# MEEN 432 –Automotive Engineering

Fall 2026

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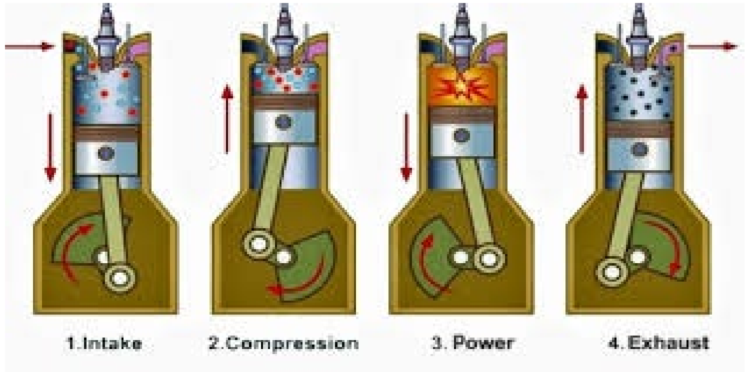
Acknowledgement: Most of the material for this class was developed by Dr. Swami Gopalswamy

# Lecture 10: Power Plant and Energy Storage

- Engine
- Electric Motor
- Battery

# (Internal Combustion) Engine

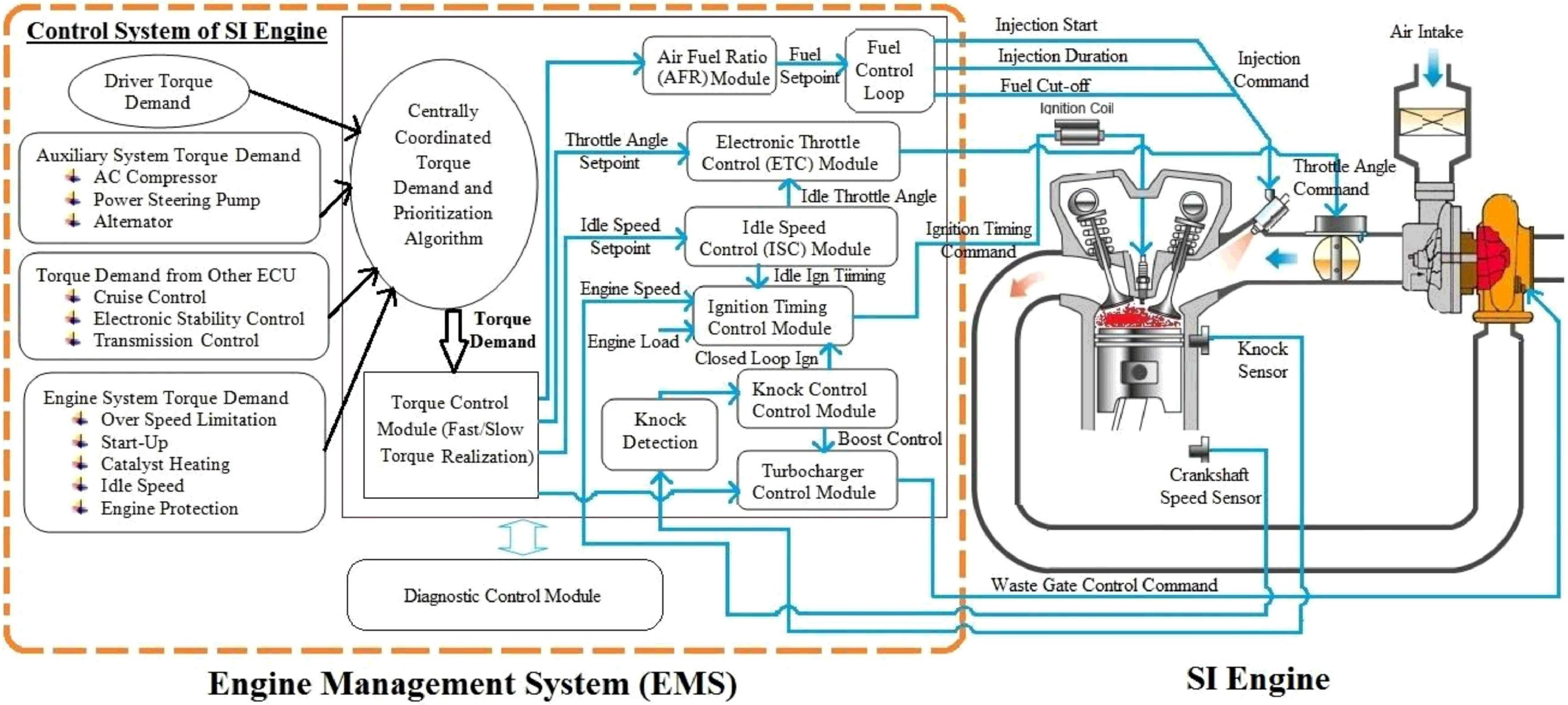
- An Engine is a Complex System of its own!
- It explodes fuel in a precisely controlled fashion, and harnesses the power generated to drive your vehicle!
- Key Elements:
  - Suck in fuel
  - Compress it
  - Explode and Push
  - Exhaust out burnt fuel and start over!
- These can be performed in 4 strokes or 2 strokes
  - Per cylinder
- Typical engines have multiple cylinders
  - Increased and Smoothened power delivery




