

DISCRETE-TO-CONTINUUM CRYSTALLINE CURVATURE FLOWS

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ABSTRACT. We consider here a fully discrete variant of the implicit variational scheme for mean curvature flow [2, 39], in a setting where the flow is governed by a crystalline surface tension defined by the limit of pairwise interactions energy on the discrete grid. The algorithm is based on a new discrete distance from the evolving sets, which prevents the occurrence of the spatial drift and pinning phenomena identified in [42, 11] in a similar discrete framework. We provide the first rigorous convergence result holding in any dimension, for any initial set and for a large class of purely crystalline anisotropies, in which the spatial discretization mesh can be of the same order or coarser than the time step.

1. INTRODUCTION

sec:intro

In this paper we analyse a space- and time-discrete approximation of crystalline mean curvature flows of the form

evol law

$$(1.1) \quad V(x, t) = -\phi(\nu_{E(t)}(x))\kappa_{E(t)}^\phi(x), \quad x \in \partial E(t), \quad t \geq 0,$$

for a class of crystalline norms ϕ . We recall that an anisotropy ϕ is said to be crystalline if and only if $\{\phi \leq 1\}$ is a polytope (or equivalently, ϕ is the support function of a polytope). Moreover in the current paper we restrict ourselves to the case where $\{\phi \leq 1\}$ is a zonotope with rational generators [41, 9]. Here $V(x, t)$ stands for the (outer) normal velocity of the boundary $\partial E(t)$ at x , ϕ is a crystalline norm on \mathbb{R}^N representing the surface tension, $\kappa_{E(t)}^\phi$ is the crystalline mean curvature of $\partial E(t)$ associated to ϕ , and $\nu_{E(t)}$ is the outer unit normal to $\partial E(t)$. The evolution law (1.1) has been considered to describe some phenomena in materials science and crystal growth; see e.g. [35, 50]. Our main result is a convergence result of the discrete approximation to the continuous evolution, as the time and space steps go to zero, even in the somewhat surprising case where the space-step is greater or equal to the time-step.

From the mathematical point of view, the lack of regularity of the differential operator involved in the definition of the crystalline curvature (see [6, 7]) is the main reason why the well-posedness of the crystalline mean curvature flow in every dimension has been a long-standing open problem. After some partial results (see for instance [1, 4, 5, 15, 26, 27, 28]), important breakthroughs have been obtained simultaneously in [29, 30, 32], where a suitable crystalline theory of viscosity

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solutions was developed, and with a different approach in [22, 21, 20], where a new notion of distributional solutions was proposed.

Let us focus on the definition of distributional solutions, referring to the nice review [31] for further information on viscosity solutions to (1.1) (we just note that the two notions are equivalent in the setting of this paper [20, Remark 6.1]). The exact definition of distributional solutions will be recalled in Definition 2.1, but when ϕ is smooth it can be motivated as follows: It is known (see for instance [49] for the isotropic case) that $E(t)$ evolves according to (1.1) if and only if the signed distance function $d(\cdot, t) := \text{sd}_{E(t)}^{\phi^\circ}$ to $\partial E(t)$ induced by the polar norm¹ ϕ° , satisfies

evol law 1

(1.2) $\partial_t d \geq \text{div}(\nabla \phi(\nabla d)) \quad \text{in } \{d > 0\},$

evol law 2

(1.3) $\partial_t d \leq \text{div}(\nabla \phi(\nabla d)) \quad \text{in } \{d < 0\}$

in the viscosity sense. The idea of the new definition introduced in [22] is to reinterpret the equations above in the distributional sense. In particular, note that replacing $\nabla \phi(\nabla u)$ by a vector field $z \in L^\infty(\{d > 0\}; \mathbb{R}^N)$ such that $z(x) \in \partial \phi(\nabla d)$ for a.e. x , where $\partial \phi$ denotes the subdifferential of ϕ , the equations (1.2), (1.3) make sense even when ϕ is crystalline. The corresponding notion of super- and sub-solutions bears a comparison principle, which yields uniqueness of the motion up to fattening. Existence is obtained either by a variant of the minimizing movements scheme of [2, 39] in the spirit of [16], which consists in building a discrete-in-time evolution obtained by a recursive minimization procedure (see [22, 20]), or by approximation with smooth anisotropies [21]. We observe that the convergence of such time discrete approaches to a motion characterized by (1.2)-(1.3) in the *viscosity sense* was shown in [38], including in the 2D crystalline setting, while convergence in a distributional sense was established in [15] in the convex case only. Briefly, given a time-step $h > 0$ and an initial closed set $E_0 =: E^{h,0}$, one defines $E^{h,k+1} = \{u^{h,k+1} \leq 0\}$, where $u^{h,k+1}$ is defined as the minimizer of a so-called ‘‘Rudin-Osher-Fatemi’’ [47] problem:

def u_k cont

(1.4) $u^{h,k+1} \in \text{argmin} \left\{ \int_{\mathbb{R}^N} \phi(Du) + \frac{1}{2h} \int_{\mathbb{R}^N} |u - \text{sd}_{E^{h,k}}^{\phi^\circ}|^2 \right\}.$

The idea of the present work is to combine this discretization in time with a simultaneous discretization in space for the particular class of purely crystalline anisotropies ϕ of the following form

def phi

(1.5) $\phi(v) = \sum_{i \in \mathcal{E}} \beta(i) |i \cdot v|,$

where $\beta(i) > 0$ and $\mathcal{E} \subseteq \mathbb{Z}^N \setminus \{0\}$ is a finite set of generators such that $\text{Span } \mathcal{E} = \mathbb{R}^N$. This kind of convex polytopes is known in the literature as *rational zonotopes*. The class of rational zonotopes is dense in the class of symmetric convex sets if $N = 2$, while for $N \geq 3$ it is nowhere dense. This fact is due to the strong symmetry properties of zonotopes, as every facet of a zonotope is itself a zonotope [41]. Note however that the Euclidean ball may be approximated by rational zonotopes in every dimension.

We now specify the discrete setting we are interested in, referring the reader to [13] for a more thorough introduction to related topics. We consider an ε -spaced square lattice $\varepsilon \mathbb{Z}^N$ and discrete functions $u : \varepsilon \mathbb{Z}^N \rightarrow \mathbb{R}$, and denote $u_i := u(i)$. We observe that we could also consider a general finite-dimensional Bravais lattice, at the expense of more tedious notation. A natural discrete

¹defined by $\phi^\circ(x) = \sup_{\phi(\nu) \leq 1} \nu \cdot x$ and which satisfies $\phi(x) = \sup_{\phi^\circ(\nu) \leq 1} \nu \cdot x$.

version of total variation-like energies are those appearing in Ising systems, namely energies of the form

$$(1.6) \quad TV_\beta^\varepsilon(v) := \varepsilon^{N-1} \sum_{i,j \in \varepsilon\mathbb{Z}^N} \beta(i/\varepsilon - j/\varepsilon) |v_i - v_j|,$$

where β is as in (1.5) and extended to 0 in $\mathbb{Z}^N \setminus \mathcal{E}$. Under the hypotheses above on β , the functionals TV_β^ε are shown to Γ -converge² as $\varepsilon \rightarrow 0$ to the total variation functional

$$TV_\phi(v) = \int_{\mathbb{R}^N} \phi(Dv)$$

where ϕ is as in (1.5), see e.g. [19]. It is thus natural to define a minimizing movements scheme based on TV_β^ε which is the discrete counterpart of the minimizing procedure (1.4), as follows: given $E_0 \subseteq \mathbb{R}^N$, we define $E_{\varepsilon,h}^0 = \{i \in \varepsilon\mathbb{Z}^N : (i + [0, \varepsilon)^N) \cap E_0 \neq \emptyset\}$ and for every $k \in \mathbb{N}$ we let $u_{\varepsilon,h}^{k+1}$ be such that

def u_k intro

$$(1.7) \quad u_{\varepsilon,h}^{k+1} \in \operatorname{argmin} \left\{ TV_\beta^\varepsilon(v) + \frac{1}{2h} \sum_{i \in \varepsilon\mathbb{Z}^N} |v_i - (\operatorname{sd}_{\varepsilon,h}^k)_i|^2 : v : \varepsilon\mathbb{Z}^N \rightarrow \mathbb{R} \right\},$$

where $\operatorname{sd}_{\varepsilon,h}^k$ denotes a suitable signed ϕ° -distance function to $E_{\varepsilon,h}^k$ defined on $\varepsilon\mathbb{Z}^N$. (Actually, the energy in (1.7) is infinite and we rather consider the Euler-Lagrange equation of the problem.) Then, one sets $E_{\varepsilon,h}^{k+1} := \{u_{\varepsilon,h}^{k+1} \leq 0\}$.

The idea is to study the asymptotic behaviour of the discrete evolutions $E_{\varepsilon,h}^k$ as both $\varepsilon, h \rightarrow 0$. A similar analysis has been performed in [11], in the planar case, for $\phi = \|\cdot\|_1$ and $\operatorname{sd}_{\varepsilon,h}^k$ the continuous signed distance function from the discrete sets $E_{\varepsilon,h}^k$ restricted to the lattice $\varepsilon\mathbb{Z}^N$, see also [42, 10, 12, 14, 40, 48] for further related results. With this choice, if $\varepsilon \gg h$ it is easy to see that the dissipation-like term in (1.7)

$$\frac{1}{2h} \sum_{i \in \varepsilon\mathbb{Z}^N} |v_i - (\operatorname{sd}_{\varepsilon,h}^{k+1})_i|^2$$

forces the functions $u_{\varepsilon,h}^k$ to be constant as k varies, therefore producing *pinning* on the moving interfaces. Moreover, when the two scales ε, h are going to zero at the same speed it is shown in [11] that a direct implementation of the standard scheme with the choice above for the distance, introduces a systematic error of order $\varepsilon = h$ at each step, which accumulates and produces a drift in the limiting evolution. As a result, low curvature shapes remain pinned, while sets with higher curvature evolve with a law which is a nonlinear modification of the crystalline curvature flow (1.1). Thus, the evolution law (1.1) can be approximated with the scheme of [11] only if $\varepsilon \ll h$. In [42], similar results are derived, still in dimension 2, for the isotropic (Euclidean) mean curvature flow.

