Approximation with Ambient B-Splines and Intrinsic PDEs on Manifolds

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Joint work with N. Lehmann and S. Odathuparambil

Approximation problem

- Given: manifold $\omega \subset \mathbb{R}^d$
  - without boundary, compact, smooth
  - codimension 1
  - arbitrary topology
- Given: function $f : \omega \to \mathbb{R}$
  - smooth
  - Sobolev class $W_p^n(\omega)$
- Sought: approximation $s : \omega \to \mathbb{R}$
  - accurate, $\|f - s\| = O(h^n)$
  - smooth, C^k
  - finite-dimensional space
  - simple concept, easy implementation
  - fast evaluation

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Approaches

- piecewise linear
  - flexible, standard in Computer Graphics
  - C^0, low approximation order
- intrinsic functions
  - explicitly known only for elementary geometry
  - otherwise comlicated
- chart-based methods
  - blending artifacts
- piecewise parametrization (subdivision, G-splines)
  - non-trivial quadrature
  - limited smoothness
- radial basis functions in ambient space
  - yes, but ...

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- radial basis functions in ambient space
  - yes, but ...
- **alternative:** ambient B-spline method (ABM)

Basic idea

Define function space on ω by restricting functions in ambient space $\mathbb{R}^d$ to ω. In particular, if S is a spline of order n on $\mathbb{R}^d$, then

$$s := S_{|\omega}$$

is a smooth function on ω.

Benefits:

- standard splines, independent of ω
- higher order smoothness
- adaptive refinement

Challenges:

- stability
- approximation order

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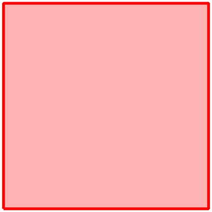
Lack of stability

Condition number of Gramian matrix of TP Bernstein basis on $[0,1]^2$:

n	2	3	4
cond	8e0	1e2	1e3



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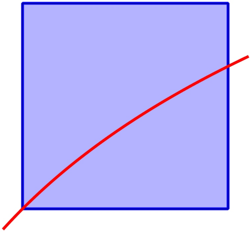
Lack of stability

Condition number of Gramian matrix of TP Bernstein basis restricted to curve ω, e.g., graph of $\ln(1+x), 0 \leq x \leq 1$:

n	2	3	4
cond	1e06	1e20	3e32

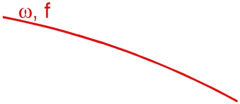


Extension

In order to use B-splines in a tubular neighborhood

$$\Omega \supset \omega$$

of ω, we need to extend the given function,



$$f : \omega \to \mathbb{R}$$

Extension

In order to use B-splines in a tubular neighborhood

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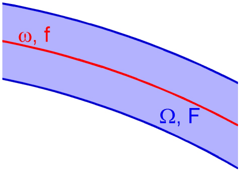
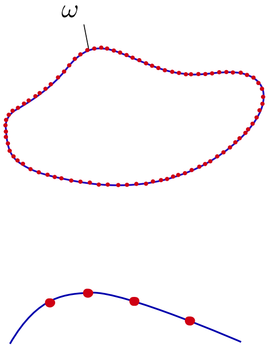
$$f : \omega \to \mathbb{R} \quad \Rightarrow \quad F : \Omega \to \mathbb{R}$$



Ambient B-Spline approximation method

- Given (scattered) data on manifold ω.



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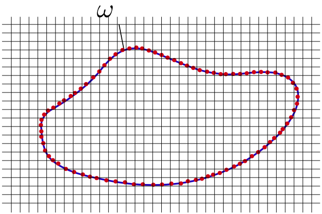
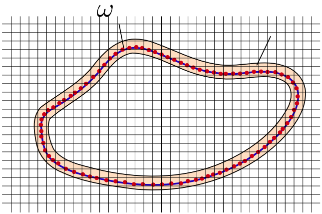
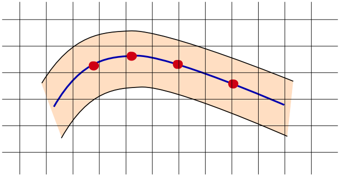


Ambient B-Spline approximation method

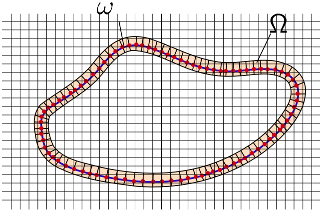
- Given (scattered) data on manifold ω.
- Define sufficiently thin tube $\Omega \supset \omega$.

