

A bound-preserving upwind DG scheme for the convective Cahn-Hilliard model



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Section 1

Linear convection

Linear convection problem

We consider the linear convection problem:

$$v_t + \nabla \cdot (\beta v) = 0 \quad \text{in } \Omega \times (0, T), \quad (1a)$$

$$v(0) = v_0 \quad \text{in } \Omega, \quad (1b)$$

where

- $\beta: \overline{\Omega} \rightarrow \mathbb{R}^d$ is continuous and **incompressible**, i.e., $\nabla \cdot \beta = 0$ in Ω ,
- $\beta \cdot \mathbf{n} = 0$ on $\partial\Omega$.

Properties:

- **Existence** and **uniqueness** of the solution.
- **Mass conservation**: $\frac{d}{dt} \int_{\Omega} v = 0$.
- **Maximum principle**: $\min_{\overline{\Omega}} v_0 \leq v \leq \max_{\overline{\Omega}} v_0$ in $\overline{\Omega} \times (0, T)$.

Discontinuous Galerkin methods

$$\mathbb{P}_k^{\text{disc}}(\mathcal{T}_h) := \left\{ v_h \in L^2(\Omega) : v_h|_{K_i} \in \mathbb{P}_k(K_i) \text{ with } K_i \in \mathcal{T}_h, \forall i \in \{1, 2, \dots, N_{\mathcal{T}_h}\} \right\}$$

with a basis $\{\phi_i\}_{i \in \{1, 2, \dots, N_h\}}$.

Notation:

- **Average:** $\{\{v\}\} := \begin{cases} \frac{v_K + v_L}{2} & \text{if } e = \partial K \cap \partial L \in \mathcal{E}_h^i, \\ v_K & \text{if } e = \partial K \in \mathcal{E}_h^b, \end{cases}$
- **Jump:** $[[v]] := \begin{cases} v_K - v_L & \text{if } e = \partial K \cap \partial L \in \mathcal{E}_h^i, \\ v_K & \text{if } e = \partial K \in \mathcal{E}_h^b, \end{cases}$
- **Positive part:** $v_{\oplus} := \frac{|v| + v}{2} = \max\{v, 0\},$
- **Negative part:** $v_{\ominus} := \frac{|v| - v}{2} = -\min\{v, 0\},$
- $v = v_{\oplus} - v_{\ominus}.$

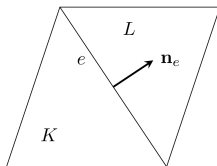


Figure: Orientation of unit normal vector.

DG upwind method

- $a_h^{\text{upw}} : \mathbb{P}_k^{\text{disc}}(\mathcal{T}_h) \times \mathbb{P}_k^{\text{disc}}(\mathcal{T}_h) \rightarrow \mathbb{R},$

$$\begin{aligned} a_h^{\text{upw}}(\beta; v, \bar{v}) &:= - \sum_{K \in \mathcal{T}_h} \int_K v(\beta \cdot \nabla \bar{v}) \\ &\quad + \sum_{e \in \mathcal{E}_h^i, e=K \cap L} \int_e ((\beta \cdot \mathbf{n}_e)_\oplus v_K - (\beta \cdot \mathbf{n}_e)_\ominus v_L) \llbracket \bar{v} \rrbracket \end{aligned}$$

Properties of the scheme for $k = 0$

Given $v^m \in \mathbb{P}_0^{\text{disc}}(\mathcal{T}_h)$, find $v^{m+1} \in \mathbb{P}_0^{\text{disc}}(\mathcal{T}_h)$ such that

$$\left(\frac{v^{m+1} - v^m}{\Delta t}, \bar{v} \right)_{L^2(\Omega)} + a_h^{\text{upw}}(\beta; v^{m+1}, \bar{v}) = 0$$

for every $\bar{v} \in \mathbb{P}_0^{\text{disc}}(\mathcal{T}_h)$.

