Invited talk:
Metaheuristics in Acoustic Topology Optimisation

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Learning outcomes

- ✓Introduce a new problem / case study: Topology optimisation
- ✓Learn how to formulate the problem
- ✓Refresh genetic algorithms
- ✓Introduce CMA-ES and Differential Evolution
- ✓Introduce multi-objective optimisation
- ✓Discuss some results

Funding acknowledgement: No2Noise project

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no2noise.eu

Acoustic materials in aircraft

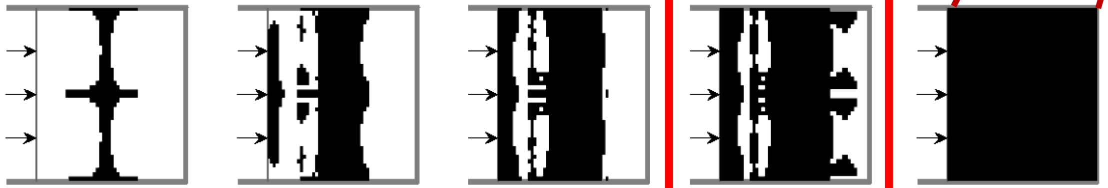
Passenger cabin noise

Fuselage with sound absorbing materials

Shapes of sound absorbing materials

Absorption values

0.49	0.82	0.87	0.89	0.83



			Best	Completely filled

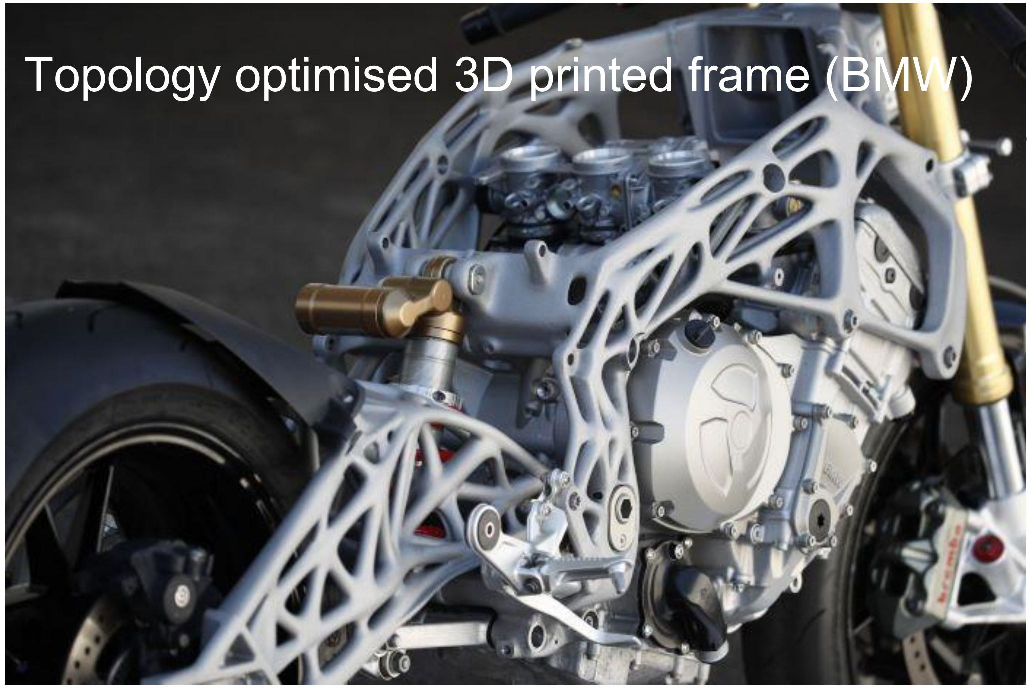
0 => no absorption
1.0 => complete absorption

! Carefully removing material can improve absorption !

Topology optimisation

Airbus A380: The largest passenger aircraft

Topology optimised parts resulted in
1000 kg reduction in weight per aircraft in Airbus A380.
L Krog, A Tucker, M Kemp, R Boyd (2004)


Topology optimised 3D printed frame (BMW)

TO flow (source: 3DPrint.com)

What is Topology?

Same Topology

Different Topologies

One hole

Three holes

Topology – Essentially, the number of holes.

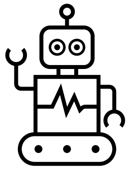
Topology vs. Shape optimisation

Shape optimisation

- ❌ No of holes (Topology) not changed
- ✅ Only the boundary of the shape is optimised

