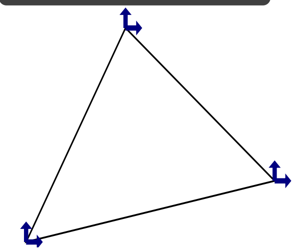
→ VELOCITY SPACE

P1 VELOCITY

4



$V_h = [\mathbb{P}^1(\mathcal{T}_h) \cap C^0(\Omega)]^2$

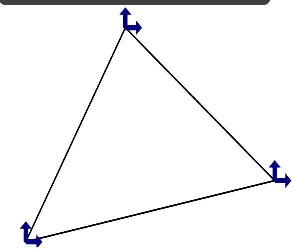
Piecewise linear functions which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). All d.o.f. are associated to vertices.

→ VELOCITY SPACE

P1 VELOCITY

4



$V_h = [\mathbb{P}^1(\mathcal{T}_h) \cap C^0(\Omega)]^2$

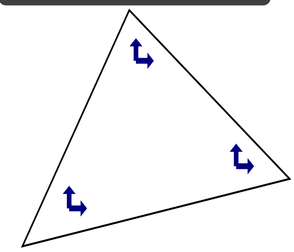
Piecewise linear functions which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). All d.o.f. are associated to vertices.

→ VELOCITY SPACE

P1* VELOCITY

4



$V_h = [\mathbb{P}^1(\mathcal{T}_h)]^2$

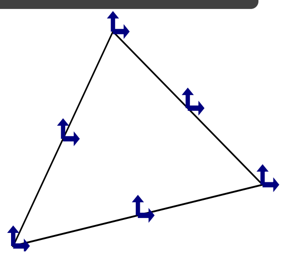
Piecewise linear functions without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

→ VELOCITY SPACE

P2 VELOCITY

3



$V_h = [\mathbb{P}^2(\mathcal{T}_h) \cap C^0(\Omega)]^2$

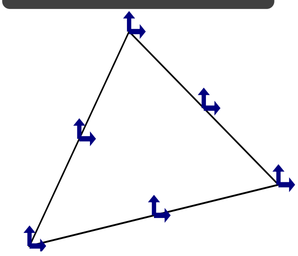
Piecewise polynomials up to degree 2 which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). If located on vertex or edge, d.o.f. are associated accordingly.

→ VELOCITY SPACE

P2 VELOCITY

3



$V_h = [\mathbb{P}^2(\mathcal{T}_h) \cap C^0(\Omega)]^2$

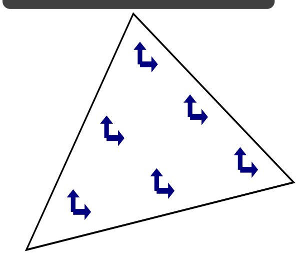
Piecewise polynomials up to degree 2 which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). If located on vertex or edge, d.o.f. are associated accordingly.

→ VELOCITY SPACE

P2* VELOCITY

3



$V_h = [\mathbb{P}^2(\mathcal{T}_h)]^2$

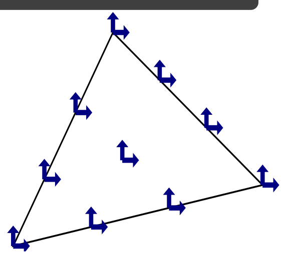
Piecewise polynomials up to degree 2 without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

→ VELOCITY SPACE

P3 VELOCITY

2



$V_h = [\mathbb{P}^3(\mathcal{T}_h) \cap C^0(\Omega)]^2$

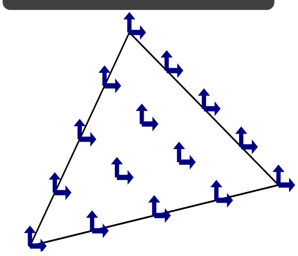
Piecewise polynomials up to degree 3 which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). If located on vertex or edge, d.o.f. are associated accordingly.

→ VELOCITY SPACE

P4 VELOCITY

1



$V_h = [\mathbb{P}^4(\mathcal{T}_h) \cap C^0(\Omega)]^2$

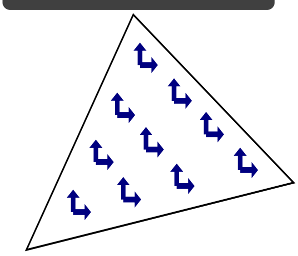
Piecewise polynomials up to degree 4 which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). If located on vertex or edge, d.o.f. are associated accordingly.

→ VELOCITY SPACE

P3* VELOCITY

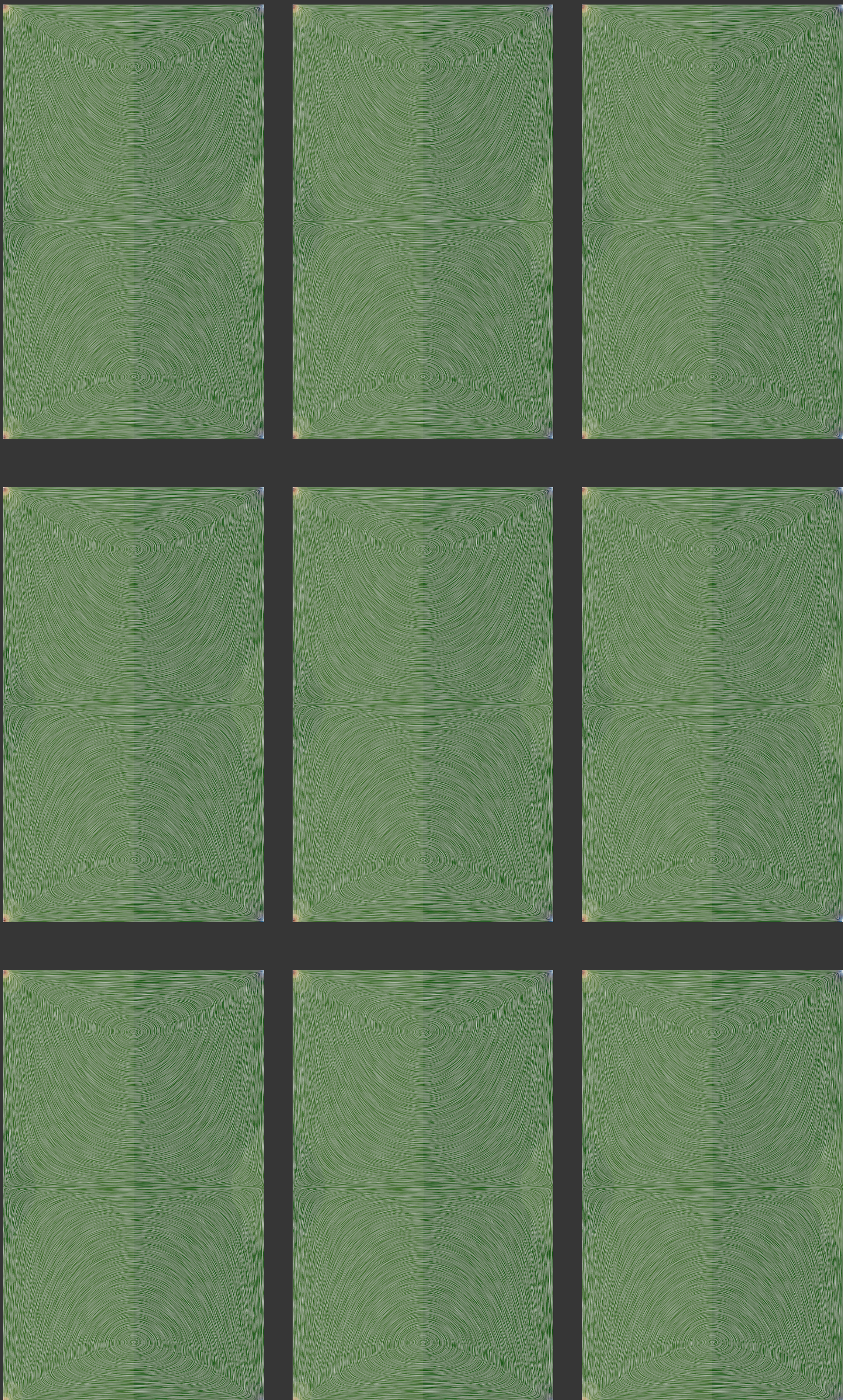
2



$V_h = [\mathbb{P}^3(\mathcal{T}_h)]^2$

Piecewise polynomials up to degree 3 without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

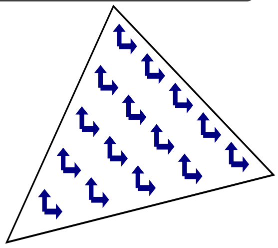


→

VELOCITY SPACE

P4* VELOCITY

1



$V_h = [\mathbb{P}^4(\mathcal{T}_h)]^2$

Piecewise polynomials up to degree 4 without continuity across element interfaces enforced in the space.

