical pressure built up because of electrochemical potential energy (it wants to be released to do work). This electrical pressure is called electrical potential.

There's a potential energy stored in the cell that causes the electrical potential difference between one electrode and the other, this potential difference can be measured with a voltmeter and it's called the **cell voltage**.

Work is performed when external circuit is completed, converting stored electrical potential energy into electrical energy.

- Rechargeable Cells

In primary cells, this electrochemical reaction is not reversible. During discharge, the chemical compounds are changed permanently and electrical energy is released until the original compounds are completely exhausted. Primary cells can only be used once.

Secondary (rechargeable) cells, this electrochemical reaction is reversible. The original chemical compounds can be reconstructed by the application of an electrical potential between the electrodes, injecting energy into the cell.

- Such cell can be discharged and recharged many times but not infinitely
- Life is limited by degradation processes, not by primary chemical reaction
- Life of sec. cell is determined by how quickly degradation processes occur

Charge Process

During charge, cations move from the positive electrode through electrolyte; electrons move from negative electrode through external circuit. This action happens in response to an externally applied voltage that is greater than the rest voltage at the terminals of a battery cell.

The energy "pumped" into the cell transforms the active chemicals back to their original state.

Manufacturers publish safe operating voltage limits for their cells. However, overcharging or overdischarging can cause irreversible damage, fire, or explosion!

For example: lead acid battery cells can be slowly overcharged with no permanent damage until happen when slowly overcharged is lead ~~water~~ in the electrolyte dissociates into hydrogen and oxygen gases. And if that's done slowly enough, the hydrogen and oxygen gases will recombine back into water.

This process at the top of charge is called a float charge and may lead acid battery chargers are designed to have a float charge to maintain the battery at a top state of charge.

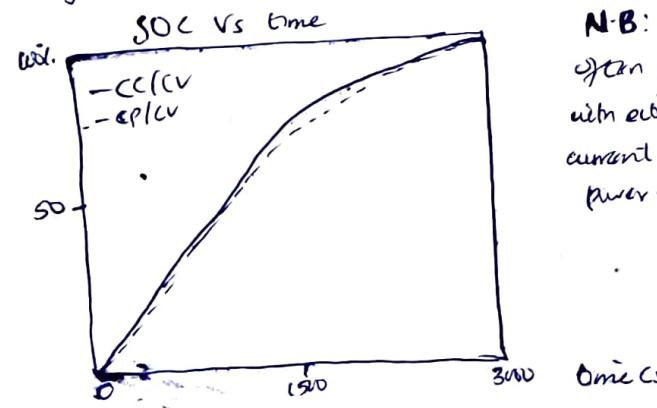
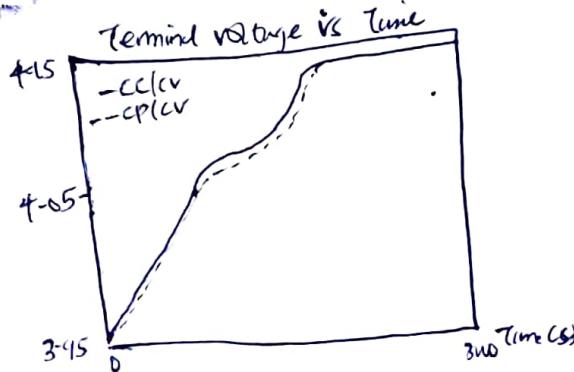
If you overcharge, Li-ion battery cell, it does not result in a chemical process happening that that is reversible. Often the electrolyte will decompose just with the lead acid, but in this case it does not recombine. When, decomposed it cause the battery to "swell-up"

For example: if a PbA battery is not maintained at a high-state of charge, lead sulfate deposits on both electrodes will begin to form hard crystals, which cannot be reconverted by a standard fixed-voltage (13.6V) battery charger.

