A multilevel algebraic error estimator and the corresponding iterative solver with *p*-robust behavior*

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ANI MIRAÇI, JAN PAPEŽ, MARTIN VOHRALÍK
Inria Paris & École des Ponts, France

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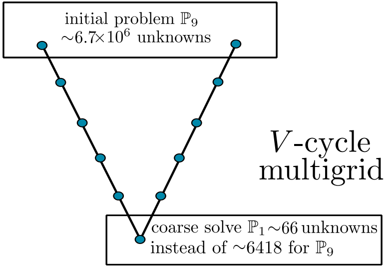
CONTEXT

- We address the issue of large linear systems of type $Ax = b$ arising from finite element method of *order* p discretizations.
- The approach is of *geometric multigrid-type* : V-cycle MG(ν_1, ν_2), where ν_1, ν_2, are the pre- and post-smoothing steps (ex. Jacobi, Gauss-Seidel, block Jacobi etc.).



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- Hackbusch. “Multi-grid methods and applications”. 1985.
- Pavarino. “Additive Schwarz methods for the *p*-version finite element method”. 1994.
- Schöberl et al. “Additive Schwarz preconditioning for *p*-version triangular and tetrahedral finite elements”. 2008.
- Kanschat. “Robust smoothers for high-order discontinuous Galerkin discretizations of advection-diffusion problems”. 2008.
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OVERVIEW

- Setting: finite element method of *order* p for the Poisson problem.
- Multilevel construction of an *algebraic residual lifting* to define:
  1. an *a posteriori algebraic error estimator*
  2. an *iterative linear solver*
- Main results:
  1. The a posteriori estimator is a **two-sided p-robust bound** on the algebraic error
  2. The iterative solver **contracts the error p-robustly** on each iteration
- Numerical results

FINITE ELEMENT DISCRETIZATION, ALGEBRAIC SYSTEM

Setting: $\Omega \subset \mathbb{R}^d$, $1 \leq d \leq 3$, an open bounded polytope, $f \in L^2(\Omega)$ a source term.

Poisson problem: find $u \in H_0^1(\Omega)$ such that $(\nabla u, \nabla v) = (f, v), \quad \forall v \in H_0^1(\Omega)$.

Fix $p \geq 1$ and define

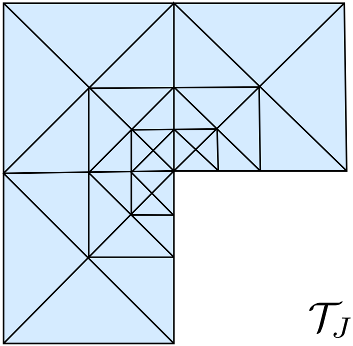
$$V_J^p = \mathbb{P}_p(\mathcal{T}_J) \cap H_0^1(\Omega),$$

where $\mathbb{P}_p(\mathcal{T}_J) = \{v_J \in L^2(\Omega), v_J \in \mathbb{P}_p(K)\ \forall K \in \mathcal{T}_J\}$.

Discrete problem: Find $u_J \in V_J^p$ such that

$$(\nabla u_J, \nabla v_J) = (f, v_J) \quad \forall v_J \in V_J^p. \qquad \text{(FE)}$$

Introducing a basis of V_J^p, then the problem can be rewritten as $\mathbb{A}_J \mathsf{U}_J = \mathsf{F}_J$.



$\mathcal{T}_J$

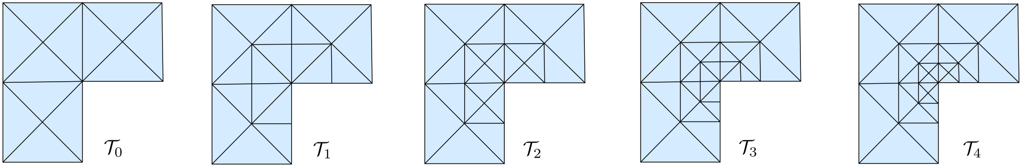
The algebraic problem is *basis-dependent*: we work instead with the functional formulation.

