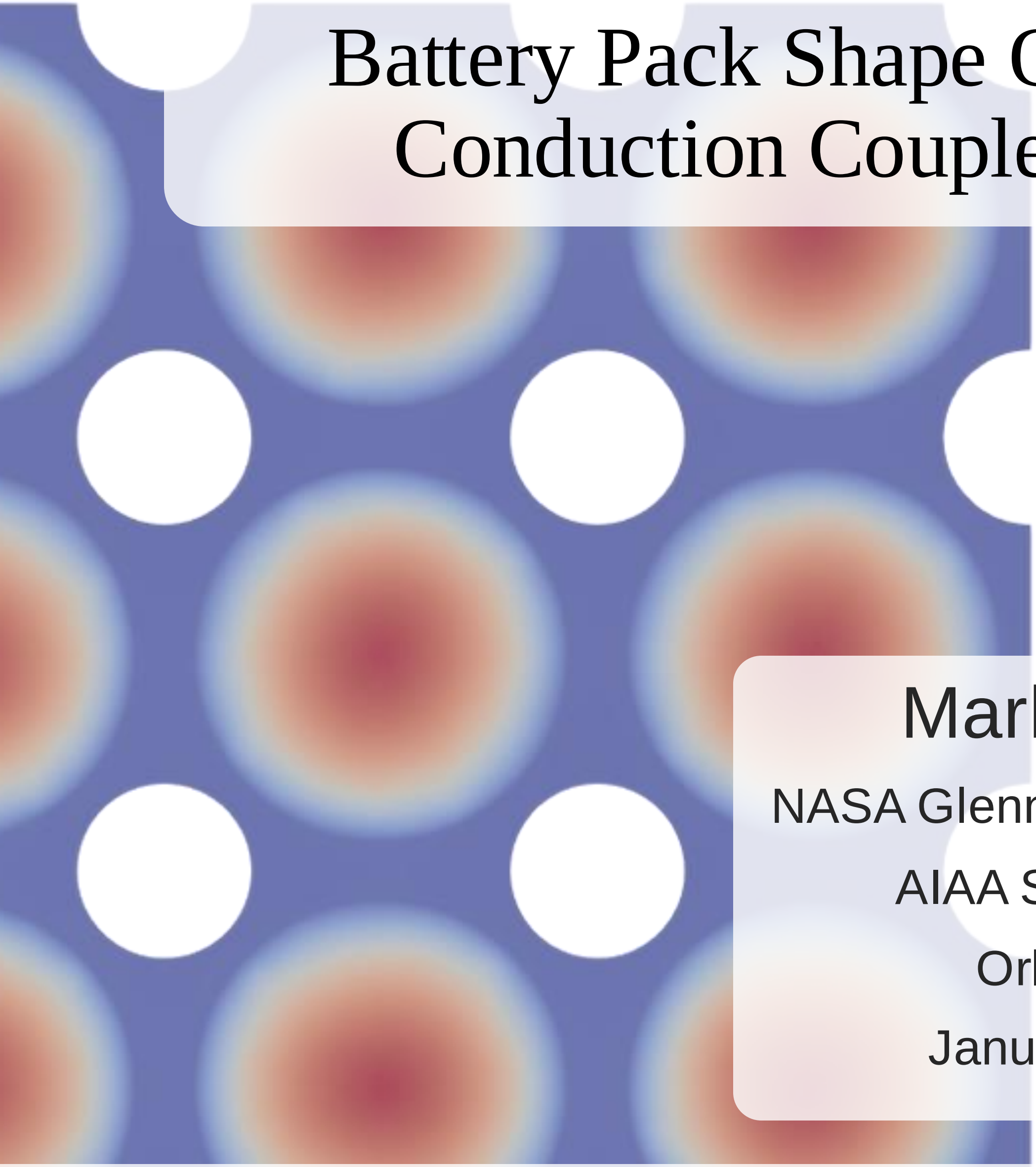
Battery Pack Shape Optimization using Transient Heat Conduction Coupled with Cell-Discharge Analysis



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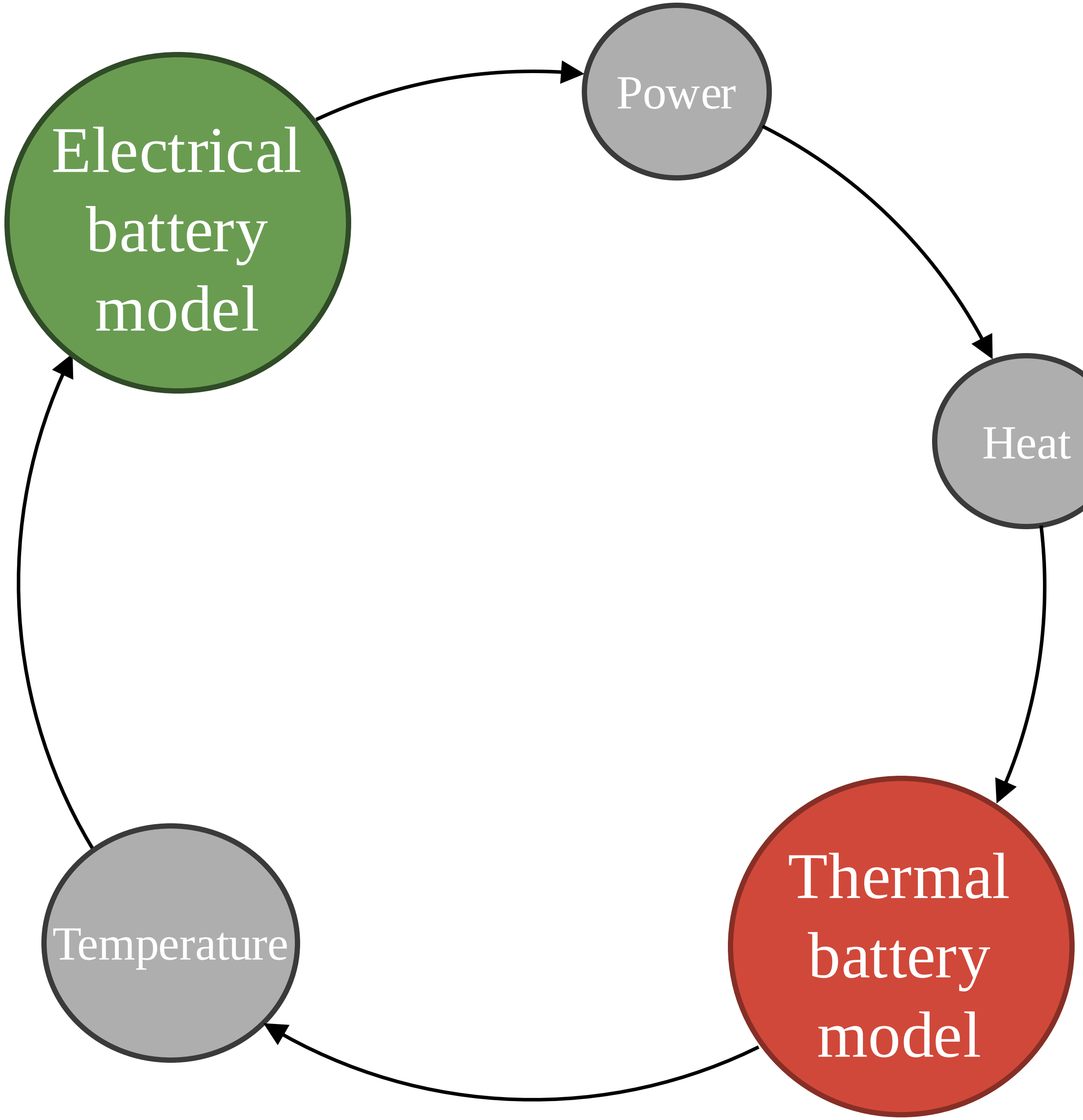
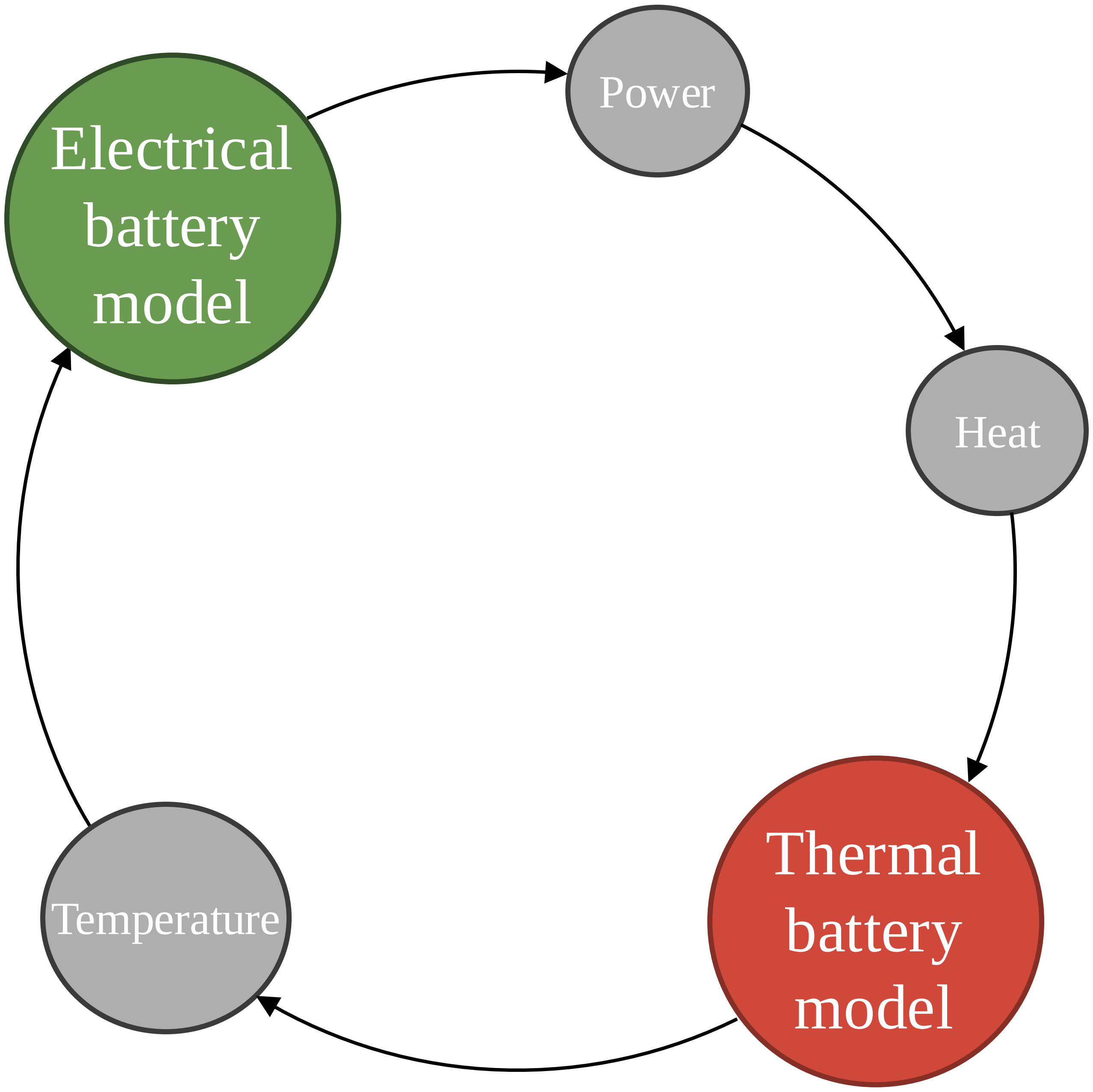
Motivation

