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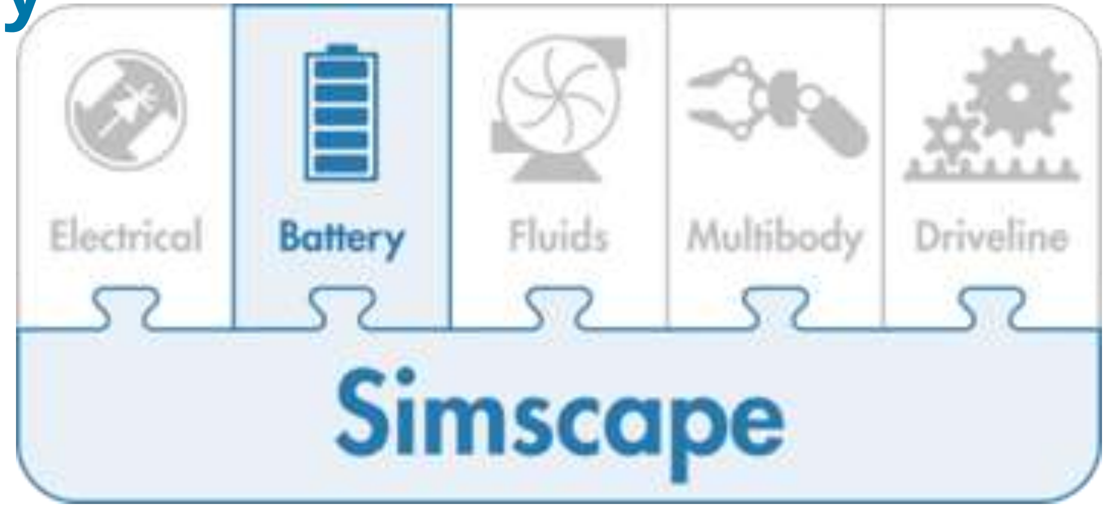
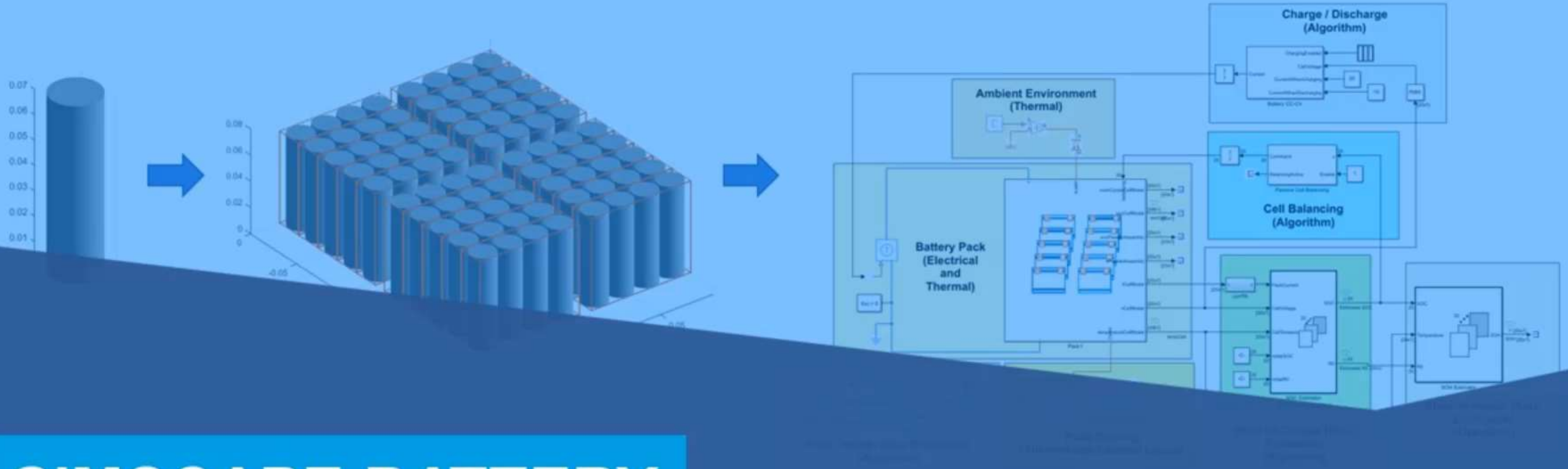
Introducing Simscape Battery



강효석 부장/Ph.D
Application Engineer
MathWorks Korea

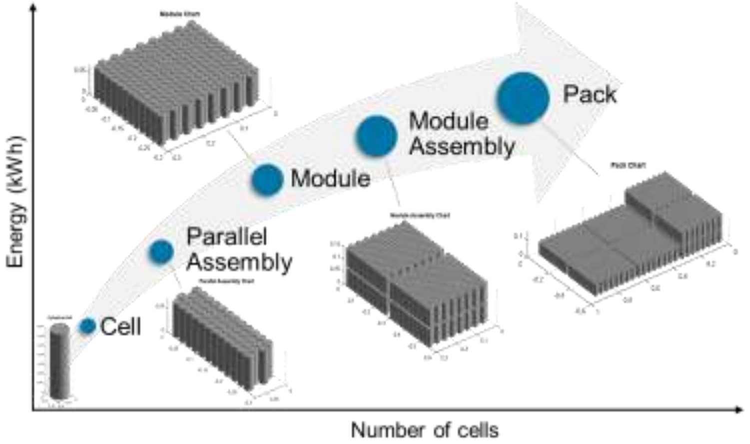


SIMSCAPE BATTERY

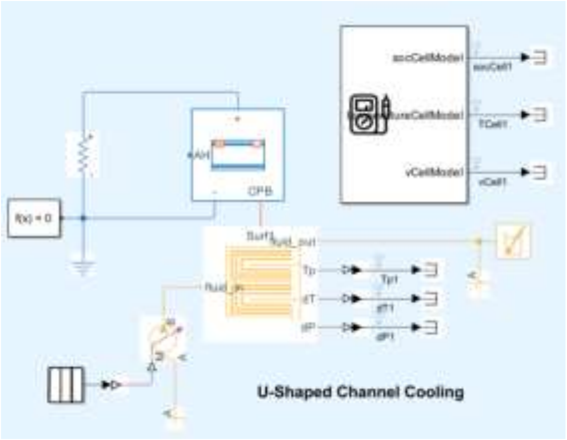
A THREE MINUTE TOUR FROM CELL TO SYSTEM

Simscape Battery – Main Workflow Themes

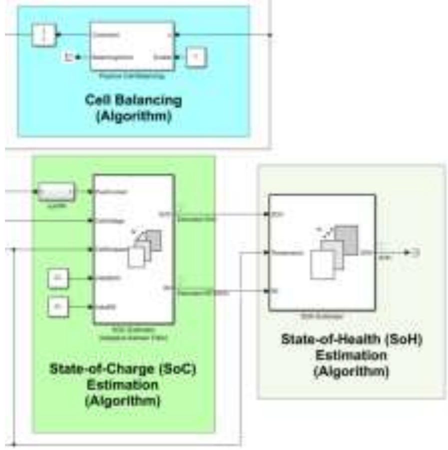
1. Battery Pack Design



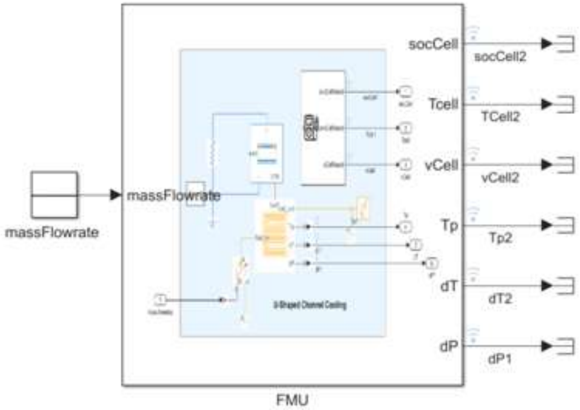
2. Thermal Management System Design



3. Battery Management System Design

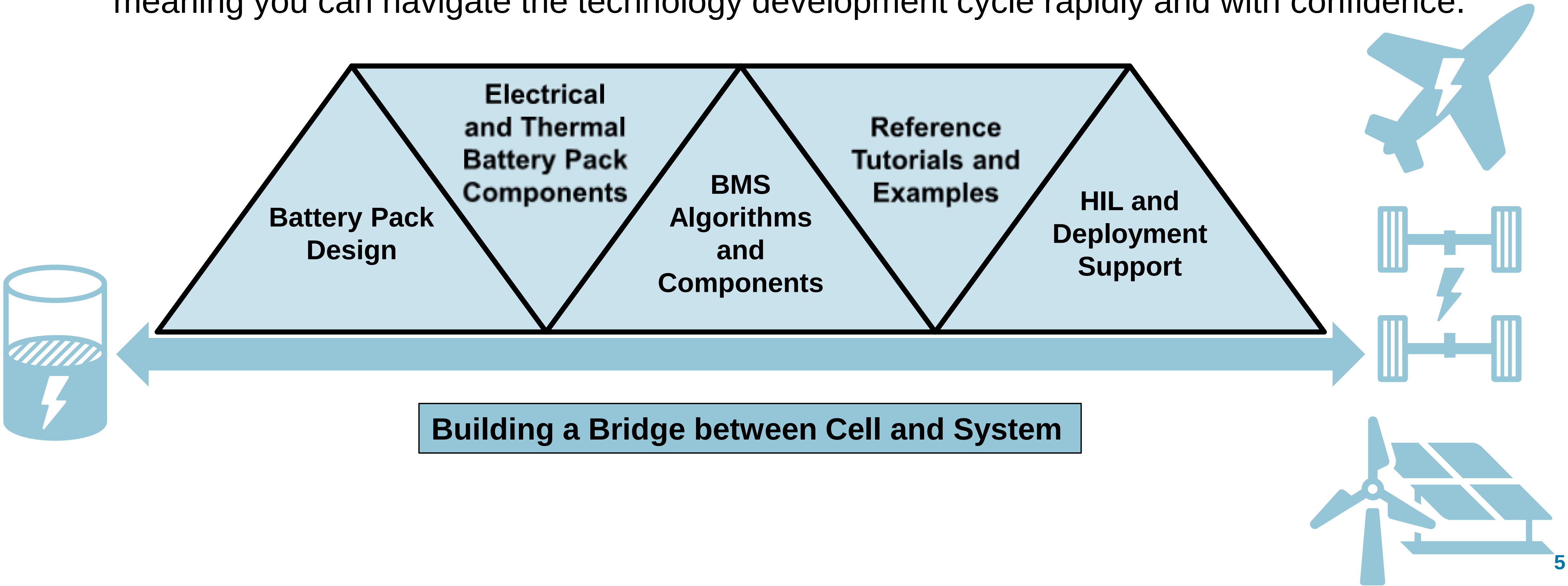


4. Support for Deployment and HIL



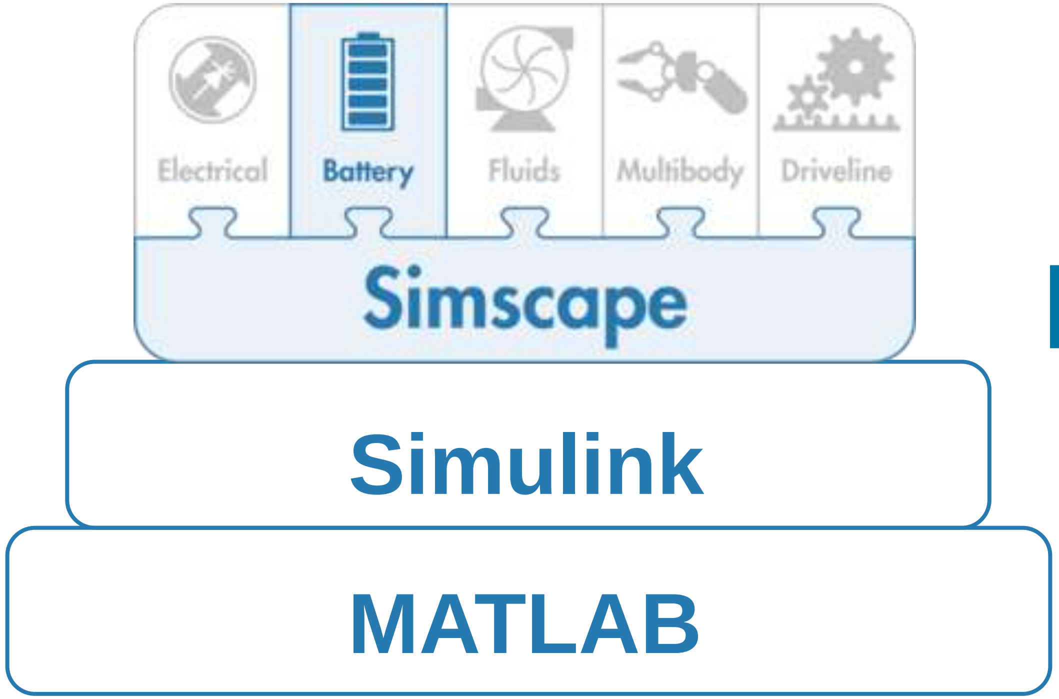
The Value of Simscape Battery

- Simscape Battery provides a framework that is assembled specifically to create a bridge between cell and system.
- The bridge directly supports upskilling as well as design exploration and design rigor, meaning you can navigate the technology development cycle rapidly and with confidence.



Technology Architecture

Technology Platform Strategy



Balanced Use of Products

Simscape Battery

Simscape

Simulink

MATLAB

Clear Onramps

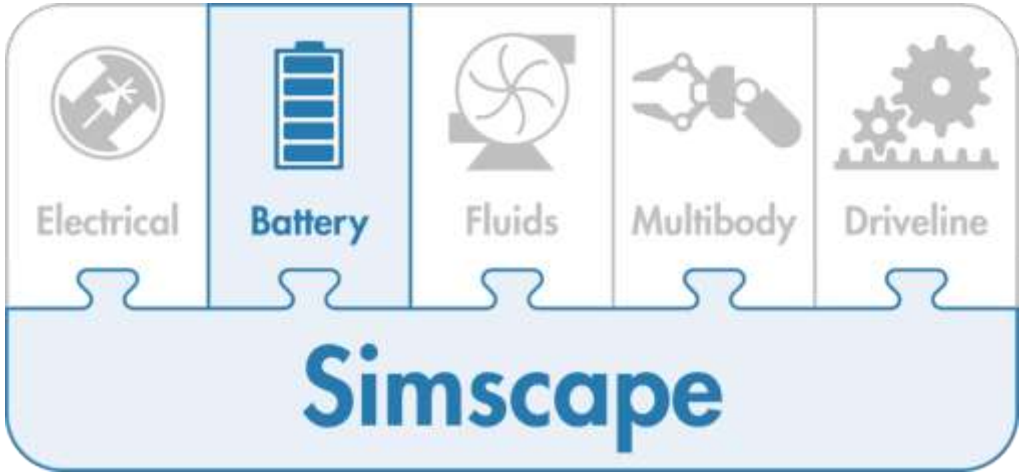
- Stateflow
- Deep Learning
- Simulink Compiler
- Simulink Coder
- Simulink Real-Time
- Powertrain Blockset
- Simscape Electrical
- Simscape Fluids

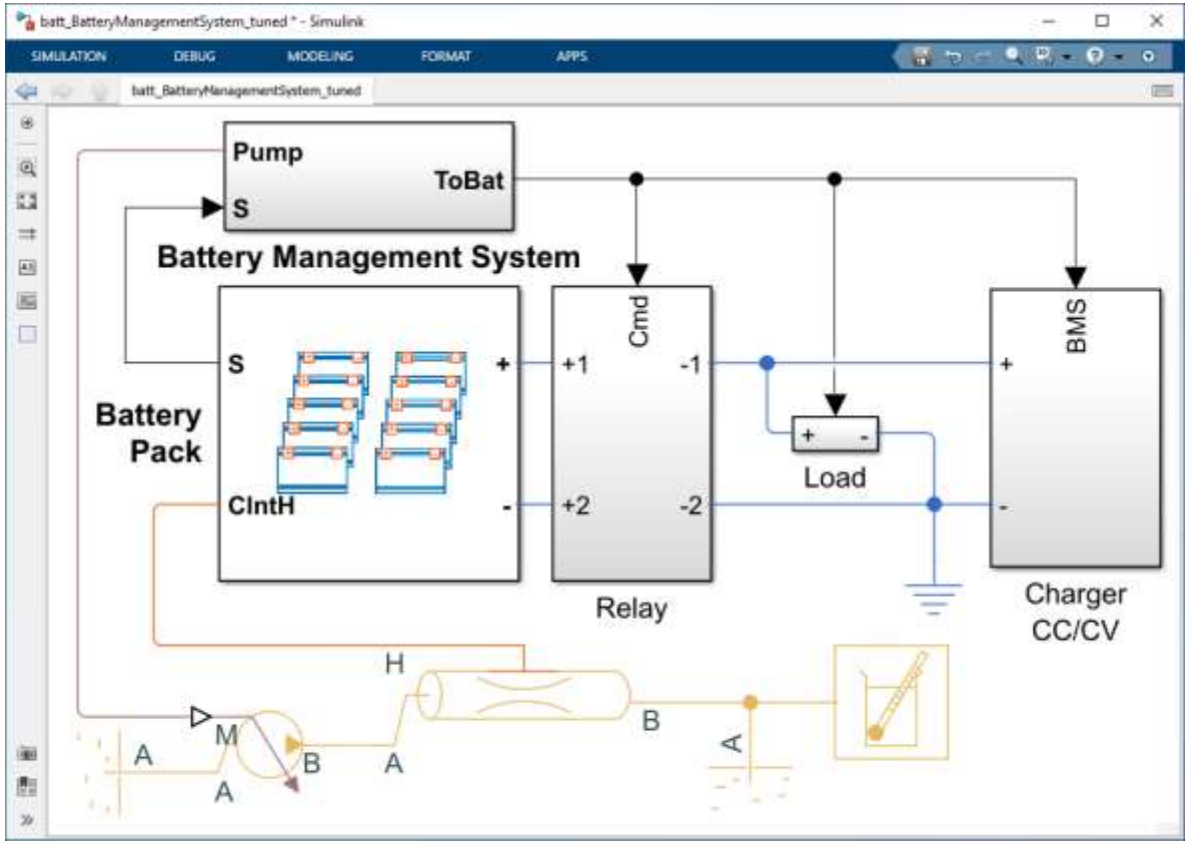
Simscape Battery

Overview

- Design and simulate battery and energy storage systems
  - Electrothermal cell behavior
  - Battery pack design
  - Battery management systems (BMS)

- With Simscape Battery you can
  - Evaluate pack architectures for electrical and thermal requirements
  - Verify robustness of discharge, charge and thermal management algorithms
  - Validate algorithms using HIL testing

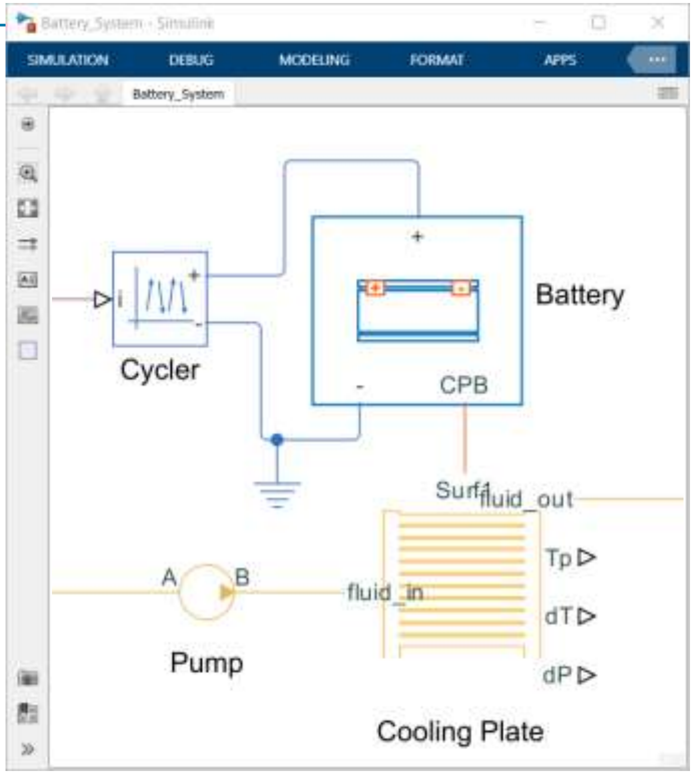


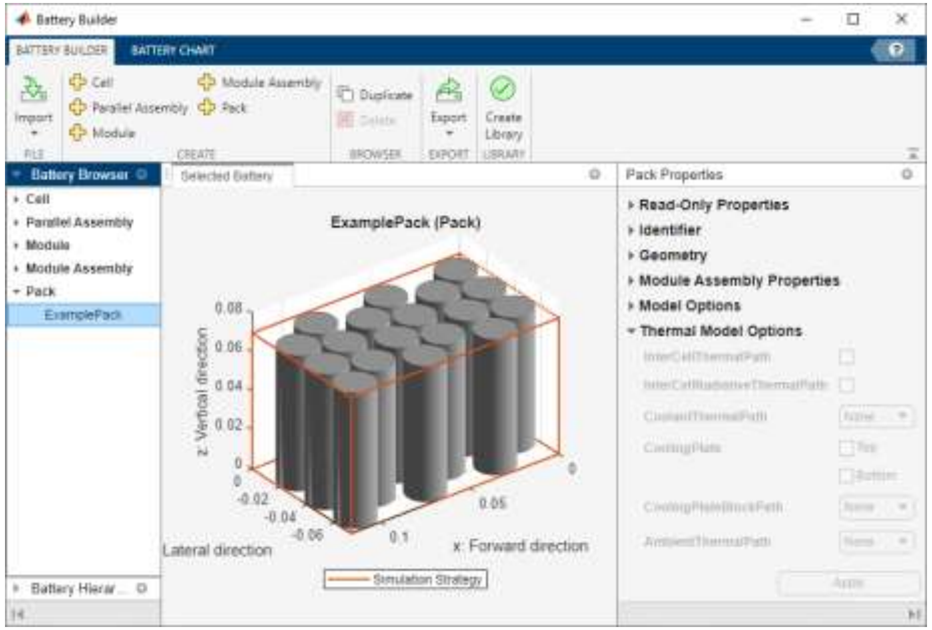


Simscape Battery

Key Features

- Battery Pack Builder (MATLAB API, App)
  - Automatically assemble cell models into battery pack
  - Define electrical and thermal connections (series, parallel)
  - Adjust tradeoff of simulation speed and model fidelity
- Cooling plate models
  - Includes edge, parallel channel, and U-shaped channel
- Battery management algorithms
  - Includes charge/discharge, SOC, SOH, cell balancing, thermal management, protection
- Application-specific examples
  - EV charging, Microgrid with BESS
- Support for C-code generation

