A priori and a posteriori error analysis in $\boldsymbol{H}(\text{curl})$: localization, minimal regularity, and p-optimality

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FOCM, Paris, June 13, 2023

Outline

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The curl–curl problem (current density $\boldsymbol{j} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div}, \Omega)$ with $\nabla \cdot \boldsymbol{j} = 0$)

The curl–curl problem

Find the magnetic vector potential $\boldsymbol{A} : \Omega \subset \mathbb{R}^3 \to \mathbb{R}^3$ *such that*

$$\begin{aligned} \nabla \times (\nabla \times \boldsymbol{A}) &= \boldsymbol{j}, \quad \nabla \cdot \boldsymbol{A} = 0 && \textit{in } \Omega, \\ \boldsymbol{A} \times \boldsymbol{n}_\Omega &= \boldsymbol{0}, && \textit{on } \Gamma_\mathrm{D}, \\ (\nabla \times \boldsymbol{A}) \times \boldsymbol{n}_\Omega &= \boldsymbol{0}, \quad \boldsymbol{A} \cdot \boldsymbol{n}_\Omega = 0 && \textit{on } \Gamma_\mathrm{N}. \end{aligned}$$

The curl–curl problem (current density $\boldsymbol{j} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div}, \Omega)$ with $\nabla\cdot\boldsymbol{j} = 0$)

Weak formulation (consequence)

$\boldsymbol{A} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$ *satisfies*

$$(\nabla\times\boldsymbol{A}, \nabla\times\boldsymbol{v}) = (\boldsymbol{j}, \boldsymbol{v}) \qquad \forall \boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$$

Property of the weak solution

$\boldsymbol{A} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$ (primal variable)

Consequence of the weak formulation

$\boldsymbol{h} := \nabla\times\boldsymbol{A} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$, $\nabla\times\boldsymbol{h} = \boldsymbol{j}$ (dual variable)

Primal Nédélec approximation

$\boldsymbol{V}_h := \boldsymbol{\mathcal{N}}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$, $p \geq 0$;
$\boldsymbol{A}_h \in \boldsymbol{V}_h$ *such that*

$$(\nabla\times\boldsymbol{A}_h, \nabla\times\boldsymbol{v}_h) = (\boldsymbol{j}, \boldsymbol{v}_h) \qquad \forall \boldsymbol{v}_h \in \boldsymbol{V}_h$$

Dual Nédélec approximation

$$\boldsymbol{h}_h := \arg \min_{\substack{\boldsymbol{v}_h \in \boldsymbol{\mathcal{N}}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega) \\ \nabla\times\boldsymbol{v}_h = \Pi_p \boldsymbol{j}}} \|\boldsymbol{v}_h\|^2$$

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A few central reflections ($\boldsymbol{H}$(curl)-setting)

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- a priori & a posteriori analysis **disconnected** (different tools)

Our approach

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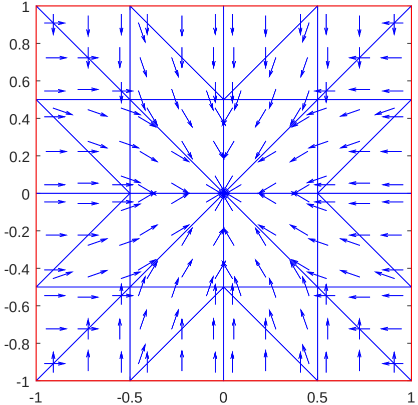
  - go **discrete straight-away** and then use a posteriori tools in a priori analysis (equilibration)

Outline

Equilibration in $\boldsymbol{H}(\mathrm{div})$ Destuynder and Métivet (1998), Braess & Schöberl (2008)



Flux $\boldsymbol{\iota}_h \notin \boldsymbol{H}(\mathrm{div})$, $\nabla{\cdot}\boldsymbol{\iota}_h \neq f$

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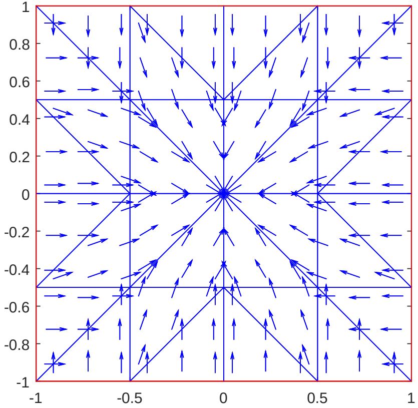

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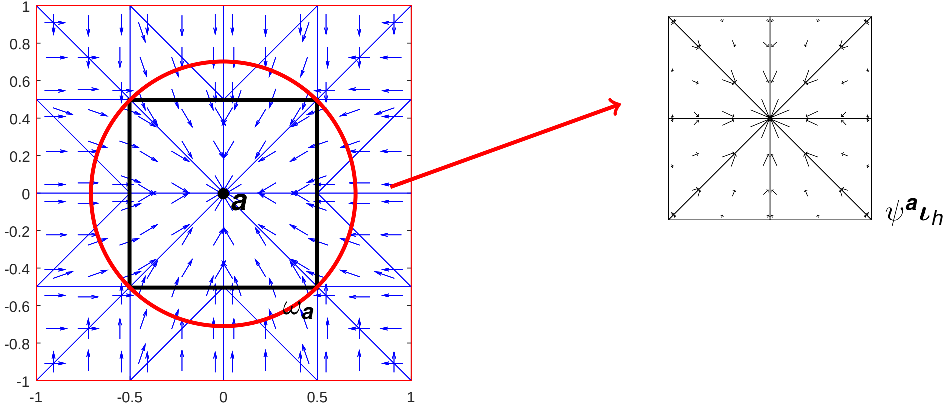

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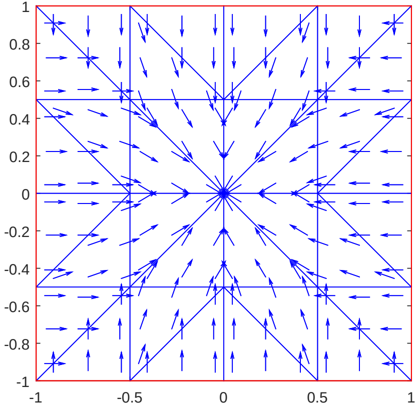

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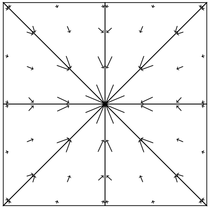

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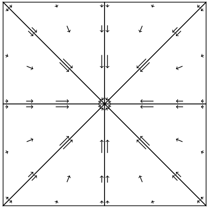

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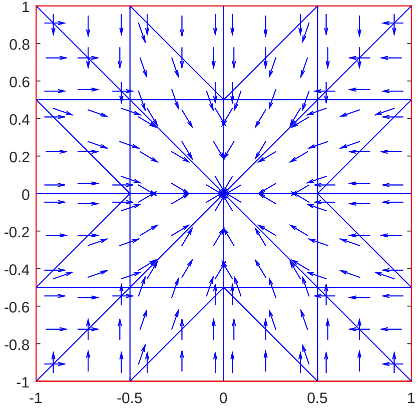

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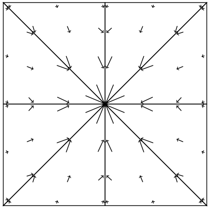

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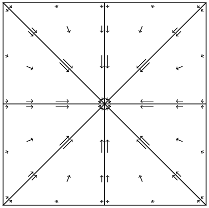

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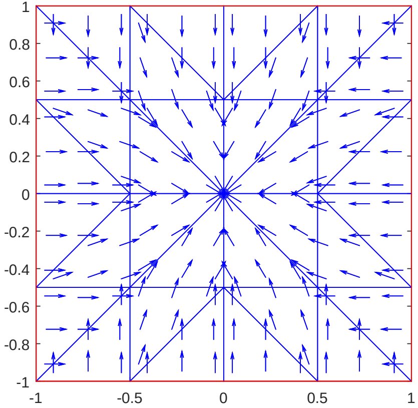

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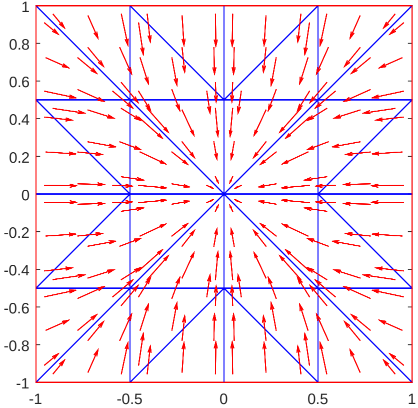

Equilibrated flux rec. $\boldsymbol{h}_h$

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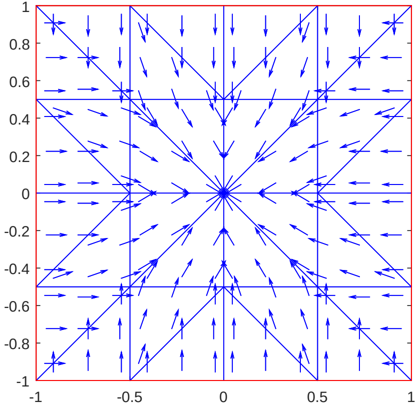

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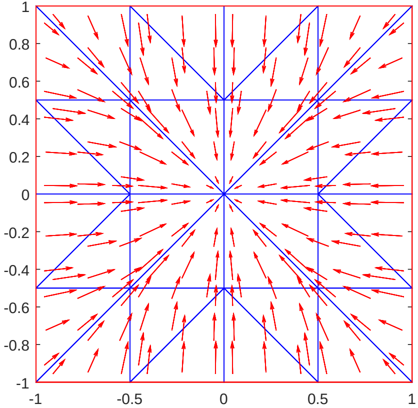

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Equilibration in $\boldsymbol{H}(\mathrm{curl})$

Previous contributions

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- Licht (2019): a conceptual discussion
- Gedicke, Geevers, & Perugia (2020): equilibrated-residual-style construction
- Gedicke, Geevers, Perugia, & Schöberl (2021): p-robust modification

Our construction

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Equilibration in $\boldsymbol{H}(\mathrm{curl})$

Previous contributions

- Braess & Schöberl (2008): lowest-order case $p = 0$
- Licht (2019): a conceptual discussion
- Gedicke, Geevers, & Perugia (2020): equilibrated-residual-style construction
- Gedicke, Geevers, Perugia, & Schöberl (2021): p-robust modification

Our construction

$$\underbrace{\iota_h \in \mathcal{N}_p(\mathcal{T}_h), \boldsymbol{j} \in \mathcal{RT}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div}, \Omega)}_{???=0\ \forall ???} \rightarrow \boldsymbol{h}_h := \sum_{\boldsymbol{a} \in \mathcal{V}_h} \boldsymbol{h}_h^{\boldsymbol{a}} \in \mathcal{N}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega), \nabla \times \boldsymbol{h}_h = \boldsymbol{j}$$

Equilibration – the bottom line

$\boldsymbol{H}(\mathrm{div})$-case

- When there exists $\boldsymbol{v}_h \in \mathcal{RT}_{p+1}(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}_0(\mathrm{div}, \omega_{\boldsymbol{a}})$ such that $\nabla{\cdot}\boldsymbol{v}_h = j_h^{\boldsymbol{a}}$

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- When $j_h^{\boldsymbol{a}} \in \mathcal{P}_{p+1}(\mathcal{T}_{\boldsymbol{a}})$ and $(j_h^{\boldsymbol{a}}, 1)_{\omega_{\boldsymbol{a}}} = 0$ if $\boldsymbol{a} \notin \overline{\Gamma_{\mathrm{D}}}$.