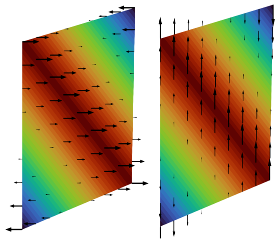
The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

→

VELOCITY SPACE

CROUZEIX-RAVIART

4



$V_h = \{v_h \in [\mathbb{P}^1(\mathcal{T}_h)]^2 \mid \Pi_F^0 [\![v_h]\!] = 0 \ \forall F \in \mathcal{F}_h\}$

Piecewise linear functions which are continuous, in both components, across edge midpoints (or equivalently continuous in the mean value across edges).

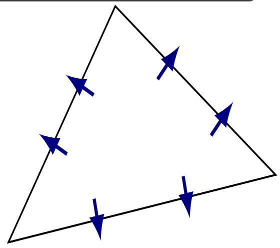
The sketch shows the two basis functions for x- and y- component associated to a single edge.

→

VELOCITY SPACE

BDM1 VELOCITY

4



$V_h = \mathbb{BDM}^1(\mathcal{T}_h) \cap H(\mathrm{div})$

Piecewise linear functions with (only) normal component continuous across element interfaces.

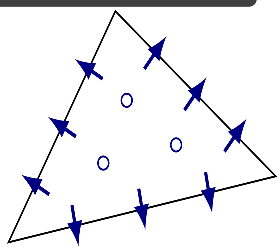
The sketch shows the d.o.f. on a triangle (each arrow indicating a scalar d.o.f.). All d.o.f. are associated to an edge.

→

VELOCITY SPACE

BDM2 VELOCITY

3



$V_h = \mathbb{BDM}^2(\mathcal{T}_h) \cap H(\mathrm{div})$

Piecewise polynomials up to degree 2 with (only) normal component continuous across element interfaces.

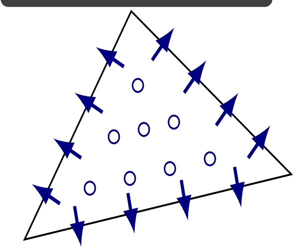
The sketch shows the d.o.f. on a triangle (each arrow/circle indicating a scalar d.o.f.). If located there d.o.f. are associated to an edge.

→

VELOCITY SPACE

BDM3 VELOCITY

2



$V_h = \mathbb{BDM}^3(\mathcal{T}_h) \cap H(\mathrm{div})$

Piecewise polynomials up to degree 3 with (only) normal component continuous across element interfaces.

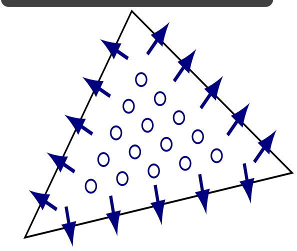
The sketch shows the d.o.f. on a triangle (each arrow/circle indicating a scalar d.o.f.). If located there d.o.f. are associated to an edge.

→

VELOCITY SPACE

BDM4 VELOCITY

1



$V_h = \mathbb{BDM}^4(\mathcal{T}_h) \cap H(\mathrm{div})$

Piecewise polynomials up to degree 4 with (only) normal component continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each arrow/circle indicating a scalar d.o.f.). If located there d.o.f. are associated to an edge.

→

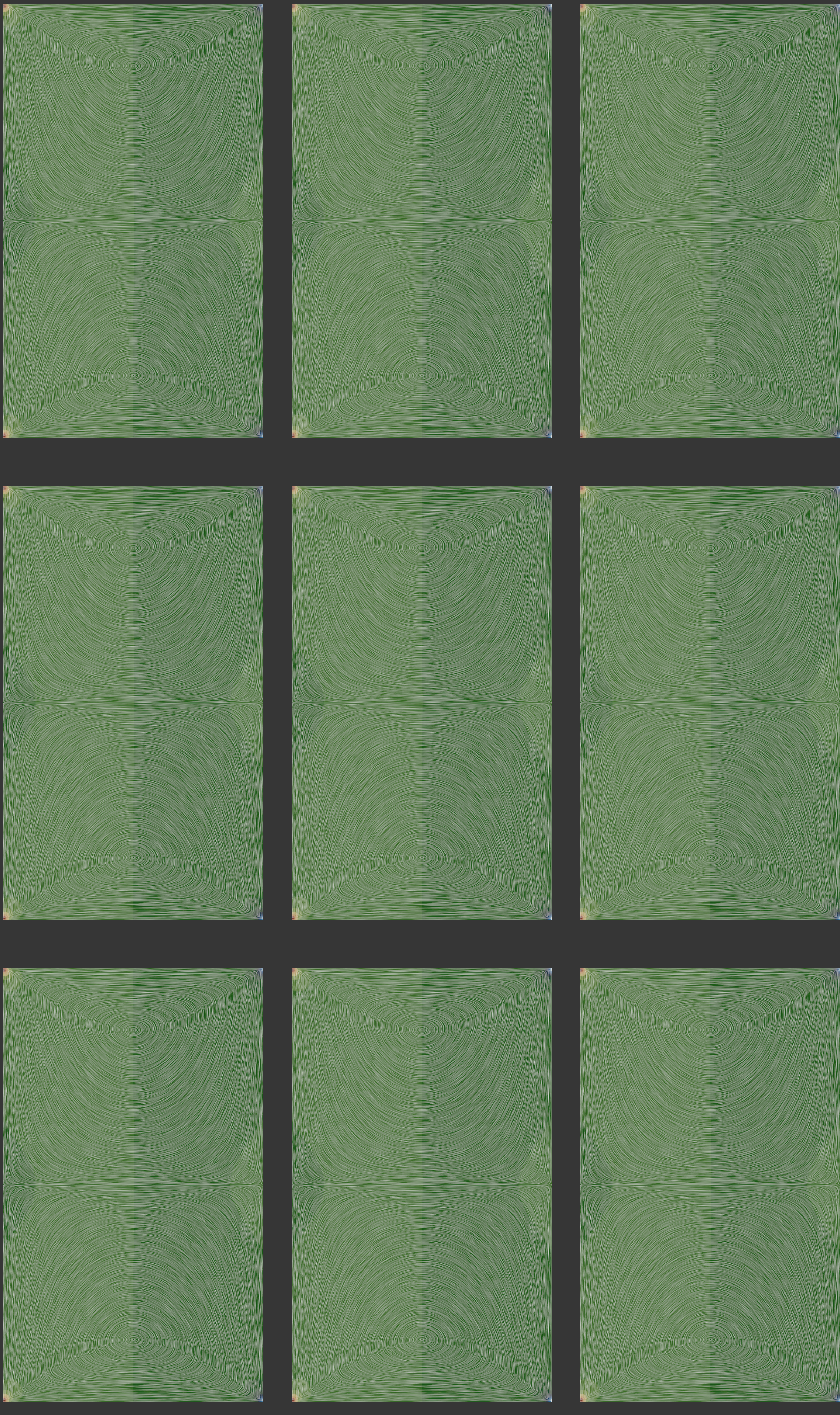
VELOCITY SPACE

→

VELOCITY SPACE

→

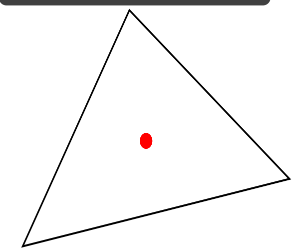
VELOCITY SPACE



PRESSURE SPACE

P0 PRESSURE

1



$Q_h = \mathbb{P}^0(\mathcal{T}_h)$

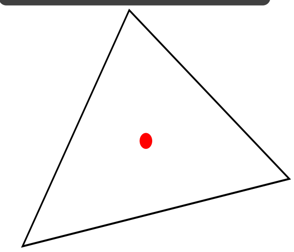
Piecewise constant functions without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

