Topology Optimization for Thermo-mechanics

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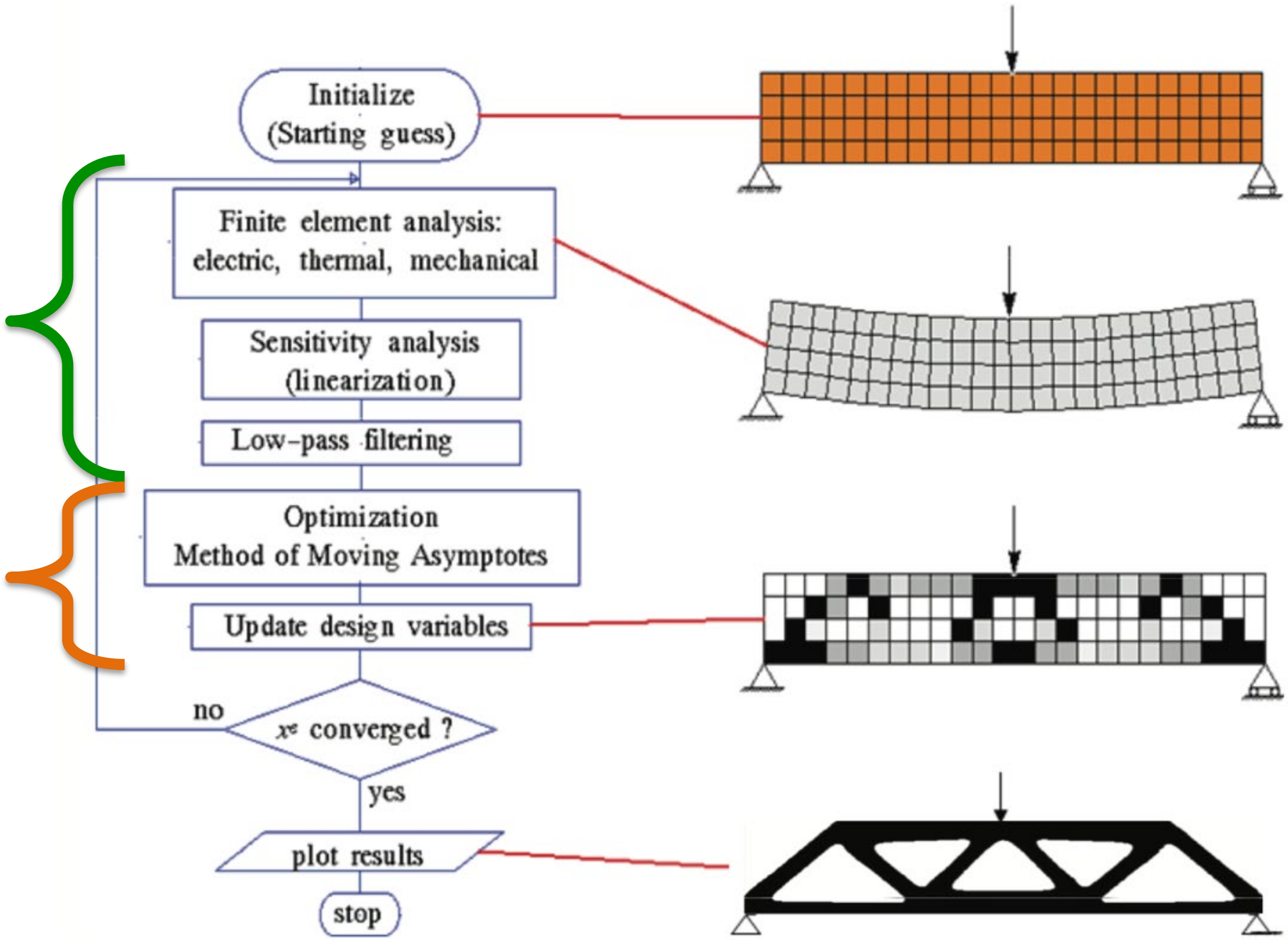
UC San Diego

Topology Optimization

Topology Optimization

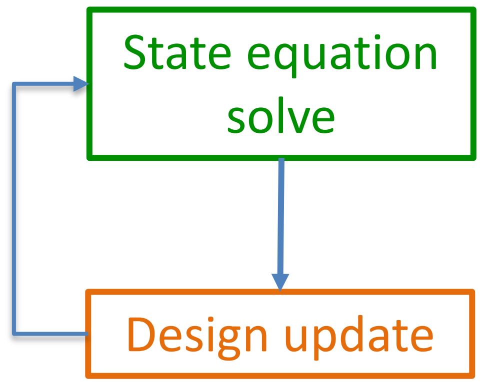
State equation solve

Design update

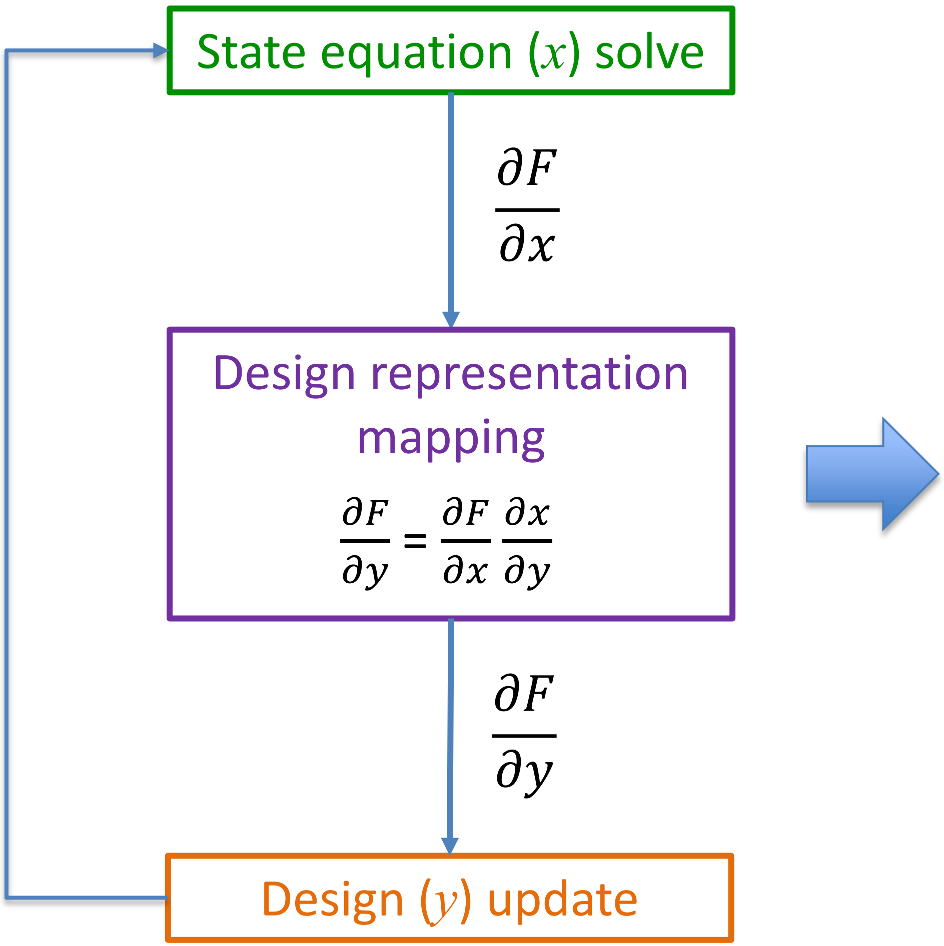


Sigmund (2001) "A 99 line topology optimization code written in Matlab," SMO 21.

Topology Optimization

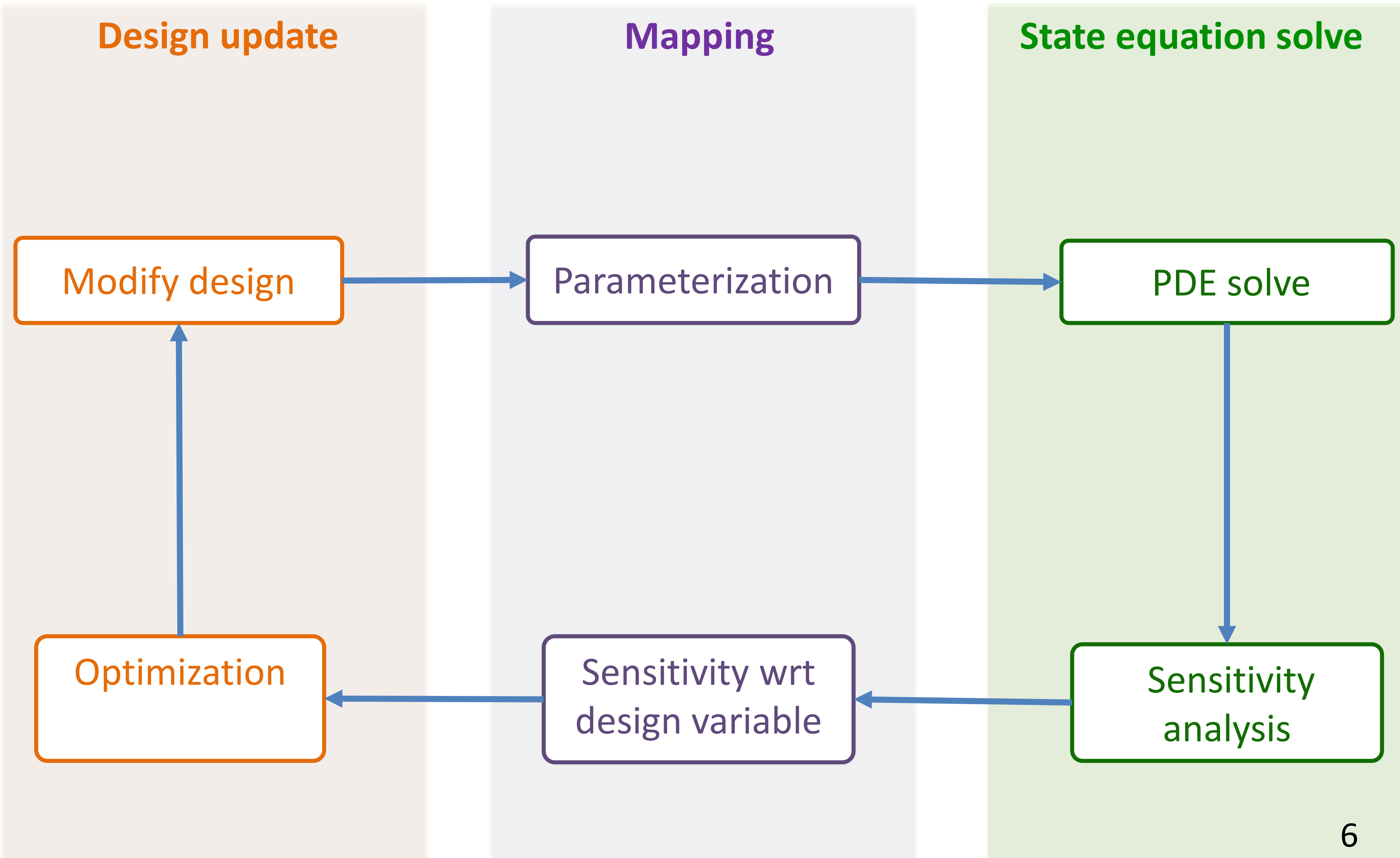


Topology Optimization



- Any PDE solver with adjoint sensitivity can be used.
- Any design parameterization can be used.