We show in our main result, Theorem 5.2, that with a new appropriate definition of the distance $\operatorname{sd}_{\varepsilon,h}^k$, we can recover in the limit $\varepsilon, h \rightarrow 0$ the actual distributional solution to (1.1) for every initial set $E_0 \subseteq \mathbb{R}^N$, for every purely crystalline anisotropy ϕ of the form (1.5) with rational coefficients, in any dimension and irrespective of relative size of the space- and time-steps. In fact, the assumption of the rational character of β can be removed in the regime $\varepsilon \leq O(h)$. To the best of our knowledge this is the first general rigorous convergence result for a fully discrete scheme without restrictions

²Note that we do not need to assume that the lattice generated by $\{e_k\}_{k=1,\dots,m}$ is \mathbb{Z}^N , which is necessary to ensure the equi-coercivity of the discrete functionals.

on the dimension, on the initial sets and in which the spatial mesh is allowed to be of the same order or even coarser than the time step.

Let us further comment on the analysis carried out in [11] in the planar case (see also [13] for many more references on the topic). One important change between these older results and ours is that we consider distributional solutions to the crystalline mean curvature flow (1.1), instead of relying on the characterization of the motion via ODEs, which dates back to [1, 4]. The latter notion of solution is indeed suited only for planar evolutions, thus the limitation $N = 2$ in the past works. With the ODE definition and for $\phi = \|\cdot\|_1$, the authors of [11] precisely prove the following results. If $\varepsilon \ll h$ then the limiting motion is consistent with (1.1), while if $h \ll \varepsilon$ pinning happens for any nonempty initial data. As already mentioned, in the critical case $\varepsilon = h$, the limit planar motion is not driven by (1.1), but instead by a slightly modified nonlinear crystalline mean curvature flow, and pinning may happen for some particular (low curvature) initial data. This striking difference with our result may be (vaguely) justified by the following remark. While in [11], the focus is on discrete sets, we rather evolve, in accordance with the definition of distributional solutions, the *signed distance functions* to the boundaries. In this way we can effectively achieve a sub-pixel precision in our approximation, as $u_{\varepsilon,h}$ and the signed distance function carry more information than the evolving level set $\{u_{\varepsilon,h}(t) \leq 0\}$. Our new definition of the interpolated signed distance is detailed in Section 4.

The consistency result in this paper validates the numerical experiments which we carry on in Section 6 to illustrate our results. These experiments are derived from previous experiments in [18], which however were using a different redistancing operation for which no consistency was proven. Numerical schemes based on the variational approach [2, 39] have been introduced for crystal growth [3]. Since then, there have been many attempts to implement implicit schemes based on this approach for isotropic and anisotropic curvature flows in various settings [16, 25, 44, 46, 24]. We are however not aware of a formal convergence proof for these schemes in the fully discrete setting, which is not relying on the consistency of the spatial discretization with respect to the time-discrete scheme (hence assuming $\varepsilon \ll h$, even if in practice these implementations seem very robust).

Many other techniques have been considered to simulate crystalline flows after [51, 52], see e.g. [33, 34, 23] for the evolution of planar curves and [43, 45] for higher-dimensional algorithms.

Let us conclude this introduction with two comments. The first one concerns the hypothesis that ϕ is purely crystalline. It seems quite technical, as it implies that the associated interaction function β (in the sense of (1.5)) has finite range. While this is not necessary to carry out the existence part for the discrete minimizing movements scheme, it is essential for building a calibration which yields a bound on the speed of Wulff shapes, see Appendix A. In practice, being the open Wulff shape $\mathcal{W} := \{\phi^\circ \leq 1\}$ a finite Minkowski sum of (rational) segments (which is called a *zonotope*), we can effectively handcraft a calibration along the directions identified by these segments. It is a remarkable difference between this discrete setting and the continuous one, where instead the vector field $x/\phi^\circ(x)$ in \mathbb{R}^N is the right calibration *for any* anisotropy ϕ .

The second one is on possible generalizations of the present analysis to more general evolution laws than (1.1). The more general evolution law which is shown to admit a unique distributional solution is

$$(1.8) \quad V(x, t) = \psi(\nu_{E(t)}(x)) \left(-\kappa_{E(t)}^\phi(x) + f(x, t) \right), \quad x \in \partial E(t), t \geq 0,$$

where ψ is a norm (usually referred to as the *mobility*), and f is a forcing term, see [22, 20]. We expect most of the present analysis to be valid even if $\psi \neq \phi$, under suitable compatibility assumptions on ψ (see [22, 20] for details), and it should not be difficult to consider a driving force f as long as it is Lipschitz in space and globally bounded, see [20] again.

The paper is organized as follows: in the next Section 2, we recall the definition of distributional crystalline curvature flows from [22, 20]. Then, we study the discrete ‘‘Rudin-Osher-Fatemi’’ problem and its Euler-Lagrange equation in Section 3. In Section 4, we introduce the discrete minimizing movement scheme, with our particular definition of the signed distance function. We study in detail the properties of these distances, then in Section 4.3 we analyse the particular case of an initial Wulff shape. In the continuous setting, it is well known that under the law (1.1), it decreases in a self-similar way with a speed proportional to the inverse of its radius. We show an estimate bounding the decay of the discrete Wulff shapes, it relies on the delicate construction of a calibration z for the Rudin-Osher-Fatemi problem with datum ϕ° , detailed in Appendix A.

Our main result, which is that in the limit $\varepsilon, h \rightarrow 0$, the motion defined in Section 4 converges to a crystalline flow, is stated, and proved, in Section 5. We implemented the discrete scheme in 2D and show some numerical simulations in Section 6. Some technical results are collected in the Appendix.

2. DISTRIBUTIONAL CRYSTALLINE CURVATURE FLOWS

subsec:cf

We recall the distributional formulation for the crystalline mean curvature motion of sets evolving with normal velocity (1.1) introduced in [22] (see also [20]). Here and in what follows ϕ is any norm, ϕ° denotes the polar (or dual) norm of ϕ and given a closed set $F \subseteq \mathbb{R}^N$, $\text{dist}^{\phi^\circ}(\cdot, F)$ stands for the ϕ° -distance function from F defined by

$$\text{dist}^{\phi^\circ}(x, F) := \min\{\phi^\circ(x - y) : y \in F\}.$$

Analogously, for any E, F closed we set

$$\text{dist}^{\phi^\circ}(E, F) := \min\{\phi^\circ(x - y) : x \in E, y \in F\}.$$

We recall that a sequence of closed sets $(E_k)_{k \geq 1}$ in \mathbb{R}^N converges to a closed set E in the *Kuratowski sense*: if the following conditions are satisfied

- (i) if $x_k \in E_k$ for each k , any limit point of $\{x_k\}$ belongs to E ;
- (ii) for all $x \in E$ there exists a sequence $\{x_k\}$ such that $x_k \in E_k$ for each k and $x_k \rightarrow x$.

We will write in this case:

$$E_k \xrightarrow{\mathcal{K}} E.$$

One can easily verify that $E_k \xrightarrow{\mathcal{K}} E$ if and only if (for any norm ψ) $\text{dist}^\psi(\cdot, E_k) \rightarrow \text{dist}^\psi(\cdot, E)$ locally uniformly in \mathbb{R}^N . Hence, by Ascoli-Arzelà Theorem we have that any sequence of closed sets admits a converging subsequence in the Kuratowski sense (possibly to \emptyset , when $\text{dist}^\psi(\cdot, E_k) \rightarrow +\infty$).

Defsol

Definition 2.1. Let $E_0 \subseteq \mathbb{R}^N$ be a closed set. Let E be a closed set in $\mathbb{R}^N \times [0, +\infty)$ and for each $t \geq 0$ denote $E(t) := \{x \in \mathbb{R}^N : (x, t) \in E\}$. We say that E is a *superflow* for (1.1) with initial datum E_0 if

- (a) $E(0) \subseteq E_0$;
- (b) $E(s) \xrightarrow{\mathcal{K}} E(t)$ as $s \nearrow t$ for all $t > 0$;
- (c) If $E(t) = \emptyset$ for some $t \geq 0$, then $E(s) = \emptyset$ for all $s > t$.

(d) Set $T^* := \inf\{t > 0 : E(s) = \emptyset \text{ for } s \geq t\}$, and

$$d(x, t) := \text{dist}^{\phi^\circ}(x, E(t)) \quad \text{for all } (x, t) \in \mathbb{R}^N \times (0, T^*) \setminus E.$$

Then,

eq:supersol

$$(2.1) \quad \partial_t d \geq \text{div} z$$

holds in the distributional sense in $\mathbb{R}^N \times (0, T^*) \setminus E$ for a suitable $z \in L^\infty(\mathbb{R}^N \times (0, T^*))$ such that $z \in \partial\phi(\nabla d)$ a.e., $\text{div} z$ is a Radon measure in $\mathbb{R}^N \times (0, T^*) \setminus E$, and $(\text{div} z)^+ \in L^\infty(\{(x, t) \in \mathbb{R}^N \times (0, T^*) : d(x, t) \geq \delta\})$ for every $\delta \in (0, 1)$.

