



A polytopal domain-specific language with a Rust interpreter

Daniele A. Di Pietro

Université de Montpellier
NEMESIS workgroup
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Amarcord



A workflow you know all too well...



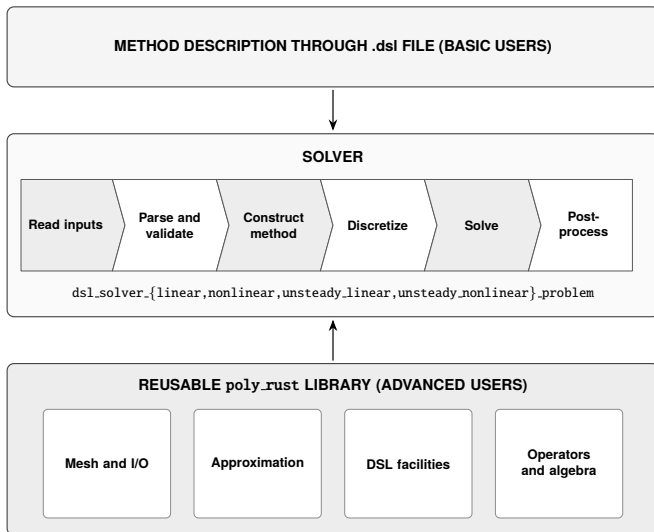
A workflow you know all too well...



Implementation: translate from human (mathematical) language to computer language

- FreeFEM++
- Feel++
- Unified Form Language in FEniCS
- deal.II
- ...but none of them can naturally express reconstructions!

Architecture



The DSL

Driving example

- Let $\Omega \subset \mathbb{R}^2$ a polygonal domain with boundary Γ s.t.

$$\Gamma = \Gamma^D \sqcup \Gamma^N$$

- Let $f : \Omega \rightarrow \mathbb{R}$, $g : \Gamma^D \rightarrow \mathbb{R}$, and $\phi : \Gamma^N \rightarrow \mathbb{R}$ be given data
- We consider a **Hybrid High-Order (HHO)** scheme¹ for the problem:
Find $u : \Omega \rightarrow \mathbb{R}$ s.t.

$$\begin{aligned} -\Delta u &= f && \text{in } \Omega, \\ u &= g && \text{on } \Gamma^D, \\ -\nabla u \cdot n &= \phi && \text{on } \Gamma^N, \end{aligned}$$

where n denotes the outward unit normal to Γ

¹Di Pietro et al. 2014

Method

```
method hho_poisson {  
  // Parameters and functions  
  // Discrete spaces  
  // Interpolants  
  // Operators  
  // Forms  
  // Norm functionals  
  // Boundary conditions  
  // Problem description  
}
```

Parameters and functions

```
parameter pi = 3.14159265358979

function exact_solution(vector X) -> scalar = sin(pi * X[0])
  * sin(pi * X[1])
function exact_solution_gradient(vector X) -> vector
  = vector(
    pi * cos(pi * X[0]) * sin(pi * X[1]),
    pi * sin(pi * X[0]) * cos(pi * X[1])
  )
function exact_normal_flux(vector X) -> scalar on edge E of
  element T
  = - exact_solution_gradient(X) dot normal

function source(vector X) -> scalar = 2.0 * pow(pi, 2.0) *
  sin(pi * X[0]) * sin(pi * X[1])
```

Discrete spaces

The standard HHO space is defined by:

$$\underline{U}_h^k := \left\{ \underline{v}_h = ((v_T)_{T \in \mathcal{T}_h}, (v_E)_{E \in \mathcal{E}_h}) : \right. \\ \left. v_T \in \mathcal{P}^k(T) \text{ for all } T \in \mathcal{T}_h, v_E \in \mathcal{P}^k(E) \text{ for all } E \in \mathcal{E}_h \right\}$$

```
space Uh {  
  element Poly(k, scalar)  
  edge Poly(k, scalar)  
}
```