A hierarchy of meshes and spaces

Assumptions on $\{\mathcal{T}_j\}_{0\le j\le J}$

- *Shape regularity*: The ratio element diameter over the diameter of the largest ball inscribed in the element is bounded for all elements by $\kappa_{\mathcal{T}} > 0$.
- *Strength of refinement* on the ratio of child-parent element diameters.

Example: A mesh hierarchy with $J = 4$, associated spaces



$V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H_0^1(\Omega)$ $V_1^p = \mathbb{P}_p(\mathcal{T}_1) \cap H_0^1(\Omega)$ $V_2^p = \mathbb{P}_p(\mathcal{T}_2) \cap H_0^1(\Omega)$ $V_3^p = \mathbb{P}_p(\mathcal{T}_3) \cap H_0^1(\Omega)$ $V_4^p = \mathbb{P}_p(\mathcal{T}_4) \cap H_0^1(\Omega)$

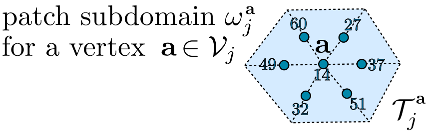
Note: *Highly refined meshes* are allowed, but dependent on J the number of refinements.

PATCHES

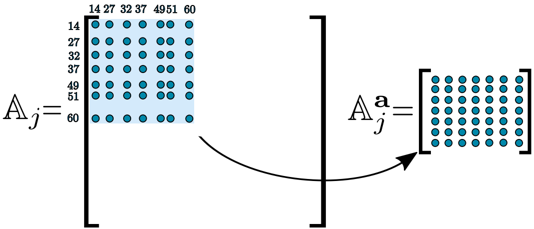
Let $\mathcal{V}_j$ be the set of vertices of the mesh $\mathcal{T}_j$, $j \in \{1, \dots, J\}$. Given a vertex $\mathbf{a} \in \mathcal{V}_j$, we denote

- $\mathcal{T}_j^{\mathbf{a}}$ the patch of elements sharing vertex **a**
- $\omega_j^{\mathbf{a}}$ the corresponding patch subdomain
- $V_j^{\mathbf{a}}$ the associated local space

Example: Geometric (left) and algebraic (right) representation of localizing the problem for $p = 2$ and a patch composed of 6 elements:

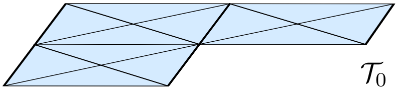


$$V_j^{\mathbf{a}} = H_0^1(\omega_j^{\mathbf{a}}) \cap \mathbb{P}_p(\mathcal{T}_j)$$



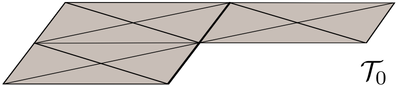
Multilevel lifting of the algebraic residual: Case $J = 2$

$j = 0:$



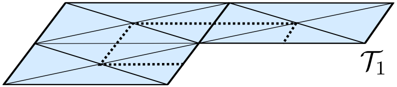
Multilevel lifting of the algebraic residual: Case $J = 2$

$$j = 0 : \rho_0^i \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H_0^1(\Omega)$$

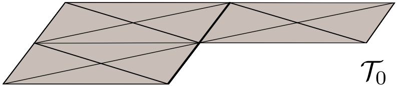


Multilevel lifting of the algebraic residual: Case $J = 2$

$j = 1 :$

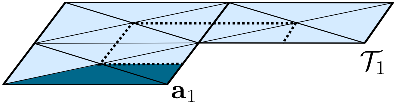


$j = 0 : \rho_0^i \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H_0^1(\Omega)$