We say that A , open set in $\mathbb{R}^N \times [0, +\infty)$, is a *subflow* for (1.1) with initial datum E_0 if $\mathbb{R}^N \times [0, +\infty) \setminus A$ is a superflow for (1.1) with initial datum $\mathbb{R}^N \setminus \text{int}(E_0)$.

Finally, we say that E , closed set in $\mathbb{R}^N \times [0, +\infty)$, is a *weak flow* for (1.1) with initial datum E_0 if it is a superflow and if $\text{int}(E)^3$ is a subflow, both with initial datum E_0 .

In [22] the following crucial inclusion principle between sub- and superflows is proven.

th:compar

Theorem 2.2. *Let E be a superflow with initial datum E_0 and F be a subflow with initial datum F_0 in the sense of Definition 2.1. Assume that $\text{dist}^{\phi^\circ}(E^0, \mathbb{R}^N \setminus F^0) =: \Delta > 0$. Then,*

$$\text{dist}^{\phi^\circ}(E(t), \mathbb{R}^N \setminus F(t)) \geq \Delta \quad \text{for all } t \geq 0$$

(with the convention that $\text{dist}^{\phi^\circ}(G, \emptyset) = \text{dist}^{\phi^\circ}(\emptyset, G) = +\infty$ for any G).

We also recall the corresponding notion of sub- and supersolution to the level set flow associated with (1.1). In what follows $\text{UC}(\mathbb{R}^N)$ stands for the space of uniformly continuous functions on \mathbb{R}^N .

deflevelset1

Definition 2.3 (Level set subsolutions and supersolutions). Let $u_0 \in \text{UC}(\mathbb{R}^N)$. A lower semi-continuous function $u : \mathbb{R}^N \times [0, +\infty) \rightarrow \mathbb{R}$ is called a *level set superflow* for (1.1), with initial datum u_0 , if $u(\cdot, 0) \geq u_0$ and if for a.e. $\lambda \in \mathbb{R}$ the closed sublevel set $\{u(\cdot, t) \leq \lambda\}$ is a superflow for (1.1) in the sense of Definition 2.1, with initial datum $\{u_0 \leq \lambda\}$.

An upper-semicontinuous function $u : \mathbb{R}^N \times [0, +\infty) \rightarrow \mathbb{R}$ is called a *level set subflow* for (1.1), with initial datum u_0 , if $-u$ is level set superflow in the previous sense, with initial datum $-u_0$.

Finally, a continuous function $u : \mathbb{R}^N \times [0, +\infty) \rightarrow \mathbb{R}$ is called a *level set flow* for (1.1) if it is both a level set sub- and superflow.

Using Theorem 2.2, it is not difficult to deduce the following parabolic comparison principle between level set sub- and superflows, which yields in particular the uniqueness of level set flows (in the sense of Definition 2.3), see [20].

th:lscomp

Theorem 2.4. *Let $u_0, v_0 \in \text{UC}(\mathbb{R}^N)$ and let u, v be respectively a level set subflow starting from u_0 and a level set superflow starting from v_0 . If $u_0 \leq v_0$, then $u \leq v$.*

We finally recall that in [22] (see also [20]) the existence of level set flows is established by implementing a level-by-level minimizing movements scheme. This in turn yields existence and uniqueness (up to fattening) for weak flows. This is made precise in the following statement, see [22, Corollary 4.6] and [20, Theorem 4.8].

³Here we are taking the interior with respect to $\mathbb{R}^N \times [0, +\infty)$

irregularlevelset

Theorem 2.5. *Let $u_0 \in \text{UC}(\mathbb{R}^N)$. Then the following holds:*

- (i) *There exists a unique level set flow u in the sense of Definition 2.3 starting u_0 .*
- (ii) *For all $\lambda \in \mathbb{R}$ the sets $\{(x, t) : u(x, t) \leq \lambda\}$ and $\{(x, t) : u(x, t) < \lambda\}$ are respectively the maximal superflow and minimal subflow with initial datum $\{u_0 \leq \lambda\}$.*
- (iii) *For all but countably many $\lambda \in \mathbb{R}$, the fattening phenomenon does not occur; that is,*

eq:nonfattening

$$(2.2) \quad \begin{aligned} \{(x, t) : u(x, t) < \lambda\} &= \text{int}(\{(x, t) : u(x, t) \leq \lambda\}), \\ \text{cl}(\{(x, t) : u(x, t) < \lambda\}) &= \{(x, t) : u(x, t) \leq \lambda\}, \end{aligned}$$

where interior and closure are relative to space-time.

For all such λ , $\{(x, t) : u(x, t) \leq \lambda\}$ is the unique weak flow in the sense of Definition 2.1, starting from $\{u_0 \leq \lambda\}$.

The aim of this paper is to show that the convergence to the continuum level set flow holds true also when the Euler implicit time discretisation is combined with a suitable spatial discretisation procedure.

sec:ROF

3. THE DISCRETE “RUDIN-OSHER-FATEMI” PROBLEM

In this part, we describe our discrete setting, we then introduce and analyse the discrete variant (1.7) of Problem (1.4).

3.1. Discrete functions spaces and operators. For $\varepsilon > 0$, we define the function spaces $X_\varepsilon = \mathbb{R}^{\varepsilon\mathbb{Z}^N}$ and $Y_\varepsilon = \mathbb{R}^{\varepsilon\mathbb{Z}^N \times \varepsilon\mathbb{Z}^N}$. Given a function $u \in X_\varepsilon$ and a discrete “vector field” $z \in Y_\varepsilon$, with a slight abuse of notation we will denote $u_i = u(i)$ and $z_{ij} = z(i, j)$, $i, j \in \varepsilon\mathbb{Z}^N$. The discrete gradient $D_\varepsilon : X_\varepsilon \rightarrow Y_\varepsilon$ is defined, for $u \in X_\varepsilon$ as

$$(D_\varepsilon u)_{ij} = \frac{u_i - u_j}{\varepsilon}.$$

We denote its adjoint operator by $D_\varepsilon^* : Y_\varepsilon \rightarrow X_\varepsilon$, namely the operator such that, for $\eta \in Y_\varepsilon$ compactly supported and for $z \in Y_\varepsilon$, is defined as

$$\sum_i (D_\varepsilon^* z)_i \eta_i := \sum_{ij} z_{ij} (D_\varepsilon \eta)_{ij} = \sum_{ij} z_{ij} \frac{\eta_i - \eta_j}{\varepsilon},$$

where the indexes, here and throughout the paper, range over $\varepsilon\mathbb{Z}^N$ if not otherwise stated. In particular, taking $\eta = \chi_{\{i\}}$, one finds that

def D^*

$$(3.1) \quad (D_\varepsilon^* z)_i = \sum_j \frac{z_{ij} - z_{ji}}{\varepsilon},$$

which can be seen as a discrete divergence operator.

3.2. Discrete ROF problem. In this section we consider the discrete anisotropic ROF problem associated with the discrete total variation functional. Without loss of generality, we consider $\varepsilon = 1$ in this section, and denote $X := X_1$, $Y := Y_1$ and $D := D_1$. Given a nonnegative $\beta \in X$, which will be called the *interaction function*, satisfying

integr beta

$$(3.2) \quad \sum_{i \in \mathbb{Z}^N} \beta(i) =: c_\beta < +\infty,$$

we set $\alpha_{ij} = \beta(i - j)$ and, for any $u \in X$ we define

$$(3.3) \quad TV(u) = \sum_{i,j \in \mathbb{Z}^N} \alpha_{ij} |u_i - u_j| = \sum_{i,j} \alpha_{ij} |(Du)_{i,j}|.$$

We also consider the discrete perimeter \mathcal{P} defined for every $E \subseteq \mathbb{Z}^N$ as

$$\mathcal{P}(E) := TV(\chi^E) = \sum_{i,j \in \mathbb{Z}^N} \alpha_{ij} |\chi_i^E - \chi_j^E|.$$

We also consider a suitable localization of the perimeter: namely, for any set $A \subseteq \mathbb{R}^N$ we define

$$\mathcal{P}(E; A) = \sum_{i \in A \cap \mathbb{Z}^N \text{ or } j \in A \cap \mathbb{Z}^N} \alpha_{ij} |\chi_i^E - \chi_j^E|.$$

Note that the quantities above may well be infinite.

Then, given $g \in X$, we consider the following problem: find a pair $(u, z) \in X \times Y$ such that

discrete EL

$$(3.4) \quad \begin{cases} D^*z + u = g \\ z_{ij}(u_i - u_j) = \alpha_{ij}|u_i - u_j|, \quad |z_{ij}| \leq \alpha_{ij} \quad \forall i, j \in \mathbb{Z}^N. \end{cases}$$

The equation above is the Euler-Lagrange equation of the discrete ROF functional

discrete ROF

$$(3.5) \quad ROF_g(v) = TV(v) + \frac{1}{2} \sum_{i \in \mathbb{Z}^N} (v_i - g_i)^2.$$

However, (3.4) makes sense also for those g such that $ROF_g \equiv +\infty$. That (3.4) is the first-order condition for optimality in (3.5) follows from standard convex analysis: the idea is that since

$$TV(v) = \sup \{ \langle z, Dv \rangle : |z_{i,j}| \leq \alpha_{i,j} \forall (i, j) \},$$

then the subgradients $\partial TV(v)$ of TV at v are precisely given by the vectors D^*z for the z 's which realize the supremum in this expression. Then, for g with bounded support (such that there is at least some u with finite energy), (3.4) expresses that $0 \in \partial ROF_g(u)$, which by definition is the condition for the minimality of u .