[Four Stroke Engine Animation]

[Two Stroke Engine Animation]

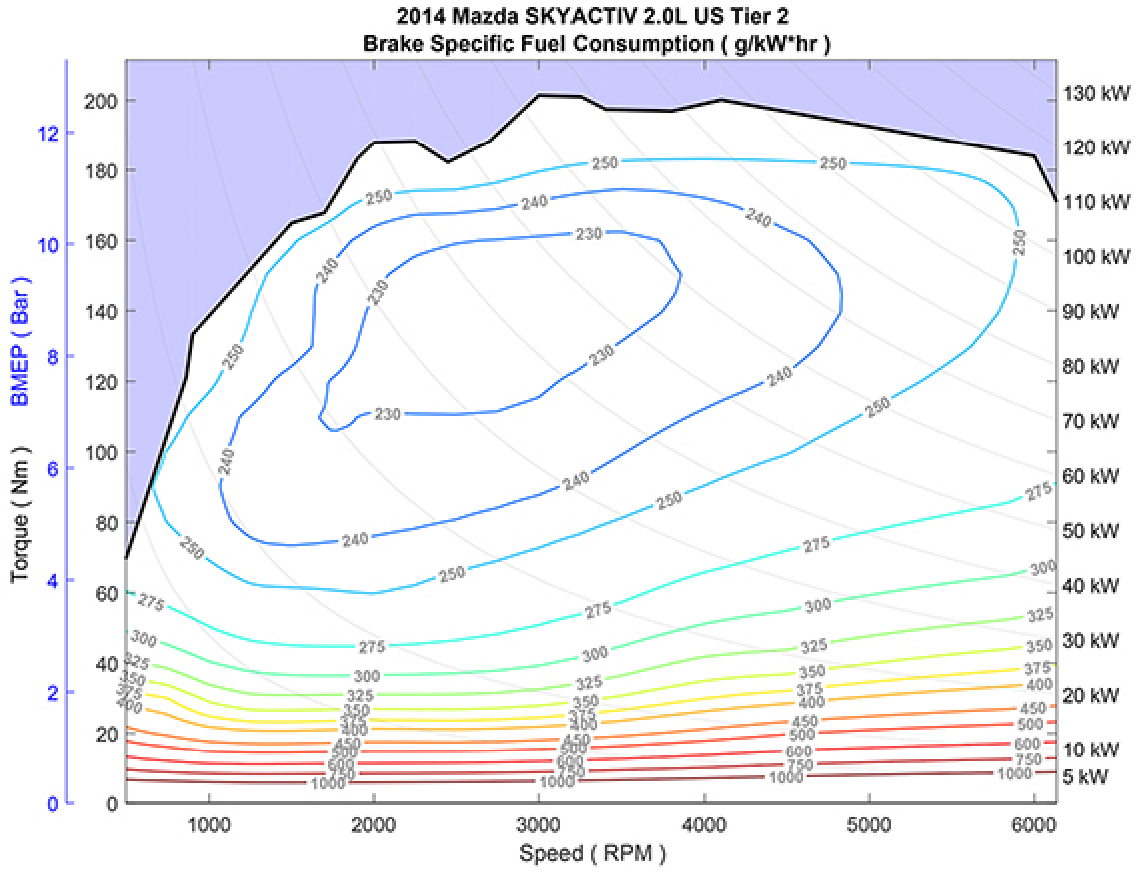
# Engine Control




B. Ashok, S. Denis Ashok, C. Ramesh Kumar, "*A review on control system architecture of a SI engine management system*", Annual Reviews in Control, Volume 41, 2016, Pages 94-118, ISSN 1367-5788, https://doi.org/10.1016/j.arcontrol.2016.04.005.