Discrete spaces

The standard HHO space is defined by:

$$\underline{U}_h^k := \left\{ \underline{v}_h = ((v_T)_{T \in \mathcal{T}_h}, (v_E)_{E \in \mathcal{E}_h}) : \right. \\ \left. v_T \in \mathcal{P}^k(T) \text{ for all } T \in \mathcal{T}_h, v_E \in \mathcal{P}^k(E) \text{ for all } E \in \mathcal{E}_h \right\}$$

```
space Uh {  
  element Poly(k, scalar) called element_dof  
  edge Poly(k, scalar) called edge_dof  
}
```

Interpolants

Components are interpreted through the interpolator $\underline{I}_h^k : H^1(\Omega) \rightarrow \underline{U}_h^k$:

$$H^1(\Omega) \ni v \mapsto \underline{I}_h^k v := ((\pi_T^k v)_{T \in \mathcal{T}_h}, (\pi_E^k v)_{E \in \mathcal{E}_h}) \in \underline{U}_h^k$$

```
interpolant interpolant_exact_solution on Uh {  
  on element T:  
    dof(T) = l2_project(exact_solution, Poly(k, scalar))  
  on edge E:  
    dof(E) = l2_project(exact_solution, Poly(k, scalar))  
}
```

Operators

The discrete gradient $G_T^k : \underline{U}_T^k \rightarrow \mathcal{P}^k(T; \mathbb{R}^2)$ is s.t., for all $\underline{v}_T \in \underline{U}_T^k$,

$$\int_T G_T^k \underline{v}_T \cdot \tau = - \int_T v_T \operatorname{div} \tau + \sum_{E \in \mathcal{E}_T} \int_E v_E (\tau \cdot n_{TE}) \quad \forall \tau \in \mathcal{P}^k(T; \mathbb{R}^2)$$

```
operator gradient_reconstruction : Uh(v) -> Poly(k, vector)
  on element T {
    forall tau in Poly(k, vector):
      int(T) gradient_reconstruction(v) dot tau =
        - int(T) dof(v, T) * div(tau)
        + sum_edges(int(E) dof(v, E) * (tau dot normal))
  }
```

Using interpolants to test polynomial exactness I

- A crucial design property is **polynomial exactness**:

$$G_T^k I_T^k v = v \quad \forall v \in \mathcal{P}^{k+1}(T)$$

- When coding a new operator, checking polynomial consistency is a common **debugging step**
- `poly_rust` provides language facilities that makes this easy!

Using interpolants to test polynomial exactness II

```
function test_linear(vector X) -> scalar = X[0] - 4.0 * X[1]
    + 7.0
function test_quadratic(vector X) -> scalar = pow(X[0], 2.0)
    - 3.0 * X[0] * X[1] + pow(X[1], 2.0) - 5.0
```

```
operator gradient_reconstruction : Uh(v) -> Poly(k, vector)
    on element T {
    ...
    test exactness for k = 0 against test_linear_gradient using
        interpolant_test_linear
    test exactness for k = 1 against test_quadratic_gradient
        using interpolant_test_quadratic
}
```

Potential and difference operators I

$$\int_T \nabla p_T^{k+1} \underline{u}_T \cdot \nabla w = \int_T G_T^k \underline{u}_T \cdot \nabla w \quad \forall w \in \mathcal{P}^{k+1}(T),$$
$$\int_T \nabla p_T^{k+1} \underline{u}_T = \int_T u_T$$

```
operator potential_reconstruction : Uh(u) -> Poly(k+1, scalar
) on element T {
  forall w in Poly(k+1, scalar):
    int(T) grad(potential_reconstruction(u)) dot grad(w) =
    int(T) gradient_reconstruction(u) dot grad(w)
  constraint int(T) potential_reconstruction(u) = int(T) dof(
    u, T)
}
```