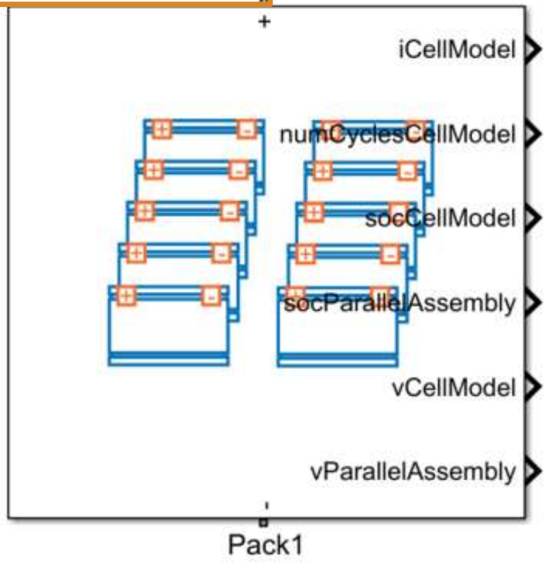




Battery Pack Builder

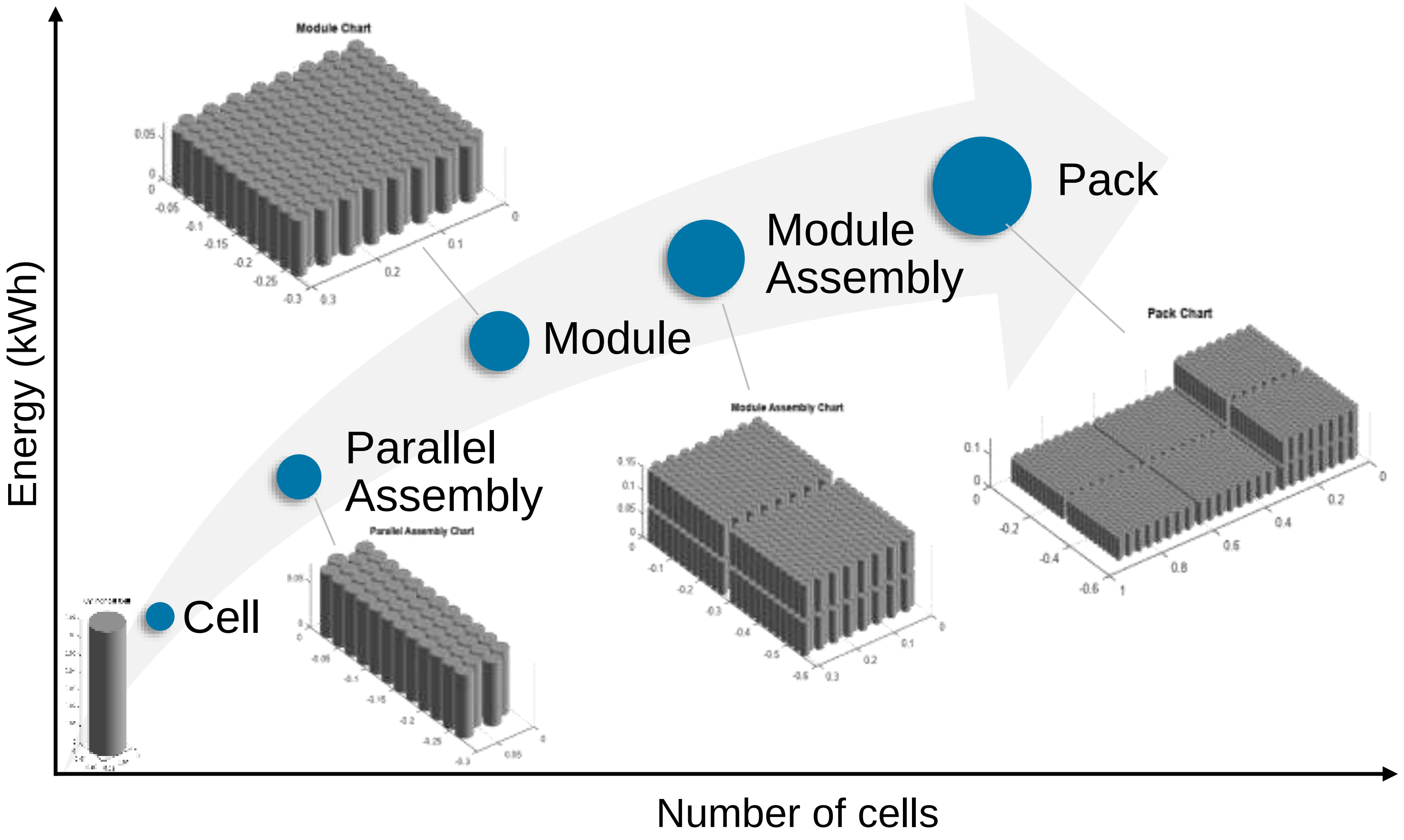
- Text-based design workflow with MATLAB API supports rapid pack design.
- Define the battery pack structure in as few as 6 lines of code.
- **Automatically create a Simscape model of the pack in 1 line of code**.

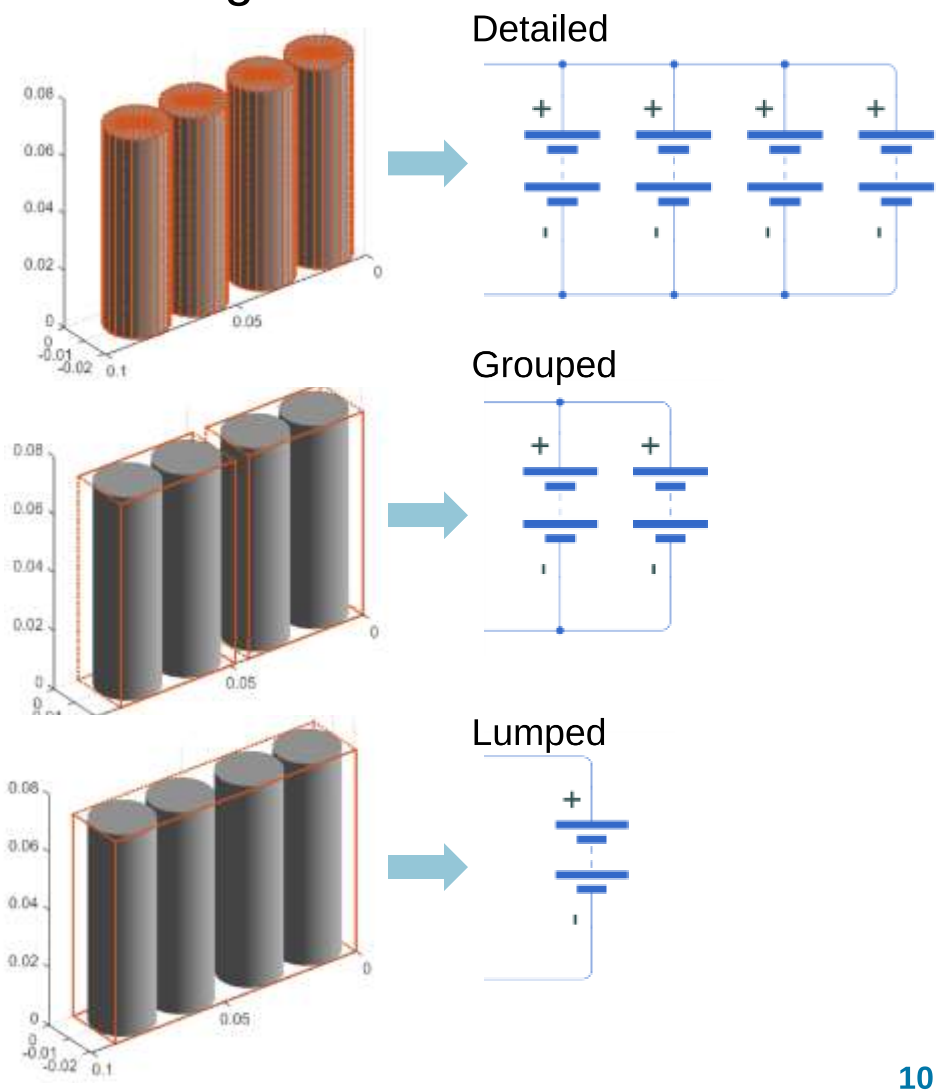
```
>> import simscape.battery.builder.*
>>
>> pouchGeometry = PouchGeometry();
>> batteryCell = Cell(Geometry = pouchGeometry);
>> batteryParallelAssembly = ParallelAssembly(Cell = batteryCell, numParallelCells = 3);
>> batteryModule = Module(ParallelAssembly = batteryParallelAssembly, numSeriesAssemblies = 11);
>> batteryModuleAssembly = ModuleAssembly(Module = repmat(batteryModule,1,2));
>> batteryPack = Pack(ModuleAssembly = repmat(batteryModuleAssembly,1,5));
>>
>> buildBattery(batteryPack,"LibraryName","packLibrary");
```



Battery Pack Builder

- Visualize the pack geometry and topology at each stage of the design.
- Define and visualize the simulation strategy.



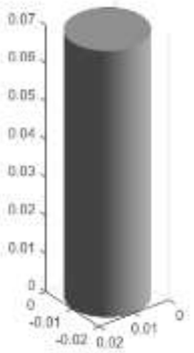


Battery Pack Builder

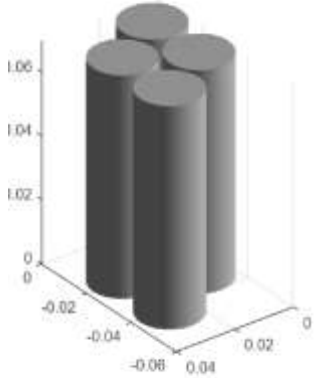
- Define cell format, stacking and topology.
- Keep track of volume, mass and dimensions.

```
>> batteryParallelAssembly.CumulativeMass

ans =

    0.4000 : kg

>> batteryParallelAssembly.PackagingVolume

ans =

    0.0082 : m^3
```

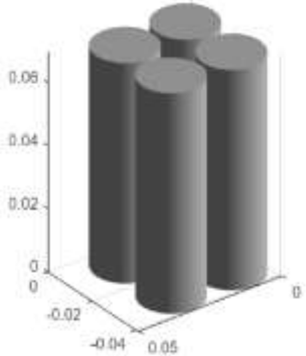
Cylindrical Cell



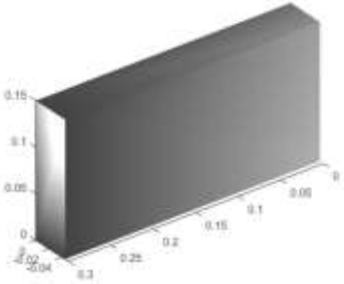
Hexagonal



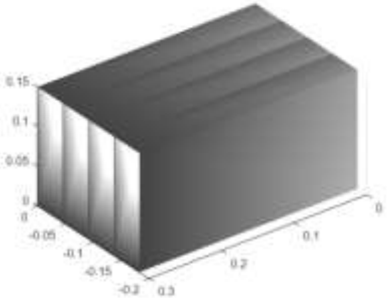
Square



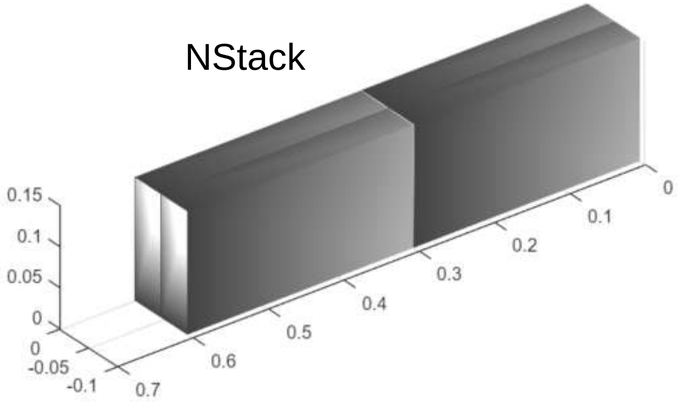
Prismatic Cell



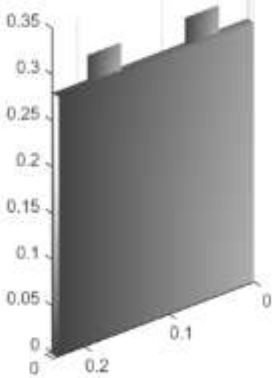
Single Stack

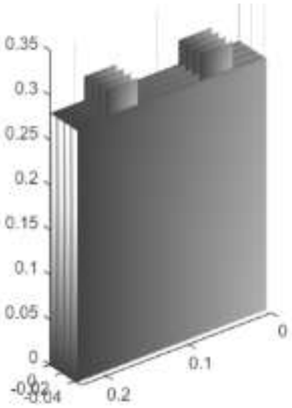


NStack



Pouch Cell



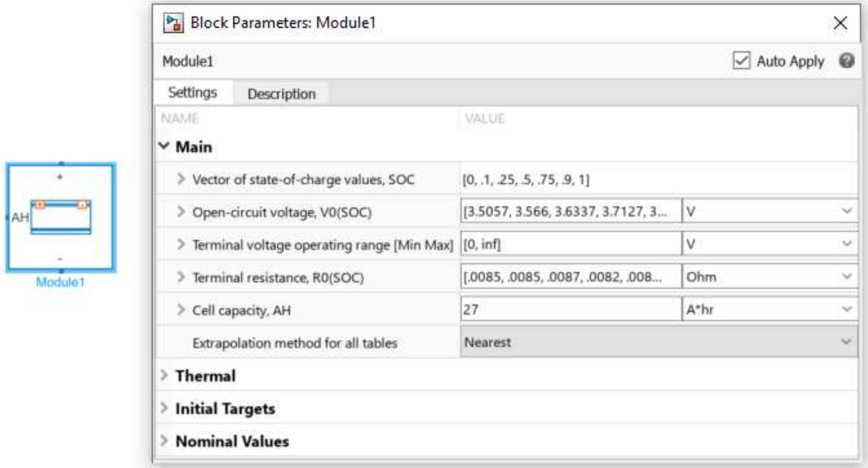


Single Stack

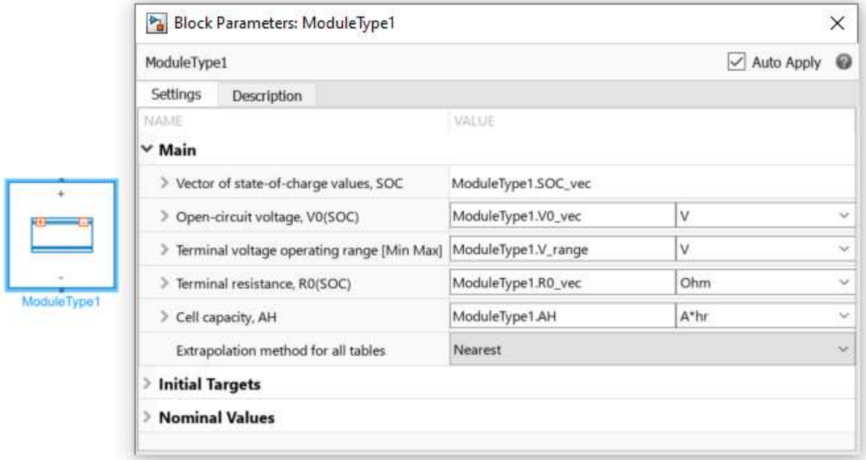
Battery Pack Builder

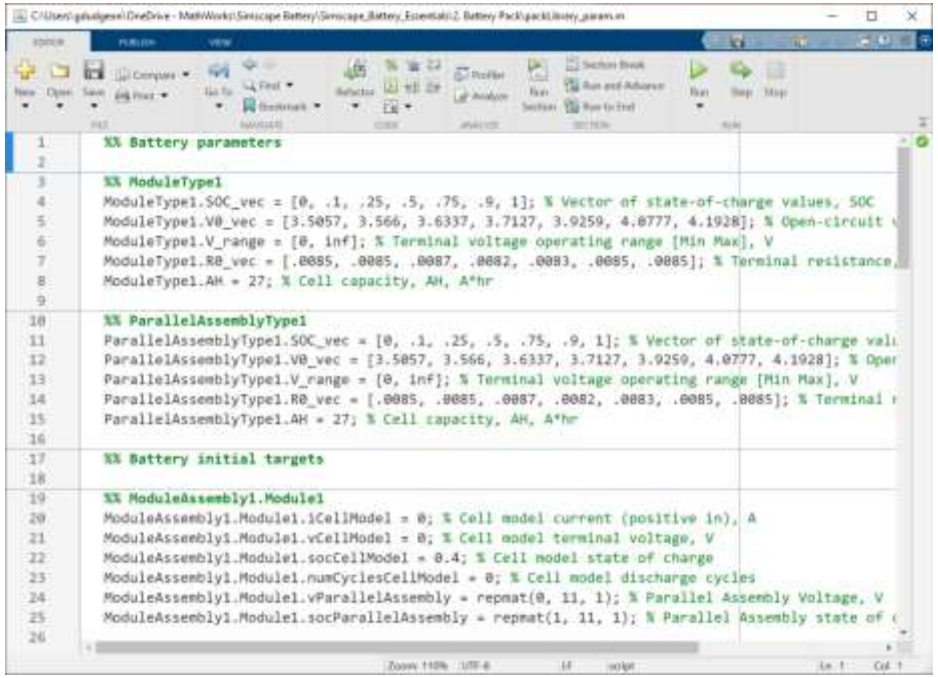
- Parameterize battery models from MATLAB scripts to support effective parameter management at scale and to support design space exploration.

```
>> buildBattery(batteryPack,"LibraryName","packLibrary")
```




```
>> buildBattery(batteryPack,"LibraryName","packLibrary",...
   "MaskInitialTargets","VariableNames",...
   "MaskParameters","VariableNames")
```

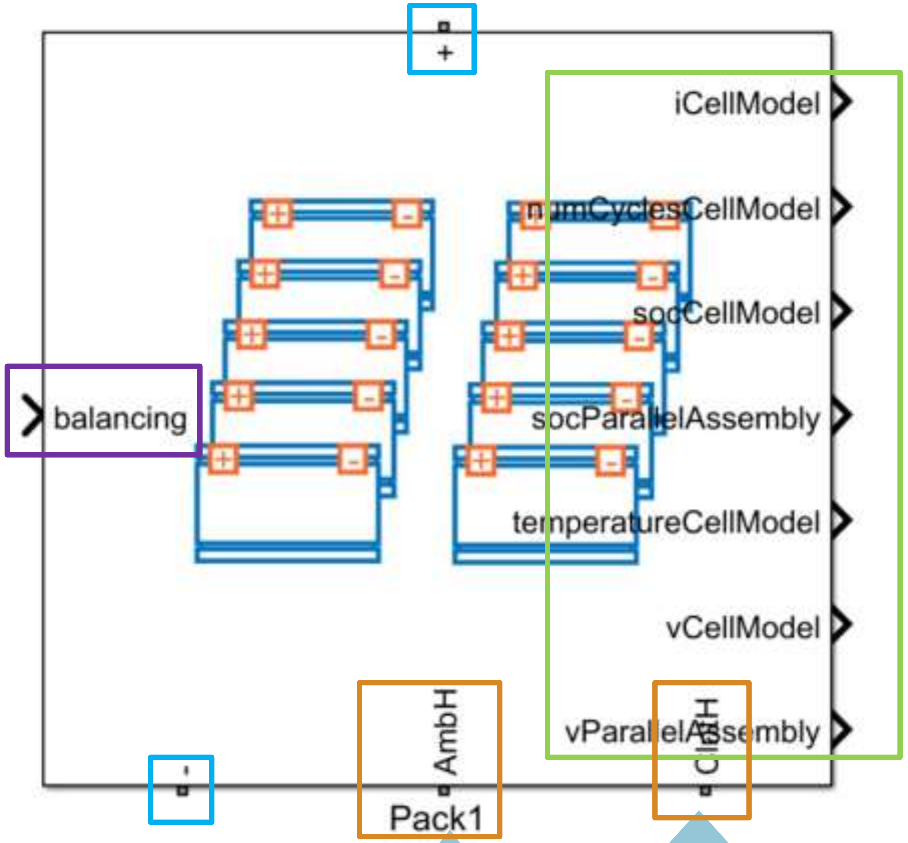




Battery Pack Builder

- Add temperature dependence, battery fade, battery aging and other cell characteristics.
- Add thermal ports that connect your battery pack to the ambient environment and to cooling systems.
- Add passive cell balancing circuits...

… define all this from MATLAB.