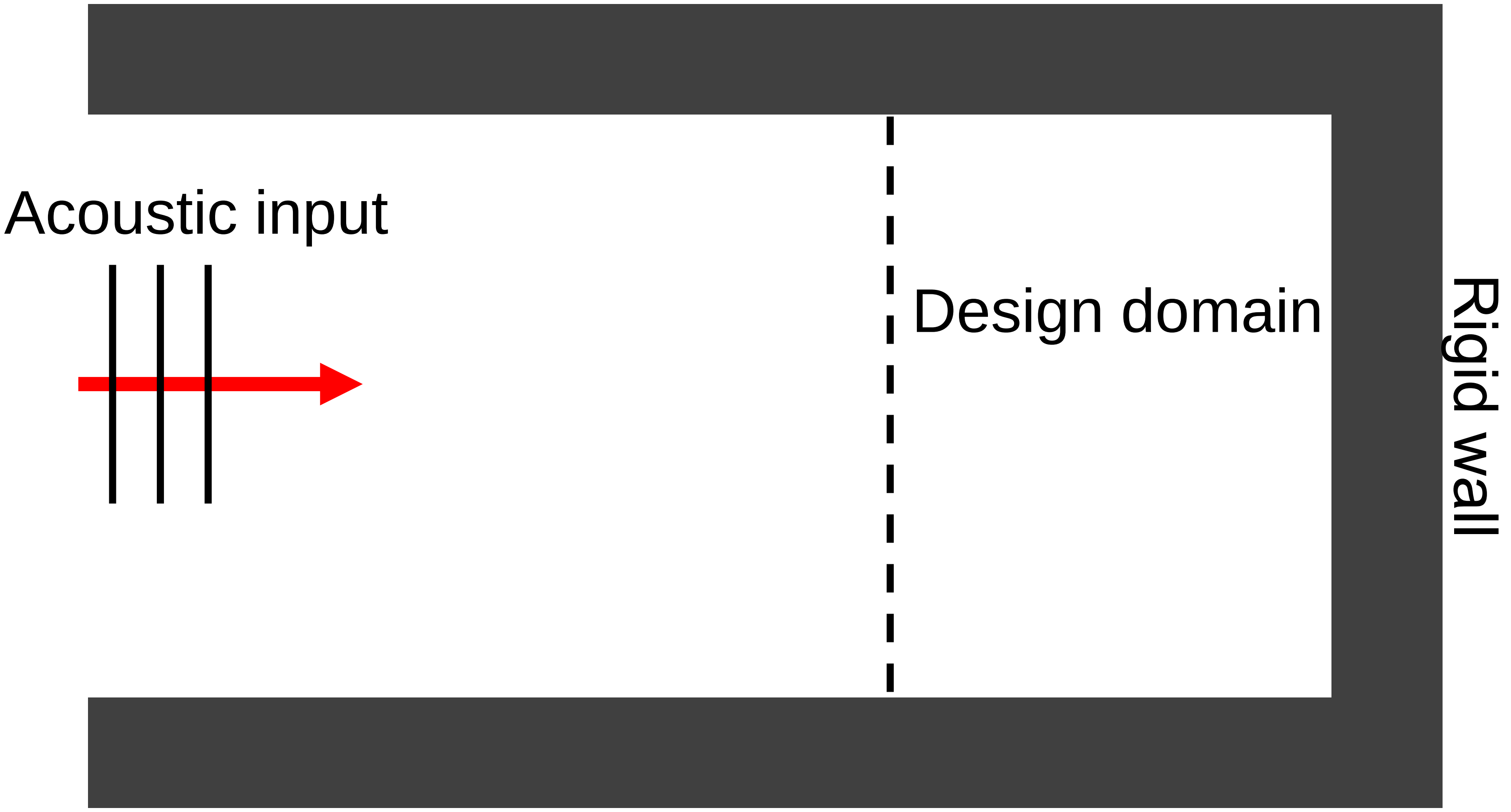
Topology optimisation

- ✅ Topology optimised &
- ✅ Shape optimised



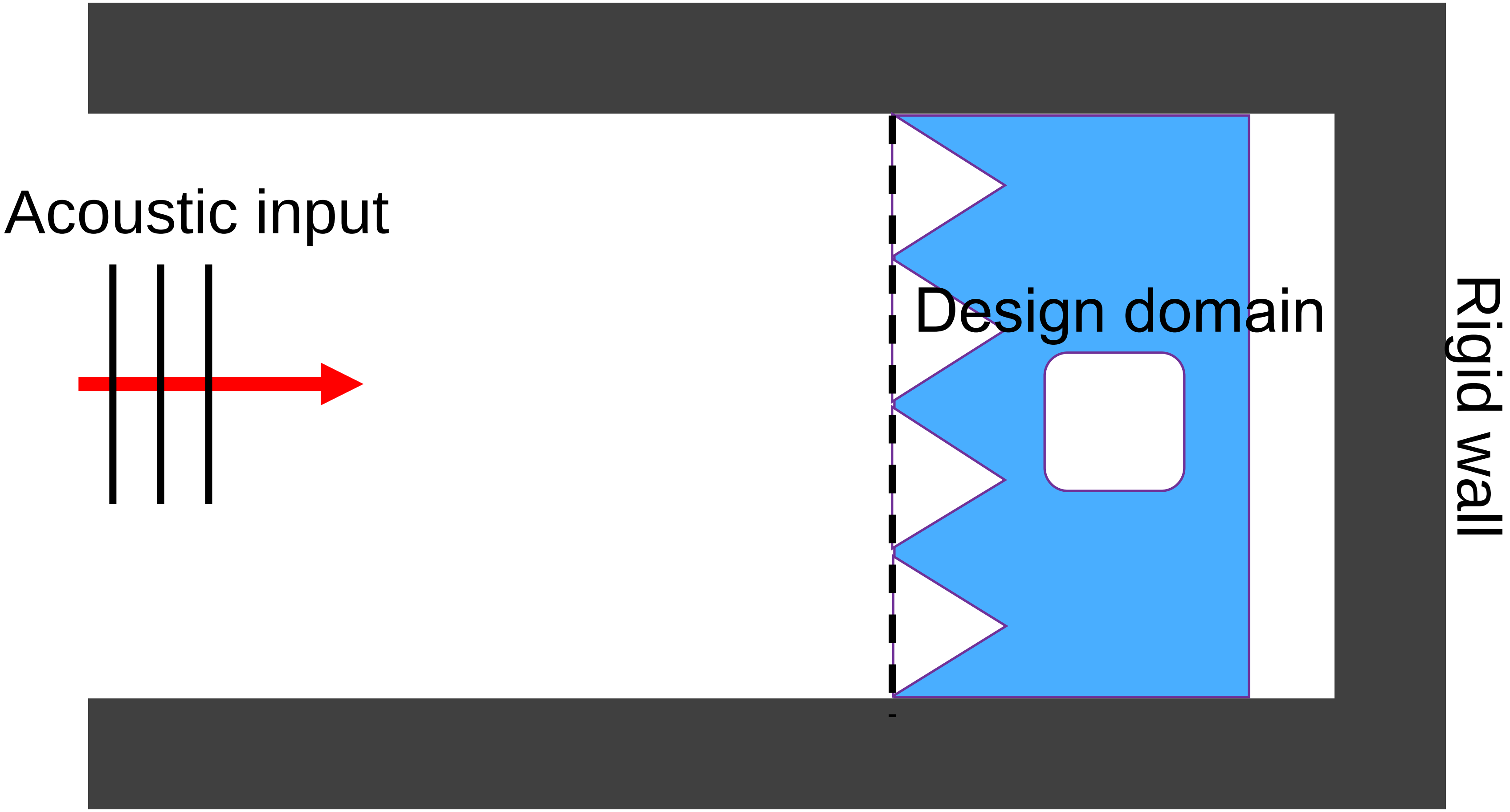
Generative Design

Canonical acoustics problem



Canonical acoustics problem

UH Anechoic chamber



What is the shape with the highest sound absorption for a given amount of acoustic material?

Problem formulation

Design domain

0	0	0	1	1	1	1	0	0
0	0	1	1	1	1	1	0	0
0	1	1	1	1	1	1	0	0
1	1	1	1	1	1	1	0	0
1	1	1	1	1	1	1	0	0
0	1	1	1	1	1	1	0	0
0	0	1	1	1	1	1	0	0
0	0	0	1	1	1	1	0	0

Sound source

Reflected

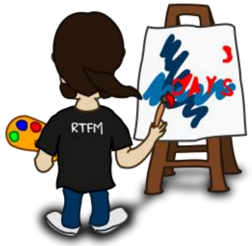
Rigid wall

Shape as an array

$$\chi = [0,0,0,1,1,\dots]$$

1 – Porous material

0 – Air



χ → **Finite Element model** → $\bar{\alpha}$

Shape

Sound absorption

Problem $\max_{\chi} \ \bar{\alpha}(\chi)$

Each $\bar{\alpha}$ evaluation takes $\approx .003\ s$

Can we brute force?

Search space size 2^n

$2^{72} \times .003 \approx 1.4 \times 10^{19} s$

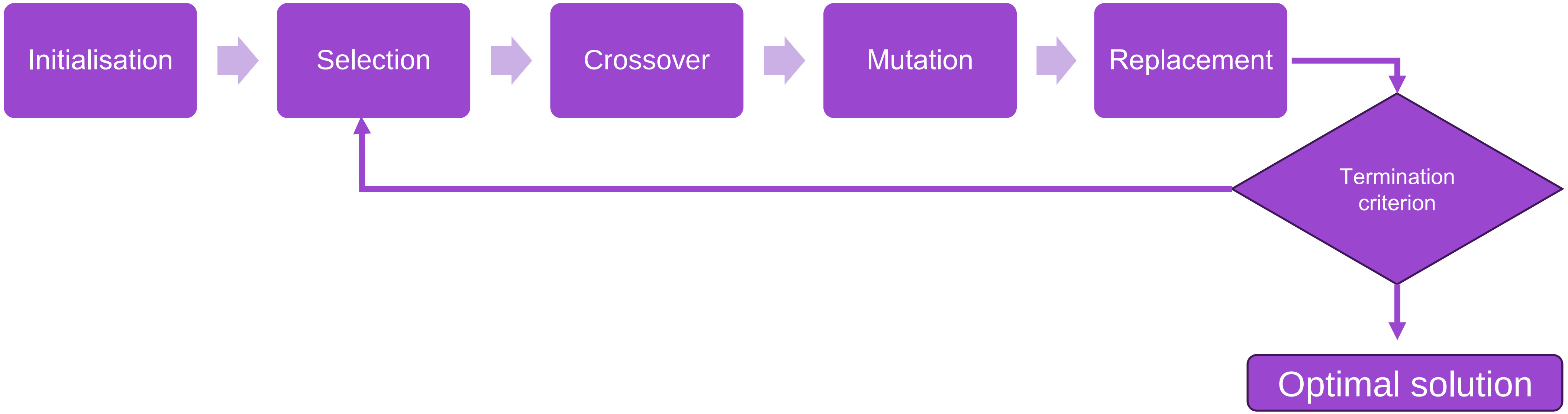
$\approx 32 \times$ Age of the universe according to the Big Bang Theory

