Minimizing Plasma-Facing Component Heat Flux Using Unsupervised Mesh Generation

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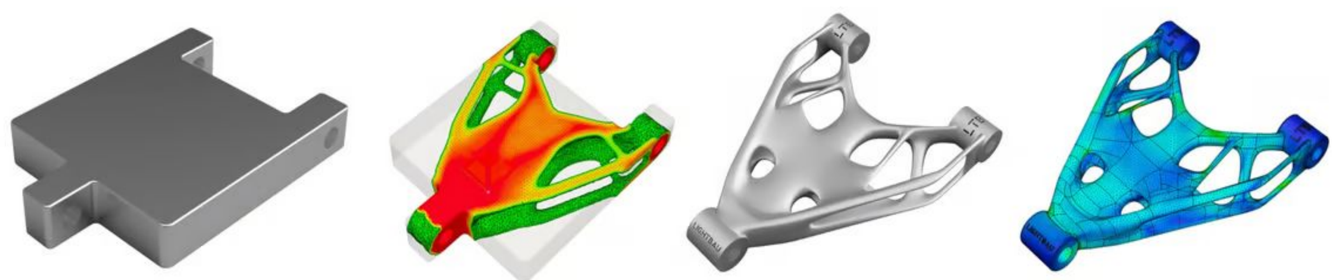
Motivation and Background

- Plasma-facing components (**PFCs**) require fine-tuned designs optimized for multiple parameters in order to survive high heat loads, heat flux - a significant design challenge
- **Topology optimization** algorithms can explore design spaces and discover novel designs beyond conventional methods, but existing tools are often strictly constrained
- A machine-learning model that **autonomously learns design parameters with minimal restrictions to generate PFC topologies that minimize peak heat flux** can be generalized for many applications



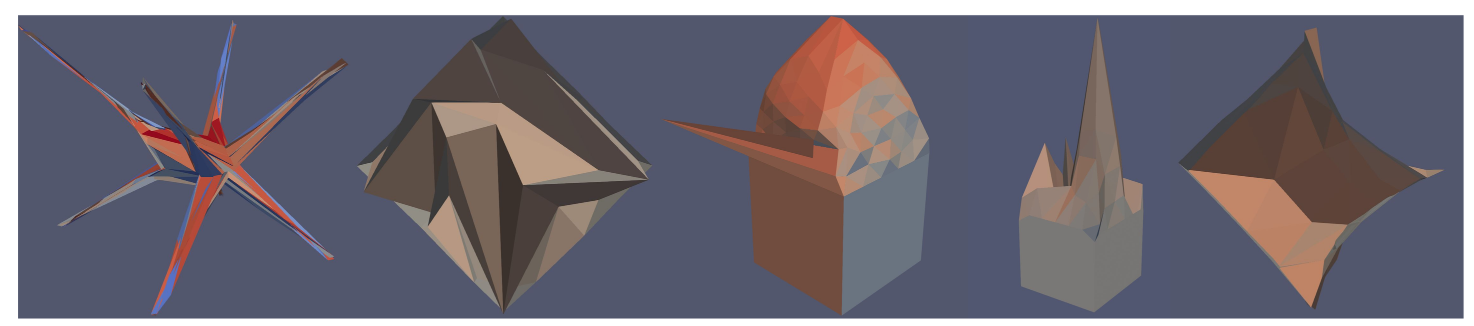
Example of topology optimization - structural optimization with finite element method