Potential and difference operators II

$$\delta_T^k \underline{v}_T := \pi_T^k(p_T^{k+1} \underline{v}_T - v_T), \quad \delta_{TE}^k \underline{v}_T := \pi_E^k(p_T^{k+1} \underline{v}_T - v_E) \quad \forall E \in \mathcal{E}_T$$

```
operator element_difference : Uh(v) -> Poly(k, scalar) on
  element T {
  forall q in Poly(k, scalar):
    int(T) element_difference(v) * q =
    int(T) (potential_reconstruction(v) - dof(v, T)) * q
}

operator edge_difference : Uh(v) -> Poly(k, scalar) on edge E
  of element T {
  forall q in Poly(k, scalar):
    int(E) edge_difference(v) * q =
    int(E) (potential_reconstruction(v) - dof(v, E)) * q
}
```

- Forms define the LHS and RHS of the discrete variational problem
- The bilinear form $a_h : \underline{U}_h^k \times \underline{U}_h^k \rightarrow \mathbb{R}$ s.t., for all $(\underline{u}_h, \underline{v}_h) \in \underline{U}_h^k \times \underline{U}_h^k$,

$$a_h(\underline{u}_h, \underline{v}_h) := \sum_{T \in \mathcal{T}_h} \left[\int_T G_T^k \underline{u}_T \cdot G_T^k \underline{v}_T + h_T^{-2} \int_T \delta_T^k \underline{u}_T \delta_T^k \underline{v}_T + h_T^{-1} \sum_{E \in \mathcal{E}_T} \int_E \delta_{TE}^k \underline{u}_T \delta_{TE}^k \underline{v}_T \right]$$

- The source linear form $\ell_h : \underline{U}_h^k \rightarrow \mathbb{R}$ s.t., for all $\underline{v}_h \in \underline{U}_h^k$,

$$\ell_h(\underline{v}_h) := \sum_{T \in \mathcal{T}_h} \int_T f v_T$$

- We also need to account for the Neumann contribution $\int_{\Gamma^N} \phi v_E$

Forms II

```

bilinear form poisson : Uh(trial u) times Uh(test v) {
  sum_elements(
    int(T) gradient_reconstruction(u) dot
    gradient_reconstruction(v)
    + pow(diameter(T), -2) * int(T) element_difference(u) *
    element_difference(v)
    + pow(diameter(T), -1) * int(dT) edge_difference(u) *
    edge_difference(v)
  )
}

```

Forms III

```
linear form load : Uh(test v) {  
    sum_elements(int(T) source * dof(v, T))  
}  
  
boundary labels { left = 1, right = 2, bottom = 3, top = 4 }  
  
linear form neumann_contribution : Uh(test v) {  
    sum_boundary_edges(right)(int(E) exact_normal_flux * dof(v,  
        E))  
}
```

Strongly-enforcing boundary conditions

- Boundary conditions can be enforced strongly considering

$$\underline{U}_{h,g}^k := \{ \underline{v}_h \in \underline{U}_h^k : v_E = \pi_E^k g \text{ for all } E \in \mathcal{E}_h^D \},$$

where $\mathcal{E}_h^D := \{ E \in \mathcal{E}_h : E \subset \Gamma^D \}$

- This is done by enforcing DOF values much like in interpolants

```
boundary conditions mixed_boundary_conditions on Uh {  
  on edge E in left, bottom, top:  
    dof(E) = l2_project(exact_solution, Poly(k, scalar))  
}
```

Linear problem

The HHO problem reads: Find $\underline{u}_h \in \underline{U}_{h,g}^k$ such that

$$a_h(\underline{u}_h, \underline{v}_h) = \ell_h(\underline{v}_h) - \int_{\Gamma^N} \phi v_E \quad \forall \underline{v}_h \in \underline{U}_{h,0}^k$$

```
linear problem hho_poisson_mixed_boundary_conditions_problem
  on Uh {
    lhs { poisson }
    rhs { load - neumann_contribution }
    boundary_conditions mixed_boundary_conditions
  }
```

Export I

- A problem block can be completed with a list of fields to export
- Exportable fields are operators defined on elements

```
operator potential_field : Uh(u) -> Poly(k, scalar) on
  element T {
    potential_field(u) = dof(u, T)
  }

linear problem hho_poisson_mixed_boundary_conditions_problem
  on Uh {
    ...
    export { potential_reconstruction, potential_field }
  }
```