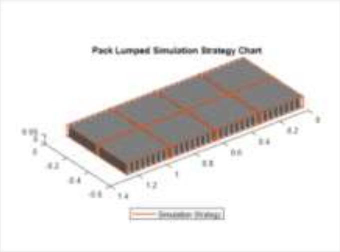



```
>> batteryPack.BalancingStrategy = "Passive"

>> batteryPack.AmbientThermalPath = "CellBasedThermalResistance"

>> batteryPack.CoolantThermalPath = "CellBasedThermalResistance"
```

Battery Pack Builder

Battery Pack Modeling — Examples

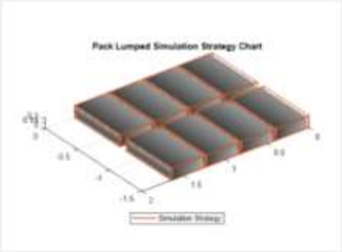
R2022b



Build Detailed Model of Battery Pack From Cylindrical Cells

Create and build Simscape™ system models for various battery designs and configurations based on cylindrical battery cells in

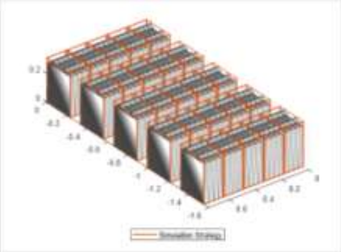
Open Live Script



Build Detailed Model of Battery Pack From Pouch Cells

Create and build Simscape™ system models for various battery designs and configurations based on pouch battery cells in Simscape™ Battery™.

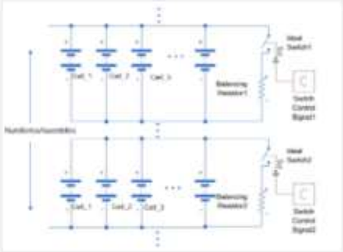
Open Live Script



Build Model of Battery Pack with Cell Aging

Create and build a Simscape system model of a battery pack with cell aging.

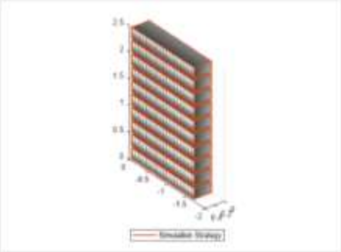
Open Live Script



Build Model of Battery Pack with Cell Balancing Circuit

Create and build a Simscape system model of a battery pack with cell balancing circuit.

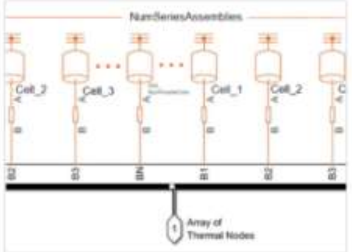
Open Live Script



Build Model of Battery Pack for Grid Application

Create and build a Simscape system model of a battery pack for grid applications.

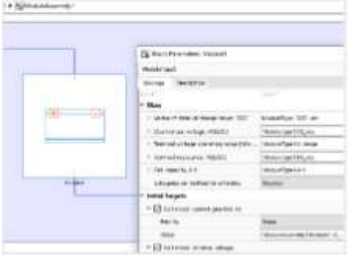
Open Live Script



Build Model of Battery Module with Thermal Effects

Create and build a Simscape system model of a battery module with thermal effects.

Open Live Script



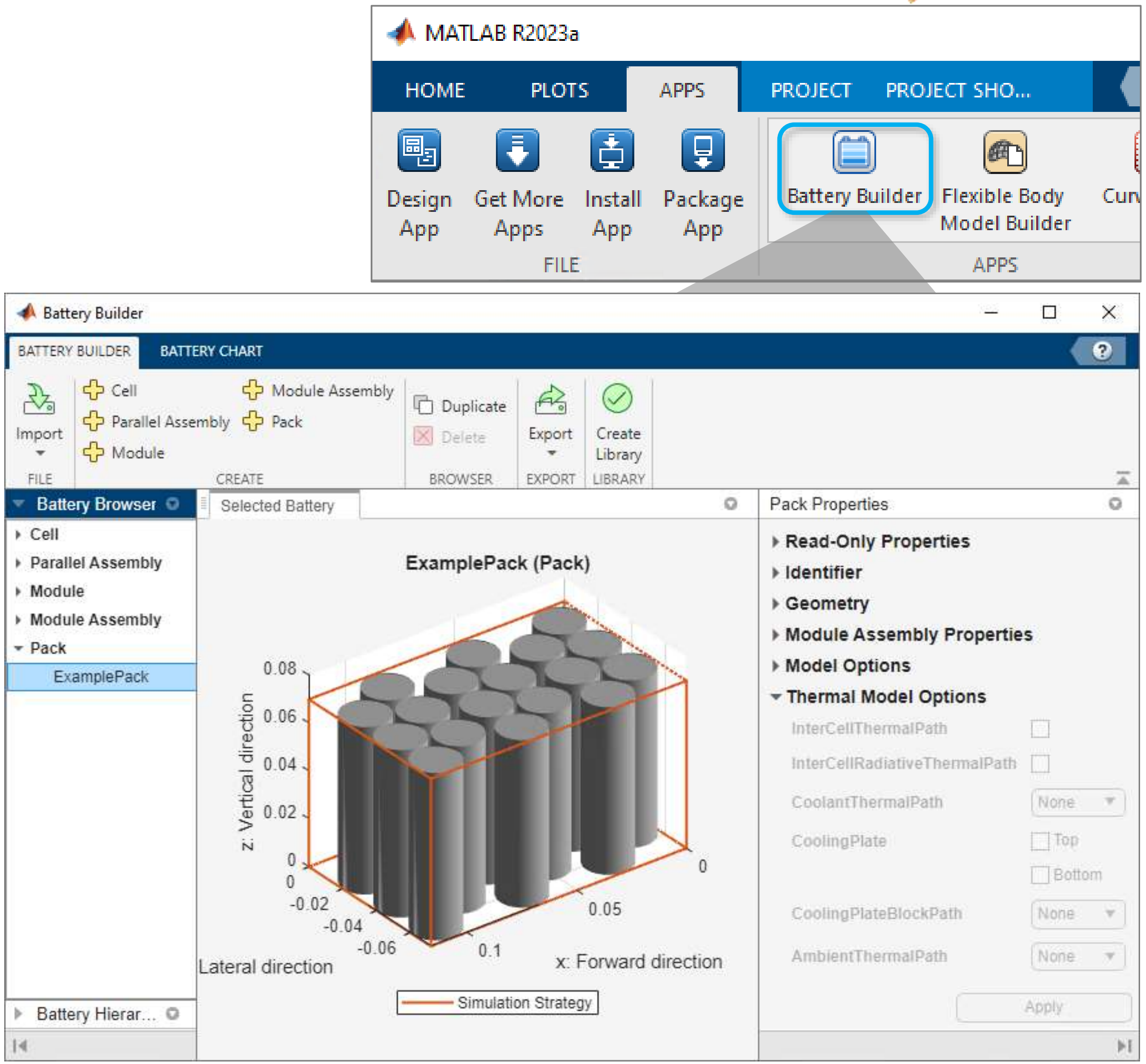
Build Model of Hybrid-Cell Battery Pack

Build a Simscape™ system model of a hybrid-cell battery pack with two sets of cell run-time parameters. The generated battery pack model

Open Live Script

Battery Builder App

- Construct battery pack models using interactive modeling app
  - Create new battery objects to model cells, modules and packs
  - Import existing battery objects from your workspace or MAT file.
  - Create a 3-D battery object plot, and export to a MATLAB figure
  - Inspect the battery object hierarchy
  - Edit the battery object properties, such as geometrical data and thermal boundary conditions.
  - Create a library model from an object



EV Fast Charging

Thermal Management

Power up to 350 kW

↓

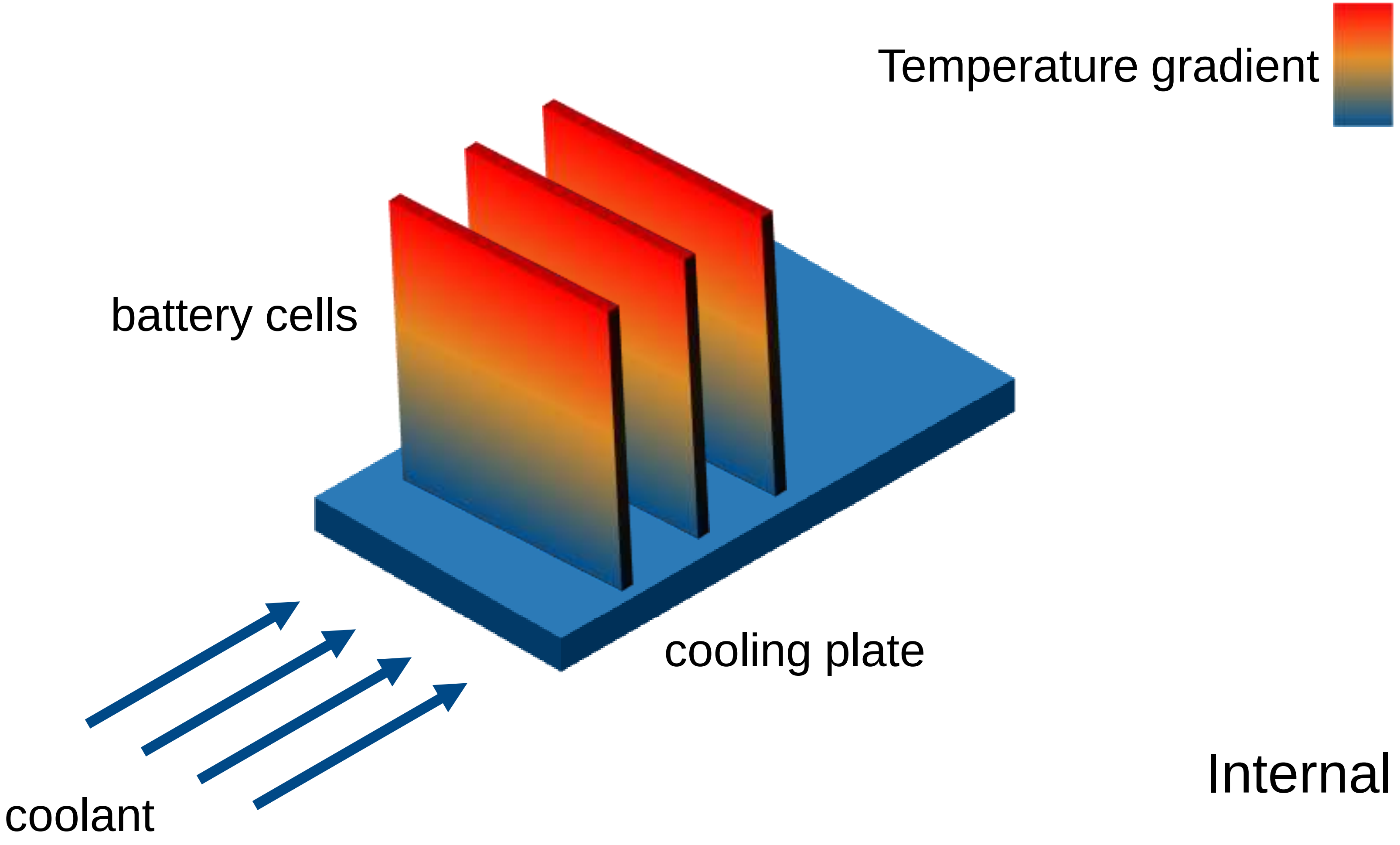
Large heat generation

↓

Fast Aging

Thermal Management

Pouch Cell with Bottom Plate Cooling



Internal Resistance
Aging Rate

$= f\,(T)$

Temperature and Thermal Gradients

Effects

- Inhomogeneous current
- Uneven aging
- Accelerated degradation
- Localized heating
- Uncertain T monitoring

Requirements

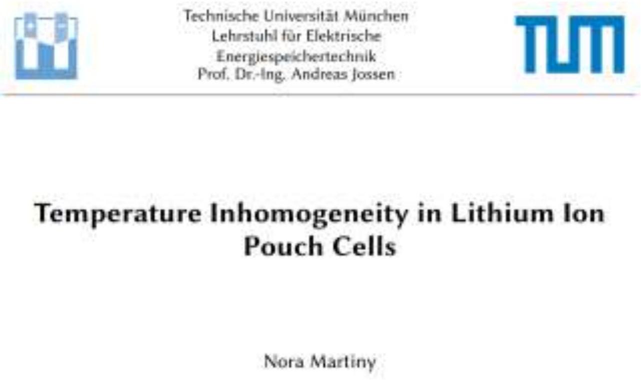
Performance – Life – Safety

$10^{o}C < T < 35^{o}C$

$\Delta T < 6^{o}C$

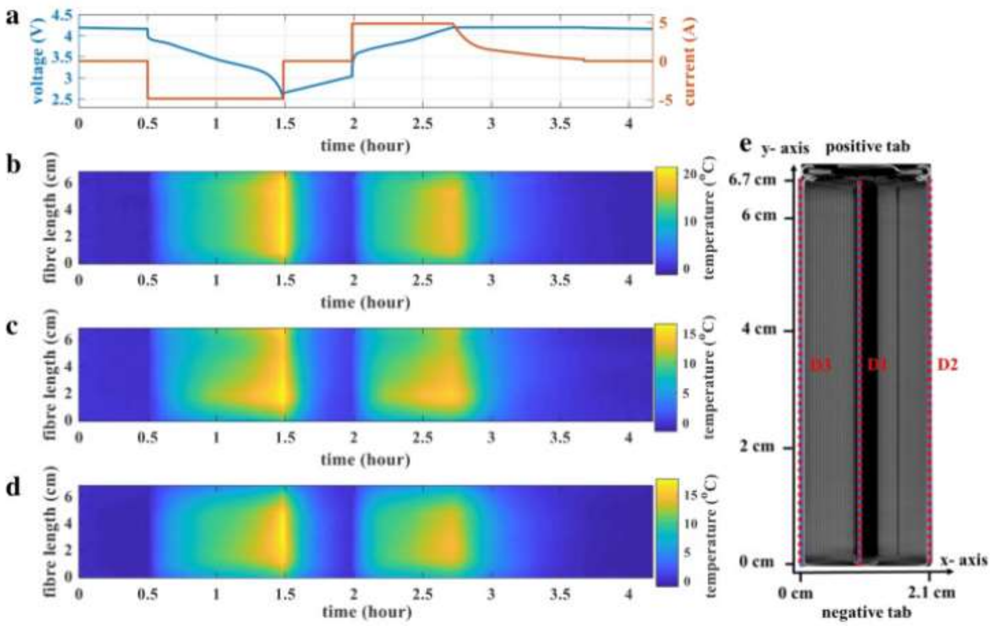
Battery ∇T - Research

1388435.pdf (tum.de)

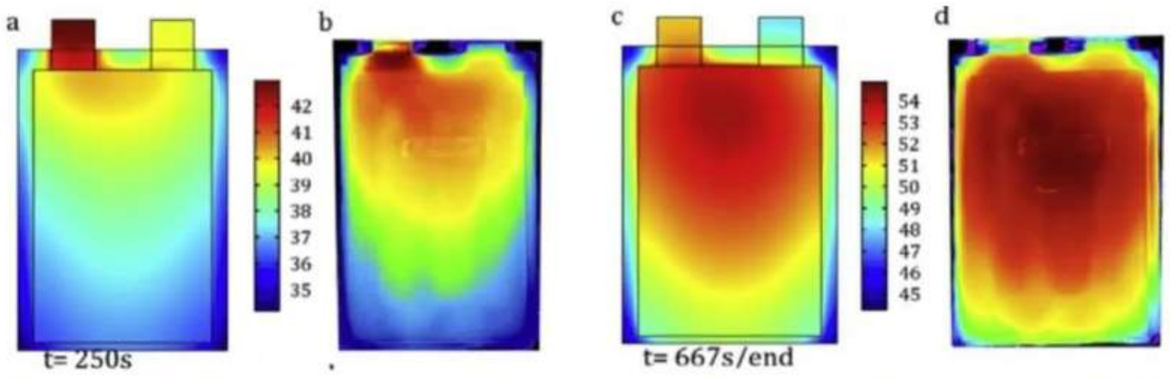

Technische Universität München
Lehrstuhl für Elektrische
Energiespeichertechnik
Prof. Dr.-Ing. Andreas Jossen

Temperature Inhomogeneity in Lithium Ion Pouch Cells

Nora Martiny



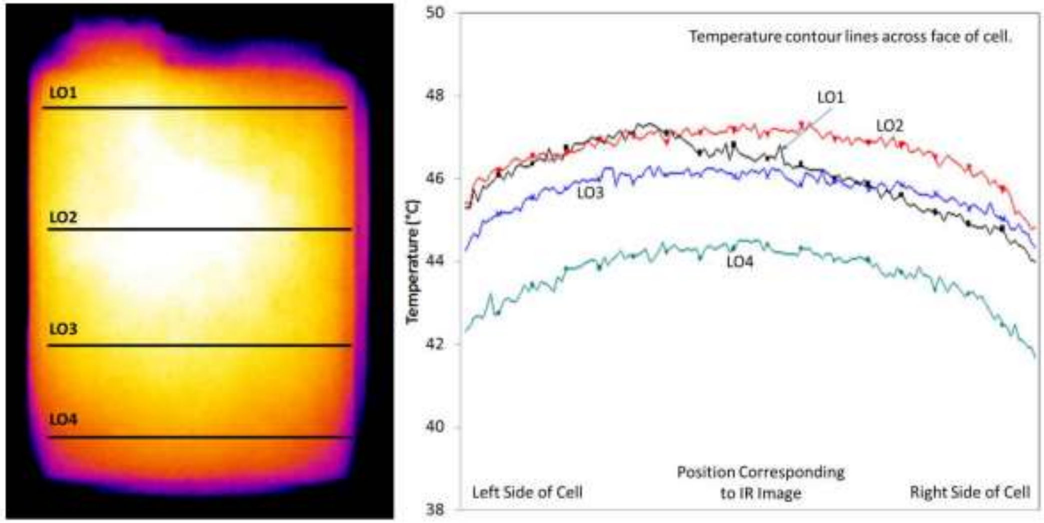
Yu et al., Distributed internal thermal monitoring of lithium ion batteries with fibre sensors - ScienceDirect



Surface temperature evolution of a pouch cell during 5C constant current discharge obtained by a) simulation and b) measurement at t ¼ 250 s; c) simulation and d) measurement at the end of discharge/t ¼ 667 s

S. Goutam et al. 10.1016/J.APPLTHERMALENG.2017.07.206
https://www.sciencedirect.com/science/article/pii/S1359431117325565?via{%}3Dihub

Enabling Fast Charging - Battery Thermal Considerations (osti.gov)



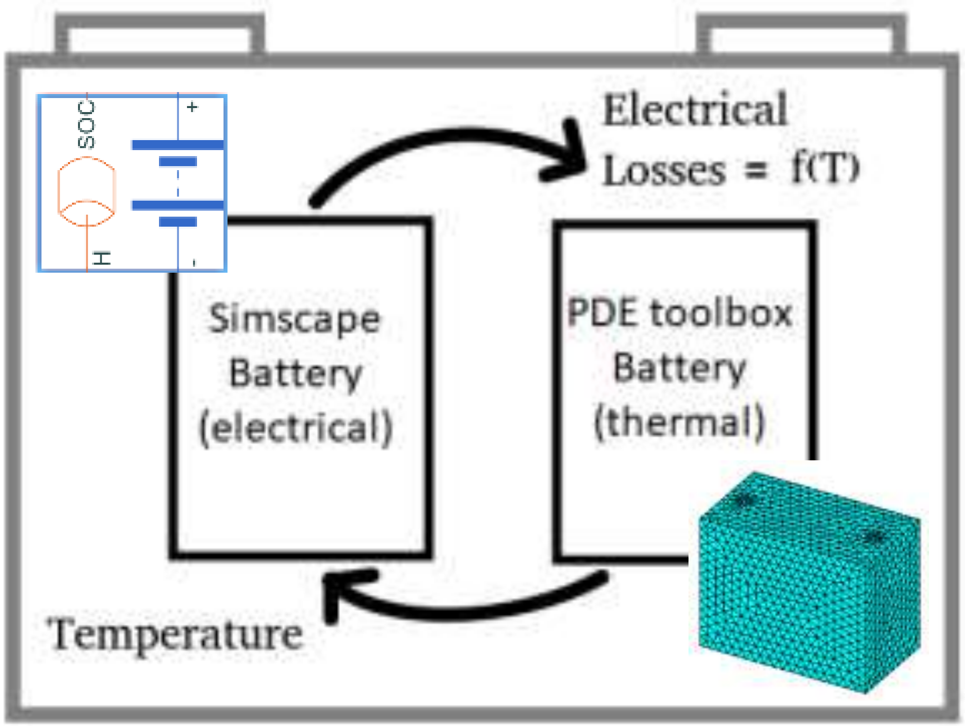
NMC/graphite, End of a 2C constant current discharge. SOC 100% to 0%

Solution

Combine

Finite Element Analysis + System Level Simulation

- Electrical Domain - Battery Cell (**Simscape Battery**)
- Thermal Domain - Reduced Order Model from FEA (**PDE Toolbox**)



Battery Model (in this example)

Thermal Model Reduction

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot \mathrm{k}\nabla T = q \xrightarrow{\text{FEM}} M\dot{T} + KT = Q$$

PDE

Size: 10^3 to 10^6

Find modes Φ_r

Projection

$$M_r = \Phi_\mathrm{r}^T M \Phi_\mathrm{r}$$

$$M_r \dot{T}_r + K_r T_r = Q_r$$

Size: 10 to 100

SAND2010-6352 (osti.gov)