Genetic algorithm

Interactive GA on MAXSUM problem

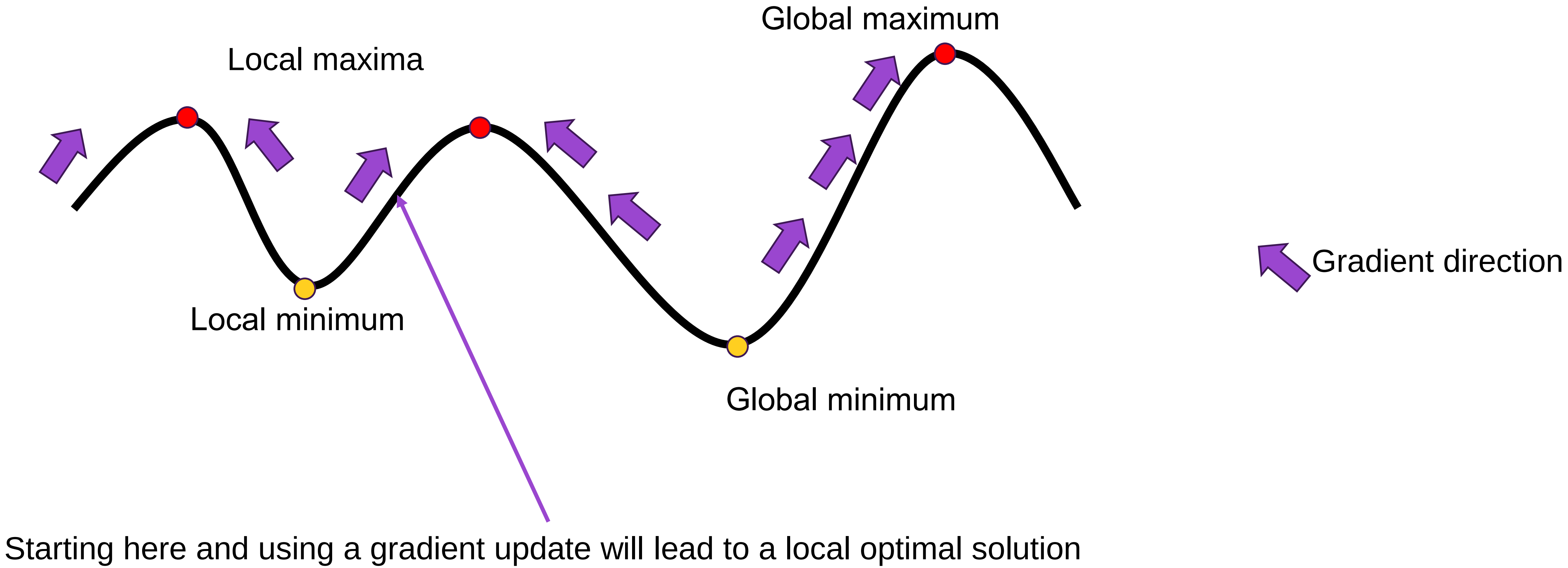
$$\max_{x_i} \sum x_i \qquad x_i \in \{0,1\}$$

https://vivektramamoorthy.github.io/GeneticAlgorithmTutorial/



Problem of local optimality

Gradient algorithms have the tendency to get stuck at local optimal solutions.



Covariance Matrix Adaptation – Evolution Strategy (CMA-ES)

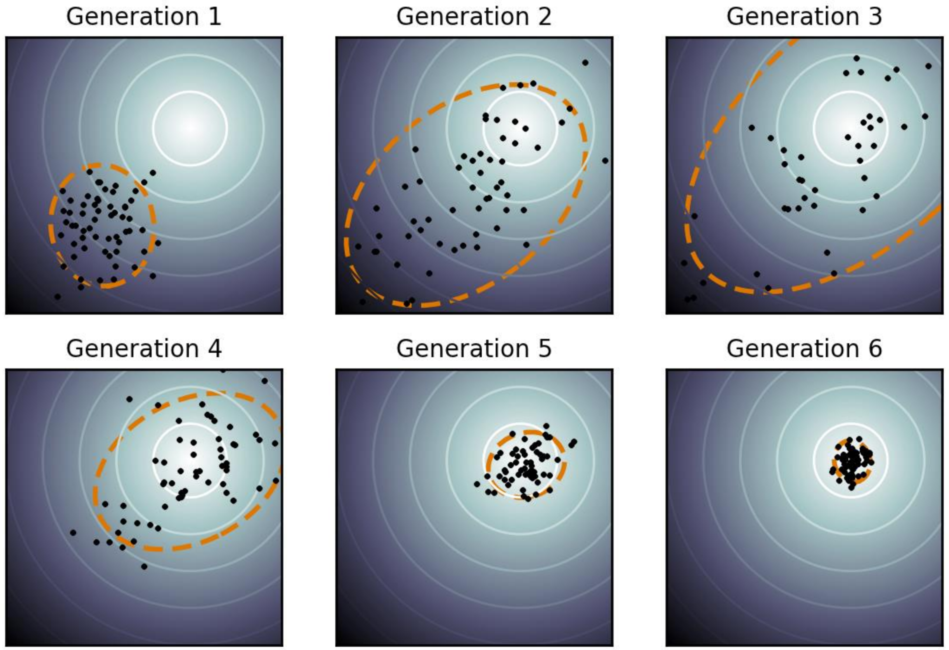
$$\min_{\boldsymbol{x}} f(\boldsymbol{x})$$

$$x \in \mathbb{R}^n, f \in \mathbb{R}$$

- Population based
- Uses a multivariate gaussian to approximate the fitness landscape

CMA-ES in action

https://vivektramamoorthy.github.io/CMAEStutorial/



Wiki-user: Sentewolf

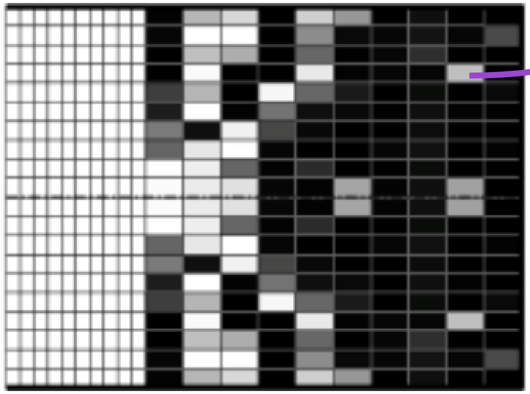
Reference:

- Hansen, Nikolaus, Sibylle D. Müller, and Petros Koumoutsakos. "Reducing the time complexity of the derandomized evolution strategy with covariance matrix adaptation (CMA-ES)." Evolutionary computation 11.1 (2003): 1-18.
- Hansen, Nikolaus. "The CMA evolution strategy: A tutorial." arXiv preprint arXiv:1604.00772 (2016).

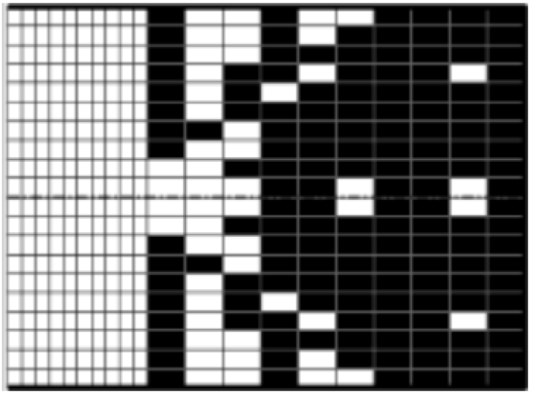
Continuous relaxation

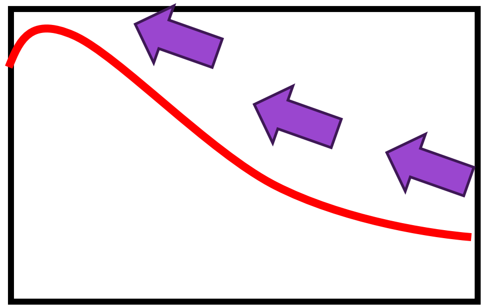
Allow intermediate materials
$\chi_i \in [0,1]$