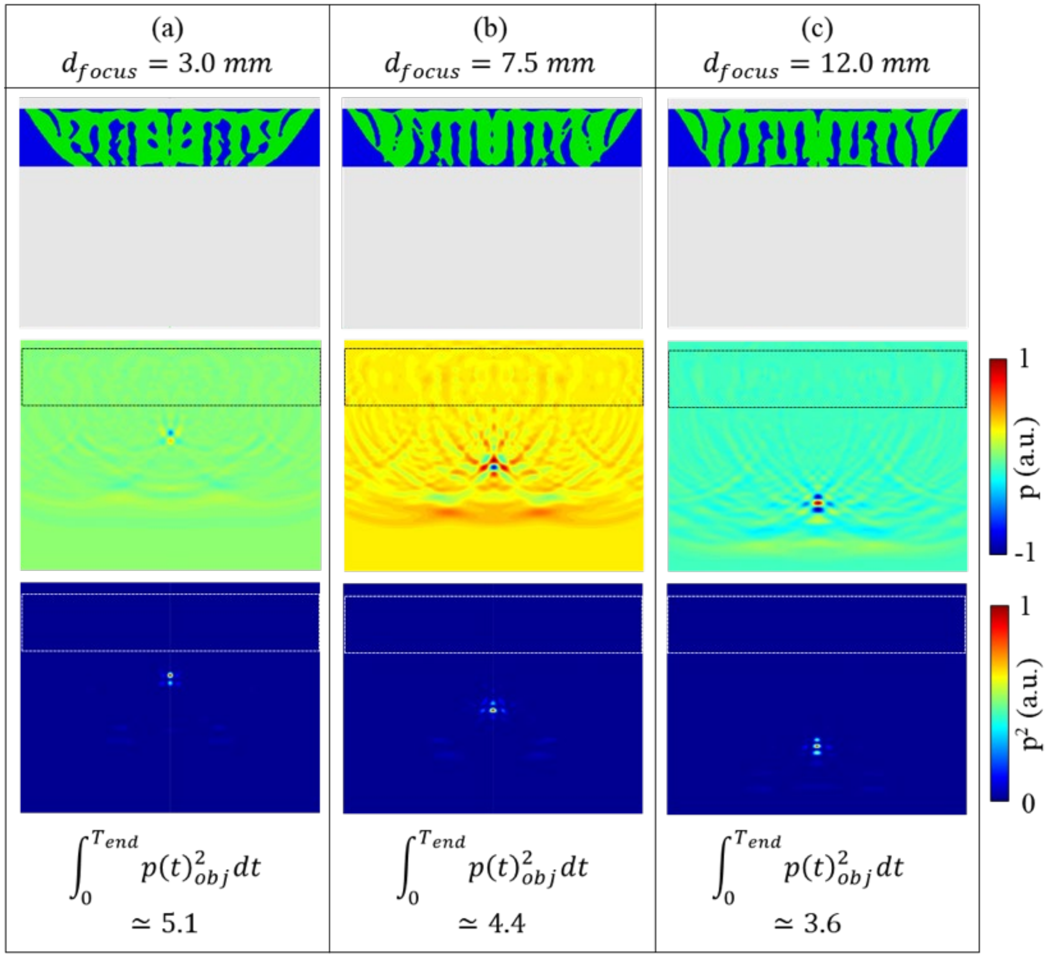
Generalized Architecture



Large-Scale Level Set Topology Optimization

Modeled only a half (symmetry)
8 million elements
160 processors (64 GB RAM/node)
Converges in 250 iterations, 6 hours

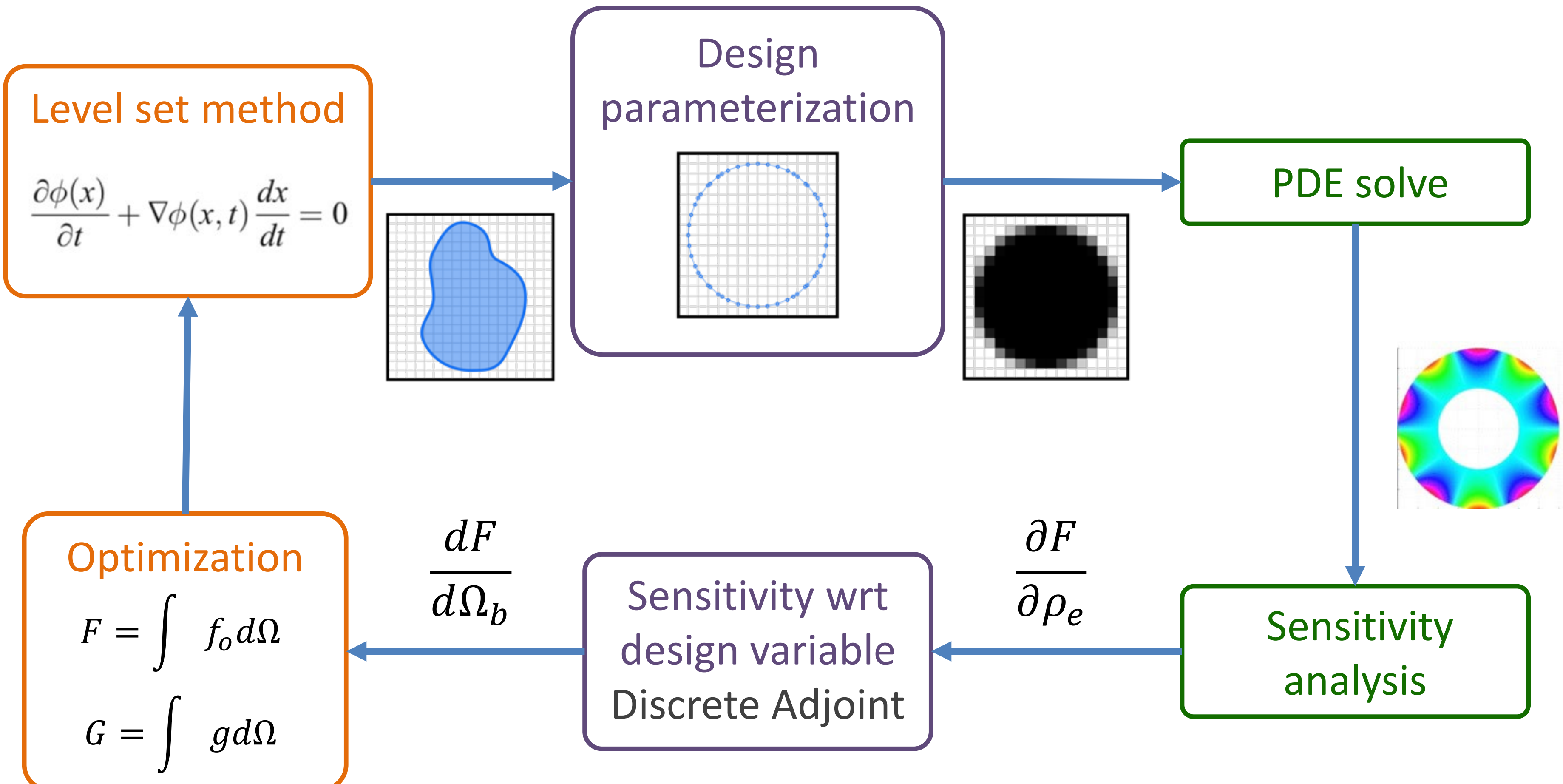
Flat Lens via Multiple Material



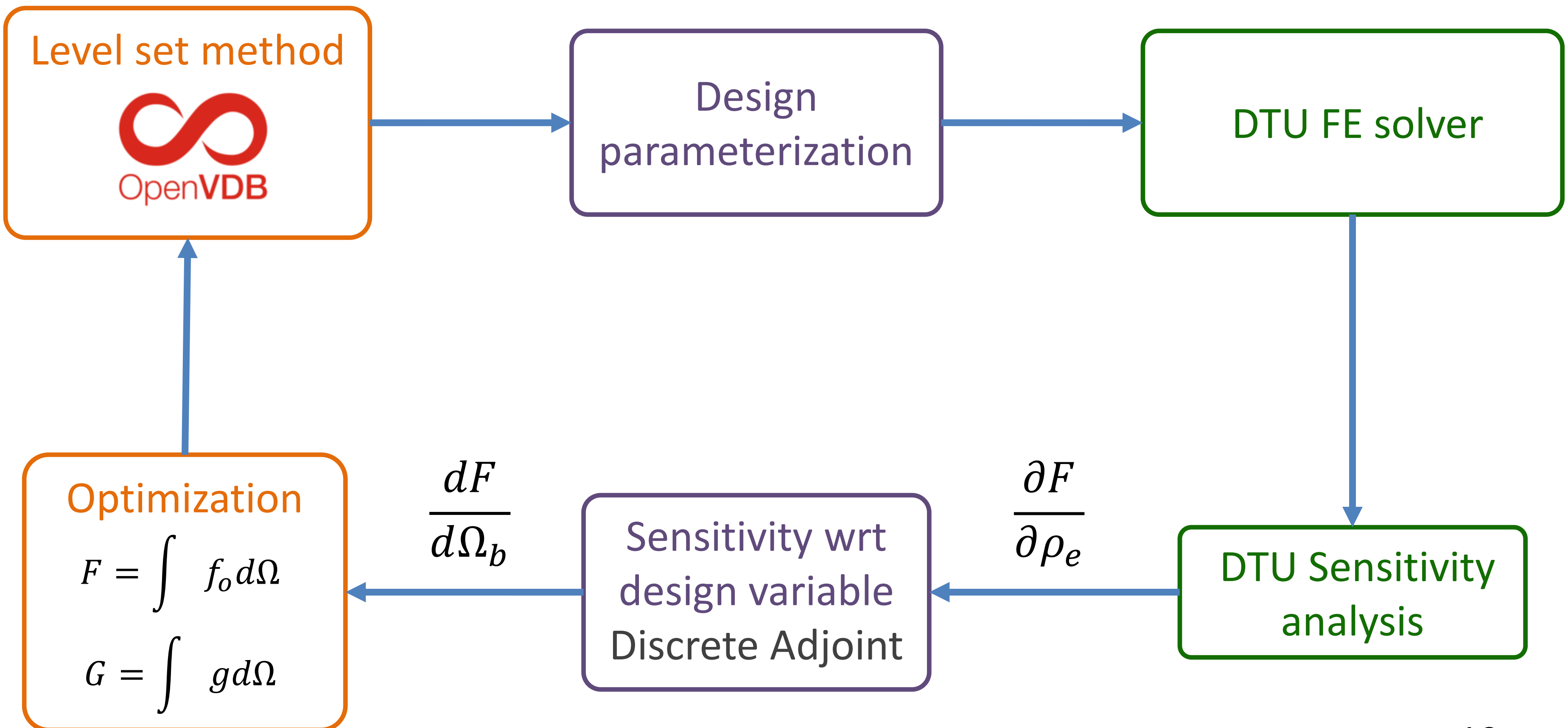
Acoustic lens design with varying focal depths