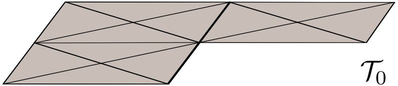


MULTILEVEL LIFTING OF THE ALGEBRAIC RESIDUAL: CASE $J = 2$

$j = 1: \underbrace{\rho^i_{1,\mathbf{a}_1}}_{\in V_1^{\mathbf{a}_1}}$



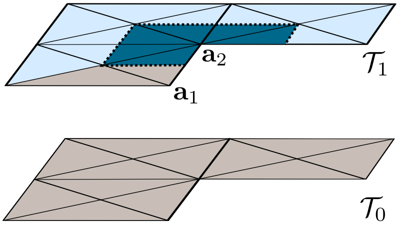
$j = 0: \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$



MULTILEVEL LIFTING OF THE ALGEBRAIC RESIDUAL: CASE $J = 2$

$j = 1: \ \rho^i_{1,\mathbf{a}_1} + \underbrace{\rho^i_{1,\mathbf{a}_2}}_{\in V_1^{\mathbf{a}_2}}$

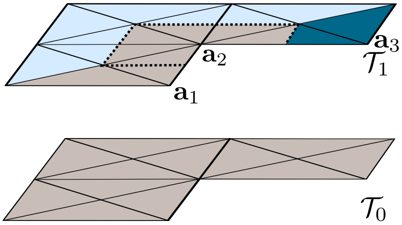
$j = 0: \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$



Multilevel lifting of the algebraic residual: Case $J = 2$

$$j = 1: \quad \rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \underbrace{\rho^i_{1,\mathbf{a}_3}}_{\in V_1^{\mathbf{a}_3}}$$

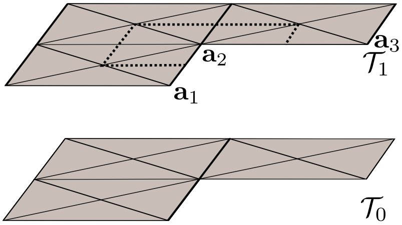
$$j = 0: \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$$



Multilevel lifting of the algebraic residual: Case $J = 2$

$j = 1: \ \rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \dots$

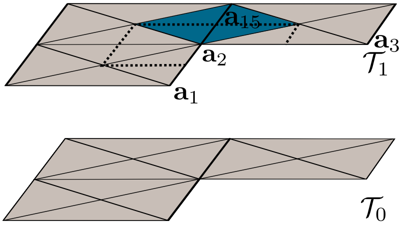
$j = 0 : \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$



Multilevel lifting of the algebraic residual: Case $J = 2$

$$j = 1 : \ \rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \underbrace{\rho^i_{1,\mathbf{a}_{15}}}_{\in V_1^{\mathbf{a}_{15}}}$$

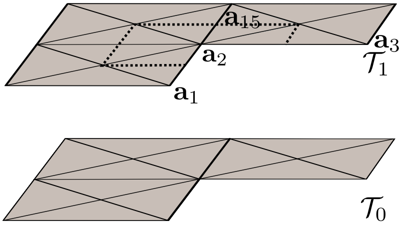
$$j = 0 : \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$$