Optimise



Then discretise





Air

Acoustic material

Gradient descent SIMP

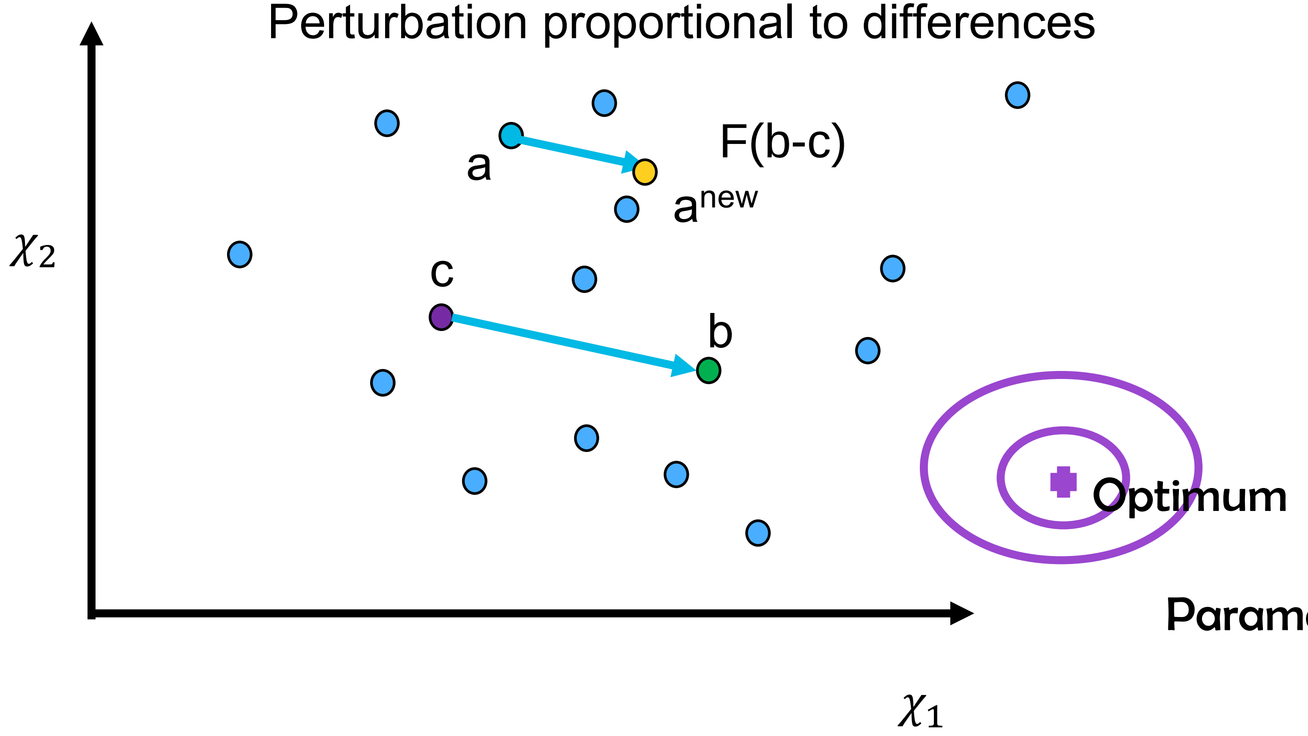
Discrete Covariance Matrix Adaptation Evolution Strategy vs. SIMP

Ramamoorthy, V. T., Özcan, E., Parkes, A. J., Sreekumar, A., Jaouen, L., & Bécot, F. X. (2020). Acoustic topology optimisation using CMA-ES. *Proceedings of ISMA2020 and USD*, 511-522.