# Engine Modeling

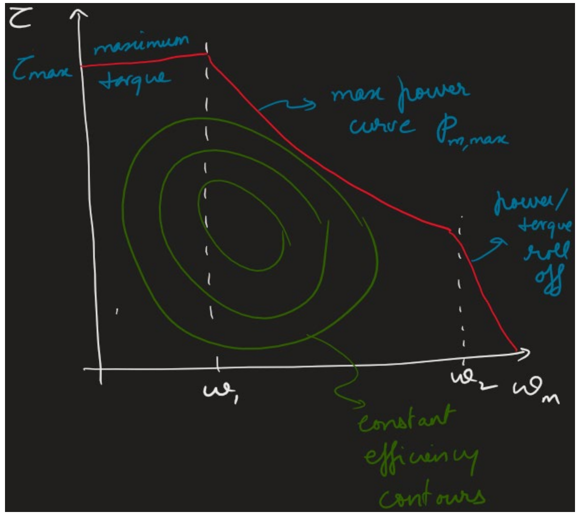
- Stead State Models
  - $\tau_{e,max} = \bar{f}(\omega_e)\,;\ \tau_{e,min} = \underline{f}\,(\omega_e);$
    - Note that $\tau_{e,min}$ could be negative (engine braking) at closed throttle
  - $\tau_e = \tau_{e,min} + \alpha(\tau_{e,max} - \tau_{e,min})$
  - $\dot{m}_{fuel} = f(\omega_e, \tau_e); P_e = k\,\dot{m}_{fuel}$
    - Alternatively: $\eta_e = f(\omega_e, \tau_e); P_e = \frac{\tau_e \omega_e}{\eta_e}$ (with corrections for idling and engine braking conditions)
- $\alpha \in [0,1]; \omega_e \in [\omega_{idle}, \omega_{max}]$
- $\alpha$ is a % torque command.
- Sometimes manifold dynamics are approximated with a simple first order lag:
  - $\alpha = \frac{b}{b+s}\alpha_{cmd}$
- This is a simplistic model, but sufficiently powerful to capture performance and energy consumption on typical missions

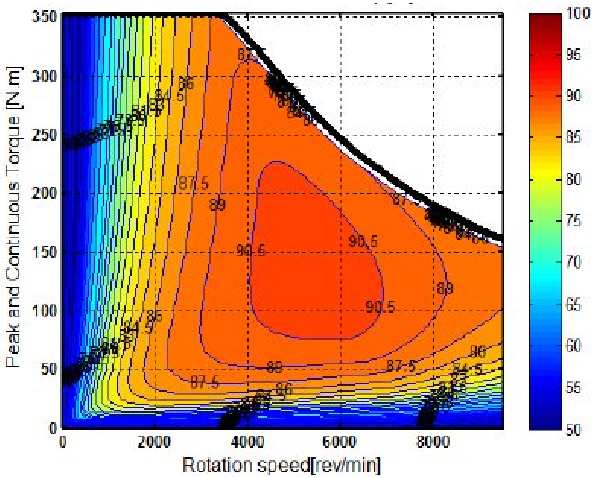



https://www.epa.gov/vehicle-and-fuel-emissions (Web view)