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one condition

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many conditions

Patchwise equilibrated fluxes

Continuous level

- $\boldsymbol{A} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$ satisfies
  $(\nabla \times \boldsymbol{A}, \nabla \times \boldsymbol{v}) = (\boldsymbol{j}, \boldsymbol{v}) \, \forall \boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$.

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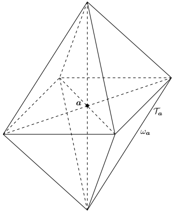

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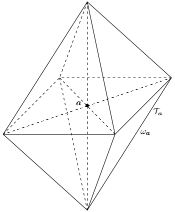

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Definition (Chaumont-Frelet, Vohralík (2022))

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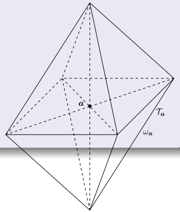

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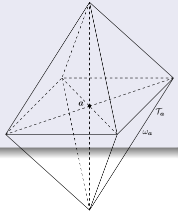

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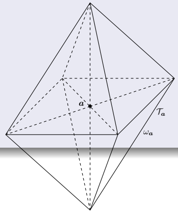

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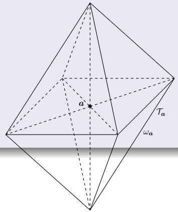

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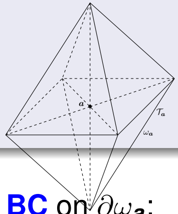

Key points

- **homogeneous tangential BC** on $\partial\omega_{\boldsymbol{a}}$: $\boldsymbol{h}_h \in \boldsymbol{\mathcal{N}}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}(\mathrm{curl}, \Omega)$
- **global equilibrium** $\nabla\times\boldsymbol{h}_h = \sum_{\boldsymbol{a}\in\mathcal{V}_h} \nabla\times\boldsymbol{h}_h^{\boldsymbol{a}}$ $= \sum_{\boldsymbol{a}\in\mathcal{V}_h} (\psi^{\boldsymbol{a}}\boldsymbol{j} + \nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)) = \boldsymbol{j}$

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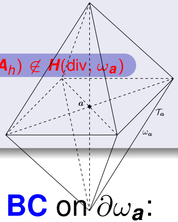
$\psi^{\boldsymbol{a}}\boldsymbol{j} \in \boldsymbol{\mathcal{RT}}_{p+1}(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}_0(\mathrm{div}, \omega_{\boldsymbol{a}})$ but $\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h) \notin \boldsymbol{H}(\mathrm{div}, \omega_{\boldsymbol{a}})$

$$\boldsymbol{h}_h := \sum_{\boldsymbol{a}\in\mathcal{V}_h} \boldsymbol{h}_h^{\boldsymbol{a}}.$$



Key points

- **homogeneous tangential BC** on $\partial\omega_{\boldsymbol{a}}$: $\boldsymbol{h}_h \in \boldsymbol{\mathcal{N}}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}(\mathrm{curl}, \Omega)$
- **global equilibrium** $\nabla\times\boldsymbol{h}_h = \sum_{\boldsymbol{a}\in\mathcal{V}_h} \nabla\times\boldsymbol{h}_h^{\boldsymbol{a}}$
  $= \sum_{\boldsymbol{a}\in\mathcal{V}_h} (\psi^{\boldsymbol{a}}\boldsymbol{j} + \nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)) = \boldsymbol{j}$

Patchwise equilibrated fluxes

Continuous level

- $\boldsymbol{A} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$ satisfies $(\nabla\times\boldsymbol{A}, \nabla\times\boldsymbol{v}) = (\boldsymbol{j}, \boldsymbol{v})\ \forall \boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$.
- Thus $\nabla\times\boldsymbol{A} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ with $\nabla\times(\nabla\times\boldsymbol{A}) = \boldsymbol{j}$.
- Take $\boldsymbol{h}^{\boldsymbol{a}} := \psi^{\boldsymbol{a}}(\nabla\times\boldsymbol{A}) \in \boldsymbol{H}_0(\mathrm{curl}, \omega_{\boldsymbol{a}})$ and note that $\sum_{\boldsymbol{a}\in\mathcal{V}_h} \boldsymbol{h}^{\boldsymbol{a}} = \nabla\times\boldsymbol{A}$.
- Rewritten implicitly,

$$\boldsymbol{h}^{\boldsymbol{a}} = \arg \min_{\substack{\boldsymbol{v}\in\boldsymbol{H}_0(\mathrm{curl},\omega_{\boldsymbol{a}})\\ \nabla\times\boldsymbol{v}=\boldsymbol{j}^{\boldsymbol{a}}}} \|\psi^{\boldsymbol{a}}(\nabla\times\boldsymbol{A})-\boldsymbol{v}\|^2_{\omega_{\boldsymbol{a}}}$$

with

$$\boldsymbol{j}^{\boldsymbol{a}} := \psi^{\boldsymbol{a}}\boldsymbol{j} + \nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}).$$

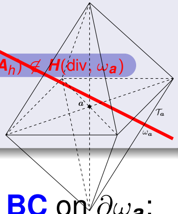
Definition (Chaumont-Frelet, Vohralík (2022))

For each vertex $\boldsymbol{a} \in \mathcal{V}_h$, solve the **local constrained minimization pb**

$$\boldsymbol{h}_h^{\boldsymbol{a}} := \arg \min_{\substack{\boldsymbol{v}_h\in\mathcal{N}_{p+1}(\mathcal{T}_{\boldsymbol{a}})\cap\boldsymbol{H}_0(\mathrm{curl},\omega_{\boldsymbol{a}})\\ \nabla\times\boldsymbol{v}_h=\psi^{\boldsymbol{a}}\boldsymbol{j}+\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)}} \|\psi^{\boldsymbol{a}}(\nabla\times\boldsymbol{A}_h)-\boldsymbol{v}_h\|^2_{\omega_{\boldsymbol{a}}}$$

▸ $\psi^{\boldsymbol{a}}\boldsymbol{j} \in \mathcal{RT}_{p+1}(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}_0(\mathrm{div}, \omega_{\boldsymbol{a}})$ but $\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h) \not\in \boldsymbol{H}(\mathrm{div}, \omega_{\boldsymbol{a}})$

$$\boldsymbol{h}_h := \sum_{\boldsymbol{a}\in\mathcal{V}_h} \boldsymbol{h}_h^{\boldsymbol{a}}.$$



Key points

- **homogeneous tangential BC** on $\partial\omega_{\boldsymbol{a}}$: $\boldsymbol{h}_h \in \mathcal{N}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}(\mathrm{curl}, \Omega)$
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$$= \sum_{\boldsymbol{a}\in\mathcal{V}_h} (\psi^{\boldsymbol{a}}\boldsymbol{j} + \nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)) = \boldsymbol{j}$$

Stage 1: Raviart–Thomas projection

Projection of $\nabla\psi^{\mathbf{a}}\times(\nabla\times\boldsymbol{A}_h)$ to a Raviart–Thomas space

For all vertices $\mathbf{a}\in\mathcal{V}_h$, consider $p' := \min\{p,1\}$-degree patchwise minimizations:

$$\boldsymbol{\theta}_h^{\mathbf{a}} := \arg \min_{\substack{\boldsymbol{v}_h\in\mathcal{RT}_{p'}(\mathcal{T}_{\mathbf{a}})\cap\boldsymbol{H}_0(\mathrm{div},\omega_{\mathbf{a}})\\ \nabla\cdot\boldsymbol{v}_h=-\nabla\psi^{\mathbf{a}}\cdot\boldsymbol{j}\\ (\boldsymbol{v}_h,\boldsymbol{r}_h)_K=(\nabla\psi^{\mathbf{a}}\times(\nabla\times\boldsymbol{A}_h),\boldsymbol{r}_h)_K \quad \forall\boldsymbol{r}_h\in[\mathcal{P}_0(K)]^3,\,\forall K\in\mathcal{T}_{\mathbf{a}}}} \|\nabla\psi^{\mathbf{a}}\times(\nabla\times\boldsymbol{A}_h)-\boldsymbol{v}_h\|^2_{\omega_{\mathbf{a}}}.$$

Comments

- $\nabla\psi^{\mathbf{a}}\times(\nabla\times\boldsymbol{A}_h)\notin\mathcal{RT}_{p'}(\mathcal{T}_{\mathbf{a}})\cap\boldsymbol{H}_0(\mathrm{div},\omega_{\mathbf{a}})$
- remainder $\boldsymbol{\delta}_h := \sum_{\mathbf{a}\in\mathcal{V}_h}\boldsymbol{\theta}_h^{\mathbf{a}}$
  - should be zero ($\sim$ partition of unity $\sum_{\mathbf{a}\in\mathcal{V}_h}\{\nabla\psi^{\mathbf{a}}\times(\nabla\times\boldsymbol{A})\}=0$), but is not
  - $\boldsymbol{\delta}_h\in\mathcal{RT}_{p'}(\mathcal{T}_h)\cap\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div},\Omega)$ and $\nabla\cdot\boldsymbol{\delta}_h=0$
- additional orthogonality constraint
  - crucial for stage 2 below
  - only possible thanks to the lowest-order Galerkin orthogonality of $\boldsymbol{A}_h$
  - requests $\min\{p,1\}$ (and not simply p)

Stage 1: Raviart–Thomas projection

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Comments

- $\nabla\psi^{\mathbf{a}}\times(\nabla\times\boldsymbol{A}_h)\notin\mathcal{RT}_{p'}(\mathcal{T}_{\mathbf{a}})\cap\boldsymbol{H}_0(\mathrm{div},\omega_{\mathbf{a}})$
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  - only possible thanks to the lowest-order Galerkin orthogonality of $\boldsymbol{A}_h$
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Stage 1: Raviart–Thomas projection