- Battery-electric propulsion will be a significant contributing factor in reducing net carbon aviation emissions
- We need MDAO-enabled battery pack models to support these objectives

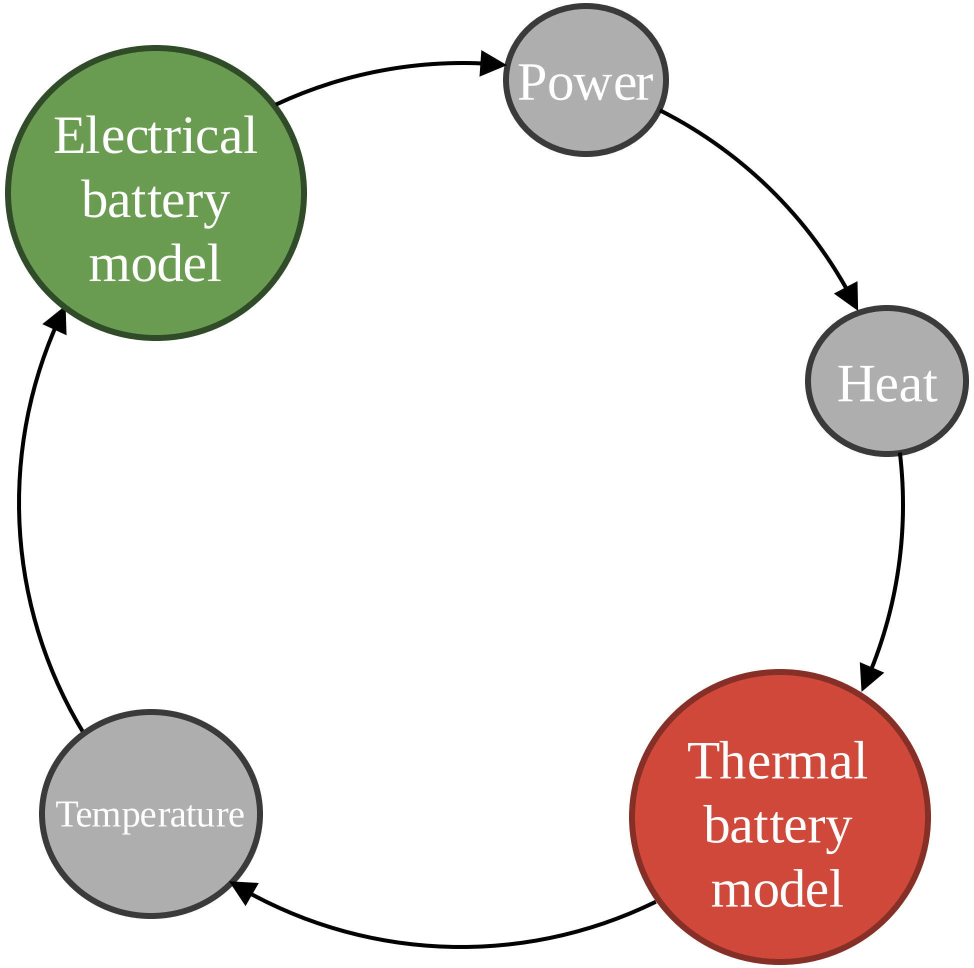
- Challenges associated with battery pack optimization and design:
  - Batteries must be kept below their temperature limit for operational safety
  - Electrical and thermal behavior are coupled, and highly transient
  - Battery packs should be as light-weight as possible to improve pack-energy-density


Electrical battery model
Power
Heat
Thermal battery model
Temperature

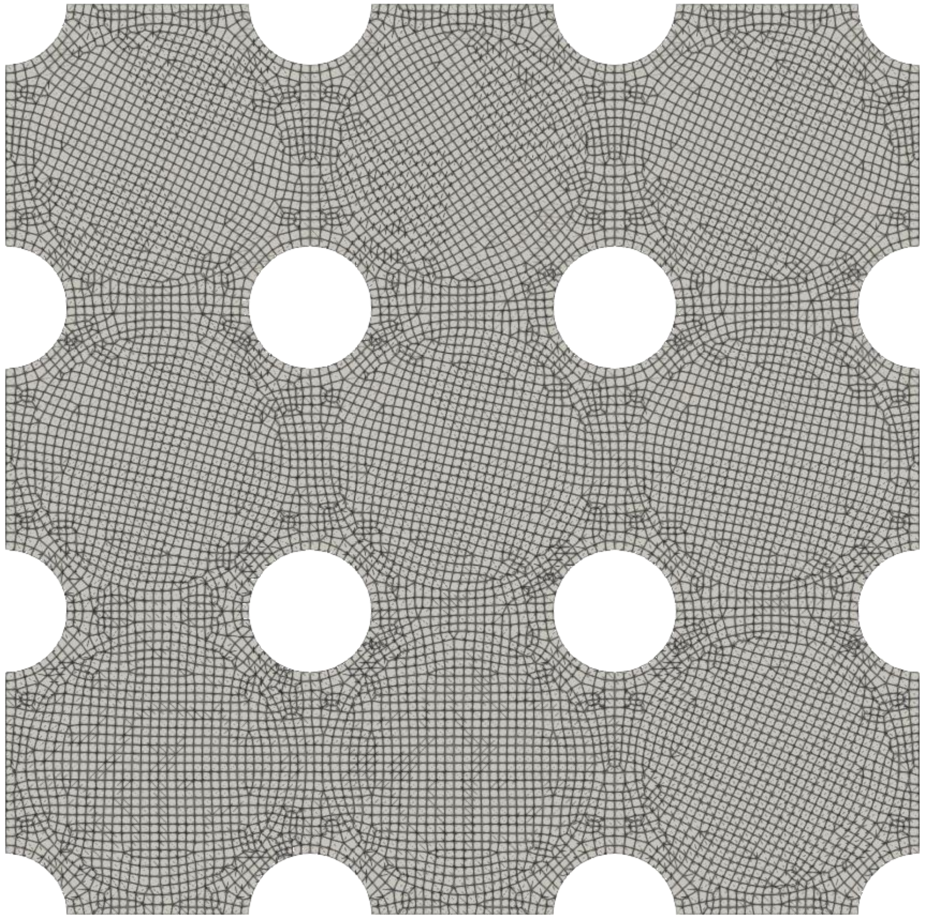
These are all a function of time



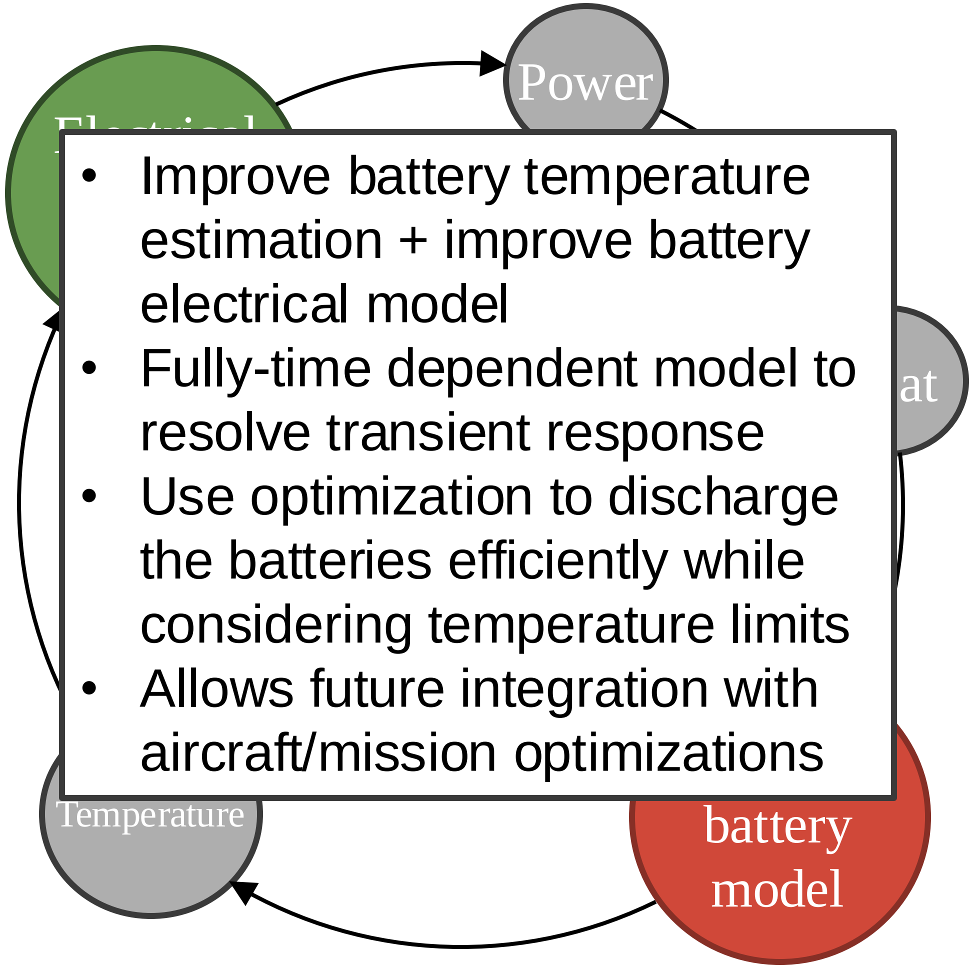
Coupled transient thermal-electrical battery model



Shape optimization

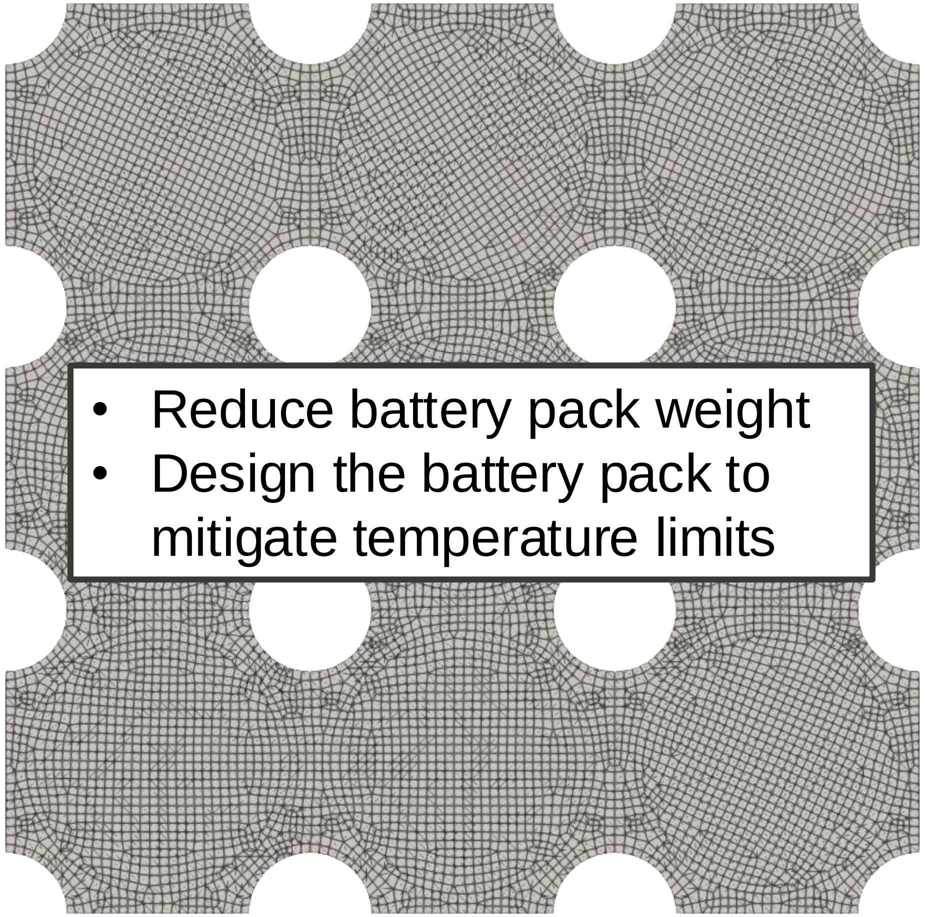


Coupled transient thermal-electrical battery model



- Improve battery temperature estimation + improve battery electrical model
- Fully-time dependent model to resolve transient response
- Use optimization to discharge the batteries efficiently while considering temperature limits
- Allows future integration with aircraft/mission optimizations

