A fully adaptive Poisson solver for smooth two-dimensional domains

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David Stein

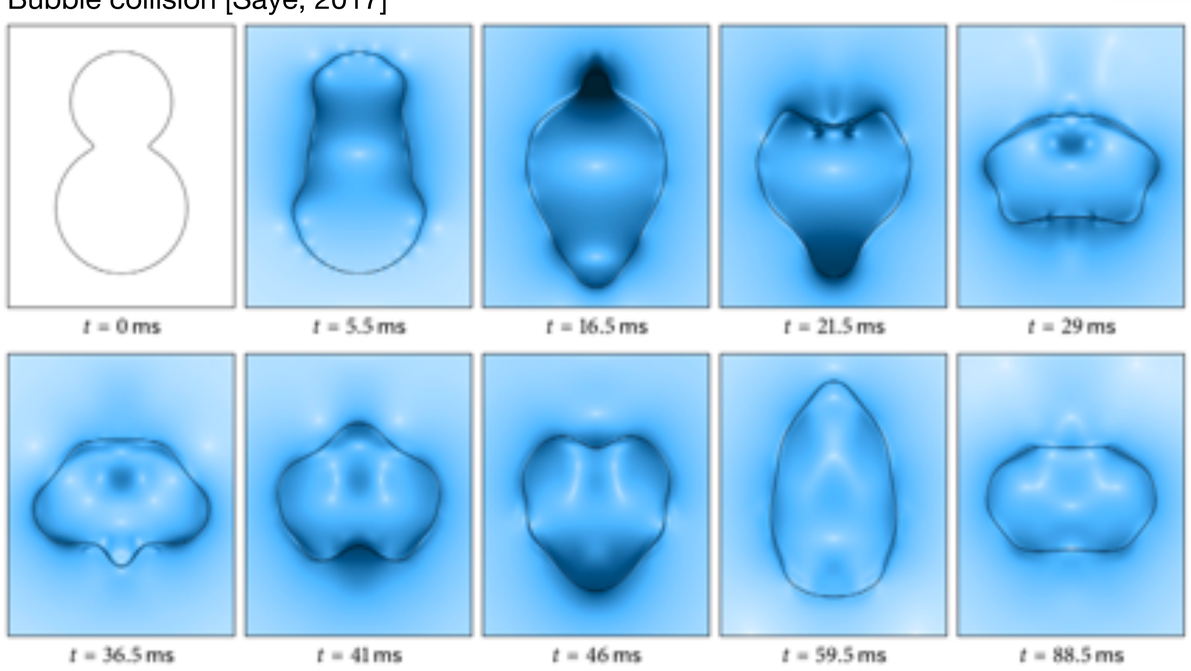
Introduction
Inhomogeneous elliptic BVP

Many applications involve solving an inhomogeneous elliptic BVP.

$$Lu = f \quad \text{in } \Omega \qquad \text{(e.g. Poisson, Helmholtz, Stokes, …)}$$
$$Bu = g \quad \text{on } \Gamma \qquad \text{(e.g. Dirichlet, Neumann, Robin, …)}$$

(Today's focus: $L = \Delta$, interior Dirichlet)

Bubble collision [Saye, 2017]



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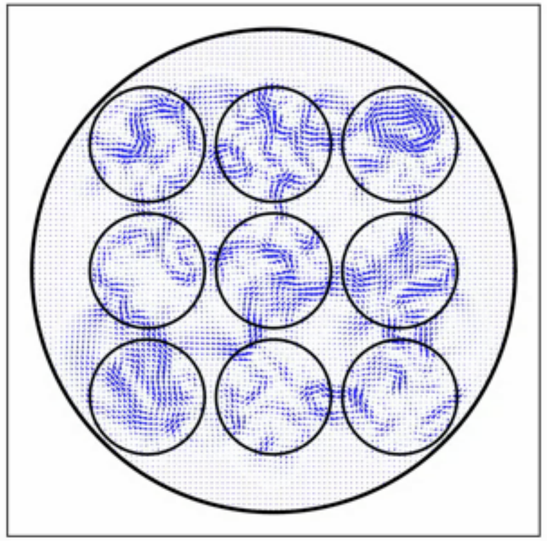
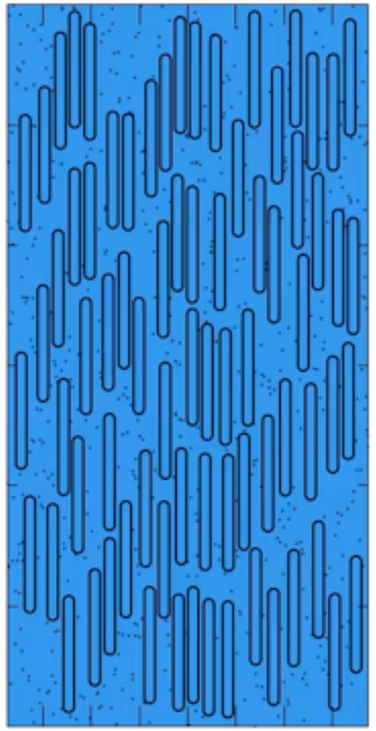


Fluid-structure interaction
[Rycroft et al., 2020]



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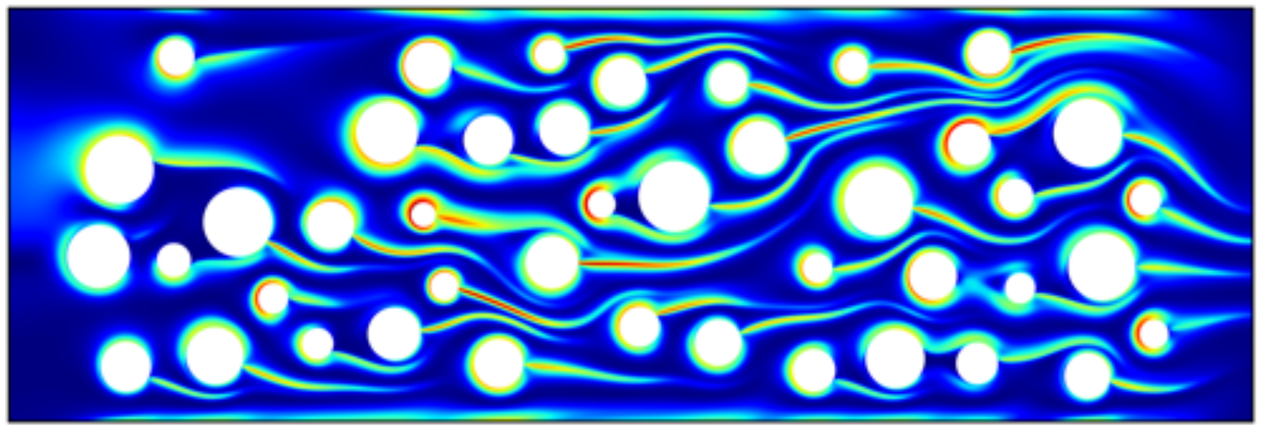

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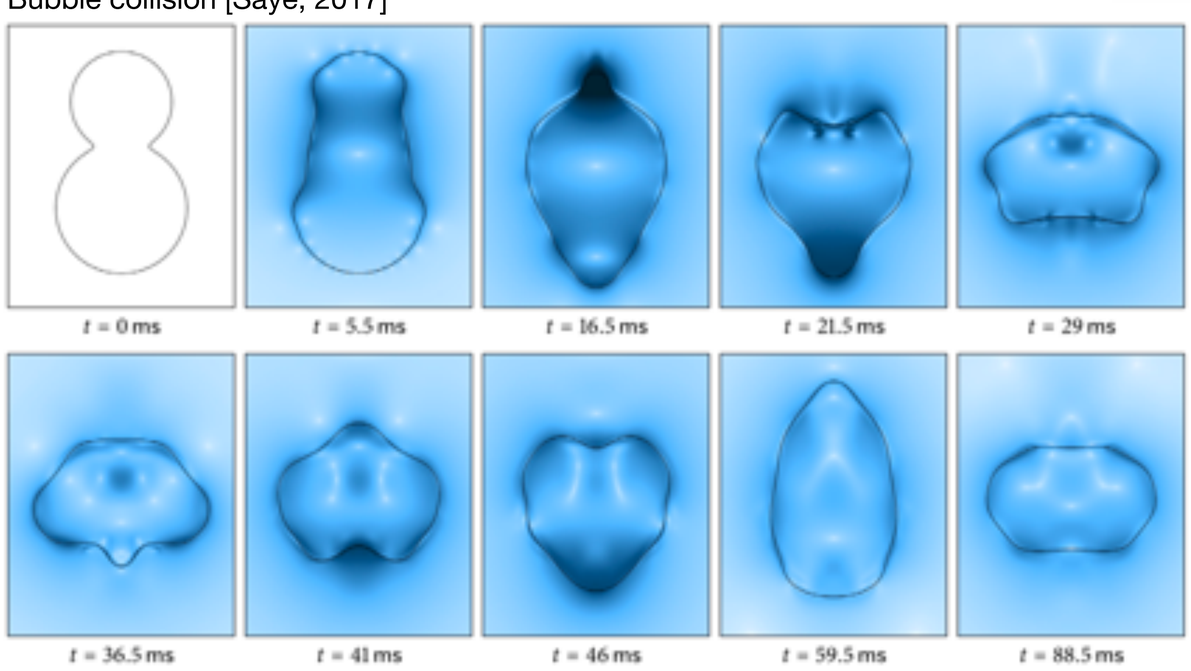

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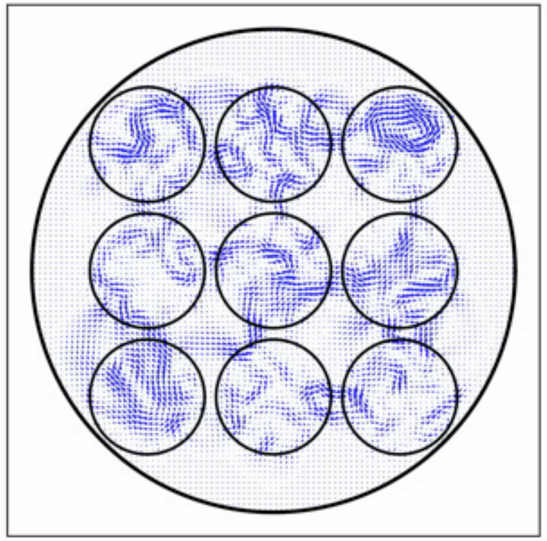

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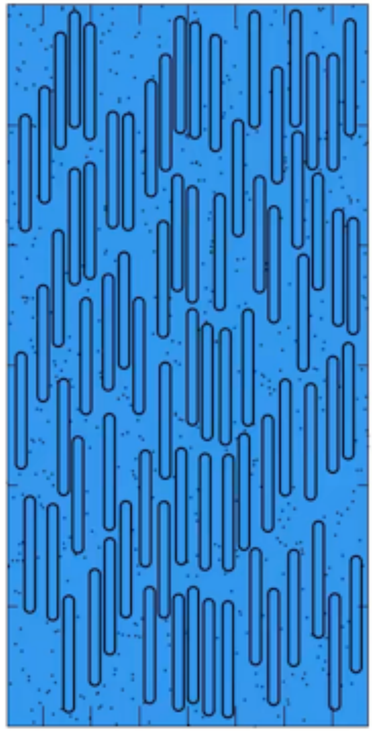

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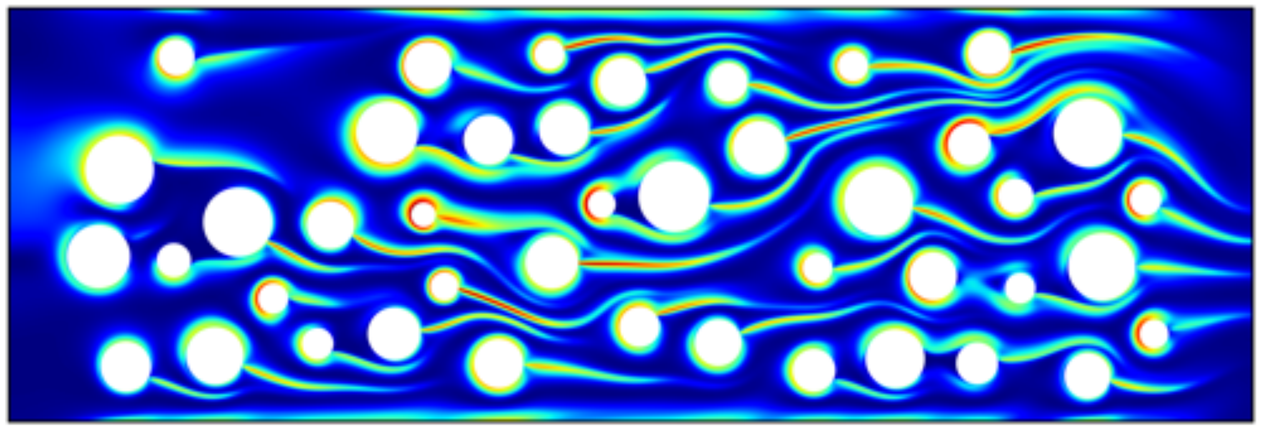

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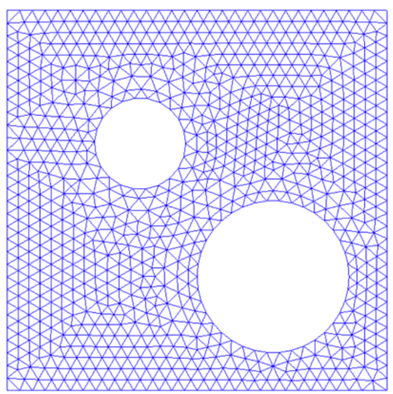
Many approaches for inhomogeneous BVP

Traditional



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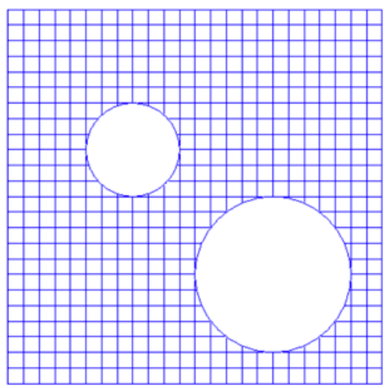

Cut-cell

- Mesh generation (or cut-cell generation)
- Directly discretize with FEM, FDM, SEM, …

$$Ax = b$$

Solve linear system for volume DoFs.
Sparse but preconditioning needed.

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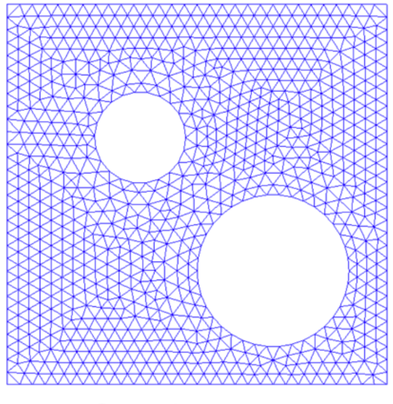

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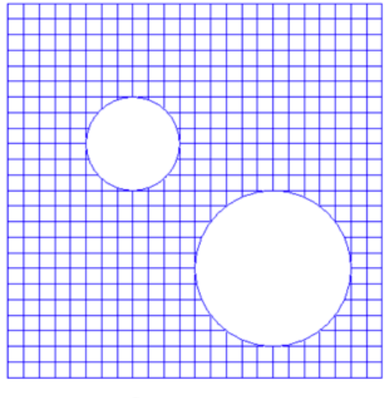

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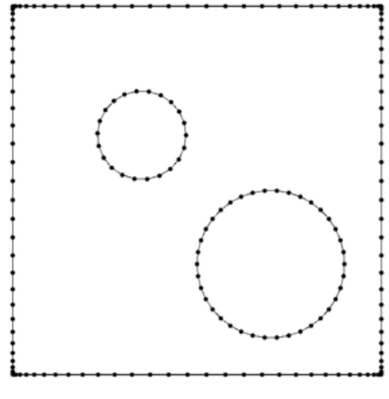
Analysis-based



- Write solution as $u = u^{\mathrm{h}} + u^{\mathrm{p}}$

homogeneous solution *particular solution*

- Find **some** (any!) function u^{p} such that

$$Lu^{\mathrm{p}} = f \quad \text{in } \Omega$$

No solve required. Convolve with Green's function.

- Compute u^{h} to satisfy boundary conditions:

$$\begin{aligned} Lu^{\mathrm{h}} &= 0 && \text{in } \Omega \\ Bu^{\mathrm{h}} &= g - Bu^{\mathrm{p}} && \text{on } \Gamma \end{aligned}$$

Solve linear system for boundary DoFs using BIE.