Properties:

- **Existence** and **uniqueness** of the solution.
- **Mass conservation**: $\int_{\Omega} v^{m+1} = \int_{\Omega} v^m$.
- **Maximum principle**: $\min_{\bar{\Omega}} v^m \leq v^{m+1} \leq \max_{\bar{\Omega}} v^m$ in $\bar{\Omega}$.

Section 2

Convective Cahn-Hilliard model

Cahn-Hilliard equation

Fourth order problem:

$$\begin{aligned} u_t &= \nabla \cdot (M(u) \nabla (-\varepsilon^2 \Delta u + F'(u))) && \text{in } \Omega \times (0, T), \\ \nabla u \cdot \mathbf{n} &= \nabla (-\varepsilon^2 \Delta u + F'(u)) \cdot \mathbf{n} = 0 && \text{on } \partial\Omega \times (0, T), \\ u(0) &= u_0 && \text{in } \Omega. \end{aligned}$$

- $F(u) = \frac{1}{4}u^2(1-u)^2$ Ginzburg-Landau double well functional.
- $M(u) = u(1-u)$ degenerate mobility function.
- u minimizes energy functional:

$$E(u(t)) := \frac{\varepsilon^2}{2} \int_{\Omega} |\nabla u(t)|^2 dx + \int_{\Omega} F(u(t)) dx.$$

Convective Cahn-Hilliard model

$$\begin{aligned}\partial_t u &= \nabla \cdot (M(u) \nabla \mu) - \nabla \cdot (u \mathbf{v}) && \text{in } \Omega \times (0, T), \\ \mu &= F'(u) - \varepsilon^2 \Delta u && \text{in } \Omega \times (0, T), \\ \nabla u \cdot \mathbf{n} &= (M(u) \nabla \mu - u \mathbf{v}) \cdot \mathbf{n} = 0 && \text{on } \partial\Omega \times (0, T), \\ u(0) &= u_0 && \text{in } \Omega.\end{aligned}$$

where

- $\mathbf{v}: \overline{\Omega} \times (0, T) \rightarrow \mathbb{R}^d$ is continuous and **incompressible**, i.e.,
 $\nabla \cdot \mathbf{v} = 0$ in Ω ,
- $\mathbf{v} \cdot \mathbf{n} = 0$ on $\partial\Omega$.

Properties:

- **Mass conservation:** $\frac{d}{dt} \int_{\Omega} u = 0$.
- **Maximum principle:** $u \in [0, 1]$ in $\overline{\Omega} \times (0, T)$ if $u_0 \in [0, 1]$ in $\overline{\Omega}$.

Nonlinear flux direction

Notice that

$$\nabla \cdot (M(u)\nabla\mu) = M'(u)\nabla\mu \cdot \nabla u + M(u)\Delta\mu.$$

Hence, $M'(u)$ determines the direction of the flux.

- If $u \in [0, 1]$ then $M(u) = M(u)_{\oplus}$.

Consider:

- Increasing part of $M(u)_{\oplus}$: $M^{\uparrow}(u) = \begin{cases} M(u)_{\oplus} & \text{if } u \leq \frac{1}{2} \\ M(\frac{1}{2}) & \text{if } u > \frac{1}{2} \end{cases}.$
- Decreasing part of $M(u)_{\oplus}$: $M^{\downarrow}(u) = \begin{cases} 0 & \text{if } u \leq \frac{1}{2} \\ M(u)_{\oplus} - M(\frac{1}{2}) & \text{if } u > \frac{1}{2} \end{cases}.$

Notice that $M(u)_{\oplus} = M^{\uparrow}(u) + M^{\downarrow}(u)$.