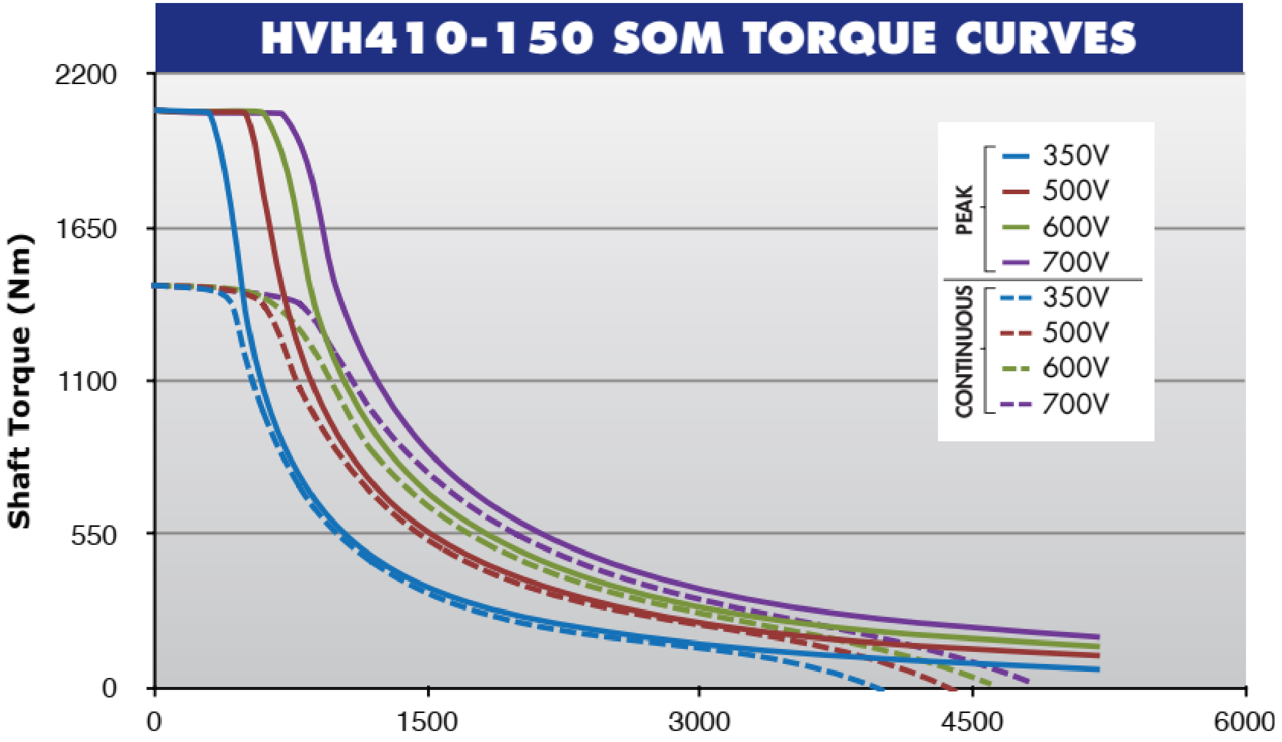
# Electric Motor Torque Generation

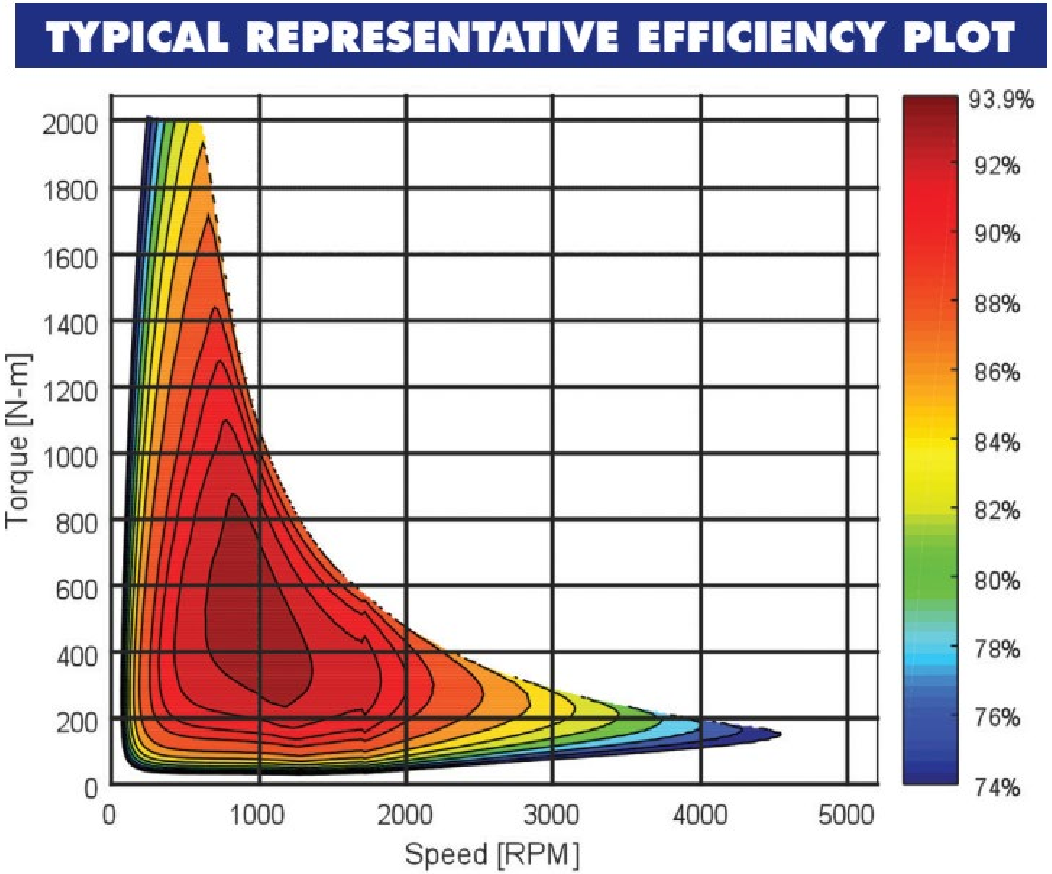
- Similar to the ICE, we use a steady state modeling approach:
  - $\tau_{m.max} = \bar{f}(\omega_m, V, T)$
    - $V$ voltage available for motor, $T$ motor temperature
  - $\tau_m = \alpha \tau_{m,max}$; $\alpha \in [-1, 1]$; $\omega_m \in [-\bar{\omega}_m, \bar{\omega}_m]$
    - $\alpha < 0 \Rightarrow$ regeneration
  - $\eta_m = f(\omega_m, \tau_m)$
  - $P_e = P_m \eta_m^{-\operatorname{sgn} P_m}$; $P_m = \tau_m \omega_m$
- Key differences:
  - Negative speeds are possible
  - Stall torque possible
  - Regeneration possible (positive speed, negative torque)