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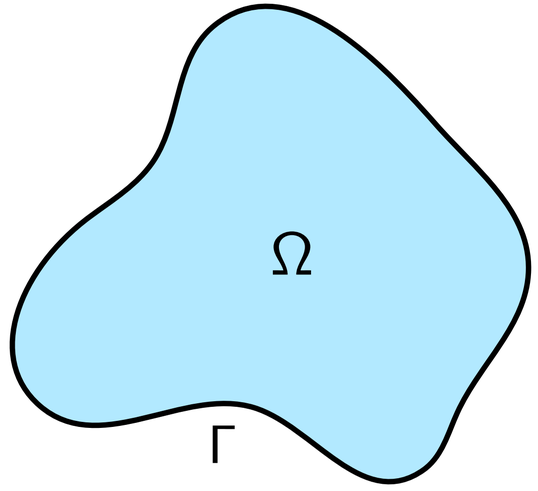
Computing a particular solution

Suppose we only know $f(x)$ inside Ω. We have a few options…



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- Build accurate quadrature scheme over Ω (e.g. adaptive boxes with cut cells near boundary) and compute

$$u^{\mathrm{p}}(x) = \int_{\Omega} G(x,y) f(y) dy$$

free space fundamental solution

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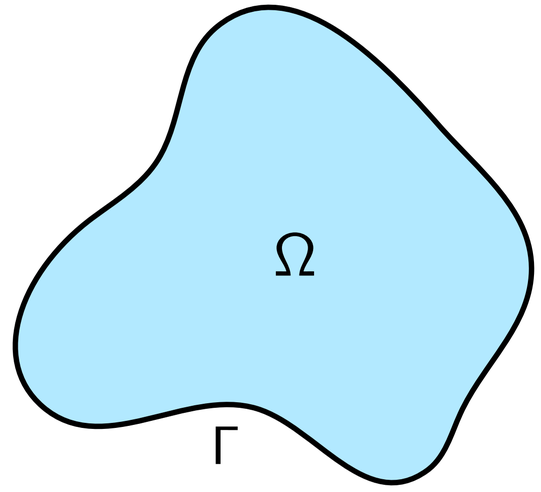

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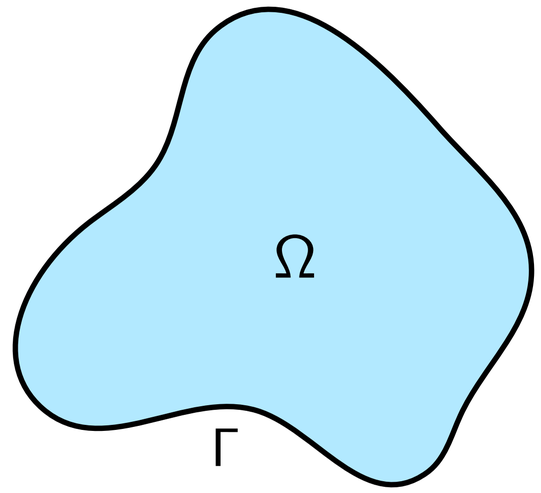
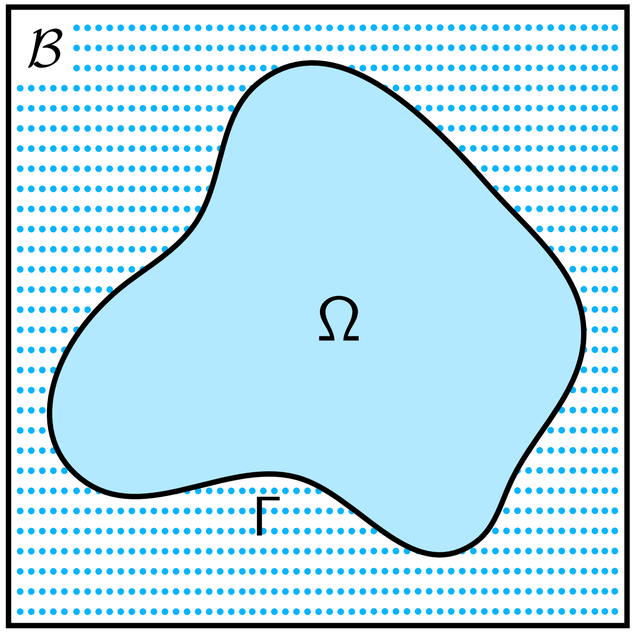


- Extend f to $\tilde{f}$ outside Ω ("function extension"). Adaptively resolve $\tilde{f}$ and compute

$$u^{\mathrm{p}}(x) = \int_{\mathcal{B}} G(x,y) \tilde{f}(y) dy$$

Quadrature tables for boxes can be **precomputed** (FMM "box code")



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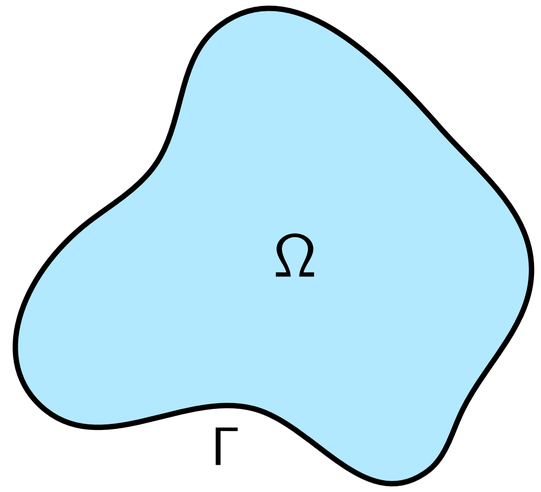

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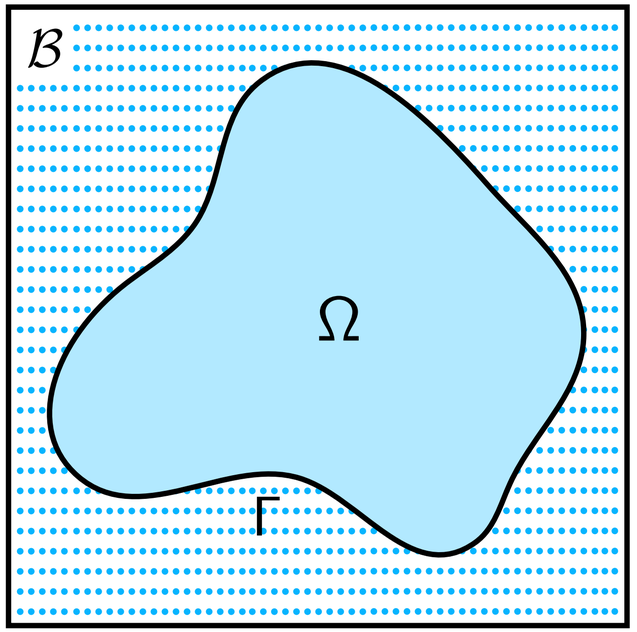

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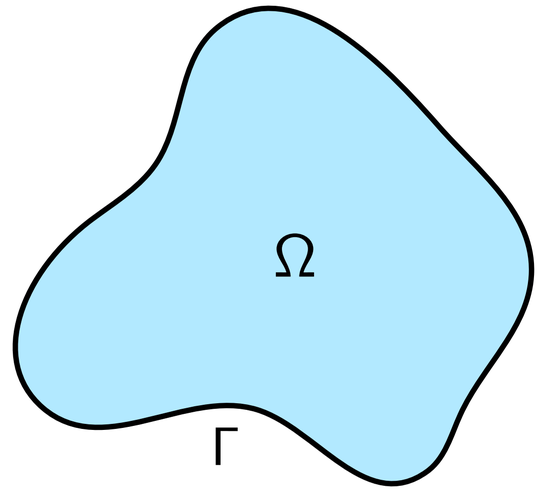

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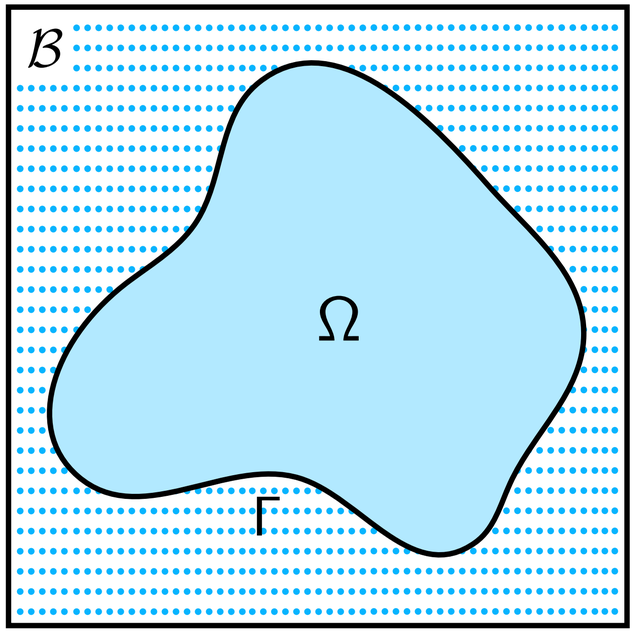
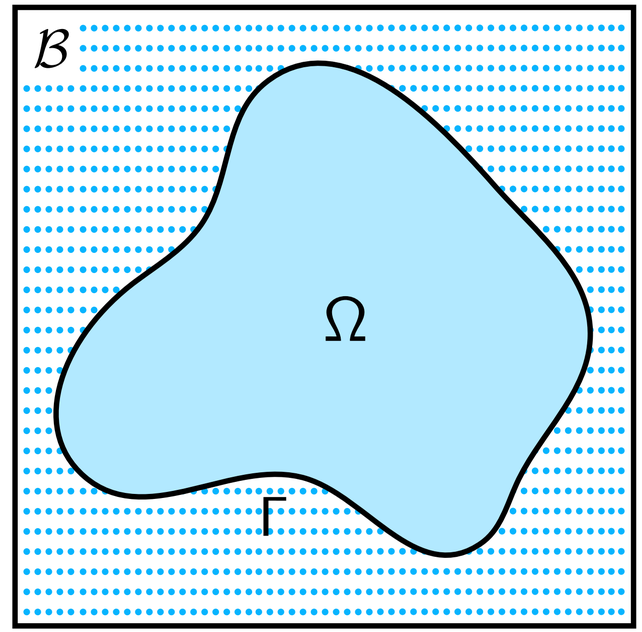
Want $\tilde{f}$ as smooth as f for fast convergence. How?



Function extension
Prior work

- Finite difference extension, second-order accurate [Mayo, 1984]
- Fourier continuation [Bruno & Lyon, 2010], [Bruno & Paul, 2020]
- Immersed boundary smooth extension [Stein, Guy, & Thomases, 2015]
- C^k polyharmonic extension + box code, fourth-order accurate [Askham & Cerfon, 2017]
- Partition of unity extension [Fryklund, Lehto, & Tornberg, 2018]



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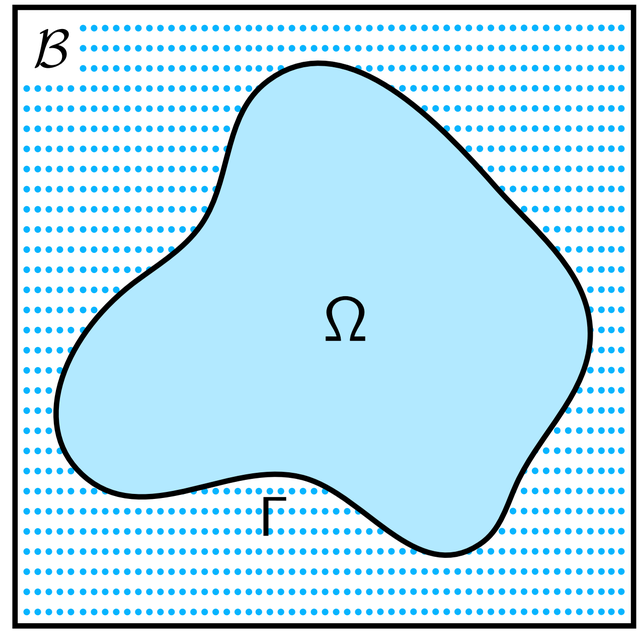
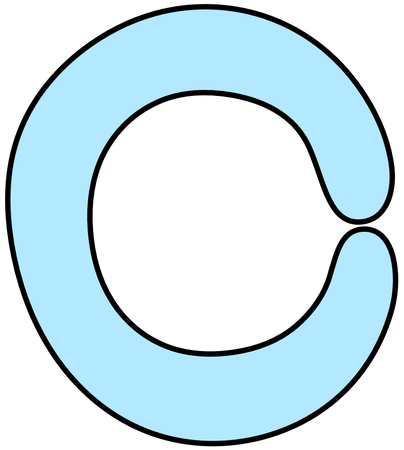


In general, smoothly extending f in a robust way is challenging.
(Especially for multiscale geometry, multiscale f, close-to-touching regions, …)



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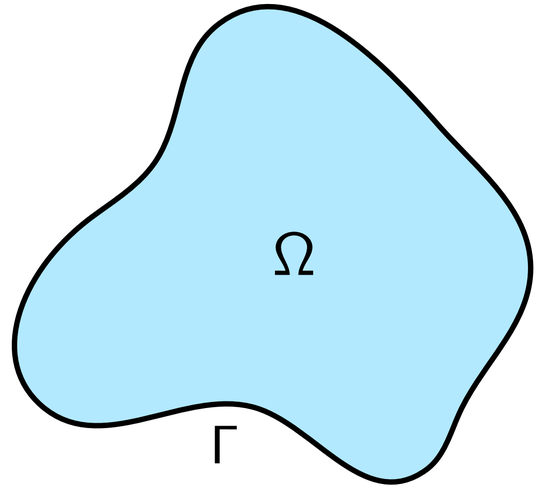

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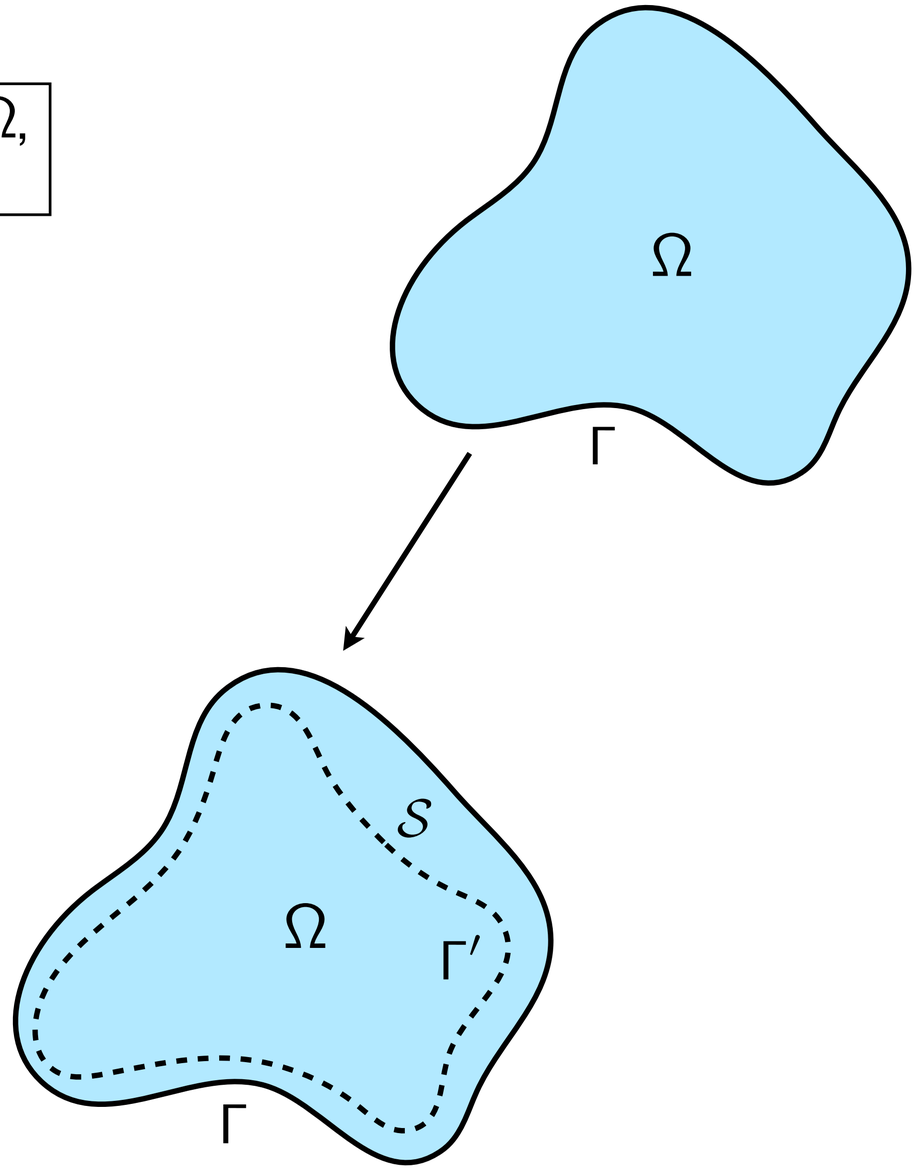