Generalized upwind method

- $a_h^{\text{upw}} : \mathbb{P}_k^{\text{disc}}(\mathcal{T}_h) \times \mathbb{P}_k^{\text{disc}}(\mathcal{T}_h) \rightarrow \mathbb{R}$,

$$\begin{aligned}
 a_h^{\text{upw}}(\beta; M(u)_{\oplus}, \bar{u}) &:= - \int_{\Omega} (\beta \cdot \nabla \bar{u}) M(u)_{\oplus} \\
 &+ \sum_{e \in \mathcal{E}_h^i, e=K \cap L} \int_e \left((\{\beta\} \cdot \mathbf{n}_e)_{\oplus} (M^{\uparrow}(u_K) + M^{\downarrow}(u_L)) \right. \\
 &\quad \left. - (\{\beta\} \cdot \mathbf{n}_e)_{\ominus} (M^{\uparrow}(u_L) + M^{\downarrow}(u_K)) \right) [\![\bar{u}]\!],
 \end{aligned}$$

where $\beta: \bar{\Omega} \rightarrow \mathbb{R}^d$ can be discontinuous over \mathcal{E}_h^i .

Fully discrete scheme

Given $u^m \in \mathbb{P}_0^{\text{disc}}(\mathcal{T}_h)$ with $u^m \in [0, 1]$, find $u^{m+1} \in \mathbb{P}_0^{\text{disc}}(\mathcal{T}_h)$, with $\mu^{m+1}, w^{m+1} \in \mathbb{P}_1^{\text{cont}}(\mathcal{T}_h)$, solving

$$\begin{aligned} \left(\frac{u^{m+1} - u^m}{\Delta t}, \bar{u} \right)_{L^2(\Omega)} + a_h^{\text{upw}}(-\nabla \mu^{m+1}; M(u^{m+1})_{\oplus}, \bar{u}) + a_h^{\text{upw}}(\mathbf{v}(t_{m+1}); u^{m+1}, \bar{u}) &= 0, \\ (\mu^{m+1}, \bar{\mu})_{L^2(\Omega)} &= \varepsilon^2 (\nabla w^{m+1}, \nabla \bar{\mu})_{L^2(\Omega)} + (f(u^{m+1}, u^m), \bar{\mu})_{L^2(\Omega)}, \\ (w^{m+1}, \bar{w})_{L^2(\Omega)}^h &= (u^{m+1}, \bar{w})_{L^2(\Omega)}, \end{aligned}$$

for all $\bar{u} \in \mathbb{P}_0^{\text{disc}}(\mathcal{T}_h)$ and $\bar{\mu}, \bar{w} \in \mathbb{P}_1^{\text{cont}}(\mathcal{T}_h)$.

$(\cdot, \cdot)_{L^2(\Omega)}^h$ denotes the scalar product with mass-lumping.

Properties:

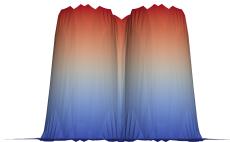
- **Existence** of a solution.
- **Mass conservation**: $\int_{\Omega} u^{m+1} = \int_{\Omega} u^m$, $\int_{\Omega} w^{m+1} = \int_{\Omega} w^m$.
- **Maximum principle**: $u^{m+1}, w^{m+1} \in [0, 1]$ in $\bar{\Omega}$ if $u^m, w^m \in [0, 1]$.

Section 3

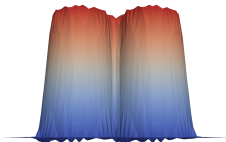
Numerical tests

Non-convective Cahn-Hilliard ($\mathbf{v} = 0$)