Defining the Objective Function

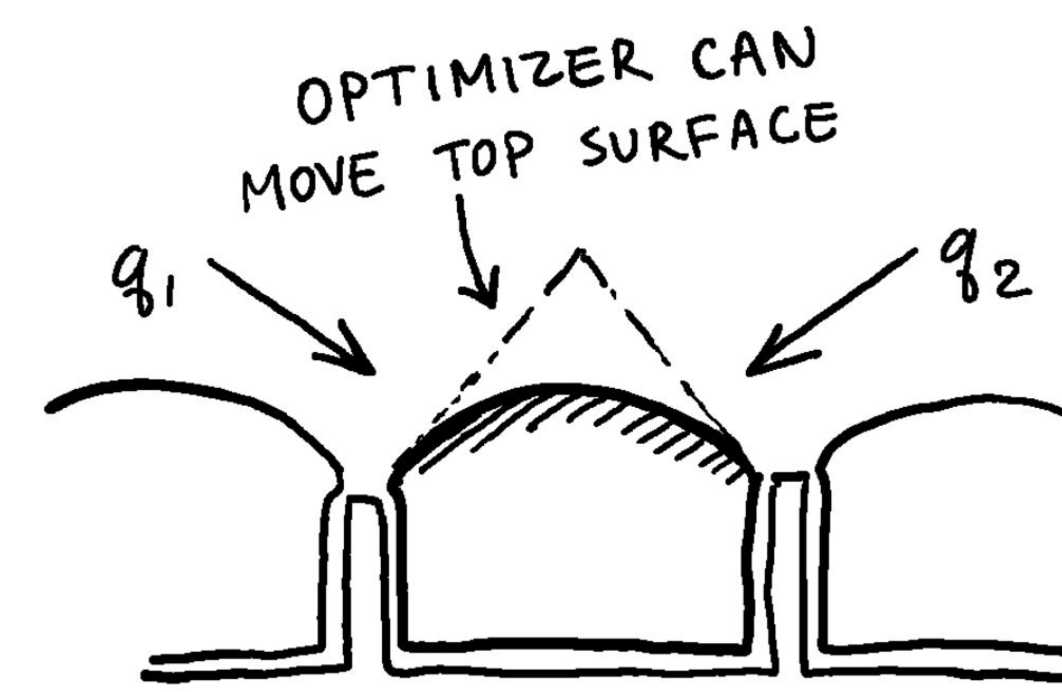
- **What defines an "optimal" PFC design?**
  - Peak heat flux must be minimized
  - Surface must be sufficiently smooth - machining constraint and avoiding features with high heat loads
  - Algorithm should modify individual elements while moving elements together with awareness of global geometry

$$\underbrace{C_0 \cdot \mathrm{MAX}(q) + C_1 \cdot \sum_i \frac{q_i}{(\Sigma q)_0}}_{\text{MINIMIZE PEAK HEAT FLUX — WITH LOCAL \& GLOBAL CHANGES}} + \overbrace{C_2 \cdot \underbrace{\sum_{ij} \frac{\frac{1}{2}\alpha_{ij} E_{ij}}{\left(\sum_{ij} \frac{1}{2}\alpha_{ij} E_{ij}\right)_0}}_{\text{APPROX. INTEGRAL OF MEAN CURVATURE}}}^{\text{SMOOTHING TERM}}$$

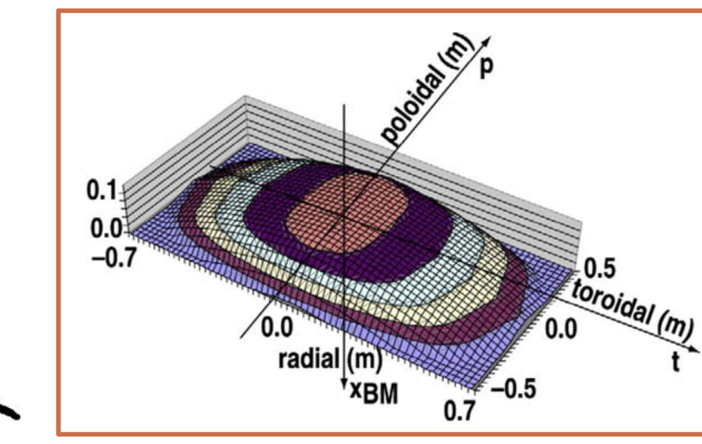
- Choosing objective function takes tuning - many solutions possible