We will also consider the following geometric minimization problem. Given $g \in X$, find

discr per pb

$$(3.6) \quad \min_{F \subseteq \mathbb{Z}^N} \mathcal{P}(F) + \sum_{i \in \mathbb{Z}^N} \chi_i^F g_i.$$

In order to deal with unbounded sets, possibly with infinite perimeter, we will consider the following notion of global minimality with respect to compactly supported perturbations.

def loc minimizer

Definition 3.1. A set $E \subseteq \mathbb{Z}^N$ is a global minimizer for the problem (3.6) if for every $R > 0$

discr per pb loc

$$(3.7) \quad \mathcal{P}(E; B_R) + \sum_{|i| < R} \chi_i^E g_i \leq \mathcal{P}(F; B_R) + \sum_{|i| < R} \chi_i^F g_i$$

for every $F \subseteq \mathbb{Z}^N$ such that $F \triangle E \subseteq B_R$. Here $B_R = \{x \in \mathbb{R}^N : |x| < R\}$ is the open ball of radius R centered in the origin.

metric-comparison

Proposition 3.2. Let $g, g' \in X$ such that $g' - g \geq \delta > 0$. Let E, E' be two global minimizers of problem (3.7), in the sense of Definition 3.1, corresponding to g, g' respectively. Then, $E' \subseteq E$.

Proof. Let us denote in the following $\chi := \chi^{E_s}, \chi' := \chi^{E'_s}$. For a given $R > 0$ we define the competitor sets $F = (E_s \setminus B_R) \cup ((E'_s \cup E_s) \cap B_R)$ and $F' = (E'_s \setminus B_R) \cup ((E'_s \cap E_s) \cap B_R)$. By

minimality of E_s, E'_s in B_R one has

comparison 1

$$(3.8) \quad \sum_{|i| < R \text{ or } |j| < R} \alpha_{ij} |\chi'_i - \chi'_j| + \sum_{|i| < R} g'_i (\chi'_i - \chi'_i \wedge \chi_i) \leq \sum_{\substack{|i| < R \\ |j| < R}} \alpha_{ij} |\chi'_i \wedge \chi_i - \chi'_j \wedge \chi_j| \\ + \sum_{\substack{|i| < R \\ |j| \geq R}} (\alpha_{ij} + \alpha_{ji}) |\chi'_i \wedge \chi_i - \chi'_j|$$

comparison 2

$$(3.9) \quad \sum_{|i| < R \text{ or } |j| < R} \alpha_{ij} |\chi_i - \chi_j| + \sum_{|i| < R} g_i (\chi_i - \chi'_i \vee \chi_i) \leq \sum_{\substack{|i| < R \\ |j| < R}} \alpha_{ij} |\chi'_i \vee \chi_i - \chi'_j \vee \chi_j| \\ + \sum_{\substack{|i| < R \\ |j| \geq R}} (\alpha_{ij} + \alpha_{ji}) |\chi'_i \vee \chi_i - \chi_j|.$$

Using the inequality⁴ $|a \wedge b - c \wedge d| + |a \vee b - c \vee d| \leq |a - c| + |b - d|$ and summing together (3.8) and (3.9) we obtain

comparison 3

$$(3.10) \quad \sum_{\substack{|i| < R \\ |j| \geq R}} (\alpha_{ij} + \alpha_{ji}) (|\chi_i - \chi_j| + |\chi'_i - \chi'_j|) + 2 \sum_{|i| < R} (g'_i - g_i) (\chi'_i - \chi_i)^+ \\ \leq \sum_{\substack{|i| < R \\ |j| \geq R}} (\alpha_{ij} + \alpha_{ji}) (|\chi'_i \wedge \chi_i - \chi'_j| + |\chi'_i \vee \chi_i - \chi_j|).$$

We then remark that $|\chi'_i \wedge \chi_i - \chi'_j| \leq |\chi'_i \wedge \chi_i - \chi'_i| + |\chi'_i - \chi'_j| = (\chi'_i - \chi_i)^+ + |\chi'_i - \chi'_j|$ and analogously $|\chi'_i \vee \chi_i - \chi_j| \leq (\chi'_i - \chi_i)^+ + |\chi_i - \chi_j|$. Therefore, (3.10) entails

comparison 4

$$(3.11) \quad \sum_{|i| < R} (g'_i - g_i) (\chi'_i - \chi_i)^+ \leq \sum_{|i| < R} (\chi'_i - \chi_i)^+ \sum_{|j| \geq R} (\alpha_{ij} + \alpha_{ji}).$$

Fix now $R_\delta > 0$ such that

$$\sum_{|k| \geq R_\delta} \beta(k) \leq \frac{\delta}{4}$$

and define $V_R := \sum_{|i| < R} (\chi'_i - \chi_i)^+$. Assuming $R > R_\delta$, for every $\ell < R$ we use (3.11) and $g + \delta \leq g'$ to get

comparison 5

$$(3.12) \quad \delta V_R \leq \sum_{|i| < \ell} (\chi'_i - \chi_i)^+ \sum_{|j| \geq R} (\alpha_{ij} + \alpha_{ji}) + 2c_\beta \sum_{\ell \leq |i| < R} (\chi'_i - \chi_i)^+ \\ \leq 2 \sum_{|i| < \ell} (\chi'_i - \chi_i)^+ \sum_{|k| \geq R - \ell} \beta(k) + 2c_\beta (V_R - V_\ell).$$

Therefore, choosing $\ell = R - R_\delta$ in (3.12) we obtain

iter 1

$$(3.13) \quad \frac{\delta}{2} V_R \leq 2c_\beta (V_R - V_{R-R_\delta}),$$

which implies that for every $k, \ell \in \mathbb{N}$ it holds

iter 2

$$(3.14) \quad V_{kR_\delta} \leq \left(1 - \frac{\delta}{4c_\beta}\right)^\ell V_{(k+\ell)R_\delta}.$$

Letting $\ell \rightarrow +\infty$, since $V_{(k+\ell)R_\delta} = O(\ell^N)$, we infer that $V_{kR_\delta} = 0$ for every $k \in \mathbb{N}$. In particular, this implies that $(\chi' - \chi)^+ = 0$ i.e. $\chi' \leq \chi$. \square

⁴Indeed, if $a \geq b$ and $c \geq d$, this is an equality, while if $a > b$ and $c < d$, one deduces that $b - d < a - d < a - c$, $b - d < b - c < a - c$ so that there exists $t \in (0, 1)$ with $a - d = t(b - d) + (1 - t)(a - c)$, $b - c = (1 - t)(b - d) + t(a - c)$: the conclusion follow by convexity of $|\cdot|$.

We will prove the following theorem.

thm exist

Theorem 3.3. *Given $g \in X$ there exists a unique function $u^g \in X$ and there exists a discrete vector field $z \in Y$ such that (u^g, z) is a solution of (3.4). Moreover, the following comparison principle holds: if $g \leq g'$ then $u^g \leq u^{g'}$. Finally, for any $R > 0$ and $s \in \mathbb{R}$ the sublevel set $E_s := \{i \in \mathbb{Z}^N : u_i^g \leq s\}$ is a global minimizer (in the sense of Definition 3.1) for (3.6) with g replaced by $g - s$.*

Proof. Step 1. (Existence) For every $n \in \mathbb{N}$ set $g^n := g\chi^{B_n}$ and note that $g^n \in \ell^2(\mathbb{Z}^N)$. Therefore, by standard methods and by strict convexity the functional (3.5), with g replaced by g^n admits a unique minimizer u^n and, as previously observed, the optimality condition is the existence of a discrete field z^n such that (u^n, z^n) solves (3.4) (with g^n in place of g). Note that, for any $k \in \mathbb{Z}^N$, by equation (3.4) it holds

equi L inf

$$(3.15) \quad |u_k^n| \leq |g_k^n| + |(D^*z)_k| \leq |g_k| + c_\beta \quad \text{for every } n \in \mathbb{N},$$

where the last inequality follows from the definition (3.1) and from $|z_{ij}| \leq \alpha_{ij}$ and $|g^n| \leq |g|$. Now, it is clear that we can extract a subsequence n_k and find (u, z) such that $u_i^{n_k} \rightarrow u_i$ and $z_{ij}^{n_k} \rightarrow z_{ij}$ as $k \rightarrow +\infty$. Clearly we have that $|z_{ij}| \leq \alpha_{ij}$ and $z_{ij}(u_i - u_j) = \alpha_{ij}|u_i - u_j|$ and it is immediate to check that (u, z) satisfies equation (3.4).

Step 2. (Minimality of the sublevelsets) Let $R > 0$, $s \in \mathbb{R}$ and let $F \subseteq \mathbb{Z}^N$ such that $E_s \triangle F \subseteq \subseteq B_R$. We first remark that $\alpha_{ij}|\chi_i^{E_s} - \chi_j^{E_s}| = -z_{ij}(\chi_i^{E_s} - \chi_j^{E_s})$, which follows easily from the definition of E_s and $z_{ij}(u_i - u_j) = \alpha_{ij}|u_i - u_j|$.