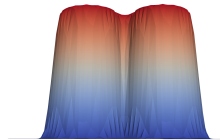
FEM



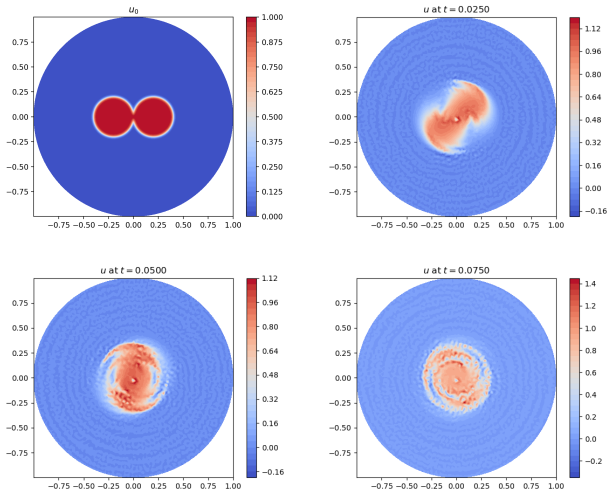
DG-SIP



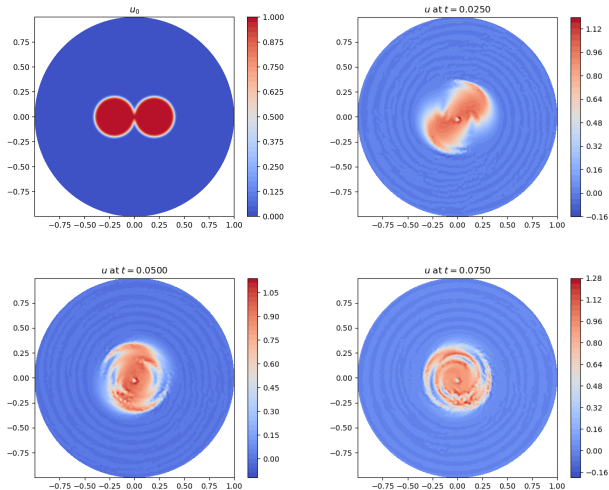
DG-UPW



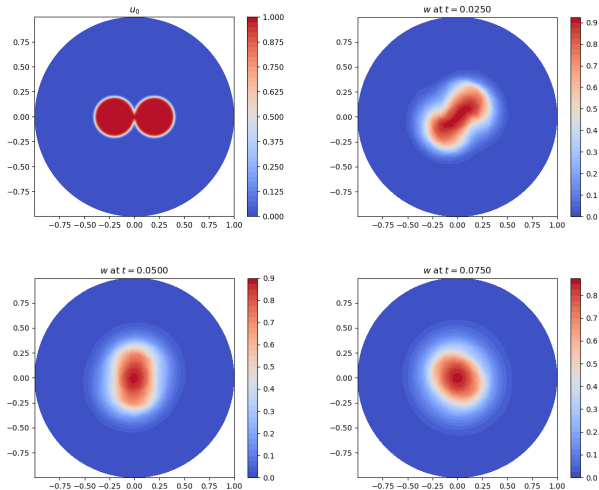
Convective Cahn-Hilliard with FEM ($\mathbf{v} = 100(y, -x)$)



Convective Cahn-Hilliard with DG-SIP ($\nu = 100(y, -x)$)

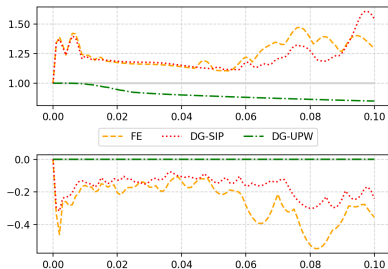


Convective Cahn-Hilliard with DG-UPW ($\mathbf{v} = 100(y, -x)$)



Convective Cahn-Hilliard ($\mathbf{v} = 100(y, -x)$)