Export II

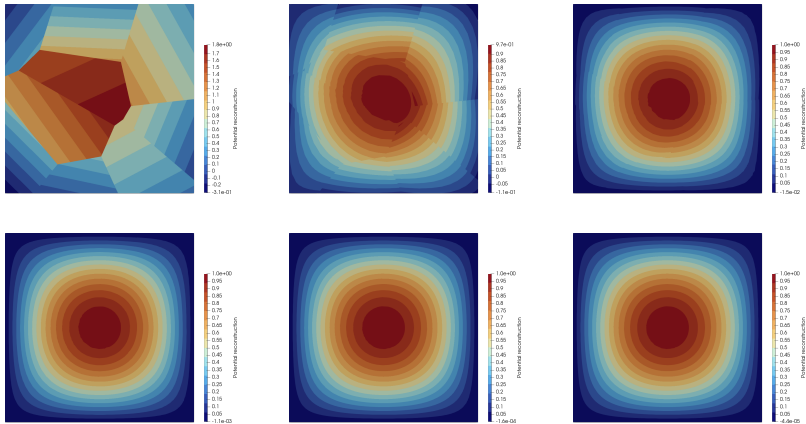


Figure: Evolution of the HHO potential field on a coarse polygonal mesh upon degree-refinement from $k = 0$ to $k = 5$. Notice the high-order representation.

Functionals and error computation I

- When prototyping, one usually need to perform error computations
- In the fully discrete setting, the error is measured by

$$\underline{e}_h := \underline{u}_h - \underline{I}_h^k u$$

- Appropriate error measures in our context are, e.g.,

$$\|\underline{v}_h\|_{a,h} := a_h(\underline{v}_h, \underline{v}_h)^{\frac{1}{2}},$$

$$\|\underline{v}_h\|_{1,h} := \sum_{T \in \mathcal{T}_h} \left[\|\nabla v_T\|_{L^2(T)}^2 + h_T^{-1} \sum_{E \in \mathcal{E}_T} \|v_E - v_T\|_{L^2(E)}^2 \right]$$

- These norms can be implemented in the DSL through **functionals**

Functionals and error computation II

- Functionals are similar to functions, but act on discrete variables

```
function h1_operator_norm : Uh(v) -> scalar {  
  sqrt(poisson(v, v))  
}  
  
function h1_component_norm : Uh(v) -> scalar {  
  sqrt(  
    sum_elements(  
      int(T) squared_norm(grad(dof(v, T)))  
      + pow(diameter(T), -1) * int(dT) pow(dof  
(v, E) - dof(v, T), 2)  
    )  
  )  
}
```

Functionals and error computation III

- We can now tell the code to compute errors as follows:

```
linear problem
  hho_poisson_mixed_boundary_conditions_problem on Uh {
  ...
  compute errors using interpolant_exact_solution {
    h1_component_norm, h1_operator_norm
  }
}
```

- The field `report` can be used to export functionals evaluated at $\underline{u}_h$

Functionals and error computation IV

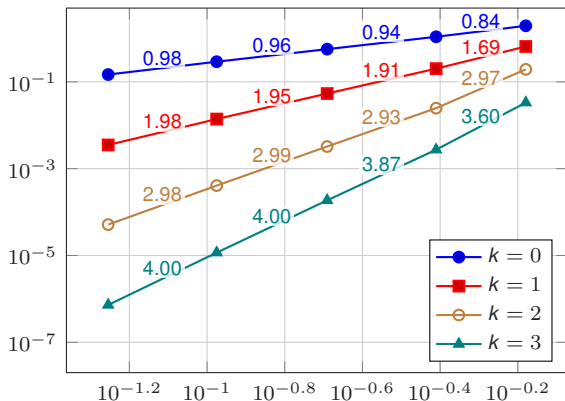


Figure: Convergence plot generated by the script `convergence_test.sh`.

