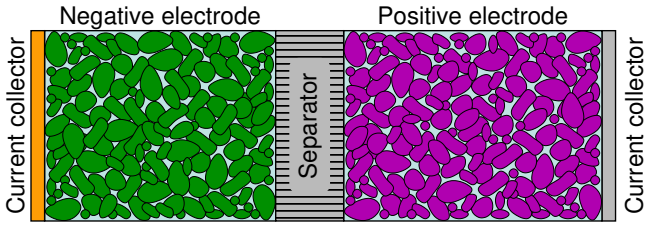
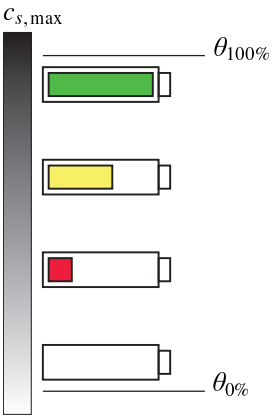
What really is state-of-charge (SOC)?

- BMS must estimate SOC as input to algorithms that compute available energy and available power
- But, what really is a good physical/electrochemical understanding of SOC?
  - Dis/charging cell moves lithium between negative and positive electrodes



  - Cell SOC related to average Li concentration in the negative-electrode particles

What is physical basis for cell SOC?



- Maximum theoretical concentration of lithium in electrode particle is $c_{s,\max}$
- Average concentration of Li in particle at time k is $c_{s,\text{avg},k}$
  - Then, present lithium stoichiometry is $\theta_k = c_{s,\text{avg},k}/c_{s,\max}$
  - This is a kind of electrode SOC, different from cell SOC
- Stoichiometry must remain between $\theta_{0\%} > 0$ and $\theta_{100\%} < 1$
- Then, cell SOC is (note: $\theta^{\text{neg}}_{0\%} < \theta^{\text{neg}}_{100\%}$, but $\theta^{\text{pos}}_{0\%} > \theta^{\text{pos}}_{100\%}$)

$$\begin{aligned} z_k &= (\theta^{\text{neg}}_k - \theta^{\text{neg}}_{0\%})/(\theta^{\text{neg}}_{100\%} - \theta^{\text{neg}}_{0\%}) \\ &= (\theta^{\text{pos}}_k - \theta^{\text{pos}}_{0\%})/(\theta^{\text{pos}}_{100\%} - \theta^{\text{pos}}_{0\%}) \end{aligned}$$

How does SOC relate to cell voltage?

- Cell voltage depends on Li *surface* concentration in particles that contact positive and negative current collectors
- SOC depends on *average* concentrations over entire electrode: not the same
- Further, average concentrations not affected by
  - Changing temperature, which changes voltage: doesn't change SOC
  - Resting a cell, which changes voltage: doesn't change SOC
  - Entire current profile vs. net current, which changes voltage but not SOC
- In summary, SOC changes only due to passage of current, either charging or discharging the cell due to external circuitry, or due to self-discharge within the cell
  - Voltage useful as indirect indicator of SOC, but not as measurement of SOC

How does SOC relate to cell current?

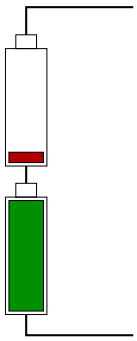
- SOC is related to cell current via

$$z(t) = z(0) - \frac{1}{Q}\int_0^t \eta i(\tau)\,\mathrm{d}\tau$$

  - Cell current is positive on discharge, negative on charge
  - η is cell coulombic efficiency ≈ 1 but ≤ 1
  - Q is the cell total capacity in ampere seconds (coulombs)
- Note, Q measures number of vacancies in the electrode crystal structure between $\theta_{0\%}$ and $\theta_{100\%}$ that could hold lithium: It is not a function of temperature, rate, etc.
- Estimating SOC via this integral equation is called "coulomb counting"
  - We'll see in course 3 that coulomb counting has some serious limitations

What about "pack state-of-charge"?

- Final point: What is "pack SOC?"
- Consider example
  - Should "pack SOC" be 0 % because we cannot discharge?
  - Should "pack SOC" be 100 % because we cannot charge?
  - Should "pack SOC" be the average of the two, 50 %?
- The term "pack SOC" is ill-defined, and should never be used
- One issue this points out is the need for cell balancing (course 5)
- Why might we even want to know "pack SOC"?
  - Setpoint control: Average SOC of all cells might work for this
  - Fuel gauge: Real issue is battery-pack available energy



Summary

- SOC has a real physical basis that can be connected directly to cell electrochemistry
- If we know average Li concentration in either electrode, then

$$\begin{aligned} z_k &= (\theta_k^{\mathrm{neg}} - \theta_{0\%}^{\mathrm{neg}})/(\theta_{100\%}^{\mathrm{neg}} - \theta_{0\%}^{\mathrm{neg}}) \\ &= (\theta_k^{\mathrm{pos}} - \theta_{0\%}^{\mathrm{pos}})/(\theta_{100\%}^{\mathrm{pos}} - \theta_{0\%}^{\mathrm{pos}}) \end{aligned}$$

- Generally, we don't: so can direct measurements of voltage or current tell us SOC?
  - Not by themselves. We must somehow combine (cf. course 3)
- Finally, "pack SOC" doesn't make sense and should not be used
  - "Pack-average SOC" is a more careful wording if that is what is meant