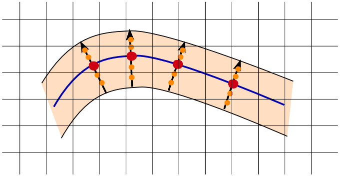




Ambient B-Spline approximation method

- Given (scattered) data on manifold ω.
- Define sufficiently thin tube $\Omega \supset \omega$.
- Extend data to Ω.





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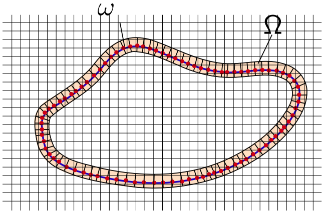
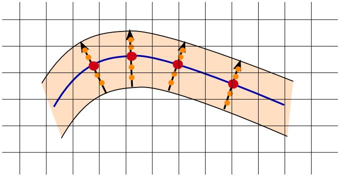
Ambient B-Spline approximation method

manifold ω

f

ambient space $\mathbb{R}^d$



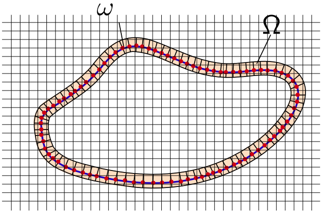


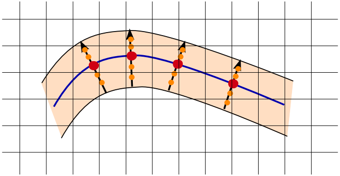
Ambient B-Spline approximation method

manifold ω

ambient space $\mathbb{R}^d$

$$f \xrightarrow{\text{extension}} F = Ef$$





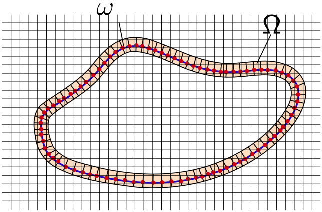
Ambient B-Spline approximation method

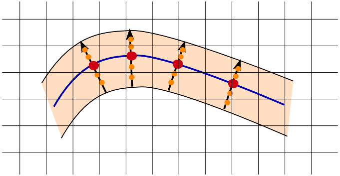
manifold ω

$f \xrightarrow{\text{extension}} F = Ef$

ambient space $\mathbb{R}^d$

$$
\begin{array}{c}
F = Ef \\
\Big\downarrow \text{approx.} \\
S = PF
\end{array}
$$

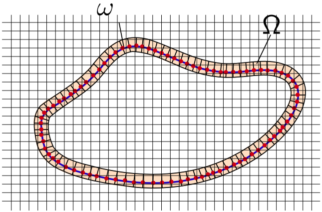


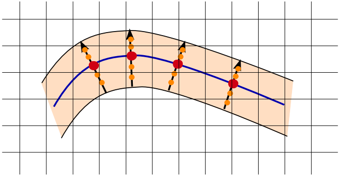


Ambient B-Spline approximation method

manifold ω | ambient space $\mathbb{R}^d$

$$
\begin{tikzcd}
f \arrow[r, "\text{extension}"] & F = Ef \arrow[d, "\text{approx.}"] \\
s = RS & S = PF \arrow[l, "\text{restriction}"']
\end{tikzcd}
$$

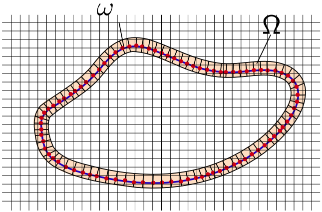


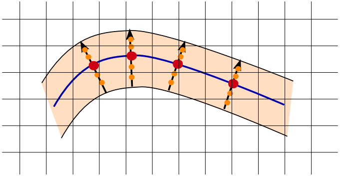


Ambient B-Spline approximation method

manifold ω | ambient space $\mathbb{R}^d$

$$\begin{tikzcd} f \arrow[r, "\text{extension}"] \arrow[d, "\text{ambient method}"'] & F = Ef \arrow[d, "\text{approx.}"] \\ s = RS & S = PF \arrow[l, "\text{restriction}"] \end{tikzcd}$$





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manifold ω | **ambient space $\mathbb{R}^d$**

$$
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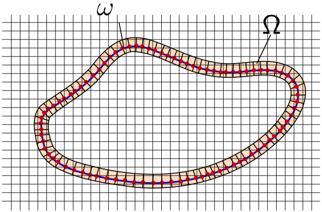
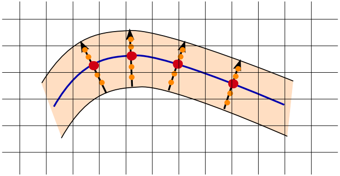