We set $I_R := \{(i, j) \in \mathbb{Z}^N \times \mathbb{Z}^N : |i| < R \text{ or } |j| < R\}$ and compute

calibra

$$(3.16) \quad \begin{aligned} \mathcal{P}(F; B_R) - \mathcal{P}(E_s; B_R) &= \sum_{(i,j) \in I_R} \alpha_{ij}|\chi_i^F - \chi_j^F| - \sum_{(i,j) \in I_R} \alpha_{ij}|\chi_i^{E_s} - \chi_j^{E_s}| \\ &\geq - \sum_{(i,j) \in I_R} z_{ij}(\chi_i^F - \chi_j^F) + \sum_{(i,j) \in I_R} z_{ij}(\chi_i^{E_s} - \chi_j^{E_s}) \\ &= \sum_{(i,j) \in I_R} z_{ij}(\chi_i^{E_s} - \chi_i^F - (\chi_j^{E_s} - \chi_j^F)) \\ &= \sum_{ij} z_{ij}(\chi_i^{E_s} - \chi_i^F - (\chi_j^{E_s} - \chi_j^F)), \end{aligned}$$

where in the last equality we used the fact that $\chi_i^{E_s} = \chi_i^F$ if $|i| \geq R$. Noting that the function $\chi^{E_s} - \chi^F$ is compactly supported, we may use it as a test function for (3.4). Therefore, from (3.16) we deduce

$$\begin{aligned} \mathcal{P}(F; B_R) - \mathcal{P}(E_s; B_R) &\geq \sum_{ij} z_{ij}(\chi_i^{E_s} - \chi_i^F - (\chi_j^{E_s} - \chi_j^F)) \\ &= \sum_i (\chi_i^{E_s} - \chi_i^F)(g_i - u_i) \geq \sum_{i \in E_s \setminus F} (g_i - s) - \sum_{i \in F \setminus E_s} (g_i - s), \end{aligned}$$

which shows the minimality of E_s .

Step 3. (Comparison and uniqueness for (3.4)) Assume $g \leq g'$ and let $(u, z), (u', z')$ two corresponding solutions for (3.4). Let $s > s'$ and recall that by Step 2 $\{u' \leq s'\}$ and $\{u \leq s\}$ are global minimizers for (3.6) according to Definition 3.1, with g replaced by $g' - s'$ and $g - s$ respectively. Since $g' - s' - (g - s) \geq s - s' > 0$, from Proposition 3.2 we obtain $\{u' \leq s'\} \subseteq \{u \leq s\}$. By the arbitrariness of s, s' we conclude that $u \leq u'$. □

rmk stup**Remark 3.4.** We remark that, given $g \in X$ it clearly holds that $u^{-g} = -u^g$.

4. THE MINIMIZING MOVEMENTS SCHEME

section MMS

In this section we provide a combined spatial and time discretisation of the flow (1.1) for a particular class of norms ϕ and show the convergence of the scheme to the continuum flow. In what follows, we consider $\{e_1, \dots, e_m\} \subseteq \mathbb{Z}^N$ a finite number of integer vectors spanning the whole \mathbb{R}^N , and set $\mathcal{E} = \{\pm e_k\}_{k=1}^m$. We let $\beta \in X$ be a non-negative function such that

$$\beta(-i) = \beta(i) \quad \text{and} \quad \beta(i) > 0 \text{ if and only if } i \in \mathcal{E}.$$

One can naturally associate an anisotropy ϕ with the function β setting

phi special

$$(4.1) \quad \phi(v) = \sum_{i \in \mathcal{E}} \beta(i) |i \cdot v| = \sum_{k=1}^m 2\beta(e_k) |v \cdot e_k|.$$

Note that, in particular, it holds

hp3

$$(4.2) \quad \#\{k \in \mathbb{Z}^N : \beta(k) \neq 0\} < +\infty.$$

We recall that the ϕ -perimeter associated with (4.1)

$$P_\phi(E) = \int_{\partial^* E} \phi(\nu_E) d\mathcal{H}^{N-1}$$

(defined for every $E \subseteq \mathbb{R}^N$ of finite perimeter) is the Γ -limit (in a suitable sense) as $\varepsilon \rightarrow 0$ of the following scaled discrete perimeters

$$\mathcal{P}^\varepsilon(E) := \varepsilon^{N-1} \sum_{i,j \in \varepsilon \mathbb{Z}^N} \alpha_{ij}^\varepsilon |\chi_i^E - \chi_j^E| = \varepsilon^N \sum_{i,j \in \varepsilon \mathbb{Z}^N} \alpha_{i,j}^\varepsilon |(D_\varepsilon \chi^E)_{i,j}|$$

defined for all $E \subseteq \varepsilon \mathbb{Z}^N$, see for instance [9]. Here we have set

eq:alphah

$$(4.3) \quad \alpha_{ij}^\varepsilon := \beta\left(\frac{i}{\varepsilon} - \frac{j}{\varepsilon}\right).$$

Given ϕ a norm on \mathbb{R}^N and a closed set $E \not\subseteq \{\emptyset, \mathbb{R}^N\}$, we denote with $\text{sd}_E^{\phi^\circ}$ the signed ϕ° -distance function from E , which is defined as

$$\text{sd}_E^{\phi^\circ}(x) := \min_{y \in E} \phi^\circ(x - y) - \min_{y \notin E} \phi^\circ(x - y).$$

We also set $\text{sd}_\emptyset^{\phi^\circ} \equiv +\infty$ and $\text{sd}_{\mathbb{R}^N}^{\phi^\circ} \equiv -\infty$. We denote

def c phi

$$(4.4) \quad C_\phi = \min_{i \in \mathbb{Z}^N \setminus \{0\}} \phi^\circ(i) > 0$$

and define the ϕ -Wulff shape $\mathcal{W}_R(x)$ of radius $R > 0$ and center $x \in \mathbb{R}^N$ as $\mathcal{W}_R(x) = \{y \in \mathbb{R}^N : \phi^\circ(x - y) \leq R\}$.

4.1. A discrete redistancing operator. In this section we introduce a discrete proxy for the signed distance function to a set, and study some of its properties.

Given $u \in X_\varepsilon$ we define the operators $d_\pm^{\varepsilon, \phi^\circ}, \text{sd}_\pm^{\varepsilon, \phi^\circ}, \text{sd}^{\varepsilon, \phi^\circ} : X_\varepsilon \rightarrow X_\varepsilon$ in the following way: letting $E = \{i \in \varepsilon\mathbb{Z}^N : u_i \leq 0\}$, we first set

$$\begin{aligned}
 (d_-^{\varepsilon, \phi^\circ}(u))_i &= \sup_{j \in \{u \geq 0\}} \{u_j - \phi^\circ(i - j)\}, \\
 (\text{sd}_-^{\varepsilon, \phi^\circ}(u))_i &= \inf_{j \in \{u \leq 0\}} \left\{ (d_-^{\varepsilon, \phi^\circ}(u))_j + \phi^\circ(i - j) \right\}, \\
 (d_+^{\varepsilon, \phi^\circ}(u))_i &= \inf_{j \in \{u \leq 0\}} \{u_j + \phi^\circ(i - j)\}, \\
 (\text{sd}_+^{\varepsilon, \phi^\circ}(u))_i &= \sup_{j \in \{u \geq 0\}} \left\{ (d_+^{\varepsilon, \phi^\circ}(u))_j - \phi^\circ(i - j) \right\}, \\
 (\text{sd}^{\varepsilon, \phi^\circ}(u))_i &= \frac{1}{2}(\text{sd}_+^{\varepsilon, \phi^\circ}(u))_i + \frac{1}{2}(\text{sd}_-^{\varepsilon, \phi^\circ}(u))_i.
 \end{aligned}
 \tag{4.5}$$

Note that $d_+^{\varepsilon, \phi^\circ}(u) = -d_-^{\varepsilon, \phi^\circ}(-u)$ and $\text{sd}_+^{\varepsilon, \phi^\circ}(u) = -\text{sd}_-^{\varepsilon, \phi^\circ}(-u)$.

We will say that $f \in X_\varepsilon$ is (L, ϕ°) -Lipschitz if for all $i, j \in \varepsilon\mathbb{Z}^N$ it holds $|f_i - f_j| \leq L\phi^\circ(i - j)$.

lip sd

Remark 4.1. We assume in what follows that u is $(1, \phi^\circ)$ -Lipschitz. Then, concerning $d_-^{\varepsilon, \phi^\circ}, \text{sd}_-^{\varepsilon, \phi^\circ}$, we remark that

def sd min

$$d_-^{\varepsilon, \phi^\circ}(u) = \min \{f \in X_\varepsilon : f \geq u \text{ in } \{u \geq 0\}, f \text{ is } (1, \phi^\circ)\text{-Lipschitz}\},$$

and analogously

def sd max

$$\text{sd}_-^{\varepsilon, \phi^\circ}(u) = \max \left\{ f \in X_\varepsilon : f \leq d_-^{\varepsilon, \phi^\circ}(u) \text{ in } \{u \leq 0\}, f \text{ is } (1, \phi^\circ)\text{-Lipschitz} \right\}.$$

Correspondingly it holds

def sd+

$$\begin{aligned}
 d_+^{\varepsilon, \phi^\circ}(u) &= \max \{f \in X_\varepsilon : f \leq u \text{ in } \{u \leq 0\}, f \text{ is } (1, \phi^\circ)\text{-Lipschitz}\}, \\
 \text{sd}_+^{\varepsilon, \phi^\circ}(u) &= \min \left\{ f \in X_\varepsilon : f \geq d_+^{\varepsilon, \phi^\circ}(u) \text{ in } \{u \geq 0\}, f \text{ is } (1, \phi^\circ)\text{-Lipschitz} \right\},
 \end{aligned}
 \tag{4.8}$$