PRESSURE SPACE

P0 PRESSURE

1



$Q_h = \mathbb{P}^0(\mathcal{T}_h)$

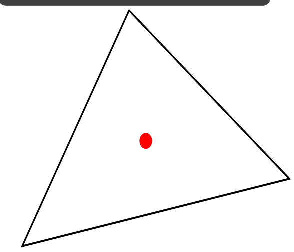
Piecewise constant functions without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

PRESSURE SPACE

P0 PRESSURE

1



$Q_h = \mathbb{P}^0(\mathcal{T}_h)$

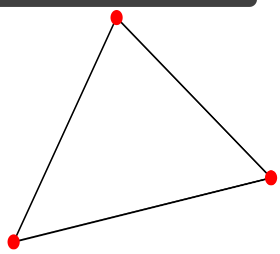
Piecewise constant functions without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

PRESSURE SPACE

P1 PRESSURE

2



$Q_h = \mathbb{P}^1(\mathcal{T}_h) \cap C^0(\Omega)$

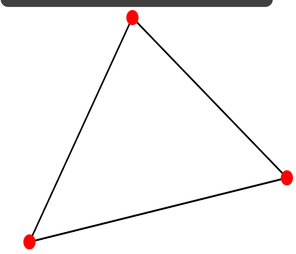
Piecewise linear functions which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). All d.o.f. are associated to vertices.

PRESSURE SPACE

P1 PRESSURE

2



$Q_h = \mathbb{P}^1(\mathcal{T}_h) \cap C^0(\Omega)$

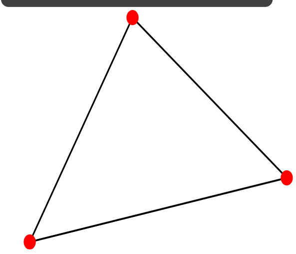
Piecewise linear functions which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). All d.o.f. are associated to vertices.

PRESSURE SPACE

P1 PRESSURE

2



$Q_h = \mathbb{P}^1(\mathcal{T}_h) \cap C^0(\Omega)$

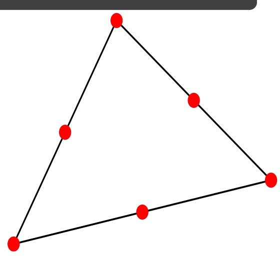
Piecewise linear functions which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). All d.o.f. are associated to vertices.

PRESSURE SPACE

P2 PRESSURE

3



$Q_h = \mathbb{P}^2(\mathcal{T}_h) \cap C^0(\Omega)$

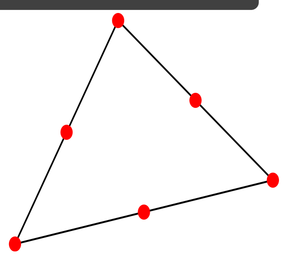
Piecewise polynomials up to degree 2 which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). If located on vertex or edge, d.o.f. are associated accordingly.

PRESSURE SPACE

P2 PRESSURE

3



$Q_h = \mathbb{P}^2(\mathcal{T}_h) \cap C^0(\Omega)$

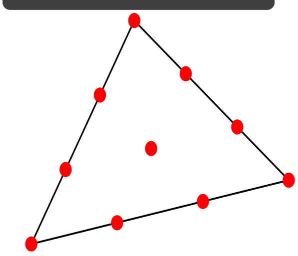
Piecewise polynomials up to degree 2 which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). If located on vertex or edge, d.o.f. are associated accordingly.

PRESSURE SPACE

P3 PRESSURE

4



$Q_h = \mathbb{P}^3(\mathcal{T}_h) \cap C^0(\Omega)$

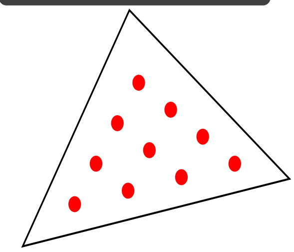
Piecewise polynomials up to degree 3 which are continuous across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). If located on vertex or edge, d.o.f. are associated accordingly.

4

P3* PRESSURE

PRESSURE SPACE



$Q_h = \mathbb{P}^3(\mathcal{T}_h)$

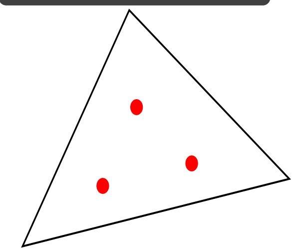
Piecewise polynomials up to degree 2 without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

2

P1* PRESSURE

PRESSURE SPACE



$Q_h = \mathbb{P}^1(\mathcal{T}_h)$

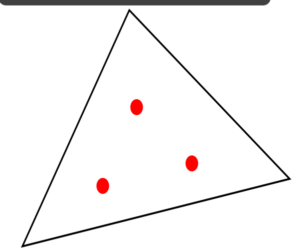
Piecewise linear functions without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

2

P1* PRESSURE

PRESSURE SPACE



$Q_h = \mathbb{P}^1(\mathcal{T}_h)$

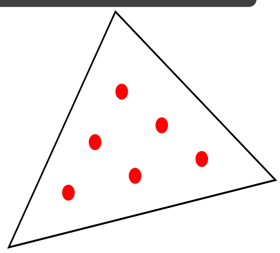
Piecewise linear functions without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

3

P2* PRESSURE

PRESSURE SPACE



$Q_h = \mathbb{P}^2(\mathcal{T}_h)$

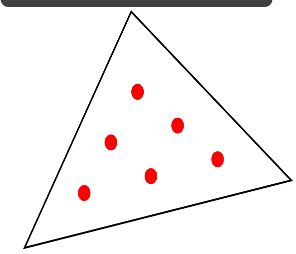
Piecewise polynomials up to degree 2 without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

3

P2* PRESSURE

PRESSURE SPACE



$Q_h = \mathbb{P}^2(\mathcal{T}_h)$

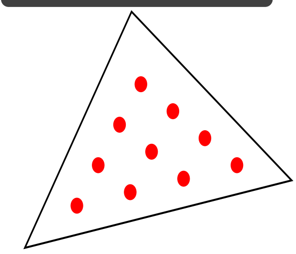
Piecewise polynomials up to degree 2 without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

4

P3* PRESSURE

PRESSURE SPACE



$Q_h = \mathbb{P}^3(\mathcal{T}_h)$

Piecewise polynomials up to degree 2 without continuity across element interfaces.

The sketch shows the d.o.f. on a triangle (each dot indicating a scalar d.o.f.). No d.o.f. is associated to a vertex or edge.

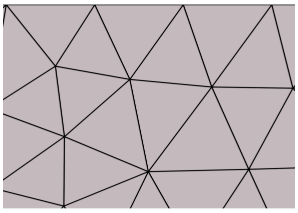
PRESSURE SPACE

PRESSURE SPACE

PRESSURE SPACE

MESHES

UNSTRUCTURED M. 2

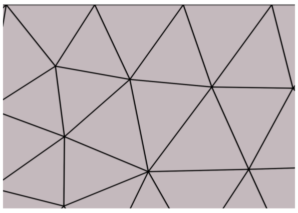


Unstructured mesh

Unstructured triangular mesh with shape regular straight elements.

MESHES

UNSTRUCTURED M. 2

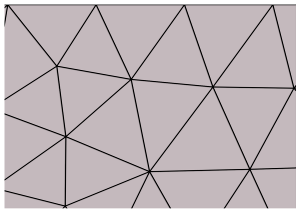


Unstructured mesh

Unstructured triangular mesh with shape regular straight elements.