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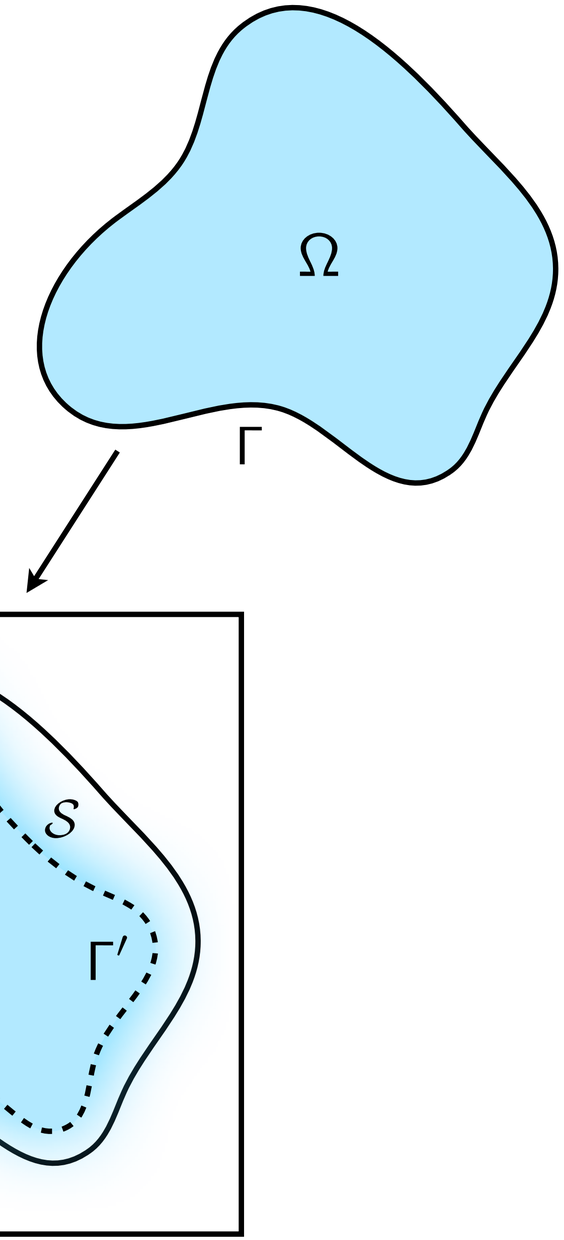

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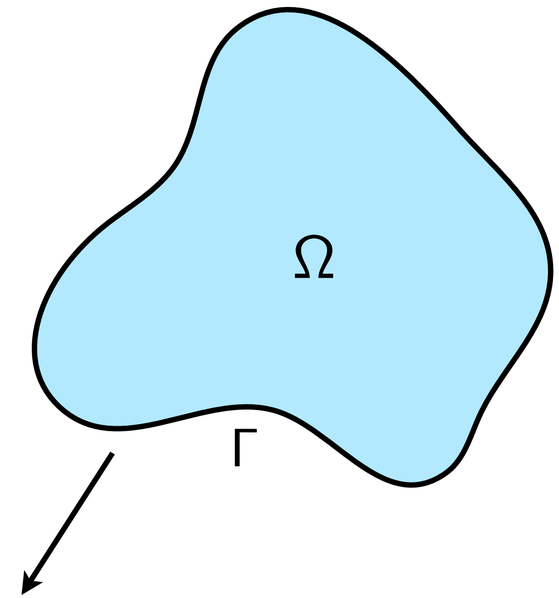

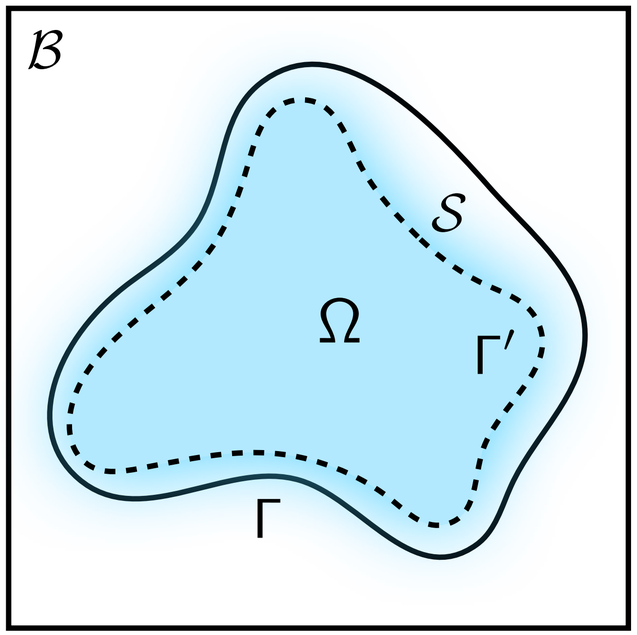

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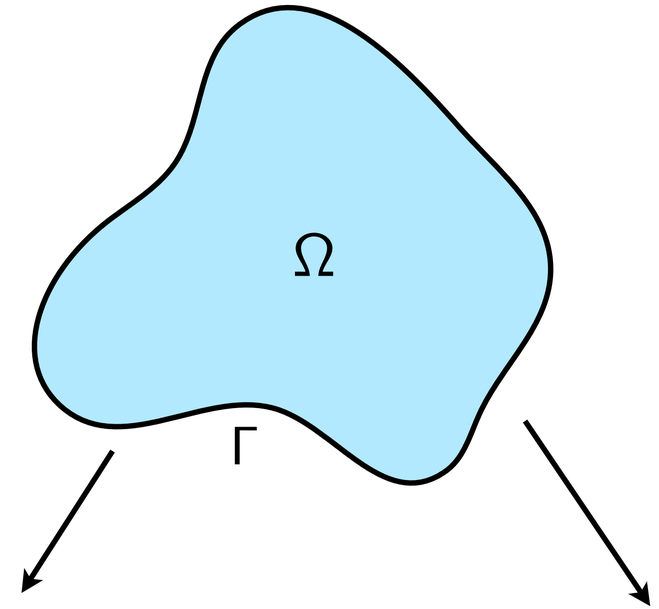

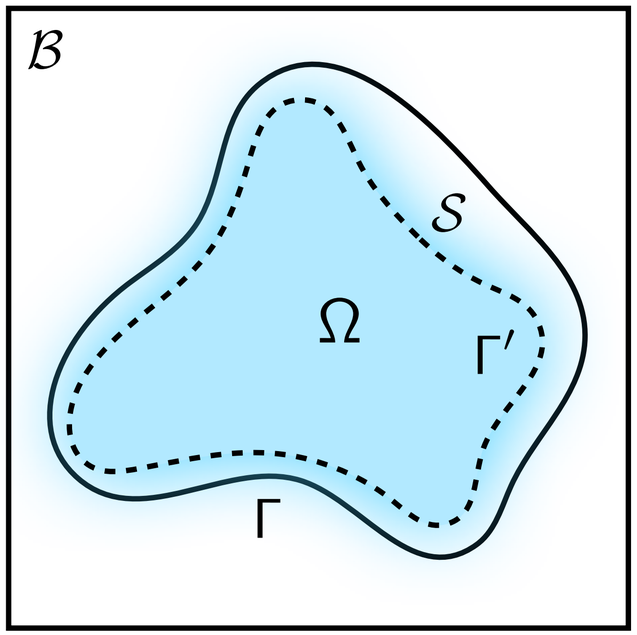

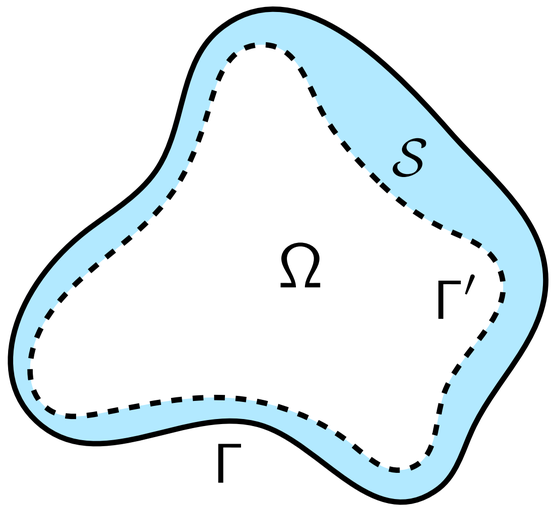

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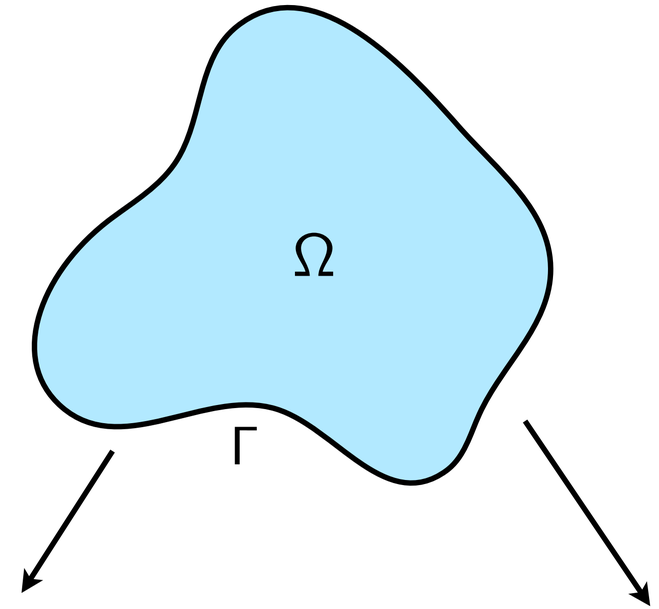

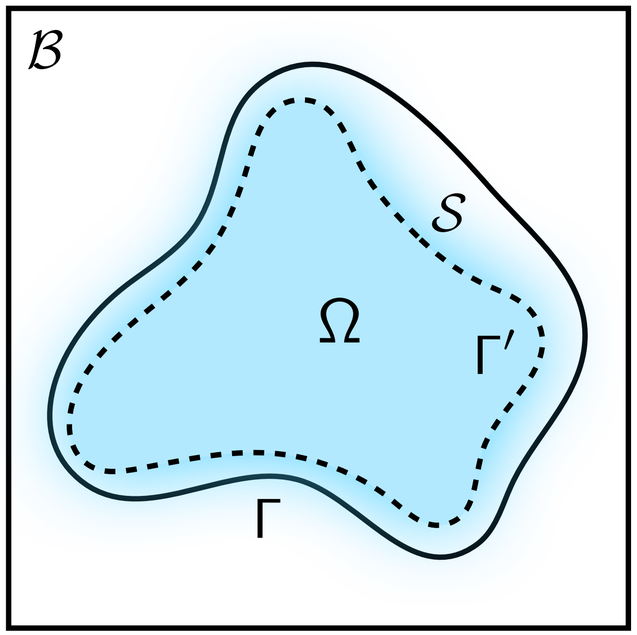

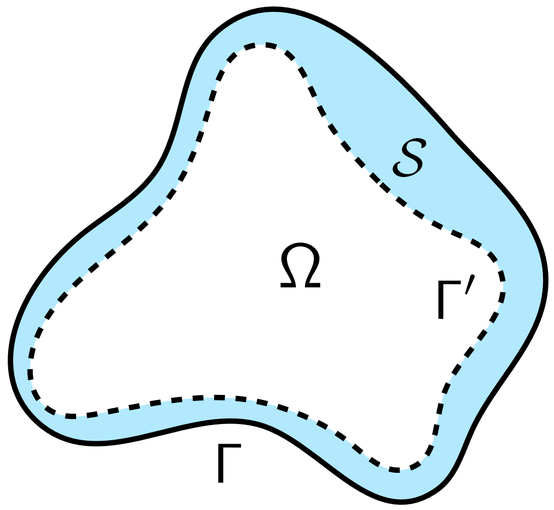

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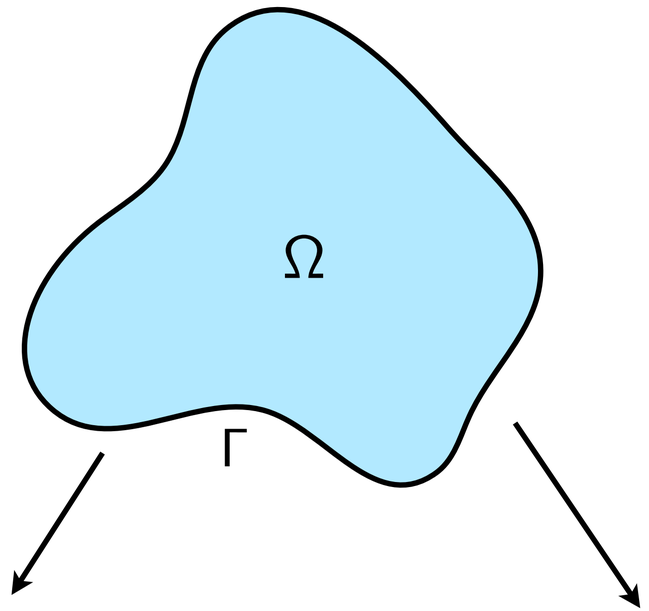

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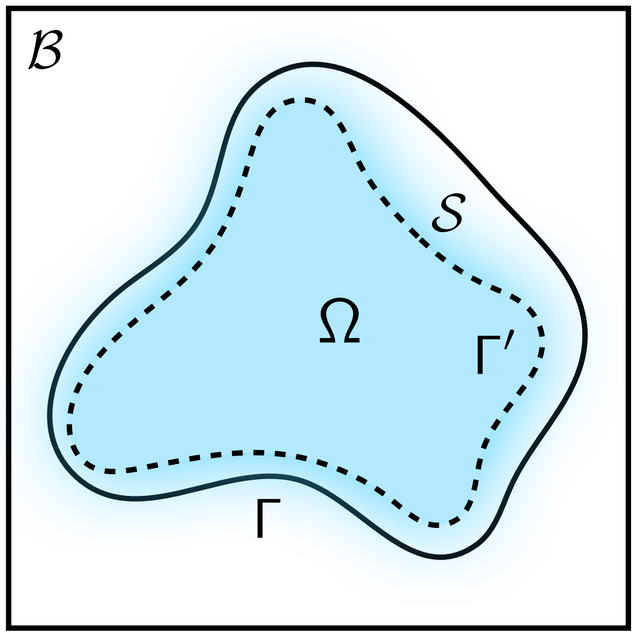
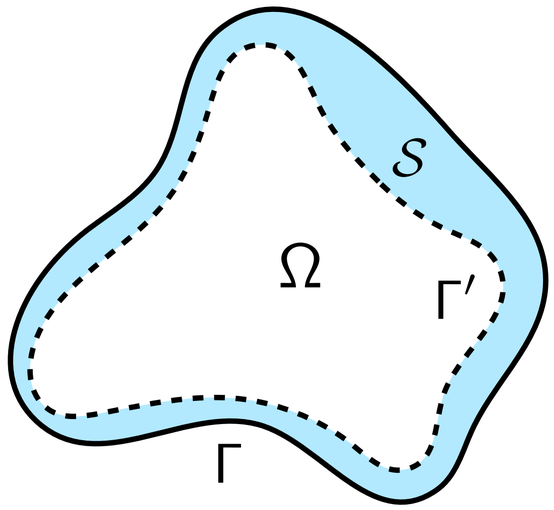
How to define the strip?

How to solve in the strip?

How to patch the solutions?





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Wish list

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- not too far from Γ (or the strip will be large → extra work).