Thermal Model Reduction - Workflow

1- Create geometry

2- Create thermal problem as `'modal'`

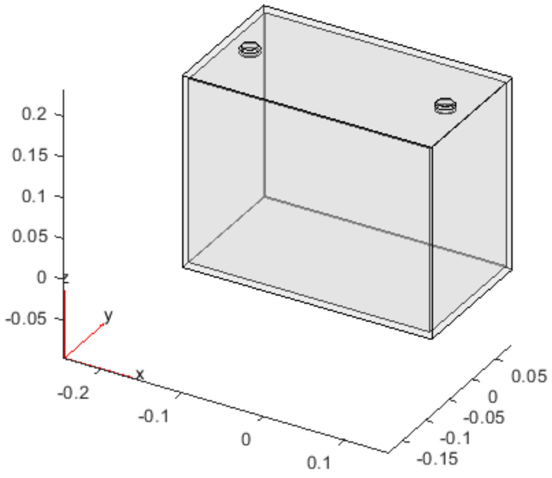
3- Assign material properties

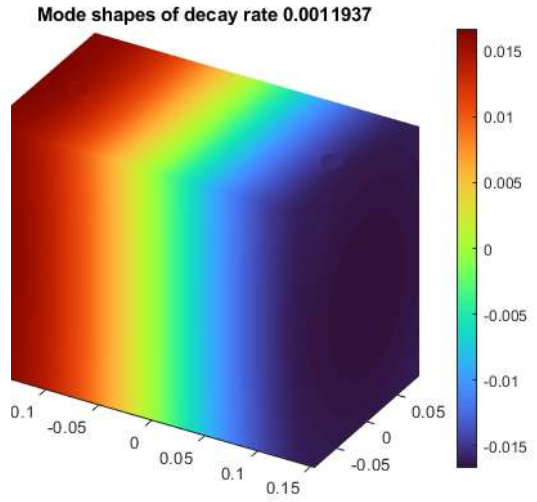
4- Mesh

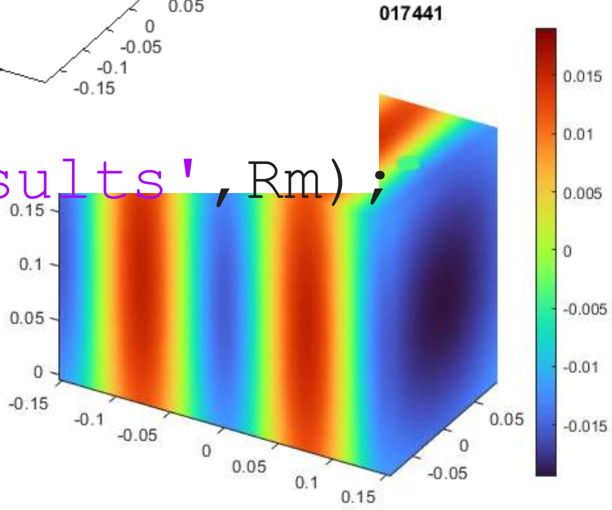
5- Solve modal problem (no loads)

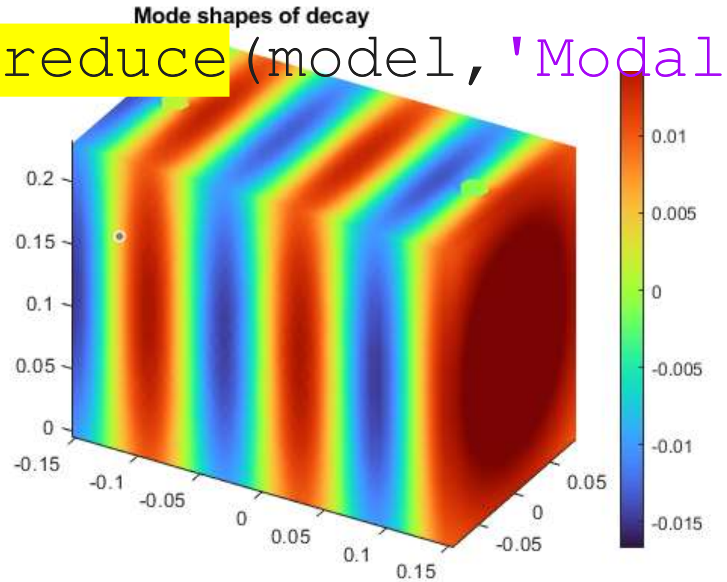
6- Reduce

```
rom = reduce(model,'ModalResults',Rm);
```



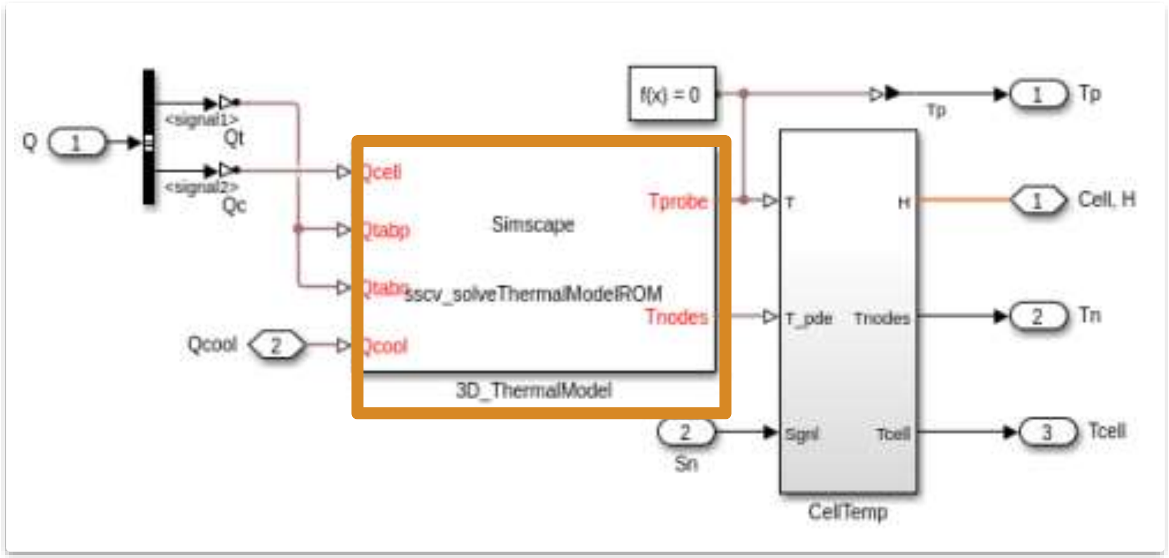







```
Rm = solve(model,'DecayRange',[-inf,0.05]);
```

Reduced Order Model (ROM) in Simscape Language



Block Parameters: 3D_ThermalModel

Reduced Order Model matrices and operations for battery cell thermal analysis — Auto Apply

Settings | Description

Parameters

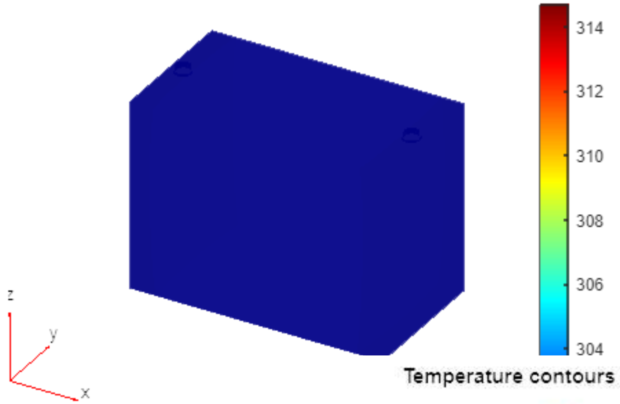
NAME	VALUE	
Mass matrix	pde_rom.rom.M	<15x15 double>
Conductivity matrix	pde_rom.rom.K	<15x15 double>
Modal transformation matrix for probes	pde_rom.thermocouples.W	<3x15 double>
Heat loss from boundary	pde_rom.Q.boundaryLoad_full	<15684x1 double>
Cell volumetric heat generation	pde_rom.Q.heatGenUnit_full	<15684x1 double>
Positive tab volumetric heat generation	pde_rom.Q.heatGenUnitPosTab_full	<15684x1 double>
Negative tab volumetric heat generation	pde_rom.Q.heatGenUnitNegTab_full	<15684x1 double>

```
component sscv_solveThermalModelROM
% Reduced Order Model matrices and operations for battery cell thermal analysis

% Copyright 2022 The MathWorks, Inc.

 equations
     pdeTemp == T;
     romTemp == probeTransformMat*T;
     romMassMatrix * T.der  + romCondMatrix * T == {romQmodalTransform'*(...
         romQheatGenUnitFull*value(cellHeatSrc,'W')/jellyVolume + ...
         romQheatGenUnitPosTabFull*value(tabHeatSrcPos,'W')/posTabVolume + ...
         romQheatGenUnitNegTabFull*value(tabHeatSrcNeg,'W')/negTabVolume + ...
         romQboundaryLoadFull*value(heatLossToCoolant,'W')/coolingSurfArea...
         ),'W'};
```

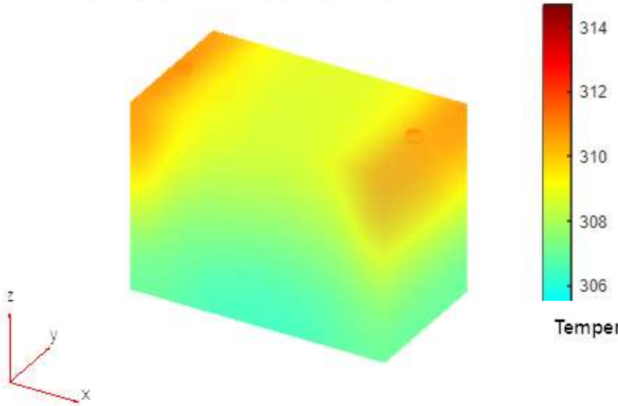
$$M_r \dot{T}_r + K_r T_r = Q_r$$

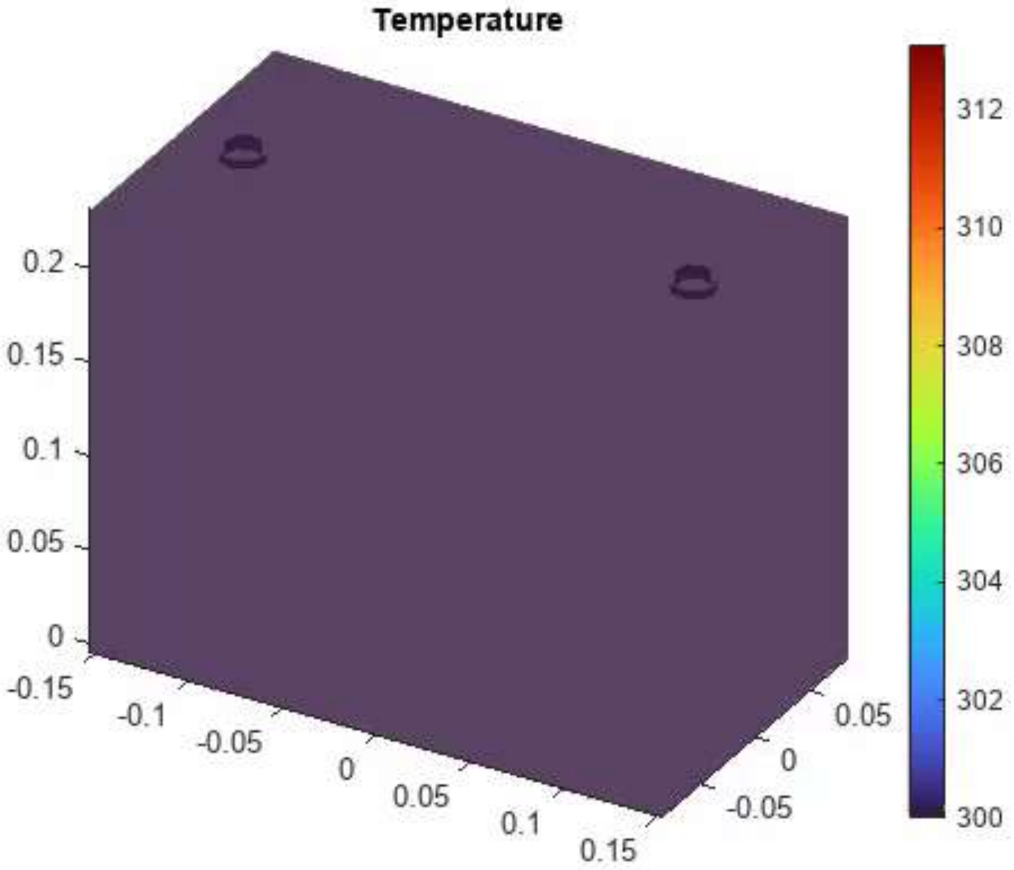
Temperature Distribution

Temperature contours at time t = 0.016667min

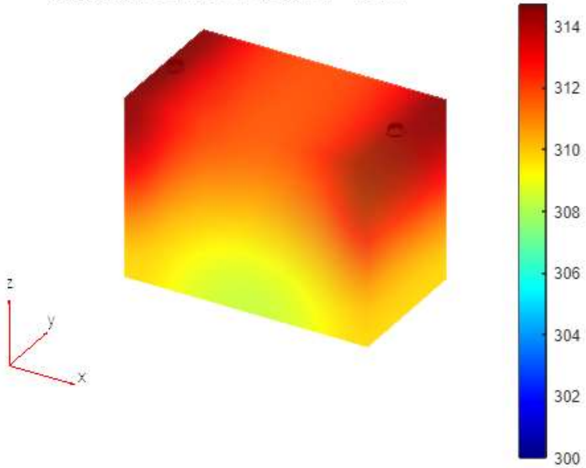


Temperature contours at time t = 5min



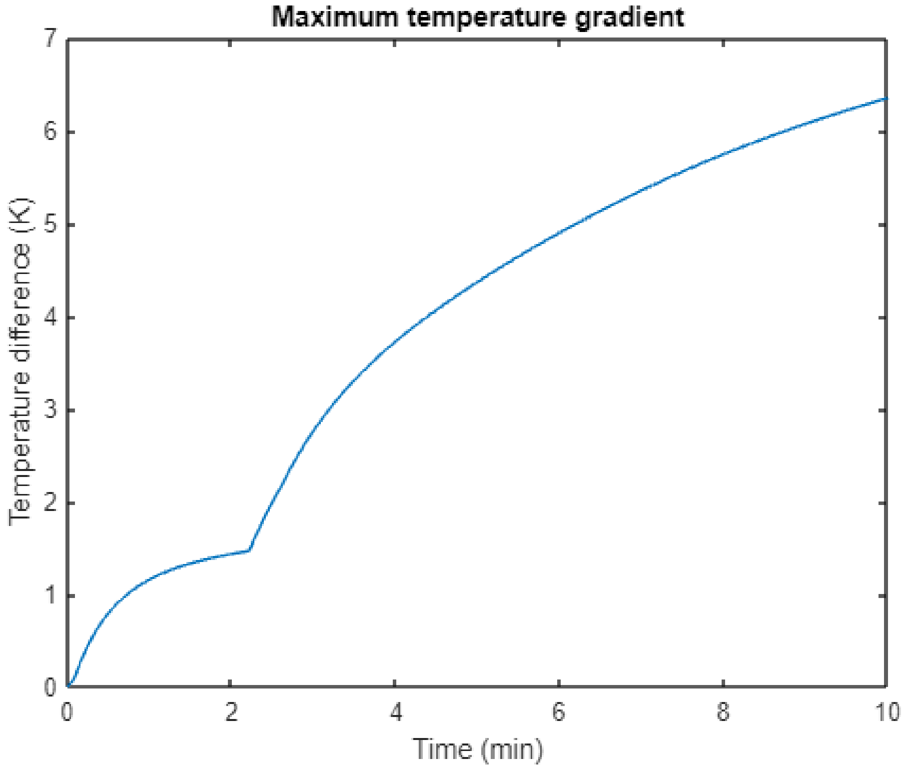


Temperature contours at time t = 10min

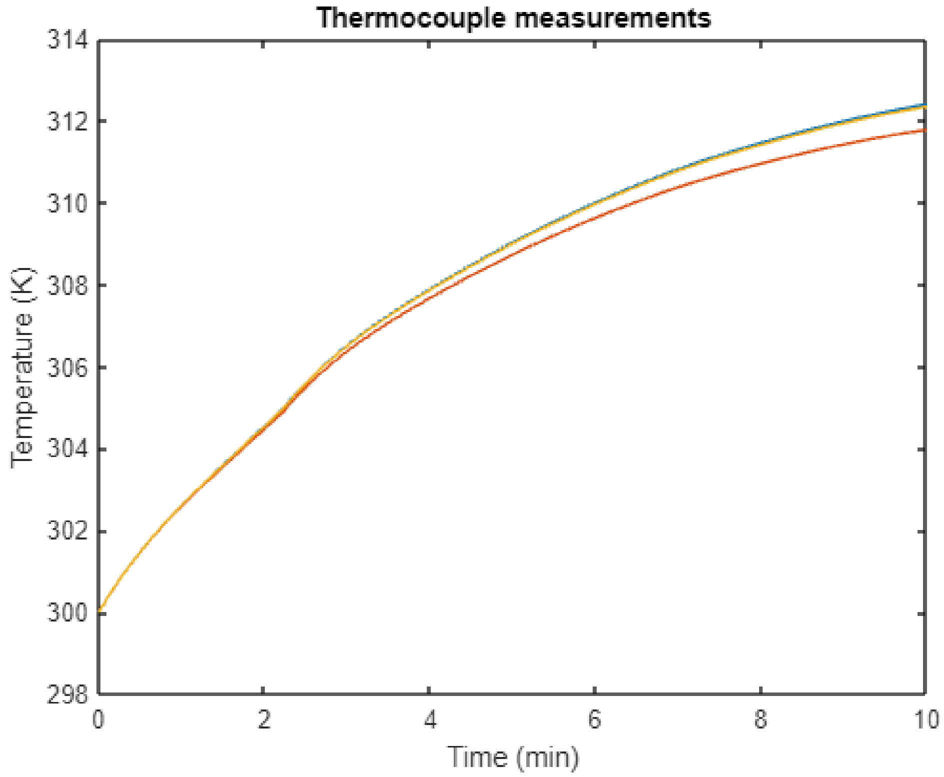


Thermal Differences

$\Delta T_{max} \sim 6K$

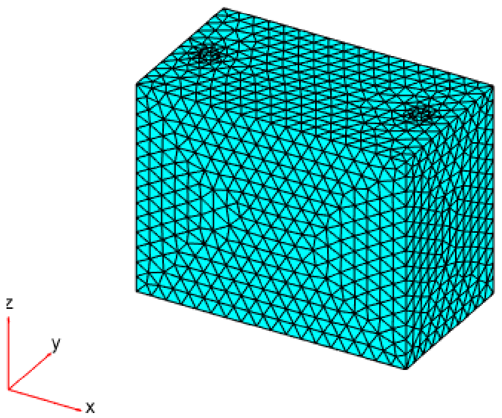


Thermocouple Readings

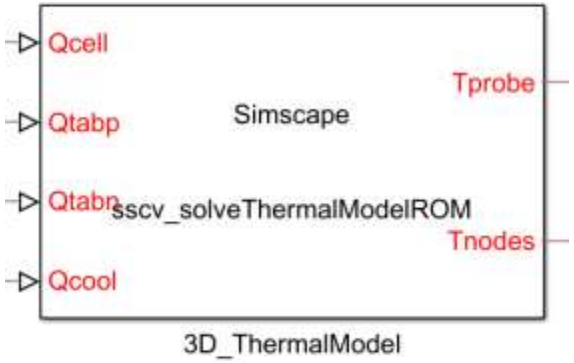


Summary

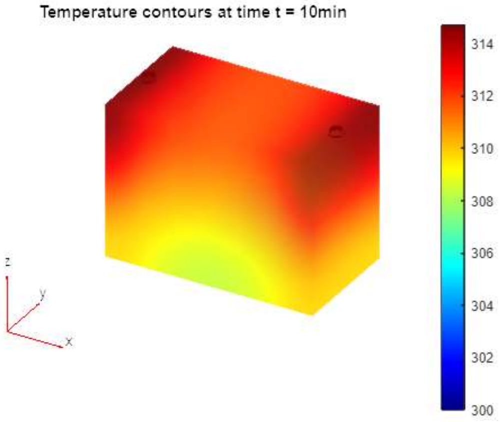
- Reduced Order Model of Battery Thermal Behavior
- FEA to System Level




```
Rm = solve(model,'DecayRange',[-inf,0.05]);

rom = reduce(model,'ModalResults',Rm);
```