Functionals and error computation V

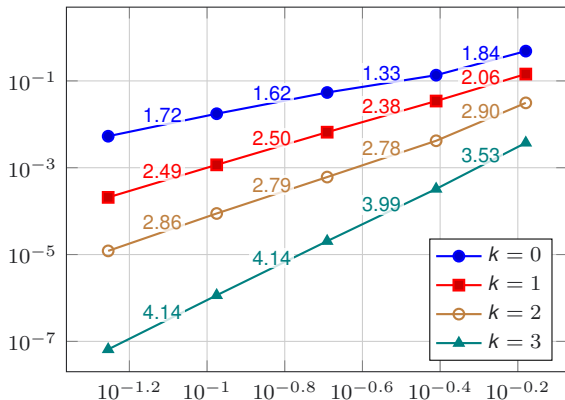


Figure: And DDR^2 for comparison, since we were all waiting for this 🤖.

The solvers

- Basic solvers **without static condensation**
- Optimized for both singleton and Cartesian product spaces
- For non-linear problems, **line search** and **Newton** are implemented
 - ▶ Line search requires **fixed_point** to be defined
 - ▶ Newton requires **jacobian** to be defined
- If both are defined, line search is used for warming-up and as a fallback
- Initialization can be done solving a linear problem or interpolating

- Based on Singly Diagonally Implicit Runge-Kutta (SDIRK):
 - ▶ **Diagonally Implicit:** each stage only depends on the current and previous stages
 - ▶ **Singly Implicit:** all the diagonal elements of the method's internal stage matrix are identical
- Available schemes: `implicit-euler`, `sdirk-4-3`, `sdirk-5-4`
- General formulation possibly including **non-linear unsteady terms**

Highlights

- Thread-based parallelism using rayon
- Automatic **fast polynomial integration**³ through polynomial algebra
- **Centralized repositories** for polynomial families and operators
- Integration of leading **linear solver libraries**:
 - ▶ UMFPACK for direct solvers
 - ▶ PETSc for Krylov solvers

³Chin et al. 2015

Advanced features

Cartesian product spaces

```
space Uh {  
  element Poly(k, vector)  
  edge Poly(k, vector)  
}  
  
space Ph {  
  element Poly(k, scalar)  
}  
  
product space Xh = Uh times Ph  
  
bilinear form velocity_pressure : Uh(trial u) times Ph(test q  
  ) {  
  sum_elements(-int(T) dof(u, T) dot grad(q) + int(dT) (dof(u  
    , E) dot normal) * q)  
}
```

Operators between polynomial spaces

```
operator raviart_thomas_interpolator_polykpo
: Poly(k+1, vector)(u) -> RaviartThomasPoly(k+1) on element
  T {
forall v in Poly(k-1, vector):
  int(T) raviart_thomas_interpolator_polykpo(u) dot v = int
  (T) u dot v
forall edge E, forall q in Poly(k, scalar):
  int(E) (raviart_thomas_interpolator_polykpo(u) dot normal
  ) * q
  = int(E) (u dot normal) * q
}
```

Comparison between HHO and HYPRE for the Kovasznay problem I

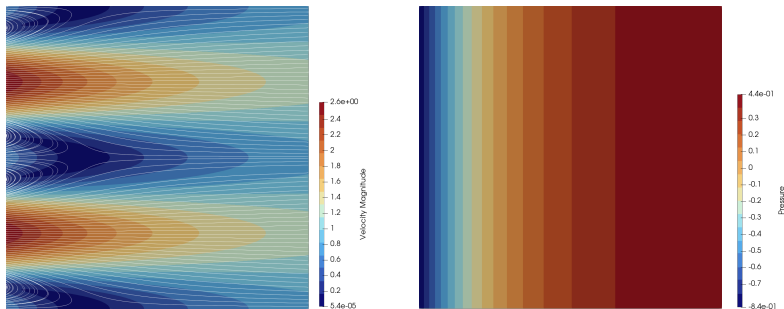


Figure: Velocity streamlines and magnitude (left) and pressure magnitude (right) for the HHO solution of the Kovasznay problem with the scheme of Botti et al. 2019 on a Cartesian mesh.