Multilevel lifting of the algebraic residual: Case $J = 2$

$$j = 1 : \frac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$$

$$j = 0 : \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$$

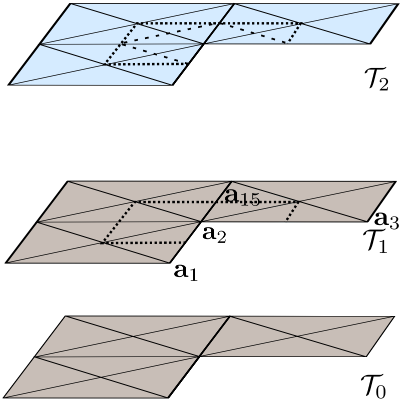


Multilevel lifting of the algebraic residual: Case $J = 2$

$j = 2:$

$j = 1: \; \dfrac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V^p_1$

$j = 0: \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$

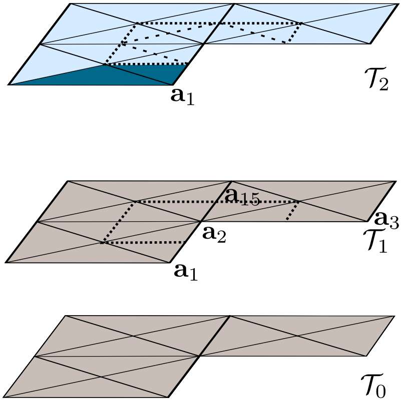


Multilevel lifting of the algebraic residual: Case $J = 2$

$$j = 2 : \underbrace{\rho^i_{2,\mathbf{a}_1}}_{\in V_2^{\mathbf{a}_1}}$$

$$j = 1 : \frac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$$

$$j = 0 : \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$$

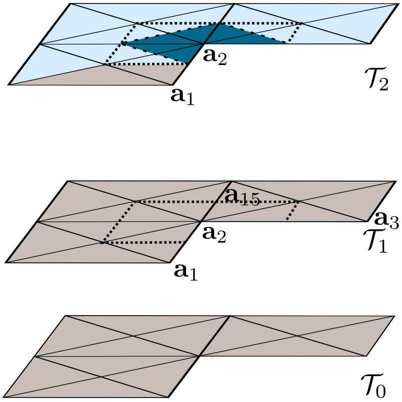


MULTILEVEL LIFTING OF THE ALGEBRAIC RESIDUAL: CASE $J = 2$

$$j = 2 : \rho^i_{2,\mathbf{a}_1} + \underbrace{\rho^i_{2,\mathbf{a}_2}}_{\in V_2^{\mathbf{a}_2}}$$

$$j = 1 : \frac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$$

$$j = 0 : \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$$



Multilevel lifting of the algebraic residual: Case $J = 2$

$$j = 2 : \rho^i_{2,\mathbf{a}_1} + \rho^i_{2,\mathbf{a}_2} + \underbrace{\rho^i_{2,\mathbf{a}_3}}_{\in V_2^{\mathbf{a}_3}}$$

$$j = 1 : \frac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$$

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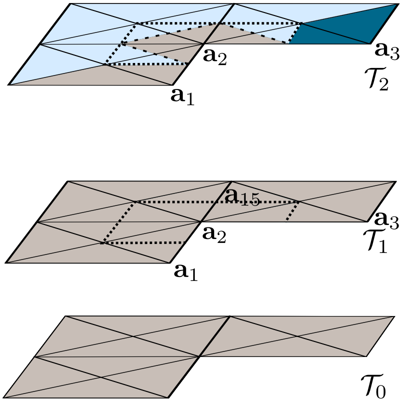

Multilevel lifting of the algebraic residual: Case $J = 2$

$j = 2: \; \rho^i_{2,\mathbf{a}_1} + \rho^i_{2,\mathbf{a}_2} + \rho^i_{2,\mathbf{a}_3} + \dots$

$j = 1: \; \dfrac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \dots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$

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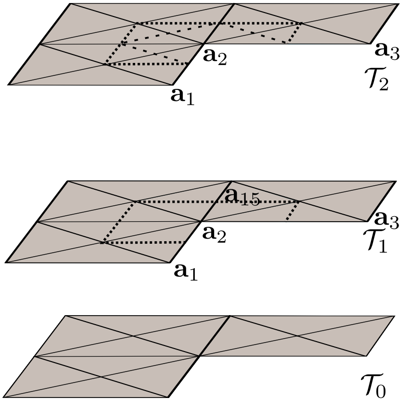