Differential evolution

Population-based continuous optimisation metaheuristic

Perturbation proportional to differences



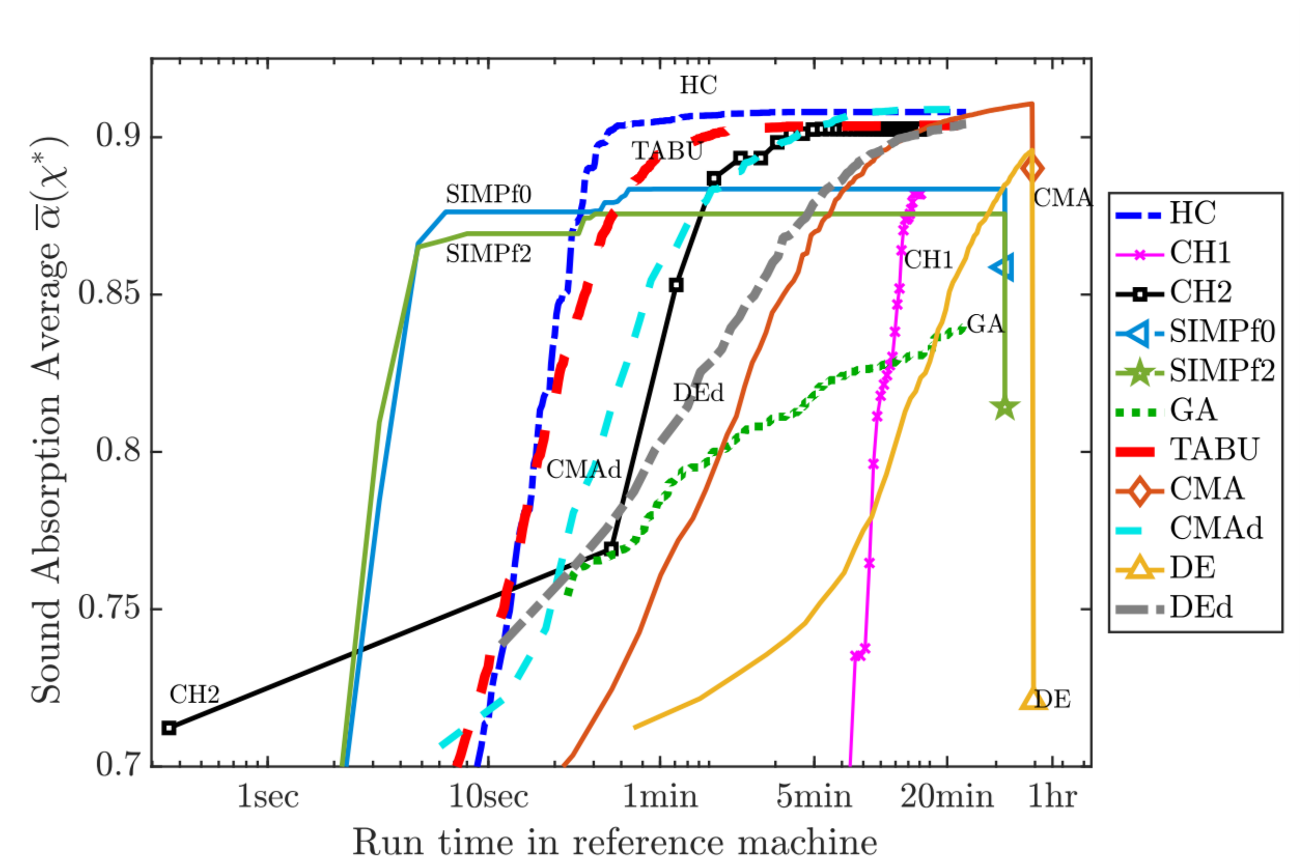
Parameters: F,CR

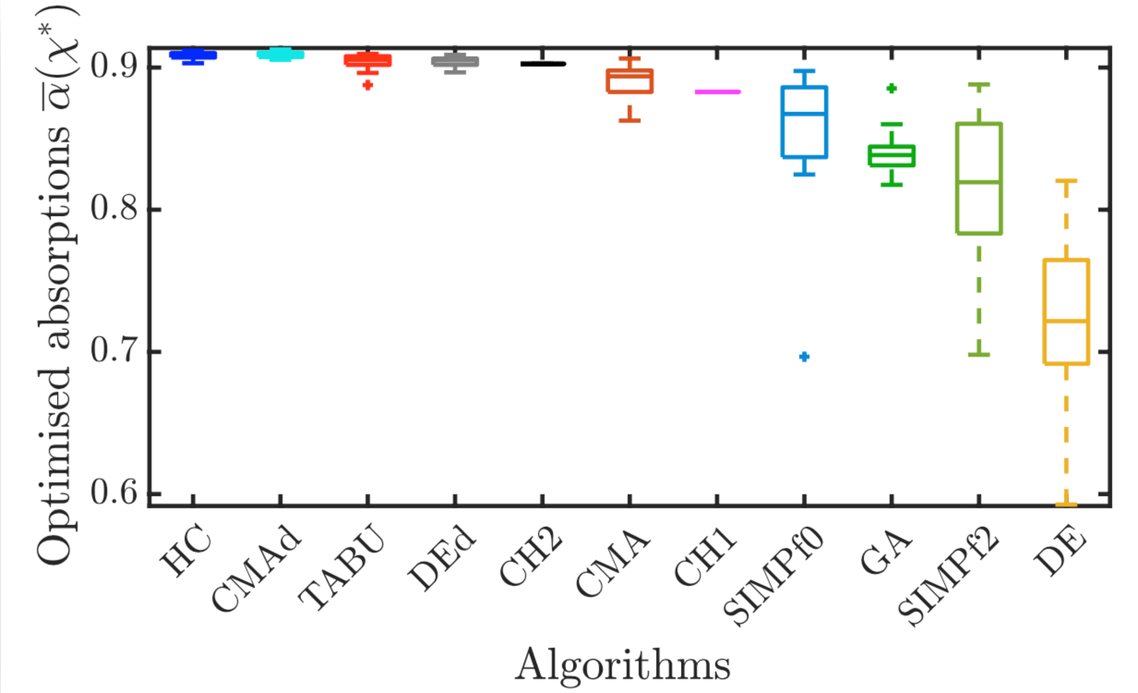
χ^j ←Generate Initial Population;
Evaluate their Fitnesses $\overline{\alpha}_j \leftarrow \overline{\alpha}(\chi^j)$;
while $fevals < budget$ **do**
  for $j = 0, j = length[pop], j{+}{+}$ **do**
    Randomly select $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$ from pop;
    $\boldsymbol{y} \leftarrow \boldsymbol{a} + F \times (\boldsymbol{b} - \boldsymbol{c})$;
    for $i = 0, i = length[\chi^j], i{+}{+}$ **do**
      if $rand < CrossoverRate$ **then**
        $y_i \leftarrow \chi_i^j$;
      end
    end
    Evaluate $\overline{\alpha}(\boldsymbol{y})$;
    if $\overline{\alpha}(\boldsymbol{y})$ *is better than* $\overline{\alpha}(\chi)$ **then**
      Replace $\chi^j \leftarrow \boldsymbol{y}$
    end
    Keep track of the best solution χ^*;
  end
end
return χ^*;

References:

- Storn, Rainer, and Kenneth Price. "Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces." *Journal of global optimization* 11.4 (1997): 341-359.
- Price, Kenneth, Rainer M. Storn, and Jouni A. Lampinen. Differential evolution: a practical approach to global optimization. Springer Science & Business Media, 2006.

Comparison of algorithms





HC – Hill climbing
CMA – CMAES
CMAd – Discrete CMAES
TABU – Tabu search
DEd – Discrete Differential evolution

HC – Hill climbing
CMAd – Discrete CMAES
TABU – Tabu search
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Not the full picture!

Results for other problem instances reveal more:
Vivek T. Ramamoorthy, Ender Özcan, Andrew J. Parkes, Abhilash Sreekumar, Luc Jaouen and François-Xavier Bécot, Comparison of heuristics and metaheuristics for topology optimisation in acoustic porous materials, The Journal of Acoustical Society of America, Vol. 150, Issue 4, pp. 3164-3176, (October 2021).

Multi objective optimisation

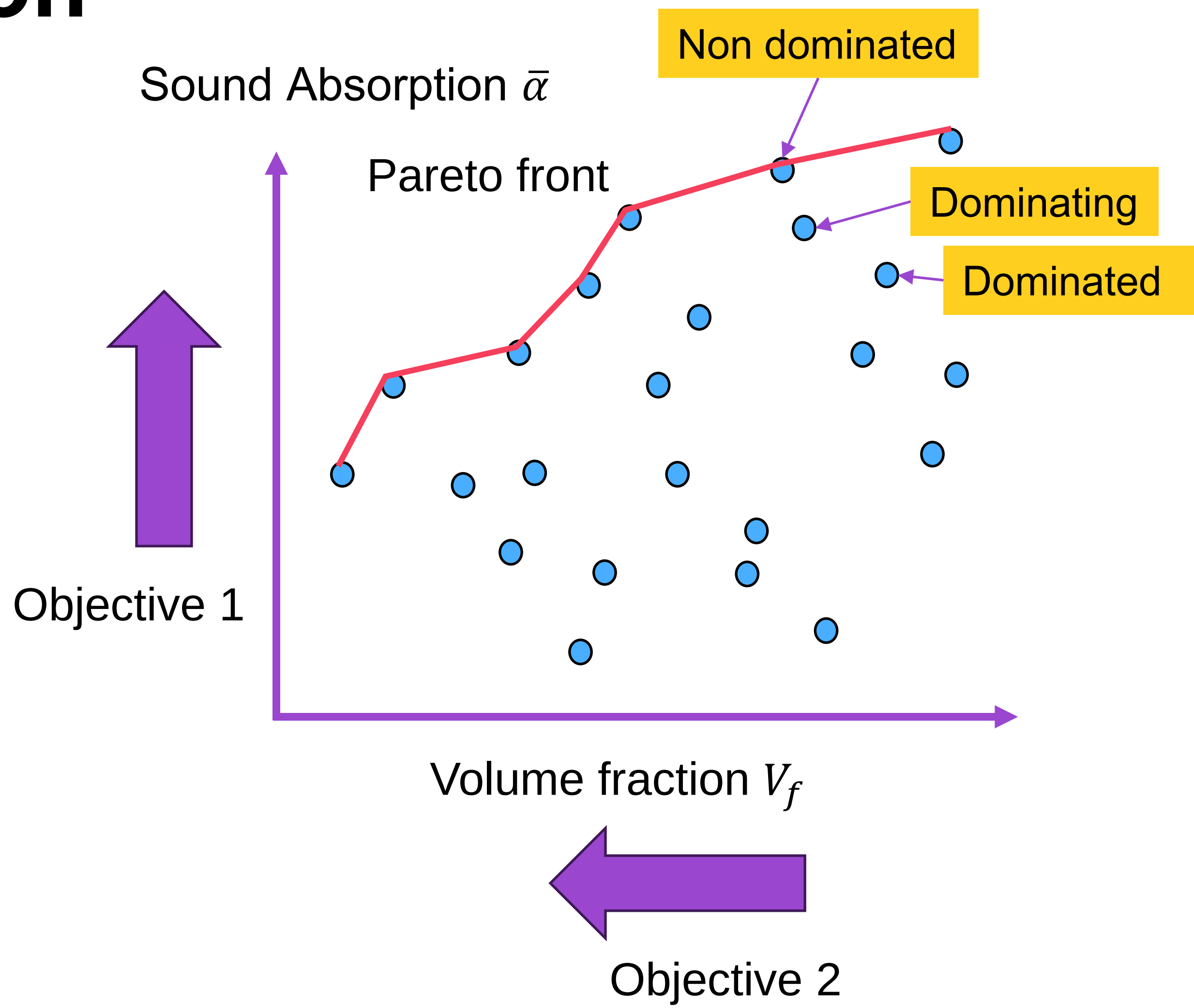
More than one objective function

For ex: Simultaneously,

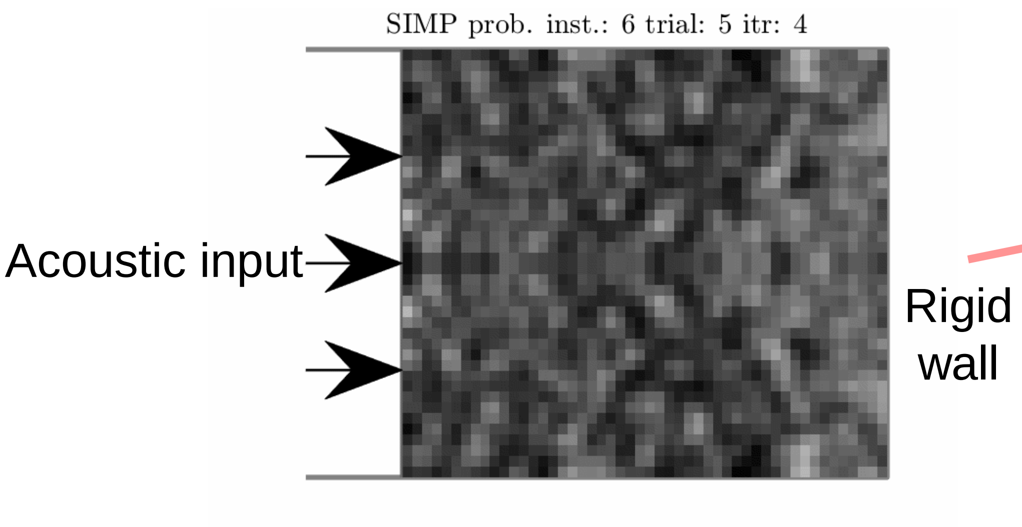
1. Maximise sound absorption $\bar{\alpha}$
2. Minimise weight V_f