Projection of $\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)$ to a Raviart–Thomas space

For all vertices $\boldsymbol{a}\in\mathcal{V}_h$, *consider* $p' := \min\{p,1\}$*-degree patchwise minimizations:*

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Comments

- $\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)\notin\mathcal{RT}_{p'}(\mathcal{T}_{\boldsymbol{a}})\cap\boldsymbol{H}_0(\mathrm{div},\omega_{\boldsymbol{a}})$
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  - should be zero ($\sim$ partition of unity $\sum_{\boldsymbol{a}\in\mathcal{V}_h}\{\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A})\}=0$), but is not
  - $\boldsymbol{\delta}_h\in\mathcal{RT}_{p'}(\mathcal{T}_h)\cap\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div},\Omega)$ and $\nabla\cdot\boldsymbol{\delta}_h=0$
- additional orthogonality constraint
  - crucial for stage 2 below
  - only possible thanks to the lowest-order Galerkin orthogonality of $\boldsymbol{A}_h$
  - requests $\min\{p,1\}$ (and not simply p)

Stage 1: overconstrained Raviart–Thomas projection

Projection of $\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)$ to a Raviart–Thomas space

For all vertices $\boldsymbol{a}\in\mathcal{V}_h$, *consider* $p' := \min\{p,1\}$*-degree patchwise minimizations:*

$$\boldsymbol{\theta}_h^{\boldsymbol{a}} := \arg \min_{\substack{\boldsymbol{v}_h\in\mathcal{RT}_{p'}(\mathcal{T}_{\boldsymbol{a}})\cap\boldsymbol{H}_0(\mathrm{div},\omega_{\boldsymbol{a}})\\ \nabla\cdot\boldsymbol{v}_h=-\nabla\psi^{\boldsymbol{a}}\cdot\boldsymbol{j}\\ (\boldsymbol{v}_h,\boldsymbol{r}_h)_K=(\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h),\boldsymbol{r}_h)_K\quad\forall\boldsymbol{r}_h\in[\mathcal{P}_0(K)]^3,\forall K\in\mathcal{T}_{\boldsymbol{a}}}} \|\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)-\boldsymbol{v}_h\|^2_{\omega_{\boldsymbol{a}}}.$$

Comments

- $\nabla\psi^{\boldsymbol{a}}\times(\nabla\times\boldsymbol{A}_h)\notin\mathcal{RT}_{p'}(\mathcal{T}_{\boldsymbol{a}})\cap\boldsymbol{H}_0(\mathrm{div},\omega_{\boldsymbol{a}})$
- remainder $\boldsymbol{\delta}_h := \sum_{\boldsymbol{a}\in\mathcal{V}_h}\boldsymbol{\theta}_h^{\boldsymbol{a}}$
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  - $\boldsymbol{\delta}_h\in\mathcal{RT}_{p'}(\mathcal{T}_h)\cap\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div},\Omega)$ and $\nabla\cdot\boldsymbol{\delta}_h=0$
- additional orthogonality constraint
  - crucial for stage 2 below
  - only possible thanks to the lowest-order Galerkin orthogonality of $\boldsymbol{A}_h$
  - requests $\min\{p,1\}$ (and not simply p)

Stage 2: **divergence-free decomposition** of the given divergence-free Raviart–Thomas piecewise polynomial $\boldsymbol{\delta}_h$

Divergence-free decomposition of $\boldsymbol{\delta}_h$

For all tetrahedra $K \in \mathcal{T}_h$, consider $(p+1)$-degree elementwise minimizations:

$$\boldsymbol{\delta}_h^{\boldsymbol{a}}|_K := \arg \min_{\substack{\boldsymbol{v}_h \in \mathcal{RT}_1(K) \\ \nabla\cdot\boldsymbol{v}_h = 0 \\ \boldsymbol{v}_h\cdot\boldsymbol{n}_K = \boldsymbol{I}^1_{\mathcal{RT}}(\psi^{\boldsymbol{a}}\boldsymbol{\delta}_h)\cdot\boldsymbol{n}_K \text{ on } \partial K}} \|\boldsymbol{v}_h - \boldsymbol{I}^1_{\mathcal{RT}}(\psi^{\boldsymbol{a}}\boldsymbol{\delta}_h)\|_K^2 \quad \forall \boldsymbol{a} \in \mathcal{V}_K \ \text{ when } p = 0,$$

$$\boldsymbol{\delta}_h^{\boldsymbol{a}}|_K := \arg \min_{\substack{\boldsymbol{v}_h \in \mathcal{RT}_{p+1}(K) \\ \nabla\cdot\boldsymbol{v}_h = 0 \\ \boldsymbol{v}_h\cdot\boldsymbol{n}_K = \psi^{\boldsymbol{a}}\boldsymbol{\delta}_h\cdot\boldsymbol{n}_K \text{ on } \partial K}} \|\boldsymbol{v}_h - \psi^{\boldsymbol{a}}\boldsymbol{\delta}_h\|_K^2 \quad \forall \boldsymbol{a} \in \mathcal{V}_K \ \text{ when } p \geq 1.$$

Comments

- patchwise contributions

$$\boldsymbol{\delta}_h^{\boldsymbol{a}} \in \mathcal{RT}_{p+1}(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}_0(\mathrm{div}, \omega_{\boldsymbol{a}}) \quad \text{and} \quad \nabla\cdot\boldsymbol{\delta}_h^{\boldsymbol{a}} = 0 \qquad \forall \boldsymbol{a} \in \mathcal{V}_h$$

- $\boldsymbol{\delta}_h^{\boldsymbol{a}}$ form a divergence-free decomposition of $\boldsymbol{\delta}_h$, $\boldsymbol{\delta}_h = \sum \boldsymbol{\delta}_h^{\boldsymbol{a}}$

Stage 2: **divergence-free decomposition** of the given divergence-free Raviart–Thomas piecewise polynomial $\boldsymbol{\delta}_h$

Divergence-free decomposition of $\boldsymbol{\delta}_h$

For all tetrahedra $K \in \mathcal{T}_h$, consider $(p+1)$-degree elementwise minimizations:

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- $\boldsymbol{\delta}_h^{\boldsymbol{a}}$ form a **divergence-free decomposition** of $\boldsymbol{\delta}_h$, $\boldsymbol{\delta}_h = \sum_{\boldsymbol{a} \in \mathcal{V}_h} \boldsymbol{\delta}_h^{\boldsymbol{a}}$

Stage 2: **divergence-free decomposition** of the given divergence-free Raviart–Thomas piecewise polynomial δ_h

Divergence-free decomposition of δ_h

For all tetrahedra $K \in \mathcal{T}_h$, consider $(p+1)$-degree elementwise minimizations:

$$\delta_h^{\mathbf{a}}|_K := \arg \min_{\substack{\mathbf{v}_h \in \mathcal{RT}_1(K)\\ \nabla\cdot\mathbf{v}_h = 0\\ \mathbf{v}_h\cdot\mathbf{n}_K = \mathbf{I}^1_{\mathcal{RT}}(\psi^{\mathbf{a}}\delta_h)\cdot\mathbf{n}_K \text{ on } \partial K}} \|\mathbf{v}_h - \mathbf{I}^1_{\mathcal{RT}}(\psi^{\mathbf{a}}\delta_h)\|_K^2 \quad \forall \mathbf{a} \in \mathcal{V}_K \text{ when } p = 0,$$

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Comments

- patchwise contributions

$$\delta_h^{\mathbf{a}} \in \mathcal{RT}_{p+1}(\mathcal{T}_{\mathbf{a}}) \cap \mathbf{H}_0(\mathrm{div}, \omega_{\mathbf{a}}) \quad \text{and} \quad \nabla\cdot\delta_h^{\mathbf{a}} = 0 \qquad \forall \mathbf{a} \in \mathcal{V}_h$$

- $\delta_h^{\mathbf{a}}$ form a **divergence-free decomposition** of δ_h, $\delta_h = \sum_{\mathbf{a}\in\mathcal{V}_h} \delta_h^{\mathbf{a}}$

Stage 2: **divergence-free decomposition** of the given divergence-free Raviart–Thomas piecewise polynomial δ_h

Divergence-free decomposition of δ_h

For all tetrahedra $K \in \mathcal{T}_h$, consider $(p+1)$-degree elementwise minimizations:

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Comments

- patchwise contributions

$$\delta_h^{\boldsymbol{a}} \in \mathcal{RT}_{p+1}(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}_0(\mathrm{div}, \omega_{\boldsymbol{a}}) \quad \text{and} \quad \nabla \cdot \delta_h^{\boldsymbol{a}} = 0 \qquad \forall \boldsymbol{a} \in \mathcal{V}_h$$

- $\delta_h^{\boldsymbol{a}}$ form a **divergence-free decomposition** of δ_h, $\delta_h = \sum_{\boldsymbol{a} \in \mathcal{V}_h} \delta_h^{\boldsymbol{a}}$

Stage 2: divergence-free decomposition of the given divergence-free current density $\boldsymbol{j}$

Divergence-free decomposition of the current density $\boldsymbol{j}$

Set

$$\boldsymbol{j}_h^{\boldsymbol{a}} := \psi^{\boldsymbol{a}} \boldsymbol{j} + \boldsymbol{\theta}_h^{\boldsymbol{a}} - \boldsymbol{\delta}_h^{\boldsymbol{a}}.$$

Then

$$\begin{aligned} \boldsymbol{j}_h^{\boldsymbol{a}} &\in \mathcal{RT}_{p+1}(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}_0(\mathrm{div}, \omega_{\boldsymbol{a}}), \\ \nabla \cdot \boldsymbol{j}_h^{\boldsymbol{a}} &= 0, \\ \sum_{\boldsymbol{a} \in \mathcal{V}_h} \boldsymbol{j}_h^{\boldsymbol{a}} &= \boldsymbol{j}. \end{aligned}$$

Stage 3: discrete patchwise equilibrated fluxes

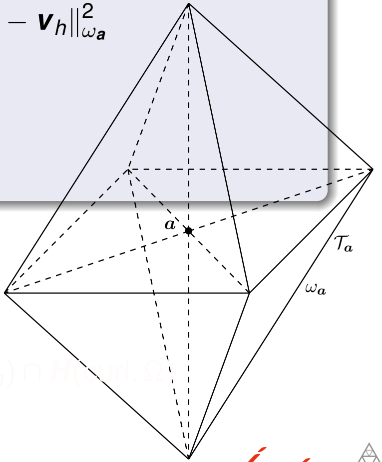
Definition (Chaumont-Frelet, Vohralík (2021))