Comparison between HHO and HYPRE for the Kovasznay problem II

i	h	size	velocity h1 norm		velocity l2 norm		pressure l2 norm	
			error	rate	error	rate	error	rate
$k = 0$								
1	3.5355e-01	736	4.3351e+00	—	1.6481e+00	—	1.5461e-01	—
2	1.7678e-01	3008	2.9067e+00	0.58	5.5621e-01	1.57	7.1725e-02	1.11
3	8.8388e-02	12160	1.5853e+00	0.87	1.5297e-01	1.86	3.0772e-02	1.22
4	4.4194e-02	48896	7.9540e-01	1.00	3.8816e-02	1.98	1.3839e-02	1.15
$k = 1$								
1	3.5355e-01	1856	1.7135e+00	—	3.1462e-01	—	2.7420e-02	—
2	1.7678e-01	7552	4.7569e-01	1.85	4.6311e-02	2.76	5.9505e-03	2.20
3	8.8388e-02	30464	1.1923e-01	2.00	5.8691e-03	2.98	1.4300e-03	2.06
4	4.4194e-02	122368	2.8157e-02	2.08	6.8695e-04	3.09	3.7818e-04	1.92

Table: Convergence of the HHO method using the velocity-pressure coupling bilinear form `velocity_pressure`.

Comparison between HHO and HYPRE for the Kovasznay problem III

i	h	size	velocity h1 norm		velocity l2 norm		pressure l2 norm	
			error	rate	error	rate	error	rate
$k = 0$								
1	3.5355e-01	1073	2.7186e+00	—	9.7862e-01	—	1.8236e-01	—
2	1.7678e-01	4321	2.1961e+00	0.31	4.0189e-01	1.28	9.1591e-02	0.99
3	8.8388e-02	17345	1.4356e+00	0.61	1.3301e-01	1.60	4.1867e-02	1.13
4	4.4194e-02	69505	8.5016e-01	0.76	4.0344e-02	1.72	1.9450e-02	1.11
$k = 1$								
1	3.5355e-01	2529	9.8806e-01	—	1.6405e-01	—	3.0343e-02	—
2	1.7678e-01	10177	2.3755e-01	2.06	2.2946e-02	2.84	5.7044e-03	2.41
3	8.8388e-02	40833	6.6929e-02	1.83	3.2898e-03	2.80	1.4608e-03	1.97
4	4.4194e-02	163585	1.8953e-02	1.82	4.6687e-04	2.82	3.6503e-04	2.00

Table: Convergence of the HYPRE method of Beirão da Veiga et al. 2025 using the `raviart_thomas_interpolator_polykpo` operator.

Edge operators with vertex terms I

- Let

$$\underline{u}_E = (u_E, g_{n,E}, (u_V, g_V)_{V \in \mathcal{V}_E}) \in \mathcal{P}^{k-1}(E) \times \mathcal{P}^k(E) \times \bigtimes_{V \in \mathcal{V}_E} (\mathbb{R} \times \mathbb{R}^2)$$

- Consider the **edge Hessian reconstruction** s.t., for all $w \in \mathcal{P}^{k+1}(E)^2$,

$$\begin{aligned} \int_E \mathbf{H}_E^{k+1} \underline{u}_E \cdot w &= \int_E u_E \partial_{t_E}^2 w \cdot t_E - \int_E g_{n,E} \partial_{t_E} w \cdot n_E \\ &\quad + \sum_{V \in \mathcal{V}_E} \omega_{EV} (g_V \cdot w(V) - u_V \partial_{t_E} w(V) \cdot t_E) \end{aligned}$$