Multilevel lifting of the algebraic residual: Case $J = 2$

$$j = 2 : \rho^i_{2,\mathbf{a}_1} + \rho^i_{2,\mathbf{a}_2} + \rho^i_{2,\mathbf{a}_3} + \ldots + \underbrace{\rho^i_{2,\mathbf{a}_{18}}}_{\in V_2^{\mathbf{a}_{18}}}$$

$$j = 1 : \frac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$$

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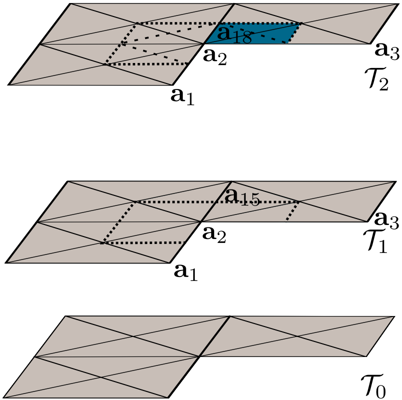

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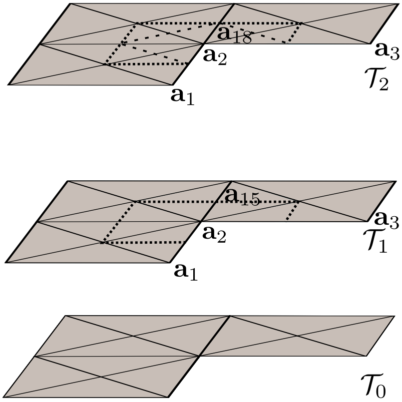
$$j = 1 : \frac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$$

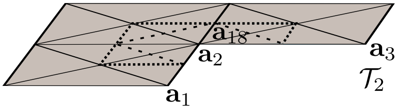
$$j = 0 : \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$$



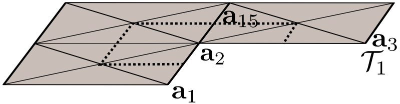
Multilevel lifting of the algebraic residual: Case $J = 2$

$$\rho^i_{2,\mathrm{alg}} = \rho^i_0 + \sum_{j=1}^{2} \frac{\sum_{a \in \mathcal{V}_j} \rho^i_{j,a}}{J(d+1)}$$

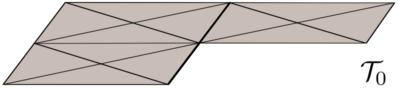
$$j = 2 : \frac{\rho^i_{2,\mathbf{a}_1} + \rho^i_{2,\mathbf{a}_2} + \rho^i_{2,\mathbf{a}_3} + \ldots + \rho^i_{2,\mathbf{a}_{18}}}{J(d+1)} \in V_2^p$$



$$j = 1 : \frac{\rho^i_{1,\mathbf{a}_1} + \rho^i_{1,\mathbf{a}_2} + \rho^i_{1,\mathbf{a}_3} + \ldots + \rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$$



$$j = 0 : \rho^i_0 \in V_0 = \mathbb{P}_1(\mathcal{T}_0) \cap H^1_0(\Omega)$$



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$$j = 2 : \frac{\rho^i_{2,\mathbf{a}_1}+\rho^i_{2,\mathbf{a}_2}+\rho^i_{2,\mathbf{a}_3}+\ldots+\rho^i_{2,\mathbf{a}_{18}}}{J(d+1)} \in V_2^p$$

$$j = 1 : \frac{\rho^i_{1,\mathbf{a}_1}+\rho^i_{1,\mathbf{a}_2}+\rho^i_{1,\mathbf{a}_3}+\ldots+\rho^i_{1,\mathbf{a}_{15}}}{J(d+1)} \in V_1^p$$

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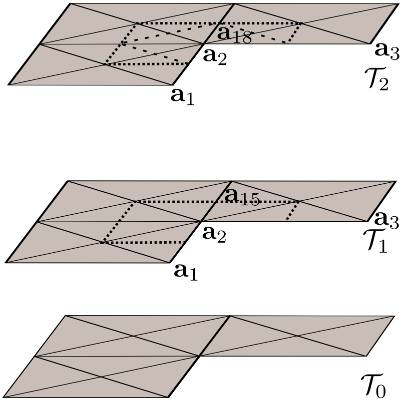


MULTILEVEL LIFTING OF THE ALGEBRAIC RESIDUAL[1]

Let $u_J^i \in V_J^p$ be *arbitrary*. We define its associated *algebraic residual lifting*.