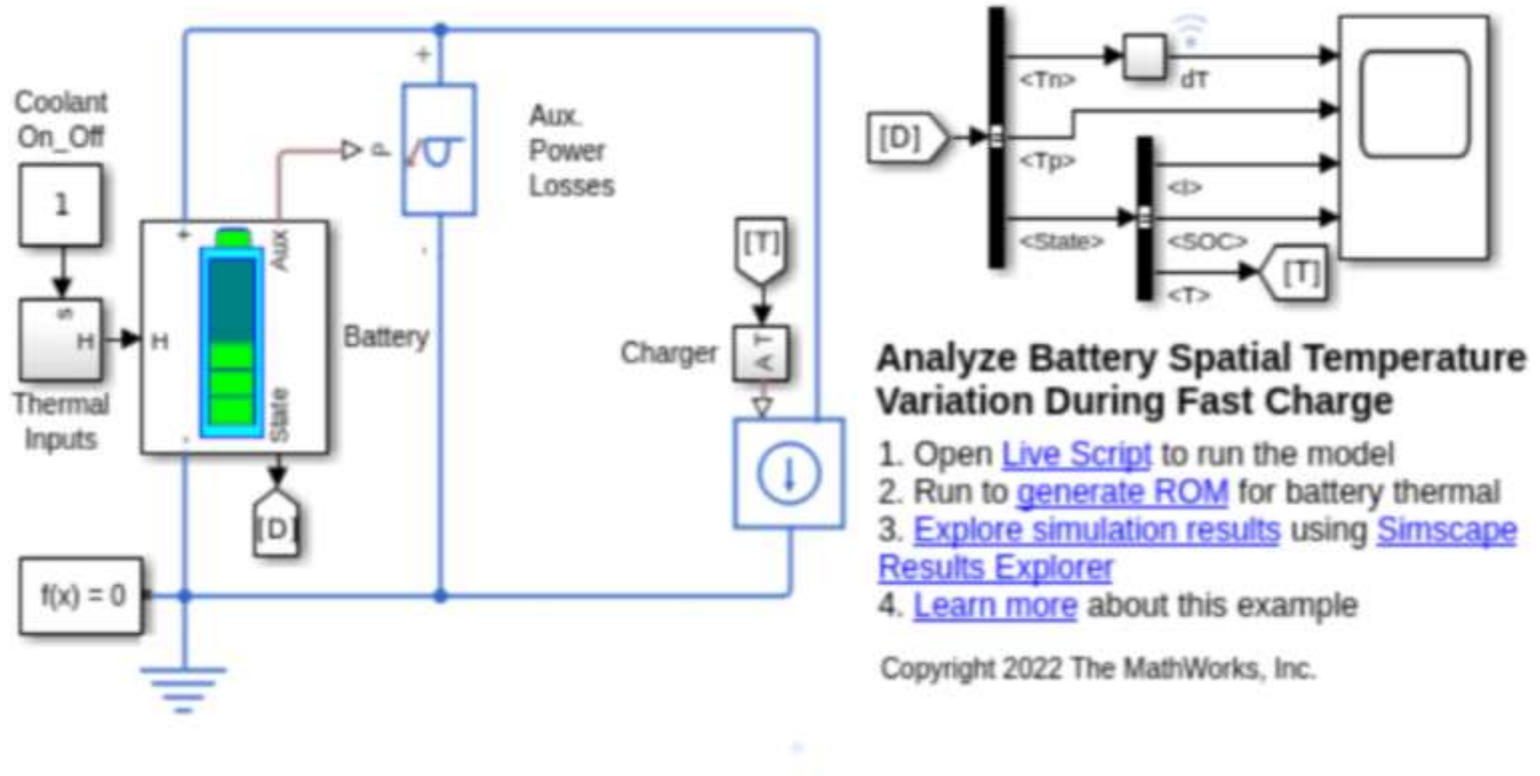


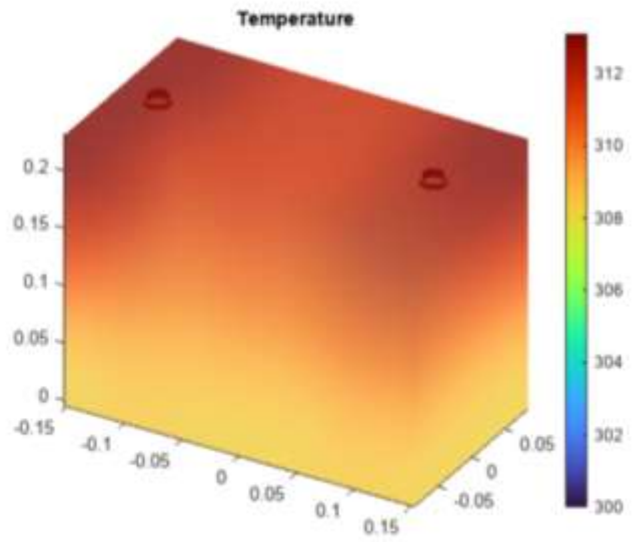
- Find Temperature Distribution
- Solve in Simulink



Analyze Battery Spatial Temperature Variation During Fast Charge

New Demo

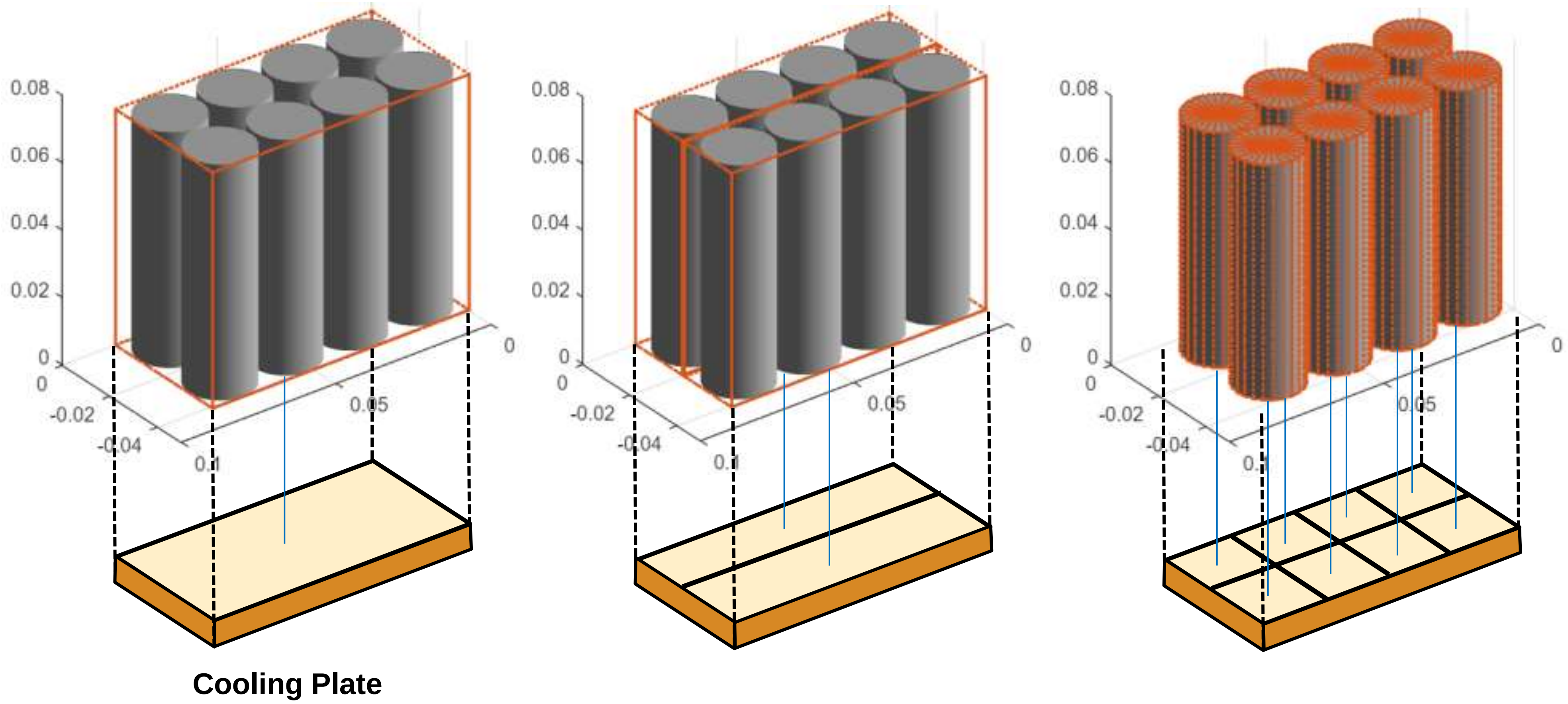


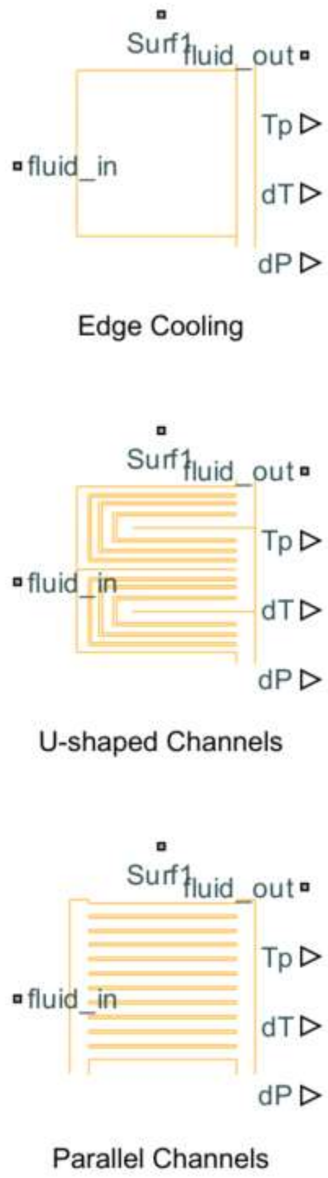


https://kr.mathworks.com/help/simscape-battery/ug/battery-spatial-temperature-variation-during-fast-charge.html

Thermal Management

- Change the simulation strategy of cooling plates to meet your model resolution needs for the combined electrical and thermal system.





Thermal Management

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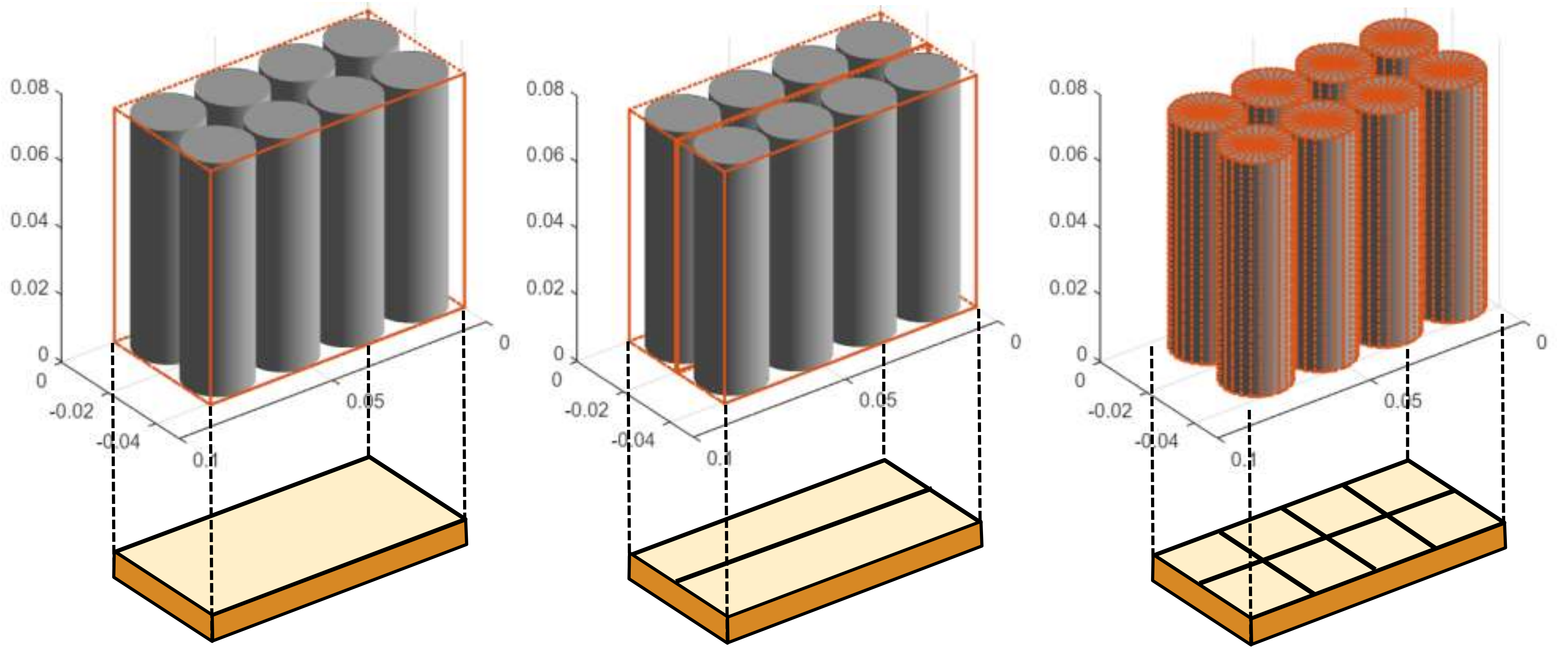
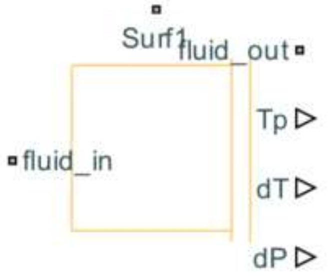
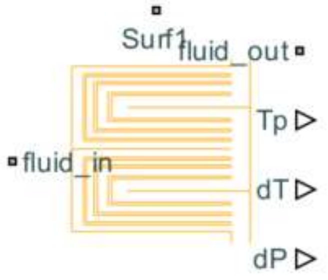


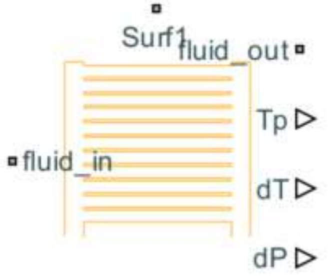
Cooling Plate



Edge Cooling



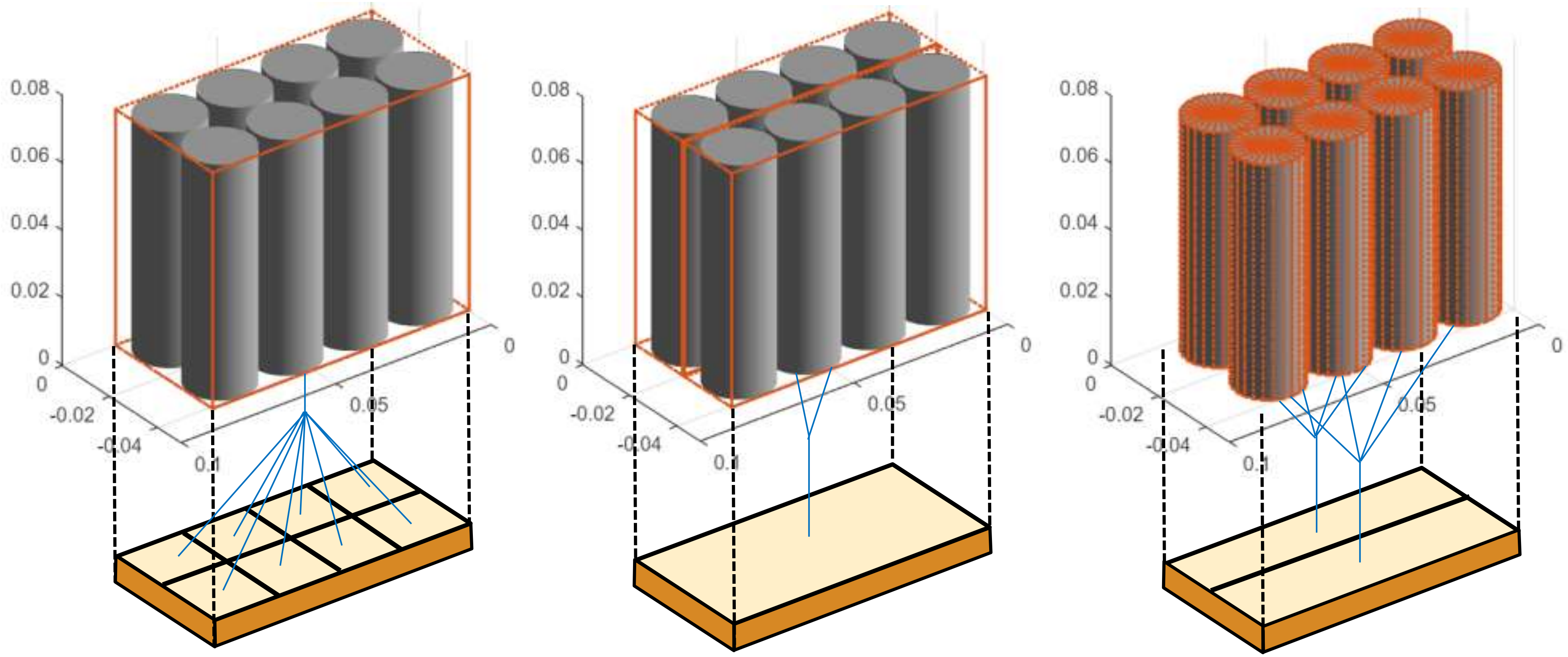
U-shaped Channels



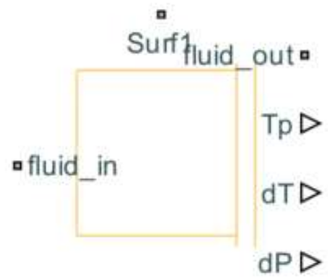
Parallel Channels

Thermal Management

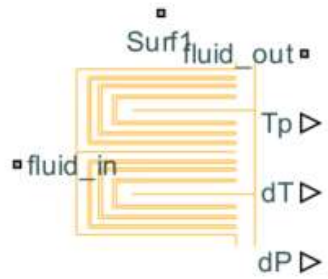
- Change the simulation strategy of cooling plates to meet your model resolution needs for the combined electrical and thermal system.



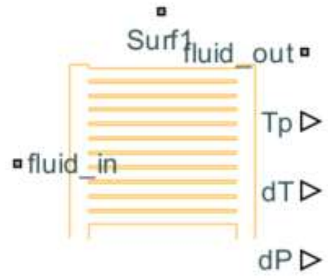
Cooling Plate



Edge Cooling



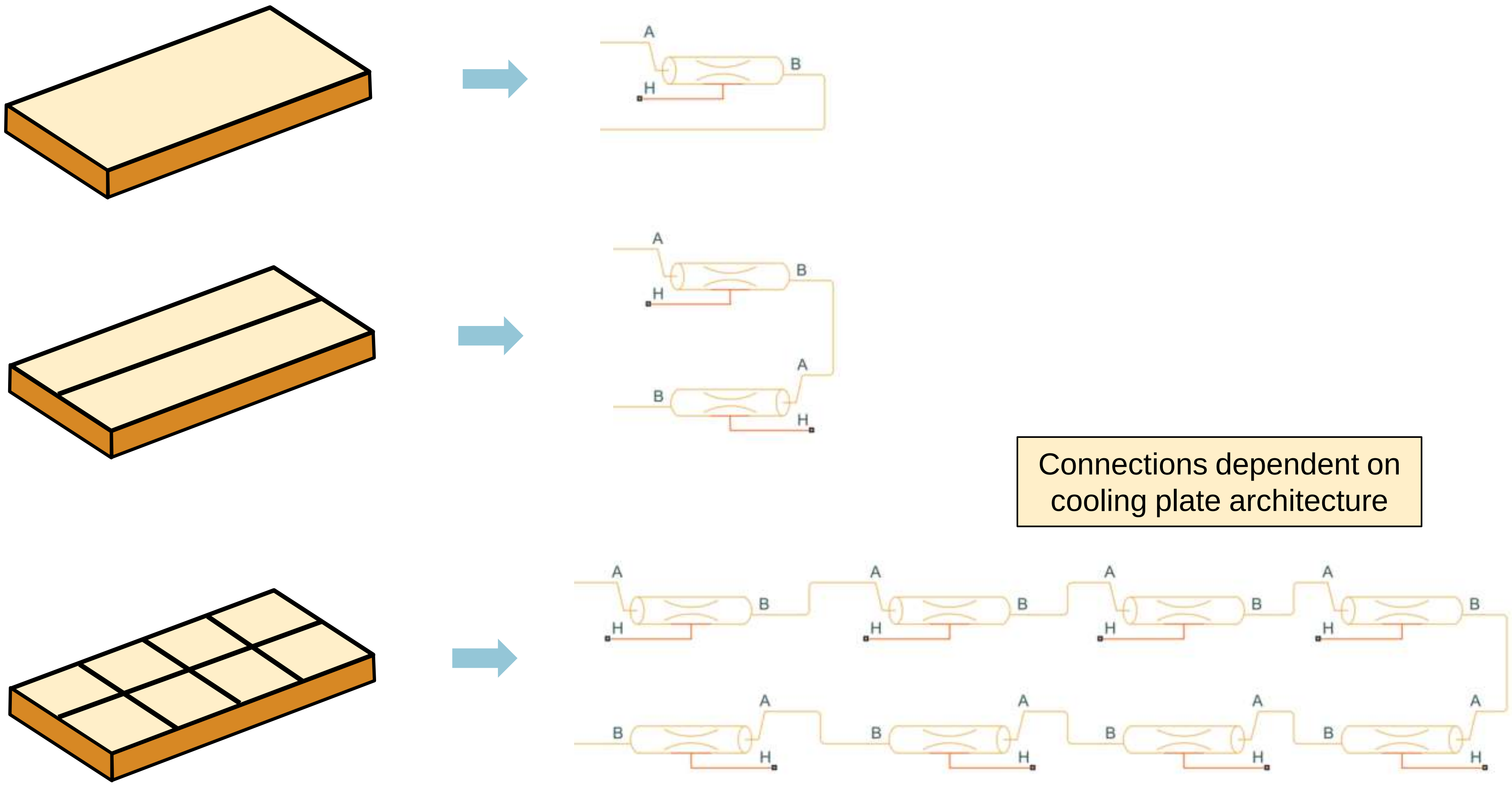
U-shaped Channels

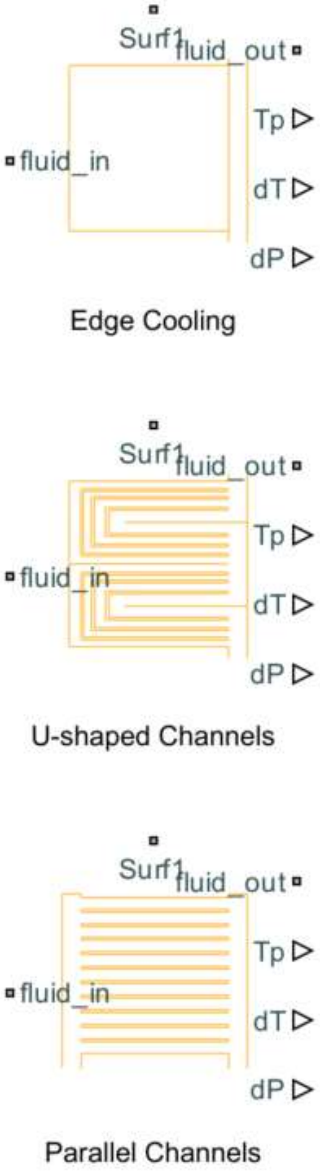


Parallel Channels

Thermal Management

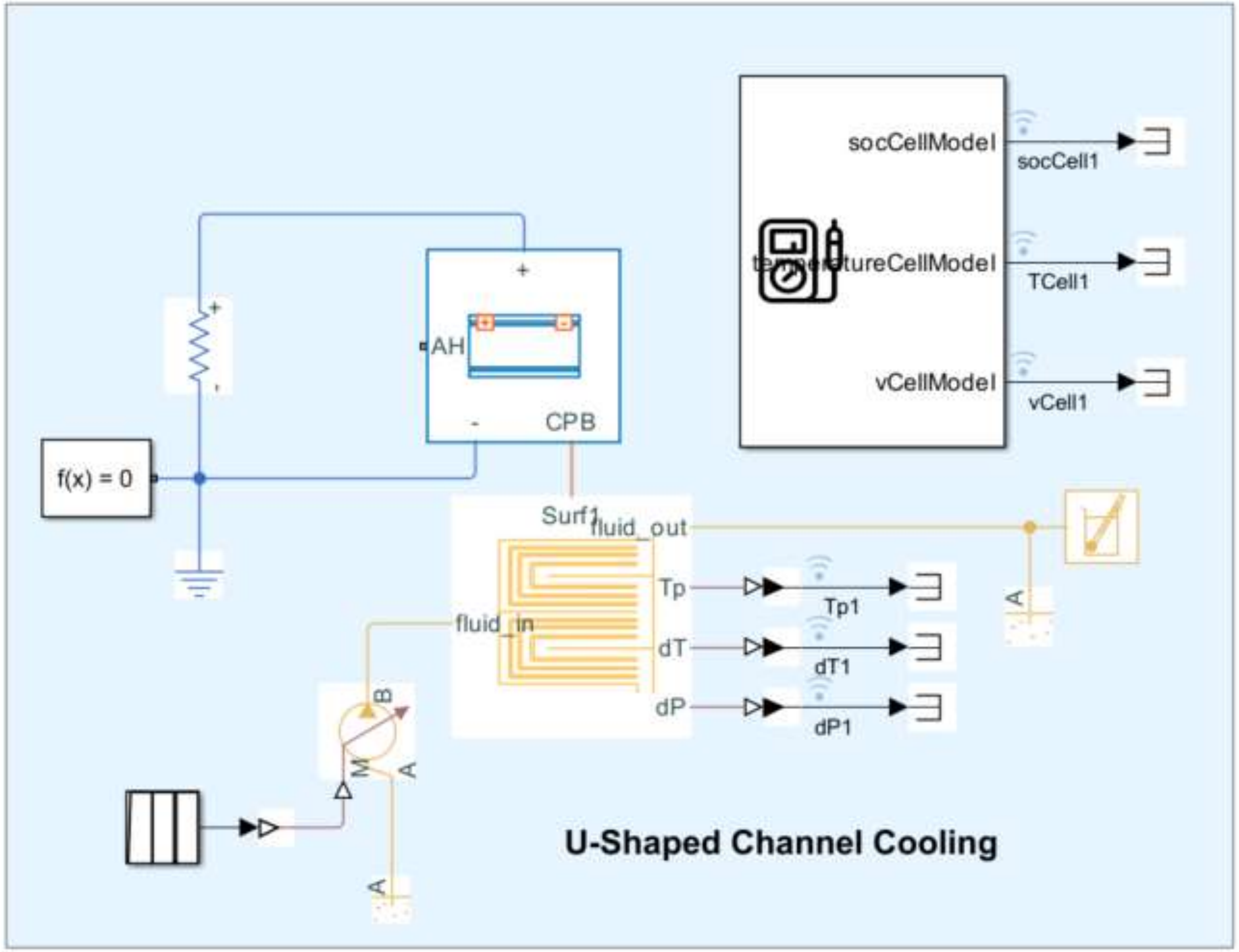
- Change the simulation strategy of cooling plates to meet your model resolution needs for the combined electrical and thermal system.