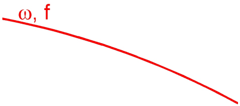
The ambient method: $\quad s = RPEf$

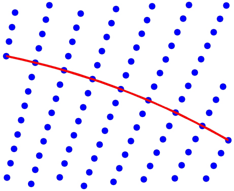
Extension

Given $f : \omega \to \mathbb{R}$, it is not difficult to construct an extension $F : \Omega \to \mathbb{R}$, provided that Ω is small enough:

- constant in normal direction

$$F(x + tn) = f(x), \quad x \in \omega$$





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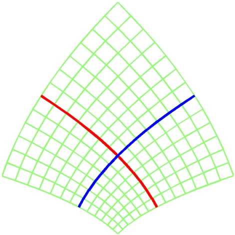
- constant in normal direction

$$F(x + tn) = f(x), \quad x \in \omega$$

- orthogonal flow, if $\omega = \varphi^{-1}(0)$ is given as a levelset

$$F(\psi(x,t)) = f(x), \quad \partial_t \psi = \frac{\nabla \varphi}{|\nabla \varphi|}, \quad \psi(x,0) = \psi(x)$$



Ambient B-Spline approximation method

Properties:

- based on standard tensor product B-splines

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Ambient B-Spline approximation method

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- higher dimension, but comparable number of control points

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Ambient B-Spline approximation method

Properties:

- based on standard tensor product B-splines
- arbitrary smoothness for free
- no problem with extraordinary points
- higher dimension, but comparable number of control points
- approximation order?

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Approximation order

Theorem (Odathuparambil, R. '15)

Let E_ψ be the extension operator based on some transversal flow ψ. For $f \in W_p^n(\omega)$, the approximation error $\Delta = RPE_\psi f - f$ is bounded by

$$\|\Delta\|_{W_p^m(\omega)} \leq \mathrm{c}\, h^{n-m} \|f\|_{W_p^n(\omega)}, \quad m < n,$$

where c depends on ψ.

Proof is based on:

- approximation properties of P
- Friedrichs' inequality
- Markov inequality
- Faà di Bruno formula

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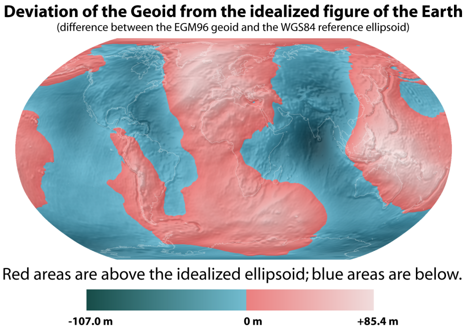
Example: The geoid

The geoid is the equipotential surface of gravitational field corresponding to the mean-ocean surface.
Model currently used **EGM2008**:

- spherical harmonics up to degree 2190 and order 2159,
- more than 4 million coefficients.



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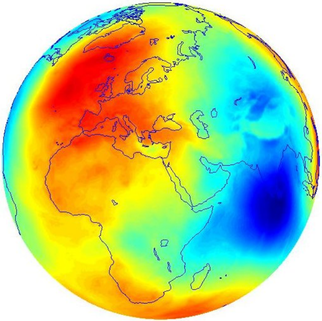
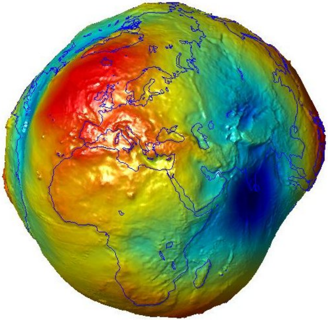
Example: The geoid

Using ambient B-spline approximation method:

- drastically improves evaluation time,
- reduces number of coefficients (hierarchical B-splines).