Shape optimization



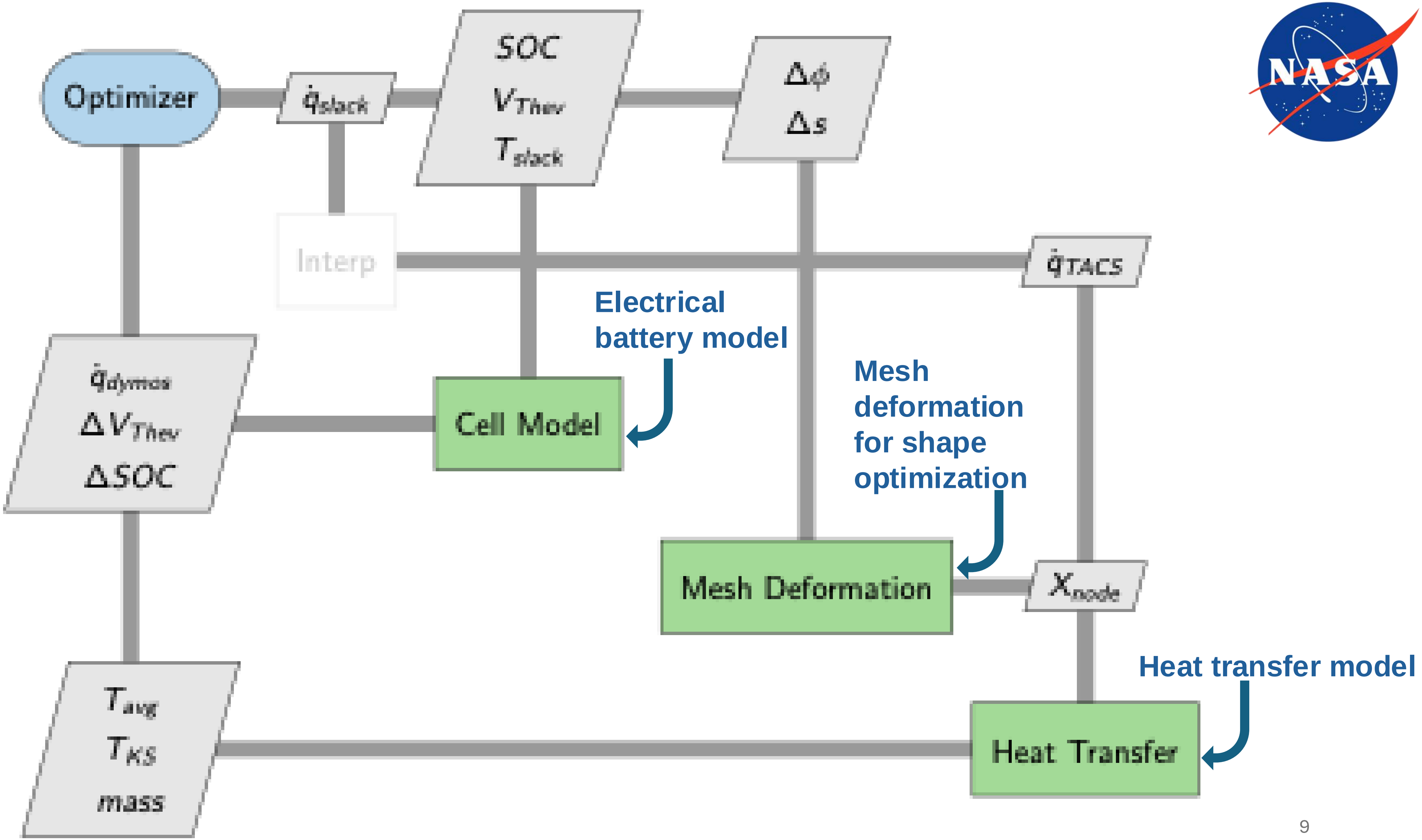
- Reduce battery pack weight
- Design the battery pack to mitigate temperature limits

Optimization:
https://github.com/OpenMDAO/OpenMDAO

Heat transfer analysis:
https://github.com/smdogroup/tacs

TACS

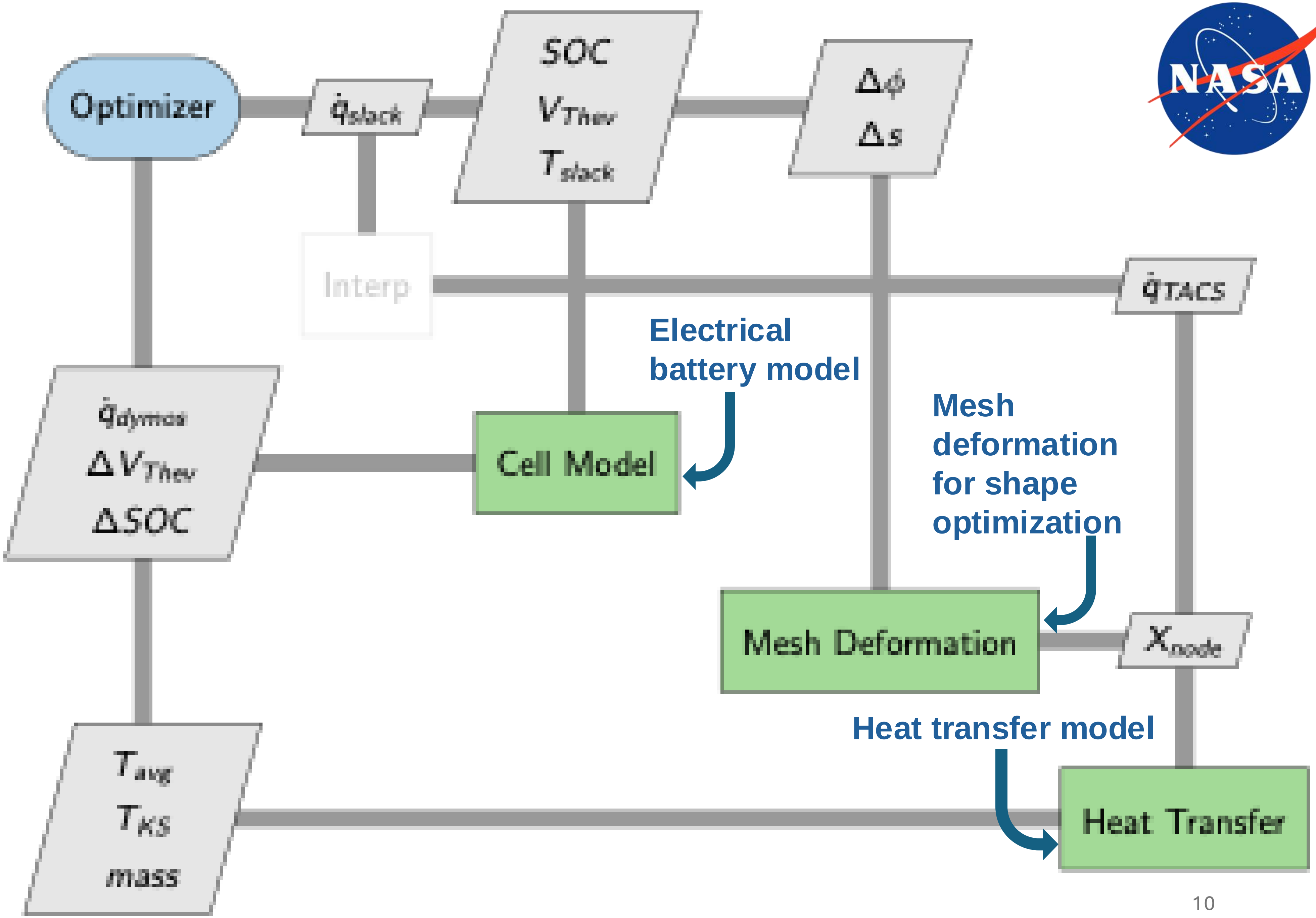
Electrical battery model:
https://github.com/OpenMDAO/dymos


Optimizer
$\dot{q}_{slack}$
SOC
V_{Thev}
T_{slack}
$\Delta\phi$
Δs
Interp
$\dot{q}_{TACS}$
Electrical battery model
$\dot{q}_{dymos}$
ΔV_{Thev}
ΔSOC
Cell Model
Mesh deformation for shape optimization
Mesh Deformation
X_{node}
Heat transfer model
Heat Transfer
T_{avg}
T_{KS}
$mass$