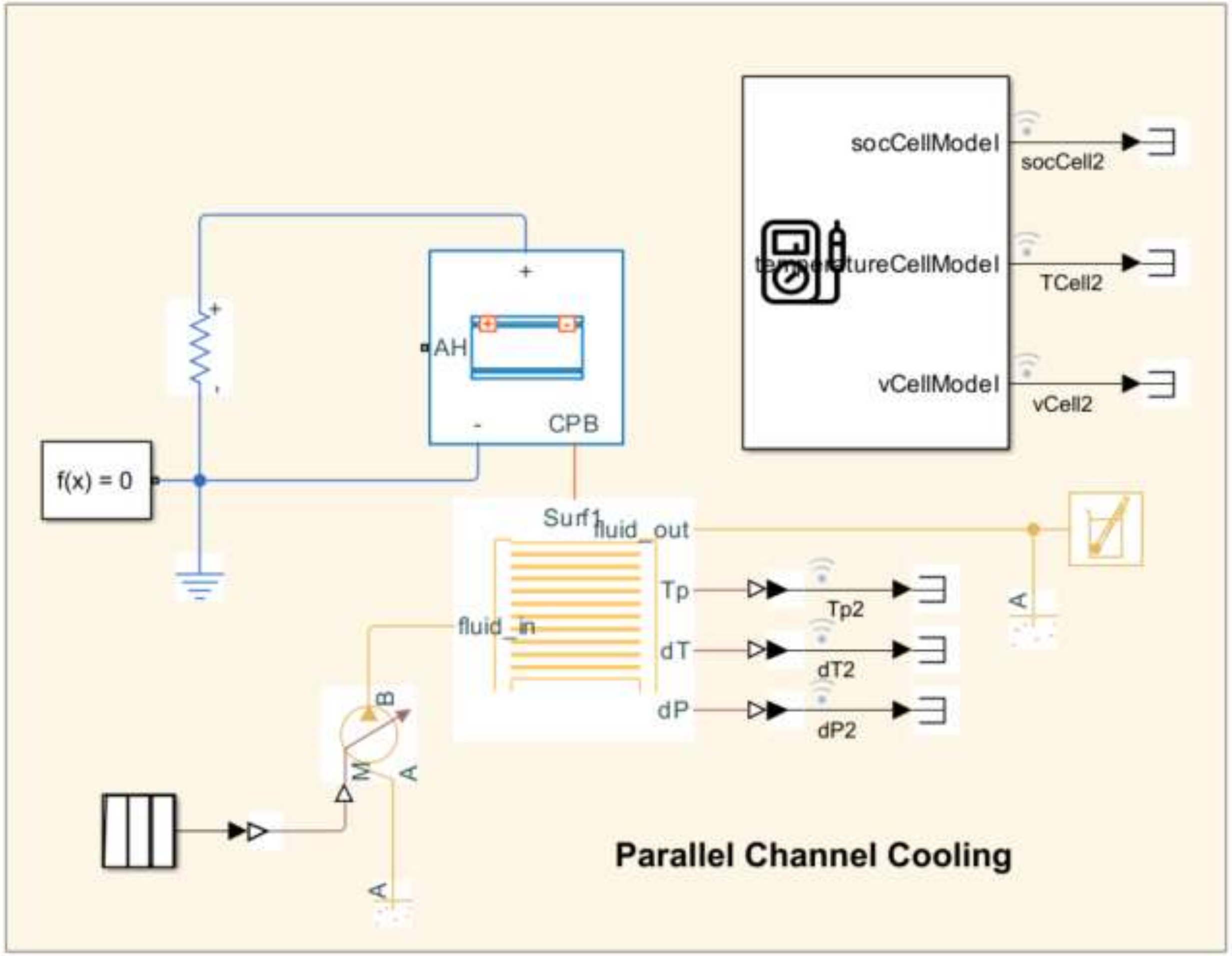




Thermal Management

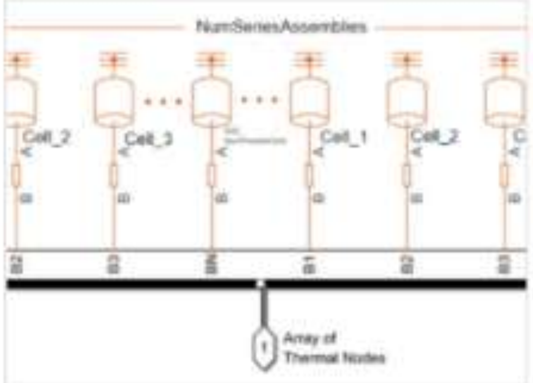
- Build out your cooling systems with Simscape Foundation components (Thermal Liquid).
- Clear onramp to Simscape Fluids if additional modeling capability is needed.





Thermal Management

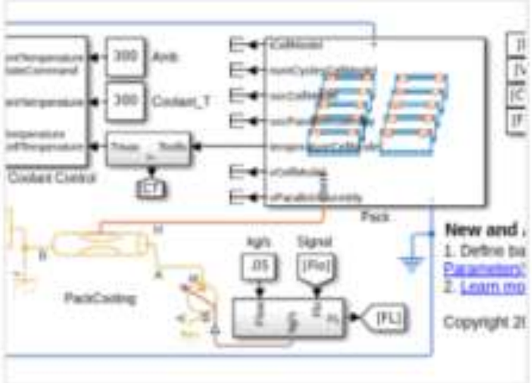
Thermal Management – Examples



Build Model of Battery Module with Thermal Effects

Create and build a Simscape system model of a battery module with thermal effects.

Open Live Script



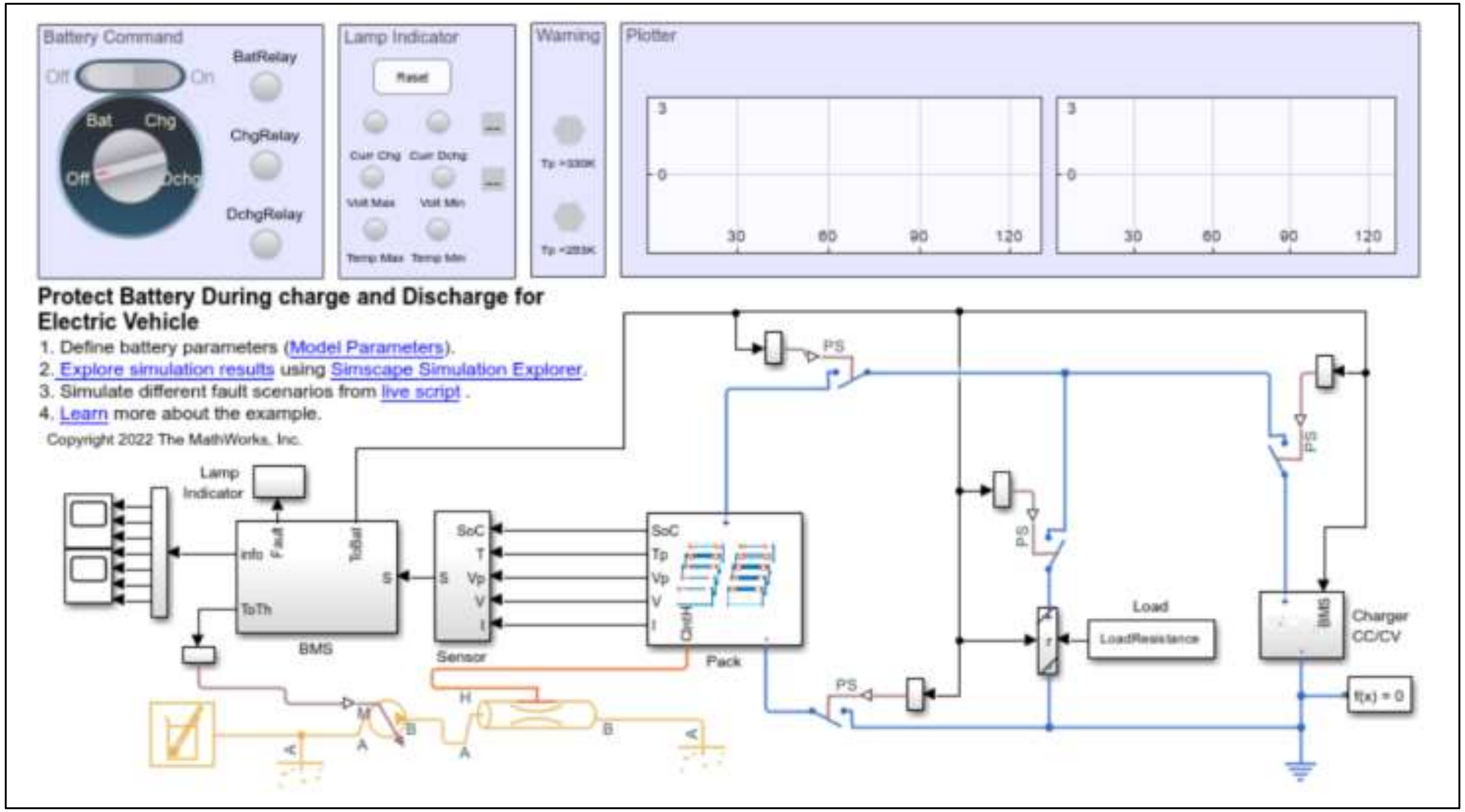
Thermal Analysis for New and Aged Battery Packs

Evaluate a new and end-of-life (EOL) lithium-ion battery pack. With cell usage and time, the capacity of the cell degrades and the resistance

Open Live Script

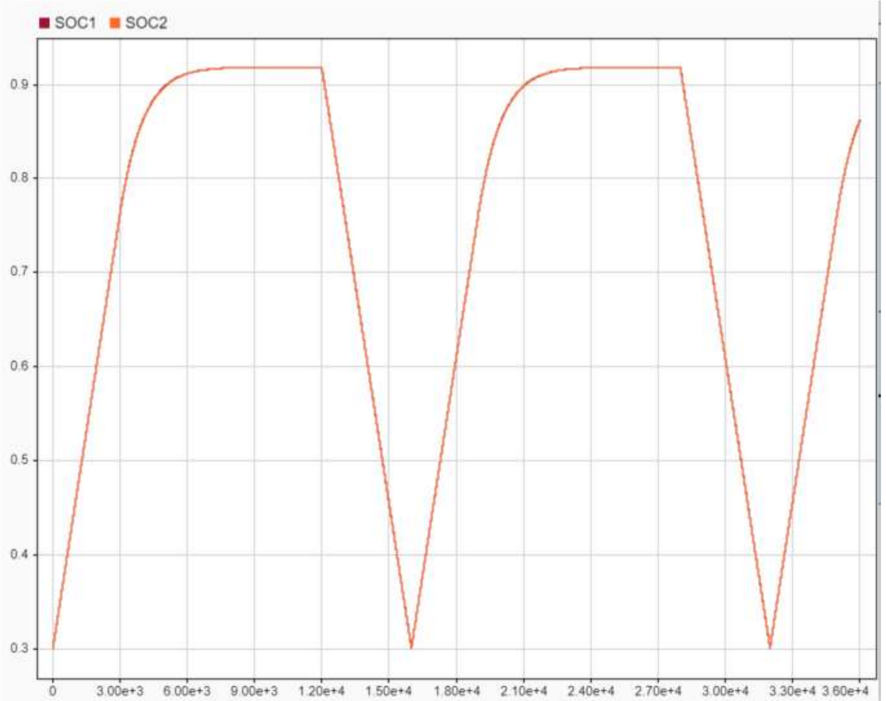
Battery Management

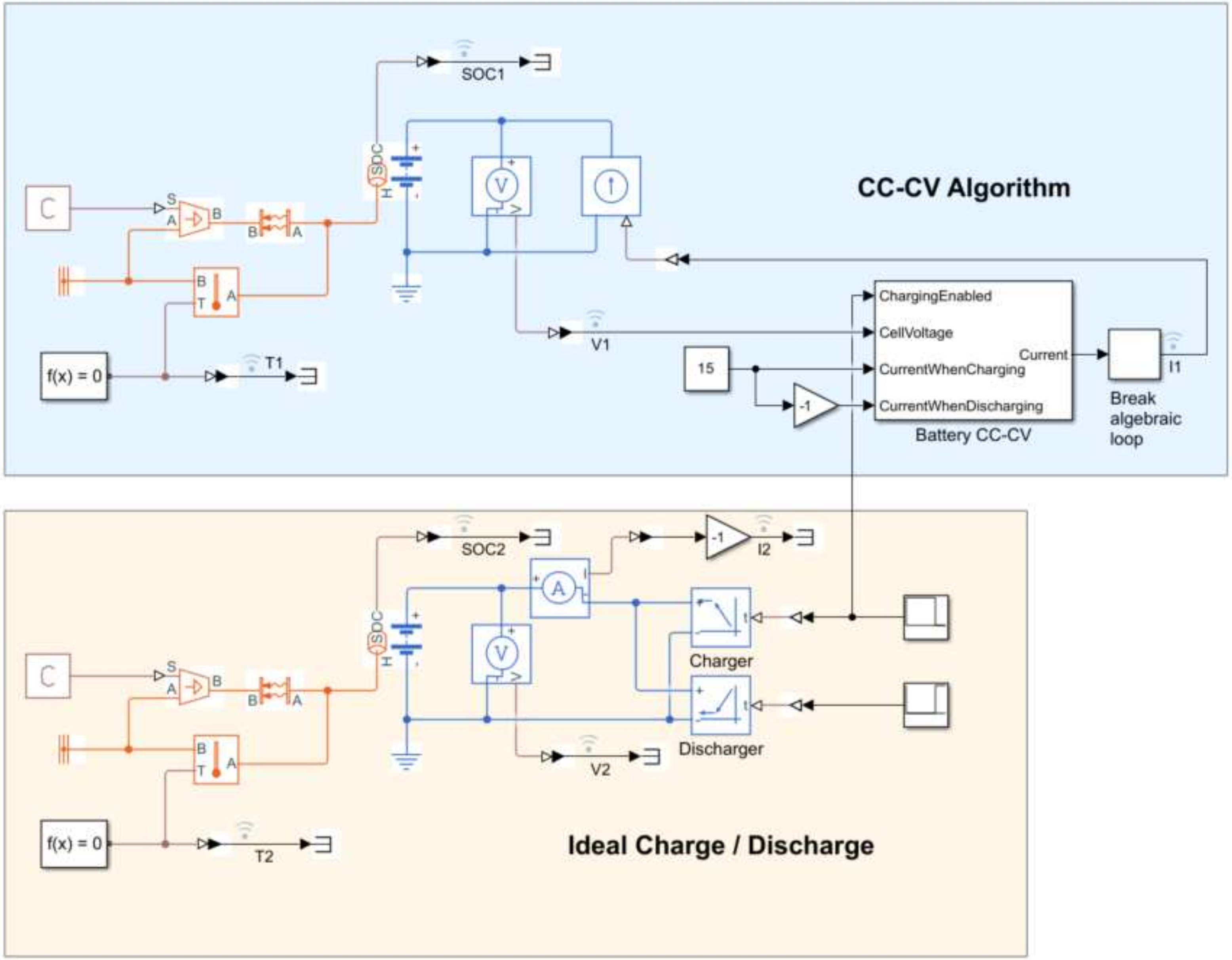
- Algorithms for cell balancing, current management, state-of-charge (SOC) and state-of-health (SOH) estimation, protection, and thermal management.
- Build out your electrical system with Simscape Foundation components (Electrical).
- Clear onramp to Simscape Electrical if additional electrical modeling capability is needed.



Battery Management

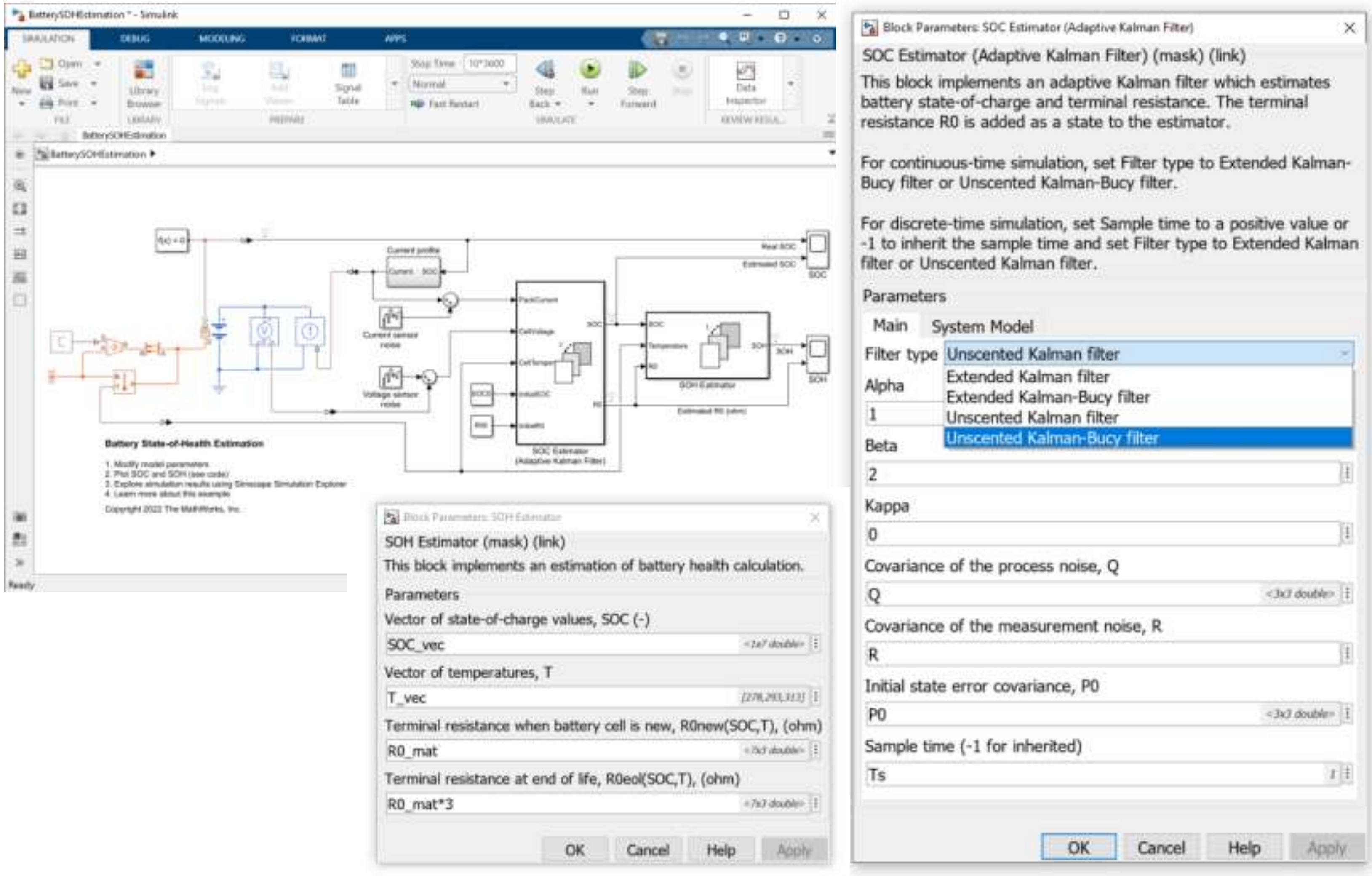
- Ideal charge/discharge components can be used to assess functional response of the battery pack prior to detailed control design.