# Example Data




*Source: Borg Warner HVH410-150 Manuals*

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# Electric Motor Model

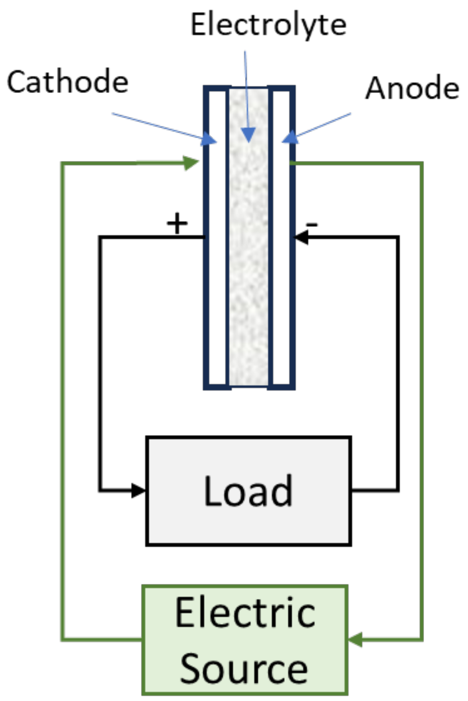
- There are fundamentally two parts to the electric motor:
- Electric Part:
  - Electric Power $p_{e,m} = i_m V_m$ where $i_m$ is the effective current draw on the motor, and $V_m$ is the effective bus voltage seen by the motor
  - This model abstracts away the underlying dynamics of electrical circuitry
    - Based on the rationale that such dynamics are faster than the dynamics associated with the mechanical inertias
    - All losses in the electrical circuit can be combined with the losses on the mechanical side and captured through the efficiency numbers
  - The model also does not distinguish between AC and DC power
    - A detailed model would consider them separately
  - The Voltage is the output of a power inverter that transforms a battery voltage to the needed amounts at the motor
    - For the class you will assume that the motor bus voltage is the same as the battery voltage

# Electric Motor Model

- Mechanical Part:
  - $\tau_m = \alpha\, f(\omega_m, V_m)$ as already seen
    - This is often implemented through table lookups using specification data (from motor suppliers)
  - $I_m \dot{\omega}_m = \tau_m - \tau_l$ where
    - $I_m$ is the motor inertia, $\tau_l$ is the load torque (coming from the transmission)
  - As before, considering the motor to be rigidly connected to downstream shafts, we can simply provide the pair $(\tau_m, I_m)$ to downstream components when modeling
- Combine the mechanical parts and electrical parts:
  - $p_{e,m} = \tau_m \omega_m\, \eta^{\operatorname{sgn} \tau_m \omega_m}$

# Electric Energy Storage

- The electric power source for the electric motor could be from many devices:
  - Battery (this will be our focus at the moment)
  - Ultracapacitors
  - Fuel Cells
- An electric battery stores energy in electro-chemical form. In the most abstract representation (figure on right):
  - The battery receives energy from an electric power source connected at its cathode and anode. This energy is stored in the electrolyte.
  - Later, when a load needs the energy, it is delivered, restoring the electrolyte status.
- There are many types of battery, mostly characterized by their underlying electro-chemistry
  - Most common is the Lead Acid Battery – quite heavy, easy to make, robust and inexpensive. So they are very popular in automotive applications
  - Lithium Ion (and its variants: Lithium Polymer, …) – lighter, solid electrolyte allowing for interesting packaging and design. Expensive and difficult to manufacture. Temperature sensitive. Popular for EV powertrain applications




Voltage across a cell $V_{cell}$ is determined directly by the electro-chemistry of the electrolyte and electrodes, and the "state" of the cell

- Multiple cells are connected together (in series and parallel) to form Battery Packs

# Open Circuit Voltage

- This is the voltage across the terminals of the battery when there is **no** current flowing. This reflects the underlying electrochemical state of the battery, and is directly related to the SOC
  - $OCV = V_{OC} = f(SOC, temp, \dots)$
  - As usual, the complex function, that depends on the battery design, and many other factors, above will be identified empirically as data coming form the manufacturer

| | | |
|---|---|---|
| $R_i$ | Series resistance | 0.1695 Ω |
| $R_{diff}$ | Diffusion resistance | 0.0249 Ω |
| $C_{diff}$ | Diffusion capacitance | 7000 F |

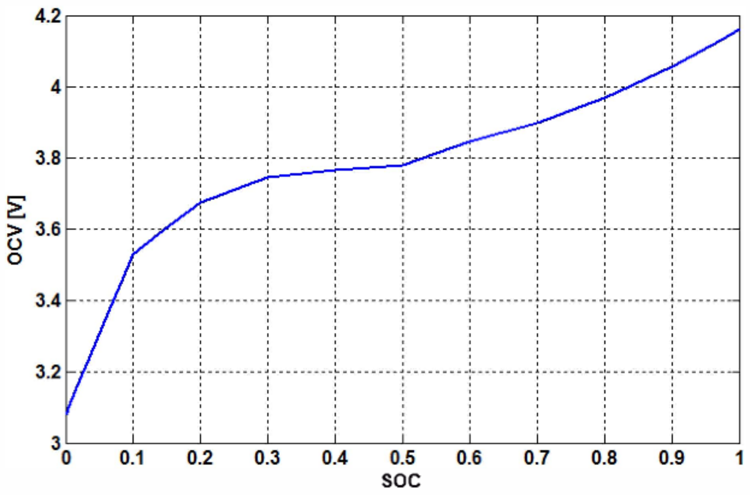
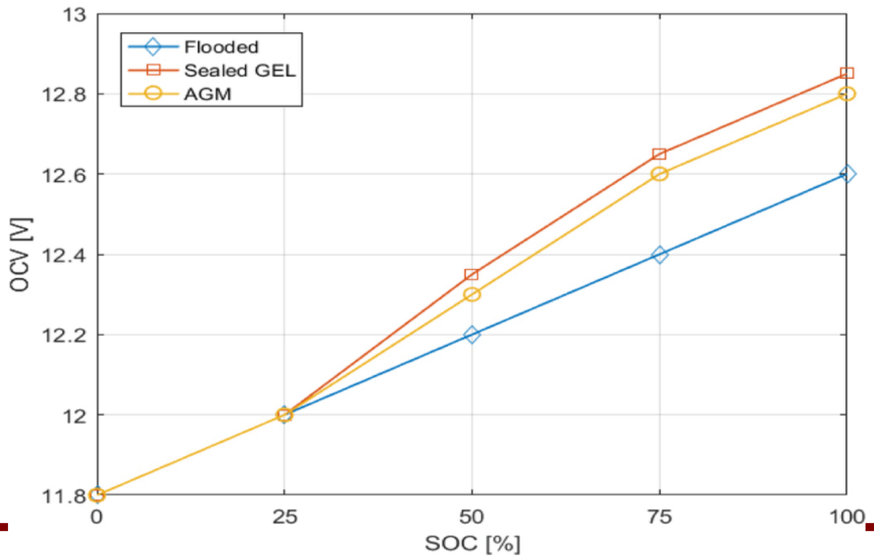



