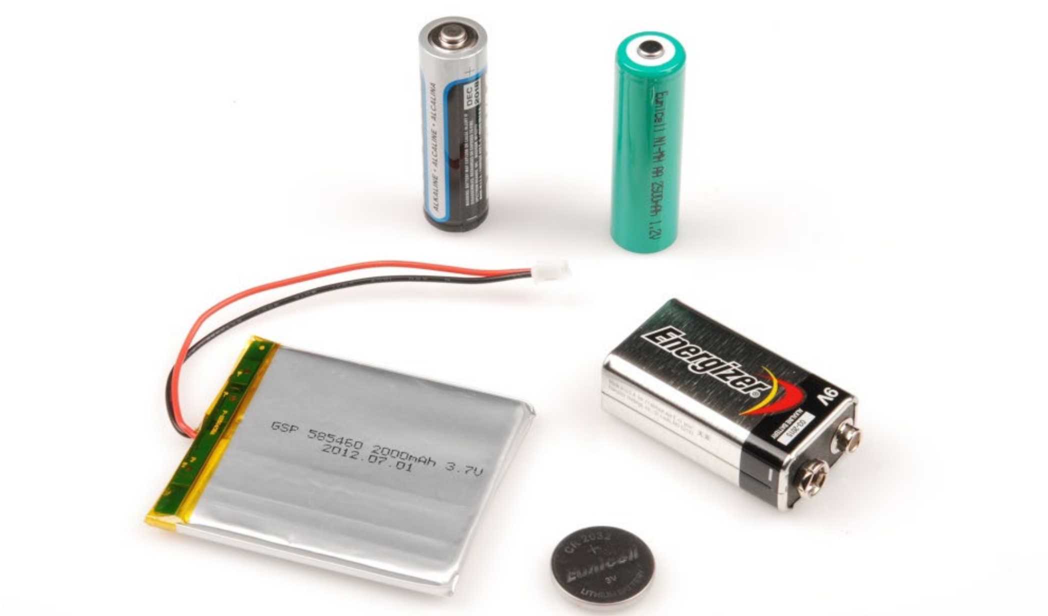
CLASS 18: BATTERIES

ENGR 102 – Introduction to Engineering

Batteries

- ***Batteries*** – electrochemical energy-storage devices
  - Electrical input and output
  - Chemical energy storage
- Allow us to ***use energy when and where we want***



Batteries - Uses

- **Portable electronics**
  - Phones, laptops, watches, etc.
- **Power tools**
- **Vehicles**
  - EVs, HEVs, ICE vehicles
- **Off-grid power**
  - Homes, remote sensing, communications
- **Grid energy storage**
  - Integration of renewable generation
  - Power backup, UPS

Batteries - Specifications

- ***Capacity***
  - Total energy or charge stored in a battery
- ***Specific energy***
  - Energy stored per unit mass
- ***Energy density***
  - Energy stored per unit volume
- ***Specific power***
  - Maximum available power per unit mass
- ***Power density***
  - Maximum available power per unit volume

Capacity

- ***Capacity***
  - Total energy or charge stored in a battery
- Typically expressed one of two ways:
  - Ampere-hours (Ah)
  - Watt-hours (Wh)

Capacity – Ampere-Hours

- **Ampere-hours** (Ah)
  - Product of current and corresponding discharge time

- For example, a 40 Ah battery could supply the equivalent of 40 A for 1 hour

$$40\ Ah = 40\ A \cdot 1\ h = 40\frac{\mathrm{C}}{\mathrm{s}} \cdot 1\ h \cdot \frac{3600\ s}{1\ h} = 144 \times 10^3\ C$$

  - Or, 1 A for 40 hours (or any other equivalent combination)

$$40\ Ah = 1\ A \cdot 40\ h = 1\frac{\mathrm{C}}{\mathrm{s}} \cdot 40\ h \cdot \frac{3600\ s}{1\ h} = 144 \times 10^3\ C$$

- Clearly, this is a quantity of ***charge***, ***not energy***

Capacity – Watt-Hours

- **Watt-hours** (Wh)
  - Product of power and corresponding discharge time
- For example, a 9.88 Wh battery could supply the equivalent of 9.88 W for 1 hour

$$9.88\,Wh = 9.88\,W \cdot 1\,h = 9.88\frac{\text{J}}{\text{s}} \cdot 1\,h \cdot \frac{3600\,s}{1\,h} = 35.6 \times 10^3\,J$$