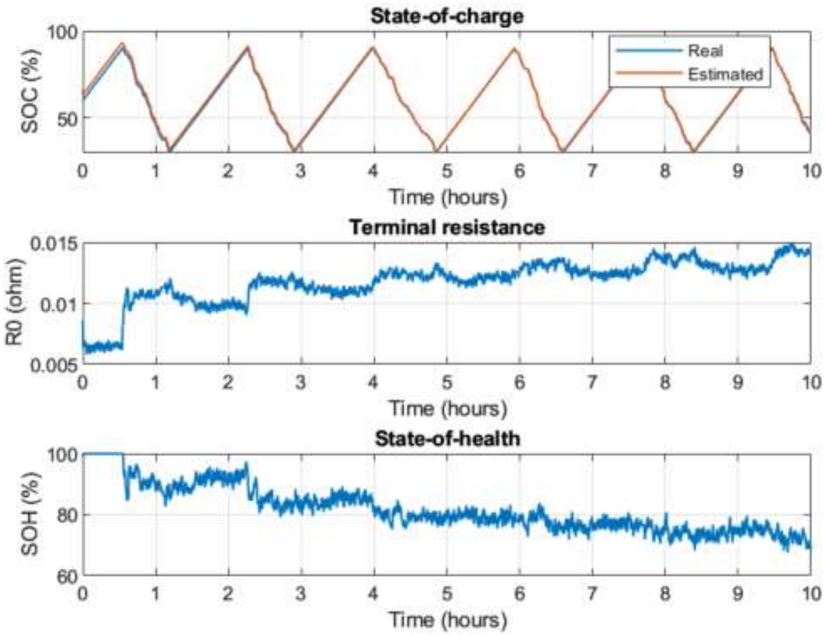




Battery Management

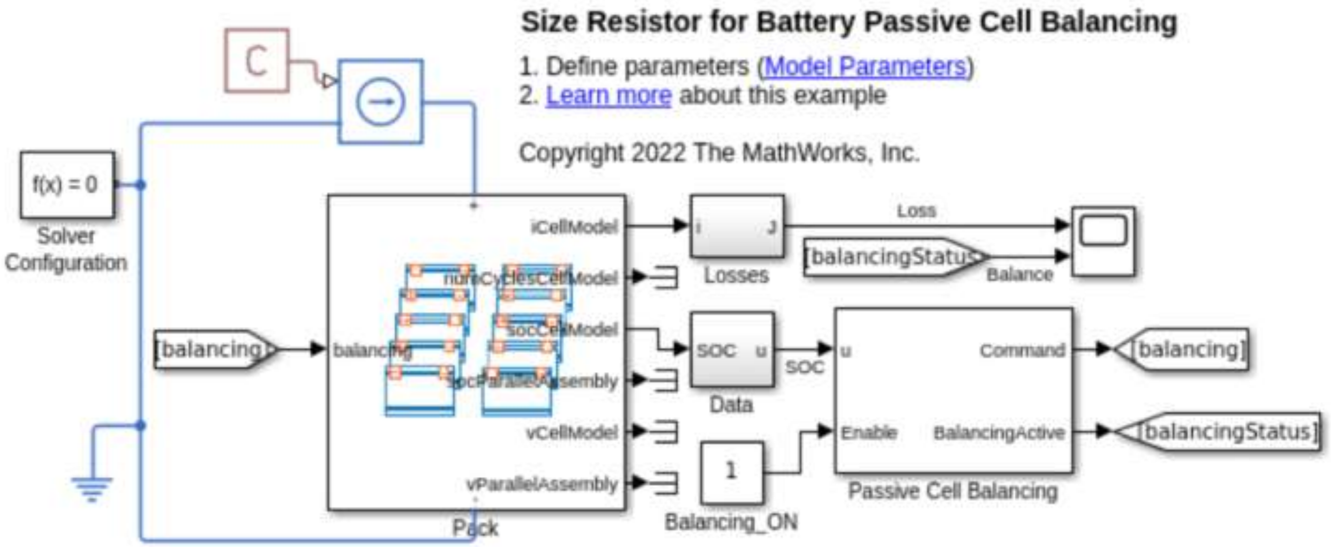
- A range of Kalman filters are available to estimate State-of-Charge (SOC), which can form an input to State-of-Health (SOH) estimation.

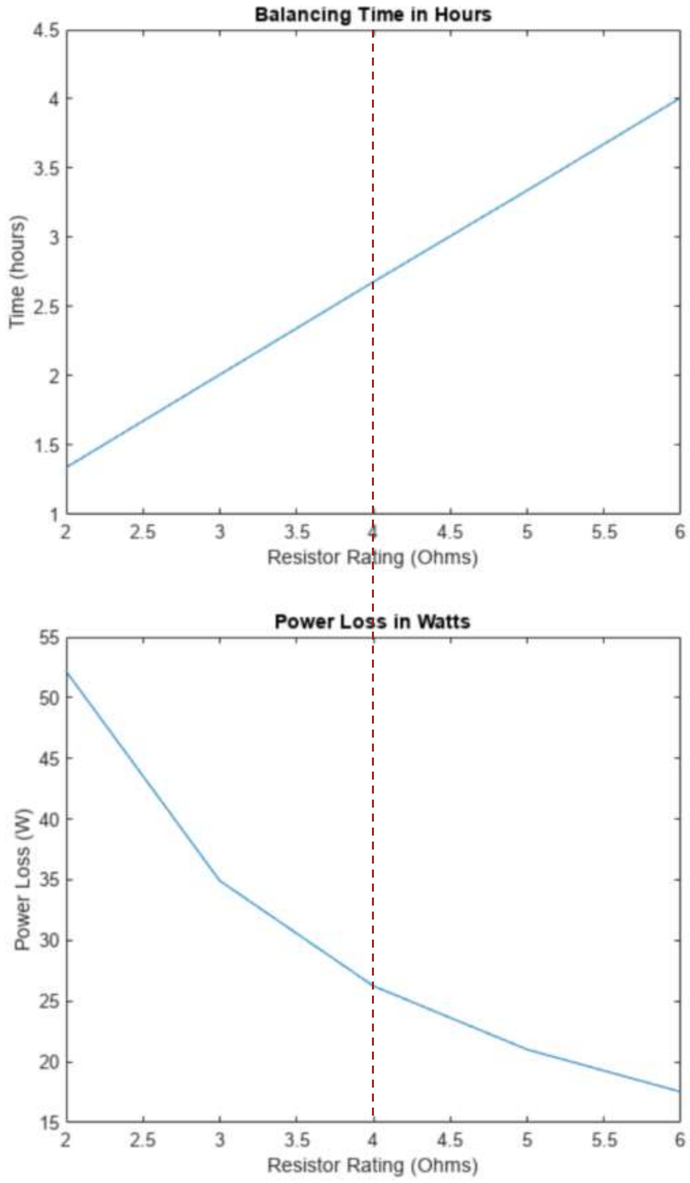




Battery Management

- Explore the design space by running multiple simulations programmatically.

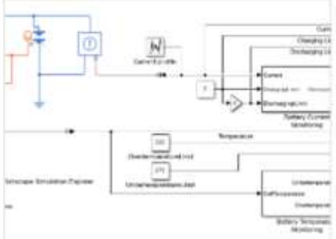




Battery Management

Battery Management System — Examples

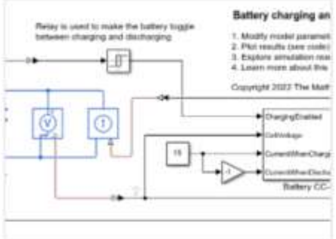
R2022b



Battery Monitoring

Use battery management system blocks to monitor the current and temperature of a battery. A random current and temperature profile is

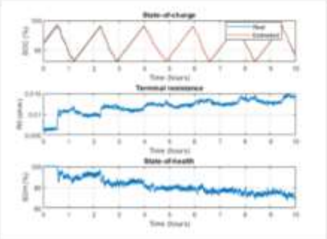
Open Script



Battery Charging and Discharging

Use a constant current and constant voltage algorithm to charge and discharge a battery. The Battery CC-CV block is charging and

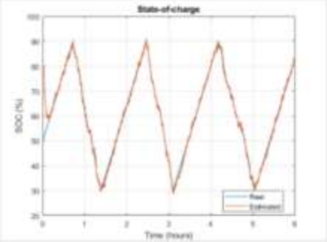
Open Script



Battery State-of-Health Estimation

Estimate the battery internal resistance and state-of-health (SOH) by using an adaptive Kalman filter. The initial state-of-charge (SOC) of

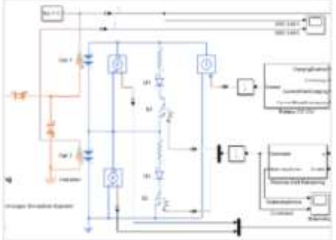
Open Script



Battery State-of-Charge Estimation

Estimate the battery state-of-charge (SOC) by using a Kalman filter. The initial SOC of the battery is equal to 0.5. The estimator uses an initial

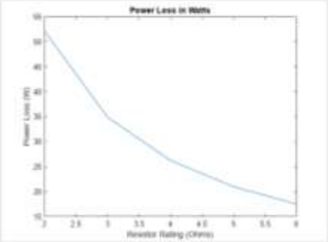
Open Script



Battery Passive Cell Balancing

Balance a battery with two cells connected in series by using a passive cell balancing algorithm. The initial state-of-charge (SOC) for

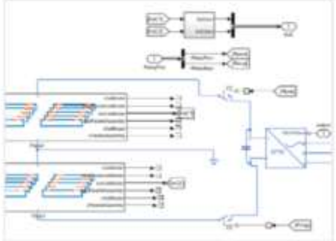
Open Script



Size Resistor for Battery Passive Cell Balancing

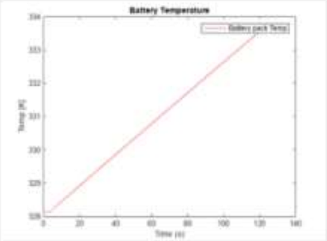
Implement a passive cell balancing for a lithium-ion battery pack. Cell-to-cell differences in the battery module create imbalances in the cell

Open Live Script



Peak Shaving with Battery Energy Storage System

Open Live Script



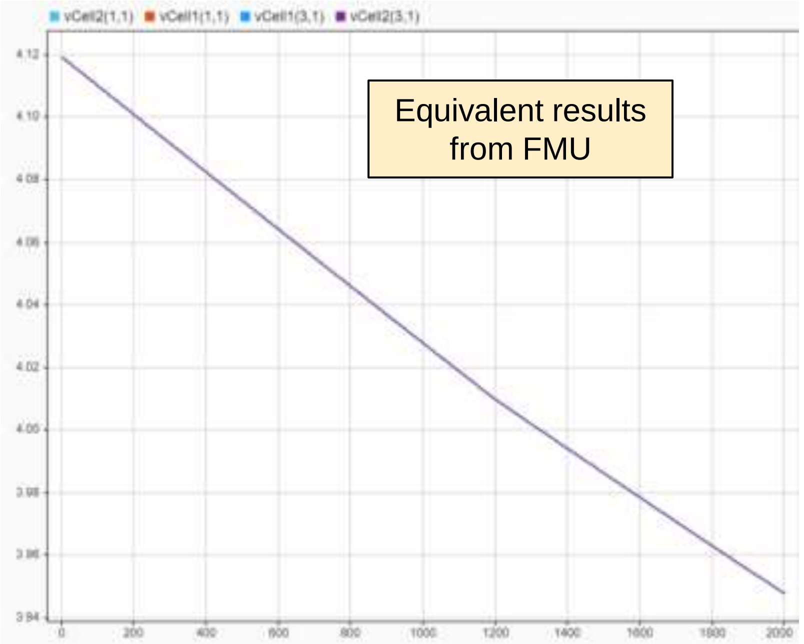
Protect Battery During Charge and Discharge for Electric Vehicle

Efficiently charge and discharge a battery for an electric vehicle (EV) and handle battery faults. Portable electronics and EV widely use li-ion

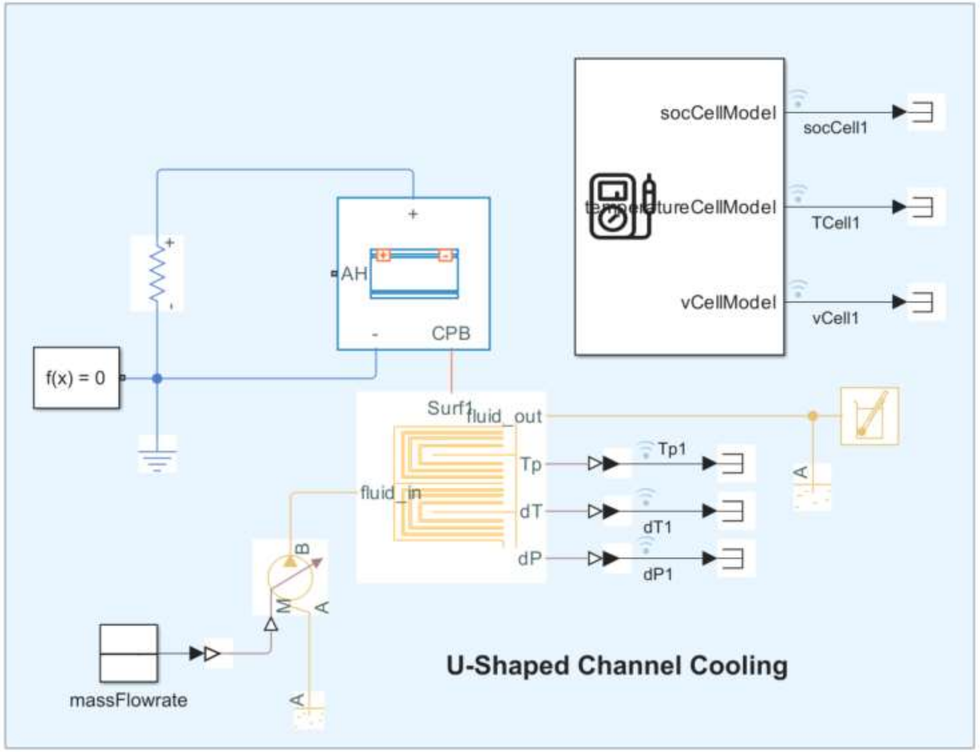
Open Live Script

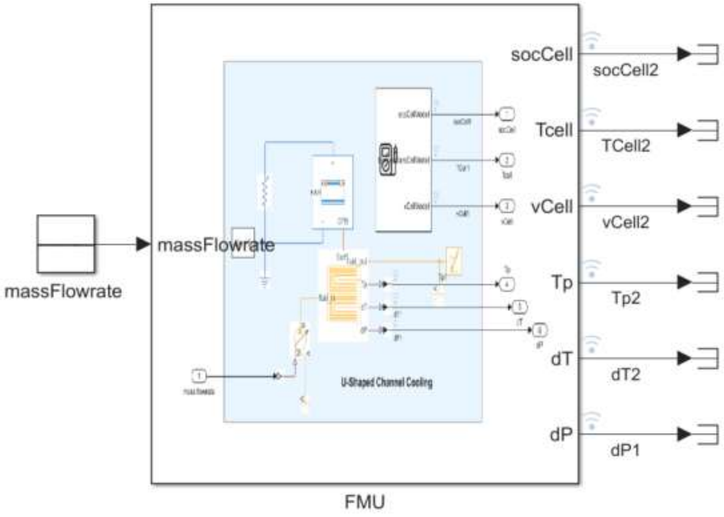
Deployment and Hardware-in-the-Loop (HIL)

- BMS algorithms and Simscape Battery models are compatible with [Simulink Compiler](), [Simulink Coder]()and [Simulink Real-Time]().
- BMS algorithms generate readable and efficient C/C++ code.



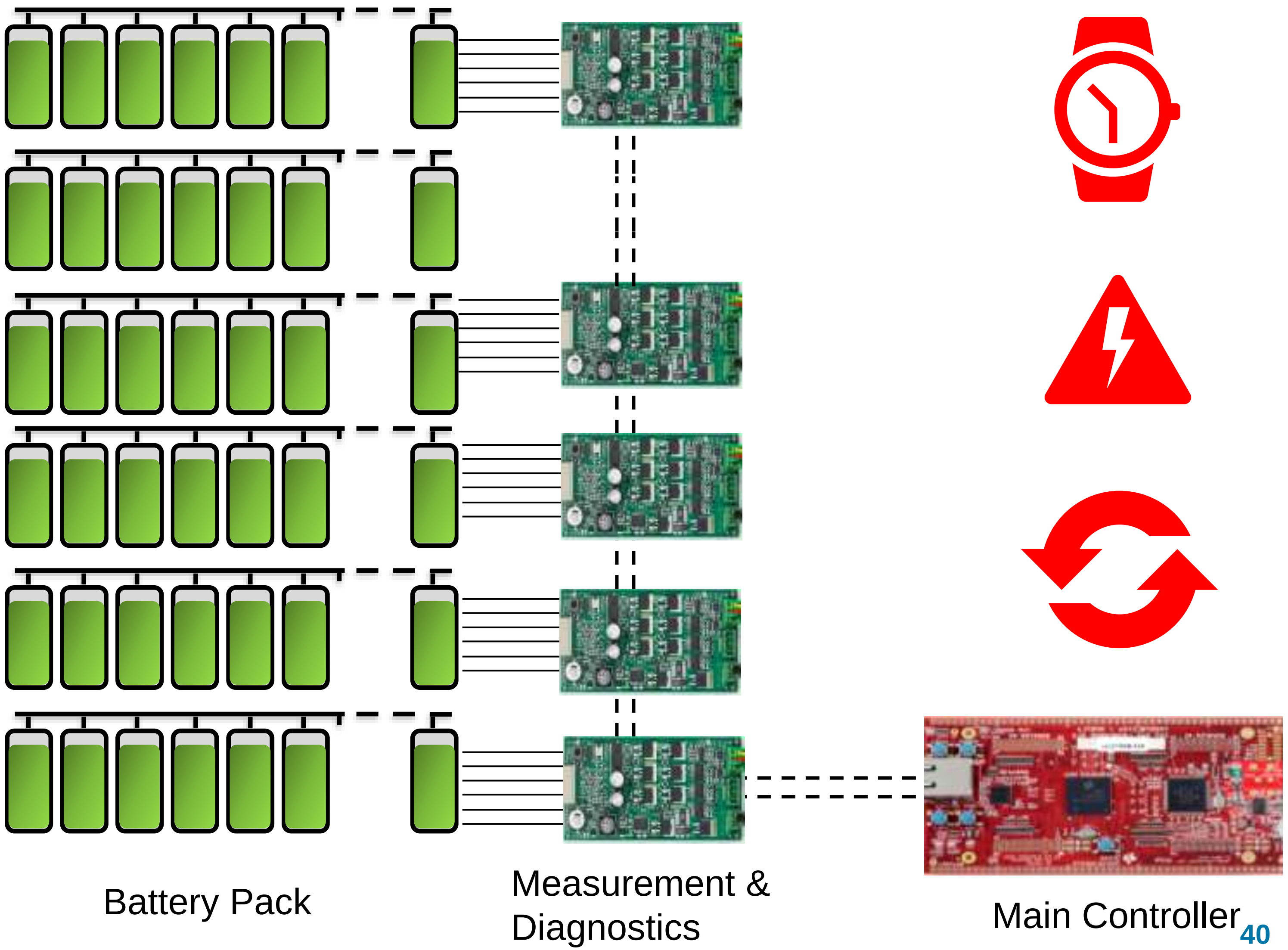
Example – Create an FMU from a Simscape Battery model





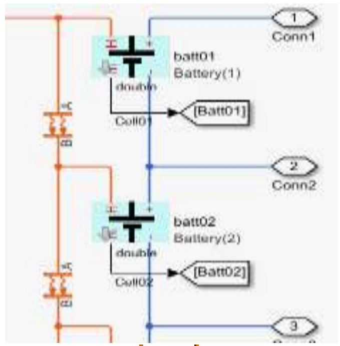
Real-Time Testing of Battery Management System

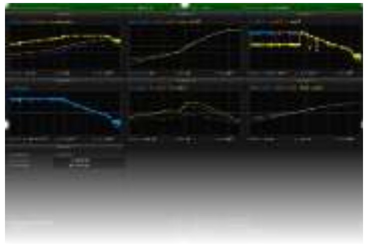
- Testing BMS with Battery Cells
  - Longer test cycles
  - Difficult to reproduce results
  - Difficult to test fault conditions
  - Limited test automation