Fig. 2. OCV-SOC curve of a typical 18650 Li-ion battery.

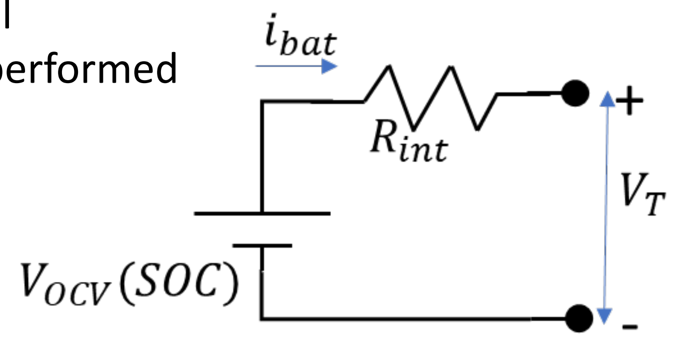


# Battery Capacity and State of Charge

- "Capacity" of a battery (pack):
  - The amount of electric charge it can hold, in Amp.hr
  - $C_{bat} = f$(battery design parameters, past and intended usage patterns (current drawn, charge current, duty cycles), temperatures, …)
    - This is indeed a complex function, and is outside the scope of this class.
    - However test protocols have been developed to get nominal estimates of $C_{bat}$ and will be provided by the battery pack manufacturer
- "Used Capacity":
  - $C_{used} = \int_0^t i_{bat} dt$ where $i_{bat}$ is the current drawn from the battery
- "State of Charge":
  - $SOC = \frac{C_{remaining}}{C_{bat}} = \frac{C_{bat} - C_{used}}{C_{bat}} = 1 - \frac{1}{C_{bat}} \int_0^t i_{bat} dt$
  - The $SOC$ is defined as a percentage or fraction.
  - This is a very important quantity to be estimated – like the fuel gauge!
- An alternate definition is also popular: "State of Energy"

# Basic Battery Circuit

- Terminal Voltage $V_T$: This is the actual voltage across the terminals of the battery when you start drawing current, or pump-in current (for charging)
- Effective Internal Resistance $R_{int}$: The movement of the ions and electrons through the electrolyte (and the other parts of the battery) contribute to an effective internal resistance
- While there is more complex dynamics for the current flow (because of some inductive and capacitive elements inside the battery circuit) we will use a simple equivalent model for the battery – but defined at the "cell" level:
  - $V_T = V_{OC} - i_{bat} R_{int}$
  - Note that when battery cells are put together in a battery pack, either in a series or parallel arrangement, the appropriate integration of the individual battery equations needs to be performed
- For our models, we will use this convention:
  - Discharging: $i > 0$
  - Charging: $i < 0$



# Single Cell

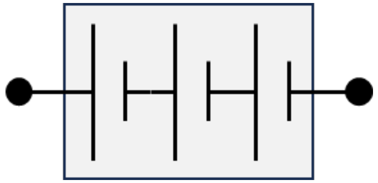
- Thus, a single cell is characterized by its
  - Cell Voltage – which is based on the Open Circuit Voltage, which is based on the chemistry of the cell (electrodes and electrolyte)
  - Cell Current Capacity – this is dependent on the “size” of the cell
    - This includes the chemistry and volume of the electrolytes, but also the physical design of the cell
  - Cell Internal Resistance – this refers to the difficulty of the electrons/ions to flow internally through the electrolyte