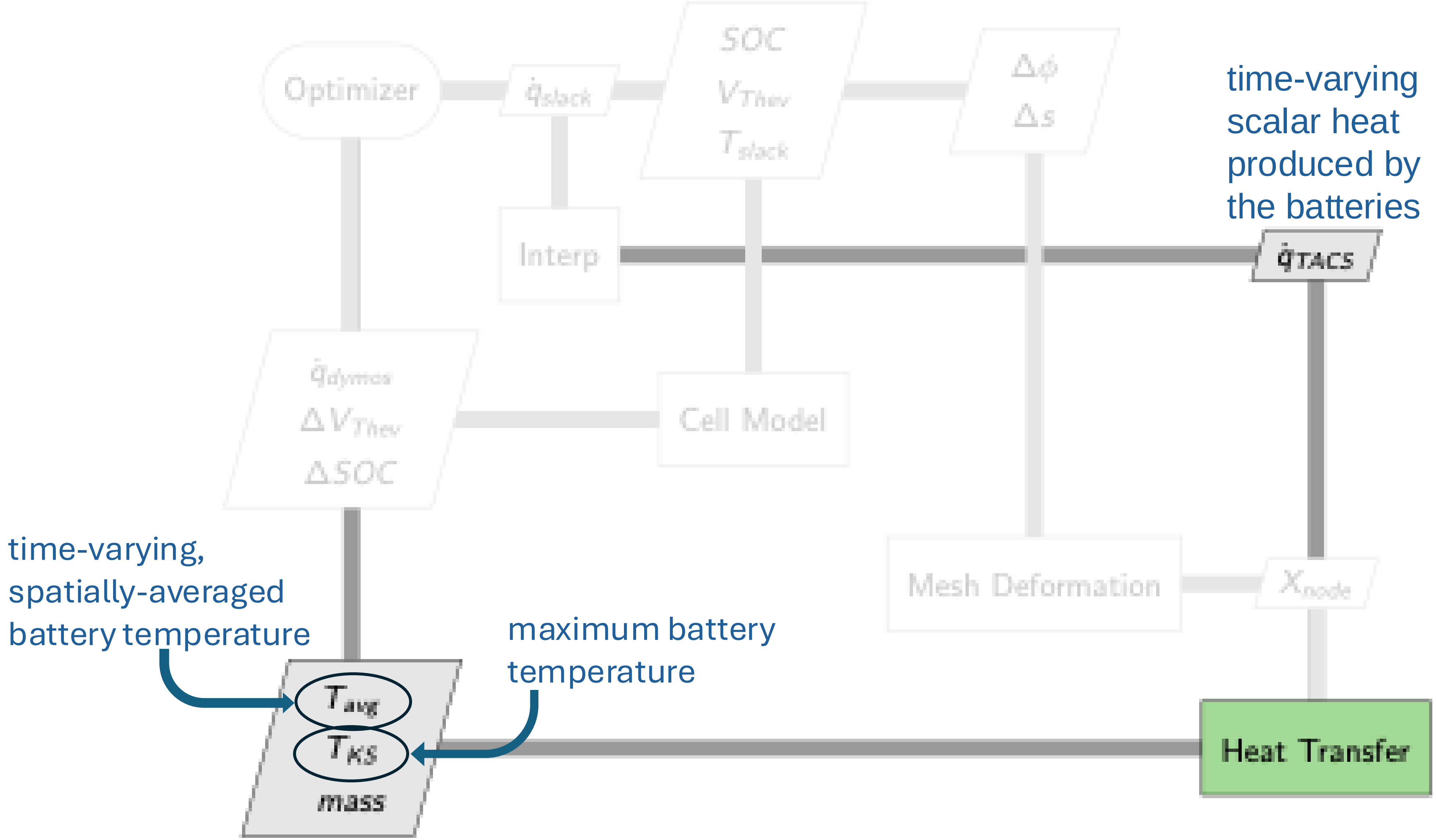
<List all of the software used here>

- OpenMDAO
- Dymos
- TACS

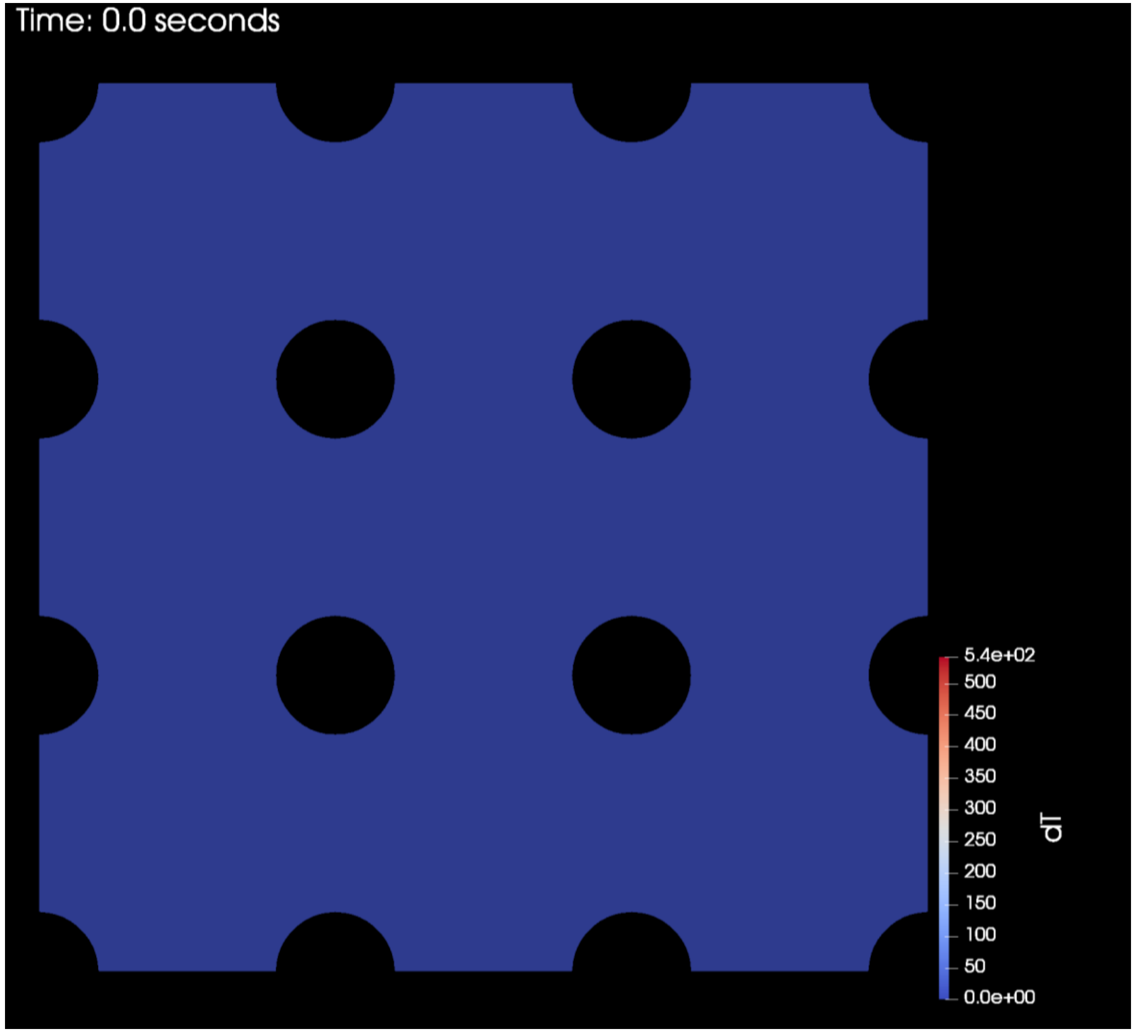
https://github.com/smdogroup/tacs



Transient heat-conduction using TACS



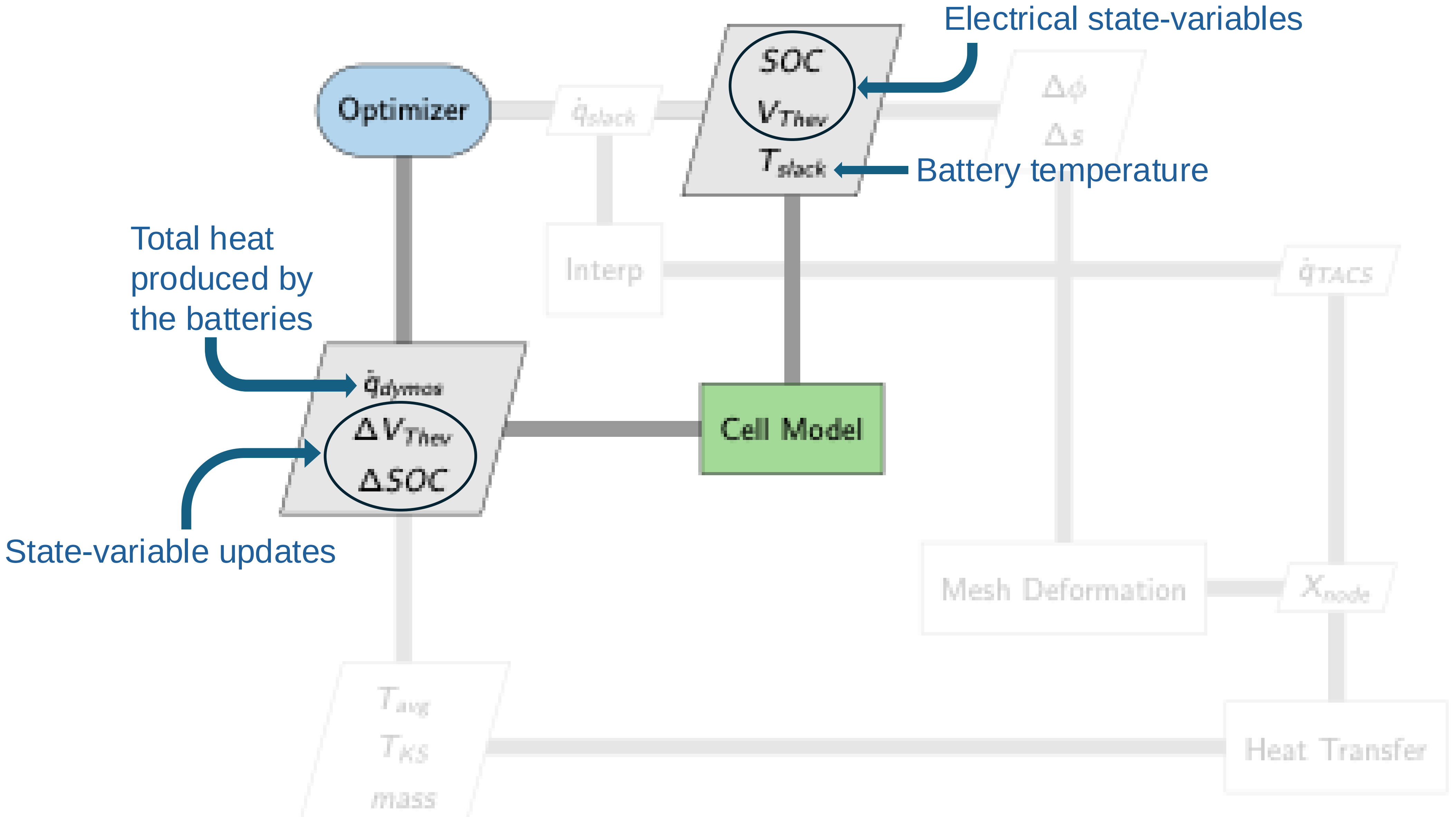
Transient heat-conduction using TACS



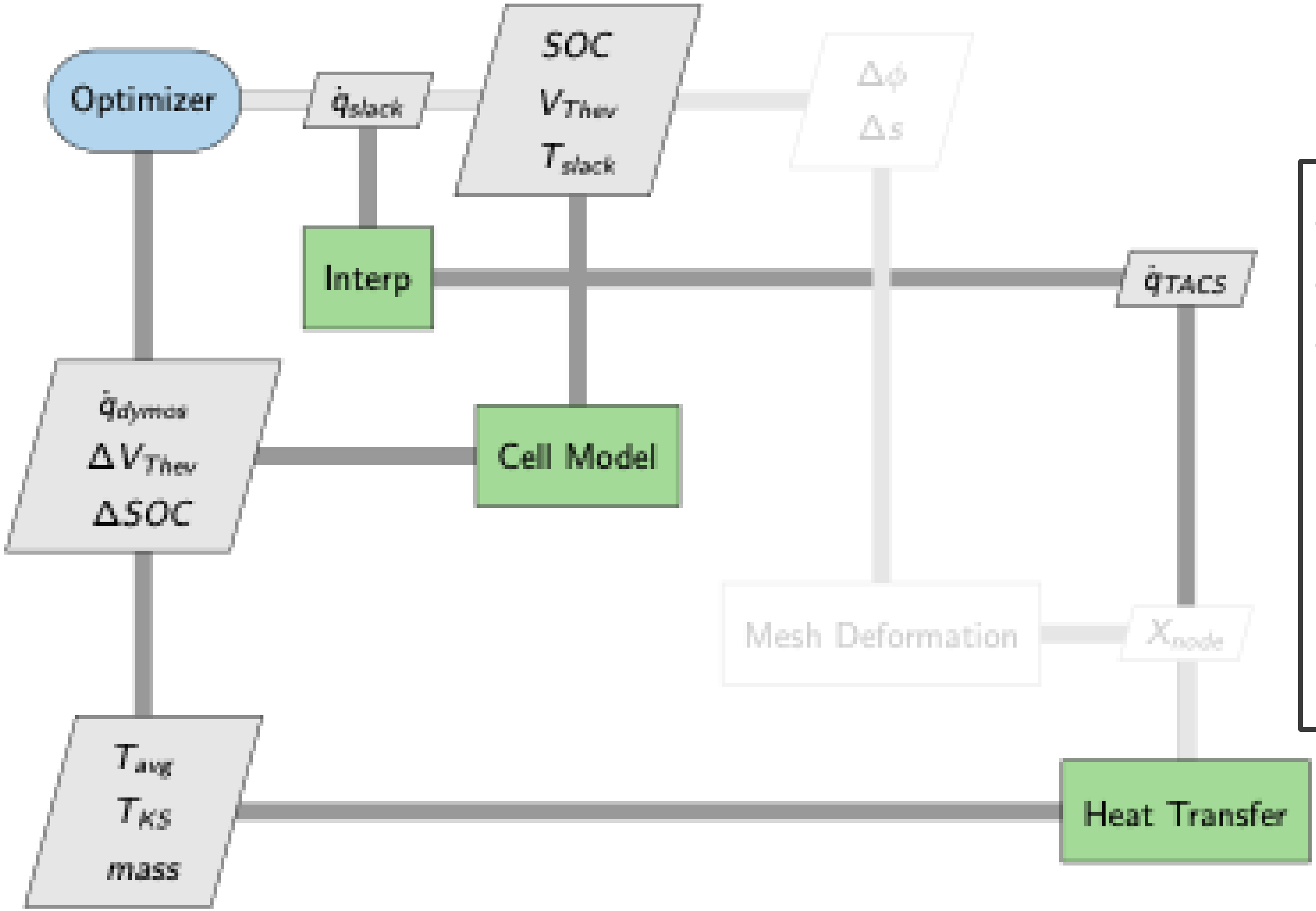
Solve the transient finite-element heat-transfer equations

- Uses 2D thermal elements; assumes symmetry out of the plane
- Reduced 3 x 3 geometry to improve computational cost
- Total elements: 9,989
- Heat is applied to the battery cells uniformly
- A small, constant (5 W) cooling boundary condition is applied to the pack surface as an approximation for natural convection
- Pack case material properties of aluminum