Coarse solve: Define $\rho_0^i \in V_0$ by: $(\nabla \rho_0^i, \nabla v_0) = (f, v_0) - (\nabla u_J^i, \nabla v_0), \quad \forall v_0 \in V_0.$

Construction: Consider $\rho_{J,\mathrm{alg}}^i \in V_J^p$

$$\rho_{J,\mathrm{alg}}^i = \rho_0^i + \sum_{j=1}^J \rho_j^i = \rho_0^i + \sum_{j=1}^J \frac{\sum_{\mathbf{a} \in \mathcal{V}_j} \rho_{j,\mathbf{a}}^i}{J(d+1)},$$

where $\rho_j^i \in V_j^p$, for all $j = \{1, \ldots, J\}$, $\rho_{j,\mathbf{a}}^i \in V_j^{\mathbf{a}}$:

$$(\nabla \rho_{j,\mathbf{a}}^i, \nabla v_{j,\mathbf{a}})_{\omega_j^{\mathbf{a}}} = (f, v_{j,\mathbf{a}})_{\omega_j^{\mathbf{a}}} - (\nabla u_J^i, \nabla v_{j,\mathbf{a}})_{\omega_j^{\mathbf{a}}} - \sum_{k=0}^{j-1} (\nabla \rho_k^i, \nabla v_{j,\mathbf{a}})_{\omega_j^{\mathbf{a}}}, \quad \forall v_{j,\mathbf{a}} \in V_j^{\mathbf{a}}.$$

Remark: $\rho_{J,\mathrm{alg}}^i$ approximates the algebraic error $u_J - u_J^i$ by

- a V-cycle MG(0,1) with piecewise affine coarse solve
- the smoother is *damped additive Schwarz* / *block Jacobi* associated to the patches

[1] Papež et al. “Sharp algebraic and total a posteriori error bounds for h and p finite elements via a multilevel approach”. HAL preprint 01662944, 2017.

Definition 1 (Multilevel a posteriori estimator)

Let $u_J^i \in V_J^p$ be **arbitrary**, and let $\rho_{J,\mathrm{alg}}^i$ be the associated algebraic residual lifting.

Set $\eta_{\mathrm{alg}}^i := \dfrac{(f, \rho_{J,\mathrm{alg}}^i) - (\nabla u_J^i, \nabla \rho_{J,\mathrm{alg}}^i)}{\|\nabla \rho_{J,\mathrm{alg}}^i\|}$, or else $\eta_{\mathrm{alg}}^i := 0$ if $\rho_{J,\mathrm{alg}}^i = 0$.

Definition 2 (Multilevel solver)

1. Initialize $u_J^0 \in V_0$ as the solution of $(\nabla u_J^0, \nabla v_0) = (f, v_0), \quad \forall v_0 \in V_0$.
2. Let $i \geq 0$. Set $u_J^{i+1} := u_J^i + \dfrac{(f, \rho_{J,\mathrm{alg}}^i) - (\nabla u_J^i, \nabla \rho_{J,\mathrm{alg}}^i)}{\|\nabla \rho_{J,\mathrm{alg}}^i\|^2} \rho_{J,\mathrm{alg}}^i$, or else $u_J^{i+1} := u_J^i$ if $\rho_{J,\mathrm{alg}}^i = 0$.