Local B-Spline method (order 3, $1e6$ coefficients):





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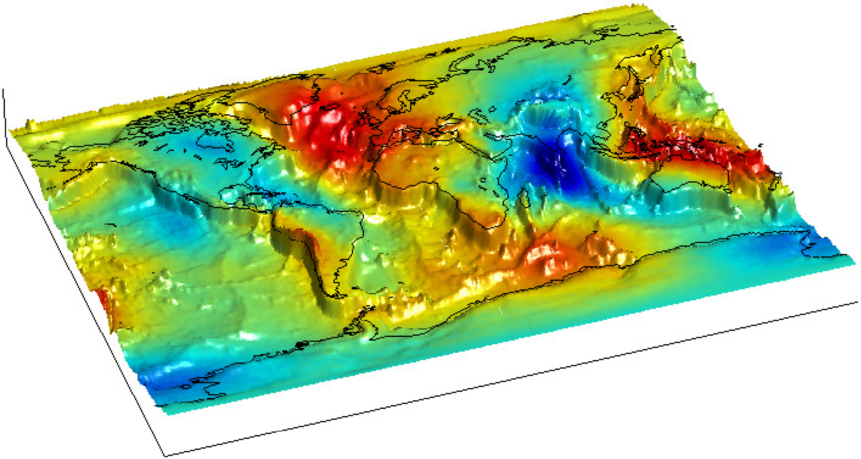
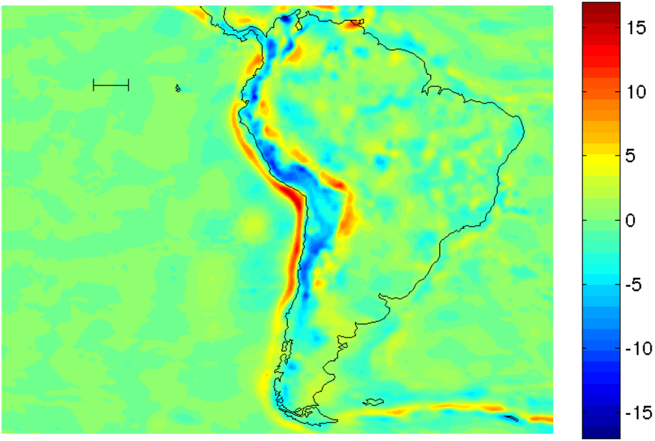
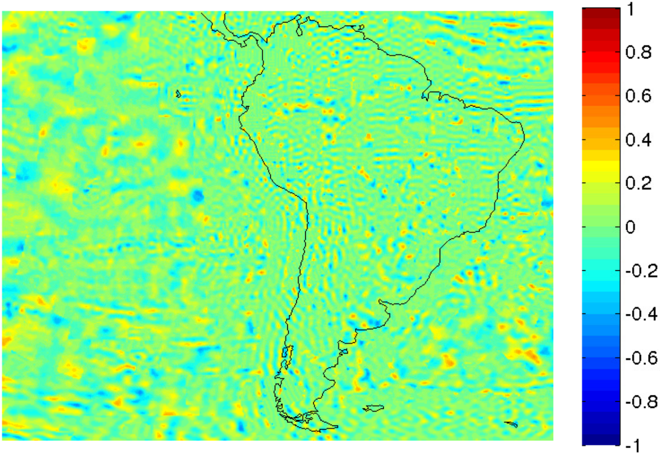


Example: The geoid



approximation error for $h = \frac{1}{10} R_{\mathrm{earth}}$

Example: The geoid, adaptive refinement



error for $h_{\min} = \frac{1}{160} R_{\text{earth}}$ and $\sim$ 750.000 B-splines

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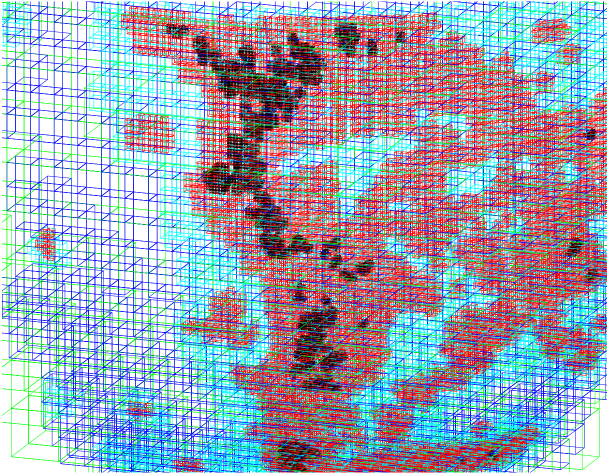
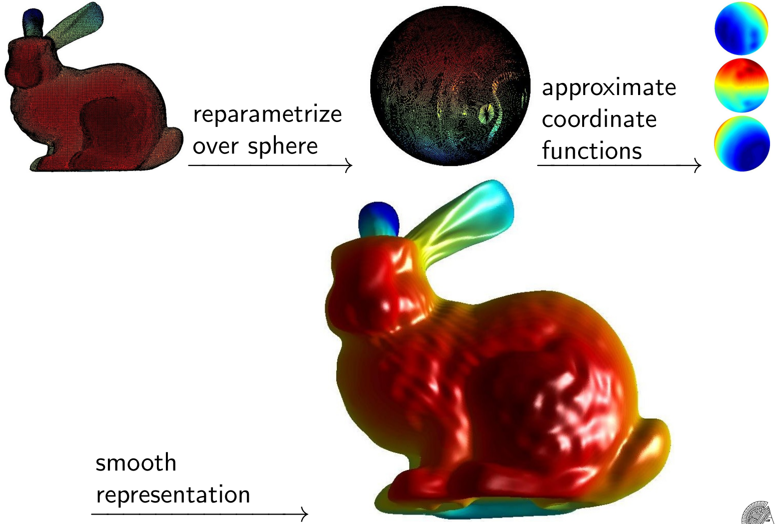
Example: The geoid, adaptive refinement