- Battery cell material properties representative of an 18650-type cylindrical cell

Thevenin-equivalent circuit cell-discharge model



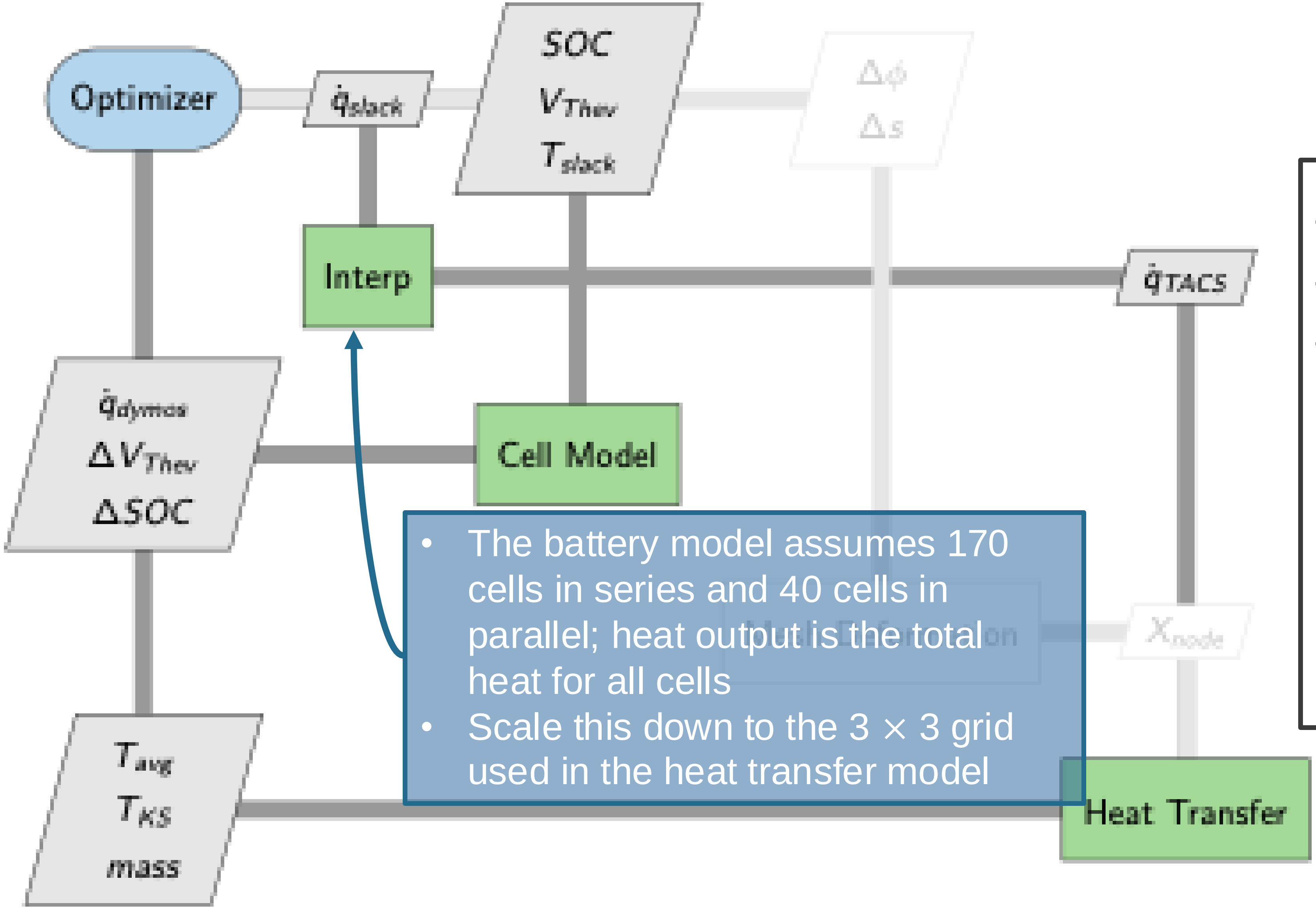
How do we couple these two models?



<u>TACS and dymos use different time-integration schemes</u>

→ Keep them independent, and use interpolation slack design variables with an equality constraint

How do we couple these two models?



- The battery model assumes 170 cells in series and 40 cells in parallel; heat output is the total heat for all cells
- Scale this down to the 3×3 grid used in the heat transfer model

<u>TACS and dymos use different time-integration schemes</u>

→ Keep them independent, and use interpolation slack design variables with an equality constraint

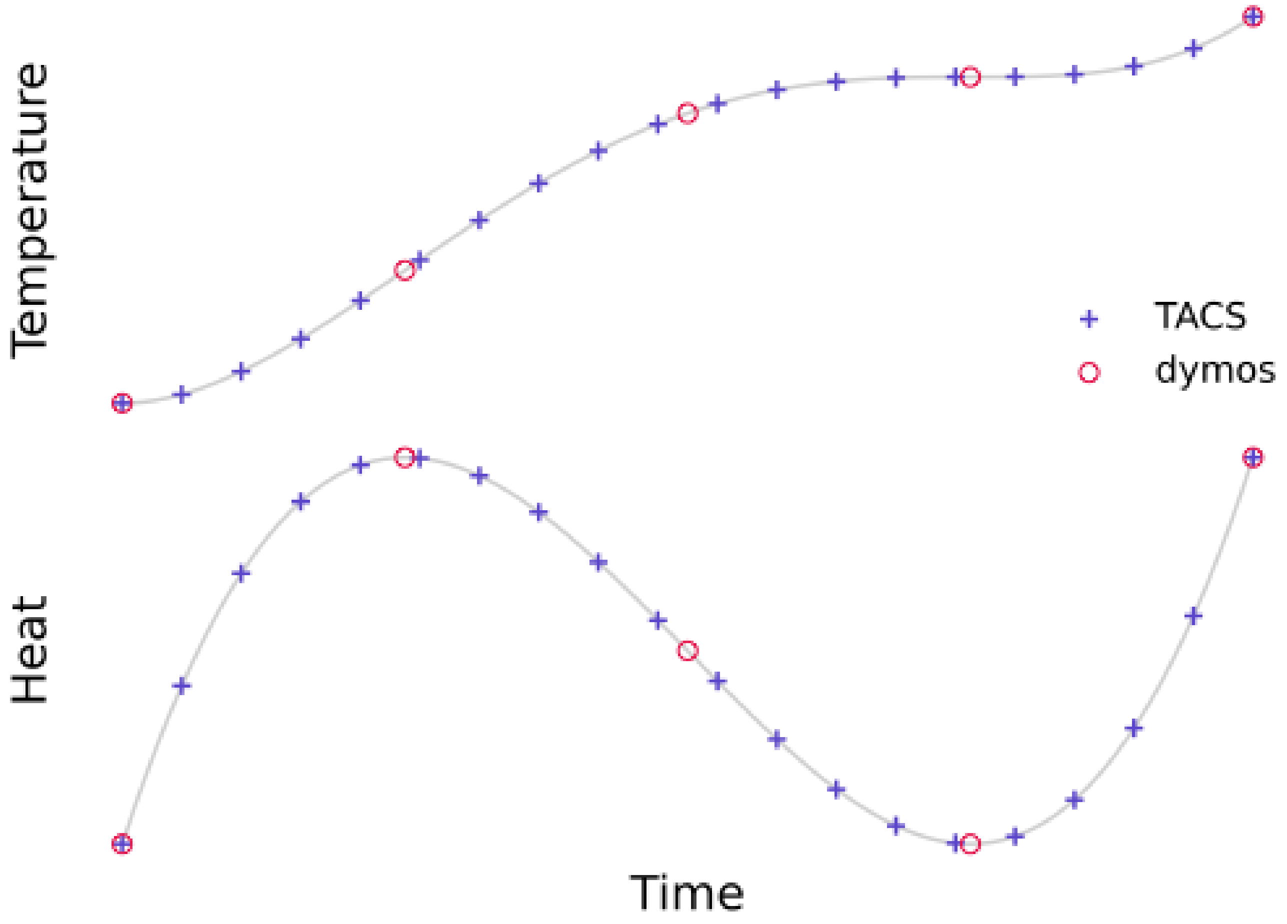
How do we couple these two models?