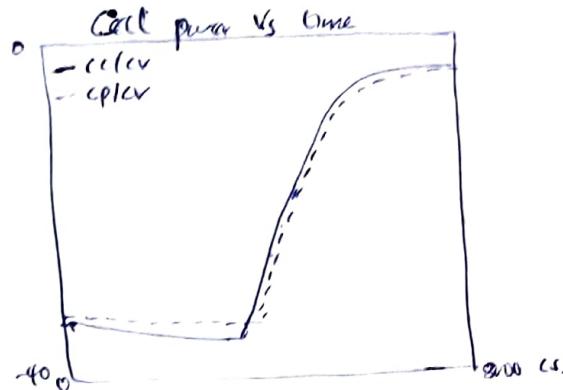
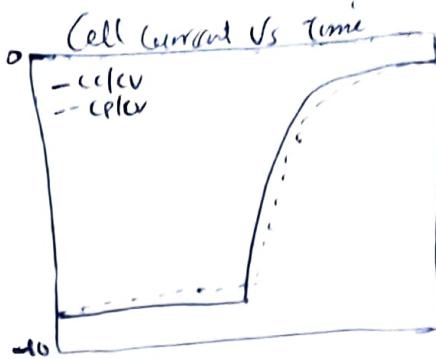
So most lead acid battery cells are used in applications that must maintain a high state of charge. e.g. the automobile lead acid battery really should never be discharged below about 80% state of charge. Otherwise, it will start to age quite rapidly because of the formation of these crystals.

- CC/CV & CP/CW charging mode

→ constant current, constant voltage; constant power constant voltage



N.B: cell are often first charged with either constant current or constant power.



In constant-current, constant-voltage charging, you regulate the charging current at a constant value until the cell's measured terminal voltage reaches some maximum magnitude or specified value. At that point in time, you switch from a constant-current operation mode to a mode where you simply hold the voltage of the cell constant at that maximum value, and you wait until current decays to a very small absolute level.

Constant-power, constant voltage charging is similar, except during the first phase we don't apply a constant electrical current to the cell, but instead, we apply a constant charging power to the cell until a charging ~~voltage~~ voltage limit is reached. ~~After~~ In the second phase, you simply hold that voltage constant until the charging power decrease to a small number in magnitude.

* Designing a Cell's Electrochemistry

Battery cell electrochemistry is designed to optimise a number of factors. We desire high specific energy and/or energy density (energy/volume or energy per mass) → Specific energy: how much energy can be stored per unit volume
→ Energy Density: how much energy can store per unit mass

We also desire high specific power and/or power density
→ Specific power: how much power we can pull out of a battery per unit volume
→ Power density: how much power we can get per unit mass.

We desire low cost, long life, low toxicity, high recyclability etc.
High energy and high power capabilities of battery cells depends on overall minimum cell voltage and current, and ultimately all these factors depend directly on the specific materials used in the electrodes and electrolyte

- Electrode potential
The propensity of one material to gain or lose electrons in relation to another material is known as its electrode potential

- Compounds with negative electrode potential are used for negative electrodes, and those with positive electrode potential for positive electrodes.
- The larger the difference between the electrode potentials of the two electrodes, the greater the voltage of the cell and greater the amount of energy that can be produced by the cell.
- Can electrode potential be tuned arbitrarily? No! We have to work with the materials supplied to us by nature, and these are the elements in the periodic table.
- On the periodic table, strong reducing elements grouped on left, strong oxidizing elements grouped on right. So, one might consider building a battery cell that has a negative electrode using an element from the left of the table and some positive electrode using an element from the right side of the table.
- Emerging battery technology: Lithium-air could have greatest energy and power density of any known combination of elements. A lithium-air battery uses a negative electrode that's built from solid lithium metal. The positive electrode in the lithium-air battery is oxygen that's harvested or scavenged from air.
- In general, however, lithium air are not. Whenever we build an electrochemical cell, we desire to use elements from the far left and the far right of the table whenever possible, because it will end up with less weight, less mass.