Surface reconstruction



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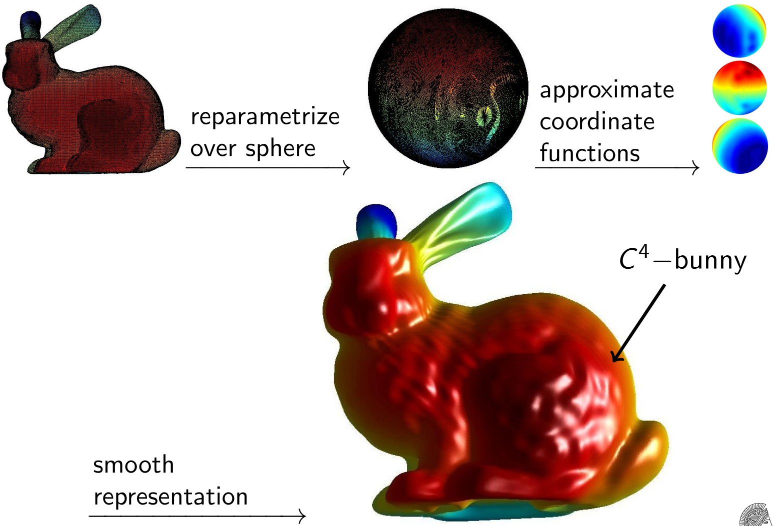

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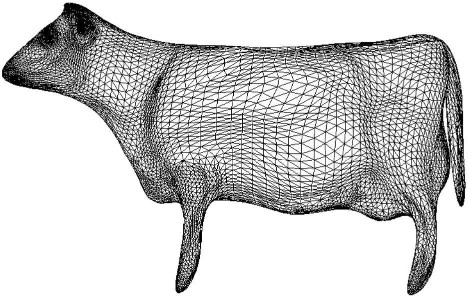
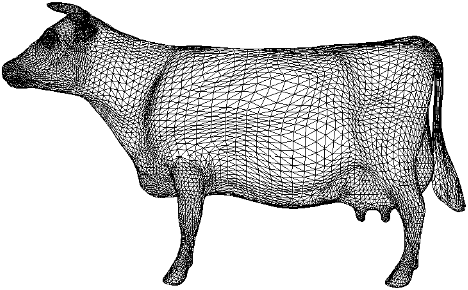


Approximation with $h = 0.2$ and ~ 2000 B-Splines.

Surface reconstruction



Adaptive approximation with $h_{\mathrm{min}} = 0.02$ and ~ 6000 B-Splines.

Surface reconstruction

Benefits:

- simple construction
- arbitrary smoothness
- adaptive refinement
- no extraordinary vertices

Challenges:

- How to find a *good* parametrization?
- How to build an interactive modeling tool?
- How to model sharp creases?

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Intrinsic PDEs on manifolds

Intrinsic model equations:

- elliptic

$$\Delta_\omega u + cu = f, \quad c < 0$$

- parabolic

$$u_t = -\Delta_\omega u$$

Applications:

- Computer Graphics (parametrization, segmentation)
- Fluid Dynamics
- Biology/Medicine
- Meteorology
- ...

Intrinsic PDEs on manifolds

- Piecewise linear FE approximation (Wardetzki '07).
- Embedding methods for parabolic PDEs (Bertalmio et. al. '01, Ruuth and Merriman '08). The Laplace-Beltrami operator is computed by

$$\Delta_\omega u = \Delta E_n u$$

instead of

$$\Delta_\omega u = \frac{\operatorname{div}\left(\sqrt{\det G}\, G^{-1} \nabla u\right)}{\sqrt{\det G}}.$$

- Embedding method for elliptic PDEs (Dziuk and Elliott '13). Problem: Loss of elipticity.