In particular, the functions $d_\pm^{\varepsilon, \phi^\circ}(u), \text{sd}_\pm^{\varepsilon, \phi^\circ}(u), \text{sd}^{\varepsilon, \phi^\circ}(u)$ are also $(1, \phi^\circ)$ -Lipschitz. Let us show (4.6) the other identities being analogous. To this aim, denote by \hat{d} the function defined by the right-hand side of (4.6). Since $d_-^{\varepsilon, \phi^\circ}(u)$ is the pointwise supremum of $(1, \phi^\circ)$ -Lipschitz functions, we clearly have that $d_-^{\varepsilon, \phi^\circ}(u)$ is itself $(1, \phi^\circ)$ -Lipschitz. Moreover, testing with $j = i$ in the definition of $d_-^{\varepsilon, \phi^\circ}(u)$, we get $d_-^{\varepsilon, \phi^\circ}(u) \geq u$ in $\{u \geq 0\}$. Thus, we infer $\hat{d} \leq d_-^{\varepsilon, \phi^\circ}(u)$. For the opposite inequality, let f be any functions as in the minimisation problem on the right-hand side of (4.6). Then for any $i \in \varepsilon\mathbb{Z}^N$ and $j \in \{u \geq 0\}$ we have

$$f_i \geq f_j - \phi^\circ(i - j) \geq u_j - \phi^\circ(i - j).$$

By maximising with respect to $j \in \{u \geq 0\}$, we get $f \geq d_-^{\varepsilon, \phi^\circ}(u)$ and in turn, by the arbitrariness of f , $\hat{d} \geq d_-^{\varepsilon, \phi^\circ}(u)$, which concludes the proof of (4.6)

Since the functions $d_\pm^{\varepsilon, \phi^\circ}(u), \text{sd}_\pm^{\varepsilon, \phi^\circ}(u), \text{sd}^{\varepsilon, \phi^\circ}(u)$ are $(1, \phi^\circ)$ -Lipschitz, from (4.6) it follows that

d=-

$$d_-^{\varepsilon, \phi^\circ}(u) \leq u \text{ in } \varepsilon\mathbb{Z}^N, \quad d_-^{\varepsilon, \phi^\circ}(u) = u \text{ in } \{u \geq 0\},$$

while (4.7) implies that

sd=-

$$\text{sd}_-^{\varepsilon, \phi^\circ}(u) \geq d_-^{\varepsilon, \phi^\circ}(u) \text{ in } \varepsilon\mathbb{Z}^N, \quad \text{sd}_-^{\varepsilon, \phi^\circ}(u) = d_-^{\varepsilon, \phi^\circ}(u) \text{ in } \{u \leq 0\}.$$

Reasoning in the same way, we see that

$$\boxed{\text{sd}+=} \quad (4.11) \quad \begin{aligned} d_+^{\varepsilon, \phi^\circ}(u) &\geq u \text{ in } \varepsilon\mathbb{Z}^N, & d_+^{\varepsilon, \phi^\circ}(u) &= u \text{ in } \{u \leq 0\}, \\ \text{sd}_+^{\varepsilon, \phi^\circ}(u) &\leq d_+^{\varepsilon, \phi^\circ}(u) \text{ in } \varepsilon\mathbb{Z}^N, & \text{sd}_+^{\varepsilon, \phi^\circ}(u) &= d_+^{\varepsilon, \phi^\circ}(u) \text{ in } \{u \geq 0\}. \end{aligned}$$

In particular we conclude

$$\boxed{\text{sd}=} \quad (4.12) \quad \text{sd}^{\varepsilon, \phi^\circ}(u) \geq u \text{ in } \{u \geq 0\}, \quad \text{sd}^{\varepsilon, \phi^\circ}(u) \leq u \text{ in } \{u \leq 0\}.$$

Note that (4.12) implies $\{\text{sd}_+^{\varepsilon, \phi^\circ}(u) \geq 0\} \supseteq \{u \geq 0\}$, and (4.11) yields $\{\text{sd}_+^{\varepsilon, \phi^\circ}(u) < 0\} \supseteq \{u < 0\}$, thus $\{\text{sd}_+^{\varepsilon, \phi^\circ}(u) \geq 0\} = \{u \geq 0\}$ (and analogously for $\text{sd}_-^{\varepsilon, \phi^\circ}$). Similarly, one shows that $\{\text{sd}_\pm^{\varepsilon, \phi^\circ}(u) \leq 0\} = \{u \leq 0\}$. In particular, if the level set 0 of u is “fat”, then this is preserved by these discrete “signed distance functions”. Further properties of these discrete signed distance functions are presented in Lemma 4.3 below and in Remark 4.9

Moreover, it follows directly from the definition of $d_\pm^{\varepsilon, \phi^\circ}(u)$, $\text{sd}_\pm^{\varepsilon, \phi^\circ}(u)$ that the function $\text{sd}^{\varepsilon, \phi^\circ}(u)$ is invariant under integer translations, meaning that for any $i, \tau \in \varepsilon\mathbb{Z}^N$ it follows

$$\boxed{\text{transl invar sd}} \quad (4.13) \quad \left(\text{sd}^{\varepsilon, \phi^\circ}(u(\cdot + \tau)) \right)_i = \left(\text{sd}^{\varepsilon, \phi^\circ}(u) \right)_{i+\tau}.$$

We now show that the redistancing operator $\text{sd}^\varepsilon(u)$ is indeed a discrete approximation of the signed distance function to the 0-sublevel set of the function u .

Given a set $E \subseteq \varepsilon\mathbb{Z}^N$, we will denote with $\widehat{E} \subseteq \mathbb{R}^N$ the closed set defined by

$$\widehat{E} := E + [0, \varepsilon]^N.$$

$\boxed{\text{lemma sd sd hat}}$ **Lemma 4.2.** *Given a $(1, \phi^\circ)$ -Lipschitz function $u \in X_\varepsilon$, it holds*

$$\boxed{\text{comp sd sd hat}} \quad (4.14) \quad \sup_{\varepsilon\mathbb{Z}^N \setminus E} |\text{sd}_\pm^{\varepsilon, \phi^\circ}(u) - \text{sd}_E^{\phi^\circ}| \leq c_\phi \varepsilon,$$

for a suitable positive constant c_ϕ , where $E = \{i \in \varepsilon\mathbb{Z}^N : u_i \leq 0\}$. Moreover,

$$\boxed{\text{mp sd sd hat bis}} \quad (4.15) \quad \text{sd}_\pm^{\varepsilon, \phi^\circ}(u) \geq \text{sd}_E^{\phi^\circ} - c_\phi \varepsilon \quad \text{in } \varepsilon\mathbb{Z}^N.$$

Proof. In this proof we let c_ϕ denote a positive constant which depends on ϕ and that may change from line to line and also within the same line.

We start introducing a slightly modified definition of the discrete signed distance $\text{sd}^{\varepsilon, \phi^\circ}(u)$. Namely, setting

$$\boxed{\text{def boundary+}} \quad (4.16) \quad \begin{aligned} \partial_\varepsilon^+ E &:= \{i \in \varepsilon\mathbb{Z}^N \setminus E : \exists j \in E \text{ with } \|i - j\|_\infty = \varepsilon\} \\ \partial_\varepsilon^- E &:= \{i \in E : \exists j \in \varepsilon\mathbb{Z}^N \setminus E \text{ with } \|i - j\|_\infty = \varepsilon\}, \end{aligned}$$

we define

$$(4.17) \quad \tilde{d}_i = \begin{cases} \inf \{u_j + \phi^\circ(i - j) : j \in \partial_\varepsilon^- E\}, & \text{for } i \in \varepsilon\mathbb{Z}^N \setminus E \\ \sup \{u_j - \phi^\circ(i - j) : j \in \partial_\varepsilon^+ E\} & \text{for } i \in E \end{cases}.$$

We start by showing that

$$\boxed{\text{eq comp 3}} \quad (4.18) \quad \begin{aligned} \text{sd}_\pm^{\varepsilon, \phi^\circ}(u) &\geq \tilde{d} \quad \text{in } E, \\ \text{sd}_\pm^{\varepsilon, \phi^\circ}(u) &\leq \tilde{d} \quad \text{in } \varepsilon\mathbb{Z}^N \setminus E. \end{aligned}$$

Indeed, we note that for every $i \in E$ we have

$$(\text{sd}_-^{\varepsilon, \phi^\circ}(u))_i = (d_-^{\varepsilon, \phi^\circ}(u))_i = \sup_{j \in \{u \geq 0\}} \{u_j - \phi^\circ(i - j)\} \geq \sup_{j \in \partial_\varepsilon^+ E} \{u_j - \phi^\circ(i - j)\} = \tilde{d}_i.$$

On the other hand, recalling that $d_-^{\varepsilon, \phi^\circ}(u) \leq u$ in E , for every $i \in \varepsilon\mathbb{Z}^N \setminus E$ we see

$$(\text{sd}_-^{\varepsilon, \phi^\circ}(u))_i = \inf_{j \in \{u \leq 0\}} \{(d_-^{\varepsilon, \phi^\circ}(u))_j + \phi^\circ(i - j)\} \leq \inf_{j \in \partial_\varepsilon^- E} \{u_j + \phi^\circ(i - j)\} = \tilde{d}_i.$$

Reasoning analogously we show the same inequalities between $\text{sd}_+^{\varepsilon, \phi^\circ}$ and \tilde{d} and thus prove (4.18).