- Periodic Table

- The number at the top left of each box in the table is atomic number of the element (number of protons in atom's nucleus)
- The atomic weight of an atom is equal to the weight of all of its protons plus the weight of its neutrons plus the weight of all of its electrons.
 - ↳ It is also equal to the grams per mole of the element
 - on chemistry, a mole of a material is equal 6.02×10^{23} units of that material
 - 1 mole of proton = one gram in mass
- The rows of the table are called periods. All elements in any period have the same number of electron shells
 - Period number equals number of electron shells
- The columns of the table are called groups. All elements in any group (generally) have the same number of valence electrons in their outer valence shell (but, transition metals are a little strange.)

Groups	
	Periods
1	1 H 1.00714
2	2 Li 6.941 Be 9.01
3	3 Na 22.989 Mg 24.302

→ Atomic symbol
→ Atomic weight

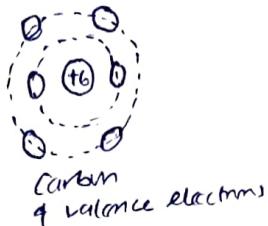
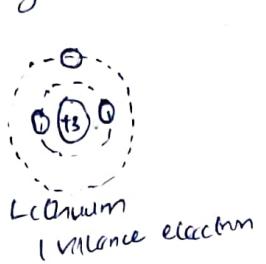
→ Avogadro's number

→ Outermost shell

- Valence Electrons

Elements within each individual group (column) have same number of valence electrons (except transition metals). Since number of valence electrons determines how the element reacts with others, those within a particular group tend to have similar chemical properties.

- When the outer electron shell is full, as in the noble gases; there are no "free" electrons available to take part in chemical reactions.
- Hence the noble gases are chemically non-reactive or inert.



Co
2 valence electron

- The most reactive elements are at the left and right of table
 - Alkaline metals, group 1, have only one valence electron.
 - Halogens, group 7, have just one valence electron.
- Atoms having one or two valence electrons more than a closed shell are highly reactive because the extra electrons are easily removed to form positive ions.
 - Reducing agents in left columns have surplus of valence-shell electrons, which may donate in a redox reaction, becoming oxidized.
 - Oxidizing agents in right columns have a deficit of valence-shell electrons and accept electrons in a redox reaction, becoming reduced.

- Electrochemical Series

The energy level of an atom is determined by the configuration of electrons into shells. An atom's energy level can be changed by moving an electron from one shell to another shell or by gaining or losing electrons from its valence shell.

A battery stores electrochemical potential energy by changing this configuration of electrons in the electron shell and its electrode materials. So when charging a battery cell, the electrons move to higher energy configurations in both electrodes, and when discharging, the electrons move to lower energy configuration in both the electrodes.

- The difference in electrical potential energy before and after a reaction can be measured as a voltage difference.

- The electrochemical series is a list of table of metal elements or ions arranged according to their electrode half-reaction potentials.
- Lithium at the top of the list has the most negative number, indicating that it is strongest reducing agent.

Strengths of oxidizing and reducing agents	
Reduction half-reaction	Potential E° (V)
$\text{Li}_{(\text{aq})} + \text{e}^- \rightarrow \text{Li}_{(\text{s})}$	-3.04
$\text{Mg}_{(\text{aq})} + \text{e}^- \rightarrow \text{Mg}_{(\text{s})}$	-2.71
$\text{Zn}^{2+}_{(\text{aq})} + 2\text{e}^- \rightarrow \text{Zn}_{(\text{s})}$	-0.76
$2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$	0.00
$\text{Cu}^{2+}_{(\text{aq})} + 2\text{e}^- \rightarrow \text{Cu}_{(\text{s})}$	0.34
$\text{Fe}^{2+}_{(\text{aq})} + 2\text{e}^- \rightarrow 2\text{F}^-$	2.87

- Fluorine is the strongest oxidizing agent, having the largest positive value for standard potential.
 - So if we were to construct a battery cell where the negative electrode or anode was fluorine, we would be combining the half reaction from the top row for the negative electrode and the half reaction from the bottom row for the positive electrode.
- Cell voltage = $2.87V - (-3.04) = 5.91V$
- N.B. We have never seen a battery cell that reaches a nominal voltage even close to 6V. ~~The reason is not because we don't know how to make electrodes for such a cell, instead the reason is that we don't know how to make an electrolyte for that cell.~~ There is presently no electrolyte which will withstand this kind of a voltage without decomposing.