  - Or, 1 W for 9.88 hours (or …)

$$9.88\,Wh = 1\,W \cdot 9.88h = 1\frac{\text{J}}{\text{s}} \cdot 9.88\,h \cdot \frac{3600\,s}{1\,h} = 35.6 \times 10^3\,J$$

- This is a ***is*** a measure of ***energy***

Capacity – Ah vs. Wh

- To relate capacity in Ah to that in Wh, we must know the battery's voltage
  - Assume nominal and constant voltage

- For example, consider a **3000 mAh**, **3.85 V** battery
  - If discharging at 300 mA, for example, the power supplied is

$$P = V \cdot I = 3.85\,V \cdot 300\,mA = 1.155\,W$$

  - At this rate, the battery can discharge for 10 h, so the total stored energy is

$$E = P \cdot t = 1.155\,W \cdot 10\,h = \mathbf{11.55\,Wh}$$

  - Capacity in Wh given by the product of capacity in Ah and voltage

$$E = (\text{capacity in Ah}) \cdot (\text{battery voltage})$$

Primary vs. Secondary Batteries

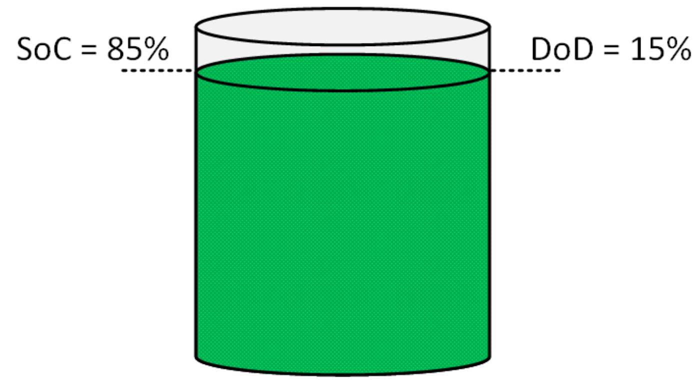
- ***Primary batteries***
  - Disposable, single-use
  - Non-rechargeable
  - E.g., alkaline

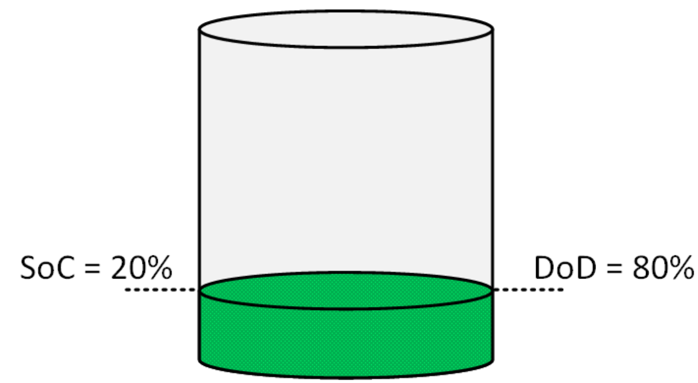
- ***Secondary batteries***
  - Rechargeable
  - E.g., lead-acid, Li-ion

State of Charge vs. Depth of Discharge

- ***State of charge*** (SoC)
  - Energy stored in a battery as a percentage of its capacity
  - 100% SoC = full
  - 0% SoC = empty
- ***Depth of discharge*** (DoD)
  - Energy removed from a fully-charged battery as a percentage of its capacity
  - 0% DoD = full
  - 100% DoD = empty
- SoC and DoD are ***complementary***