For each vertex $\boldsymbol{a} \in \mathcal{V}_h$, solve the **local constrained minimization problem**

$$\boldsymbol{h}_h^{\boldsymbol{a}} := \arg \min_{\substack{\boldsymbol{v}_h \in \boldsymbol{\mathcal{N}}_{p+1}(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}_0(\mathrm{curl},\omega_{\boldsymbol{a}}) \\ \nabla\times\boldsymbol{v}_h = \boldsymbol{j}_h^{\boldsymbol{a}}}} \|\psi^{\boldsymbol{a}}(\nabla\times\boldsymbol{A}_h) - \boldsymbol{v}_h\|^2_{\omega_{\boldsymbol{a}}}$$

and combine

$$\boldsymbol{h}_h := \sum_{\boldsymbol{a}\in\mathcal{V}_h} \boldsymbol{h}_h^{\boldsymbol{a}}.$$



Key points

- **homogeneous tangential BC** on $\partial\omega_{\boldsymbol{a}}$: $\boldsymbol{h}_h \in \boldsymbol{\mathcal{N}}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}(\mathrm{curl},\Omega)$
- **global equilibrium** $\nabla\times\boldsymbol{h}_h = \sum_{\boldsymbol{a}\in\mathcal{V}_h} \nabla\times\boldsymbol{h}_h^{\boldsymbol{a}} = \sum_{\boldsymbol{a}\in\mathcal{V}_h} \boldsymbol{j}_h^{\boldsymbol{a}} = \boldsymbol{j}$

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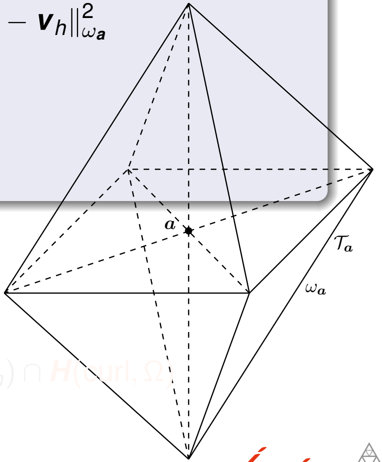

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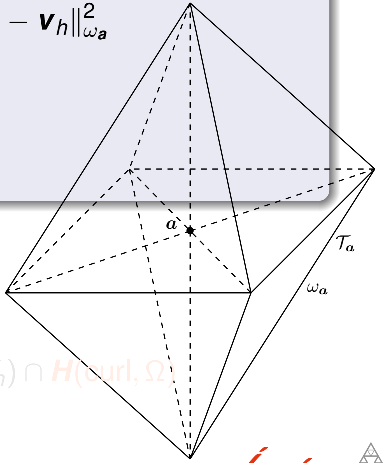

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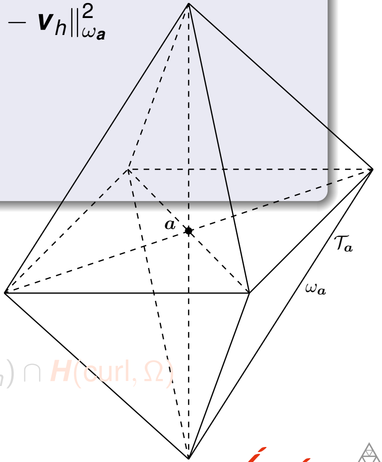

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Stage 3: discrete patchwise equilibrated fluxes

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For each vertex $\boldsymbol{a} \in \mathcal{V}_h$, solve the **local constrained minimization problem**

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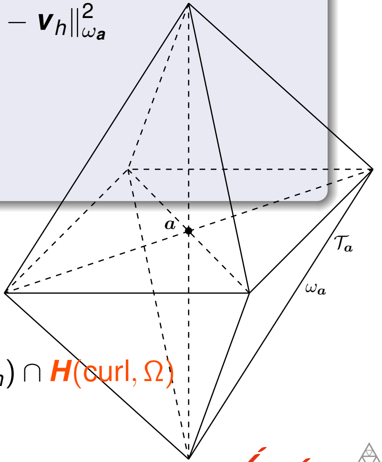
and combine

$$\boldsymbol{h}_h := \sum_{\boldsymbol{a} \in \mathcal{V}_h} \boldsymbol{h}_h^{\boldsymbol{a}}.$$



Key points

- **homogeneous tangential BC** on $\partial\omega_{\boldsymbol{a}}$: $\boldsymbol{h}_h \in \boldsymbol{\mathcal{N}}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}(\mathrm{curl}, \Omega)$
- **global equilibrium** $\nabla \times \boldsymbol{h}_h = \sum_{\boldsymbol{a} \in \mathcal{V}_h} \nabla \times \boldsymbol{h}_h^{\boldsymbol{a}} = \sum_{\boldsymbol{a} \in \mathcal{V}_h} \boldsymbol{j}_h^{\boldsymbol{a}} = \boldsymbol{j}$

Outline

A posteriori error estimates

Weak formulation (consequence)

$\boldsymbol{A} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$ *satisfies*

$$(\nabla \times \boldsymbol{A}, \nabla \times \boldsymbol{v}) = (\boldsymbol{j}, \boldsymbol{v}) \qquad \forall \boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$$

Primal Nédélec approximation

$\boldsymbol{V}_h := \mathcal{N}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{D}}(\mathrm{curl}, \Omega)$, $p \geq 0$; $\boldsymbol{A}_h \in \boldsymbol{V}_h$ *such that*

$$(\nabla \times \boldsymbol{A}_h, \nabla \times \boldsymbol{v}_h) = (\boldsymbol{j}, \boldsymbol{v}_h) \qquad \forall \boldsymbol{v}_h \in \boldsymbol{V}_h$$

$\boldsymbol{h}_h \in \mathcal{N}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ s.t. $\nabla \times \boldsymbol{h}_h = \boldsymbol{j}$: local equilibrated flux reconstruction

Theorem (Guaranteed upper bound,)

$$\underbrace{\|\nabla \times (\boldsymbol{A} - \boldsymbol{A}_h)\|}_{\text{unknown error}} \leq \underbrace{\|\nabla \times \boldsymbol{A}_h - \boldsymbol{h}_h\|}_{\text{computable estimator}} \lesssim \underbrace{\|\nabla \times (\boldsymbol{A} - \boldsymbol{A}_h)\|}_{\text{unknown error}}$$

- $\lesssim$: only depends on the shape-regularity $\kappa_{\mathcal{T}_h}$

A posteriori error estimates

Weak formulation (consequence)

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Theorem (Guaranteed upper bound, efficiency, and p-robustness)

$$\underbrace{\|\nabla \times (\boldsymbol{A} - \boldsymbol{A}_h)\|}_{\text{unknown error}} \leq \underbrace{\|\nabla \times \boldsymbol{A}_h - \boldsymbol{h}_h\|}_{\text{computable estimator}} \lesssim \underbrace{\|\nabla \times (\boldsymbol{A} - \boldsymbol{A}_h)\|}_{\text{unknown error}}$$

- $\lesssim$: only depends on the shape-regularity $\kappa_{\mathcal{T}_h}$

A posteriori error estimates

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$\boldsymbol{h}_h \in \mathcal{N}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ s.t. $\nabla\times\boldsymbol{h}_h = \boldsymbol{j}$: local equilibrated flux reconstruction

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A posteriori error estimates

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Primal Nédélec approximation

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$$(\nabla\times\boldsymbol{A}_h, \nabla\times\boldsymbol{v}_h) = (\boldsymbol{j}, \boldsymbol{v}_h) \qquad \forall \boldsymbol{v}_h \in \boldsymbol{V}_h$$

$\boldsymbol{h}_h \in \mathcal{N}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ s.t. $\nabla\times\boldsymbol{h}_h = \boldsymbol{j}$: local equilibrated flux reconstruction

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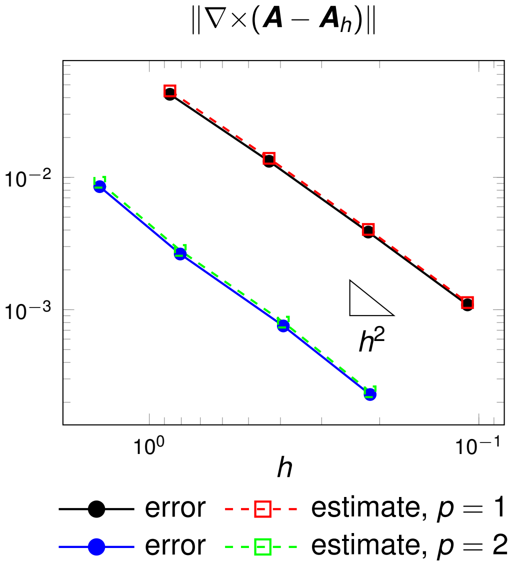
$\boldsymbol{h}_h \in \mathcal{N}_{p+1}(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ s.t. $\nabla\times\boldsymbol{h}_h = \boldsymbol{j}$: local equilibrated flux reconstruction

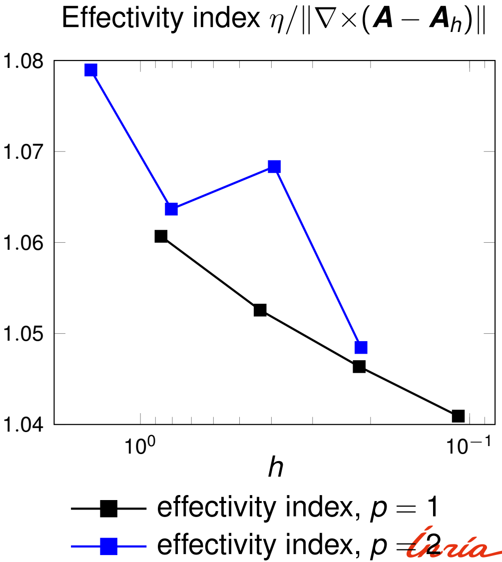
Theorem (Guaranteed upper bound, efficiency, and *p*-robustness)

$$\underbrace{\|\nabla\times(\boldsymbol{A} - \boldsymbol{A}_h)\|}_{\textit{unknown error}} \leq \underbrace{\|\nabla\times\boldsymbol{A}_h - \boldsymbol{h}_h\|}_{\textit{computable estimator}} \lesssim \underbrace{\|\nabla\times(\boldsymbol{A} - \boldsymbol{A}_h)\|}_{\textit{unknown error}}$$