MESHES

UNSTRUCTURED M. 2

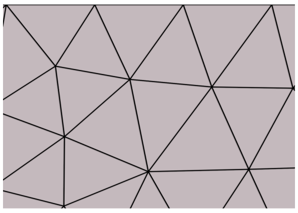


Unstructured mesh

Unstructured triangular mesh with shape regular straight elements.

MESHES

UNSTRUCTURED M. 2

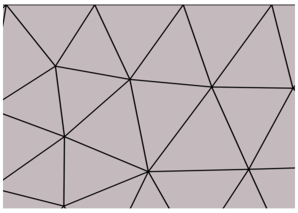


Unstructured mesh

Unstructured triangular mesh with shape regular straight elements.

MESHES

UNSTRUCTURED M. 2

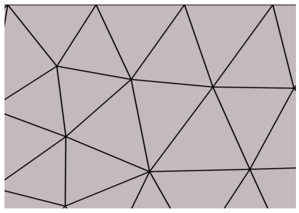


Unstructured mesh

Unstructured triangular mesh with shape regular straight elements.

MESHES

UNSTRUCTURED M. 2

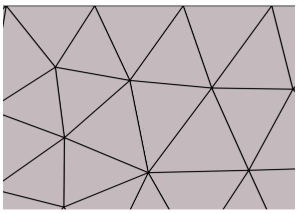


Unstructured mesh

Unstructured triangular mesh with shape regular straight elements.

MESHES

UNSTRUCTURED M. 2

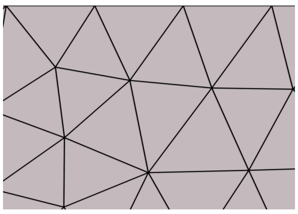


Unstructured mesh

Unstructured triangular mesh with shape regular straight elements.

MESHES

UNSTRUCTURED M. 2

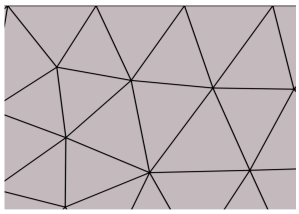


Unstructured mesh

Unstructured triangular mesh with shape regular straight elements.

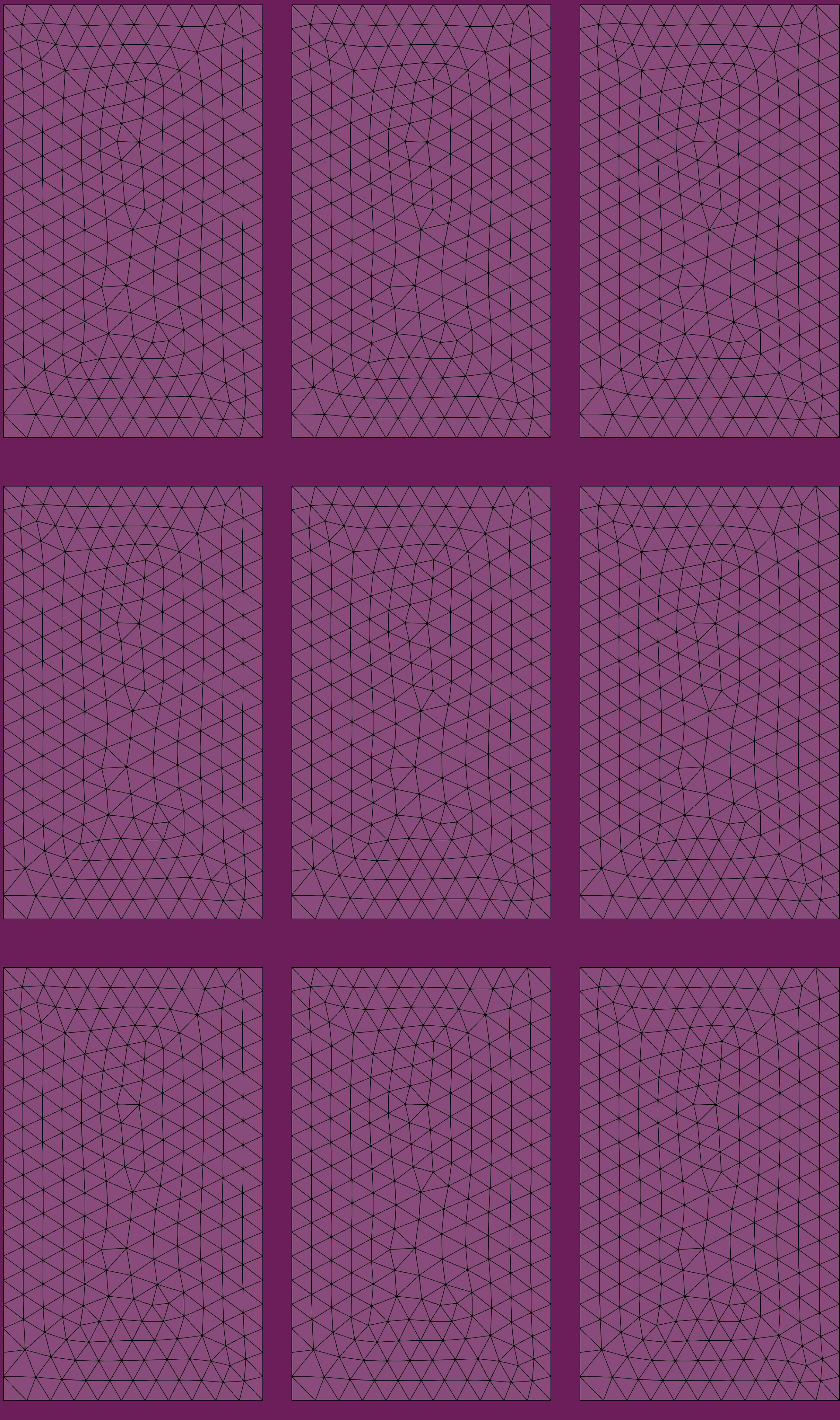
MESHES

UNSTRUCTURED M. 2



Unstructured mesh

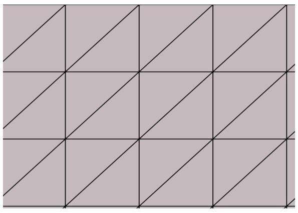
Unstructured triangular mesh with shape regular straight elements.



MESHES

TYPE ONE MESH

1



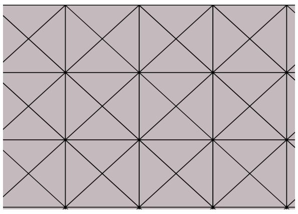
Type one mesh

Structured triangular mesh with straight elements.

MESHES

SING. VERTEX MESH

3



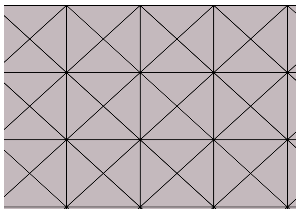
Singular vertex mesh

Triangular mesh of straight shape regular elements with singular vertices.
An example of a singular vertex mesh is a *criss-cross* mesh as shown in the sketch.

MESHES

SING. VERTEX MESH

3



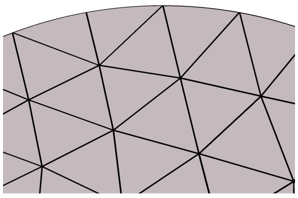
Singular vertex mesh

Triangular mesh of straight shape regular elements with singular vertices.
An example of a singular vertex mesh is a *criss-cross* mesh as shown in the sketch.

MESHES

CURVED MESH

4



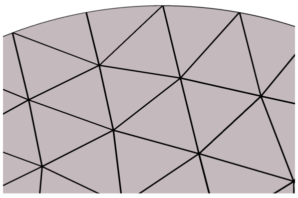
Curved mesh

Triangular mesh with shape regular elements including *curved* boundary elements as illustrated in the sketch.

MESHES

CURVED MESH

4



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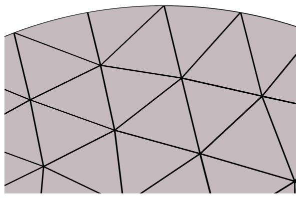
Triangular mesh with shape regular elements including *curved* boundary elements as illustrated in the sketch.