Hyun & Kim (2021) Transient level-set topology optimization of a planar acoustic lens working with short-duration pulse, *JASA*.

Level Set Topology Optimization



Large-Scale Topology Optimization

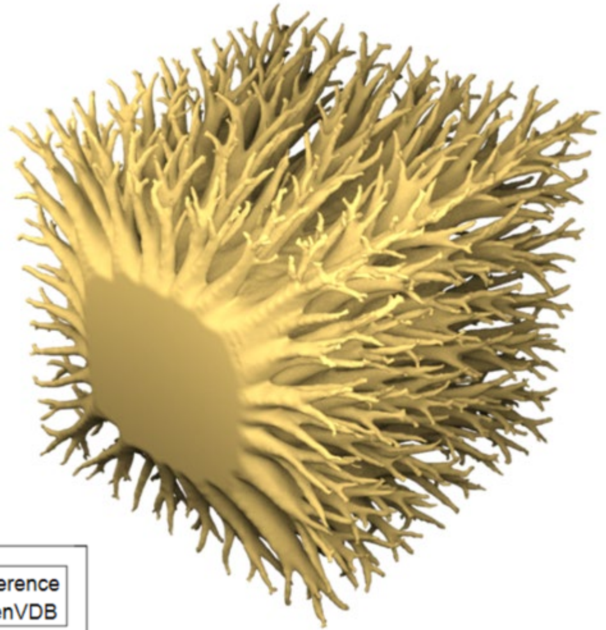


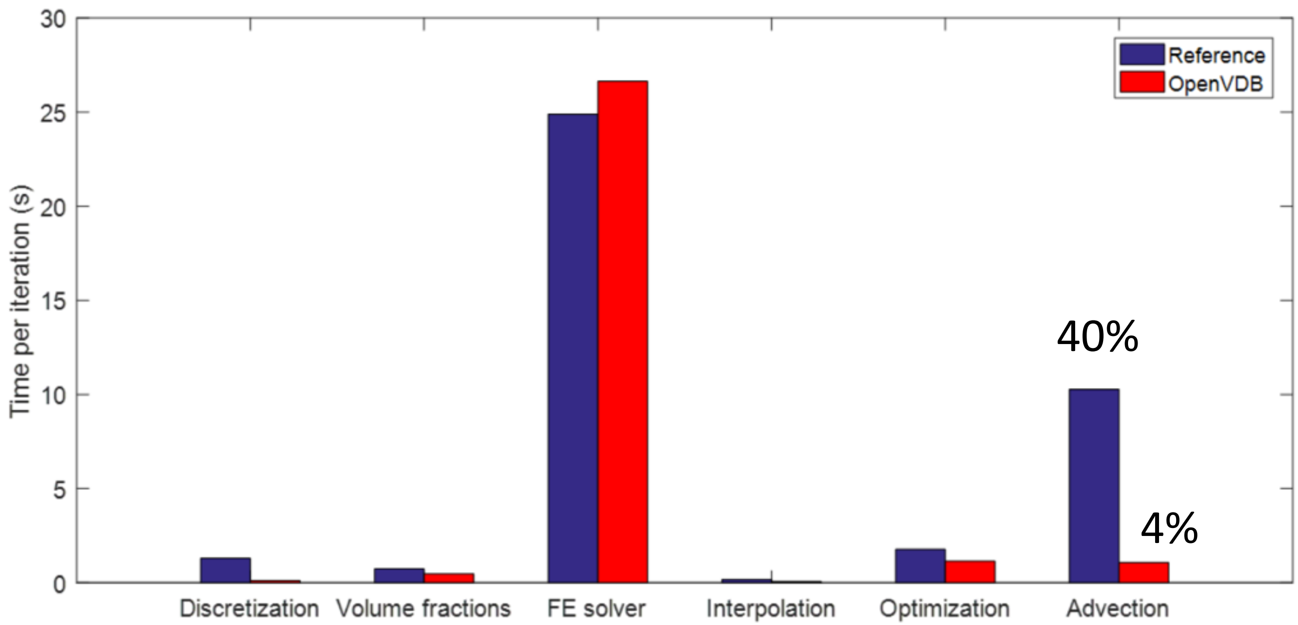
VDB-LSTO Method
[3.2 billion elements, 56 cores, 128GB]

Kambampati, Jauregui, Museth, Kim (2021) “Geometry Design Using Function Representation on a Sparse Hierarchical Data Structure,” CAD 133.

Heat conduction

- Min average temperature, st vol < 30%
- 8 million elements
- Desktop workstation, 56 cores ,128 GB RAM
- Converges in 200 iterations



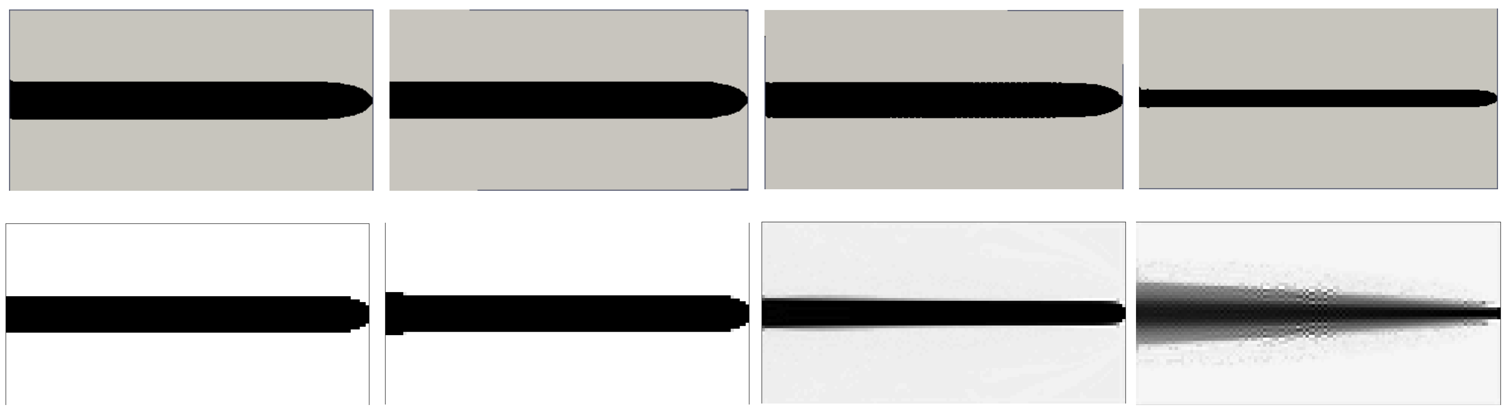


Why use Level Set Topology Optimization?

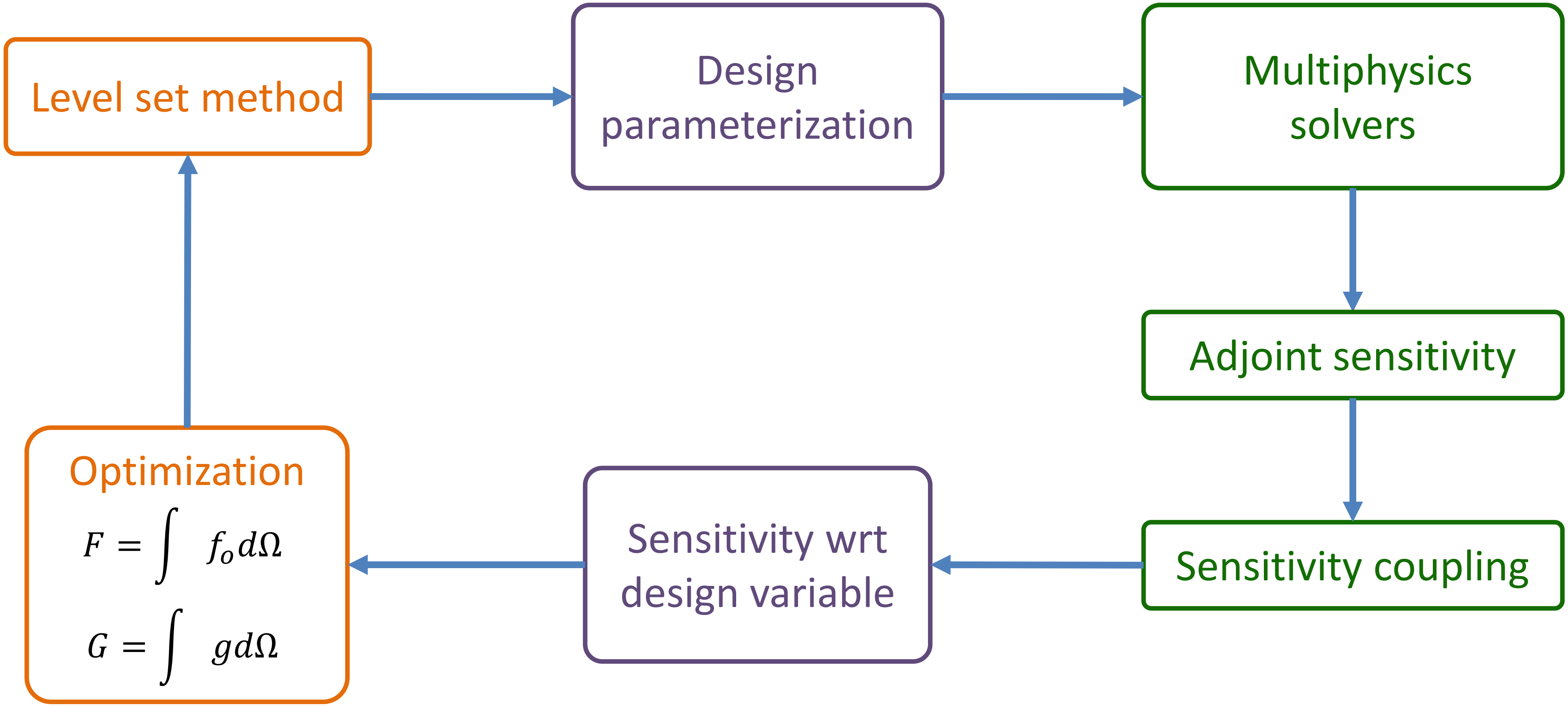
$\Delta T = 0$ | $\Delta T = 0.001$ | $\Delta T = 0.01$ | $\Delta T = 0.05$

Level set

SIMP



Generalized TO:
Interoperable Reusable Software Architecture



Hyun, Kim (2022) "On the development of an easy-accessible and non-intrusive level-set topology optimization framework via the discrete adjoint method," AIAA SciTech.