- $\lesssim$: only depends on the shape-regularity $\kappa_{\mathcal{T}_h}$

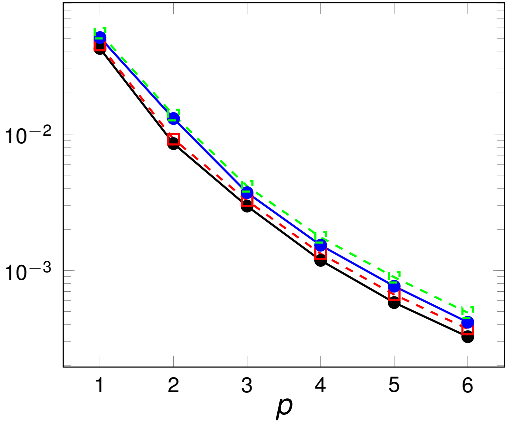
H^3 solution, uniform h-refinement



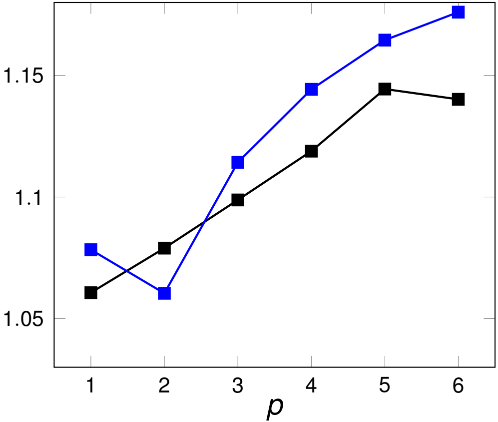


H^3 solution, uniform p-refinement

$\|\nabla\times(\boldsymbol{A}-\boldsymbol{A}_h)\|$



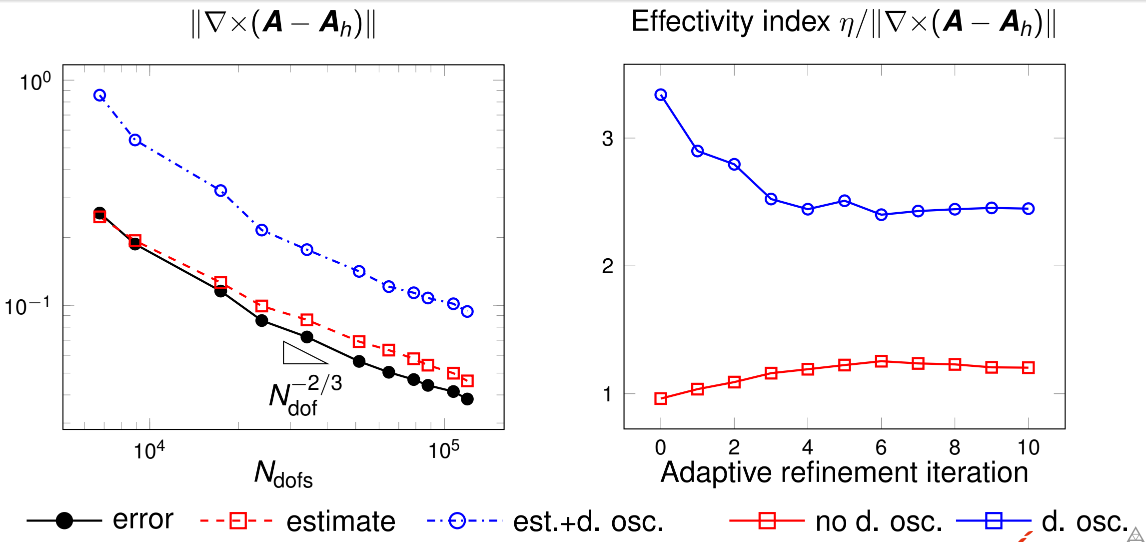
Effectivity index $\eta/\|\nabla\times(\boldsymbol{A}-\boldsymbol{A}_h)\|$



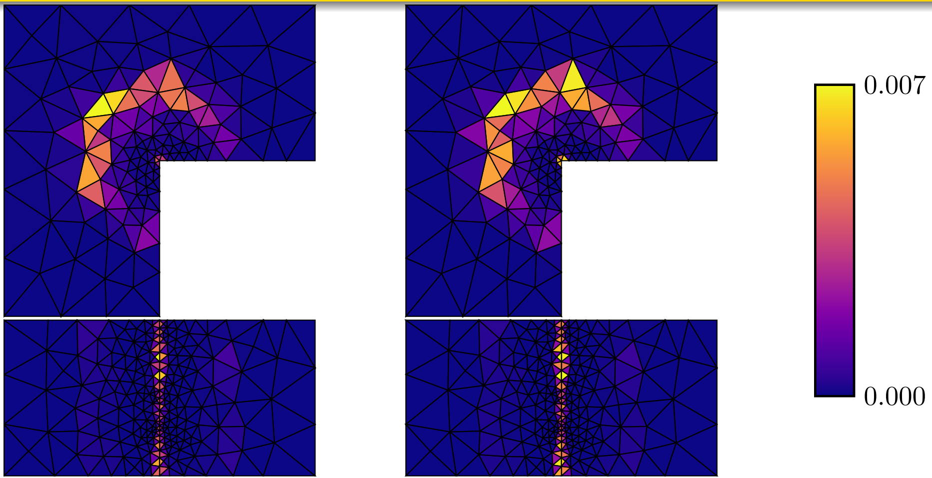
error — estimate, struct. mesh — effectivity index, struct. mesh

error — estimate, unstruct. mesh — effectivity index, unstruct. mesh

Singular solution, adaptive mesh refinement ($p = 2$)



Singular solution, adaptive mesh refinement ($p = 2$)



Estimators (left) and actual error (right), adaptive mesh refinement iteration #10.
Top view (top) and side view (bottom)

Outline

Commuting de Rham diagram with operator $\boldsymbol{P}_h^{p,\mathrm{curl}}$

Commuting de Rham diagram

$$
\begin{array}{ccccccc}
H^1_{0,\mathrm{N}}(\Omega) & \xrightarrow{\nabla} & \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega) & \xrightarrow{\nabla\times} & \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div},\Omega) & \xrightarrow{\nabla\cdot} & L^2_*(\Omega) \\
\downarrow P_h^{p+1,\mathrm{grad}} & & \downarrow \boldsymbol{P}_h^{p,\mathrm{curl}} & & \downarrow \boldsymbol{P}_h^{p,\mathrm{div}} & & \downarrow \Pi_h^p \\
\mathcal{P}_{p+1}(\mathcal{T}_h)\cap H^1_{0,\mathrm{N}}(\Omega) & \xrightarrow{\nabla} & \mathcal{N}_p(\mathcal{T}_h)\cap\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega) & \xrightarrow{\nabla\times} & \mathcal{RT}_p(\mathcal{T}_h)\cap\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div},\Omega) & \xrightarrow{\nabla\cdot} & \mathcal{P}_p(\mathcal{T}_h)\cap L^2_*(\Omega)
\end{array}
$$

Commuting de Rham diagram with operator $\boldsymbol{P}_h^{p,\mathrm{curl}}$

Commuting de Rham diagram

$$
\begin{array}{ccccccc}
H^1_{0,\mathrm{N}}(\Omega) & \xrightarrow{\nabla} & \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega) & \xrightarrow{\nabla\times} & \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div},\Omega) & \xrightarrow{\nabla\cdot} & L^2_*(\Omega) \\
\downarrow P_h^{p+1,\mathrm{grad}} & & \downarrow \boldsymbol{P}_h^{p,\mathrm{curl}} & & \downarrow \boldsymbol{P}_h^{p,\mathrm{div}} & & \downarrow \Pi_h^p \\
\mathcal{P}_{p+1}(\mathcal{T}_h)\cap H^1_{0,\mathrm{N}}(\Omega) & \xrightarrow{\nabla} & \mathcal{N}_p(\mathcal{T}_h)\cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega) & \xrightarrow{\nabla\times} & \mathcal{RT}_p(\mathcal{T}_h)\cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{div},\Omega) & \xrightarrow{\nabla\cdot} & \mathcal{P}_p(\mathcal{T}_h)\cap L^2_*(\Omega)
\end{array}
$$

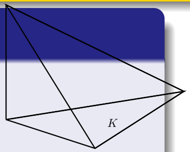
Properties of $\boldsymbol{P}_h^{p,\mathrm{curl}}$

1. is defined over the **entire $\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega)$** (**minimal regularity**)
2. is defined **locally** (in neighborhood of mesh elements)
3. is defined simply (starting from the **elementwise L^2 orthogonal projection**)
4. has optimal approximation properties, that of **elementwise curl-unconstrained L^2-orthogonal projector** (local–global equivalence)
5. is **stable in $L^2(\Omega)$** (up to data oscillation)
6. satisfies the **commuting properties** expressed by the arrows
7. is **projector**, i.e., leaves intact piecewise polynomials

Stable local commuting projectors defined on $\boldsymbol{H}(\mathrm{div})/\boldsymbol{H}(\mathrm{curl})$

- Schöberl (2001, 2005): not local
- Christiansen and Winther (2008): not local
- Bespalov and Heuer (2011): low regularity but still not $\boldsymbol{H}(\mathrm{div})/\boldsymbol{H}(\mathrm{curl})$
- Falk and Winther (2014): local and $\boldsymbol{H}(\mathrm{div})/\boldsymbol{H}(\mathrm{curl})$-stable but not $\boldsymbol{L}^2$-stable
- Ern and Guermond (2016): not local
- Ern and Guermond (2017): $\boldsymbol{H}(\mathrm{div})/\boldsymbol{H}(\mathrm{curl})$ regularity but not commuting
- Licht (2019): essential boundary conditions on part of $\partial\Omega$
- Arnold and Guzmán (2021): $\boldsymbol{L}^2$-stable
- Ern, Gudi, Smears, and Vohralík (2022): all the above properties in $\boldsymbol{H}(\mathrm{div})$

A stable local commuting projector $\boldsymbol{P}_h^{p,\mathrm{curl}}$



Definition (A stable local commuting projector $\boldsymbol{P}_h^{p,\mathrm{curl}}$)

Let $\boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ be given (minimal regularity).

1. For each $K \in \mathcal{T}_h$, prepare the datum $\boldsymbol{\tau}_h|_K$

$$\boldsymbol{\tau}_h|_K := \arg \min_{\substack{\boldsymbol{w}_h \in \mathcal{RT}_p(K) \\ \nabla \cdot \boldsymbol{w}_h = 0}} \|\nabla \times \boldsymbol{v} - \boldsymbol{w}_h\|_K$$

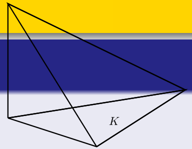
and define $\boldsymbol{\iota}_h|_K$ by the **elementwise (constrained) projection**

$$\boldsymbol{\iota}_h|_K := \arg \min_{\substack{\boldsymbol{v}_h \in \mathcal{N}_p(K) \\ \nabla \times \boldsymbol{v}_h = \boldsymbol{\tau}_h}} \|\boldsymbol{v} - \boldsymbol{v}_h\|_K$$

(discrete but nonconforming (tangential-trace discontinuous)).