MESHES

CURVED MESH

4



Curved mesh

Triangular mesh with shape regular elements including *curved* boundary elements as illustrated in the sketch.

MESHES

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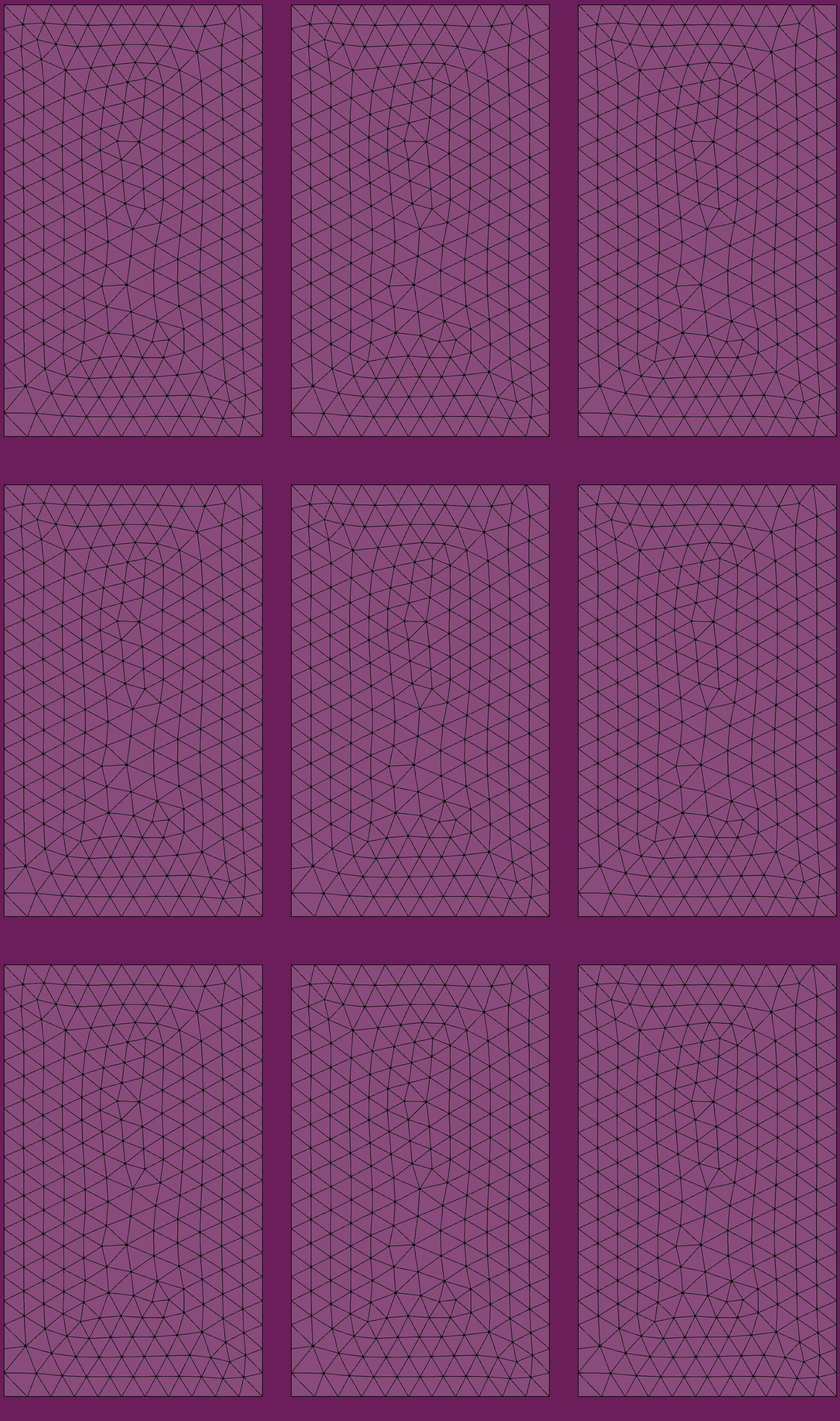
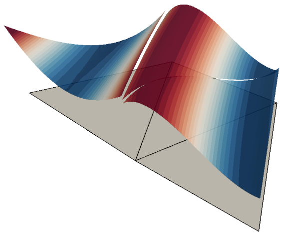


INTERIOR PENALTY 0

EXTRA TOOLS



$$s_h^{\mathrm{ip}}((u,p),(v,q)) = (\{\!\{-\nu\nabla u + pI\}\!\}\cdot n, [\![v]\!])_{\mathcal{F}_h} + ..\mathrm{sym}.. + (\tfrac{\lambda\nu}{h}[\![u]\!], [\![v]\!])_{\mathcal{F}_h}$$

Interior penalty DG terms added to the variational formulation to weakly enforce continuity of the velocity.

Keeps discretizations with continuous velocity spaces unaffected.

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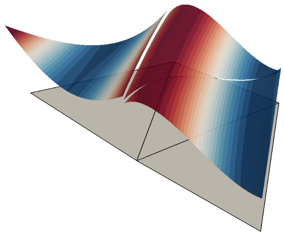

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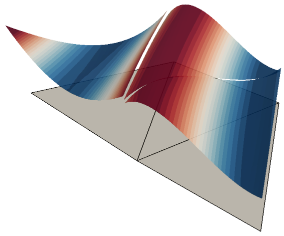

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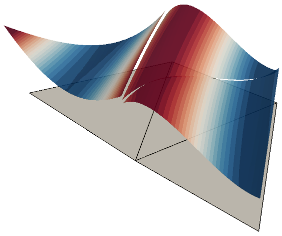

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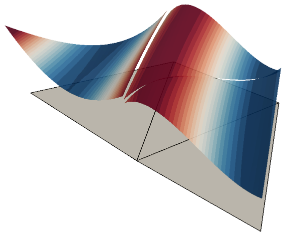

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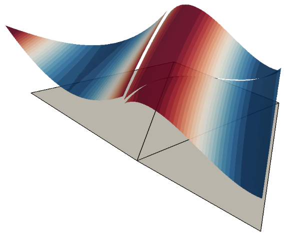

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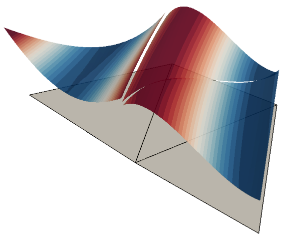

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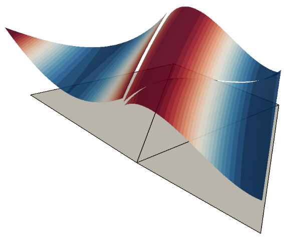

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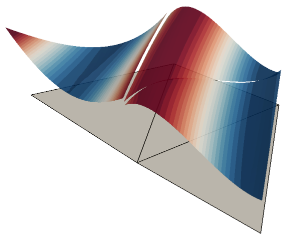