Main results

Theorem 1 (p-robust reliable and efficient bound on the algebraic error)

Let $u_J^i \in V_J^p$ be **arbitrary**, let η_{alg}^i be the associated a posteriori estimator. There holds

- reliability: $\|\nabla(u_J - u_J^i)\| \geq \eta_{\text{alg}}^i$
- efficiency: $\eta_{\text{alg}}^i \geq \beta(\kappa_{\mathcal{T}}, d, J)\|\nabla(u_J - u_J^i)\|, \qquad 0 < \beta(\kappa_{\mathcal{T}}, d, J) < 1 \qquad \text{(E)}$

Theorem 2 (p-robust error contraction of the multilevel solver)

Let $u_J^i \in V_J^p$ be **arbitrary**, let u_J^{i+1} be constructed from u_J^i using one step of the multilevel solver. Then there holds

$$\|\nabla(u_J - u_J^{i+1})\| \leq \alpha(\kappa_{\mathcal{T}}, d, J)\|\nabla(u_J - u_J^i)\|, \qquad 0 < \alpha(\kappa_{\mathcal{T}}, d, J) < 1 \qquad \text{(C)}$$

Corollary 1 (Equivalence of the two main results)

Under the assumptions of Theorems 1 and 2, (E) holds if and only if (C) holds.

Sketch of the proof of Theorem 1[2] : $\eta^i_{\rm alg} \geq \beta \|\nabla(u_J - u^i_J)\|$

- Due to the definition of $\eta^i_{\rm alg}$, it is enough to show:

$$\text{if } \rho^i_{J,\rm alg} \neq 0: \qquad \eta^i_{\rm alg} = \frac{(f, \rho^i_{J,\rm alg}) - (\nabla u^i_J, \nabla \rho^i_{J,\rm alg})}{\|\nabla \rho^i_{J,\rm alg}\|} \geq \beta \|\nabla(u_J - u^i_J)\|,$$

$$\text{if } \rho^i_{J,\rm alg} = 0: \qquad \eta^i_{\rm alg} = 0 = \|\nabla(u_J - u^i_J)\|.$$

Our approach consists in giving a:

1. lower bound on $(f, \rho^i_{J,\rm alg}) - (\nabla u^i_J, \nabla \rho^i_{J,\rm alg})$: *the damping proves to be crucial*
2. upper bound on $\|\nabla \rho^i_{J,\rm alg}\|^2$: *rather straightforward*
3. upper bound on $\|\nabla(u_J - u^i_J)\|^2$: *more delicate*

by the **splitting** $\|\nabla \rho^i_0\|^2 + \sum_{j=1}^J \sum_{\mathbf{a}\in\mathcal{V}_j} \|\nabla \rho^i_{j,\mathbf{a}}\|^2_{\omega^{\mathbf{a}}_j}$.

- Leading to:

$$\|\nabla(u_J - u^i_J)\|^2 \geq (\eta^i_{\rm alg})^2 \overset{❶\,❷}{\gtrsim} \|\nabla \rho^i_0\|^2 + \sum_{j=1}^J \sum_{\mathbf{a}\in\mathcal{V}_j} \|\nabla \rho^i_{j,\mathbf{a}}\|^2_{\omega^{\mathbf{a}}_j} \overset{❸}{\gtrsim} \|\nabla(u_J - u^i_J)\|^2$$

[2] Miraçi, Papež, and Vohralík. "A multilevel algebraic error estimator and the corresponding iterative solver with p-robust behavior". HAL preprint 02070981, 2019.

NUMERICAL RESULTS

Consider the following problem:

L-shape domain problem: $u(r,\theta) = r^{2/3}\sin(2\theta/3)$; $\Omega = (-1,1)^2 \setminus ([0,1]\times[-1,0])$.

We focus on testing numerically the p-robust behavior of our solver, a common choice for the **stopping criterion** is

$$\frac{\|\mathsf{F}_J - \mathbb{A}_J \mathsf{U}_J^{i_{\mathrm{stop}}}\|}{\|\mathsf{F}_J\|} \leq 10^{-5} \frac{\|\mathsf{F}_J - \mathbb{A}_J \mathsf{U}_J^{0}\|}{\|\mathsf{F}_J\|}.$$

We expect a p-robust solver

- to reach the above stopping criterion in a *similar number of iterations* i_{stop}
- to have *similar error contraction factors* $\|\nabla(u_J - u_J^{i+1})\|/\|\nabla(u_J - u_J^{i})\|$ at all iterations

for different polynomial degrees p, given a fixed J number of mesh levels.