- This operator approximates $\nabla^2 u t_E$

Edge operators with vertex terms II

```
operator edge_hessian : Uh(u) -> Poly(k+1, vector) on edge E
{
  forall w in Poly(k+1, vector):
    int(E) edge_hessian(u) dot w =
      int(E) dof(u, E, edge_value)
        * (tangential_derivative(tangential_derivative(w))
      dot tangent(E))
    - int(E) dof(u, E, edge_normal_derivative)
      * (tangential_derivative(w) dot normal(E))
    + sum_vertices(orientation(V, E) * (
      dof(u, V, vertex_gradient) dot w(V)
      - dof(u, V, vertex_value) * (tangential_derivative(
w) dot tangent(E))
    )
  )
}
```

Orthogonal complement polynomial spaces I

■ Let

$$\underline{u}_T = (u_T, (u_E, G_E)_{E \in \mathcal{E}_T}) \in \mathcal{P}^k(T) \times \bigtimes_{E \in \mathcal{E}_T} (\mathcal{P}^k(E)^2 \times \mathcal{P}^k(E))$$

■ Consider the **deflection reconstruction** of Bonaldi et al. 2018 s.t.

► For all $z \in \mathcal{P}^{k+2}(T)$ orthogonal to $\mathcal{P}^1(T)$,

$$\begin{aligned} \int_T \nabla^2 p_T^{k+2} \underline{u}_T : \nabla^2 w &= \int_T u_T \operatorname{div} \operatorname{div} \nabla^2 w \\ &+ \sum_{E \in \mathcal{E}_T} \left[\int_E G_E \nabla^2 w n_{TE} - \int_E u_E (\operatorname{div} \nabla^2 w \cdot n_{TE}) \right], \end{aligned}$$

► For all $z \in \mathcal{P}^1(T)$,

$$\int_T p_T^{k+2} \underline{u}_T z = \int_T u_T z$$

Orthogonal complement polynomial spaces II

```
operator deflection_reconstruction : Uh(u) -> Poly(k+2,
    scalar) on element T {
  forall w in orthogonal complement of Poly(1, scalar)
    relative to Poly(k+2, scalar):
    int(T) grad(grad(deflection_reconstruction(u))) dot grad(
      grad(w)) =
    int(T) dof(u, T) * div(div(grad(grad(w))))
    + int(dT) dof(u, E, edge_gradient) dot (grad(grad(w)) dot
      normal)
    - int(dT) dof(u, E, edge_value) * (div(grad(grad(w))) dot
      normal)
  forall w in Poly(1, scalar):
    int(T) deflection_reconstruction(u) * w = int(T) dof(u, T
    ) * w
}
```

Another comparison, this time on plates

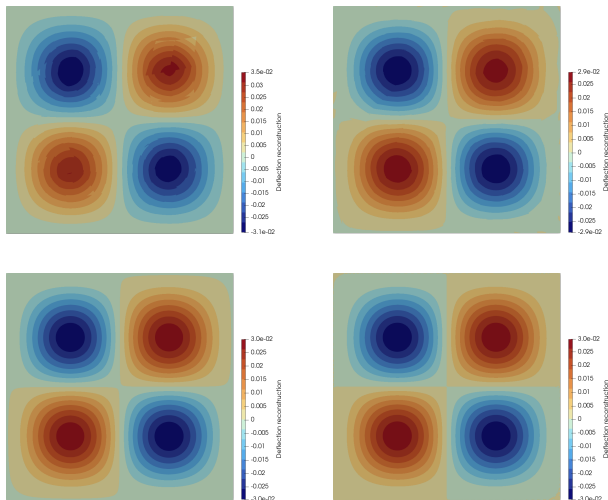


Figure: Comparison of HHO (left) and DDR (right) for the four-point load Kirchhoff–Love problem on a coarse (top) and fine (bottom) mesh.