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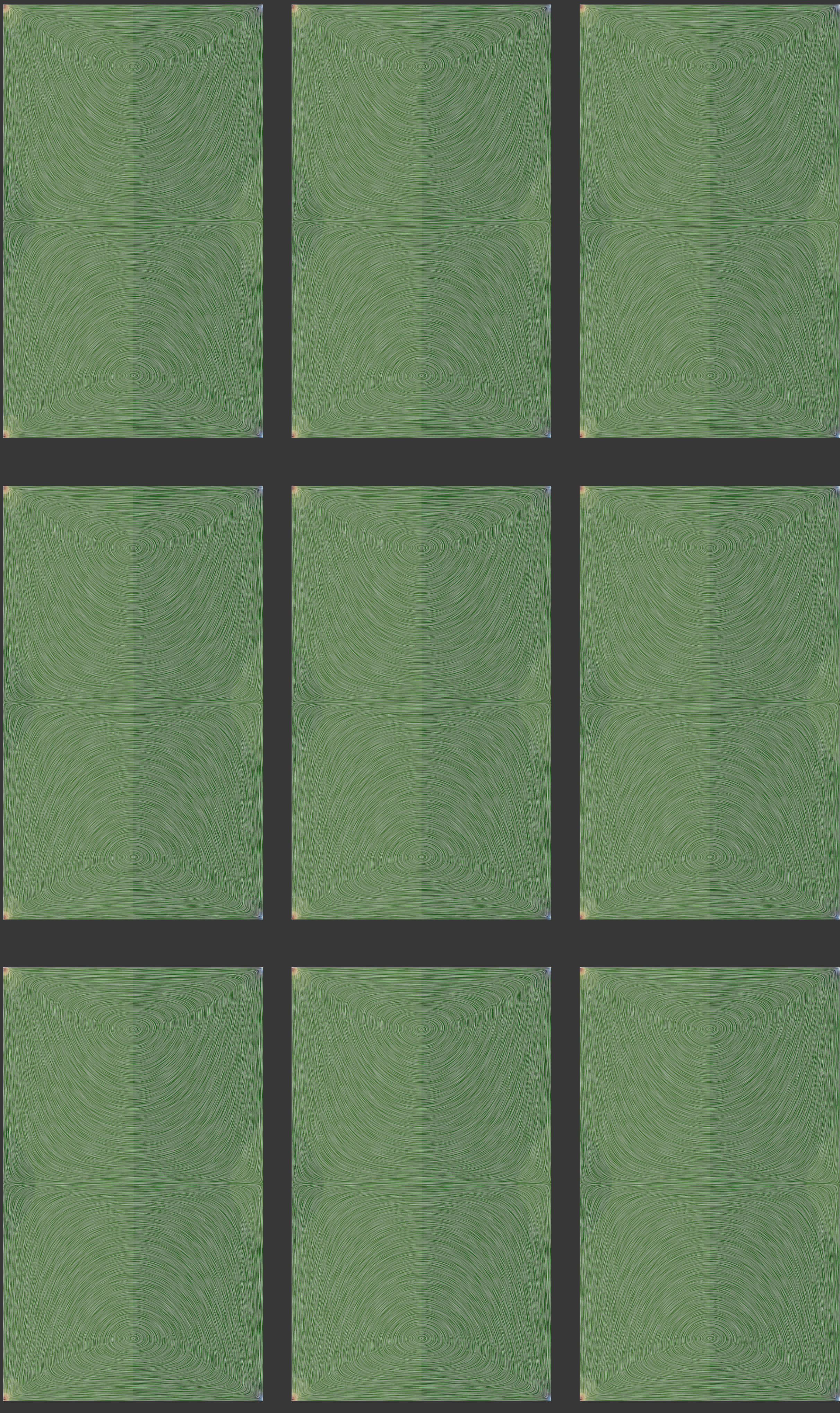
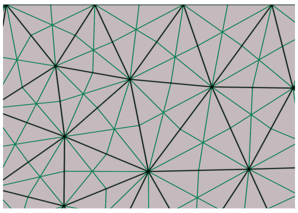


EXTRA TOOLS

POWELL-SABIN SPLIT

-1



Powell-Sabin split

Refines triangular, shape regular mesh by connecting vertices to the opposite edge by a straight line through the incircle center.

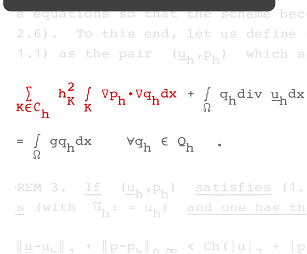
If combined with Alfeld split, the Alfeld split is ignored.

Can also be applied to curved meshes.

EXTRA TOOLS

BREZZI-PITKÄRANTA

-2



e equations so that the scheme bec
2.6). To this end, let us define
1.1) as the pair $(\underline{u}_h, p_h)$ which s

$$\sum_{K\in C_h} h_K^2 \int_K \nabla p_h\cdot\nabla q_h dx + \int_\Omega q_h \operatorname{div} \underline{u}_h dx$$

$$= \int_\Omega g q_h dx \qquad \forall q_h \in Q_h \quad .$$

REM 3. If $(\underline{u}_h, p_h)$ satisfies (1.
s (with $\tilde{u}_h := u_h$) and one has th

$$s_h^{\mathrm{bp}}((u,p),(v,p)) = (h^2\nabla p, \nabla q)_{\mathcal{T}_h}$$

Pressure stabilization that turns every Stokes pair with a continuous pressure into a stable discretization.

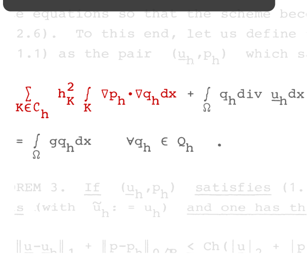
Spoils mass conservation.

Limits consistency to low order.

EXTRA TOOLS

BREZZI-PITKÄRANTA

-2



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PRESSURE-JUMP

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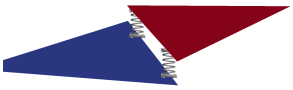

$$s_h^{\mathrm{pj}}((u,p),(v,p)) = (h[\![p]\!], [\![q]\!])_{\mathcal{F}_h}$$

Pressure stabilization penalizing pressure discontinuities.

Can be used to effectively treat a discontinuous pressure as a continuous pressure; $Q_h \rightsquigarrow Q_h \cap C^0(\Omega)$.

Spoils mass conservation.

Keeps discretizations with continuous pressure spaces unaffected.

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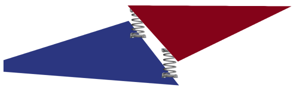

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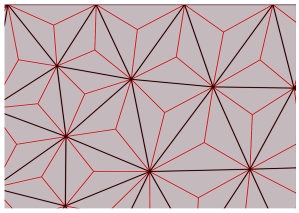
EXTRA TOOLS

ALFELD SPLIT

-1



Alfeld-split

Refines triangular, shape regular mesh by connecting vertices to the barycenter.

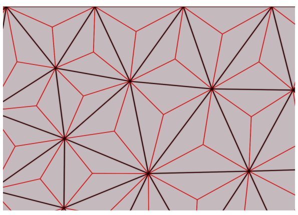
If combined with Powell-Sabin split, the Alfeld split is ignored.

Can also be applied to curved meshes.

EXTRA TOOLS

ALFELD SPLIT

-1



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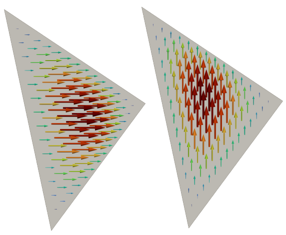
EXTRA TOOLS

P3 BUBBLE

-1



$V_h \rightsquigarrow V_h \bigoplus_{T\in\mathcal{T}_h} [\mathbb{B}^3(T)]^2$ with $\mathbb{B}^3(T) := \operatorname{span}(\lambda_1^T\cdot\lambda_2^T\cdot\lambda_3^T)$, λ_i^T : barycentric coordinate

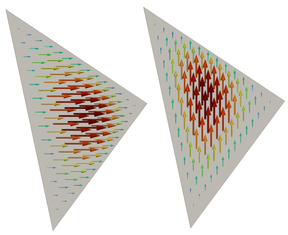
Enrichment of the velocity space with P3-bubble functions in each component.

Leaves velocity spaces with polynomials of degree 3 or higher unaffected.