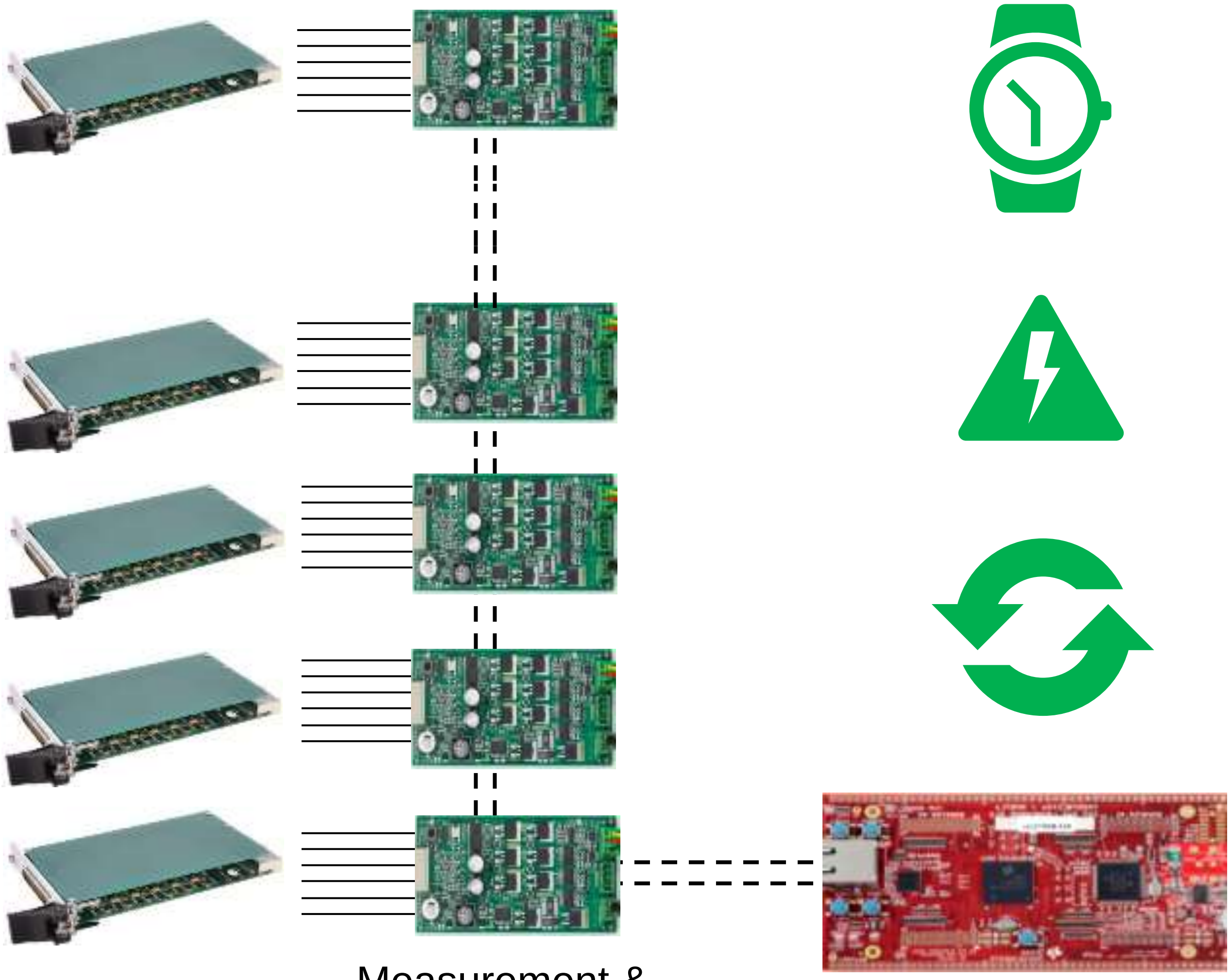


Hardware-In-Loop Testing of Battery Management System

- Testing BMS with Emulated Battery Cells
  - Reduce testing time
  - Test fault conditions safely
  - Automate testing



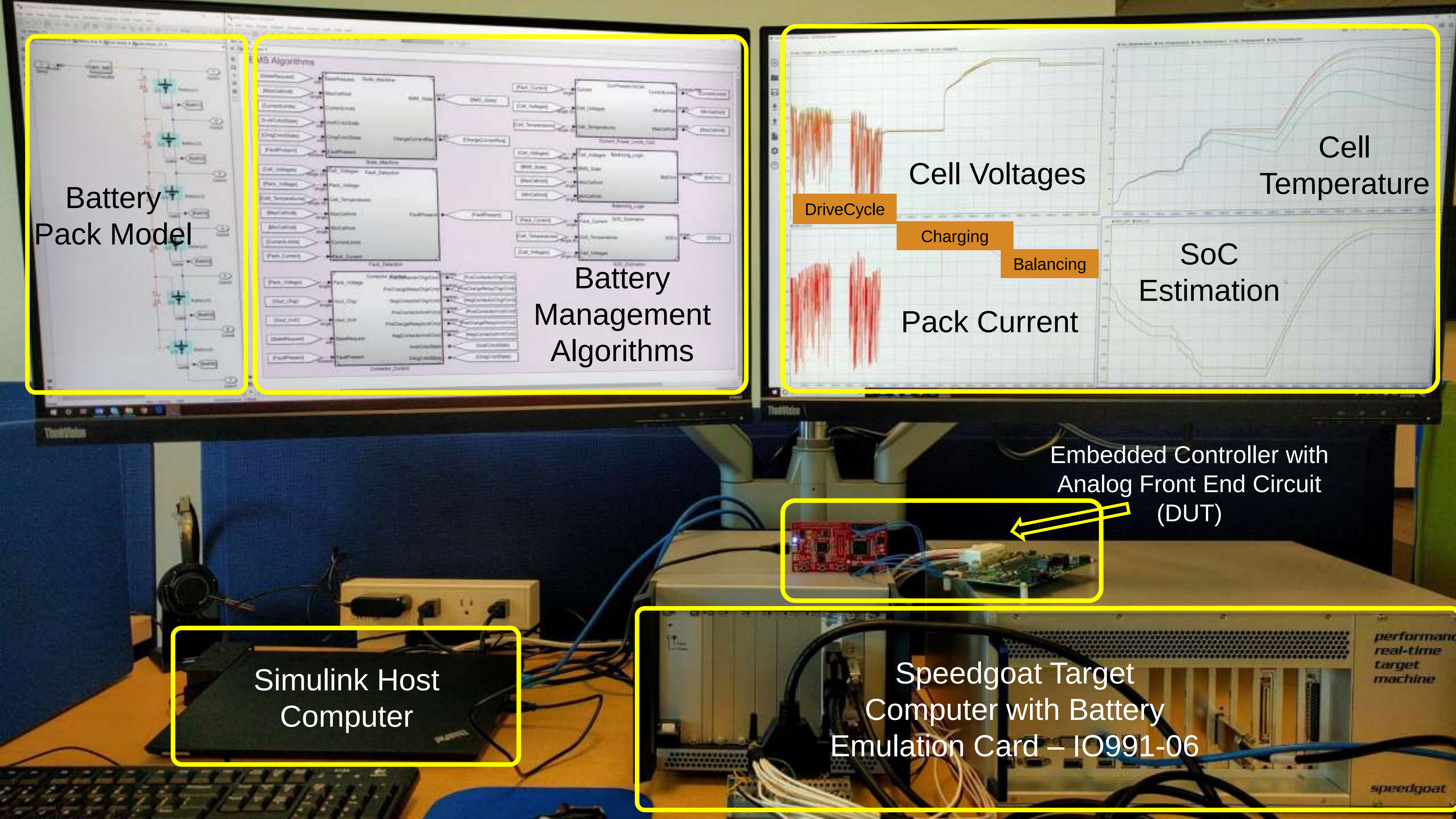




Battery Emulation

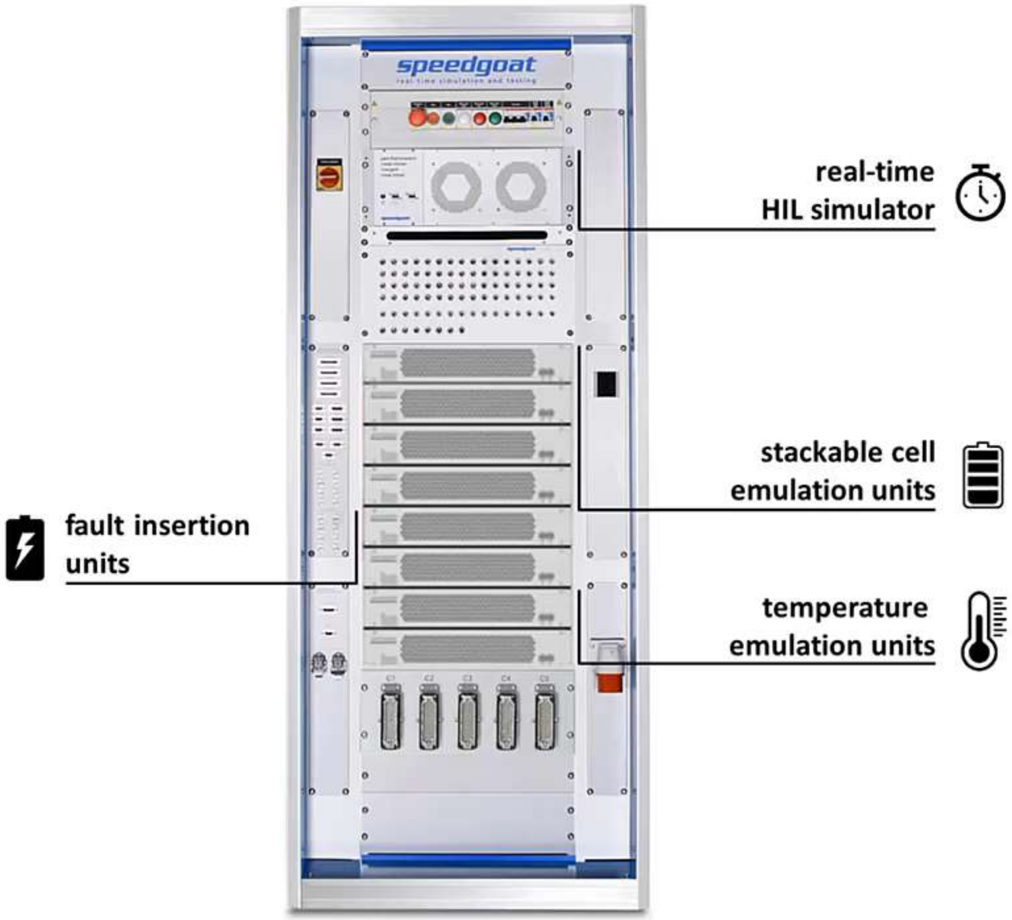
Measurement &
Diagnostics

Main Controller



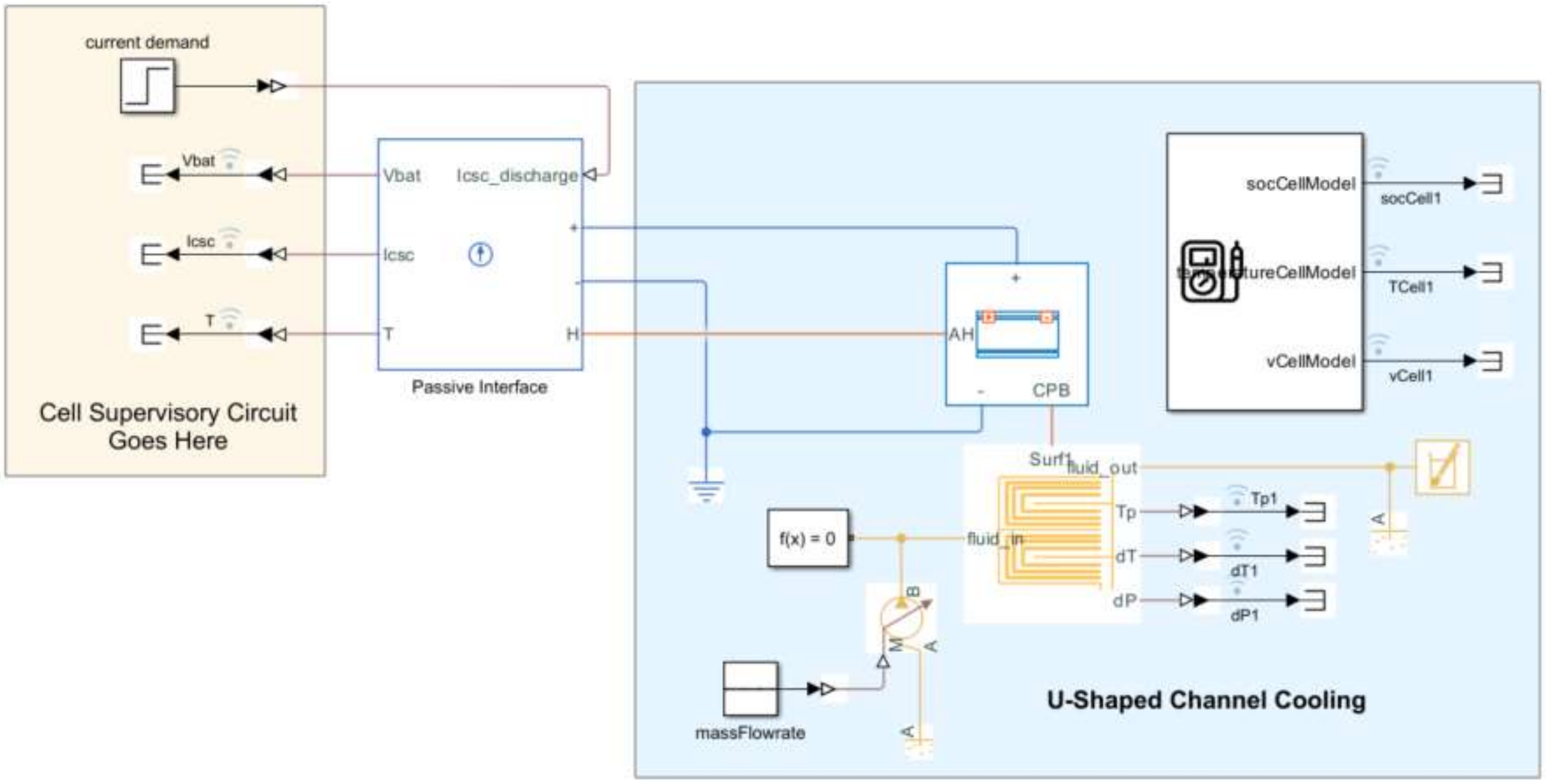
Battery Pack Model
Battery Management Algorithms
Cell Voltages
Cell Temperature
DriveCycle
Charging
Balancing
SoC Estimation
Pack Current
Embedded Controller with Analog Front End Circuit (DUT)
Simulink Host Computer
Speedgoat Target Computer with Battery Emulation Card – IO991-06
performance real-time target machine
speedgoat

HIL Testing of Battery Management Systems



Deployment and Hardware-in-the-Loop (HIL)

- HIL interface blocks (which also work in desktop simulation) offer a convenient way to connect your battery to a cell supervisory circuit by packaging input signals, measurements, and a controlled current source in a single unit.

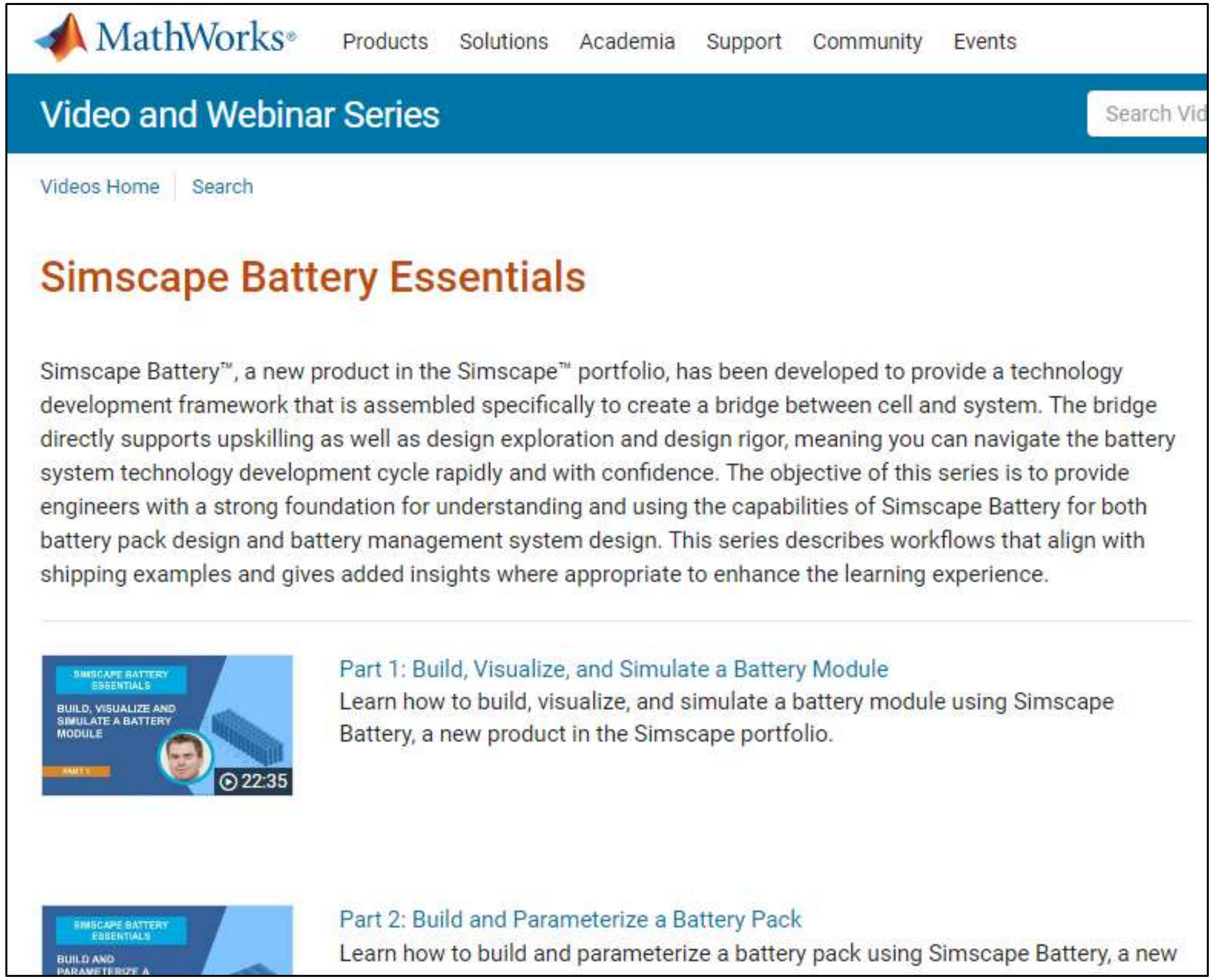


Key Takeaways

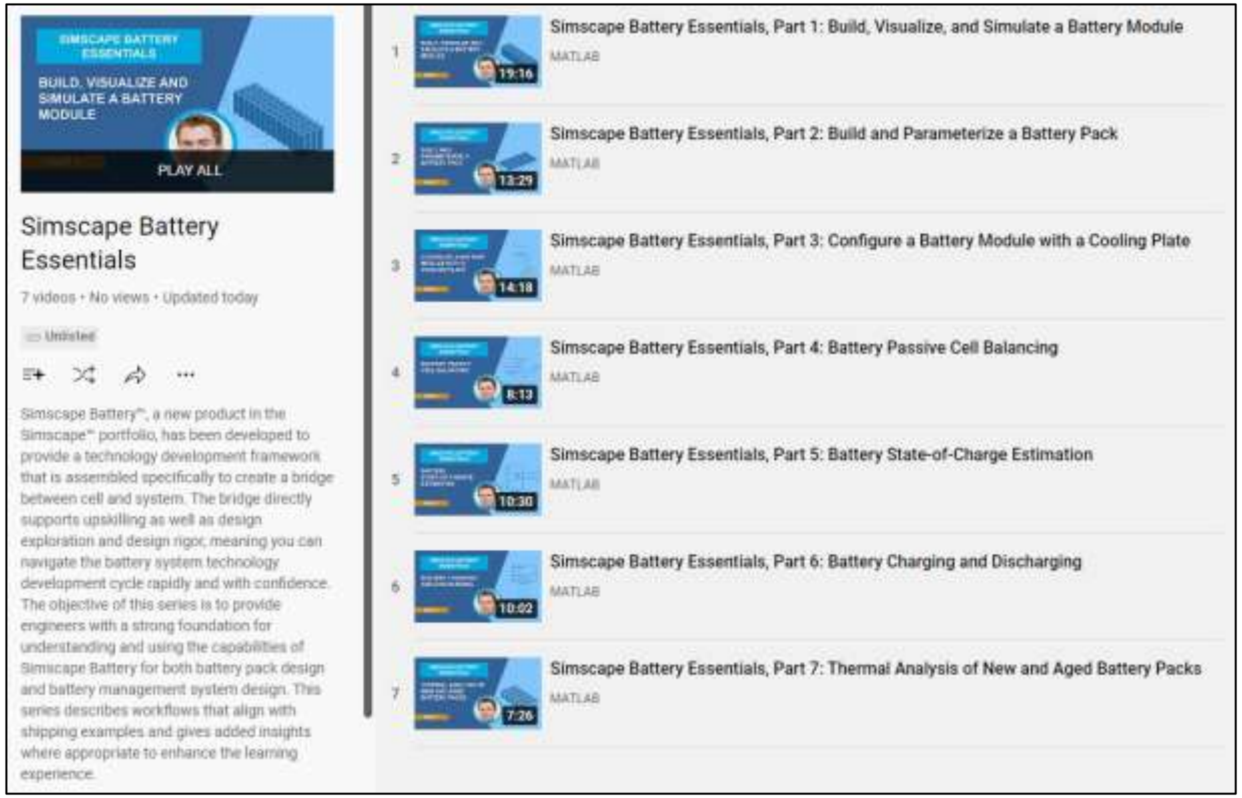
- Simscape Battery provides a framework that is assembled specifically to create a bridge between cell and system.
- The bridge directly supports upskilling as well as design exploration and design rigor, meaning you can navigate the technology development cycle rapidly and with confidence.
  - Battery Pack Design, Electrical and Thermal Battery Pack Components, BMS Algorithms and Components, HIL and Deployment Support, Reference Tutorials and Examples
- Using the PDE Toolbox and Simscape battery, you can create a Reduced Order Model(ROM) of battery thermal behavior at the system level from FEA models.

On the Web

[Simscape Battery Essentials on MathWorks.com]



[Simscape Battery Essentials on YouTube]



On the Web

[AI 기법을 사용한 전기 기술]

[HIL Testing of Battery Management Systems]

Questions?

MathWorks

전력전자학술대회 - MathWorks 산업기술세션

MathWorks Korea
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