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- Embedding method for elliptic PDEs (Dziuk and Elliott '13). Problem: Loss of elipticity.
- New: Ambient B-spline approximation of extended elliptic PDE.

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Intrinsic PDEs on manifolds

Caution: Let u be a solution of the intrinsic PDE

$$\Delta_\omega u + cu = f.$$

Consider the extensions $U := E_n u$ and $F := E_n f$ in normal direction.

Then

$$\Delta U + cU = F \quad \text{on} \quad \omega$$

but

$$\Delta U + cU \neq F \quad \text{on} \quad \Omega.$$

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New approach

Can we define an elliptic operator L such that

$$LEu = E\Delta_\omega u\,?$$

Then, we would have

$$\Delta_\omega u + cu = f$$
$$E(\Delta_\omega u + cu) = Ef$$
$$LEu + cEu = Ef$$
$$LU + cU = F$$

New approach

Theorem (Odathuparambil, R. '14)

Let d be the signed distance function of ω. Define

- *the matrix*

$$Q := (\mathrm{Id} - dH)^{-1}, \quad H := \nabla^2 d.$$

- *the differential operator*

$$LU := \Delta_Q U := \sum_{i,j} Q_{i,j} (\nabla Q \nabla U)_{i,j}.$$

Then L is uniformly elliptic in a vicinity of ω and satisfies

$$LE_n u = E_n \Delta_\omega u$$

In particular,

$$\Delta_\omega u + cu = f \quad \Rightarrow \quad LU + cU = F, \quad \nabla U \cdot \nabla d = 0.$$

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New approach for general levelsets

- $\omega = \varphi^{-1}(0)$ is given as a levelset.
- General second order differential operator on ω

$$L^0 := A^0 * \nabla^2 u + B^0 * \nabla u := \sum_{i,j} A^0_{i,j} \partial_{i,j} u + \sum_i B^0_i \partial_i u$$

- **Sought:** Extension

$$L := A * \nabla^2 U + B * \nabla U$$

to ambient space along the orthogonal flow ψ such that

$$LU = LE_\psi u = E_\psi L^0 u.$$

- **Challenge:** Find a formula for the functions $A = A(X), B = B(X), X \in \Omega$.

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New approach for general levelsets

Theorem (Odathuparambil, R. 15)

Consider the system of ODEs

$$\tilde{A}' = |\nabla\varphi|^{-1}(\tilde{A}H + H\tilde{A}), \quad H := \nabla^2\varphi$$
$$\tilde{B}' = |\nabla\varphi|^{-1}(H\tilde{B} + \tilde{A} * \partial H)$$

with initial conditions $\tilde{A}(0) := A^0, \tilde{B}(0) := B^0$ *and define*

$$A(\psi(x,t)) := \tilde{A}(t), \quad B(\psi(x,t)) := \tilde{B}(t).$$

Then the operator L*, as defined above, is uniformly elliptic in a vicinity of* ω *if so is* L^0*, and satisfies*

$$LU = E_\psi L^0 u$$

In particular,

$$L^0 u = f \quad \Leftrightarrow \quad LU = F, \quad \nabla U \cdot \nabla\varphi = 0.$$

New approach for general levelsets

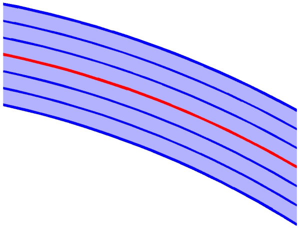
- If the boundary $\partial\Omega$ is given by levelsets, the problem

$$LU = F, \quad \nabla U \cdot \nabla \varphi = 0$$

is equivalent to an elliptic PDE with Neumann boundary conditions,

$$LU = F, \quad \nabla U \cdot \nabla \varphi = 0 \text{ on } \partial\Omega.$$

- Meshing required.

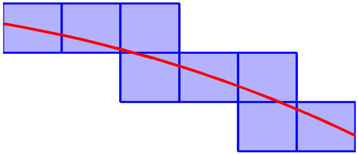


New approach for general levelsets

- If the boundary of Ω is *not* given by levelsets, the problem

$$LU = F, \quad \nabla U \cdot \nabla \varphi = 0$$

  is still well posed. In particular, Ω can be defined as a union of boxes covering ω.
- No meshing required!



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Current work

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Thanks for your attention!