- Electrical variables are integrated using dymos
  - Integration solved by collocation
- Temperature is integrated using TACS
  - Time-marching integration

$n_{TACS} > n_{dymos}$

$$T_{\text{slack}} \to \text{dymos}$$
$$T_{\text{TACS}} \to T_{\text{interp}}$$
$$\underbrace{T_{\text{slack}} = T_{\text{interp}}}_{\text{constraint}}$$

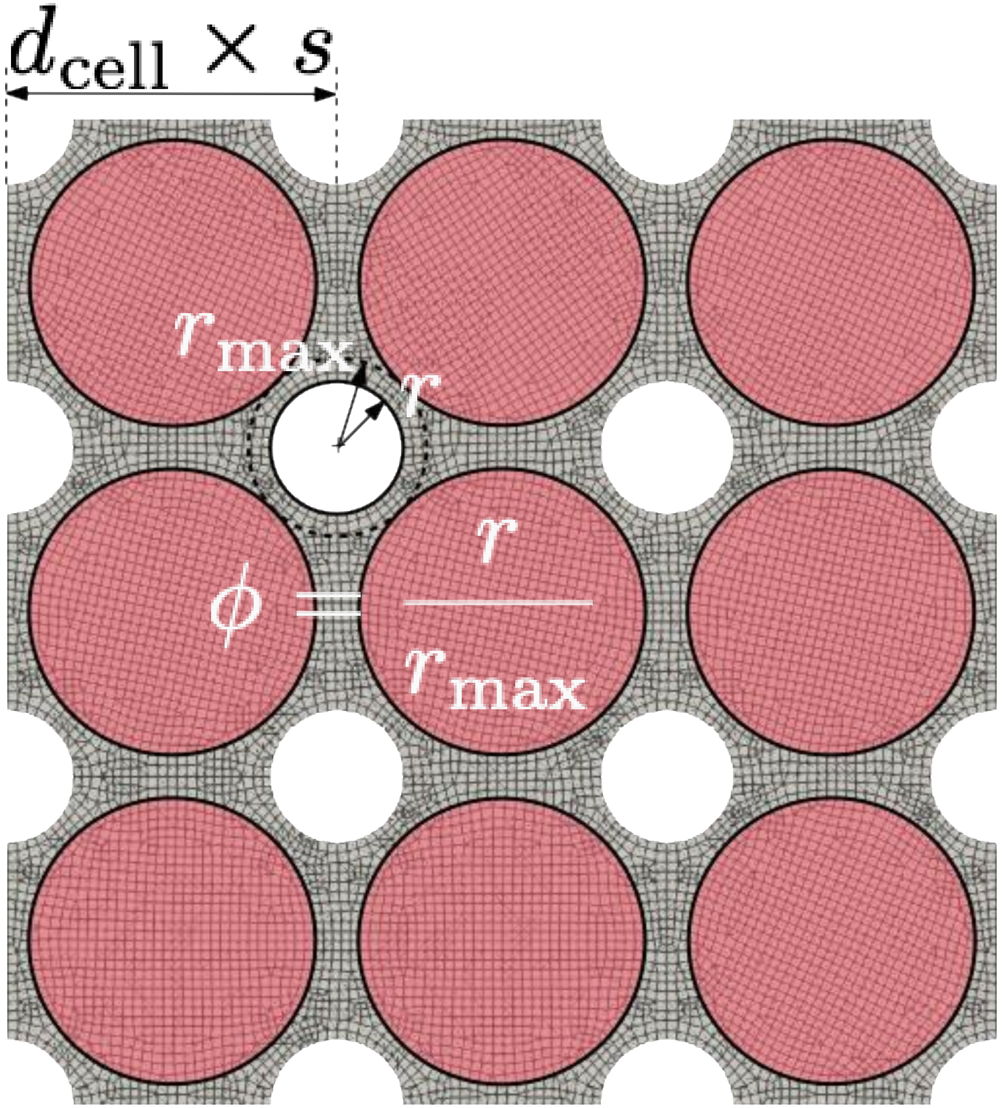
$$\dot{q}_{\text{slack}} \to \dot{q}_{\text{interp}}$$
$$\dot{q}_{\text{interp}} \to \text{TACS}$$
$$\underbrace{\dot{q}_{\text{slack}} = \dot{q}_{\text{dymos}}}_{\text{constraint}}$$



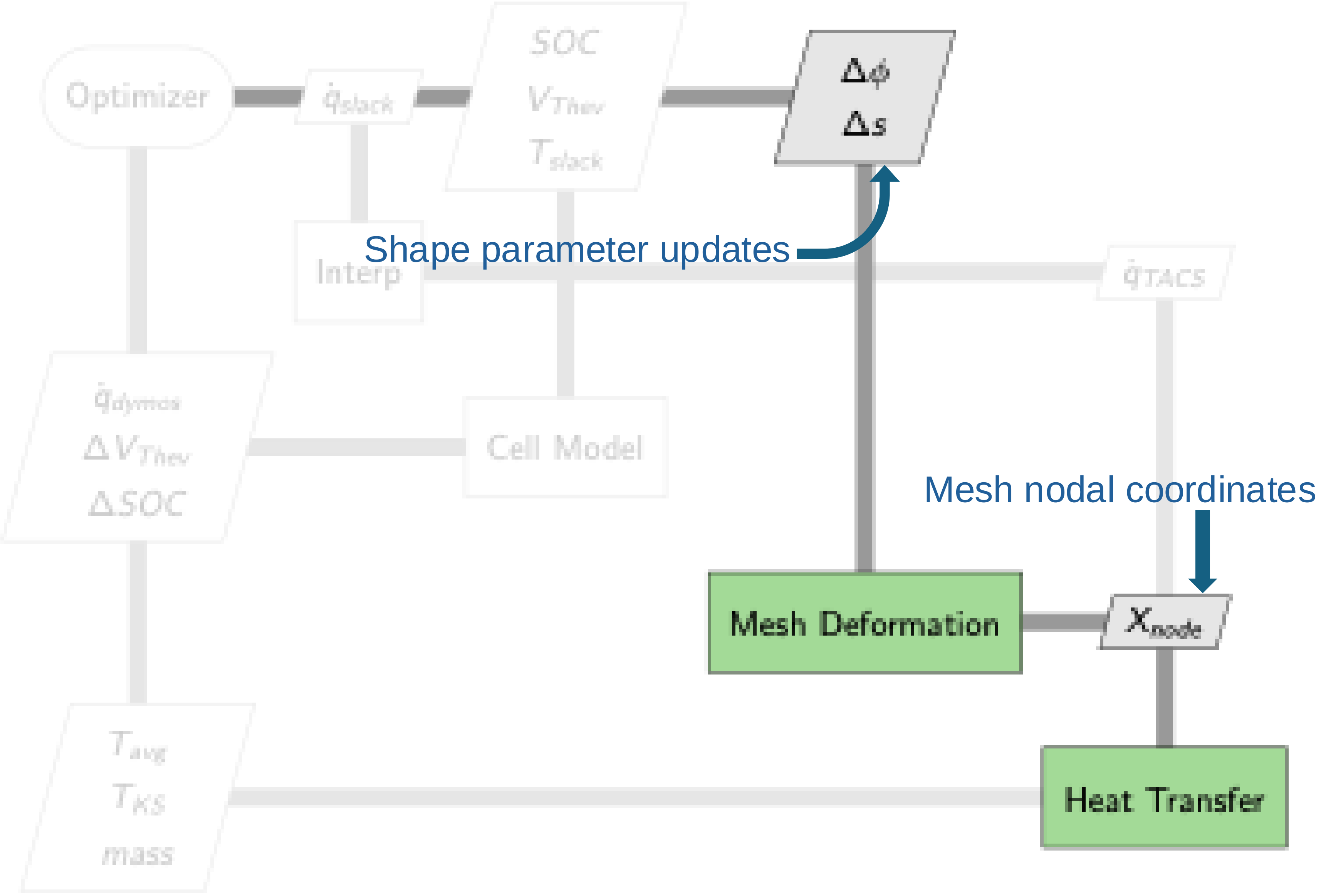
Mesh Deformation for Shape Optimization

Two shape parameters for this geometry:

1. s: <u>relative spacing between the cells</u>, normalized by the cell diameter, d_{cell}
2. ϕ: <u>relative hole size</u>; hole radius divided by the maximum possible hole size

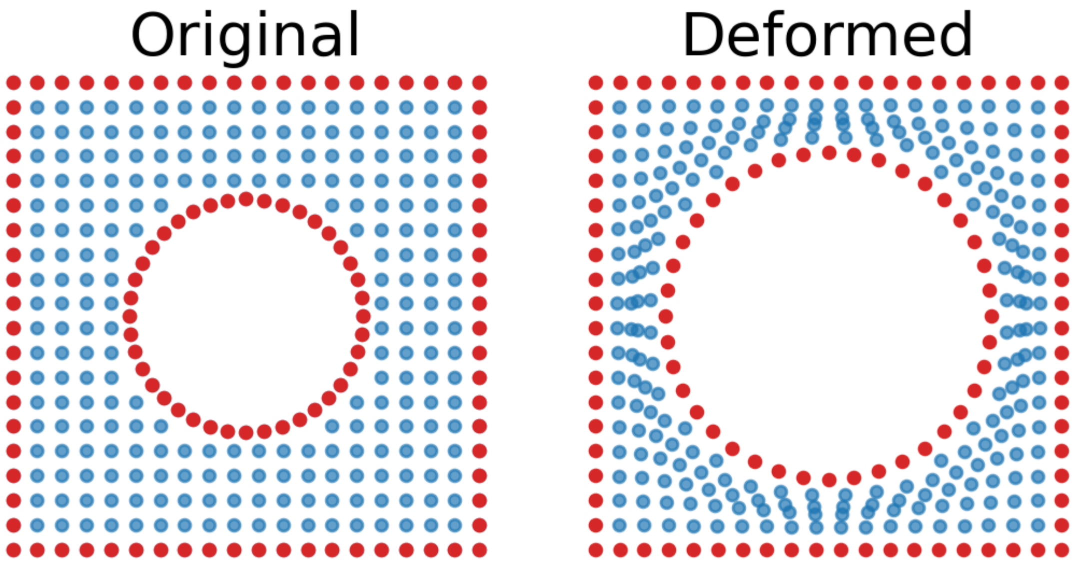


Mesh Deformation for Shape Optimization



Mesh Deformation for Shape Optimization

- For gradient-based optimization: need mesh deformation to compute derivatives
- Re-meshing is not an option → cannot take derivatives across different meshes
- Analytically deform the control nodes (red) using the shape parameters, s and ϕ



Coupled-optimization problem formulation

Initial optimization: *discharge the pack as much as possible without violating the temperature constraint*