2. Obtain $\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}) \in \mathcal{N}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ by applying the **flux equilibration procedure** to $\boldsymbol{\iota}_h$; in particular, $\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}) := \boldsymbol{h}_h := \sum_{\boldsymbol{a} \in \mathcal{V}_h} \boldsymbol{h}_h^{\boldsymbol{a}}$, where $\boldsymbol{h}_h^{\boldsymbol{a}}$ are obtained by local energy minimizations on the patch subdomains $\omega_{\boldsymbol{a}}$.

A stable local commuting projector $P_h^{p,\mathrm{curl}}$



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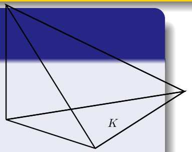
A stable local commuting projector $\boldsymbol{P}_h^{p,\mathrm{curl}}$



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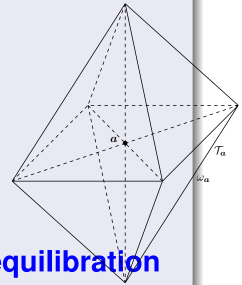

2. Obtain $\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}) \in \boldsymbol{\mathcal{N}}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ by applying the **flux equilibration procedure** to $\boldsymbol{\iota}_h$; in particular, $\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}) := \boldsymbol{h}_h := \sum_{\boldsymbol{a}\in\mathcal{V}_h} \boldsymbol{h}_h^{\boldsymbol{a}}$, where $\boldsymbol{h}_h^{\boldsymbol{a}}$ are obtained by local energy minimizations on the patch subdomains $\omega_{\boldsymbol{a}}$.

A stable local commuting projector $\boldsymbol{P}_h^{p,\mathrm{curl}}$

Theorem (A stable local commuting projector $\boldsymbol{P}_h^{p,\mathrm{curl}}$)

$\boldsymbol{P}_h^{p,\mathrm{curl}}$ *is a* **commuting projector** *since*

$$\nabla\times\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}) = \boldsymbol{P}_h^{p,\mathrm{div}}(\nabla\times\boldsymbol{v}) \qquad \forall \boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega),$$

$$\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}) = \boldsymbol{v} \qquad \forall \boldsymbol{v} \in \mathcal{N}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega).$$

Moreover, it has **local-best approximation properties** *and is* **L^2 stable** *up to data oscillation, since, for all* $\boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega)$ *and* $K \in \mathcal{T}_h$,

$$\|\boldsymbol{v} - \boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v})\|_K^2 + \left(\frac{h_K}{p+1}\|\nabla\times(\boldsymbol{v} - \boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}))\|_K\right)^2$$

$$\lesssim_p \sum_{K'\in\mathcal{T}_K}\left\{\min_{\boldsymbol{v}_h\in\mathcal{N}_p(K')}\|\boldsymbol{v}-\boldsymbol{v}_h\|_{K'}^2 + \left(\frac{h_{K'}}{p+1}\|\nabla\times\boldsymbol{v} - \boldsymbol{\Pi}_{\mathcal{RT}}^p(\nabla\times\boldsymbol{v})\|_{K'}\right)^2\right\},$$

$$\|\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v})\|_K^2 \lesssim_p \sum_{K'\in\mathcal{T}_K}\left\{\|\boldsymbol{v}\|_{K'}^2 + \left(\frac{h_{K'}}{p+1}\|\nabla\times\boldsymbol{v} - \boldsymbol{\Pi}_{\mathcal{RT}}^p(\nabla\times\boldsymbol{v})\|_{K'}\right)^2\right\}.$$

A stable local commuting projector $\boldsymbol{P}_h^{p,\mathrm{curl}}$

Theorem (A stable local commuting projector $\boldsymbol{P}_h^{p,\mathrm{curl}}$)

$\boldsymbol{P}_h^{p,\mathrm{curl}}$ *is a* **commuting projector** *since*

$$\nabla\times\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}) = \boldsymbol{P}_h^{p,\mathrm{div}}(\nabla\times\boldsymbol{v}) \qquad \forall \boldsymbol{v}\in\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega),$$

$$\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}) = \boldsymbol{v} \qquad \forall \boldsymbol{v}\in\mathcal{N}_p(\mathcal{T}_h)\cap\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega).$$

Moreover, it has **local-best approximation properties** *and is* **L^2 stable** *up to data oscillation, since, for all $\boldsymbol{v}\in\boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega)$ and $K\in\mathcal{T}_h$,*

$$\|\boldsymbol{v}-\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v})\|_K^2 + \left(\frac{h_K}{p+1}\|\nabla\times(\boldsymbol{v}-\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v}))\|_K\right)^2$$

$$\lesssim_p \sum_{K'\in\mathcal{T}_K}\left\{\min_{\boldsymbol{v}_h\in\mathcal{N}_p(K')}\|\boldsymbol{v}-\boldsymbol{v}_h\|_{K'}^2 + \left(\frac{h_{K'}}{p+1}\|\nabla\times\boldsymbol{v}-\boldsymbol{\Pi}_{\mathcal{RT}}^p(\nabla\times\boldsymbol{v})\|_{K'}\right)^2\right\},$$

$$\|\boldsymbol{P}_h^{p,\mathrm{curl}}(\boldsymbol{v})\|_K^2 \lesssim_p \sum_{K'\in\mathcal{T}_K}\left\{\|\boldsymbol{v}\|_{K'}^2 + \left(\frac{h_{K'}}{p+1}\|\nabla\times\boldsymbol{v}-\boldsymbol{\Pi}_{\mathcal{RT}}^p(\nabla\times\boldsymbol{v})\|_{K'}\right)^2\right\}.$$

Outline

Global-best approximation $\approx$ local-best approximation

Previous contributions

- Carstensen, Peterseim, Schedensack (2012): H^1 (lowest-order case $p = 1$)
- Aurada, Feischl, Kemetmüller, Page, Praetorius (2013): H^1 (boundary approximation context)
- Veeser (2016): H^1 (any p)
- Canuto, Nochetto, Stevenson, and Verani (2017): H^1 (improvement of the dependence of the equivalence constant in 2D)
- Ern, Gudi, Smears, and Vohralík (2022): $\boldsymbol{H}(\mathrm{div})$
- Chaumont-Frelet & Vohralík (2021): $\boldsymbol{H}(\mathrm{curl})$ without data oscillation

Global-best approximation ≈ local-best approximation in $\boldsymbol{H}(\mathrm{curl})$

Theorem (Constrained equivalence in $\boldsymbol{H}(\mathrm{curl})$)

$$\textit{bigger} \approx_p \textit{smaller}$$

Global-best approximation $\approx$ local-best approximation in $\boldsymbol{H}(\mathrm{curl})$

Theorem (Constrained equivalence in $\boldsymbol{H}(\mathrm{curl})$)

$$\min_{\text{smaller space } \textbf{with curl constraints}} \approx_p \min_{\text{bigger space } \textbf{without curl constraints}}$$

Global-best approximation ≈ local-best approximation in $\boldsymbol{H}(\mathrm{curl})$

Theorem (Constrained equivalence in $\boldsymbol{H}(\mathrm{curl})$)

$$\min_{\textit{conforming Nédélec space with curl constraints}} \approx_p \min_{\textit{broken Nédélec space without curl constraints}}$$

Global-best approximation ≈ local-best approximation in $\boldsymbol{H}(\mathrm{curl})$

Theorem (Constrained equivalence in $\boldsymbol{H}(\mathrm{curl})$)

Let $\boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega)$ *and* $p \geq 0$ *be arbitrary. Then,*

$$\underbrace{\min_{\substack{\boldsymbol{v}_h \in \mathcal{N}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega) \\ \nabla\times\boldsymbol{v}_h = \boldsymbol{P}_h^{p,\mathrm{div}}(\nabla\times\boldsymbol{v})}} \|\boldsymbol{v}-\boldsymbol{v}_h\|^2 + \sum_{K\in\mathcal{T}_h}\left(\frac{h_K}{p+1}\|\nabla\times\boldsymbol{v} - \Pi^p_{\mathcal{RT}}(\nabla\times\boldsymbol{v})\|_K\right)^2}_{\substack{\text{global-best on } \Omega \\ \text{tangential-trace-continuity constraint} \\ \text{curl constraint}}}$$

$$\approx_p \sum_{K\in\mathcal{T}_h}\underbrace{\left[\min_{\boldsymbol{v}_h\in\mathcal{N}_p(K)}\|\boldsymbol{v}-\boldsymbol{v}_h\|_K^2 + \left(\frac{h_K}{p+1}\|\nabla\times\boldsymbol{v} - \Pi^p_{\mathcal{RT}}(\nabla\times\boldsymbol{v})\|_K\right)^2\right]}_{\substack{\text{local-best on each } K\in\mathcal{T}_h \\ \text{no tangential-trace-continuity constraint} \\ \text{no curl constraint}}}.$$

- $\approx_p$: only depends on the shape-regularity $\kappa_{\mathcal{T}_h}$ and the polynomial degree p

Global-best approximation ≈ local-best approximation in $\boldsymbol{H}(\mathrm{curl})$

Theorem (Constrained equivalence in $\boldsymbol{H}(\mathrm{curl})$)

Let $\boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ *and* $p \geq 0$ *be arbitrary. Then,*

$$\underbrace{\min_{\substack{\boldsymbol{v}_h \in \mathcal{N}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega) \\ \nabla\times\boldsymbol{v}_h = \boldsymbol{P}_h^{p,\mathrm{div}}(\nabla\times\boldsymbol{v})}} \|\boldsymbol{v} - \boldsymbol{v}_h\|^2 + \sum_{K\in\mathcal{T}_h} \left(\frac{h_K}{p+1} \|\nabla\times\boldsymbol{v} - \Pi_{\mathcal{RT}}^p(\nabla\times\boldsymbol{v})\|_K \right)^2}_{\substack{\text{global-best on } \Omega \\ \text{tangential-trace-continuity constraint} \\ \text{curl constraint}}}$$

$$\approx_p \sum_{K\in\mathcal{T}_h} \underbrace{\left[\min_{\boldsymbol{v}_h \in \mathcal{N}_p(K)} \|\boldsymbol{v} - \boldsymbol{v}_h\|_K^2 + \left(\frac{h_K}{p+1} \|\nabla\times\boldsymbol{v} - \Pi_{\mathcal{RT}}^p(\nabla\times\boldsymbol{v})\|_K \right)^2 \right]}_{\substack{\text{local-best on each } K\in\mathcal{T}_h \\ \text{no tangential-trace-continuity constraint} \\ \text{no curl constraint}}}.$$