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Defining the strip
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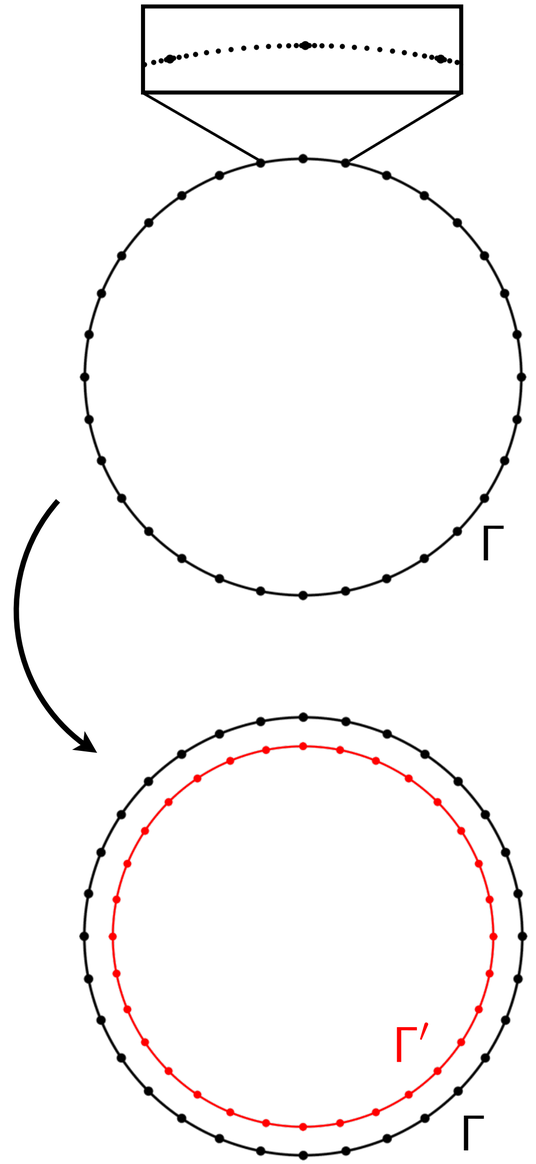

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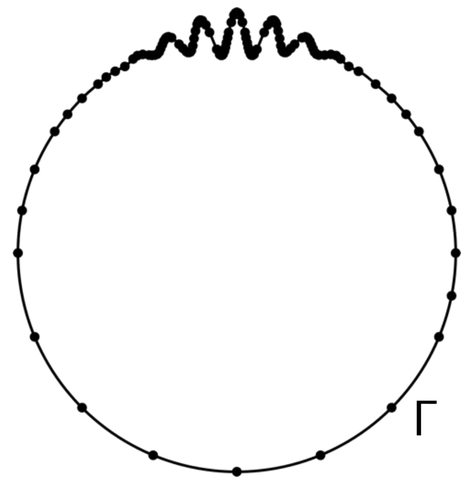

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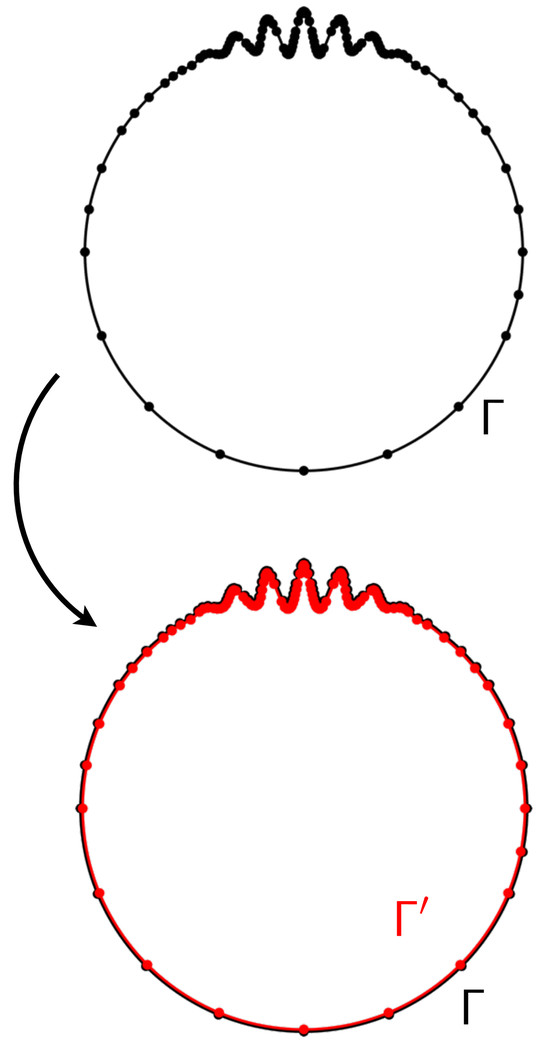

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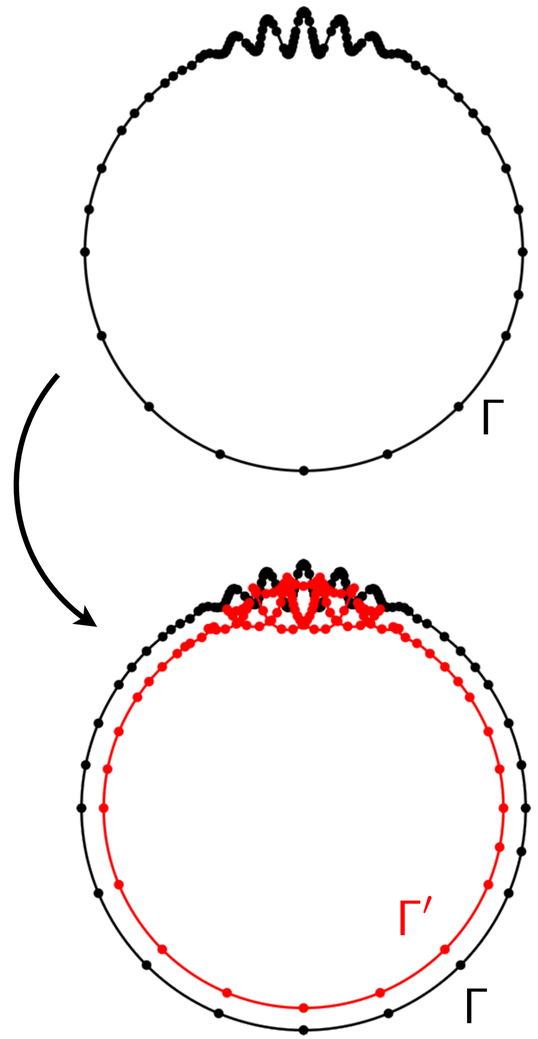

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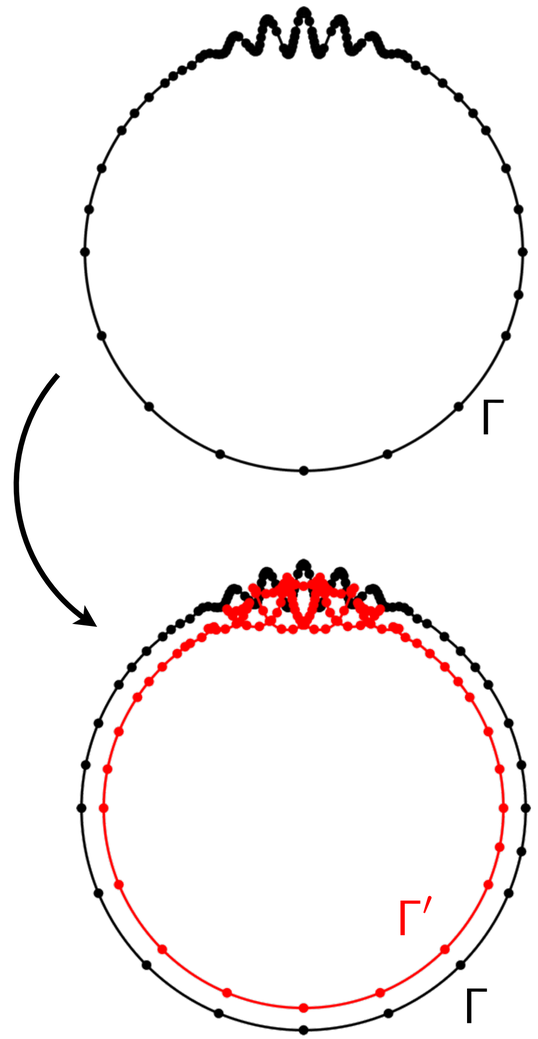

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Γ' should adapt to local panel size

Defining the strip
Adapting to local panel size

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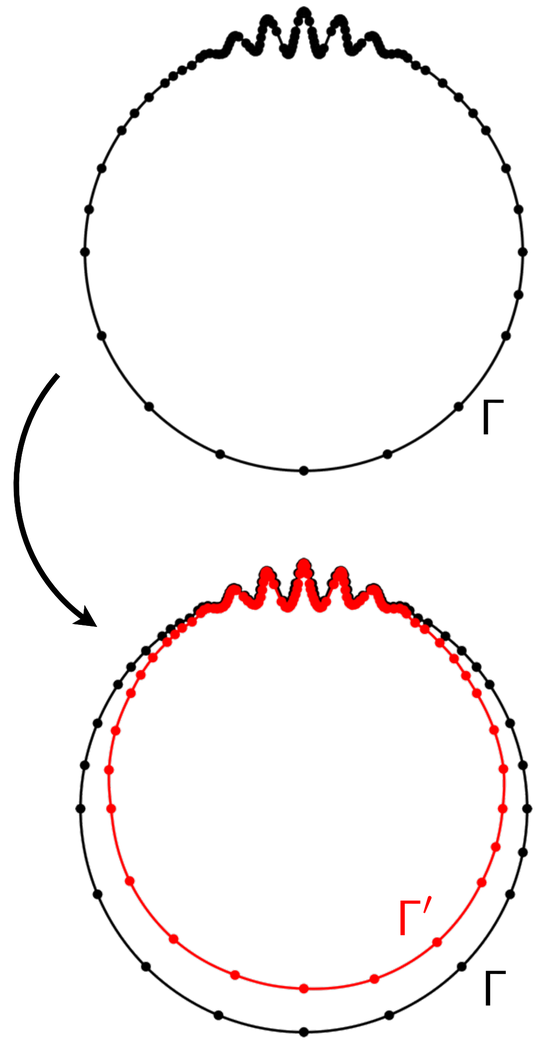
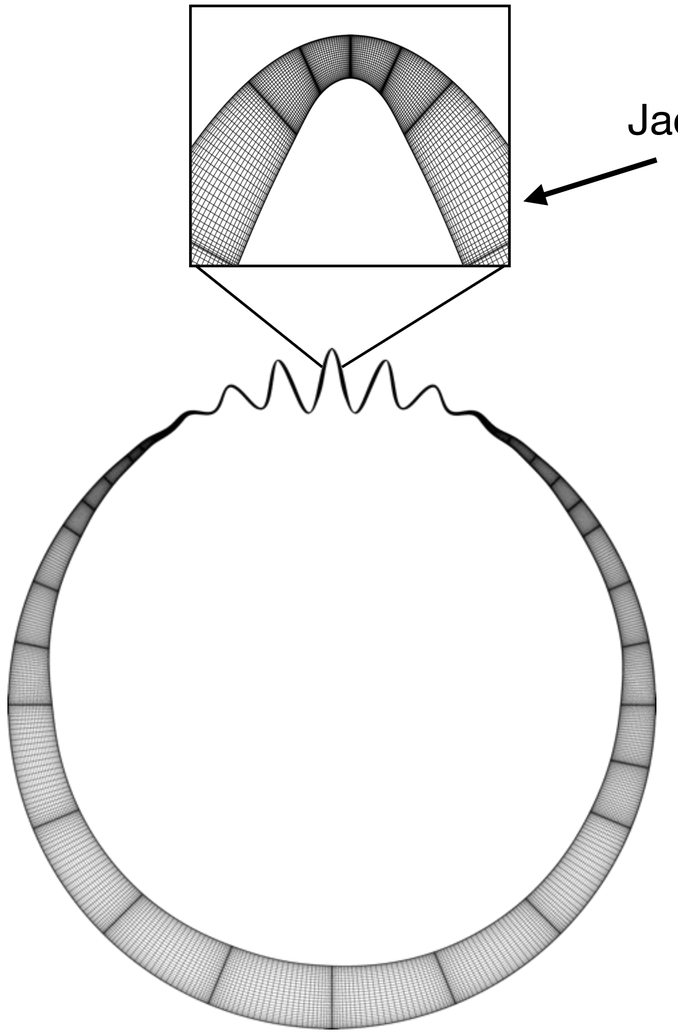


Solution:

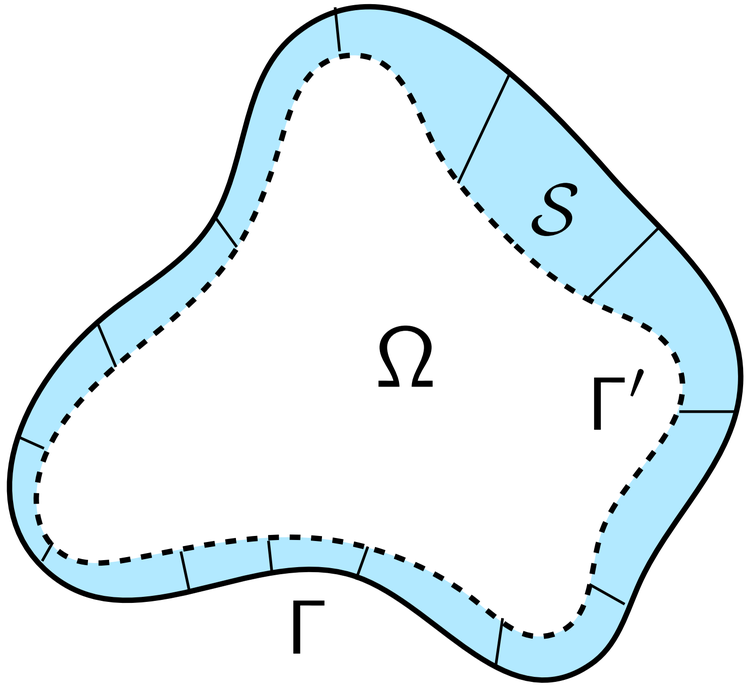
- Define piecewise linear width function based on average local panel size
- Approximate each junction by smoothed abs(x)
- Blend together using matched asymptotics
- Perturb in the normal direction

Solving the strip problem
Spectral element discretization

We use a spectral element method in $\mathcal{S}$, with spectral collocation at tensor-product Chebyshev nodes on each element.

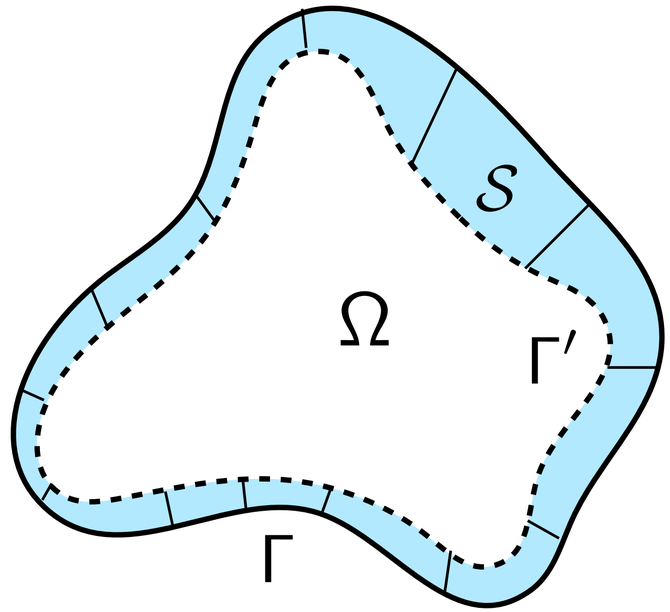


Jacobian is numerically computed at each point to form differentiation matrices.



Solving the strip problem
A fast direct solver for the strip

We use the hierarchical Poincare-Steklov scheme to build a **fast direct solver** in $\mathcal{S}$.



[Gillman & Martinsson, 2015], [Martinsson, 2015]

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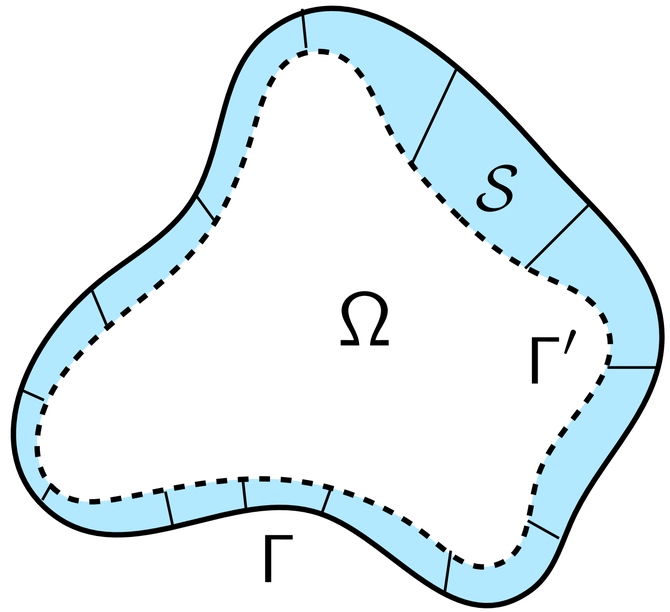

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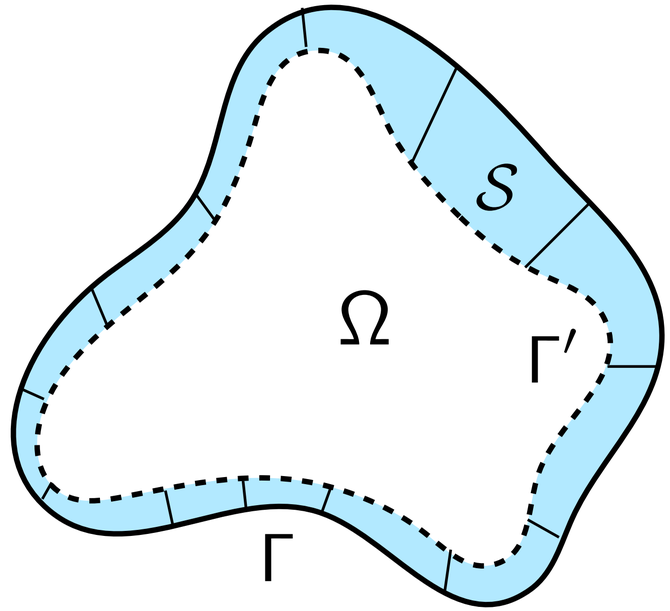