Pareto front:

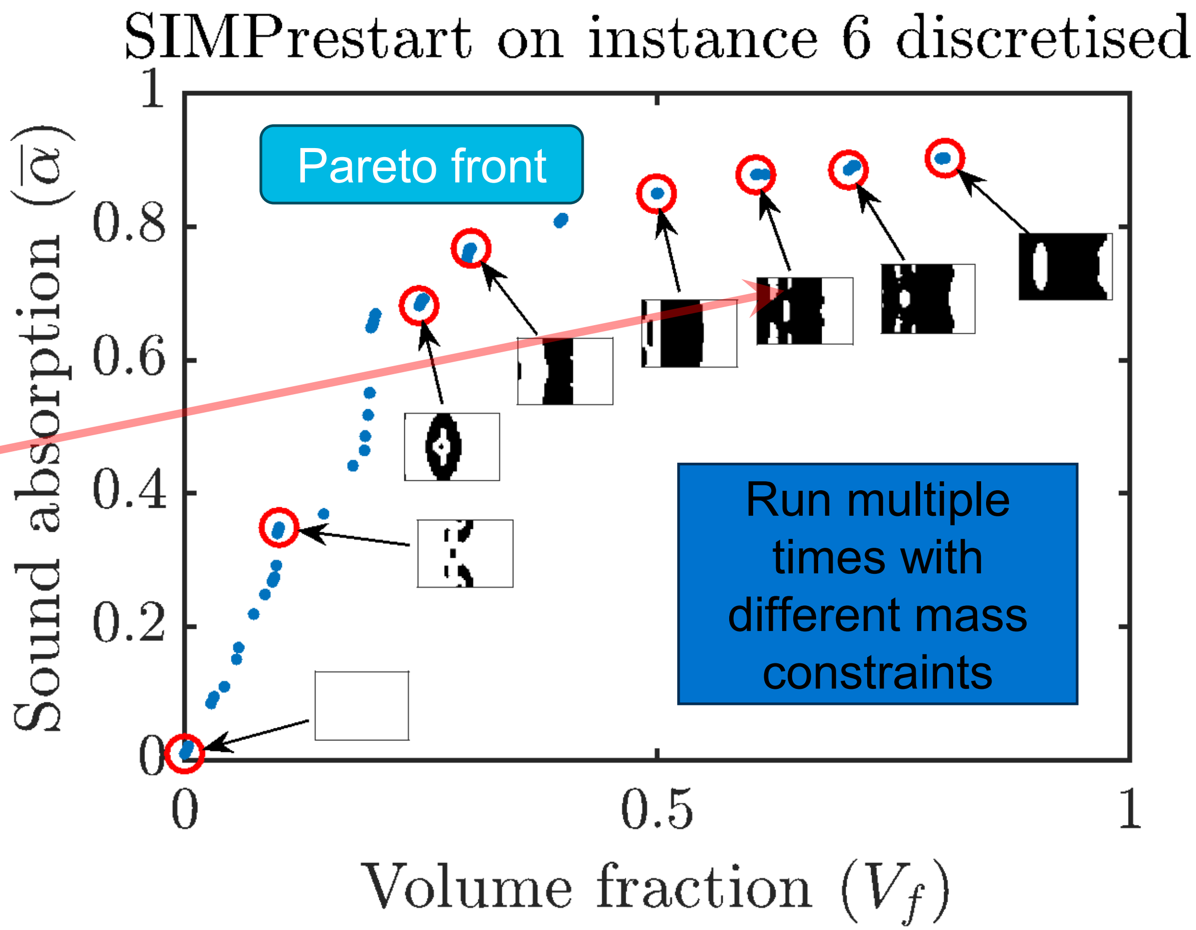
- The set of non-dominated solutions
- Non-dominated solutions: No other solution is better in terms of all objectives.
- Each non-dominated solution is considered as equally good



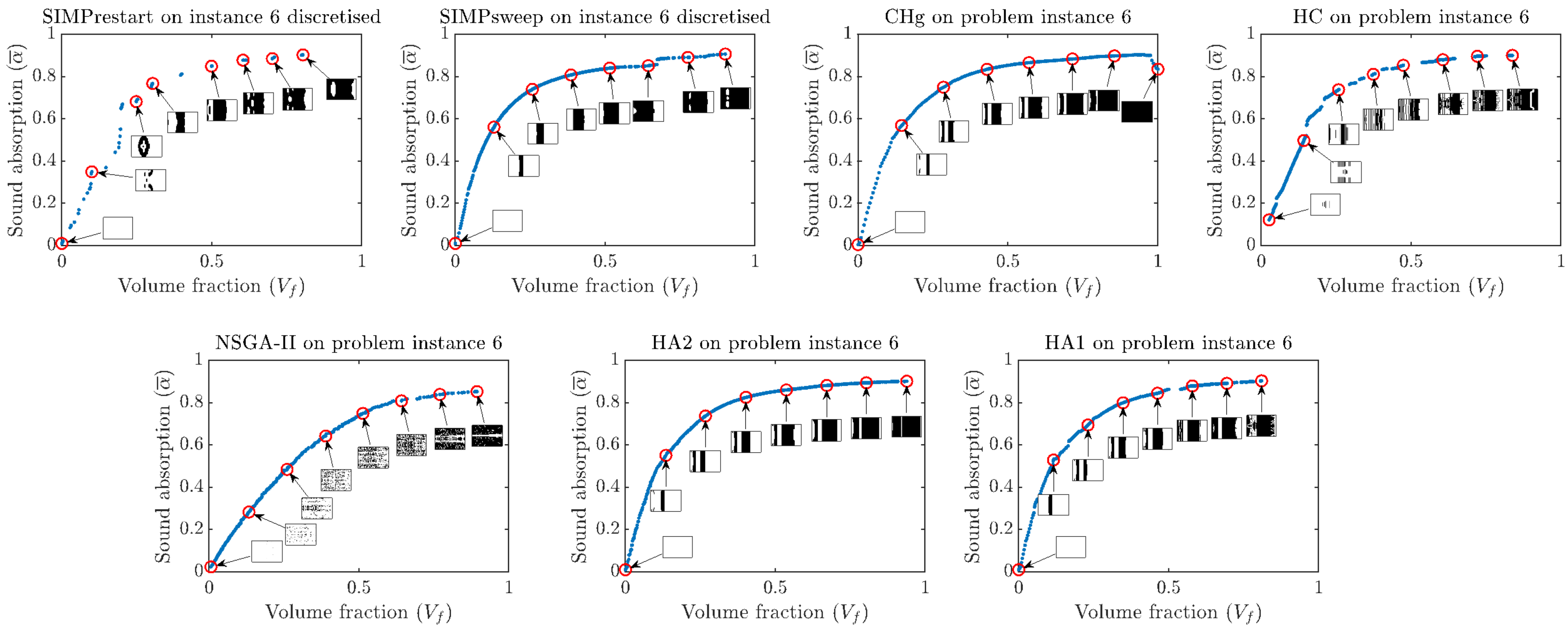
Solid Isotropic Material with Penalisation (SIMP)