Maximum-Minimum



Dynamics

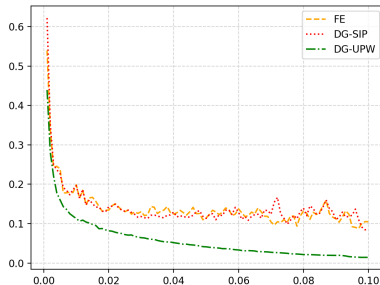
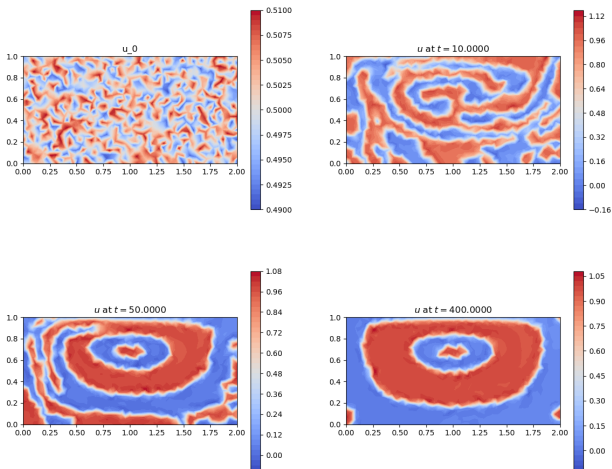
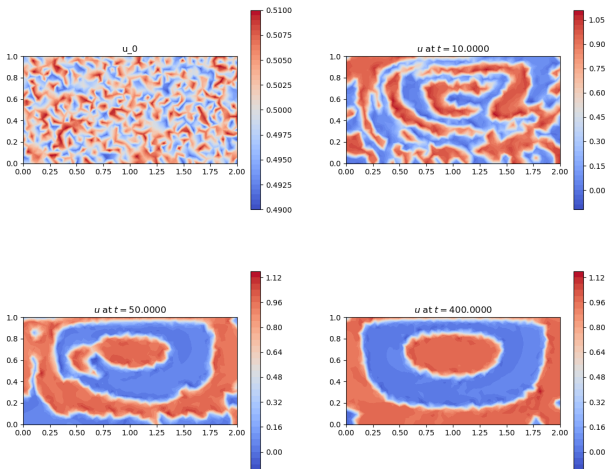


Figure: On the left, maximum and minimum of the phase field variable over time. On the right, we plot $\frac{\|u^{m+1} - u^m\|_{L^\infty(\Omega)}}{\|u^m\|_{L^\infty(\Omega)}}$ to observe the dynamics of the approximations.

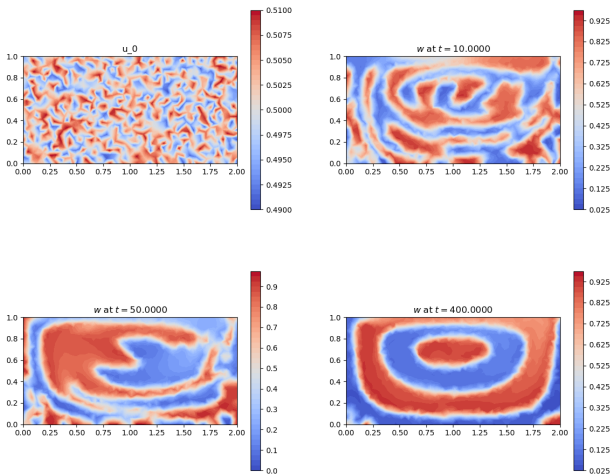
Stokes-Cahn-Hilliard with FEM (cavity test)



Stokes-Cahn-Hilliard with DG-SIP (cavity test)

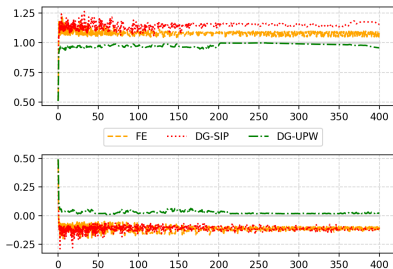


Stokes-Cahn-Hilliard with DG-UPW (cavity test)



Stokes-Cahn-Hilliard (cavity test)

Maximum-Minimum



Dynamics

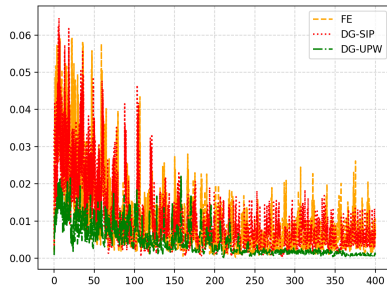


Figure: On the left, maximum and minimum of the phase field variable over time. On the right, we plot $\frac{\|u^{m+1} - u^m\|_{L^\infty(\Omega)}}{\|u^m\|_{L^\infty(\Omega)}}$ to observe the dynamics of the approximations.

Convergence order: non-convective Cahn-Hilliard

Table: Errors and convergence orders at $T = 0.001$ without convection ($v = 0$).