ParaLeSTO:
FAIR Principles for Opensource Software

- Findability
- Accessibility
- Interoperability
- Reusability

More information at http://m2do.ucsd.edu/software/

Jauregui, Hyun, Neofytou, Kim (2022) "Avoiding reinventing the wheel: developing reproducible opensource topology optimization software", SMO, submitted

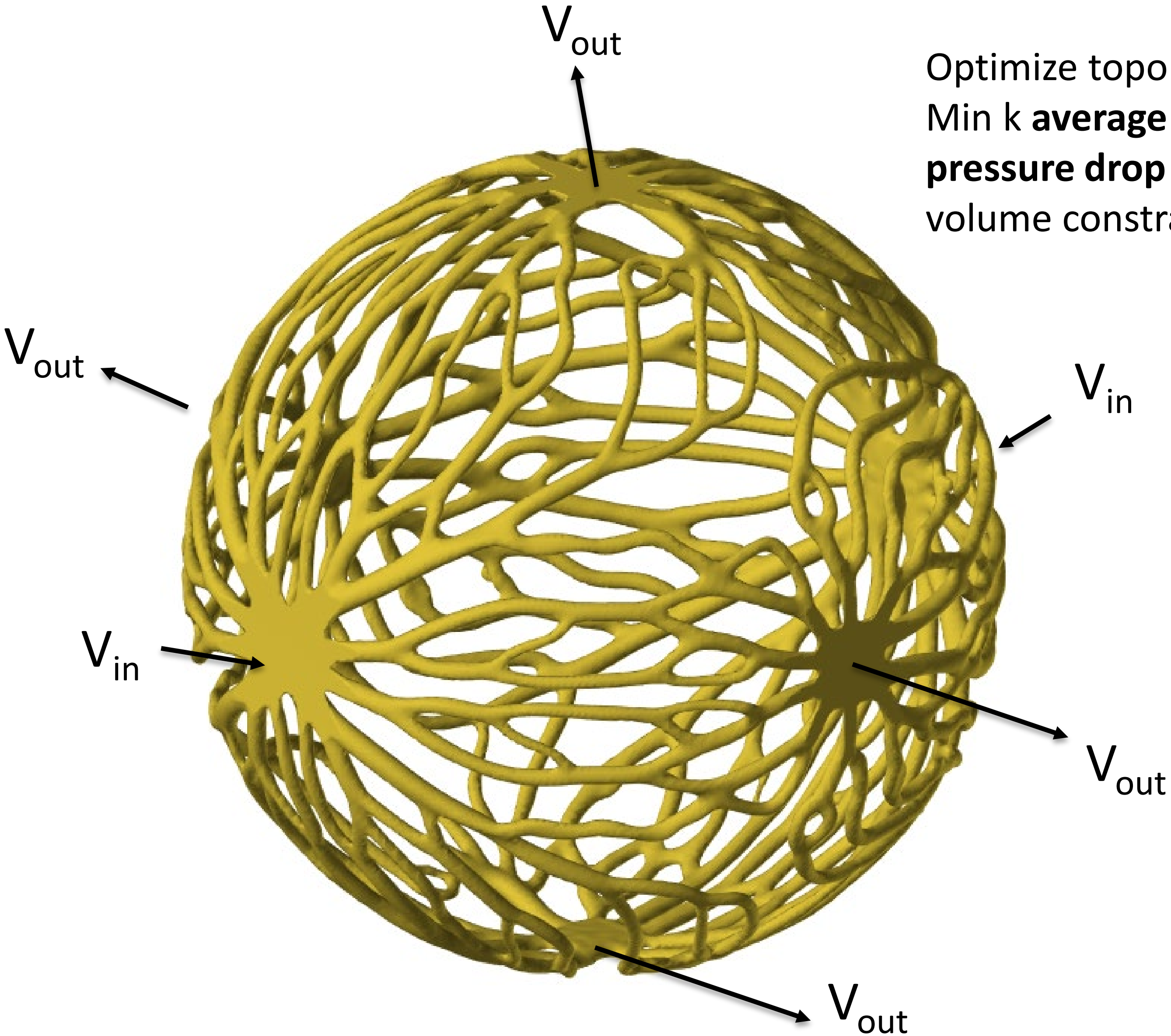
Maximizing Heat Conduction via Eigenvalue

- COMSOL (Physics solver) & Symbolic AD
- Max. 1st thermal eigenvalue s.t. Locally-averaged volume

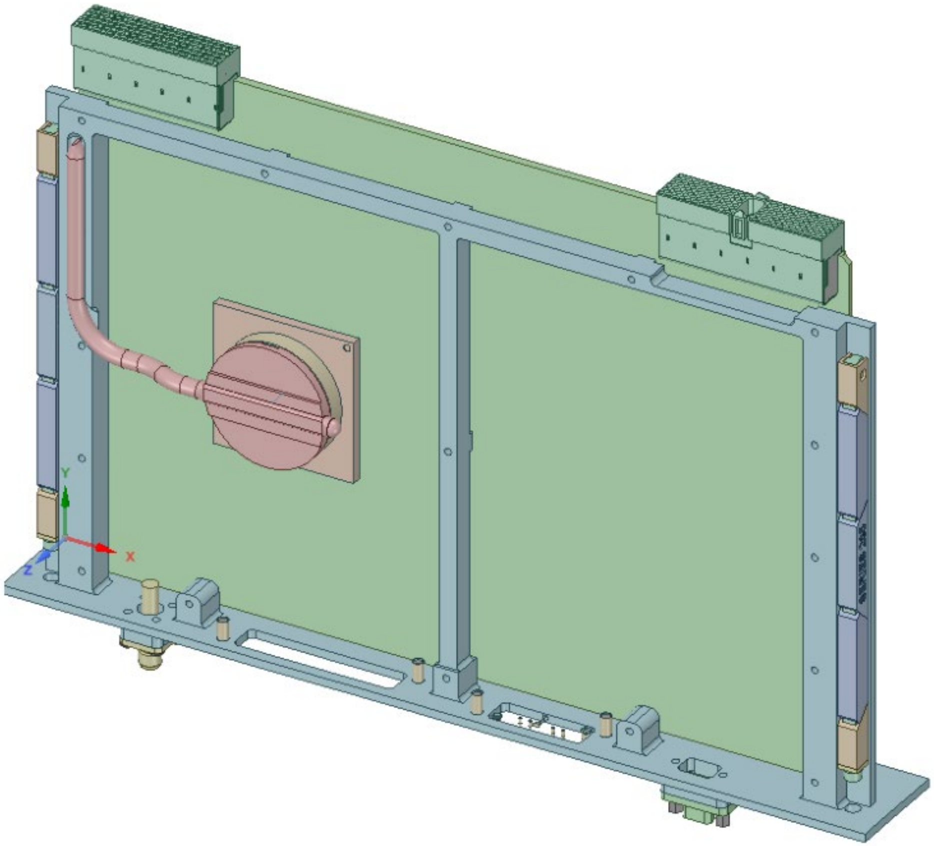
$R_{loc} = 8$ $R_{loc} = 14$

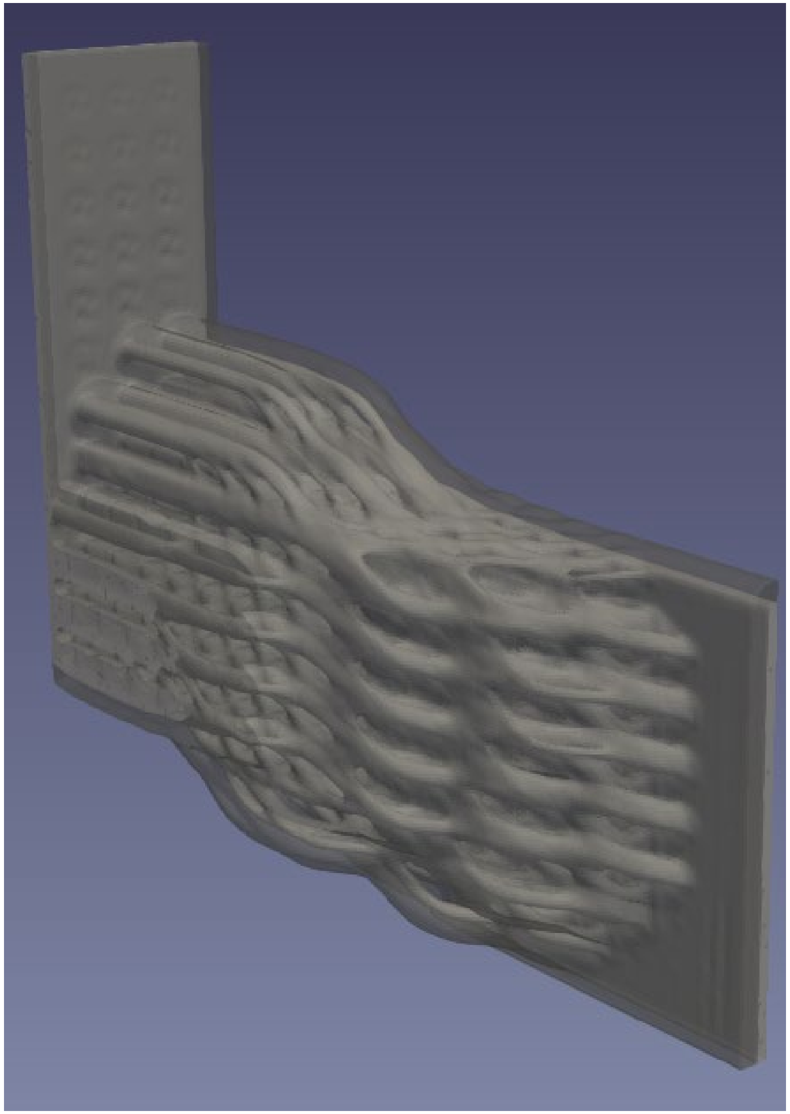
Conformal cooling channel on a sphere

Optimize topology of channel flow
Min k **average temperature** + (1-k) **pressure drop**
volume constraint 15%