Subdomains labels I

```
subdomain labels { navier_stokes = 1, darcy = 2 }

residual form convective_residual
: Uh(state w) times Uh(test v) on element T {
  sum_elements(navier_stokes)
  (
    int(T) (grad(dof(w, T)) dot dof(w, T)) dot dof(v, T)
    + 0.5 * int(dT) (dof(w, T) dot normal) * (dof(w, E) -
dof(w, T)) dot (dof(v, E) + dof(v, T))
    + 0.5 * int(dT) abs(dof(w, E) dot normal) * (dof(w, E)
- dof(w, T)) dot (dof(v, E) - dof(v, T))
  )
}
```

Subdomains labels II

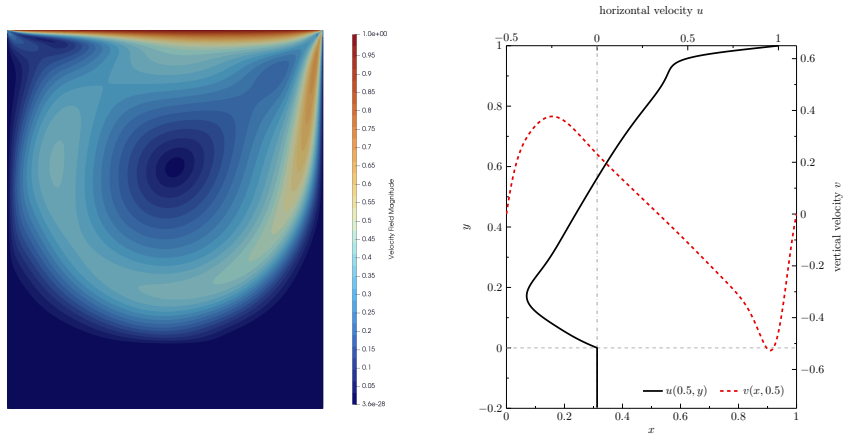


Figure: Lid-driven cavity flow over an impermeable bedding.

An unsteady non-linear problem

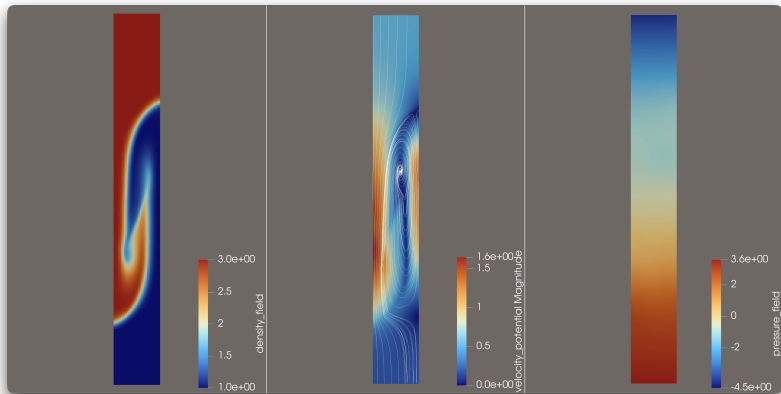


Figure: HHO simulation of the Rayleigh–Taylor instability

3D available since v0.11.0

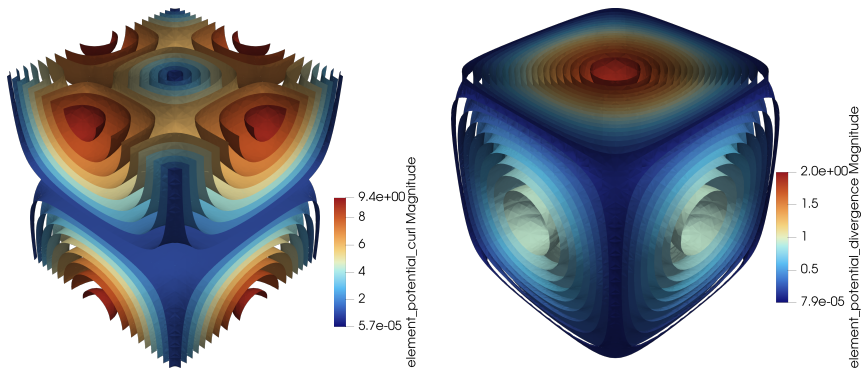


Figure: DDR simulation of the magnetostatic problem⁴

⁴Di Pietro and Droniou 2021



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Thank you for your attention!

<https://polyrust.org>

References



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