EXTRA TOOLS

P3 BUBBLE

-1



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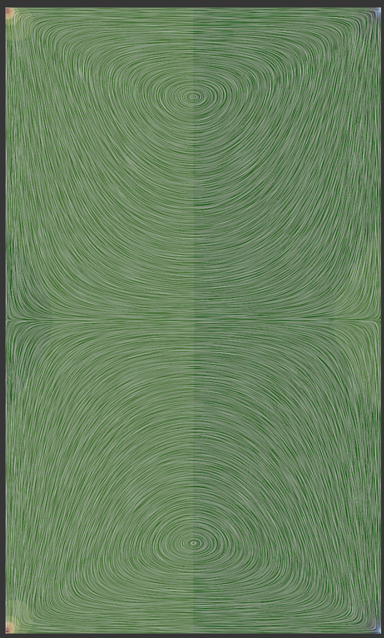
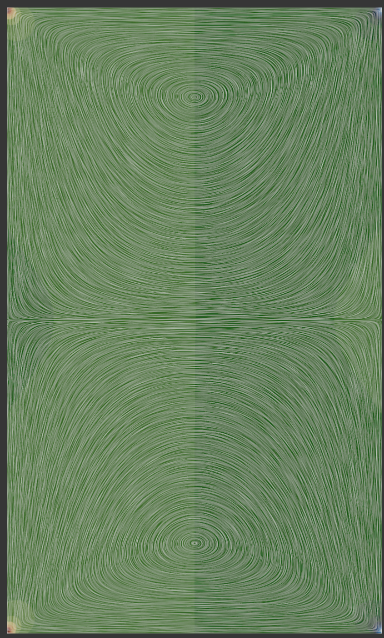
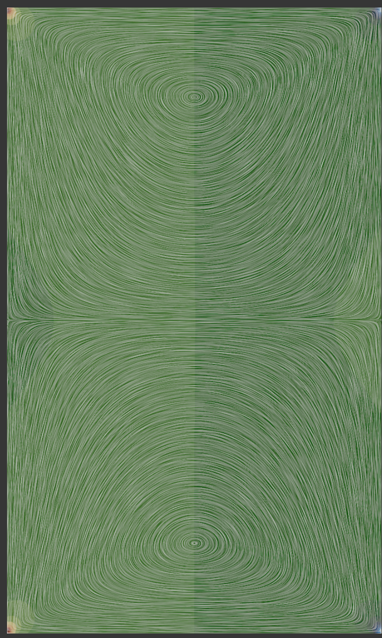
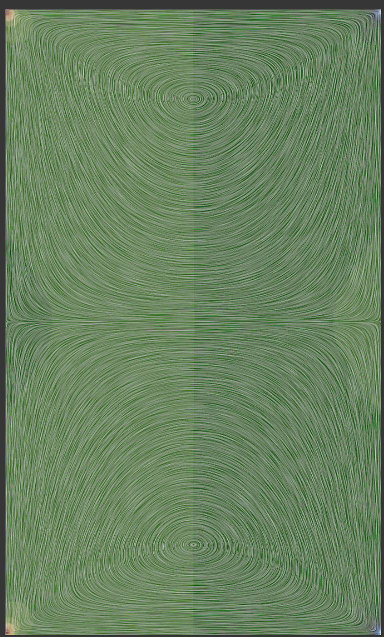
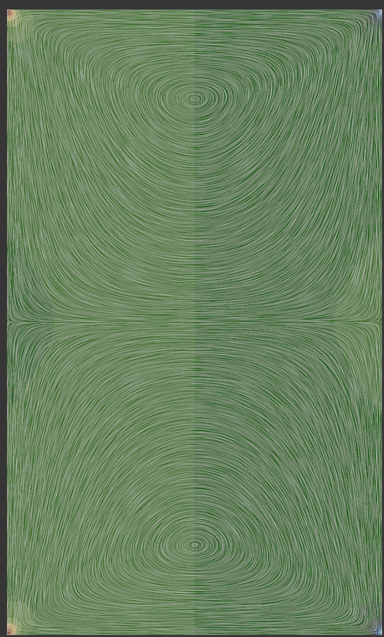
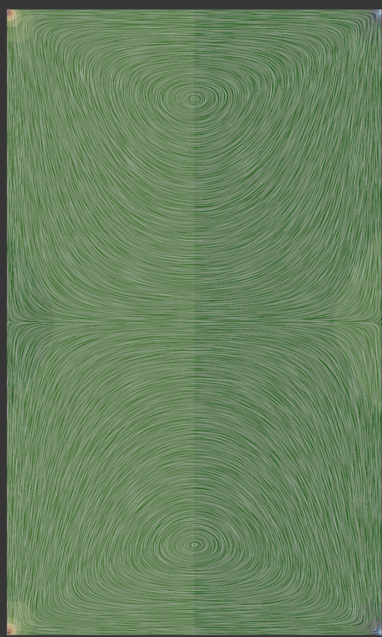
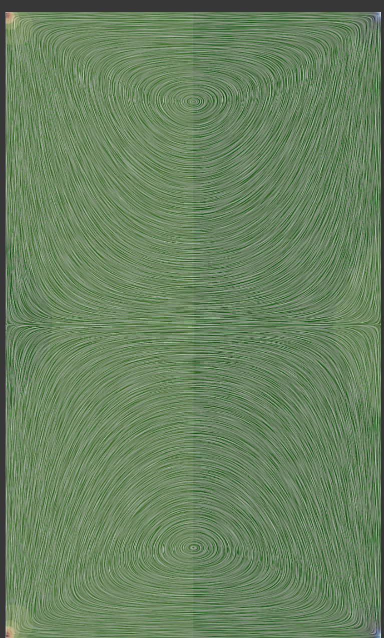
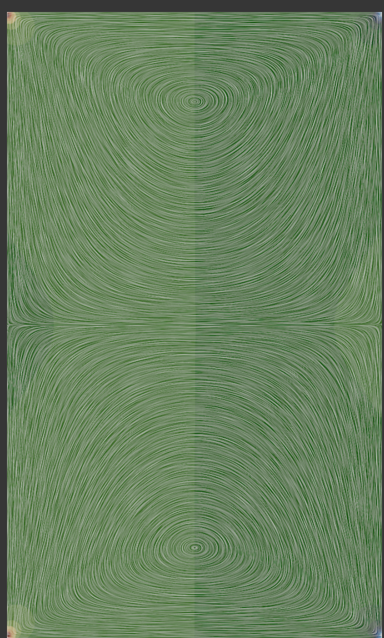


EXTRA TOOLS

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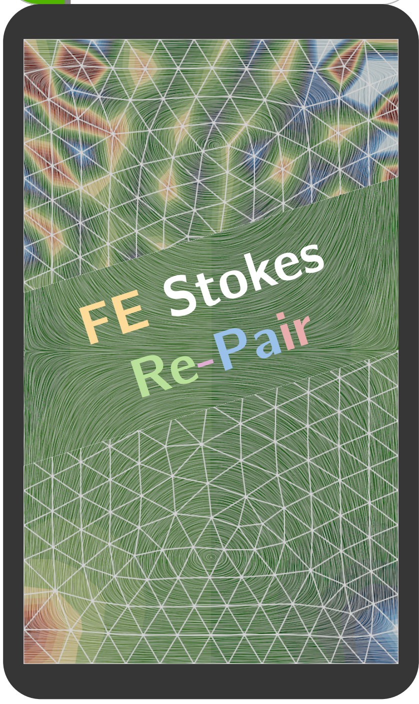