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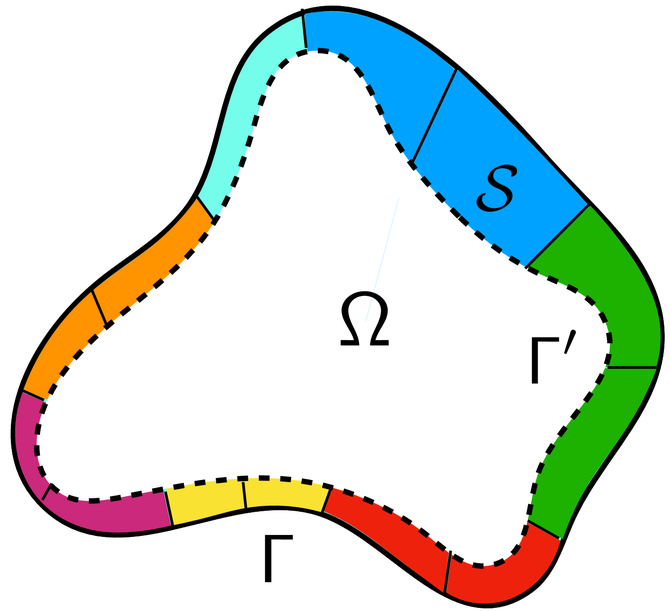

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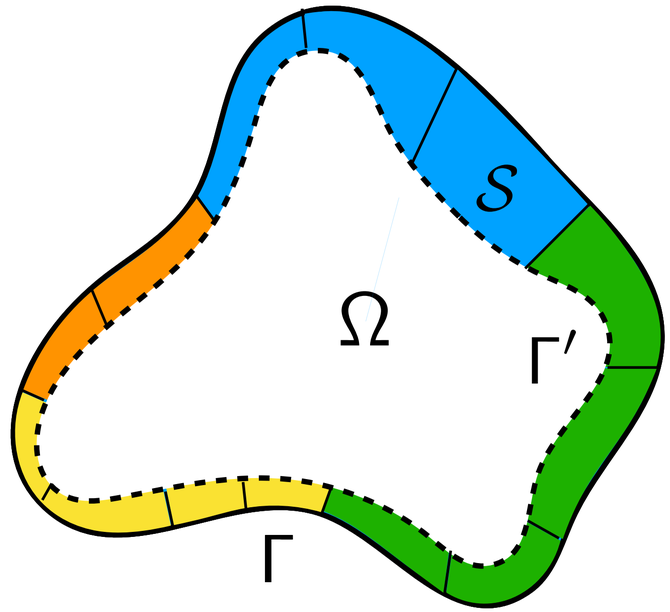

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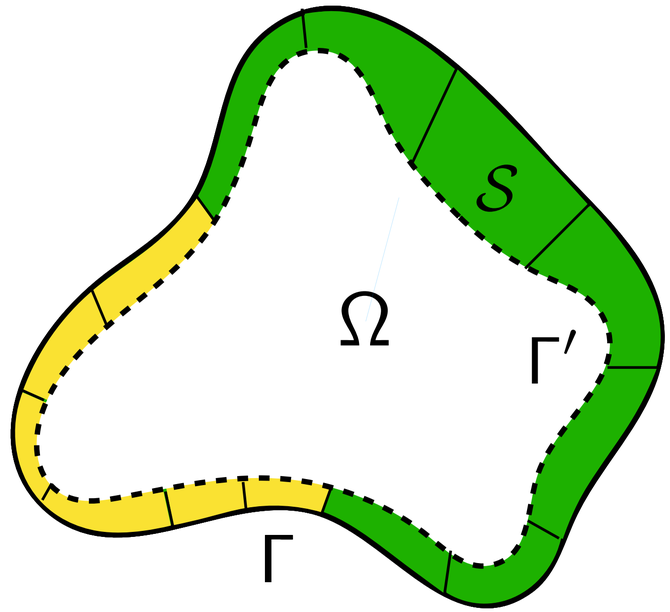

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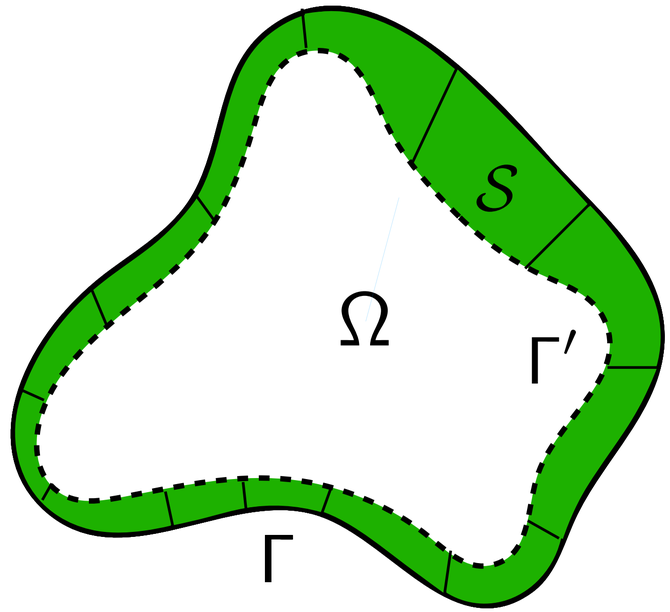

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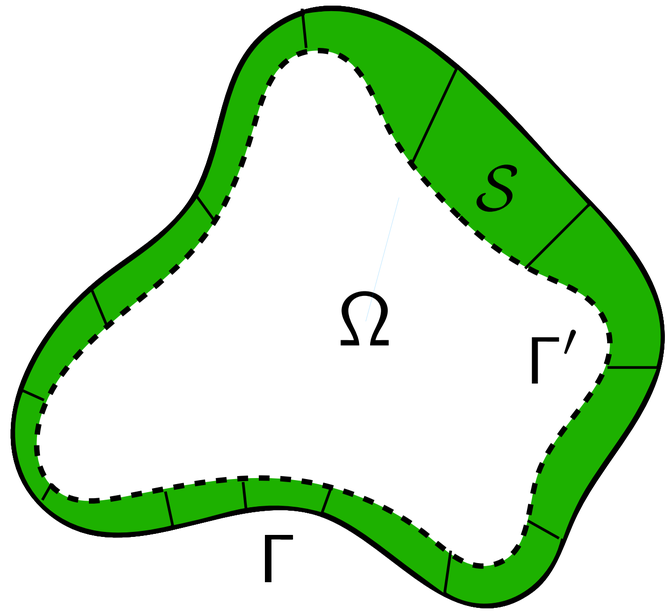

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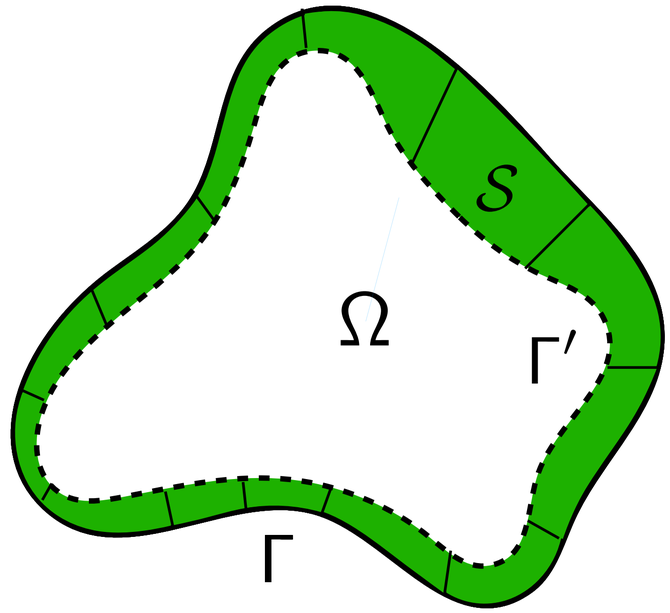

Cost: $\underbrace{\mathcal{O}(p^6 n_{\text{panel}})}_{①} + \underbrace{\mathcal{O}(p^3 n_{\text{panel}})}_{②} + \underbrace{\mathcal{O}(p^2 n_{\text{panel}})}_{③} = \mathcal{O}(n_{\text{panel}})$

We typically use p = 16 on each panel and upsample the SEM grid to 2p = 32.

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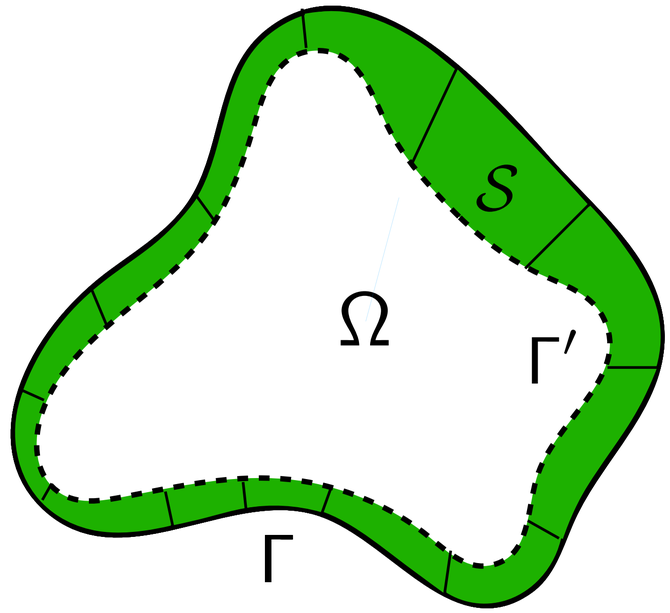

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Takeaway: 1D HPS is fast out of the box.

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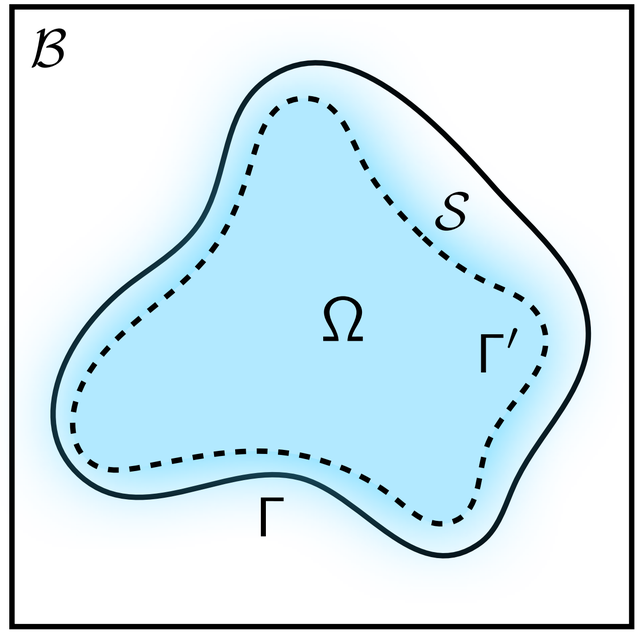
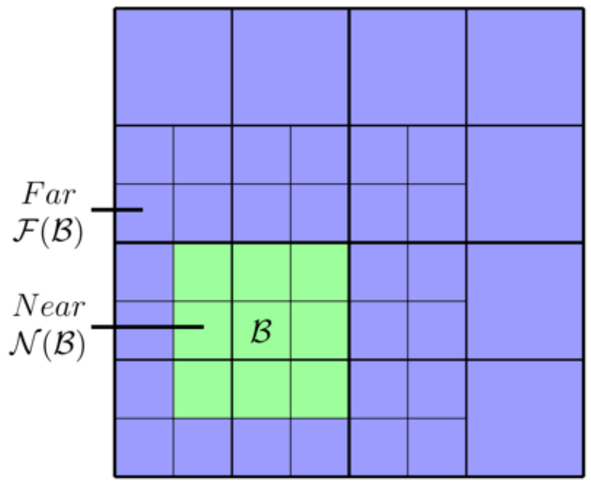
Solving the bulk problem
Evaluating the roll off function

- **Goal**: Approximate $\tilde{f}$ by quad-tree of tensor product Chebyshev nodes.





Solving the bulk problem
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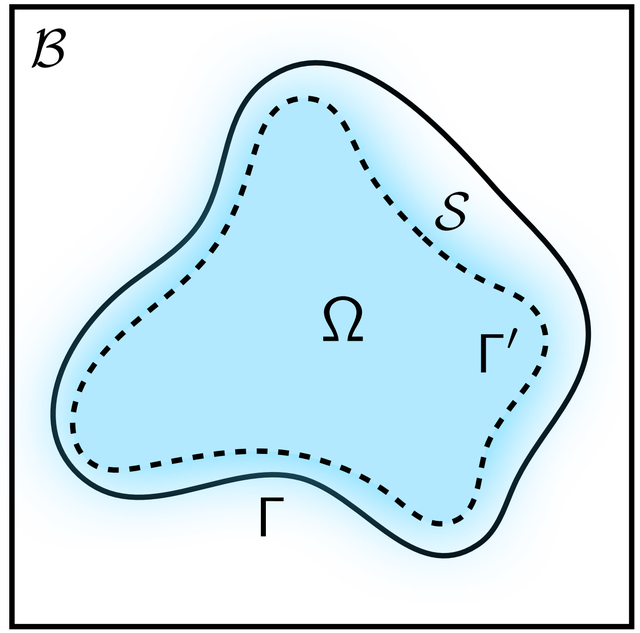

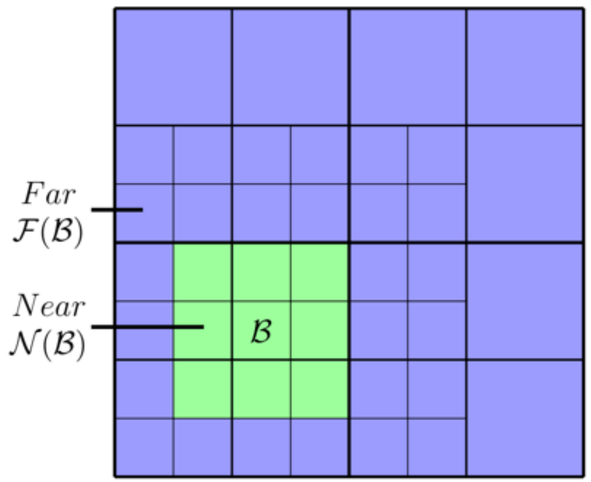

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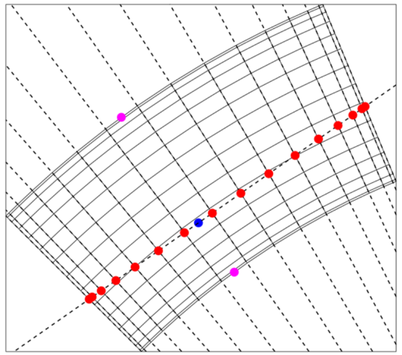
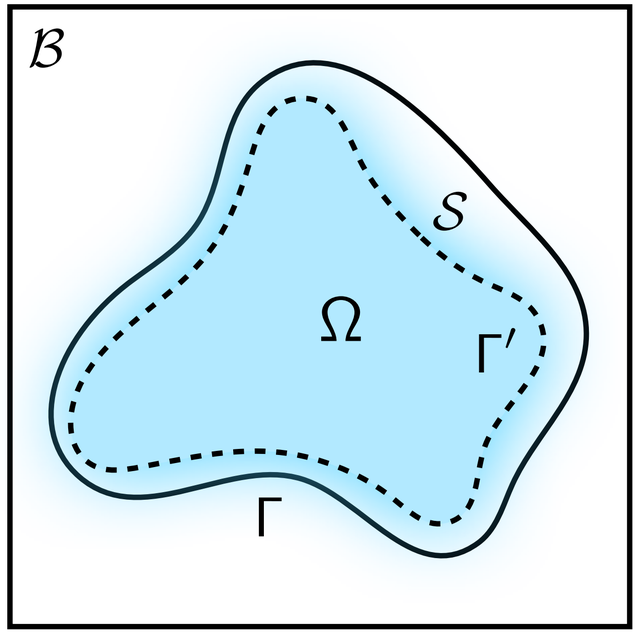
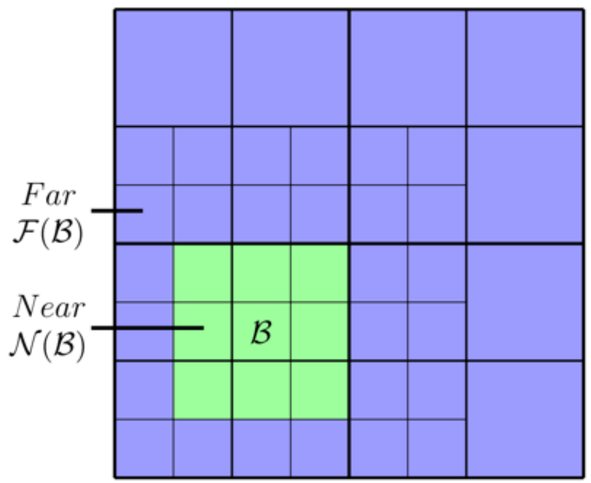
- **Solution**: Compute local coordinates via 1D interpolation through normal vectors [Bruno & Paul, 2020]