- Summary
 - For high specific energy and power, we choose light elements (near the top of the periodic table)
 - For high voltage, we want strong oxidizing and reducing agents paired together, having an excess and a deficiency of valence electrons (near left and right sides of the periodic table)
 - Other considerations include:
 - i) availability of an electrolyte to support the half-cell reactions
 - ii) low cost
 - iii) long life
 - iv) low toxicity
 - v) high recyclability.

* Examples of Electrochemical Battery Cells

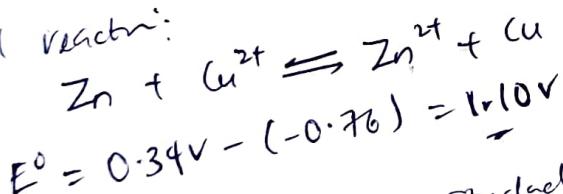
- Daniel Cell

It is probably the easiest and simplest to understand. Commonly found in basic electrochemistry textbooks.

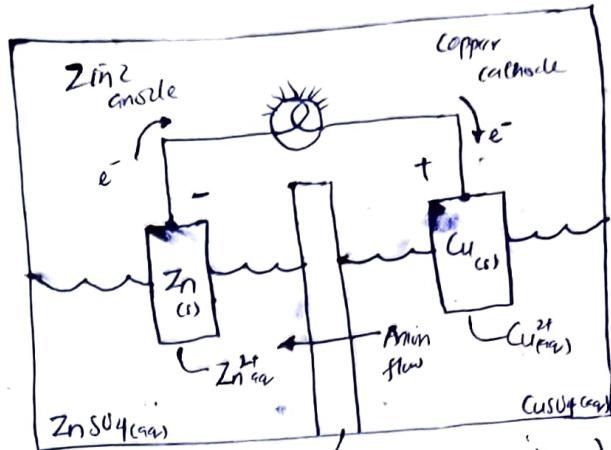
- Each "half cell" consists of a solid metal electrode submerged in an electrolyte solution
- In the negative electrode, the electrolyte is ZnSO_4 , which dissociates into Zn^{2+} plus SO_4^{2-} when dissolved in water
- In the positive electrode, the electrolyte is CuSO_4 , which dissociates into Cu^{2+} plus SO_4^{2-} when dissolved in water.

- On discharge, the zinc electrode dissolves, releasing Zn^{2+} into the electrolyte. The positive electrode consumes Cu^{2+} (copper is plated onto the copper electrode)
- This produces a temporary deficiency of SO_4^{2-} in the negative-electrode region and a surplus in the positive-electrode region. The opposite process happens on charge.
- At the negative electrode, we have the redox reaction $\text{Zn}^{2+} + 2e^- \rightleftharpoons \text{Zn}$, having standard potential $E^\circ = -0.76\text{V}$
- At the positive electrode, we have the redox reaction $\text{Cu}^{2+} + 2e^- \rightleftharpoons \text{Cu}$, having standard potential $E^\circ = 0.34\text{V}$

• Overall reaction:



N.B.: Standard potentials assume standard conditions, including specific electrolyte concentrations, temperature, and so on. So, in practice, actual voltage claimed by the cell will vary somewhat from the standard potential that we have listed here in practice.