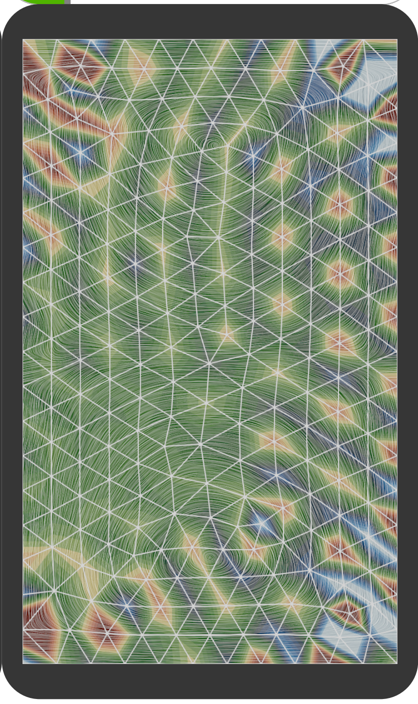

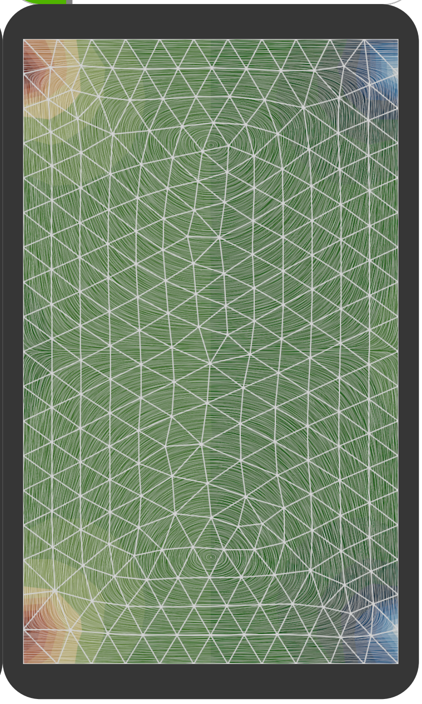

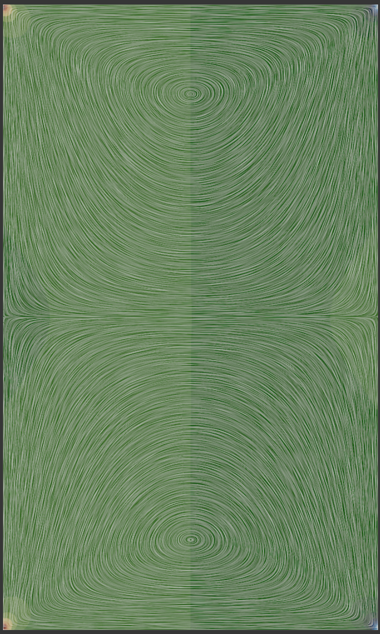
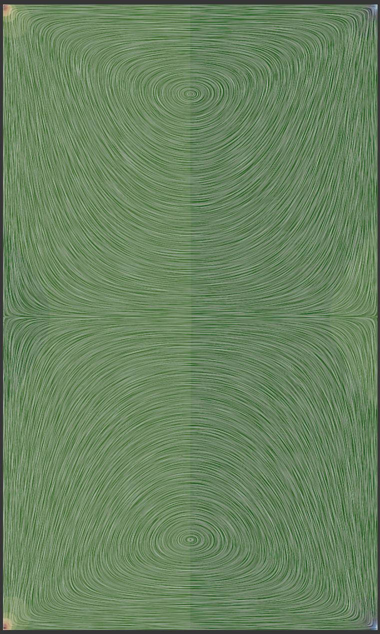
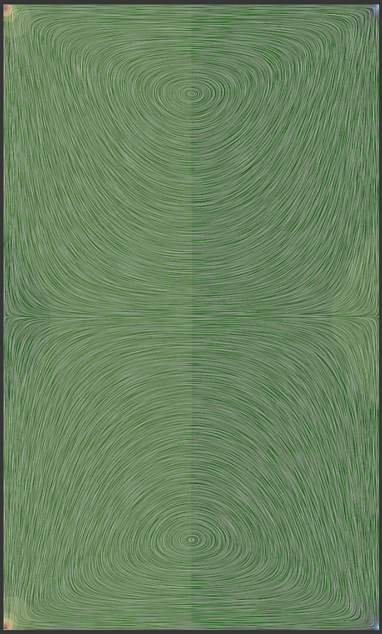
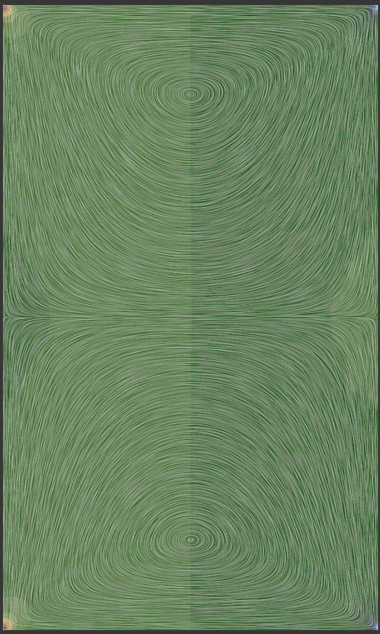
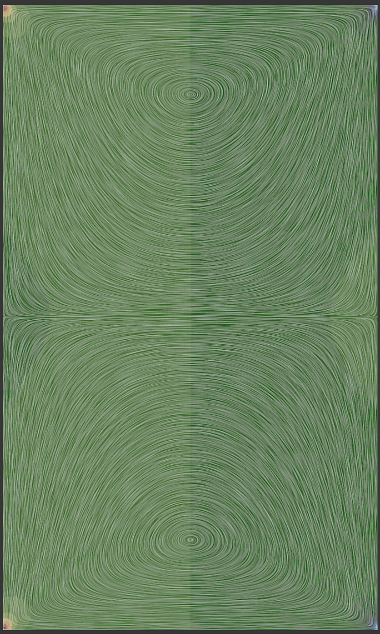
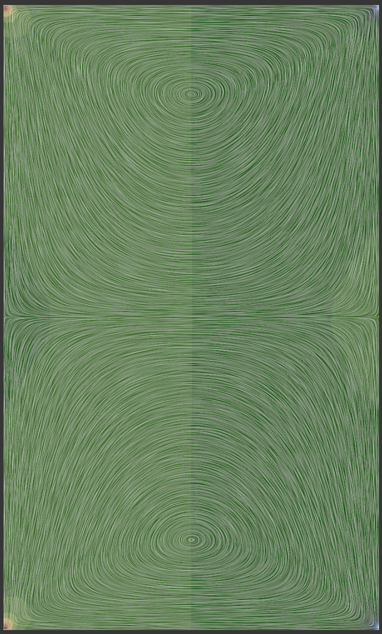
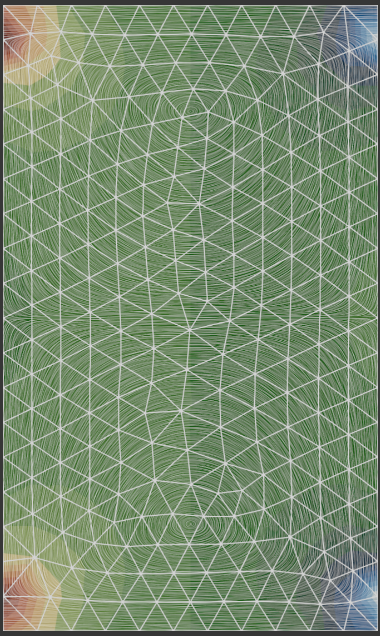
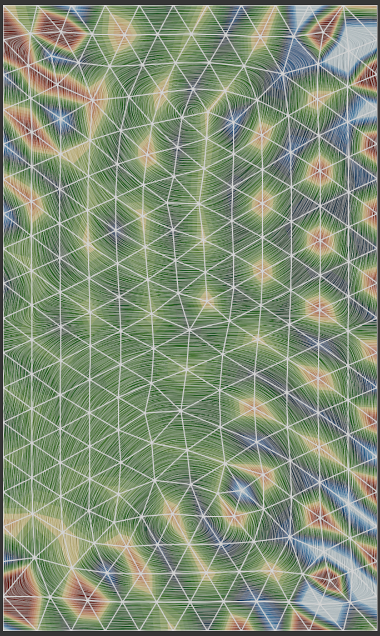

fe-nerd-games.github.io/
FEStokesRePair
rules
extensions
comments
questions
...

♡ REWARD

OPTIMAL CONVERGENCE RATES

2

Optimal convergence rates:

$\|u-u_h\|_1 \lesssim h^{k_u}$, $\|p-p_h\|_0 \lesssim h^{k_p}$,

with k_u, k_p largest numbers s.t.

$$\inf_{v_h \in V_h} \|u-v_h\|_1 \lesssim h^{k_u}$$

and $\inf_{q_h \in Q_h} \|p-q_h\|_0 \lesssim h^{k_p}$,

with L^2/H^1-type norms $\|\cdot\|_{0/1}$.

A Stokes discretization has optimal convergence rates if velocity and pressure errors converge with the same order as the approximation problem for velocity and pressure individually.

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A Stokes discretization has optimal convergence rates if velocity and pressure errors converge with the same order as the approximation problem for velocity and pressure individually.

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A pressure robust pair is a pair for which a large error in the approximation of the pressure is not reflected by a large error in the approximation of the velocity.

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