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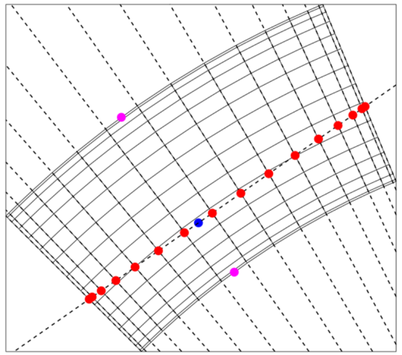
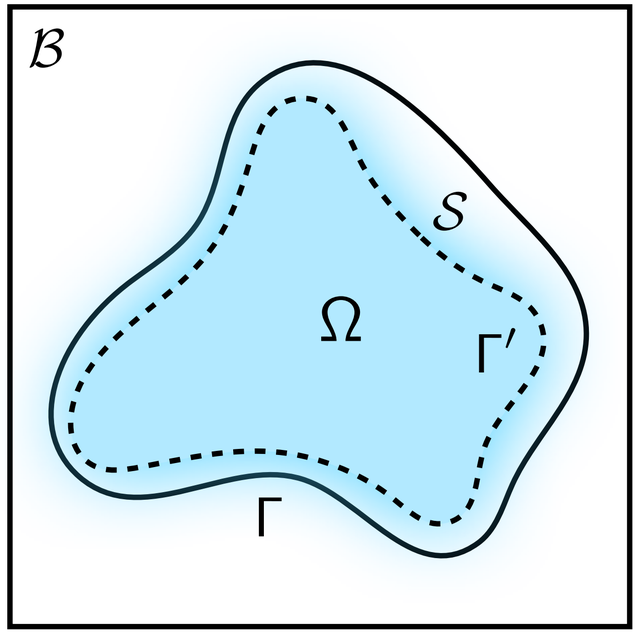
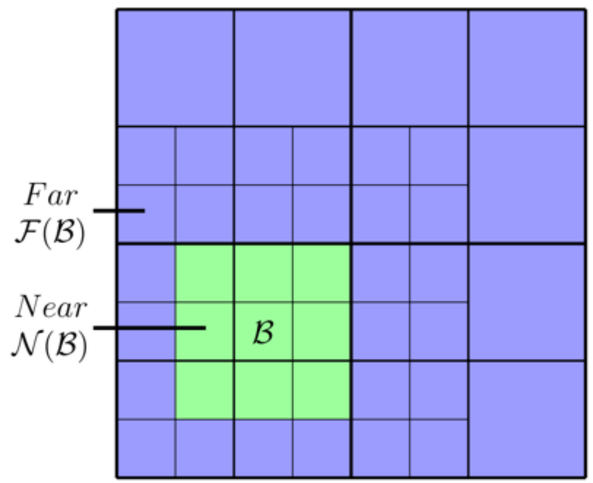




Use a box code to obtain a particular solution:

$$\Delta u_{\text{bulk}} = \tilde{f} \text{ in } \mathcal{B} \qquad \mathcal{O}(N) = \mathcal{O}(p^2 n_{\text{boxes}})$$

Then, $\Delta u_{\text{bulk}} = f$ inside Γ'.



Patching the solutions

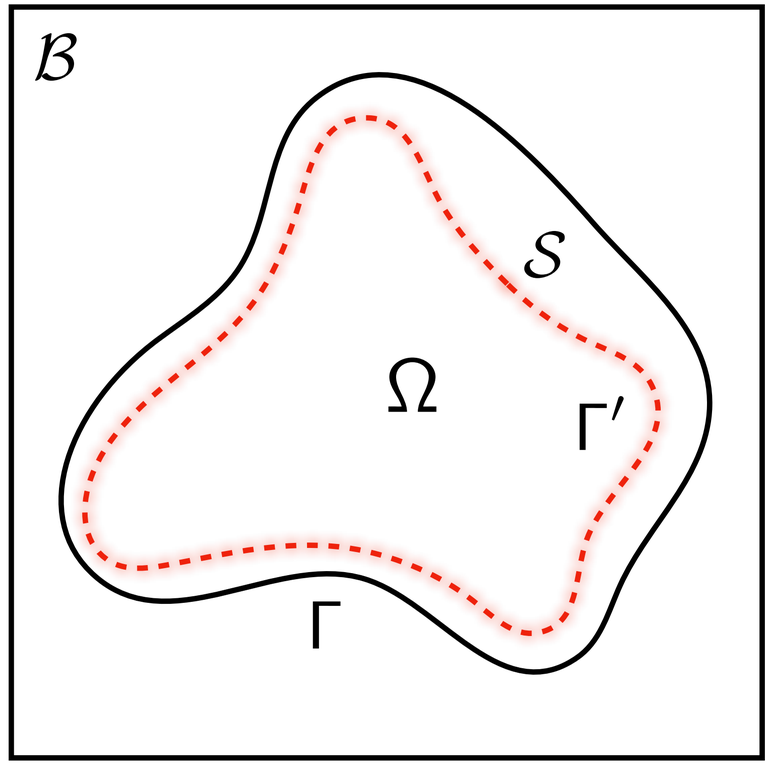
Using the value of u_{bulk} as the inner boundary condition in the SEM, the solutions will match along Γ'. However, their normal derivatives may not.

The "single-layer potential"

$$v(x) = (S\sigma)(x) = \int_{\Gamma'} G(x,y)\sigma(y)dt_y$$

satisfies $\Delta v = 0$ and the jump relation

$$\left.\frac{\partial v}{\partial n}^{+}\right|_{\Gamma'} - \left.\frac{\partial v}{\partial n}^{-}\right|_{\Gamma'} = -\sigma$$



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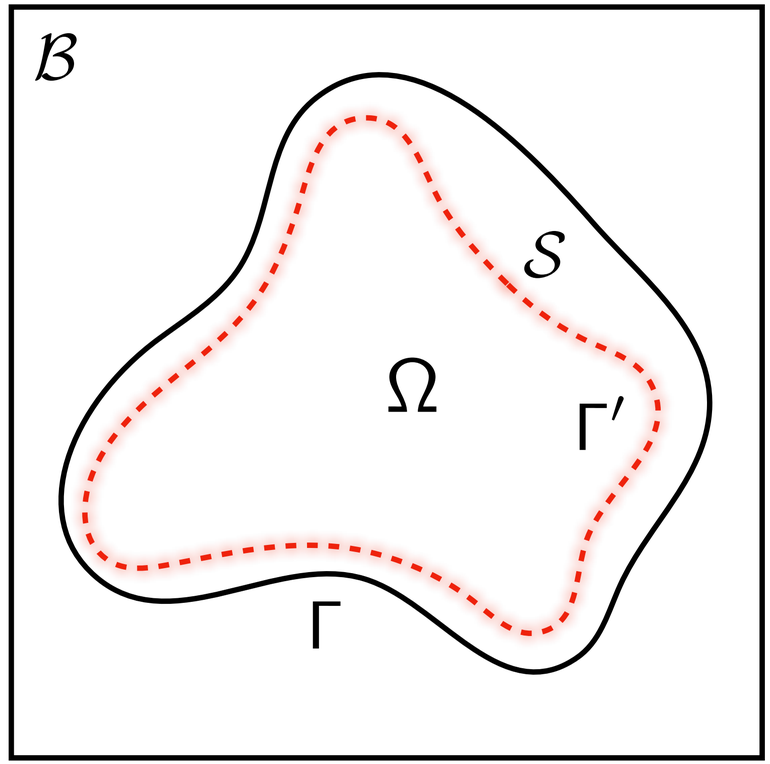
Apply SLP: $$u_{\text{glue}} = S\left(\left.\frac{\partial u_{\text{strip}}}{\partial n}\right|_{\Gamma'} - \left.\frac{\partial u_{\text{bulk}}}{\partial n}\right|_{\Gamma'}\right)$$



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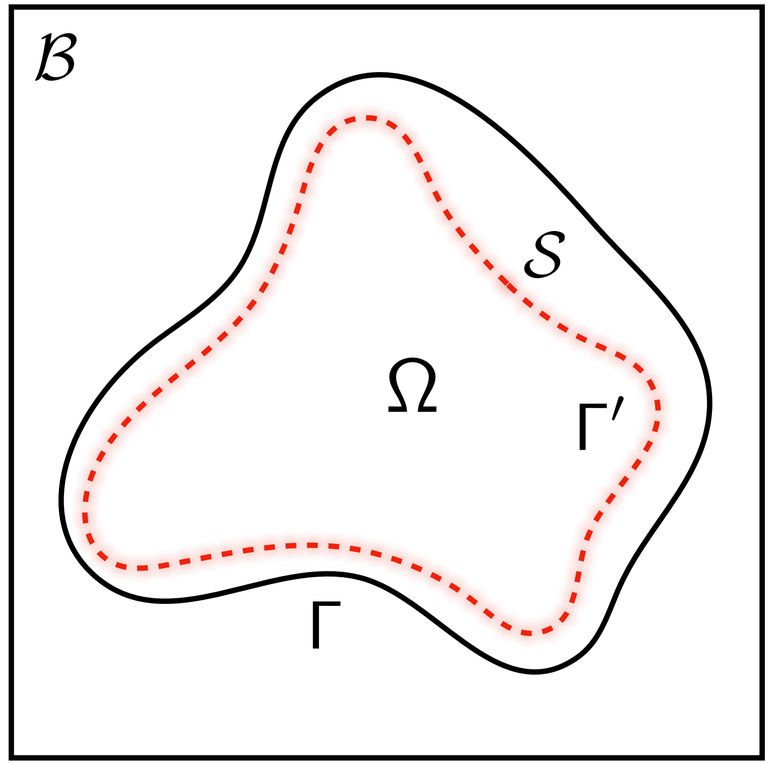
Apply SLP: $u_{\text{glue}} = S\left(\left.\frac{\partial u_{\text{strip}}}{\partial n}\right|_{\Gamma'} - \left.\frac{\partial u_{\text{bulk}}}{\partial n}\right|_{\Gamma'}\right)$



Then, $\Delta(u_{\text{bulk}} + u_{\text{glue}}) = f$ in $\Omega \setminus \mathcal{S}$

$\Delta(u_{\text{strip}} + u_{\text{glue}}) = f$ in $\mathcal{S}$

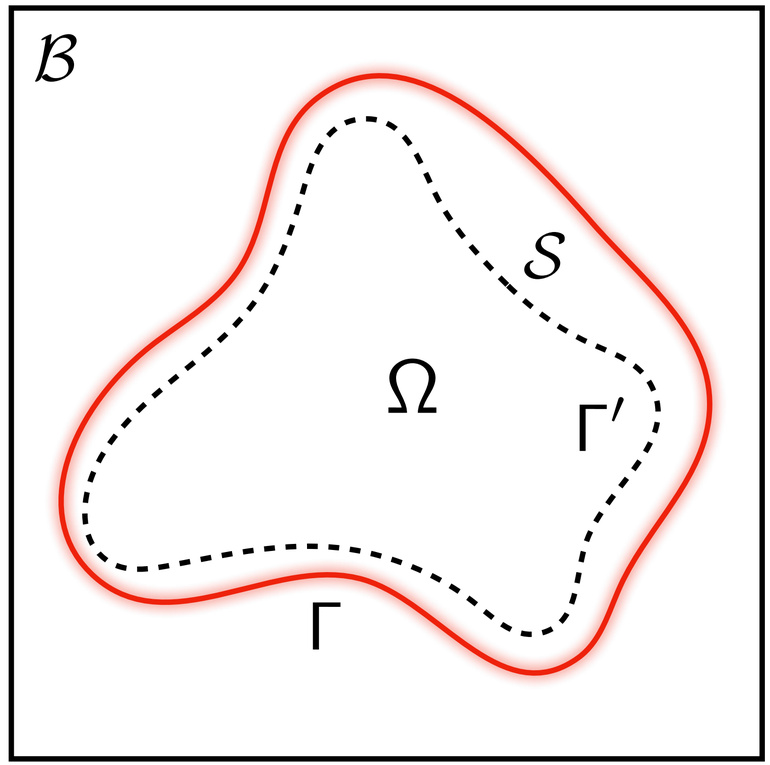
$u_{\text{strip}} = u_{\text{bulk}}$, $\frac{\partial u_{\text{strip}}}{\partial n} = \frac{\partial u_{\text{bulk}}}{\partial n}$ on Γ'

Correcting the boundary conditions

Finally, the boundary conditions may not be satisfied.

Standard BIE solve using double-layer potential:

$$\begin{aligned} \Delta u_{\text{bc}} &= 0 && \text{in } \Omega \\ u_{\text{bc}} &= g - (u_{\text{strip}}|_\Gamma + u_{\text{glue}}|_\Gamma) && \text{on } \Gamma \end{aligned}$$



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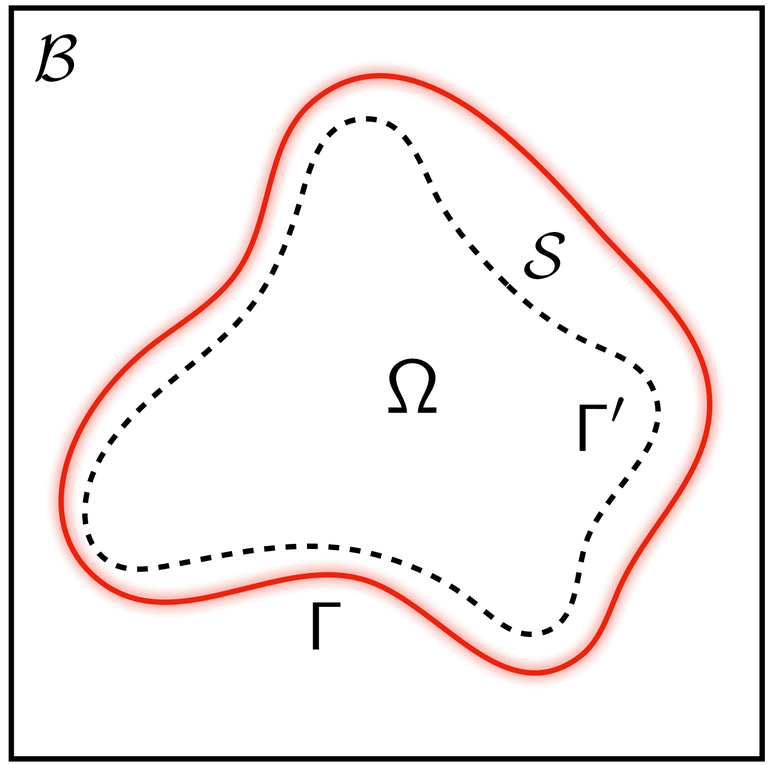
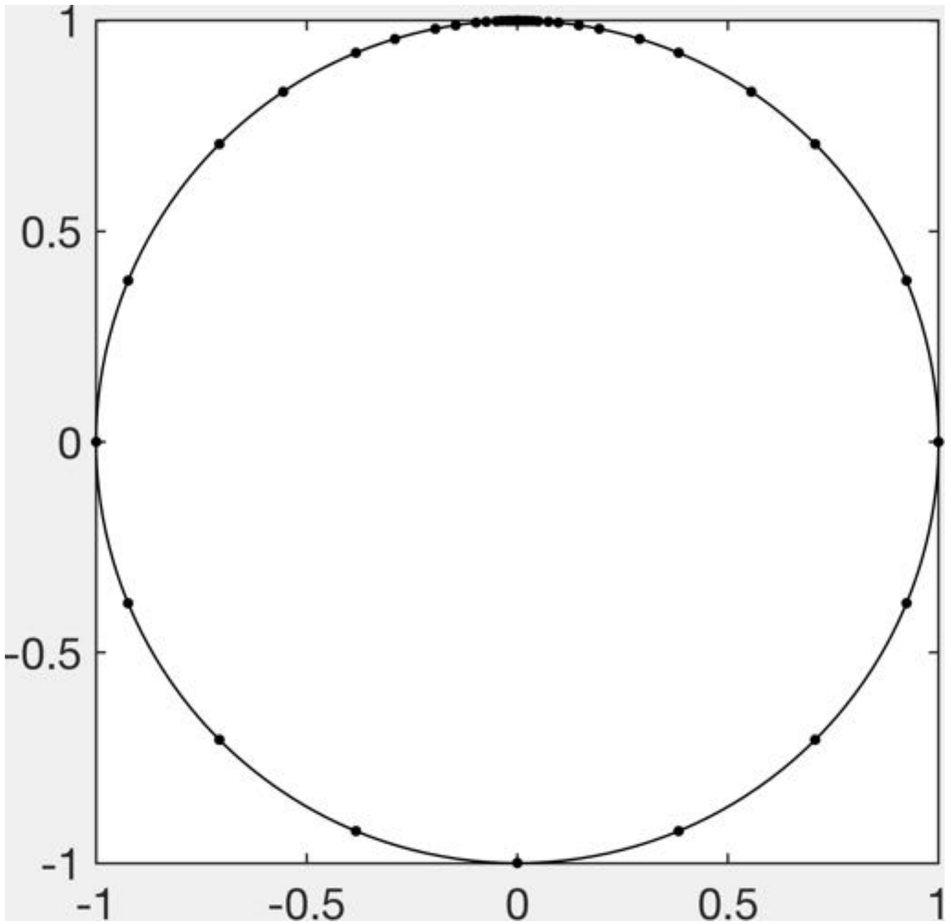
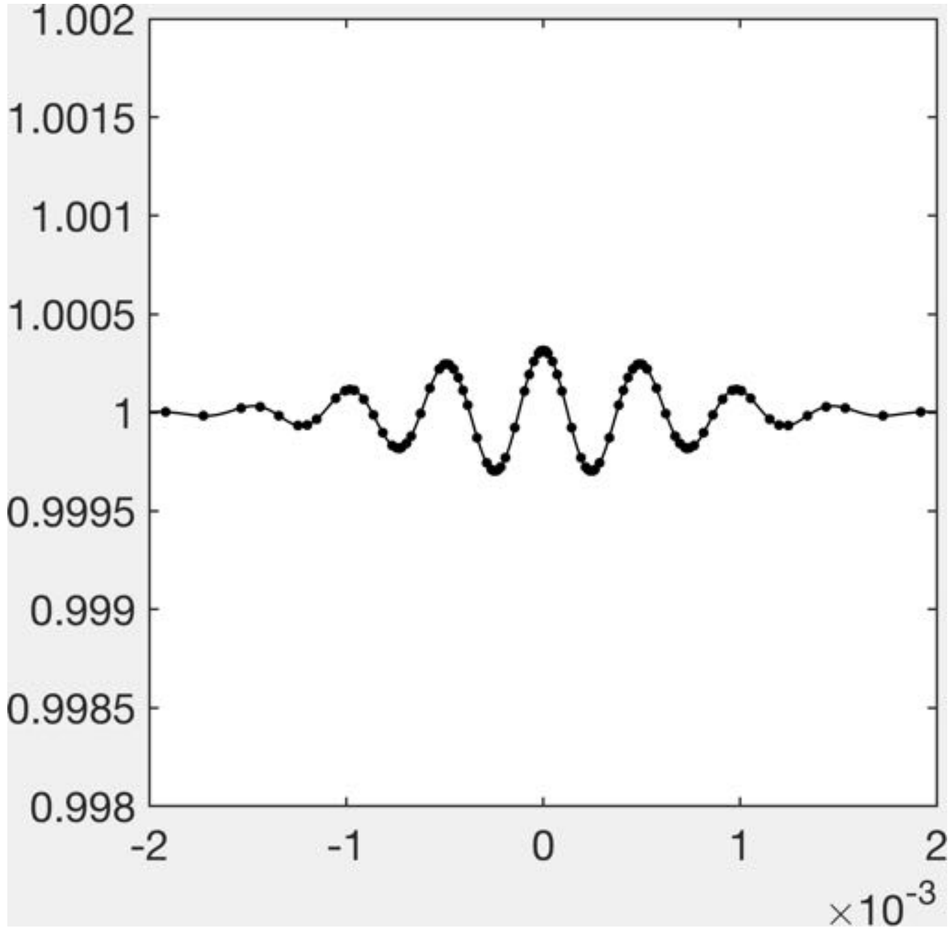
Then $u = \begin{cases} u_{\text{bulk}} + u_{\text{glue}} + u_{\text{bc}} \text{ in } \Omega \setminus \mathcal{S} \\ u_{\text{strip}} + u_{\text{glue}} + u_{\text{bc}} \text{ in } \mathcal{S} \end{cases}$ satisfies:

$$\begin{aligned} \Delta u &= f && \text{in } \Omega \\ u &= g && \text{on } \Gamma \end{aligned}$$

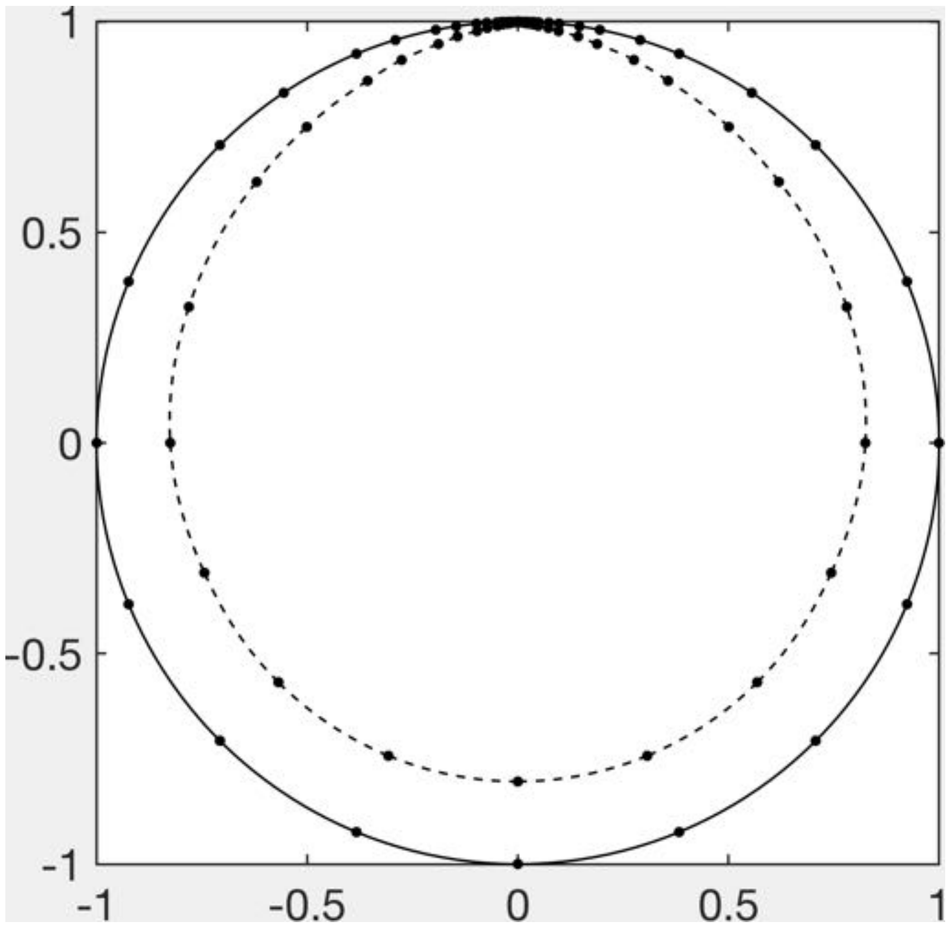


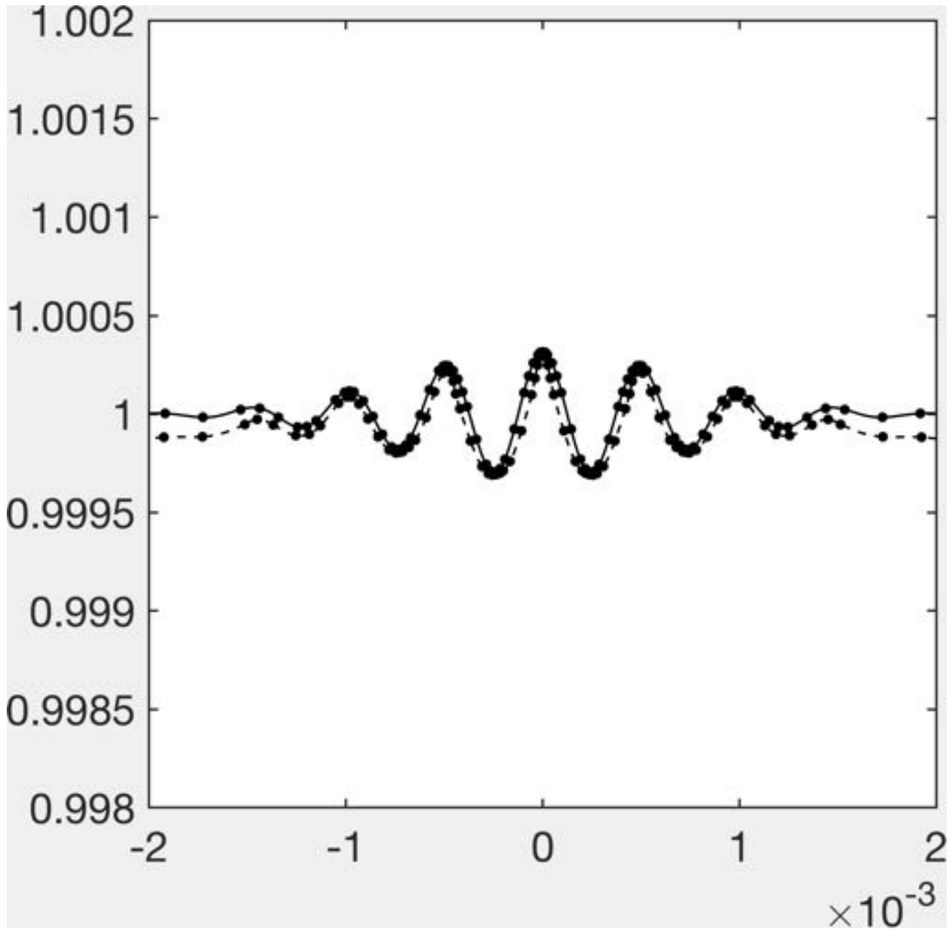
Numerical results
Example



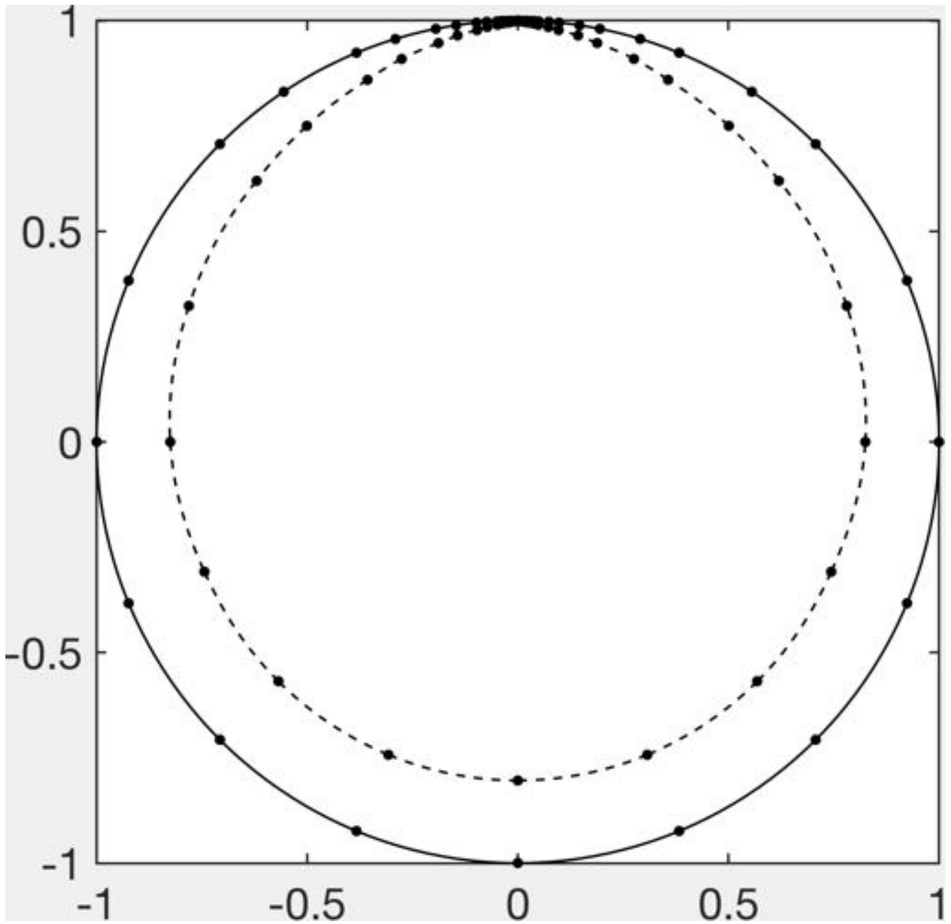


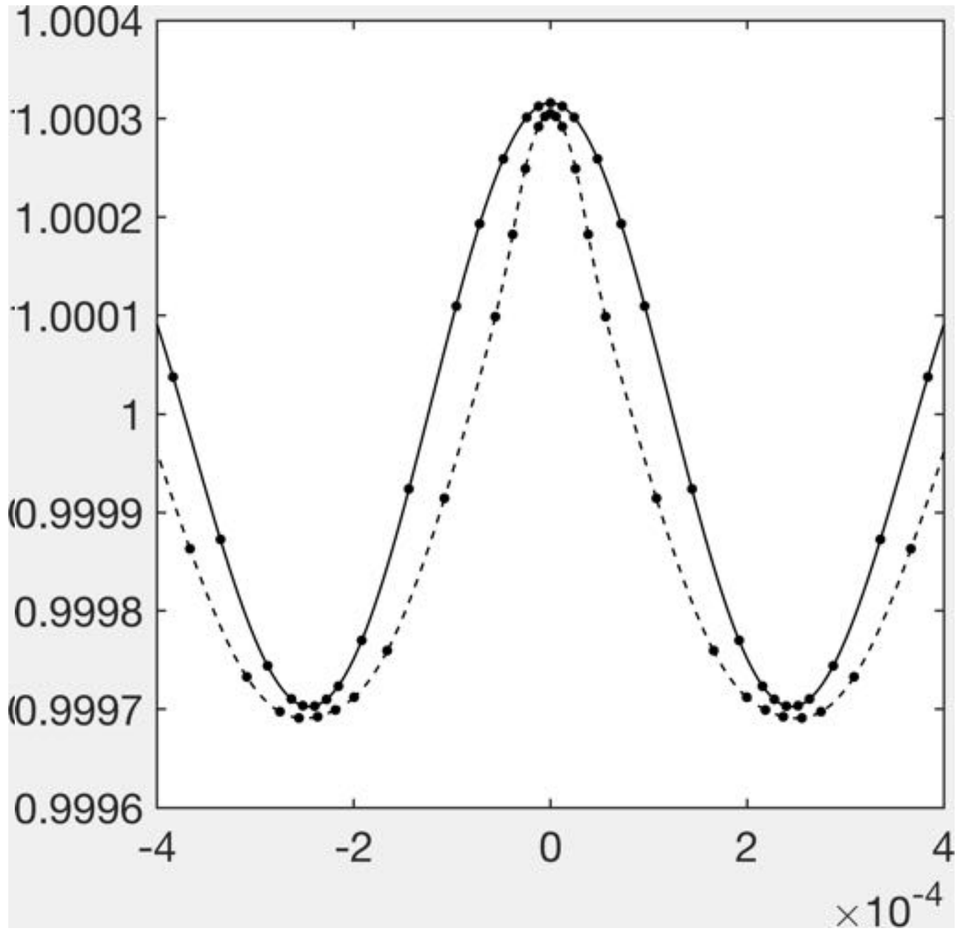
Numerical results
Example





Numerical results
Example





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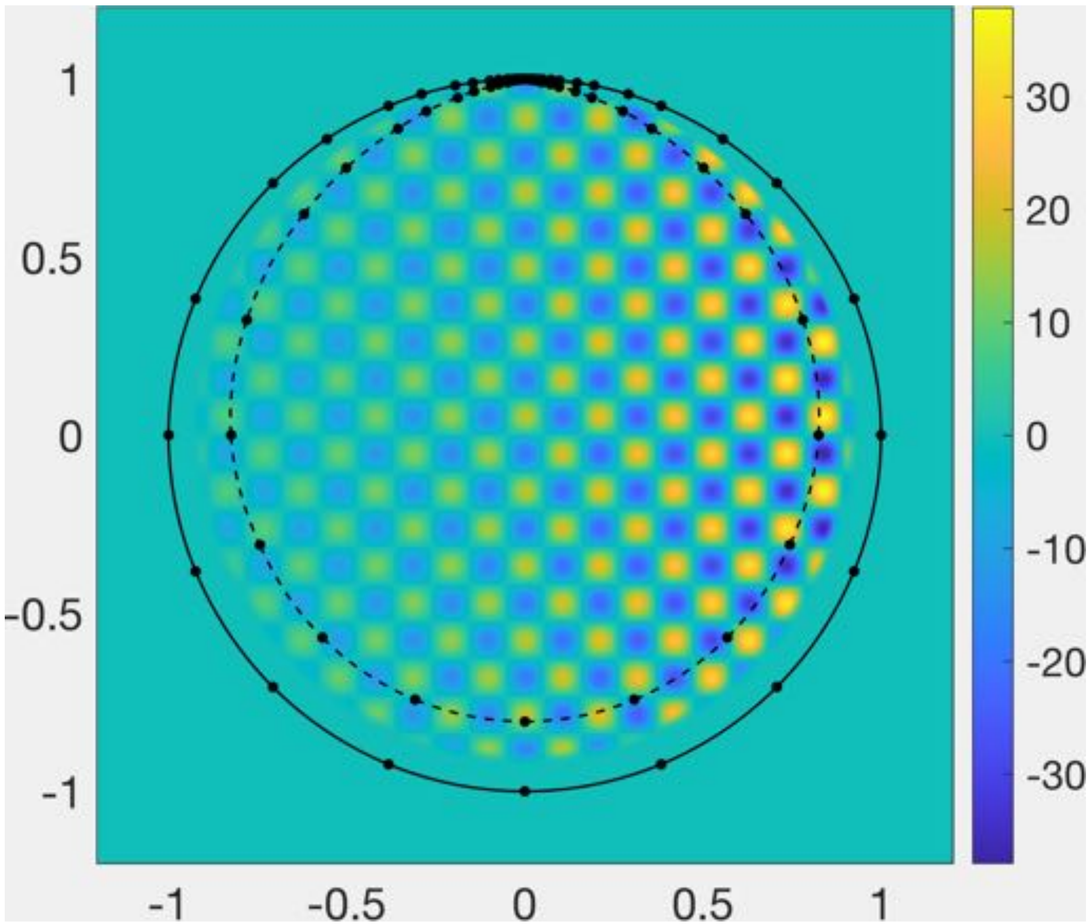