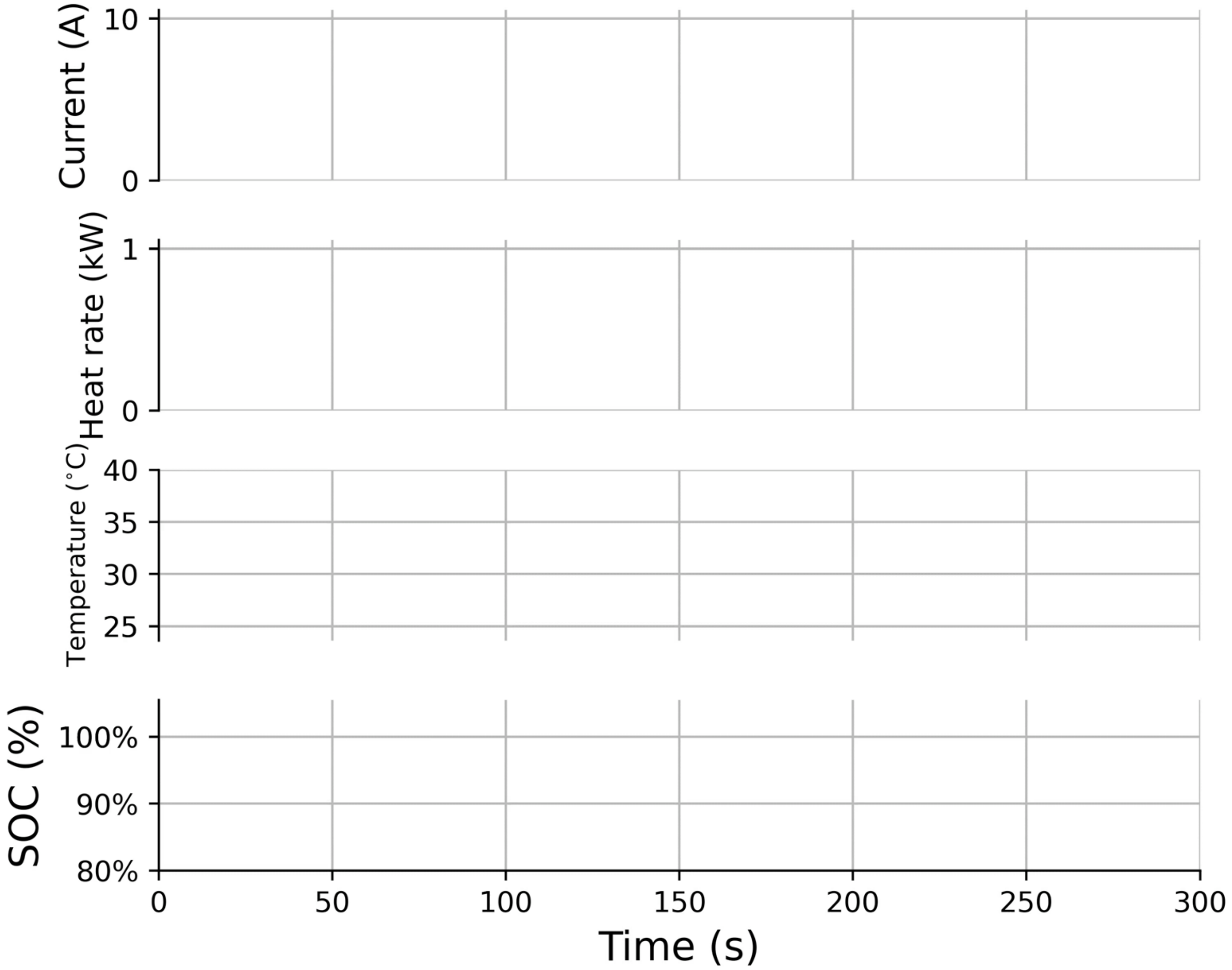
- Using transient heat-transfer finite element model coupled with the cell-discharge battery model without optimizing the batter pack shape
- Assume a fixed time duration

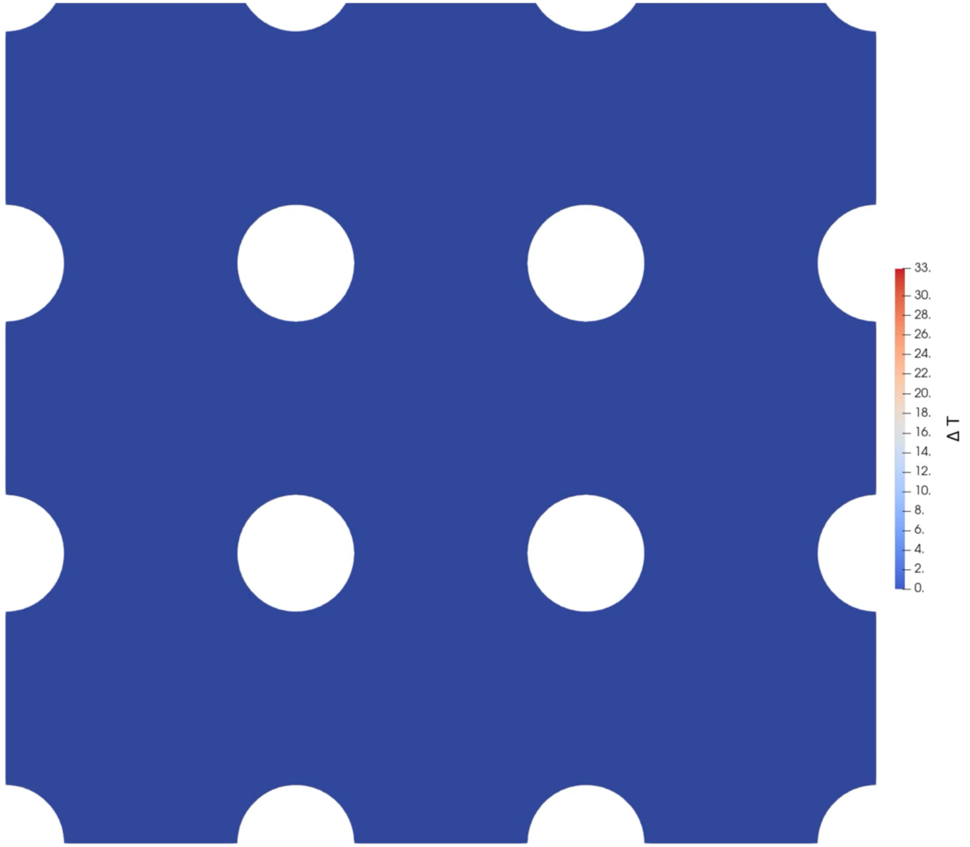
$$
\begin{aligned}
\text{min} \quad & \text{SOC}_{\text{final}} \\
\text{with respect to} \quad & I_{\min} \leq \mathbf{I} \leq I_{\max} \\
& \mathbf{T}_{\text{slack}} \\
& \dot{\mathbf{q}}_{\text{slack}} \geq 0 \\
\text{such that} \quad & T_{\text{KS}} \leq T_{\max} \\
& \dot{\mathbf{q}}_{\text{slack}} = \dot{\mathbf{q}}_{\text{dymos}} \\
& \mathbf{T}_{\text{slack}} = \mathbf{T}_{\text{avg}}
\end{aligned}
$$

Coupling variables: $\mathbf{T}_{\text{slack}}$, $\dot{\mathbf{q}}_{\text{slack}}$

Coupling constraints: $\dot{\mathbf{q}}_{\text{slack}} = \dot{\mathbf{q}}_{\text{dymos}}$, $\mathbf{T}_{\text{slack}} = \mathbf{T}_{\text{avg}}$

Coupled-optimization results





Shape optimization problem formulation

<u>Balance objectives of</u>: *discharge the pack as much as possible, and make it light-weight, without violating the temperature constraint*

- Using transient heat-transfer finite element model coupled with the cell-discharge battery model while simultaneously optimizing the batter pack shape
- Assume a fixed time duration
- $\alpha = 1$ in this case