Near optimal topology

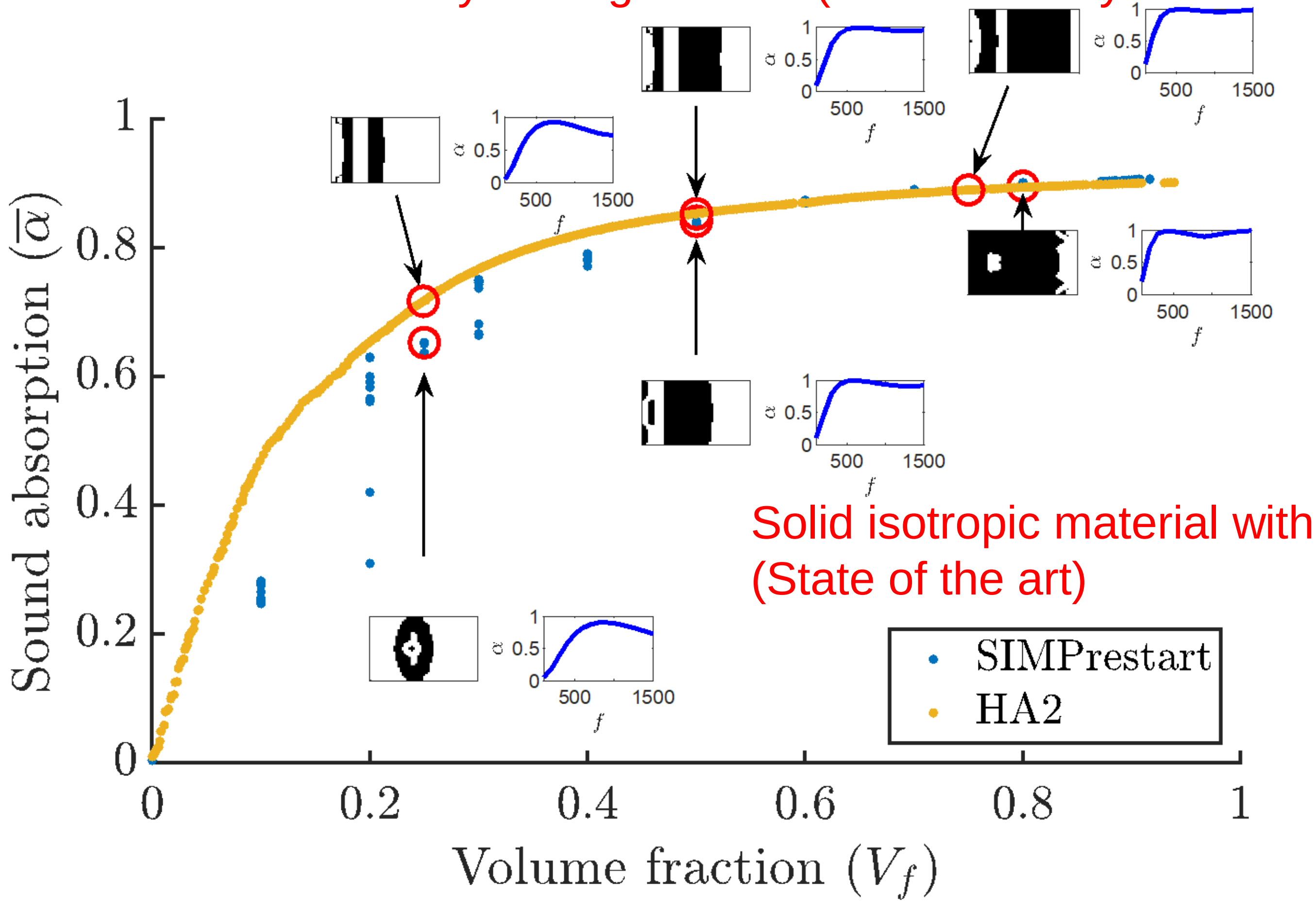


Comparison of algorithms



A comparison with the state of the art

Hybrid algorithm 2 (Ramamoorthy et al. 2023)

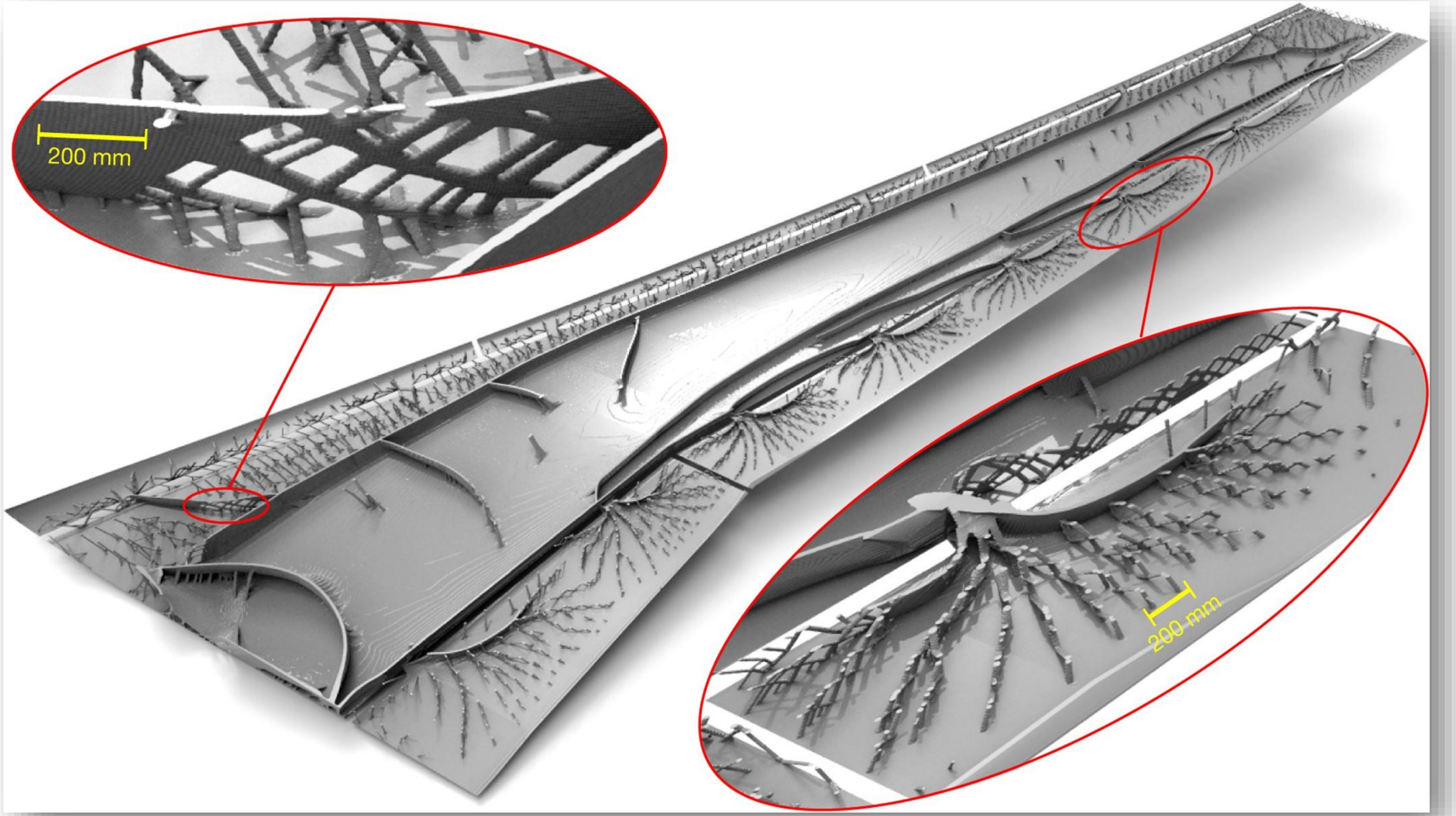


Hybrid gradient & non-gradient algorithms work better.

Solid isotropic material with penalisation (State of the art)

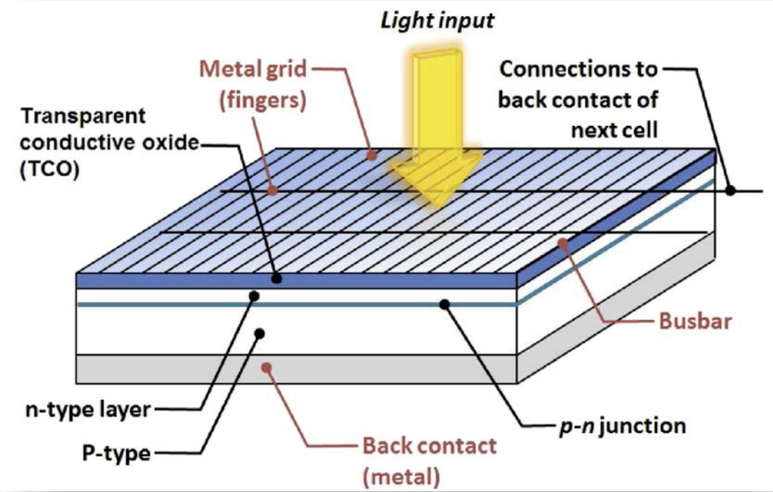
Ramamoorthy, V.T., Özcan, E., Parkes, A.J., Jaouen, L. and Bécot, F.X., 2023. Multi-objective topology optimisation for acoustic porous materials using gradient-based, gradient-free, and hybrid strategies. *The Journal of the Acoustical Society of America*, *153*(5), pp.2945-2945.