Scheme	Norm	$h \approx 2.8284 \cdot 10^{-2}$	$h/2 \approx 1.4142 \cdot 10^{-2}$	$h/3 \approx 9.428 \cdot 10^{-3}$	$h/4 \approx 7.071 \cdot 10^{-3}$			
		Error	Error	Order	Error	Order	Error	Order
DG-UPW	$\ \cdot\ _{L^2}$	$8.5268 \cdot 10^{-3}$	$3.0933 \cdot 10^{-3}$	1.46	$1.7645 \cdot 10^{-3}$	1.38	$1.2134 \cdot 10^{-3}$	1.30
	$\ \cdot\ _{H^1}$	$8.0000 \cdot 10^{-1}$	$4.0199 \cdot 10^{-1}$	0.99	$2.6081 \cdot 10^{-1}$	1.07	$1.8849 \cdot 10^{-1}$	1.13
FEM	$\ \cdot\ _{L^2}$	$5.3224 \cdot 10^{-3}$	$1.5679 \cdot 10^{-3}$	1.76	$6.9944 \cdot 10^{-4}$	1.99	$4.0191 \cdot 10^{-4}$	1.93
	$\ \cdot\ _{H^1}$	$8.9963 \cdot 10^{-1}$	$4.1080 \cdot 10^{-1}$	1.13	$2.5252 \cdot 10^{-1}$	1.2	$1.7799 \cdot 10^{-1}$	1.22
DG-SIP	$\ \cdot\ _{L^2}$	$4.6466 \cdot 10^{-3}$	$1.3023 \cdot 10^{-3}$	1.84	$5.8945 \cdot 10^{-4}$	1.96	$3.2710 \cdot 10^{-4}$	2.05
	$\ \cdot\ _{H^1}$	1.1784	$5.8331 \cdot 10^{-1}$	1.01	$3.6254 \cdot 10^{-1}$	1.17	$2.6024 \cdot 10^{-1}$	1.15

Convergence order: convective Cahn-Hilliard

Table: Errors and convergence orders at $T = 0.001$ with convection ($\mathbf{v} = (y, -x)$).

Scheme	Norm	$h \approx 4 \cdot 10^{-2}$	$h/2 \approx 2 \cdot 10^{-2}$	$h/3 \approx 1.3333 \cdot 10^{-2}$	$h/4 \approx 1 \cdot 10^{-2}$			
		Error	Error	Order	Error	Order		
DG-UPW	$\ \cdot\ _2$	$1.7288 \cdot 10^{-2}$	$6.9446 \cdot 10^{-3}$	1.32	$3.3102 \cdot 10^{-3}$	1.83	$2.0578 \cdot 10^{-3}$	1.65
	$\ \cdot\ _{H^1}$	1.4549	$6.0305 \cdot 10^{-1}$	1.27	$3.0204 \cdot 10^{-1}$	1.71	$2.0315 \cdot 10^{-1}$	1.38
FEM	$\ \cdot\ _2$	$6.8347 \cdot 10^{-3}$	$2.1213 \cdot 10^{-3}$	1.69	$9.7749 \cdot 10^{-4}$	1.91	$5.3883 \cdot 10^{-4}$	2.07
	$\ \cdot\ _{H^1}$	$8.3104 \cdot 10^{-1}$	$3.8060 \cdot 10^{-1}$	1.13	$2.1887 \cdot 10^{-1}$	1.36	$1.4991 \cdot 10^{-1}$	1.32
DG-SIP	$\ \cdot\ _2$	$6.5242 \cdot 10^{-3}$	$1.9557 \cdot 10^{-3}$	1.74	$8.9471 \cdot 10^{-4}$	1.93	$5.0257 \cdot 10^{-4}$	2.00
	$\ \cdot\ _{H^1}$	1.1980	$6.1624 \cdot 10^{-1}$	0.96	$3.8451 \cdot 10^{-1}$	1.16	$2.7439 \cdot 10^{-1}$	1.17

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Thanks for your attention!

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