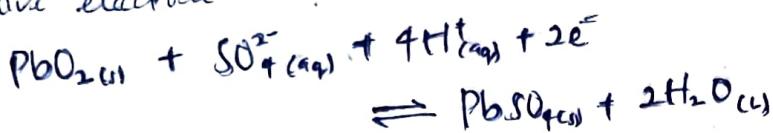
Porous disk (salt bridge)

- Lead-acid electrochemical cells

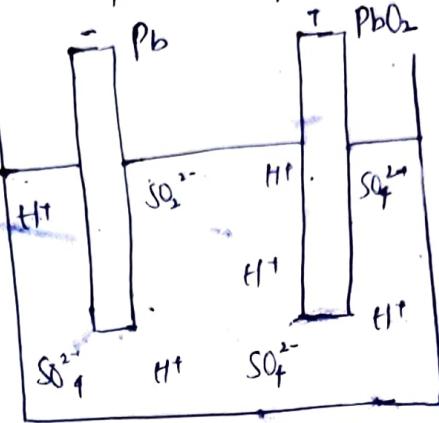
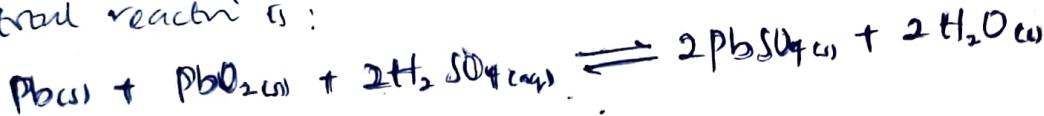
A lead-acid cell comprises two steel-based plates and an aqueous sulfuric acid (H_2SO_4) electrolyte

- In the fully discharged state, both electrodes are $Pb(s)$ and the electrolyte is a dilute H_2SO_4

- When discharging, the negative electrode reaction is
 $Pb(s) + SO_4^{2-} \rightleftharpoons PbSO_4(s) + 2e^-$, and the positive electrode reaction is



- The total reaction is:



- Opposite occurs when charging; when fully recharged, the negative electrode is Pb , the positive electrode is PbO_2 , electrolyte is more concentrated solution of H_2SO_4
- The standard potential of the negative-electrode reaction is $E^\circ = -0.356V$ and the standard potential of the reaction at the positive electrode is $E^\circ = 1.685V$
- Therefore, the full cell has standard potential

$$E^\circ = 1.685V - (-0.356V) \\ = 2.041V$$

The voltage varies with concentration of the sulfuric acid (state of charge) and with temperature.

N.B: The vehicle "12v" lead-acid batteries comprise six (6) individual lead-acid cells normally internally wired in series.

- Need to protect against overcharge:

- If we overcharge a lead-acid battery, the water in the electrolyte will decompose into hydrogen and oxygen gases.

- Under some circumstances, other compounds on the electrodes can be electrolysed as well to create poisonous gases. These gases can cause bulging and explosion of sealed lead-acid batteries

- Need to protect against overdischarge:

- If lead acid is discharged too far, the lead sulfate crystals will form and these cannot again be decomposed, causing capacity loss.

- Limit the depth of discharge of lead-acid battery, trickle charge when charged but not in use to prevent leakage damaging the battery.

The bubble charging in a lead-acid cell allows cells that are already fully charged to remain in that state while the remaining cells and the battery continue to charge until all cells are fully charged.

- Lead-acid battery construction

Lead acid battery chemistry was invented more than 150 yrs ago, so the technology is mature. Lead acid batteries aren't often built with strict lead plates. Instead, the electrodes are usually constructed from a lead-alloy grid (for strength) covered with a sponge-like lead paste - which is the actual electrode material.

Some types of lead-acid battery cells are called flooded cells. In flooded cells, the separator is a simple spacer and the electrolyte is liquid sulfuric acid.

Another type of lead-acid cell is called an "absorbent glass mat" (AGM) cells, the separator is a glass mat saturated with a minimal amount of electrolyte.