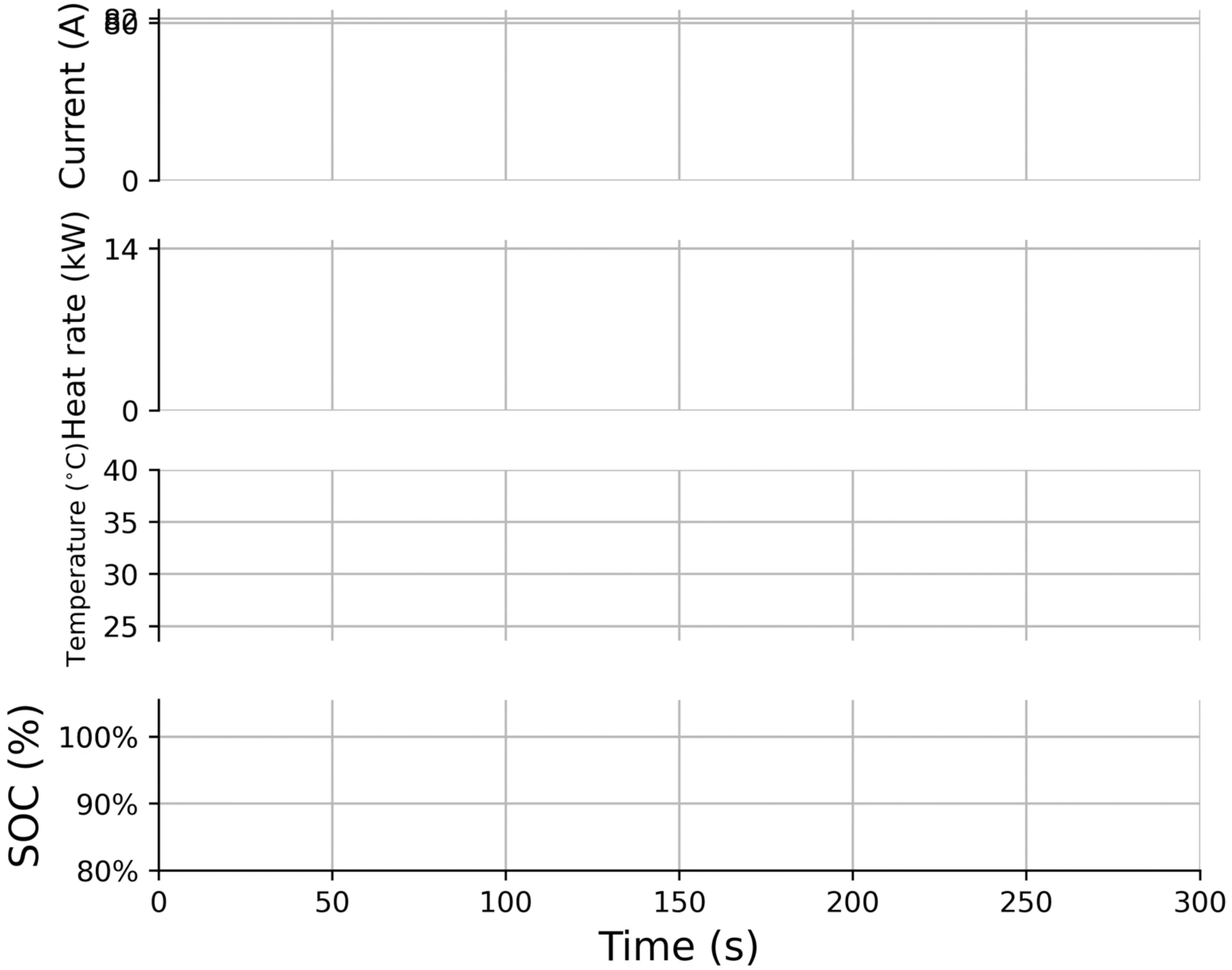
Composite objective function

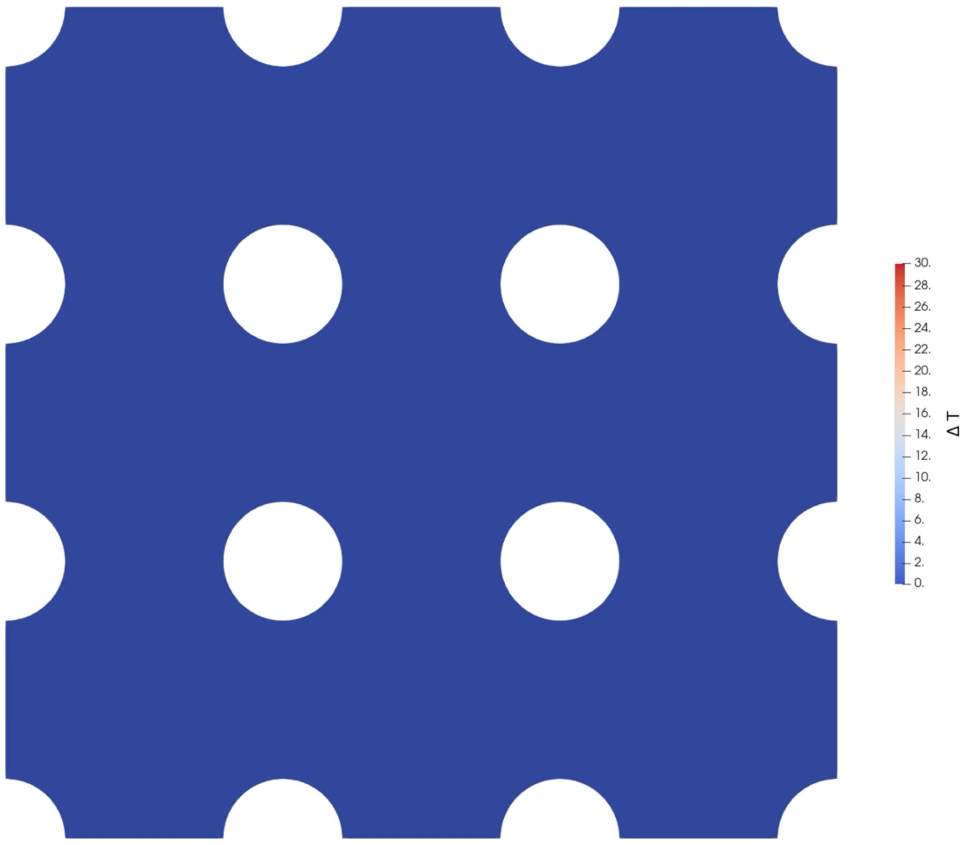
$$
\begin{aligned}
\text{min} \quad & f = \text{SOC}_{\text{final}} + \alpha \frac{m}{m_{\text{ref}}} \\
\text{with respect to} \quad & I_{\min} \leq \mathbf{I} \leq I_{\max} \\
& \mathbf{T}_{\text{slack}} \\
& \dot{\mathbf{q}}_{\text{slack}} \geq 0 \\
& \Delta\phi_{\text{lb}} \leq \Delta\phi \leq \Delta\phi_{\text{ub}} \\
& \Delta s_{\text{lb}} \leq \Delta s \leq \Delta s_{\text{ub}} \\
\text{such that} \quad & T_{\text{KS}} \leq T_{\max} \\
& \dot{\mathbf{q}}_{\text{slack}} = \dot{\mathbf{q}}_{\text{dymos}} \\
& \mathbf{T}_{\text{slack}} = \mathbf{T}_{\text{avg}} \\
& \text{SOC}_{\text{final}} \geq 20\%
\end{aligned}
$$

m_{ref} = initial mass

Shape variables: $\Delta\phi$, Δs

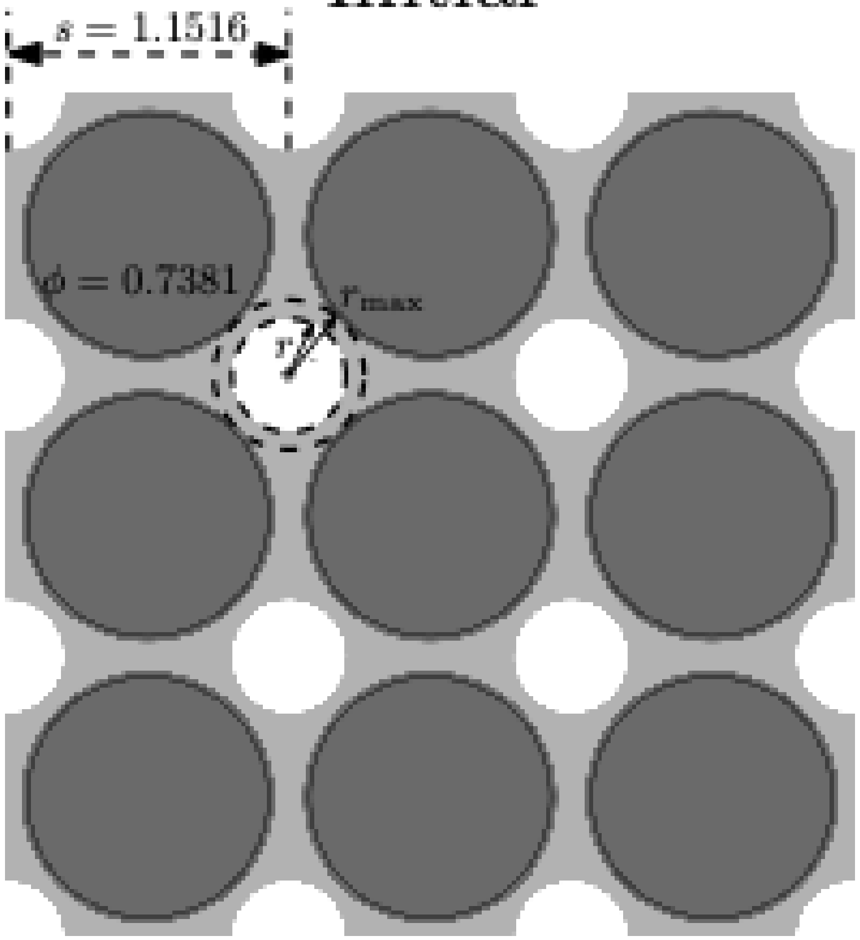
Shape optimization results



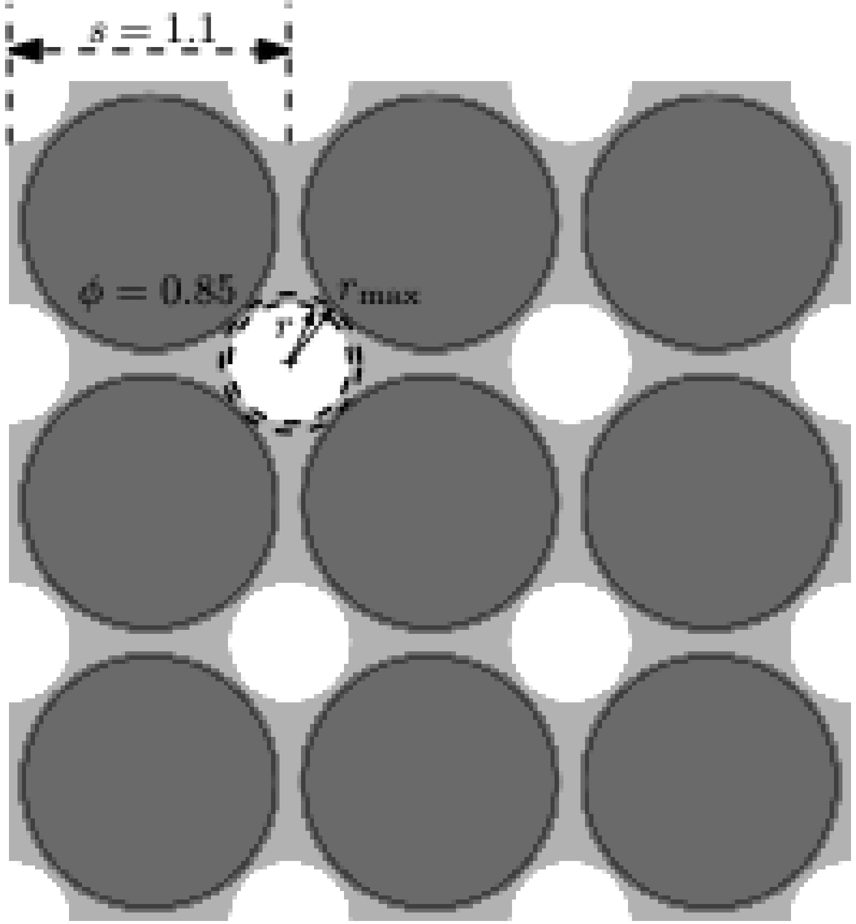


Shape optimization results

Initial



Final



Optimization results comparison

	Baseline	Final	Difference
Mass (kg)	0.408	0.345	15% ↓
Max temperature (℃)	55	55	0
Cell spacing, s	1.1516	1.10 Lower bound	4% ↓
Hole size, ϕ	0.7381	0.85 Upper bound	15% ↑
Final SOC	70%	78%	11% ↑

Conclusion

- Demonstrated transient coupling between an electrical battery model and a finite-element heat conduction model
  - Two-way coupling enforced between models using different time-integration schemes
  - Temperature is an input to the cell-discharge model $\longrightarrow$ high-fidelity temperature analysis improves model fidelity
  - Cell-discharge battery model provides time-accurate boundary conditions, improving the temperature estimation
- Demonstrated shape optimization using a composite objective function to reduce pack mass while discharging the battery pack as much as possible, while considering temperature constraints

Future work

- Integrate this with an aircraft and mission optimization in Aviary to assess system-level impacts and trade-offs
- Improve model physics:
  - Add convective heat flux boundary condition
  - Incorporate active battery pack cooling
- Include an off-nominal case to design the pack to prevent thermal runaway
- Evaluate alternate battery chemistries and the effect on increasing cell-energy-density

Questions?

Thanks to NASA's Transformational Tools and Technologies (TTT) project

Funding for TTT is provided by the Aeronautic Research Mission Directorate (ARMD)

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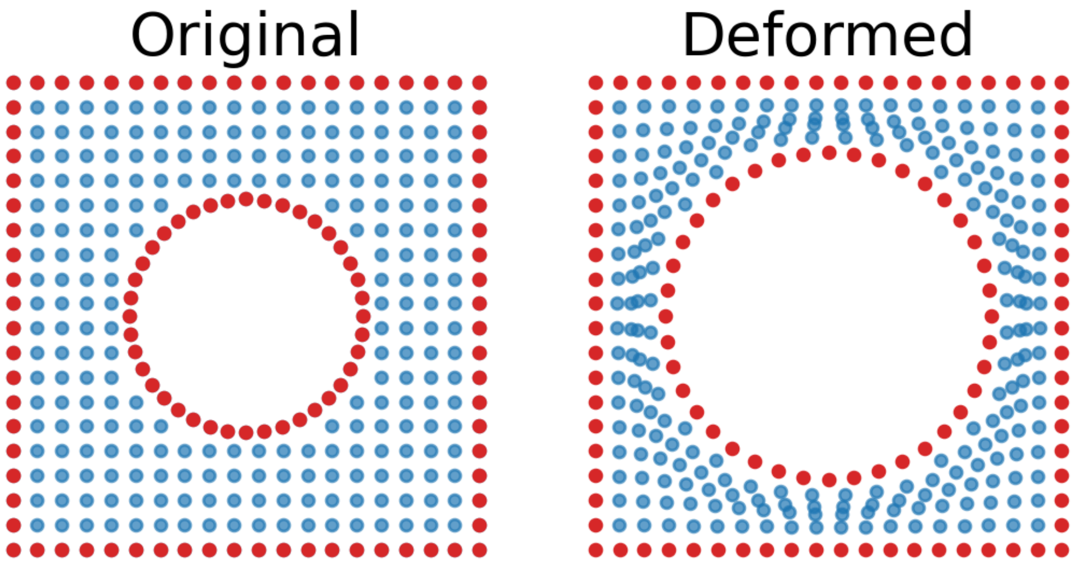

- Use an inverse distance weighted approach:

$$\Delta x_i = \frac{\sum_j^{n_c} w_{ij} \Delta x_j}{\sum_j^{n_c} w_{ij}}$$

$$w_{ij} = \frac{1}{||x_i - x_j||^m}$$