Next, we prove

tilde d and sd

$$(4.19) \quad \sup_{\varepsilon\mathbb{Z}^N} |\tilde{d} - \text{sd}_E^{\phi^\circ}| \leq c_\phi \varepsilon.$$

Recall that by definition (4.16), since $u \leq 0$ in E and $u > 0$ in $\varepsilon\mathbb{Z}^N \setminus E$ and since u is $(1, \phi^\circ)$ -Lipschitz, it holds

$$|u_j| \leq c_\phi \varepsilon \quad \text{for } j \in \partial_\varepsilon^\pm E.$$

Then, for every $i \in \varepsilon\mathbb{Z}^N \setminus E$ we have

eq comp 1

$$(4.20) \quad \tilde{d}_i = \inf_{j \in \partial_\varepsilon^- E} \{u_j + \phi^\circ(i - j)\} \geq \inf_{j \in \partial_\varepsilon^- E} \phi^\circ(i - j) - c_\phi \varepsilon \geq \text{sd}_E^{\phi^\circ}(i) - c_\phi \varepsilon.$$

On the other hand, by definition of $\text{sd}_E^{\phi^\circ}$ there exists $x \in \partial \widehat{E}$ such that $\text{sd}_E^{\phi^\circ}(i) = \phi^\circ(i - x)$. Let $k \in \varepsilon\mathbb{Z}^N$ be the closest point from x in $\partial_\varepsilon^- E$. We have

eq comp 2

$$(4.21) \quad \begin{aligned} \text{sd}_E^{\phi^\circ}(i) &= \phi^\circ(i - x) \geq \phi^\circ(i - k) - c_\phi \varepsilon \\ &\geq \phi^\circ(i - k) + u_k - c_\phi \varepsilon \geq \tilde{d}_i - c_\phi \varepsilon. \end{aligned}$$

Finally, equation (4.20) and (4.21) imply (4.19) outside E . The other case is analogous.

We now finally prove (4.14) outside E . From (4.18) and (4.19) it holds

$$d_-^{\varepsilon, \phi^\circ}(u) = \text{sd}_-^{\varepsilon, \phi^\circ}(u) \geq \tilde{d} \geq \text{sd}_E^{\phi^\circ} - c_\phi \varepsilon \quad \text{in } E.$$

In particular, $\text{sd}_E^{\phi^\circ} - c_\phi \varepsilon$ is an admissible competitor in (4.7), thus $\text{sd}_-^{\varepsilon, \phi^\circ}(u) \geq \text{sd}_E^{\phi^\circ} - c_\phi \varepsilon$ in $\varepsilon\mathbb{Z}^N$.

On the other hand, in $\varepsilon\mathbb{Z}^N \setminus E$ it holds (4.18), thus we conclude (4.14) for $\text{sd}_-^{\varepsilon, \phi^\circ}(u)$. Concerning $\text{sd}_+^{\varepsilon, \phi^\circ}(u)$, we note that by Remark 4.1 and the equation above it holds

$$u \geq \text{sd}_-^{\varepsilon, \phi^\circ}(u) \geq \text{sd}_E^{\phi^\circ} - c_\phi \varepsilon \quad \text{in } E.$$

The function $\text{sd}_E^{\phi^\circ} - c_\phi \varepsilon$ is therefore admissible in (4.8), thus by maximality

$$d_+^{\varepsilon, \phi^\circ}(u) \geq \text{sd}_E^{\phi^\circ} - c_\phi \varepsilon.$$

Since $\text{sd}_+^{\varepsilon, \phi^\circ}(u) = d_+^{\varepsilon, \phi^\circ}(u)$ in $\varepsilon\mathbb{Z}^N \setminus E$ we conclude (4.14), taking also into account again (4.18) and (4.19). Finally, (4.15) follows by combining (4.14), (4.18) and (4.19). \square

We conclude the section with some further properties of the operator $\text{sd}^{\varepsilon, \phi^\circ}$.

lem:sdcompar

Lemma 4.3. *Given $u \in X_\varepsilon$ and $(1, \phi^\circ)$ -Lipschitz, it holds*

simm sd

$$(4.22) \quad \text{sd}^{\varepsilon, \phi^\circ}(-u) = -\text{sd}^{\varepsilon, \phi^\circ}(u).$$

Furthermore, if $u_1, u_2 \in X_\varepsilon$ are $(1, \phi^\circ)$ -Lipschitz and $u_1 \leq u_2$ then

sd monotone

$$(4.23) \quad \text{sd}^{\varepsilon, \phi^\circ}(u_1) \leq \text{sd}^{\varepsilon, \phi^\circ}(u_2).$$

Finally, for any $s > 0$ and $u \in X_\varepsilon$ and $(1, \phi^\circ)$ -Lipschitz, it holds

sd level sets

$$(4.24) \quad \text{sd}^{\varepsilon, \phi^\circ}(u - s) \leq \text{sd}^{\varepsilon, \phi^\circ}(u) - s.$$

Proof. For every $i \in \varepsilon\mathbb{Z}^N$ it holds

$$(d_-^{\varepsilon, \phi^\circ}(-u))_i = \max_{j \in \{(-u) \geq 0\}} \{-u_j - \phi^\circ(i-j)\} = - \min_{j \in \{u \leq 0\}} \{u_j + \phi^\circ(i-j)\} = -(d_+^{\varepsilon, \phi^\circ}(u))_i.$$

In turn,

$$\begin{aligned} (\text{sd}_-^{\varepsilon, \phi^\circ}(-u))_i &= \min_{j \in \{(-u) \leq 0\}} \{(d_-^{\varepsilon, \phi^\circ}(-u))_j + \phi^\circ(i-j)\} \\ &= - \max_{j \in \{u \geq 0\}} \{(d_+^{\varepsilon, \phi^\circ}(u))_j - \phi^\circ(i-j)\} = -(\text{sd}_+^{\varepsilon, \phi^\circ}(u))_i. \end{aligned}$$

Reasoning in the same way for $d_+^{\varepsilon, \phi^\circ}$, $\text{sd}_+^{\varepsilon, \phi^\circ}$ we arrive at

sd pm

$$(4.25) \quad \text{sd}_\pm^{\varepsilon, \phi^\circ}(-u) = -\text{sd}_\mp^{\varepsilon, \phi^\circ}(u)$$

and thus $\text{sd}_-^{\varepsilon, \phi^\circ}(-u) = -\text{sd}_+^{\varepsilon, \phi^\circ}(u)$. The monotonicity property (4.23) follows easily from Definition (4.5). The proofs of the other results also follow from Definition (4.5), we present only the one concerning (4.24). Fix $s > 0$ and $u \in X_\varepsilon$ be a $(1, \phi^\circ)$ -Lipschitz function. By definition of $d_-^{\varepsilon, \phi^\circ}(u)$ we have

$$(d_-^{\varepsilon, \phi^\circ}(u))_i = \sup_{j \in \{u \geq 0\}} \{u_j - \phi^\circ(i-j)\} \geq s + \sup_{j \in \{u \geq s\}} \{(u_j - s) - \phi^\circ(i-j)\} = (d_-^{\varepsilon, \phi^\circ}(u-s))_i + s.$$

Analogously

$$\begin{aligned} (\text{sd}_-^{\varepsilon, \phi^\circ}(u))_i &= \inf_{j \in \{u \leq 0\}} \{(d_-^{\varepsilon, \phi^\circ}(u))_j + \phi^\circ(i-j)\} \\ &\geq s + \inf_{j \in \{u \leq s\}} \{(d_-^{\varepsilon, \phi^\circ}(u-s))_j + \phi^\circ(i-j)\} = s + (\text{sd}_+^{\varepsilon, \phi^\circ}(u-s))_i. \end{aligned}$$

Since the proofs for $d_+^{\varepsilon, \phi^\circ}(u)$, $\text{sd}_+^{\varepsilon, \phi^\circ}(u)$ are analogous, we conclude. \square

4.2. The discrete scheme. We now describe our minimizing movements scheme, discretized in both time and space. A particularity of our scheme is that in practice, it evolves the distance function to a set rather than the set itself. In particular, at the discrete level, it may depend on the initialization (even if in the limit the flow is geometric and only depends on the initial set).

Recalling (4.3), we rescale equation (3.4) on the lattice $\varepsilon\mathbb{Z}^N$ in the following way. We recall that $X_\varepsilon = \mathbb{R}^{\varepsilon\mathbb{Z}^N}$ and $Y_\varepsilon = \mathbb{R}^{\varepsilon\mathbb{Z}^N \times \varepsilon\mathbb{Z}^N}$. Given $g \in X_\varepsilon$ and a time step $h > 0$, the problem (3.4) now becomes to find $(u, z) \in X_\varepsilon \times Y_\varepsilon$ satisfying

discrete EL resc

$$(4.26) \quad \begin{cases} hD_\varepsilon^* z + u = g & \text{on } \varepsilon\mathbb{Z}^N \\ z_{ij}(u_i - u_j) = \alpha_{ij}^\varepsilon |u_i - u_j|, & |z_{ij}| \leq \alpha_{ij}^\varepsilon, \end{cases}$$

where $D_\varepsilon^* z$ is defined in (3.1). For ease of notation we assume $\varepsilon = \varepsilon(h)$, with $\varepsilon \rightarrow 0$ as $h \rightarrow 0$ and we will specify the dependence on h only.

Let $E_0 \subseteq \mathbb{R}^N$ be a closed set. We define $E^{h,0} := \{i \in \varepsilon\mathbb{Z}^N : (i + [0, \varepsilon)^N) \cap E_0 \neq \emptyset\}$. We note that

$$(4.27) \quad \widehat{E}^{h,0} \rightarrow E_0, \quad E^{h,0} \rightarrow E_0$$

as $h \rightarrow 0$ in the Kuratowski sense, where with a slight abuse of notation we write $\widehat{E}^{h,0}$ to denote the set $\widehat{E^{h,0}} = E^{h,0} + [0, \varepsilon]^N$.