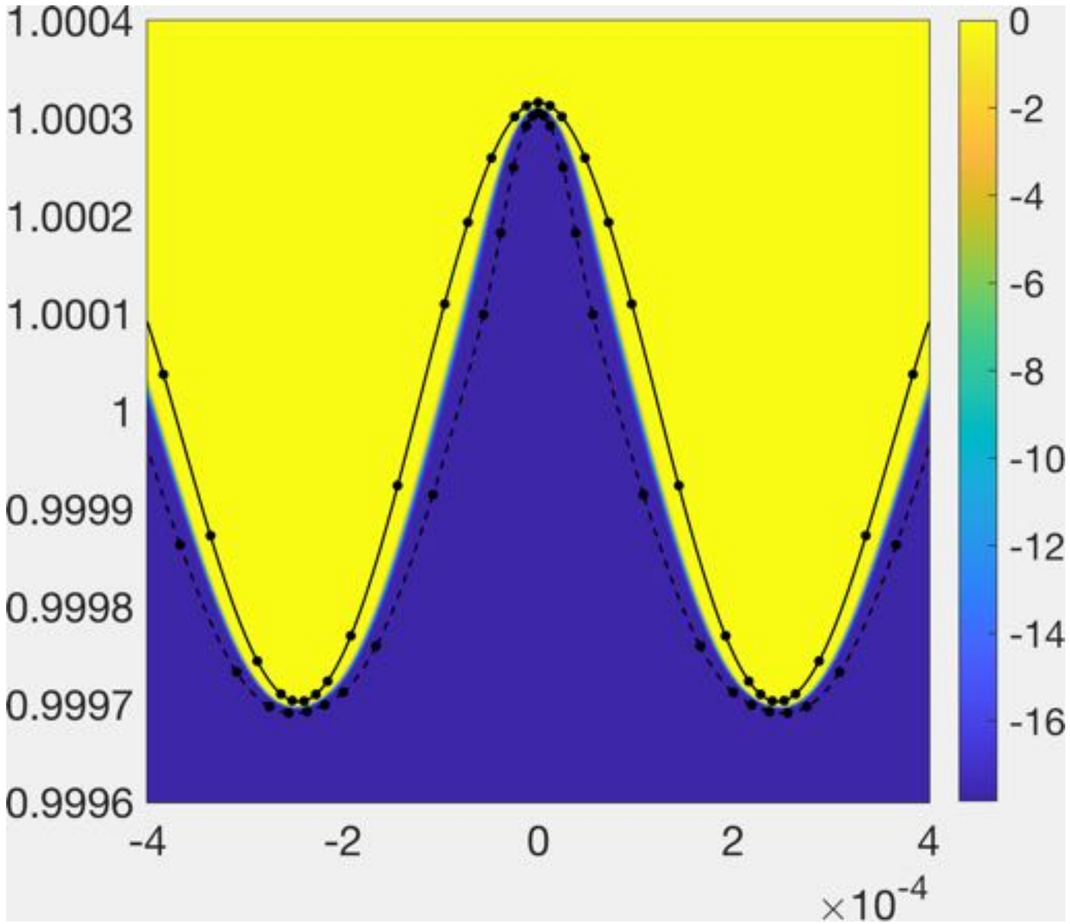

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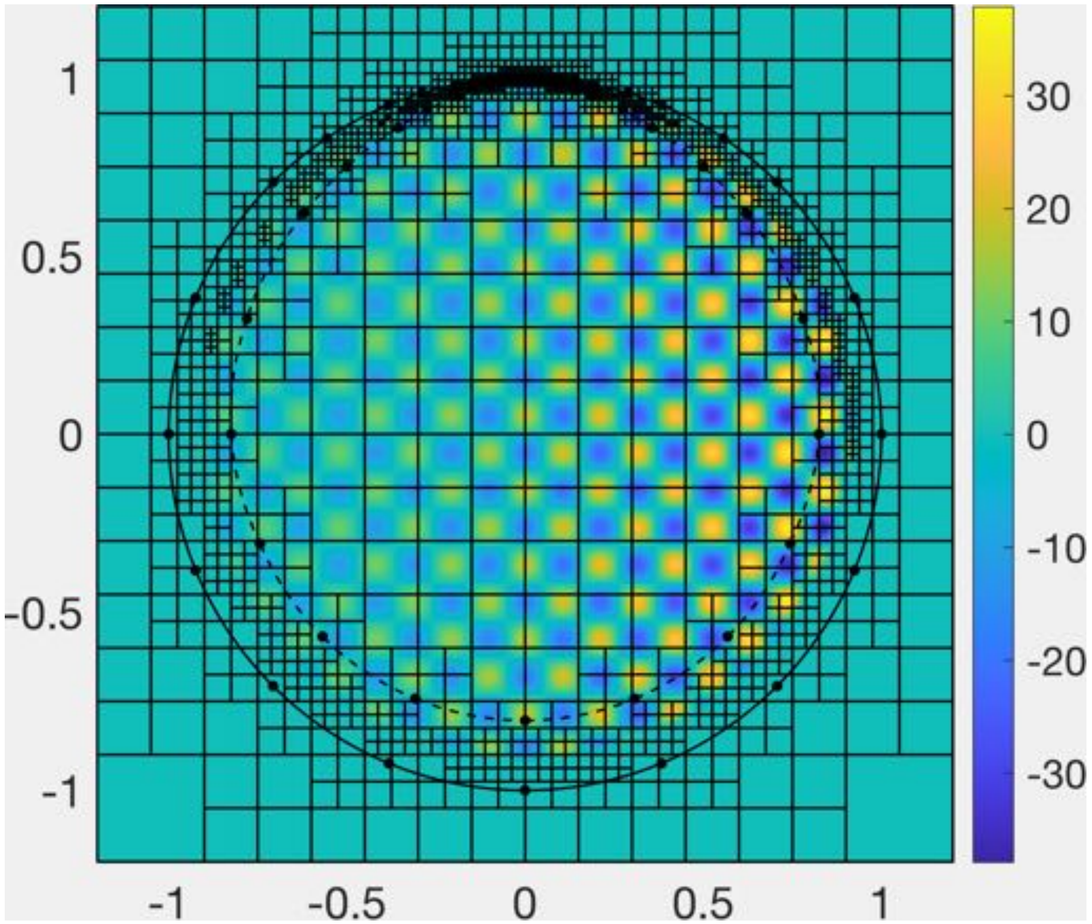
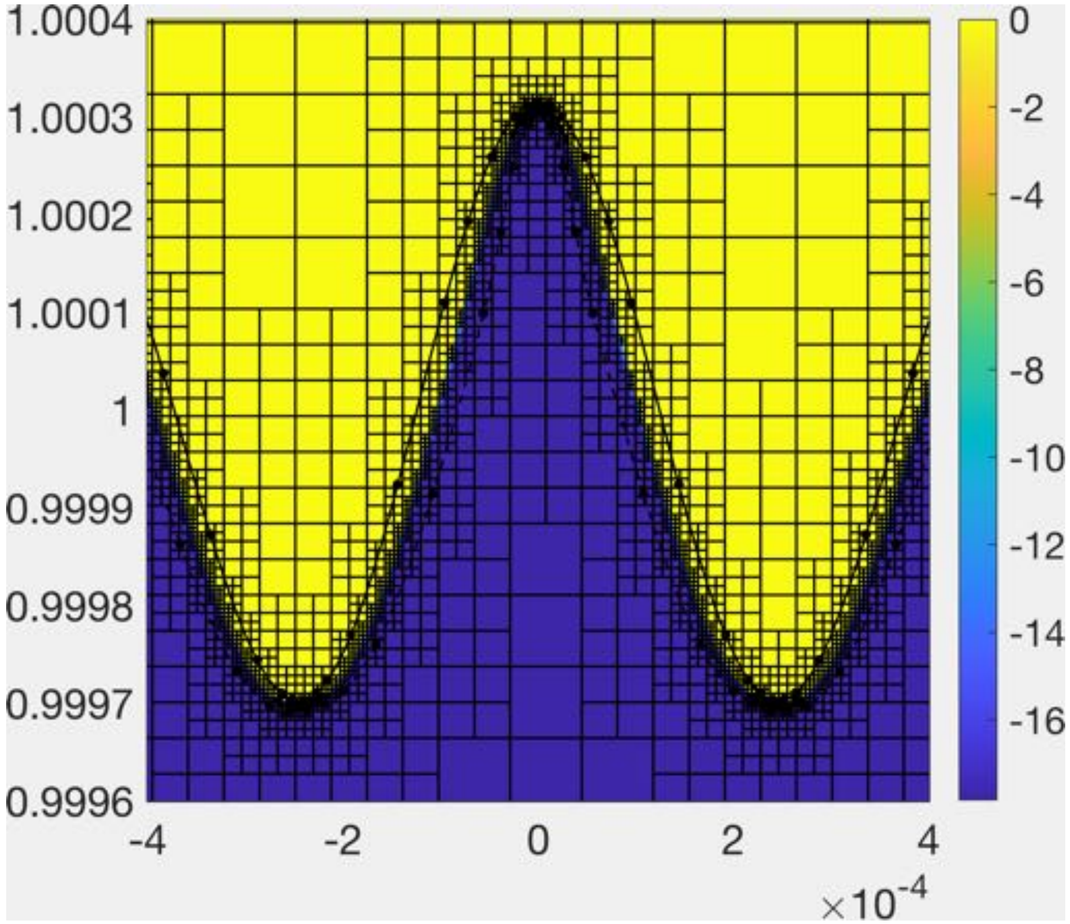
Example





Numerical results
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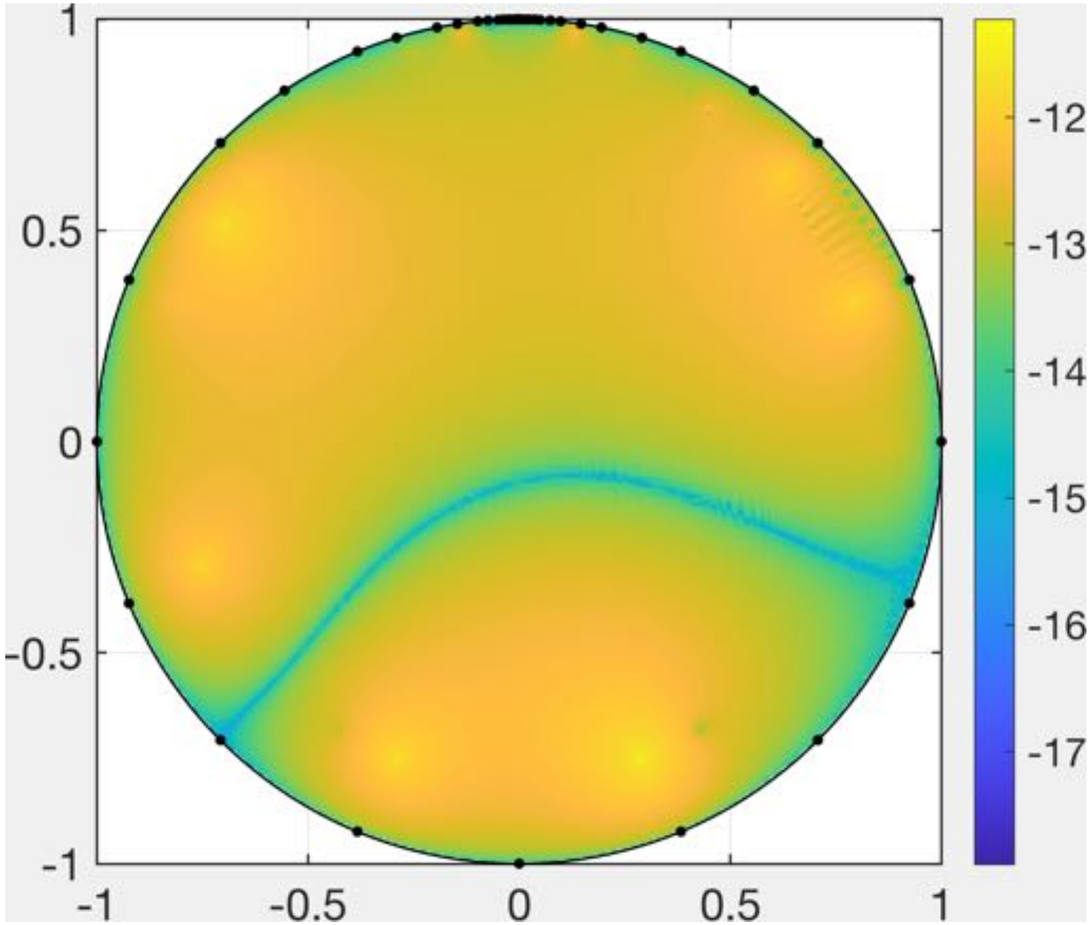

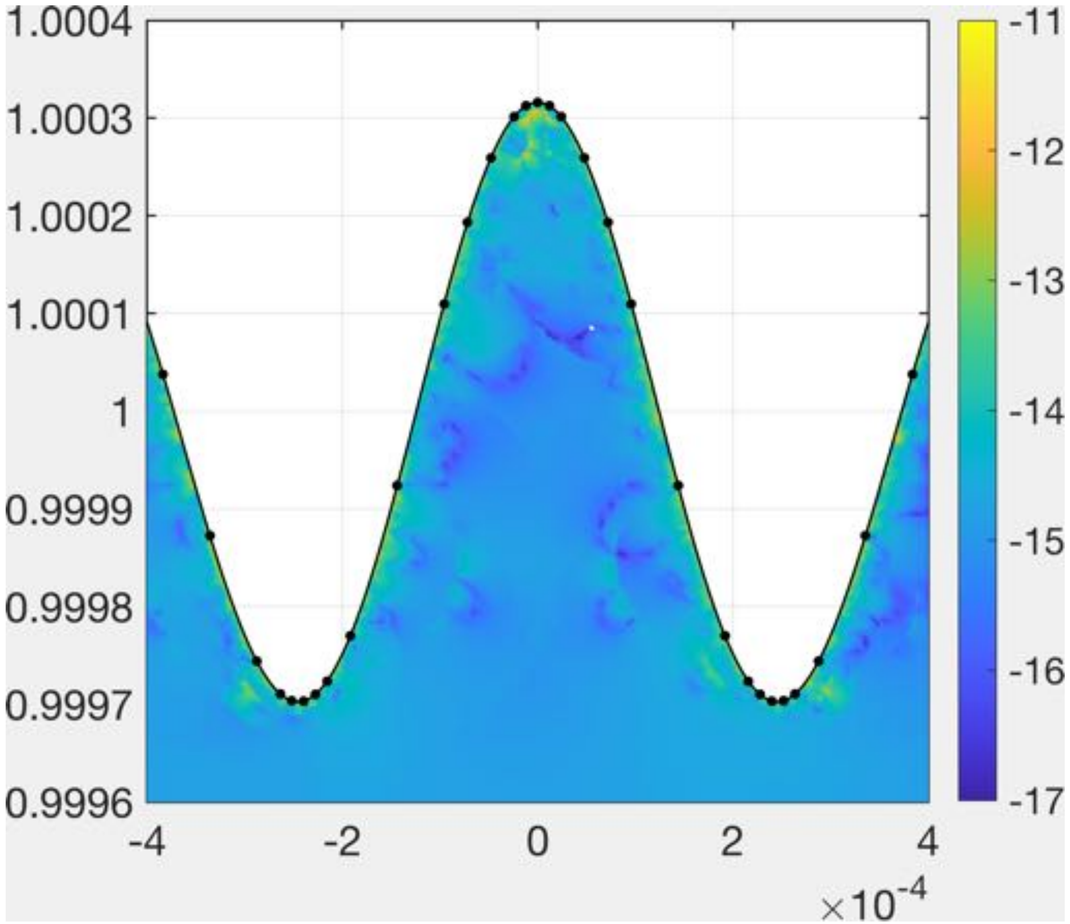

Thank you

- Still ongoing work
- Adaptivity can be performed on boundary (via panelization) and in volume (box code)
- Function “intension” can avoid pitfalls of function extension

Alex Barnett

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