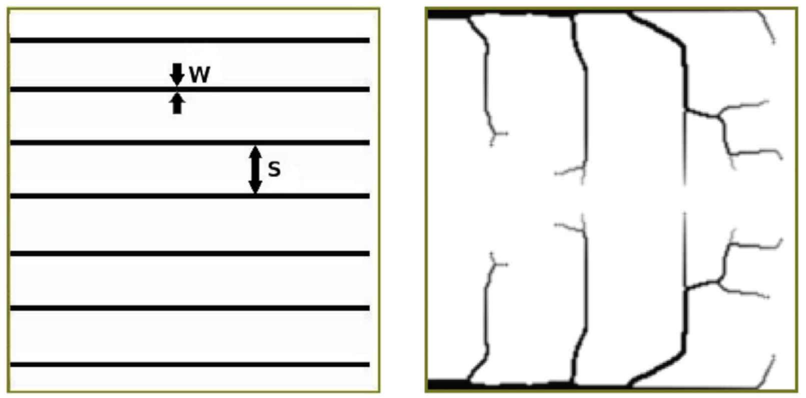
Other topology optimisation applications: Optimised ribs in an aircraft wingbox



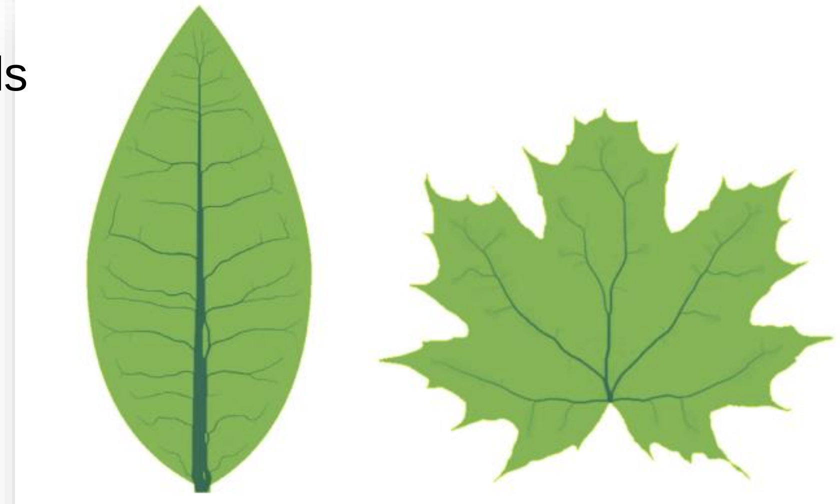
Aage, Niels, et al. "Giga-voxel computational morphogenesis for structural design." Nature 550.7674 (2017): 84-86.

Other topology optimisation applications: Solar metallization





(a) Shape optimization (b) Topology optimization


(a) Simple leaf ($\eta = 13.25\%$) (b) Maple leaf ($\eta = 14.39\%$)

Optimal layout of metallization in leaf shaped solar panels turn out to be very similar to the veins in a leaf.

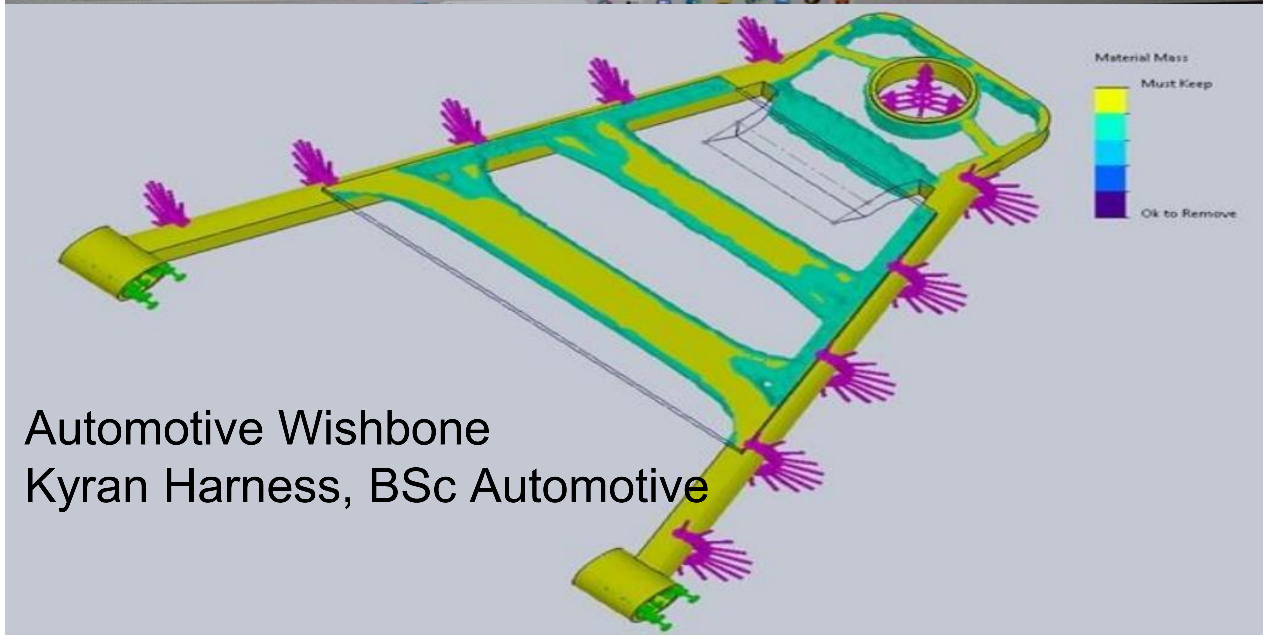
Nature has optimised it before we did. ☺

Reference:

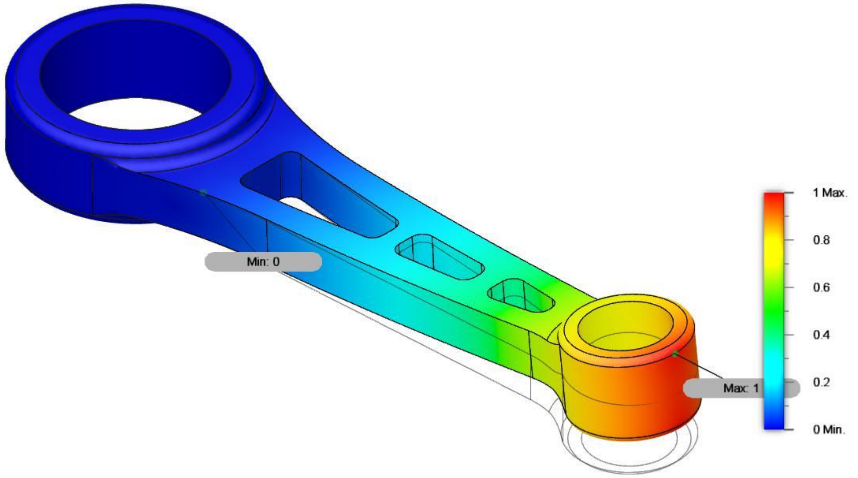
Gupta, D. K., et al. "Topology optimization of front metallization patterns for solar cells." Structural and Multidisciplinary Optimization 51.4 (2015): 941-955.

Some of my students’ TO designs

Aircraft Wing Rib
Joab Alban Salgado, BEng Aerospace



Automotive Wishbone
Kyran Harness, BSc Automotive



Connecting Rod
Amal Benadict, MSc Automotive

Summary

Intro to topology optimisation

Formulated the optimisation problem

Problem of local optimality

Refreshed Genetic algorithms

Continuous algorithms (CMA-ES and Differential evolution)

Introduction to Multi-objective optimisation

Reviewed some results

Thank you

University of Hertfordshire UH