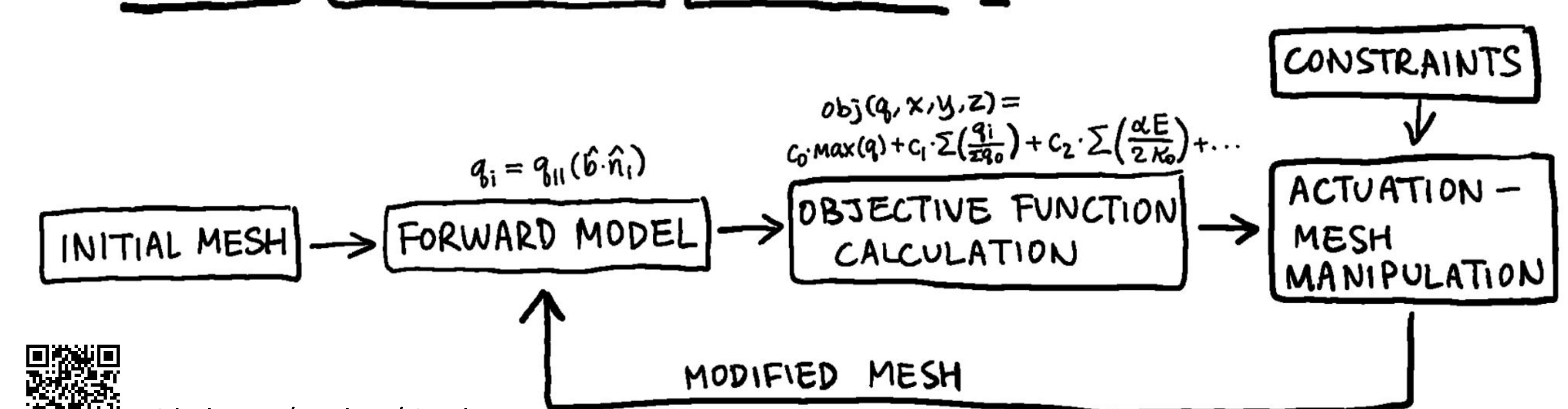


Can we can generate topology for a bi-directional plasma surface?



