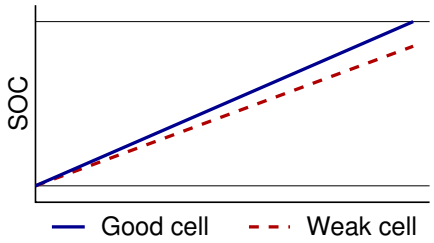
## Causes of imbalance: charge

- Imbalance is caused by anything that can make one cell's SOC diverge from another's

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

- One example is when cells have different Coulombic efficiency
- Cells may start with same $z(0)$, have same capacity $Q$, receive same net current $i_{\text{net}}(t)$



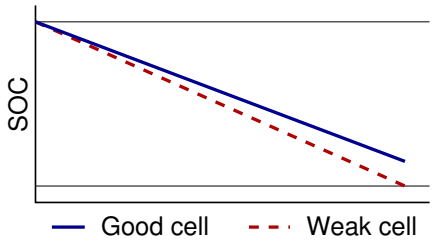

- But, because of different efficiency $\eta$, cell SOCs diverge during charging





## Causes of imbalance: discharge

- Imbalance also caused by cells having differing net current $i_{\text{net}}(t) = i_{\text{app}}(t) + i_{\text{self-disch}}(t) + i_{\text{leak}}(t)$, where $i_{\text{app}}(t)$ is load current, $i_{\text{self-disch}}(t)$ is rate of cell self-discharge, and $i_{\text{leak}}(t)$ is current that powers attached BMS electronic circuitry
- Self-discharge rates of different cells can be different, leading to different $i_{\text{net}}(t)$
- Leakage current can be different for different cells, also leading to different $i_{\text{net}}(t)$
- The bottom line is: when cells draw different net current, they become imbalanced





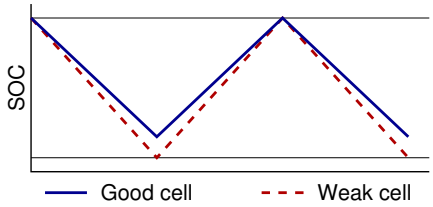



## Causes of imbalance: temperature

- Recall that self-discharge rates, electronics' performance, and coulombic efficiency are functions of temperature
- Therefore, a pack temperature gradient can make rate of growing imbalance worse
- Note that in all cases, it is *difference* in efficiency/ self-discharge/ leakage (etc.) that matters, not the absolute quantity thereof
  - If all cells are equally "bad", there will be no increase in imbalance
- Passive balancing raises temperature, can make imbalance worse

## Not causes of imbalance: capacity

- Different cell capacities cause temporary imbalance that is corrected automatically when any cell returns to original SOC
- For example: Remove 5 Ah from both a 6 Ah cell and a 5 Ah cell; then, replace the 5 Ah
  - SOCs end where they began
- But, different cell total capacities does limit available pack energy:
  - Some energy remaining in high-capacity cells not available when low-capacity cells are fully discharged
  - Fast active balancing can help








## Not causes of imbalance: resistance

- Similarly, different cell resistances cause cell voltages under load to be quite different, but not their SOCs
- A cell with high resistance will tend to hit an upper/ lower voltage limit before other cells, so will limit available pack power

$$v_k = \text{OCV}(z_k) + Mh_k + M_0 s_k - \sum R_j i_{R_j,k} - R_0 i_{\text{app},k}$$

- Fast active balancing can (intentionally) bring pack to an out-of-balance condition to equalize the power that can be sourced/sunk from cells in the pack





## Summary

- Imbalance caused by anything that tends to make SOC of one cell differ from SOC of others
  - Different coulombic efficiencies
  - Different self-discharge rates
  - Different leakage currents
- Amplified by temperature differences
- Long-term imbalance *not* caused by cells having different total capacities or series resistances
  - But, fast active "balancing" circuitry can still be used to eke more energy and power out of a pack having a distribution of total capacities and series resistances