Two-Phase Heat Exchanger

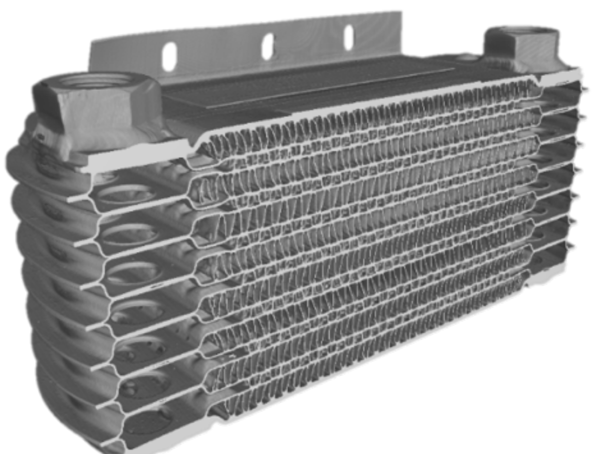




Jet Propulsion Laboratory
California Institute of Technology

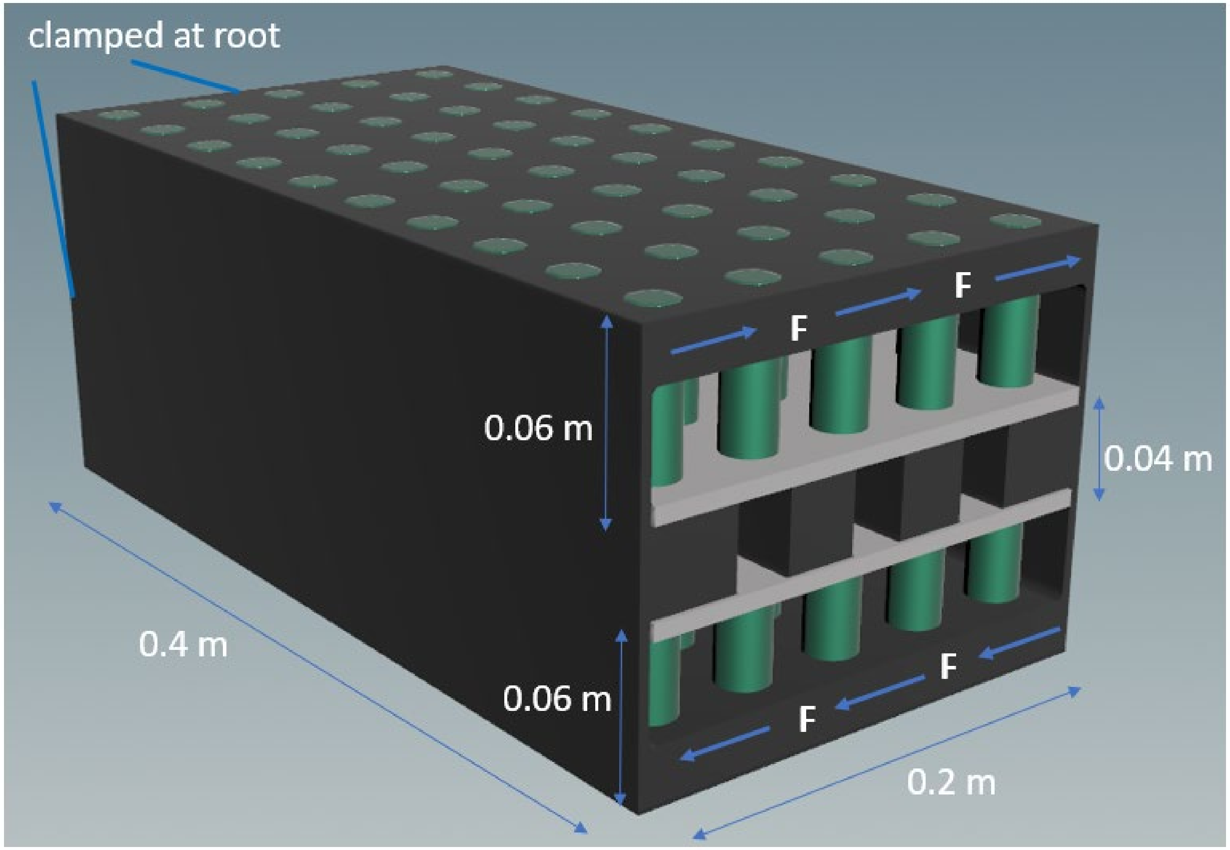
Electrical Aircraft – X57 Maxwell

https://www.anttilehikoinen.fi/technology/electric-aircraft/



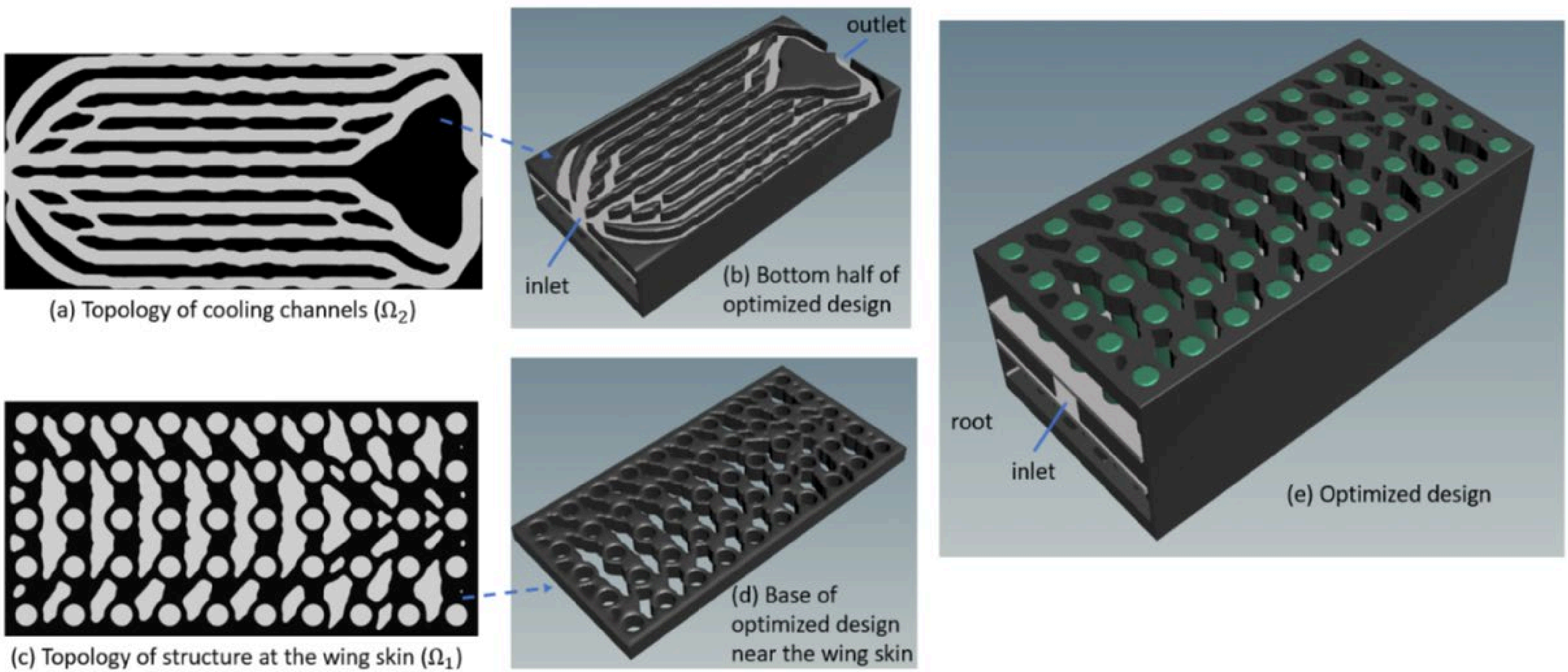
https://sacd.larc.nasa.gov/x57maxwell/

Load-carrying + Heat Exchanger + Battery Pack



Kambampati, Gray, & Kim (2021) “Level Set Topology Optimization of Load Carrying Battery Pack”, IJHMT