Example: ITER first wall, Stangeby 2009



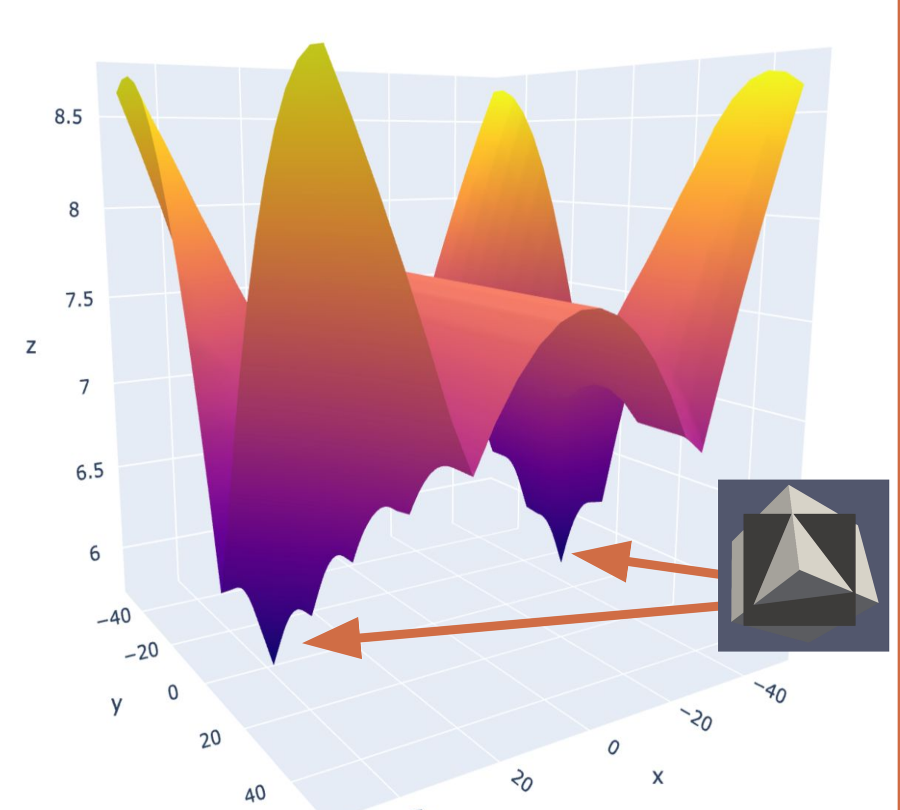


github.com/ctychen/simpleopt

First Results, Step By Step

1. Exploring space of solutions

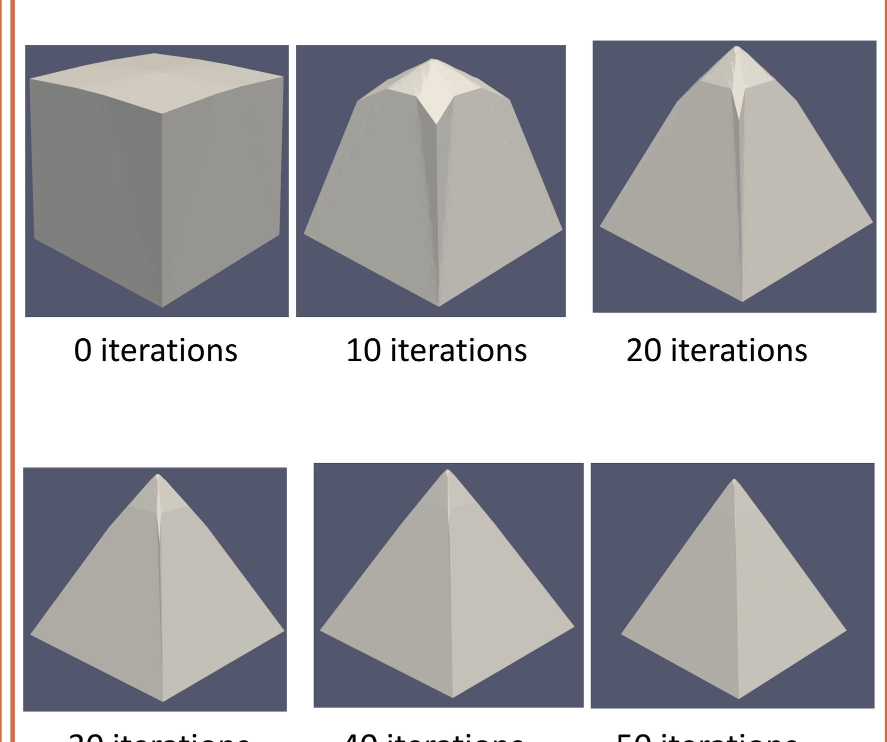
- Understanding sensitivity of objective function and optimization with simple problem with deterministic solutions
- Toy problem: rotate cube to minimize heat flux
- Solutions found at family of local minima



2. Mesh manipulation with objective function

- Toy problem: using gradient descent, transform cube ⟶ pyramid
- Objective function:

$$\left| V_{MESH} - V_{MESH \cap TARGET} \right|$$

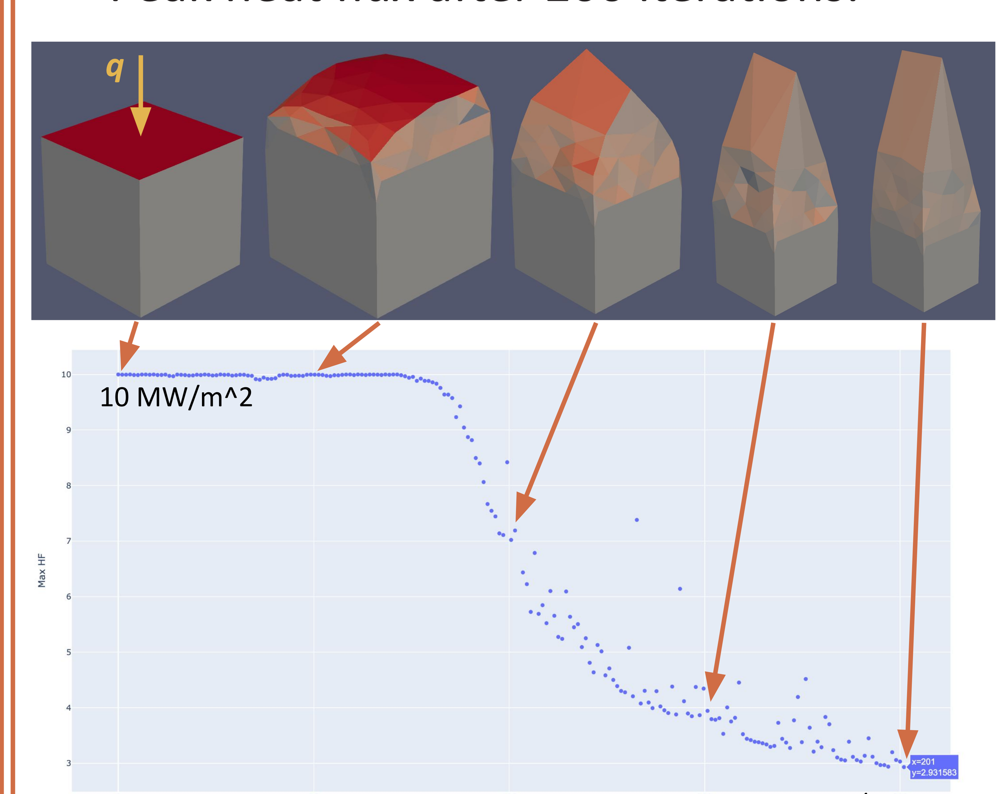


3. Generate meshes that minimize 1D heat flux, given constraints

- Objective function:

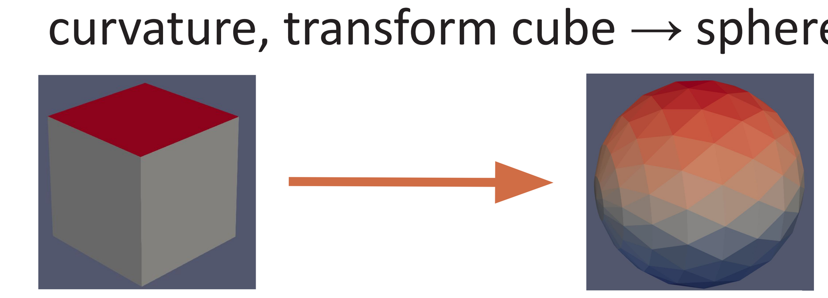
$$\underbrace{c_0 \cdot \max(q)}_{\text{PEAK HEAT FLUX}} + c_1 \cdot \underbrace{\sum \frac{q_i}{(\Sigma q)_0}}_{\text{SUMMED HEAT FLUX ON FACES}} + c_2 \cdot \underbrace{\sum \frac{|\hat{n}_i - \hat{n}_{i-1}|}{(\Sigma \Delta \hat{n})_0}}_{\text{SUM OF DIFFERENCES BETWEEN FACE NORMALS}}$$