- $\approx_p$: only depends on the shape-regularity $\kappa_{\mathcal{T}_h}$ and the polynomial degree p

Global-best approximation ≈ local-best approximation in $\boldsymbol{H}(\mathrm{curl})$

Theorem (Constrained equivalence in $\boldsymbol{H}(\mathrm{curl})$)

Let $\boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ and $p \geq 0$ be arbitrary. Then,

$$\underbrace{\min_{\substack{\boldsymbol{v}_h \in \mathcal{N}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega) \\ \nabla\times\boldsymbol{v}_h = \boldsymbol{P}_h^{p,\mathrm{div}}(\nabla\times\boldsymbol{v})}} \|\boldsymbol{v} - \boldsymbol{v}_h\|^2 + \sum_{K\in\mathcal{T}_h} \left(\frac{h_K}{p+1} \|\nabla\times\boldsymbol{v} - \Pi_{\mathcal{RT}}^p(\nabla\times\boldsymbol{v})\|_K \right)^2}_{\substack{\text{global-best on } \Omega \\ \text{tangential-trace-continuity constraint} \\ \text{curl constraint}}}$$

$$\approx_p \sum_{K\in\mathcal{T}_h} \underbrace{\left[\min_{\boldsymbol{v}_h \in \mathcal{N}_p(K)} \|\boldsymbol{v} - \boldsymbol{v}_h\|_K^2 + \left(\frac{h_K}{p+1} \|\nabla\times\boldsymbol{v} - \Pi_{\mathcal{RT}}^p(\nabla\times\boldsymbol{v})\|_K \right)^2 \right]}_{\substack{\text{local-best on each } K \in \mathcal{T}_h \\ \text{no tangential-trace-continuity constraint} \\ \text{no curl constraint}}}.$$

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Outline

Approximation error estimates: context

h approximation estimate

Let $\boldsymbol{v} \in \boldsymbol{H}(\mathrm{curl}, \Omega) \cap \boldsymbol{H}^s(\Omega)$, $s > 1/2$. *Then*

$$\min_{\boldsymbol{v}_h \in \boldsymbol{\mathcal{N}}_p(\mathcal{T}_h) \cap \boldsymbol{H}(\mathrm{curl},\Omega)} \|\boldsymbol{v} - \boldsymbol{v}_h\| \leq C(\kappa_{\mathcal{T}_h}, s, p) \quad h^{\min\{p+1,s\}} \|\boldsymbol{v}\|_{\boldsymbol{H}^s(\Omega)}.$$

- Nédélec (1980), Hiptmair (2002), Boffi, Brezzi, Fortin (2013)
- Monk (1994, rectangular meshes)

Approximation error estimates: context

h approximation estimate

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Approximation error estimates: context

hp approximation estimate

Let $\boldsymbol{v} \in \boldsymbol{H}(\mathrm{curl}, \Omega) \cap \boldsymbol{H}^s(\Omega)$, $s > 1$. *Then*

$$\min_{\boldsymbol{v}_h \in \mathcal{N}_p(\mathcal{T}_h) \cap \boldsymbol{H}(\mathrm{curl},\Omega)} \|\boldsymbol{v} - \boldsymbol{v}_h\| \leq C(\kappa_{\mathcal{T}_h}, s, \cancel{p}) \cancel{\ln(p)} \frac{h^{\min\{p+1,s\}}}{(p+1)^s} \|\boldsymbol{v}\|_{\boldsymbol{H}^s(\Omega)}.$$

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Approximation error estimates

Theorem (Local *hp*-optimal approximation under minimal Sobolev regularity)

Let $\boldsymbol{v} \in \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl}, \Omega)$ *with*

$$\boldsymbol{v}|_K \in \boldsymbol{H}^s(K), \quad (\nabla \times \boldsymbol{v})|_K \in \boldsymbol{H}^t(K) \qquad \forall K \in \mathcal{T}_h$$

for $s \geq 0$ *and* $s \geq t \geq \max\{0, s-1\}$. *Then*

$$\min_{\boldsymbol{v}_h \in \mathcal{N}_p(\mathcal{T}_h) \cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega)} \left[\|\boldsymbol{v} - \boldsymbol{v}_h\|^2 + \sum_{K \in \mathcal{T}_h} \left(\frac{h_K}{p+1} \|\nabla \times (\boldsymbol{v} - \boldsymbol{v}_h)\|_K \right)^2 \right]$$

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Comments

- *hp* case: $\Gamma_{\mathrm{D}} = \emptyset$ and convex patch subdomains $\omega_{\boldsymbol{a}}$ for all vertices

Approximation error estimates

Theorem (Local *hp-optimal* approximation under minimal Sobolev regularity)

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$$\min_{\boldsymbol{v}_h \in \mathcal{N}_p(\mathcal{T}_h)\cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega)} \left[\|\boldsymbol{v}-\boldsymbol{v}_h\|^2 + \sum_{K\in\mathcal{T}_h}\left(\frac{h_K}{p+1}\|\nabla\times(\boldsymbol{v}-\boldsymbol{v}_h)\|_K\right)^2\right]$$

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$$\min_{\boldsymbol{v}_h \in \boldsymbol{\mathcal{N}}_p(\mathcal{T}_h)\cap \boldsymbol{H}_{0,\mathrm{N}}(\mathrm{curl},\Omega)} \left[\|\boldsymbol{v}-\boldsymbol{v}_h\|^2 + \sum_{K\in\mathcal{T}_h}\left(\frac{h_K}{p+1}\|\nabla\times(\boldsymbol{v}-\boldsymbol{v}_h)\|_K\right)^2\right]$$

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Outline

1. The curl–curl problem and its Nédélec approximation
2. Equilibration in $\boldsymbol{H}$(curl)
3. A posteriori error estimates in $\boldsymbol{H}$(curl)
4. A stable local commuting projector in $\boldsymbol{H}$(curl)
5. Local-best–global-best equivalence in $\boldsymbol{H}$(curl)
6. Approximation error estimates in $\boldsymbol{H}$(curl)
7. Conclusions

Conclusions

Equilibration in $\boldsymbol{H}$(curl):

- guaranteed, locally efficient, and p-robust a posteriori error estimates
- a stable local commuting projector, local-best–global-best equivalence, and local hp approximation (a priori) error estimates under min. Sobolev regularity

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CHAUMONT-FRELET T., VOHRALÍK M. Equivalence of local-best and global-best approximations in ***H***(curl). *Calcolo* **58** (2021), 53.

CHAUMONT-FRELET T., VOHRALÍK M. *p*-robust equilibrated flux reconstruction in ***H***(curl) based on local minimizations. Application to a posteriori analysis of the curl–curl problem. *SIAM Journal on Numerical Analysis* (2023), DOI 10.1137/21M141909X.

CHAUMONT-FRELET T., VOHRALÍK M. Constrained and unconstrained stable discrete minimizations for *p*-robust local reconstructions in vertex patches in the de Rham complex. HAL Preprint 03749682, submitted for publication, 2022.

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Thank you for your attention!

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Thank you for your attention!

Outline

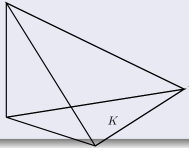
8. Main tool: stable (broken) $\boldsymbol{H}(\mathrm{curl})$ polynomial extensions

9. Local-best–global-best equivalence in H^1 in 1D

$\boldsymbol{H}(\mathrm{curl})$ polynomial extensions on a tetrahedron

Theorem ($\boldsymbol{H}(\mathrm{curl})$ polynomial extension on a single tetrahedron Costabel & Mc-Intosh (2010); Demkowicz, Gopalakrishnan, & Schöberl (2009); Braess, Pillwein, & Schöberl (2009); Chaumont-Frelet, Ern, & Vohralík (2020)**)**

Let $\emptyset \subseteq \mathcal{F} \subseteq \mathcal{F}_K$ be a (sub)set of faces of a tetrahedron K. Then, for every polynomial degree $p \geq 0$, for all $\boldsymbol{r}_K \in \mathcal{RT}_p(K)$ such that $\nabla \cdot \boldsymbol{r}_K = 0$, and for all $\boldsymbol{r}_\mathcal{F} \in \mathcal{N}_p^\tau(\Gamma_\mathcal{F})$ such that $\boldsymbol{r}_K \cdot \boldsymbol{n}_F = \mathrm{curl}_F(\boldsymbol{r}_F)$ for all $F \in \mathcal{F}$, there holds



$$\min_{\substack{\boldsymbol{v}_p \in \mathcal{N}_p(K) \\ \nabla \times \boldsymbol{v}_p = \boldsymbol{r}_K \\ \boldsymbol{v}_p|^\tau_\mathcal{F} = \boldsymbol{r}_\mathcal{F}}} \|\boldsymbol{v}_p\|_K \leq C_{\mathrm{st}} \min_{\substack{\boldsymbol{v} \in \boldsymbol{H}(\mathrm{curl}, K) \\ \nabla \times \boldsymbol{v} = \boldsymbol{r}_K \\ \boldsymbol{v}|^\tau_\mathcal{F} = \boldsymbol{r}_\mathcal{F}}} \|\boldsymbol{v}\|_K.$$

Comments

- C_{st} only depends on the shape-regularity of K
- p-robustness: for (pw) p-polynomial data $\boldsymbol{r}_K$, $\boldsymbol{r}_\mathcal{F}$, minimization over $\mathcal{N}_p(K)$ is up to C_{st} as good as minimization over the entire $\boldsymbol{H}(\mathrm{curl}, K)$
- extension to an edge patch: Chaumont-Frelet, Ern, & Vohralík (2021)
- extension to a vertex patch: Chaumont-Frelet & Vohralík (2022)

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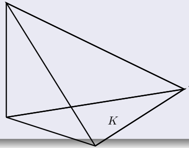

$$\min_{\substack{\boldsymbol{v}_p \in \boldsymbol{\mathcal{N}}_p(K)\\ \nabla\times\boldsymbol{v}_p = \boldsymbol{r}_K\\ \boldsymbol{v}_p|^{\tau}_{\mathcal{F}} = \boldsymbol{r}_{\mathcal{F}}}} \|\boldsymbol{v}_p\|_K \leq C_{\mathrm{st}} \min_{\substack{\boldsymbol{v} \in \boldsymbol{H}(\mathrm{curl},K)\\ \nabla\times\boldsymbol{v} = \boldsymbol{r}_K\\ \boldsymbol{v}|^{\tau}_{\mathcal{F}} = \boldsymbol{r}_{\mathcal{F}}}} \|\boldsymbol{v}\|_K.$$

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$\boldsymbol{H}(\mathrm{curl})$ polynomial extensions on a tetrahedron and on patches