Numerical results: L-shape problem

Comparing the number of iterations i_{stop} to reach the stopping criterion for **multigrid** with *Jacobi* and *Gauss-Seidel* smoothing.

			"small" patches		"big" patches	MG(0,1)	
			dAS	wRAS	wRAS	Jacobi	GS
J	p	DoF	i_{stop}	i_{stop}	i_{stop}	i_{stop}	i_{stop}
3	1	5057	76	17	8	44	9
	3	46 273	26	12	5	-	49
	6	185 857	23	10	5	-	228
	9	418 753	21	10	5	-	586
4	1	20 481	95	18	8	-	9
	3	185 857	29	12	5	-	42
	6	744 961	27	10	5	-	186
	9	1 677 313	25	9	5	-	454
5	1	82 433	112	17	8	-	8
	3	744 961	32	12	5	-	35
	6	2 982 913	31	9	5	-	147
	9	6 713 857	28	8	4	-	333

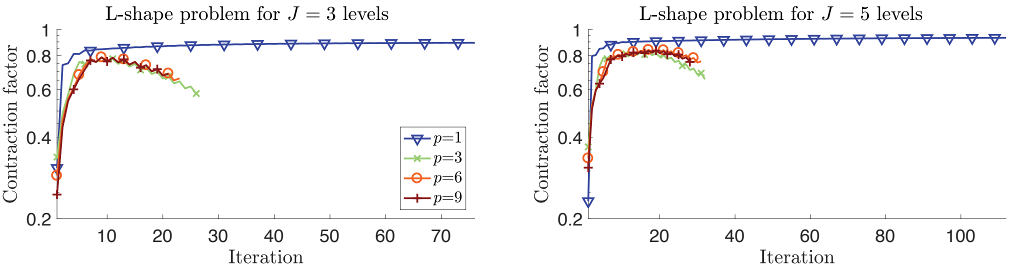
$1 \le j \le J$:

$$\rho_j^i = \frac{1}{J(d+1)} \sum_{\mathbf{a}\in\mathcal{V}_j} \rho_{j,\mathbf{a}}^i, \quad \text{(dAS)}$$

$$\rho_j^i = \sum_{\mathbf{a}\in\mathcal{V}_j} \mathcal{I}_j^p(\psi_j^{\mathbf{a}} \rho_{j,\mathbf{a}}^i), \quad \text{(wRAS)}$$

- $\mathcal{I}_j^p$ is the $\mathbb{P}^p$ Lagrange interpolation operator on mesh level j
- For vertex $\mathbf{a} \in \mathcal{V}_j$, we denote the associated hat function by $\psi_j^{\mathbf{a}}$
- The constructions of $\rho_{j,\mathbf{a}}^i \in V_j^{\mathbf{a}}$ remain unchanged and $\rho_{J,\text{alg}}^i = \sum_{j=0}^J \rho_j^i$ still holds.

NUMERICAL RESULTS: L-SHAPE PROBLEM



Error contraction factors per iteration for different polynomial degrees p and mesh levels J.

CONCLUSIONS: In this work, we presented

- a multilevel construction of the *algebraic residual lifting*
- an *a posteriori estimator* on the algebraic error and a *linear iterative solver*
- the proof of *p-robust efficiency* of the a posteriori estimator and *p-robust error contraction* of the solver
- numerical tests which agree with these theoretical findings

OUTLOOK: In future work, we aim to

- better understand the role of the mesh levels J.
- use *adaptivity* based on the derived efficient algebraic error estimator.
- apply our method to more involved problems.

THANK YOU FOR YOUR ATTENTION!