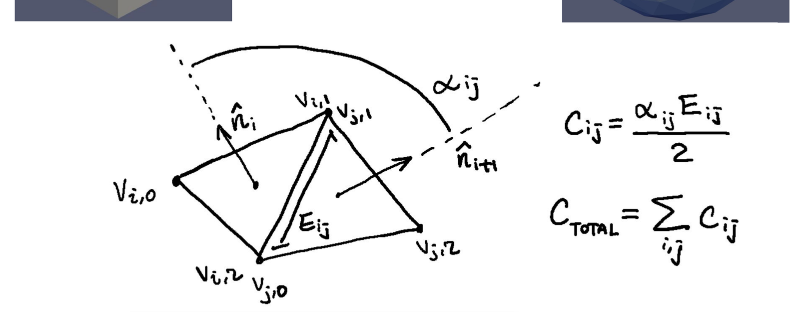
- Peak heat flux after 200 iterations:



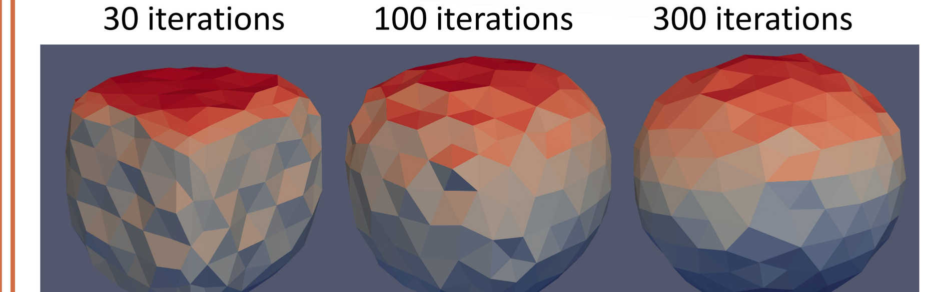
4. Find metrics to control smoothness

- Toy problem: using an objective function that represents a generalizable definition of curvature, transform cube ⟶ sphere



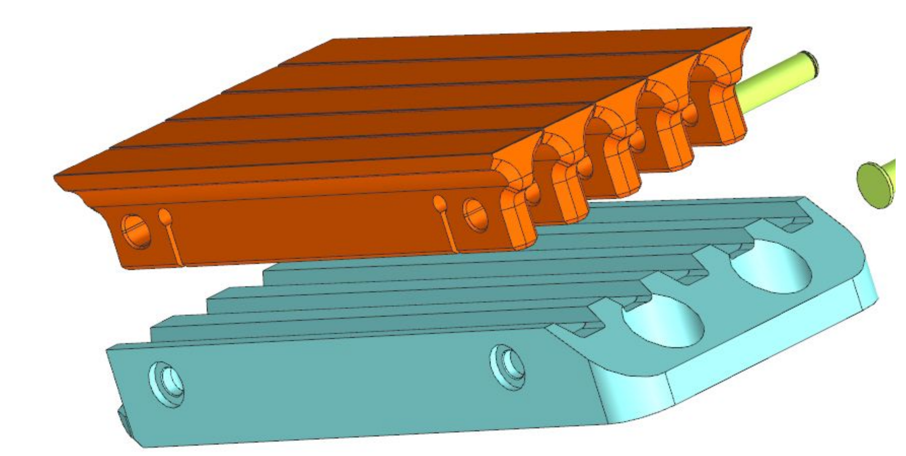


$$C_0 \cdot \left(\frac{1}{C_{TOTAL,0}} \cdot \sum_{i,j} \frac{\alpha_{ij} \cdot E_{ij}}{2} \right)$$



Future Work

- Improve smoothing and tune algorithm with heat flux, curvature terms
- Implement volume, bounding box constraints to generate surfaces of PFCs in carrier:



Above: PFCs mounted in carrier, constraining movement of surfaces and volume

- Generate limiter designs and compare to human designs eg. Stangeby 2009.
- Add more complex heat flux modeling, eg. Heat flux Engineering Analysis Toolkit (Looby 2022)
- Generalize for different constraints
  - Possible targets to attempt (eventually): Divertor R-Z contour, antenna design, …

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