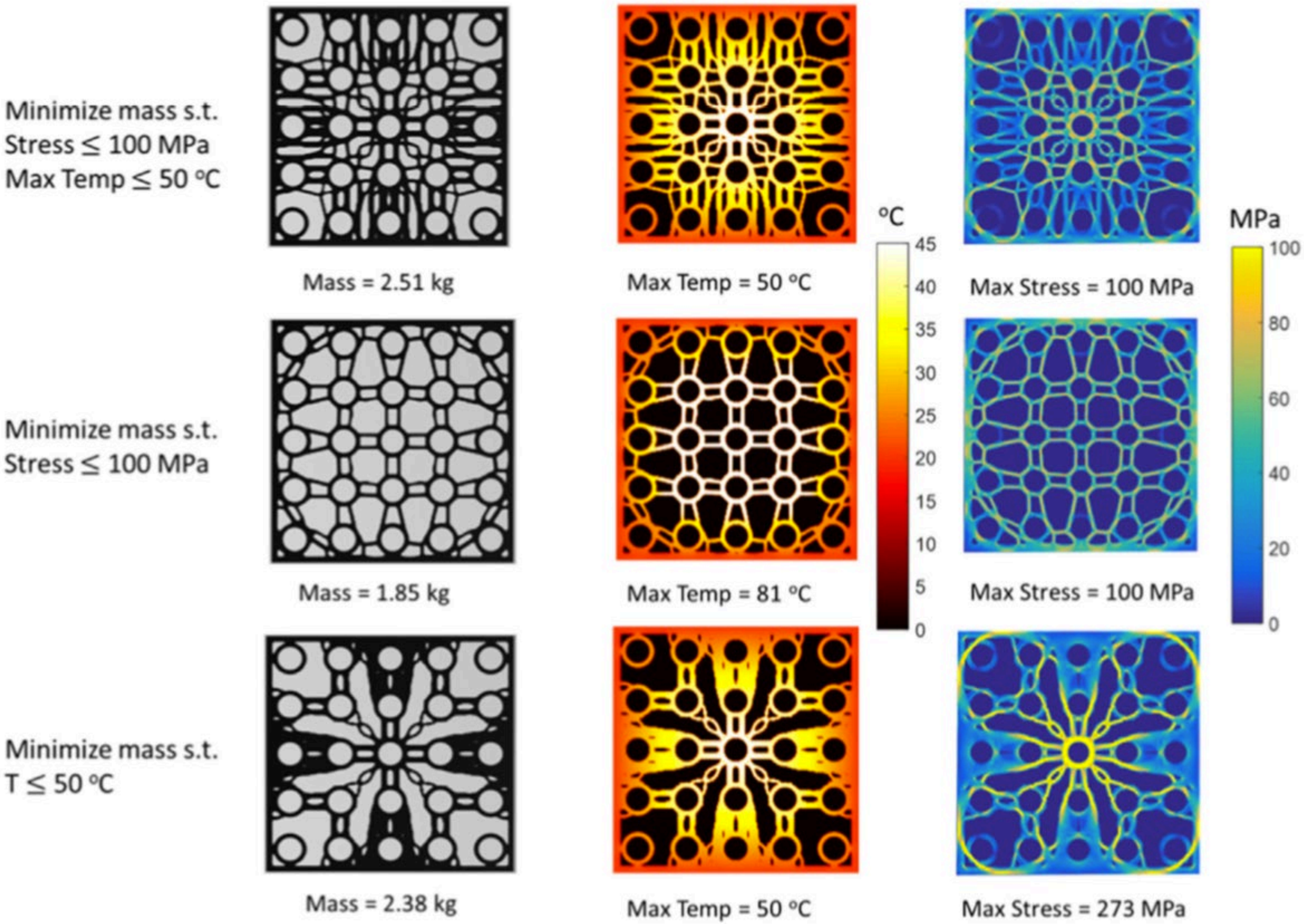
Load-carrying + Heat Exchanger + Battery Pack



(a) Topology of cooling channels (Ω_2)

(c) Topology of structure at the wing skin (Ω_1)

Heat Conduction + Stress



Kambampati, Kim (2020) Computers and Structures 235: 106265

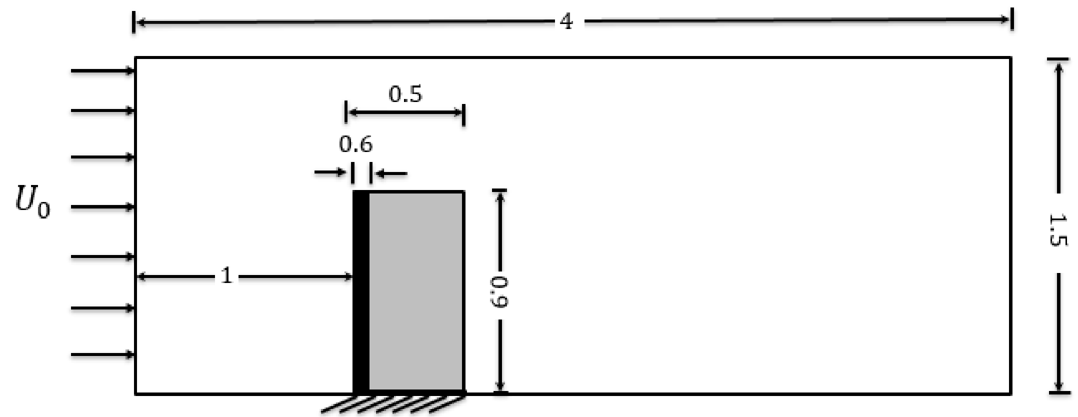
Leaflet in a Channel - FSI

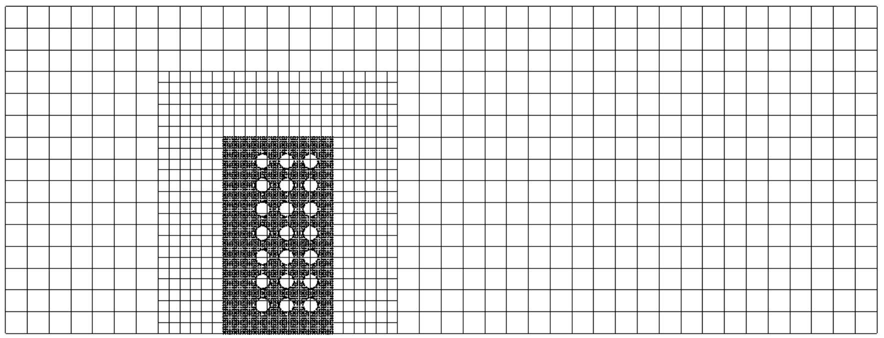
- Steady-state flow
- Linear elastic solid

- Optimization:

Min. Compliance

s.t. Volume constraint 40%

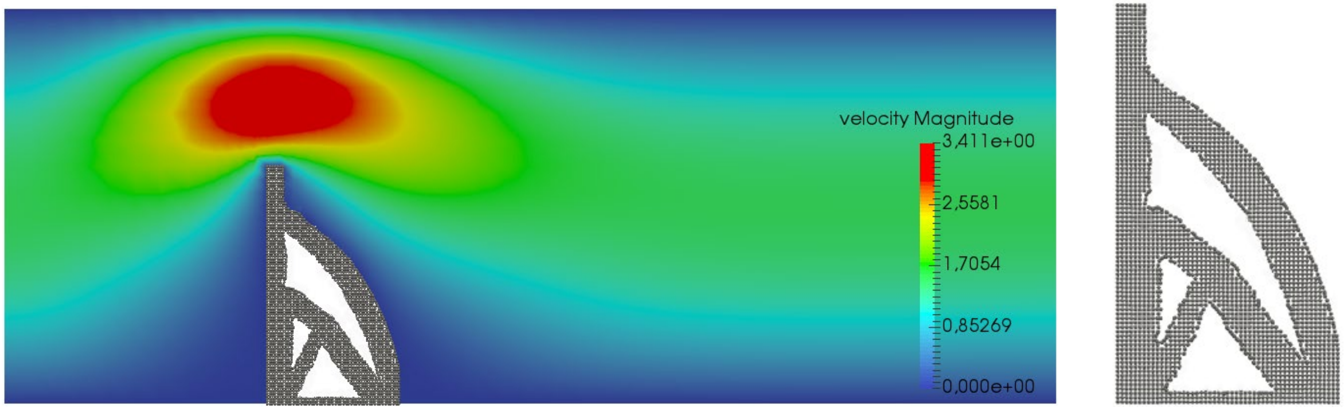




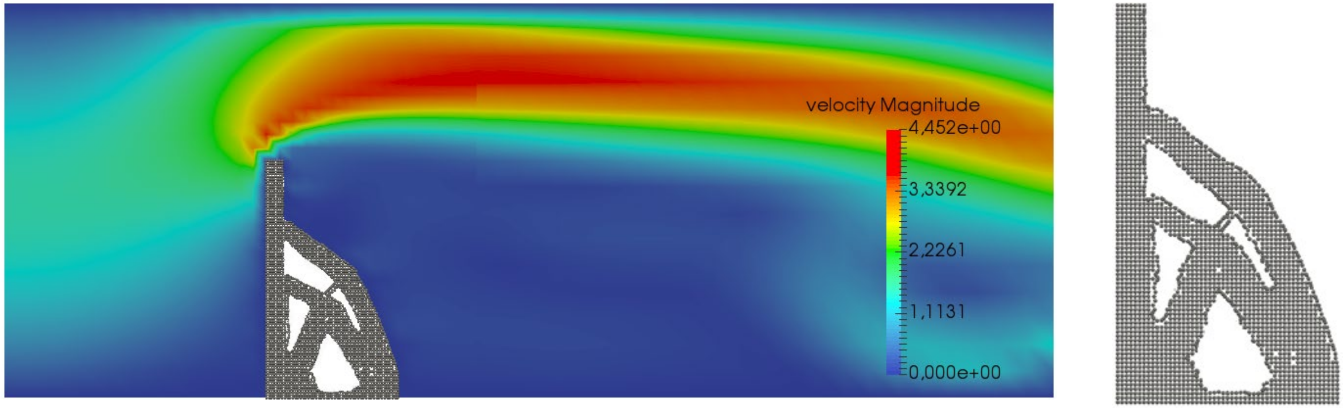
Kambampati, Kim, *et al.* (2021) "A discrete adjoint based level set topology optimization method for stress constraints". CMAME 377.