# Recall: Series and Parallel Electrical Connections

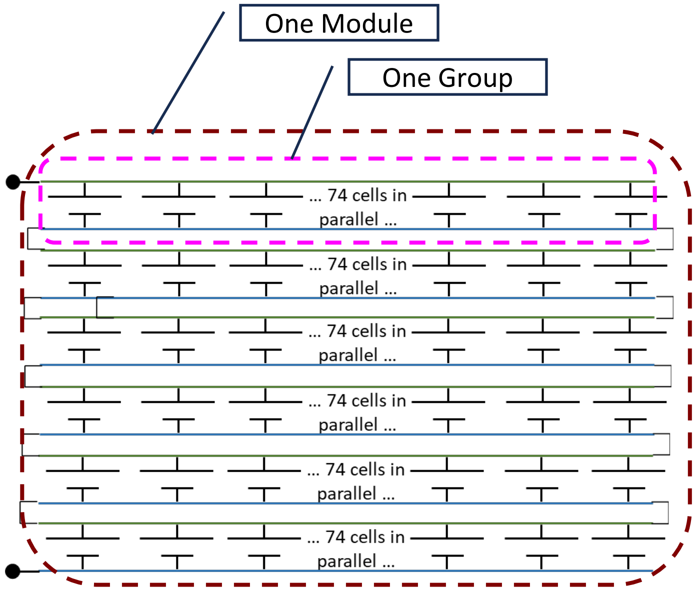
- When multiple devices are connected in series:
  - Current through the devices remains the same: $i_1 = i_2 = \ \dots = i_n$
  - Voltage across devices adds up:
    - $V_{overall} = V_1 + V_2 + \ \dots + V_n$
  - Here $i_k$ and $V_k$ are the current through and voltage across device $k$
- When multiple devices are connected in parallel:
  - Voltage across the devices the remain the same: $V_1 = V_2 = \ \dots = V_n$
  - The device current is distributed between the individual devices:
    - $i_{overall} = i_1 + i_2 + \ \dots + i_n$
- Battery Cells are packaged together into "Battery Modules" and "Battery Packs" through Series and Parallel Connections
  - The overall Battery voltage and current capacity can be designed this way

# Battery Packs

- Lead Acid Battery
  - $V_{cell,nom} = 2.05V$
  - Automotive Battery (Packs) contain 6 cells connected in *series* for nominal voltage $V_{bat,nom} = 6 \times 2.05\ V\ = 12.3\ V$



- Lithium Ion Battery
  - $V_{cell,nom} = 3.2V$
  - Tesla (as an example) Automotive Battery Pack:
    - 74 cells per group in parallel
    - 6 groups in series per module
    - 16 modules in series
  - Battery Pack voltage: $V_{bat,nom} = 3.2V \times 6 \times 16 = 307.2V$