These AGM cells, because they use a very small amount of electrolyte, do not create large volumes of gases when they're overcharged. However, this cell can have a sealed construction instead of a vented construction and it makes the cell maintenance-free which can be a huge advantage in a lot of applications.

Sometimes silica is added to the electrolyte to turn the liquid electrolyte into more of a gel. And this also allows for a sealed construction and it allows for less control over the concentration of the sulphuric acid at different parts in the cell.

When silica is added, the resulting lead acid battery is often called a gel cell; also allows for sealed construction and less stratification of the SO_4^{2-} concentration (yields longer life but lower power)

- Nickel Metal Hydride (NiMH) cells

More recently new cell chemistries have been developed using alternative chemical reactions to the traditional redox scheme

- Nickel hydride cells depend on ability of some metallic alloys ("hydrides") to absorb large amounts of hydrogen (like a sponge), which can reversibly react in a battery.

- metal hydride cells use ~~metal~~ alloys for negative electrode; and they use a nickel hydride as a positive electrode. No standard chemical reaction takes place that could deform the electrode, instead, hydrogen simply goes into the electrode and comes out of the electrode. Hence, reason why metal hydride cells often have much longer lives in a standard electric chemical battery cell.

- Inside a metal hydride battery cell, the electrolyte has some kind of a hydrogen absorbent aqueous solution, such as potassium hydroxide, and it really takes no part in the chemical reaction at all but serves as a way to transport the hydrogen ions, the protons, between the electrodes.

- The "magic" of the NiMH batteries come is how the negative electrode works, which is a rare-earth hydrogen-absorbing metal alloy and there can be different structures used.
 - o Either of the " AB_5 " form where "A" can be lanthanum, cerium, neodymium, praseodymium and "B" can be nickel, cobalt, manganese, or aluminum.
 - o Or of the " AB_2 " form where "A" can be titanium or vanadium and "B" can be zirconium or nickel, doped with chromium, cobalt, iron, or manganese.
- The key point is that hydrogen is absorbed into metal alloy without changing its chemical formulation or structure physically.
- The mechanism by which hydrogen gets adsorbed onto the electrode is called **Intercalation** and the mechanism by which it is removed from the electrode is called **deintercalation**, is very gentle when compared with standard redox reactions, leading to very long life of NiMH cells.
- Negative electrode reaction $M + H^+ + e^- \rightleftharpoons MH$ where "M" is the metal hydride and where the half-cell standard potential is generally around $-0.8V$ (depending on the metal) and where the half-cell standard potential is generally around $-0.8V$ (depending on the metal)
- Positive electrode (which is nickel hydroxide ($Ni(OH)_2$) in H_2/MH) reaction is $Ni(OH)_2 + OH^- \rightleftharpoons Ni(OH)_3 + H_2O + e^-$, having a standard potential of $E^\circ = 0.5V$
- Thus, the overall reaction is $Ni(OH)_2 + M \rightleftharpoons Ni(OH)_3 + MH$, having a standard potential $E^\circ = 0.5V - (-0.8)V = 1.3V$
- When charging a nickel-metal hydroxide battery cell, be careful to guard against over-voltage. If a nickel-metal hydroxide cell is overcharged, then oxygen gas evolves. When the positive electrode is no longer able to provide nickel hydroxide to react with one hydroxide in the electrolyte.
- If a nickel-metal hydroxide cell is charged very slowly, then oxygen gas can diffuse from one electrode to the other and combine safely with hydrogen to form water. It is actually possible to slightly overcharge a nickel-metal hydroxide batteries cell a little bit if it's done very slowly.
- We must also guard against over-discharging when hydrogen gas is evolved.

* Summary

- We have seen example of Daniel, lead-acid, and NiMH acid
- Despite many overall similarities, there were significant distinctions
 - o The Daniel cell uses two (2) different electrolytes
 - o Lead-acid uses sponge lead paste spread on a lead alloy grid to increase power
 - o NiMH uses hydrogen-absorbing metal hydride for one electrode, extending life