Solutions for Different Re

Re = 0.01



Re = 1000

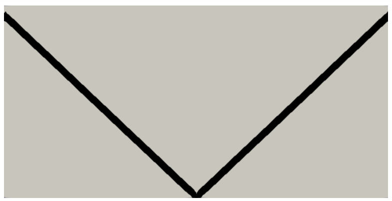
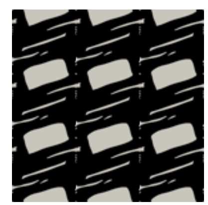
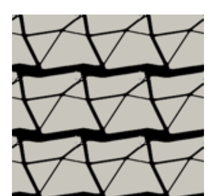


Pressure Profiles

Re = 0.01

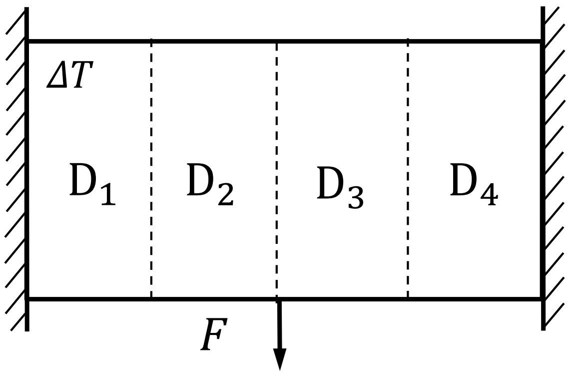
Re = 1000

Multiscale Topology Optimization

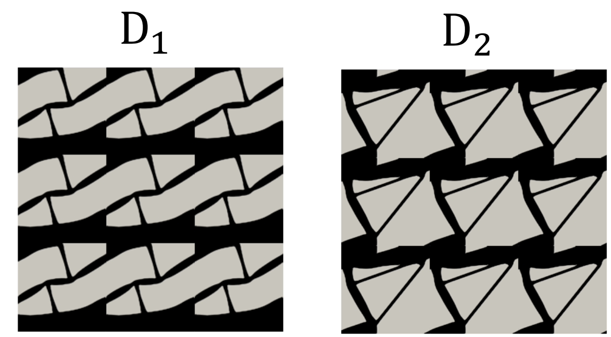
ΔT (°C)	Macroscopic design	Microscopic design: Unit cell	Microscopic design: 3x3 arrays	Effective elasticity matrix (GPa)
0				$\begin{bmatrix} 219.23 & 65.77 & 0 \\ 65.77 & 219.23 & 0 \\ 0 & 0 & 76.73 \end{bmatrix}$
75				$\begin{bmatrix} 97.32 & -0.17 & 22.38 \\ -0.17 & 27.11 & 1.63 \\ 22.38 & 1.63 & 17.02 \end{bmatrix}$
225				$\begin{bmatrix} 56.75 & -7.32 & 6.85 \\ -7.32 & 9.73 & -0.79 \\ 6.85 & -0.79 & 6.15 \end{bmatrix}$
300				$\begin{bmatrix} 26.17 & -3.96 & 2.74 \\ -3.96 & 4.66 & -0.37 \\ 2.74 & -0.37 & 2.83 \end{bmatrix}$

Multiscale Topology Optimization with Multiple materials

- 4 subdomains

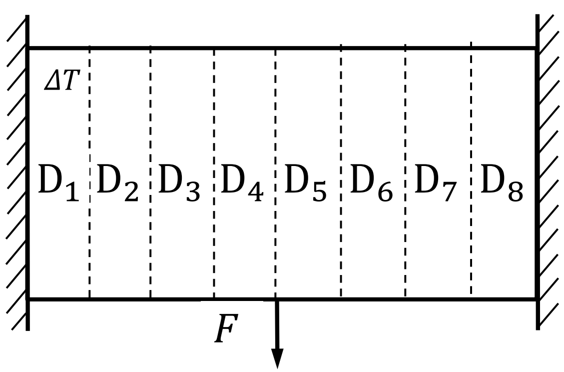


Macroscopic design
$f = 8891.31, V_{mac} = 0.128$

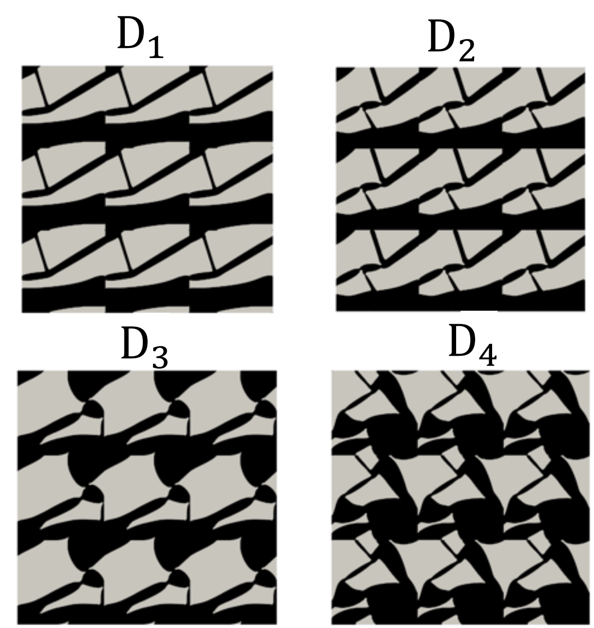


$V_{mic} = 0.391$

- 8 subdomains

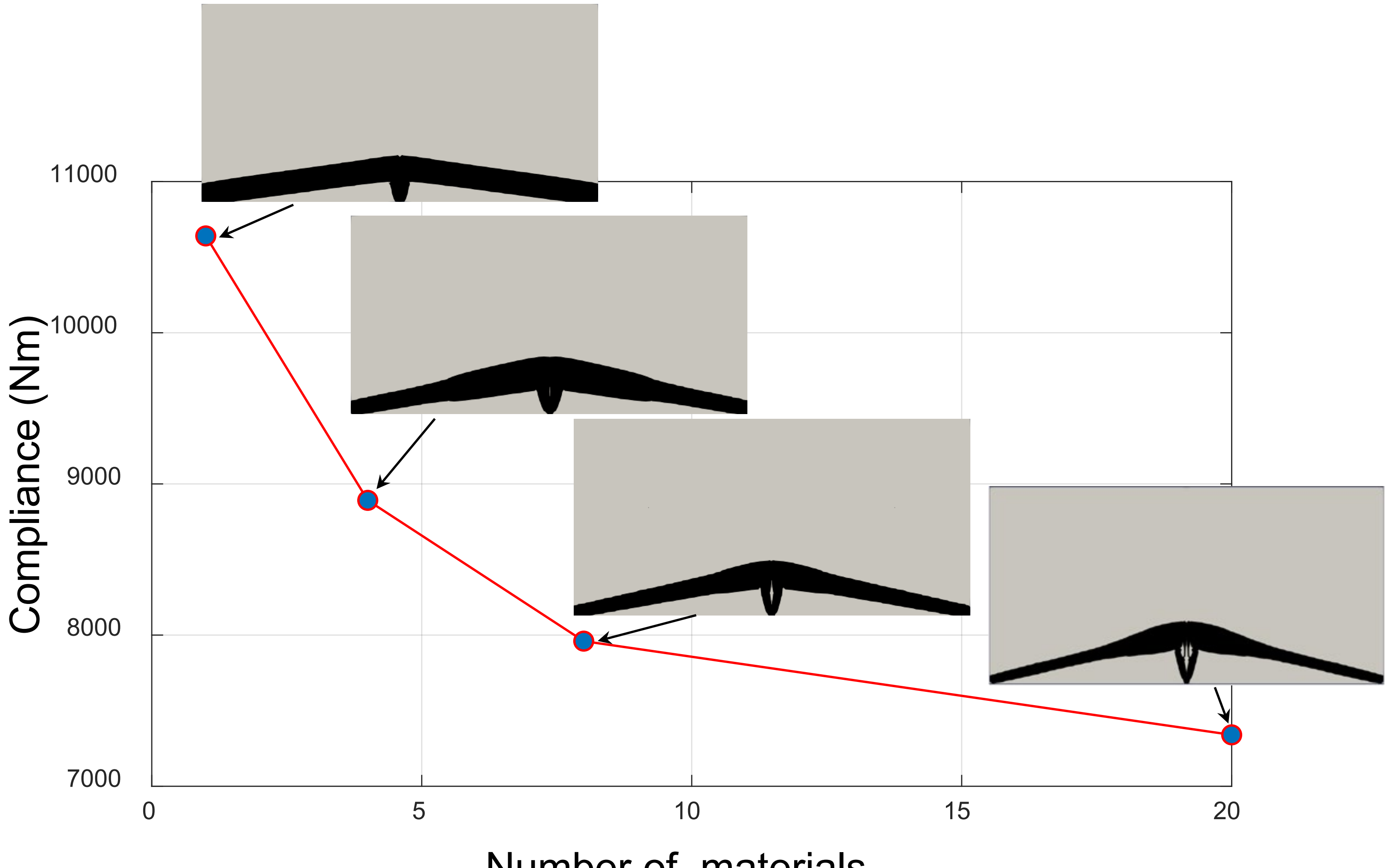


Macroscopic design
$f = 7959.96, V_{mac} = 0.103$



$V_{mic} = 0.487$

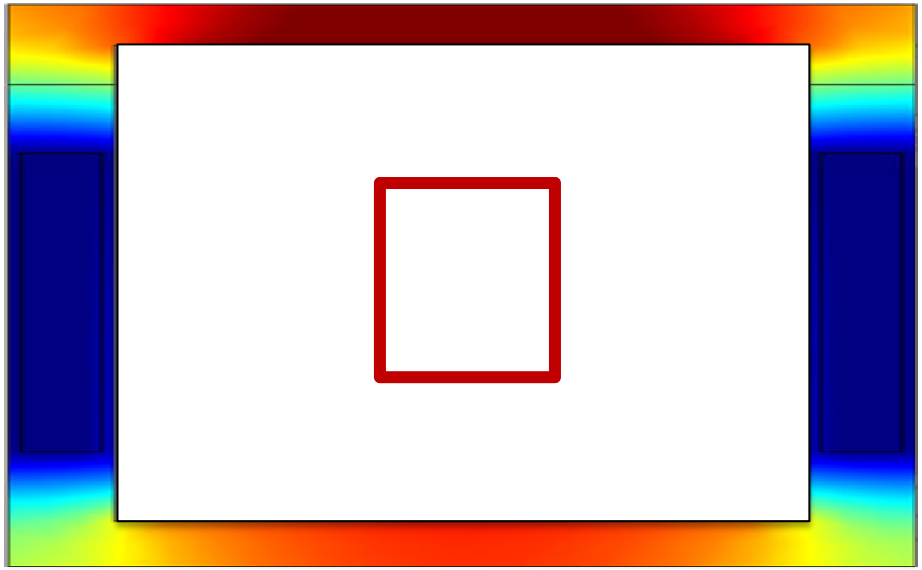
Pareto optima for multiscale solutions



Li, Du & Kim (2020). Design of Architected Materials for Thermoelastic Macrostructures Using Level Set Method. *JOM 72.*

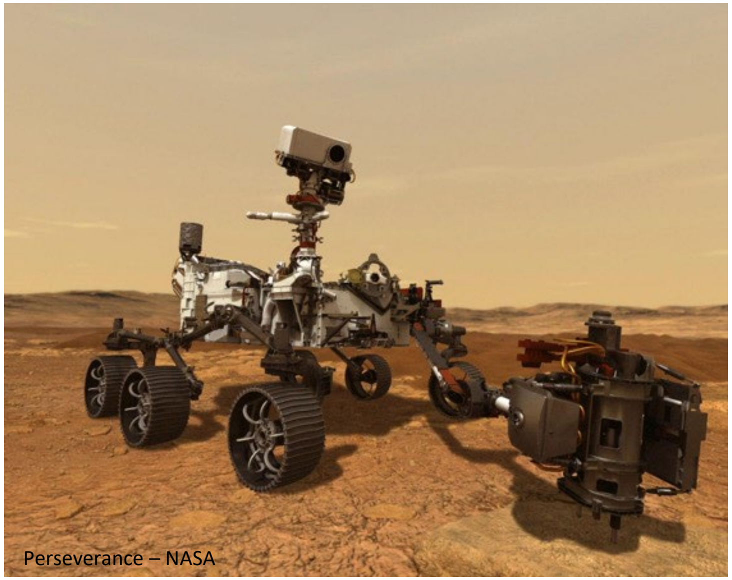
Current Research:
TO for mixed heat transfer modes