Theorem ($\boldsymbol{H}(\mathrm{curl})$ polynomial extension on a single tetrahedron Costabel & Mc-Intosh (2010); Demkowicz, Gopalakrishnan, & Schöberl (2009); Braess, Pillwein, & Schöberl (2009); Chaumont-Frelet, Ern, & Vohralík (2020)**)**

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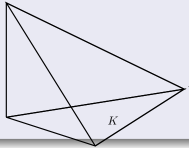
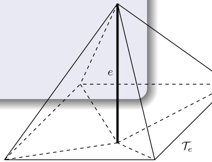


$$\min_{\substack{\boldsymbol{v}_p \in \mathcal{N}_p(K)\\ \nabla\times\boldsymbol{v}_p = \boldsymbol{r}_K\\ \boldsymbol{v}_p|^\tau_\mathcal{F} = \boldsymbol{r}_\mathcal{F}}} \|\boldsymbol{v}_p\|_K \leq C_{\mathrm{st}} \min_{\substack{\boldsymbol{v} \in \boldsymbol{H}(\mathrm{curl},K)\\ \nabla\times\boldsymbol{v} = \boldsymbol{r}_K\\ \boldsymbol{v}|^\tau_\mathcal{F} = \boldsymbol{r}_\mathcal{F}}} \|\boldsymbol{v}\|_K.$$



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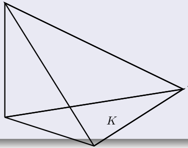

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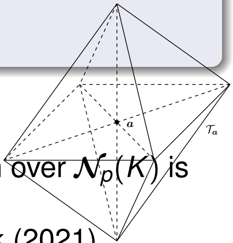

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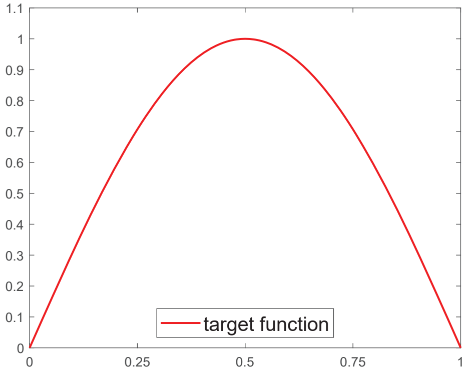
- p-robustness: for (pw) p-polynomial data $\boldsymbol{r}_K$, $\boldsymbol{r}_\mathcal{F}$, minimization over $\mathcal{N}_p(K)$ is up to C_{st} as good as minimization over the entire $\boldsymbol{H}(\mathrm{curl}, K)$
- extension to an edge patch: Chaumont-Frelet, Ern, & Vohralík (2021)
- extension to a vertex patch: Chaumont-Frelet & Vohralík (2022)

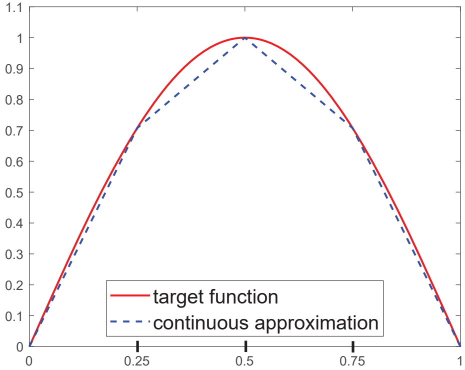
Outline

Equivalence of local- and global-best approximations in $H_0^1(\Omega)$: **1D**



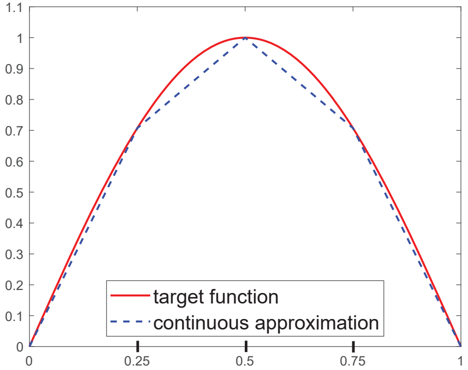
Target function in $H_0^1(\Omega)$

Equivalence of local- and global-best approximations in $H^1_0(\Omega)$: **1D**

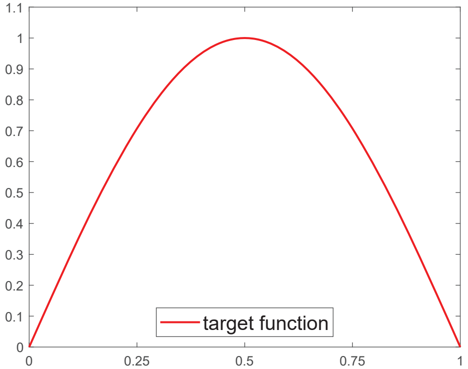


Approximation by **continuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h) \cap H^1_0(\Omega)$

Equivalence of local- and global-best approximations in $H_0^1(\Omega)$: **1D**

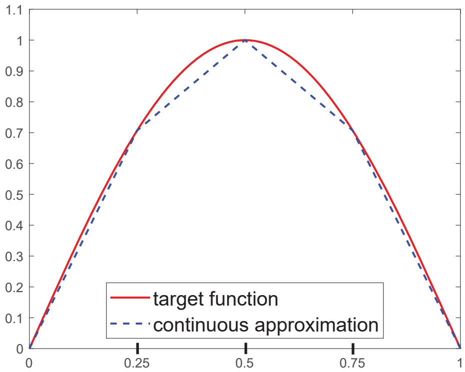


Approximation by **continuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h) \cap H_0^1(\Omega)$

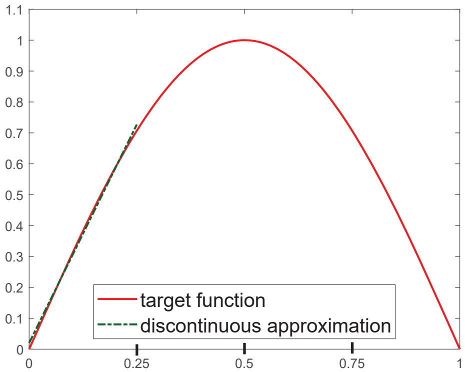


Target function in $H_0^1(\Omega)$

Equivalence of local- and global-best approximations in $H_0^1(\Omega)$: **1D**

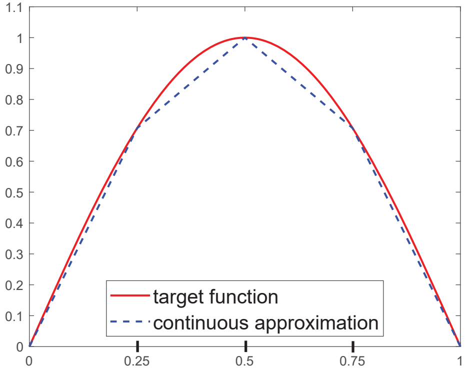


Approximation by **continuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h) \cap H_0^1(\Omega)$

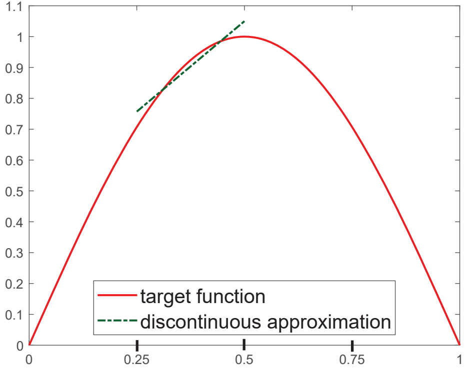


Approximation by **discontinuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h)$

Equivalence of local- and global-best approximations in $H_0^1(\Omega)$: **1D**

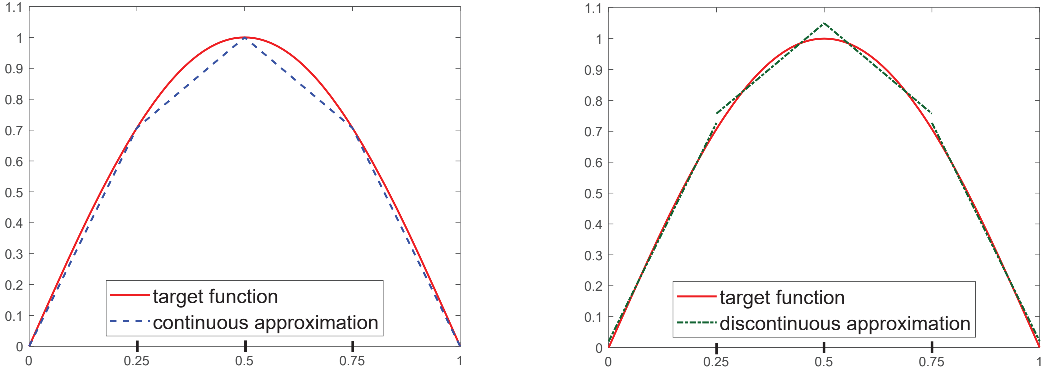


Approximation by **continuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h) \cap H_0^1(\Omega)$



Approximation by **discontinuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h)$

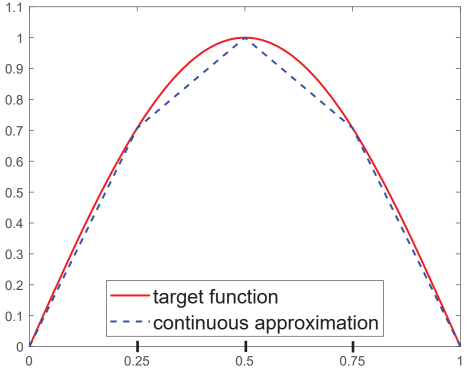
Equivalence of local- and global-best approximations in $H_0^1(\Omega)$: **1D**

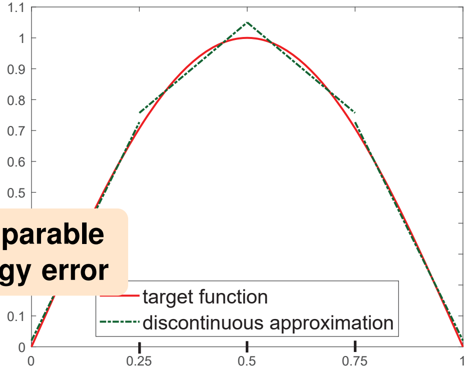


Approximation by **continuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h) \cap H_0^1(\Omega)$

Approximation by **discontinuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h)$

Equivalence of local- and global-best approximations in $H_0^1(\Omega)$: **1D**





comparable energy error

Approximation by **continuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h) \cap H_0^1(\Omega)$

Approximation by **discontinuous** piecewise polynomials in $\mathcal{P}_1(\mathcal{T}_h)$