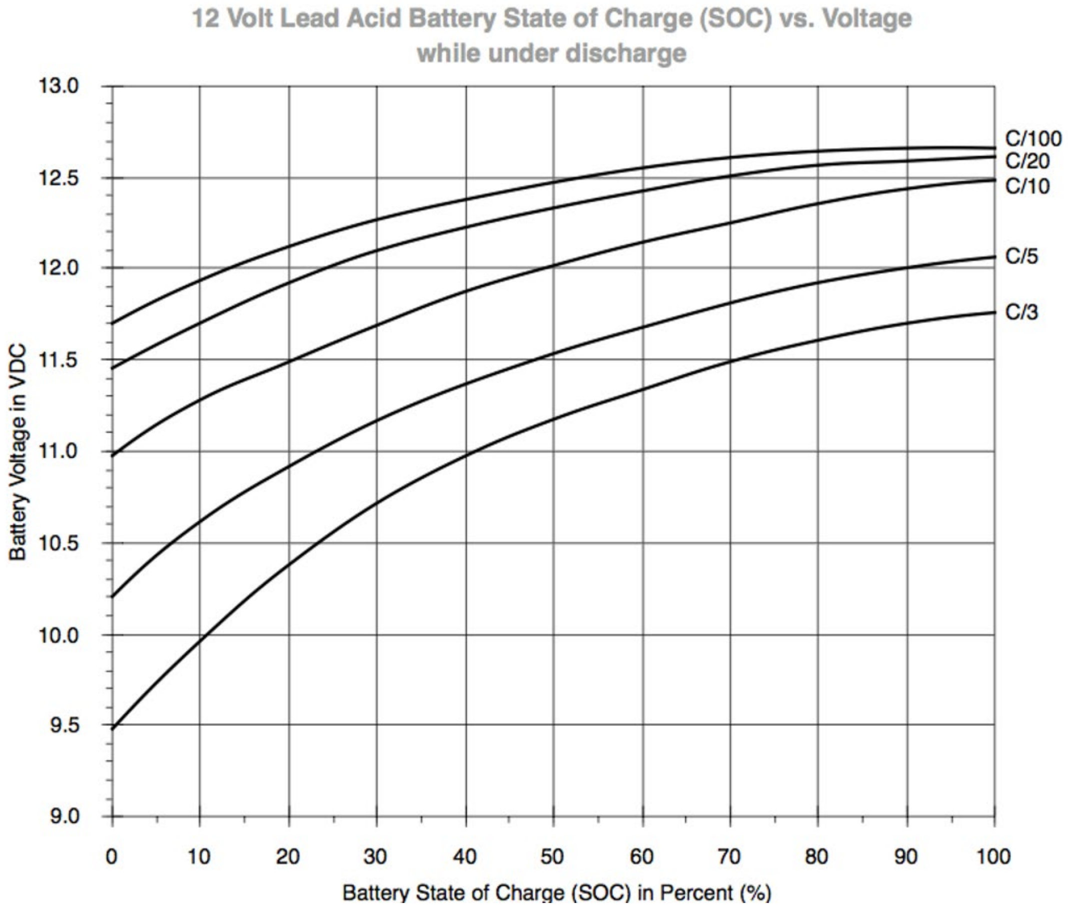


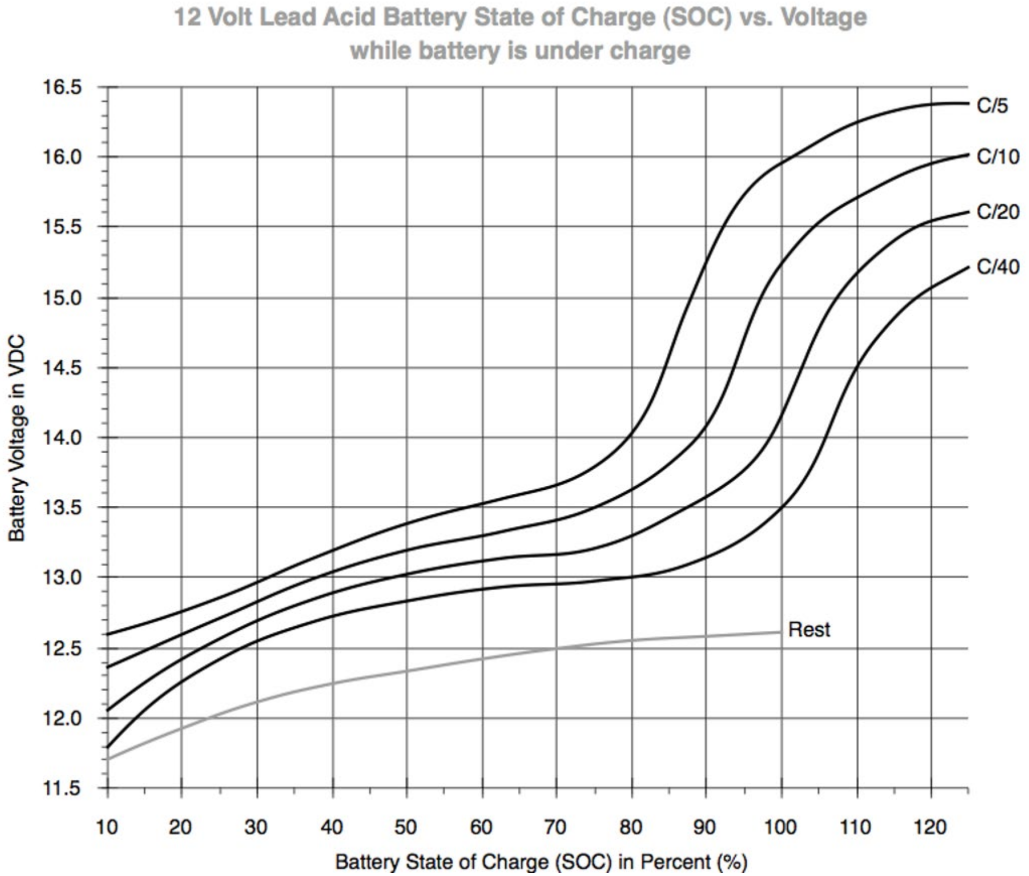
# Current Units for Batteries

- Unit of current: A (Amps)
- Unit of (charge) capacity: Amp-hr
- To normalize across different sizes of the battery, the following current unit is often used: $C_{nn}$
  - This corresponds to the current that will **discharge a full charged battery completely** in $nn$ hours
- This unit is used in defining performance of a battery

# Battery Management – Charging Discharging

- Discharging a battery when its SOC is low has higher potential for voltage drop-off below minimum useful
- Charing a battery when its SOC is high can be catastrophic!



# Battery Management – Charging Discharging

- Overcharging becomes a big challenge when multiple cells are connected together in parallel or series – but are all not equal in capacity
- Consider two cells in parallel:
  - For the same current, the charge accumulation $\int i\,dt$ is the same in both the cells.
  - Now if we assumed $C_{bat1} < C_{bat2}$ then $SOC_1 > SOC_2$. While the SOC is not measurable directly, its impact is seen in the terminal voltage: $V_{T1} > V_{T2}$
  - If we limit charging based on voltage, this implies Cell 2 can never be charged fully!
- Charging of the cells so as to ensure that the SOCs remain reasonable and balanced, and the life of the batter is improved, is done with a dedicated controller called the Battery Management System (BMS)
  - We will not discuss BMS within the scope of this class