Temperature control under Conduction + Convection + Radiation



Optimization of Rover Chassis : Alex Guibert Introduction

- R&TD Project
- Additively Manufactured Rover Chassis with Integrated Thermal Control for Extreme Cold Environments
  - Thermo-mechanical topology optimization of the chassis
  - Additively Manufactured heat switch
  - Additively Manufactured structural insulation


Perseverance – NASA

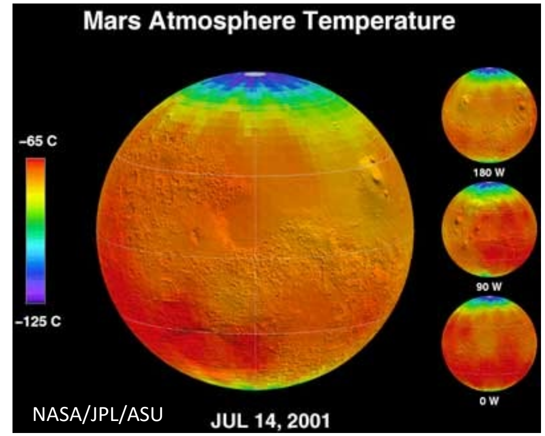
Motivations

- Develop a rover for extreme cold environment
- Cold Lunar regions / Lunar permanently shadowed regions (PSR) ~ -230 °C/50 K
- Martian high latitudes ~ -150 °C/120 K

→ These environments are very challenging for the avionics: operational temperature ~ -20 °C/250 K

→ Active heating is needed to maintain the temperature

__Objective__: minimizing the amount of energy needed while satisfying the structural requirements

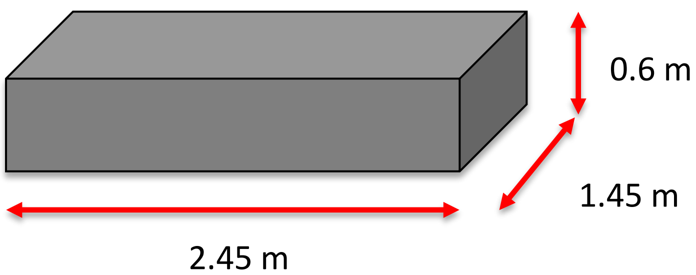


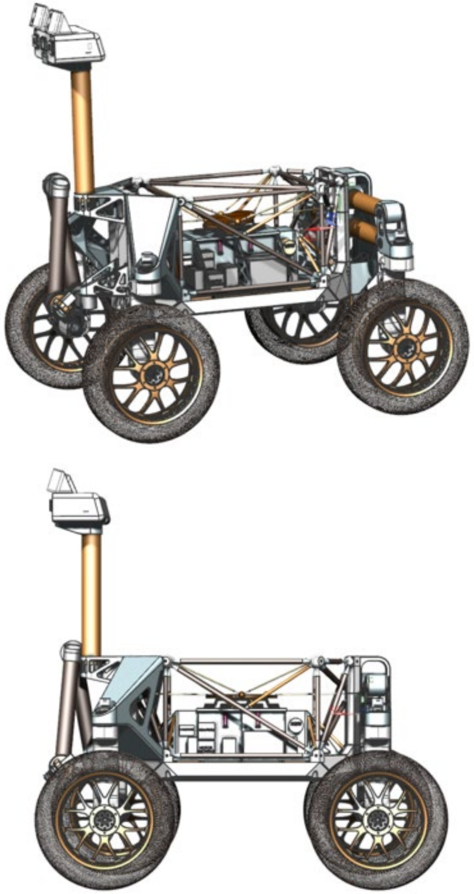
	Daytime High			Nighttime Low		
	°C	°K	°F	°C	°K	°F
Mean Surface	107	380	225	-153	120	-243
Equator (0° Latitude)	122	395	252	-158	115	-252
Mid-Latitudes	77	350	171	-143	130	-225
Poles	-43	230	-45	-63	210	-81
Dark Polar Crater	-233	40	-387	-233	40	-387

Lunar surface temperatures based on location, Heiken, 1991

Baseline

- Intrepid planetary mission concept study from 2020
- Design domain and loading conditions
- Mass of the mast ~ 120 kg
- Mass of batteries + electronics ~ 230 kg

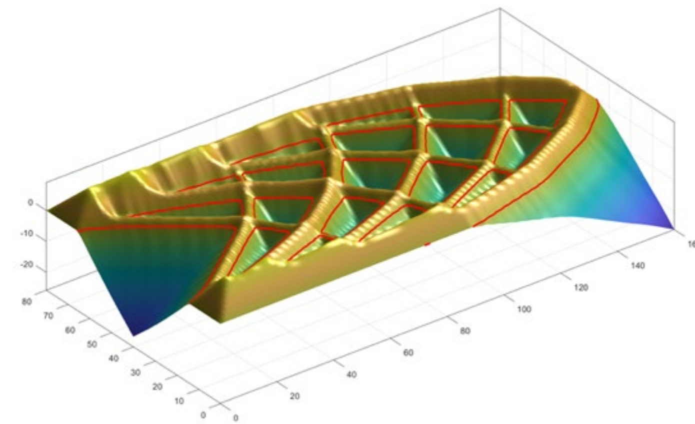




Intrepid Planetary Mission Concept Study Report, JPL/ASU, 2020

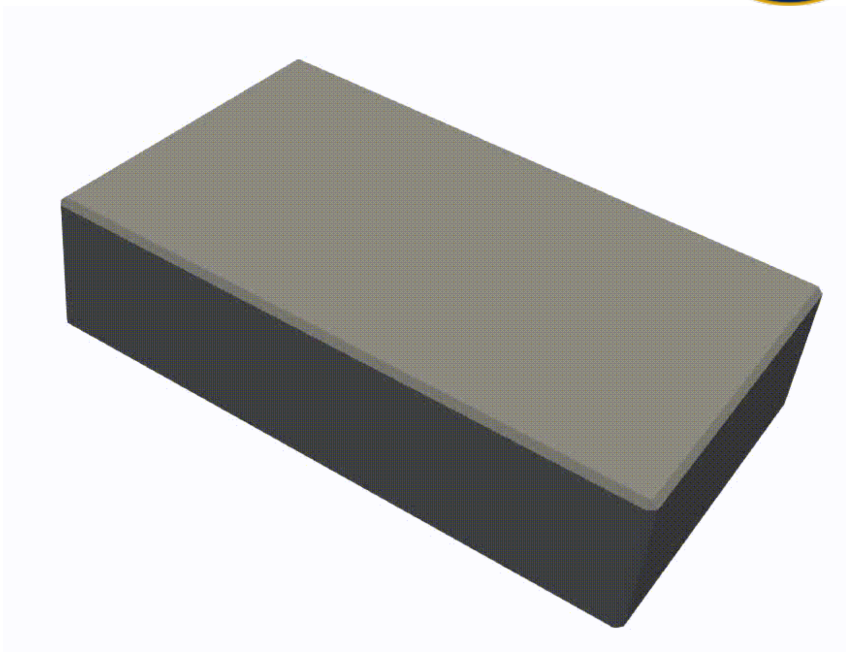
Approach

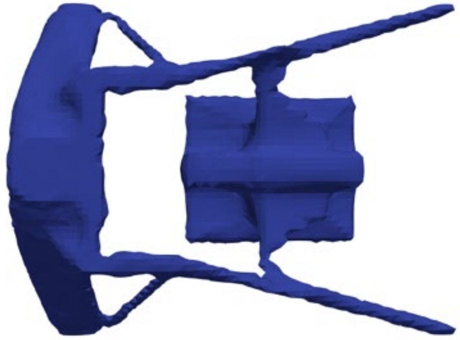
- Coupling of the thermal and structural disciplines to maximize the overall performance
- Level-set topology optimization
- Efficient implementation for large scale multiphysics optimization (parallel computing, low-level programming language for backend computation…)
- Experimental validation

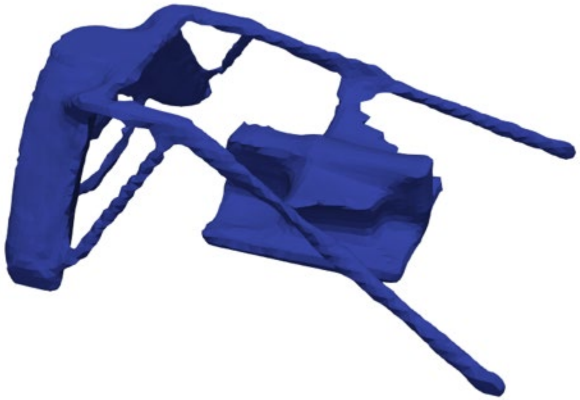


Preliminary results

Maximization of the stiffness
Subject to a volume requirement







Titanium
Mass ~ 300 kg

Next steps

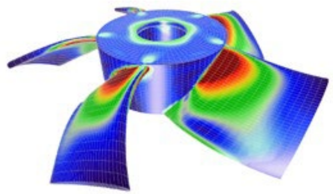
- Thermo-mechanical topology optimization of the rover chassis
- Validation through prototypes
- More complex loading conditions: launch, uneven surfaces…

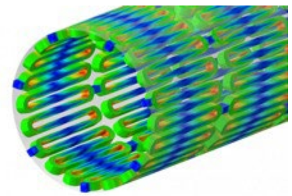
Conclusions

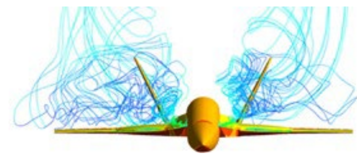
- Conflicting multiphysics environments can create unintuitive design space.
- Topology Optimization can consider coupled multiphysics effects, leading to the overall optimum design.

http://m2do.ucsd.edu/software/

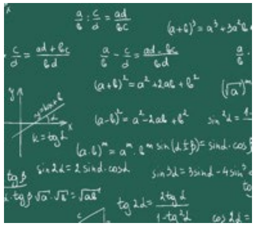
Engineering mechanics







Mathematical methods



Computer sciences