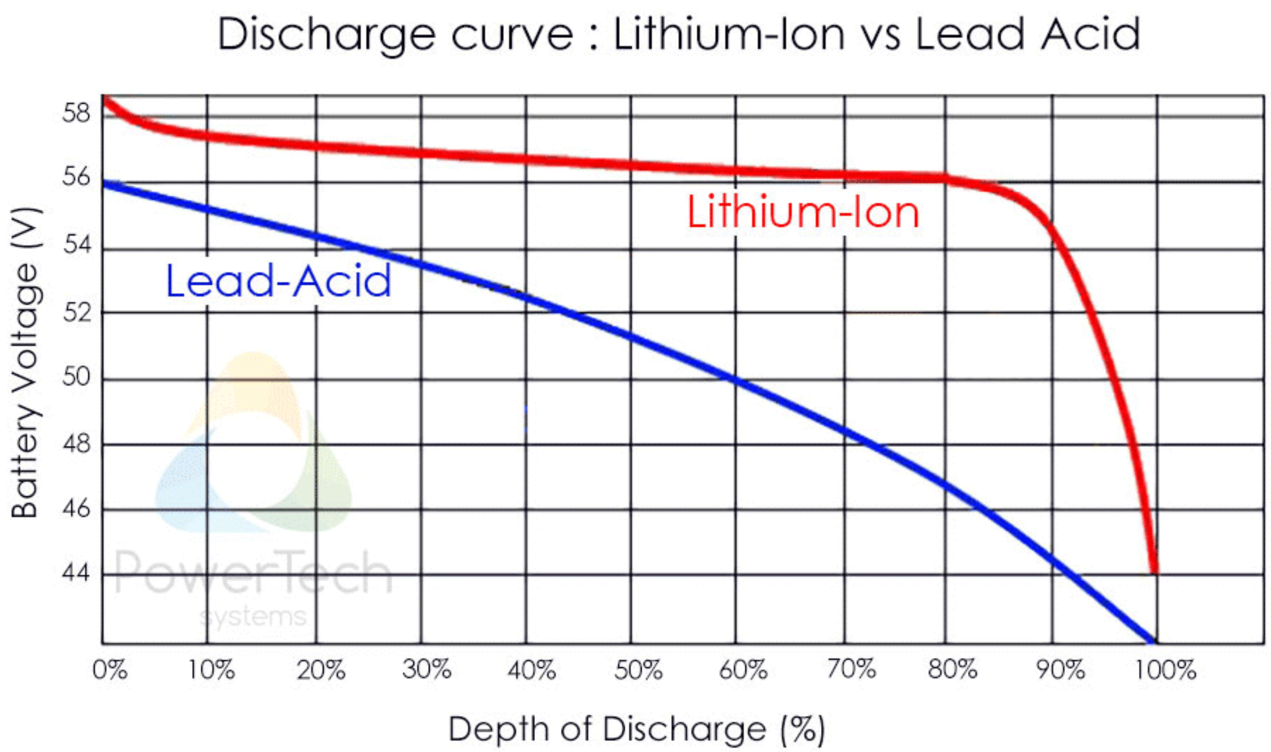
$$SoC + DoD = 100\%$$





State of Charge

- SoC can often be approximated from open-circuit voltage
  - Easier for some chemistries (e.g., lead-acid) than for others (e.g., Li-ion)



Battery Comparison

Specification	Units	Alkaline	Lead Acid	NiCd	NiMH	Li-Ion
Specific energy	[Wh/kg]	110-160	30-50	45-80	60-120	100-260
Energy density	[Wh/l]	250-430	60-75	50-150	140-300	250-670
Cell voltage	[V]	1.5	2	1.2	1.2	3.6-3.85
Self discharge	[%/mo]	<0.3	5	20	20	1.5-2
Lifetime	[# cycles]	N/A	200-300	1000	300-500	300-1000

Sources:
- https://www.epectec.com/batteries/cell-comparison.html
- https://www.cei.washington.edu/education/science-of-solar/battery-technology/
- https://en.wikipedia.org/
- https://www.eetimes.com/

Exercise – Battery Capacity & Power

Exercise

- Cell phone battery:
  - 3110 mAh
  - 3.8 V
  - Charged overnight to 100% SoC
  - 16 hours later, SoC = 18%
- What was the ***average power consumption*** of the phone during the 16 hours it was in use?

Exercise – Battery Capacity

Exercise

- A refrigerator is to be used to transport medicines to remote areas
  - 100 W, 50% duty cycle
  - Battery-powered – lead-acid
  - Solar panel charges the batteries
  - Needs to be able to go three days without any solar input
  - Max. DoD: 80%
- What is the required battery capacity in Wh?