Given a closed set $E_0 \subseteq \mathbb{R}^N$ with $E_0 \notin \{\emptyset, \mathbb{R}^N\}$, we consider $u^{h,0}$ a $(1, \phi^\circ)$ -Lipschitz function on $\varepsilon\mathbb{Z}^N$ which is negative inside $E^{h,0}$ and positive outside. For instance, we set

$$u^{h,0} := \frac{1}{2} C_\phi \varepsilon (1 - \chi_{E^{h,0}}) - \frac{1}{2} C_\phi \varepsilon \chi_{E^{h,0}},$$

where C_ϕ is defined in (4.4), so that $u^{h,0}$ is $(1, \phi^\circ)$ -Lipschitz. Let us set $(z^{h,0})_{ij} = 0$ for all $i, j \in \varepsilon\mathbb{Z}^N$. Then, as long as $E^{h,k} \notin \{\emptyset, \mathbb{R}^N\}$, we can iteratively define $u^{h,k+1}, z^{h,k+1}$ for $k \in \mathbb{N}$ by solving (4.26) with $g = \text{sd}^{\varepsilon, \phi^\circ}(u^{h,k})$; i.e.,

ete EL resc algo

$$(4.28) \quad \begin{cases} hD_\varepsilon^* z^{h,k+1} + u^{h,k+1} = \text{sd}^{\varepsilon, \phi^\circ}(u^{h,k}) & \text{on } \varepsilon\mathbb{Z}^N \\ z_{ij}^{h,k+1}(u_i^{h,k+1} - u_j^{h,k+1}) = \alpha_{ij}^\varepsilon |u_i^{h,k+1} - u_j^{h,k+1}|, & |z_{ij}^{h,k+1}| \leq \alpha_{ij}^\varepsilon. \end{cases}$$

We recall that the redistancing operator $\text{sd}^{\varepsilon, \phi^\circ}$ has been introduced in the previous section. We then set

$$E^{h,k+1} = \{i \in \varepsilon\mathbb{Z}^N : u_i^{h,k+1} \leq 0\}.$$

If either $E^{h,k} = \emptyset$ or $E^{h,k} = \mathbb{R}^N$, we define $E^{h,k+1} = E^{h,k}$. We denote by T_h^* the first discrete time hk such that $E^{h,k} = \emptyset$, if any; otherwise we let $T_h^* = +\infty$. Analogously, we set $T_h'^*$ first discrete time hk such that $E^{h,k} = \mathbb{R}^N$, if any; otherwise we let $T_h'^* = +\infty$.

For ease of notation we will set

def algo

$$(4.29) \quad \begin{aligned} E^h(t) &:= E^{h, [t/h]} \subseteq \varepsilon\mathbb{Z}^N \\ d^h(t) &:= \text{sd}^{\varepsilon, \phi^\circ}(u^{h, [t/h]}) \in X_\varepsilon \\ u^h(t) &:= u^{h, [t/h]} \in X_\varepsilon \\ z^h(t) &:= z^{h, [t/h]} \in Y_\varepsilon \\ \widehat{d}^h(\cdot, t) &:= \text{sd}_{\widehat{E}^h(t)}^{\phi^\circ} \in \text{Lip}(\mathbb{R}^N), \end{aligned}$$

where again, with a slight abuse of notation, $\widehat{E}^h(t)$ stands for $\widehat{E^h(t)}$. Note that in the definition of $\widehat{d}^h(\cdot, t)$ we are possibly using the convention $\text{sd}_\emptyset^{\phi^\circ} \equiv +\infty$ and $\text{sd}_{\mathbb{R}^N}^{\phi^\circ} \equiv -\infty$. Note also that $z^h(t)$ is well defined only for $0 \leq t < \min\{T_h^*, T_h'^*\}$; however, if needed, we can set $z^h(t) = 0$ for $t \geq \min\{T_h^*, T_h'^*\}$.

lip u

Remark 4.4. If u is the solution of (4.26) with (L, ϕ°) -Lipschitz datum g , by standard arguments, based on the comparison principle and translation invariance, one can show that u satisfies the same Lipschitz bound of g . Indeed, given $j \in \varepsilon\mathbb{Z}^N$, the function $u(\cdot - j) \pm L\phi^\circ(j)$ solves (4.26) with datum $g(\cdot - j) \pm L\phi^\circ(j)$. By comparison one concludes as $g(\cdot - j) - L\phi^\circ(j) \leq g(\cdot) \leq g(\cdot - j) + L\phi^\circ(j)$.

Lemma 4.5. Let u^h, E^h, d^h be defined as in (4.29). Then, for every $t \geq 0$, $d^h(t)$ is $(1, \phi^\circ)$ -Lipschitz and satisfies

u over d

$$(4.30) \quad \begin{cases} u^h(t) \leq d^h(t) & \text{in } \varepsilon\mathbb{Z}^N \setminus E^h(t) \\ u^h(t) \geq d^h(t) & \text{in } E^h(t). \end{cases}$$

Proof. It follows from Remarks 4.1 and 4.4. □

rmk evol compl

Remark 4.6. (Evolution of the complement) Let $E^h(t), u^h(t)$ be as in (4.29). We note that, if $F_0 \subseteq \mathbb{R}^N$ is a closed set such that $F^{h,0} = \varepsilon\mathbb{Z}^N \setminus E^{h,0}$, then the discrete evolution starting from F_0 coincides with $\{u^h(t) \geq 0\}$ for every $t \geq 0$. Indeed, denoting v^h the discrete evolution starting from F_0 , it holds by definition $v^{h,0} = -u^{h,0}$, thus recalling (4.22) we have

$$\text{sd}^{\varepsilon, \phi^\circ}(v^{h,0}) = -\text{sd}^{\varepsilon, \phi^\circ}(u^{h,0})$$

and, by uniqueness for (4.26) it follows that $v^h(h) = -u^h(h)$. Then we can iterate to conclude.

rmk: comparison

Remark 4.7 (Comparison principle). Let E_0, F_0 be closed sets in \mathbb{R}^N such that $E^{h,0} \subseteq F^{h,0}$ (note that this condition is satisfied if $E_0 \subseteq F_0$). Let $E^h(t), F^h(t)$ be the corresponding discrete evolutions and let $u^h(t), v^h(t)$ be the associated functions as in (4.29). Then, for every $t \geq 0$ it holds $E^h(t) \subseteq F^h(t)$. This follows easily by iteration from the monotonicity property (4.23) and from the comparison principle for (4.26). One in fact could also consider the “open” discrete evolution given by $\mathring{E}^h(t) := \{u^h(t) < 0\}$ and $\mathring{F}^h(t) := \{v^h(t) < 0\}$. Then, by the same argument one also have that $\mathring{E}^h(t) \subseteq \mathring{F}^h(t)$.

rmk: avoidance

Remark 4.8 (Avoidance principle). Let $E_0, F_0 \subseteq \mathbb{R}^N$ be closed sets such that $E^{h,0} \cap F^{h,0} = \emptyset$ (which is, for example, implied by $\text{dist}(E_0, F_0) > c_\phi \varepsilon$ for a suitable $c_\phi > 0$). Let E^h, u^h and $\mathring{F}^h(t), v^h$ be the closed and open discrete evolutions starting from E_0, F_0 respectively (where the open discrete evolution has been defined in Remark 4.7). Then,

$$\mathring{F}^h(t) \subseteq \varepsilon \mathbb{Z}^N \setminus E^h(t).$$

Indeed, $F^{h,0} \subseteq \varepsilon \mathbb{Z}^N \setminus E^{h,0}$ implies that $-u^{h,0} \leq v^{h,0}$ and thus by (4.22) and (4.23)

$$-\text{sd}^{\varepsilon, \phi^\circ}(u^{h,0}) = \text{sd}^{\varepsilon, \phi^\circ}(-u^{h,0}) \leq \text{sd}^{\varepsilon, \phi^\circ}(v^{h,0}).$$

By the comparison principle for (4.26) and iterating one sees that $-u^h(t) \leq v^h(t)$ for all $t \geq 0$, which implies

$$\mathring{F}^h(t) = \{v^h(t) < 0\} \subseteq \{u^h(t) > 0\} = \varepsilon \mathbb{Z}^N \setminus E^h(t).$$

rmk:sd

Remark 4.9. We conclude this section by observing that we could have made different choices of the distance function, without affecting the final convergence result. In definition (4.5) we could have set

$$\begin{aligned} (d^<(u))_i &= \inf_{j \in \{u < 0\}} \{u_j + \phi^\circ(i - j)\}, \\ (\text{sd}^<(u))_i &= \sup_{j \in \{u \geq 0\}} \{(d^<(u))_j - \phi^\circ(i - j)\}, \\ (d^{\leq}(u))_i &= \inf_{j \in \{u \leq 0\}} \{u_j + \phi^\circ(i - j)\}, \\ (\text{sd}^{\leq}(u))_i &= \sup_{j \in \{u > 0\}} \{(d^<(u))_j - \phi^\circ(i - j)\}. \end{aligned} \tag{4.31}$$

def sd weird

One can see that $\text{sd}^{\leq}(u)$ mimics the signed distance function to the boundary of $\{u \leq 0\}$ while $\text{sd}^<(u)$ mimics the signed distance function to the boundary of $\{u < 0\}$. Defining the algorithm as in (4.28) but with $\text{sd}^<, \text{sd}^{\leq}$ replacing $\text{sd}^{\varepsilon, \phi^\circ}$, adapting our proof one can conclude the same convergence result. Let us further comment on the relation between $\text{sd}^{\varepsilon, \phi^\circ}, \text{sd}^{\leq}, \text{sd}^<$. One can prove that for any $(1, \phi^\circ)$ -Lipschitz function $u \in X_\varepsilon$, then

$$\text{sd}^{\leq}(u) \leq \text{sd}_-^{\varepsilon, \phi^\circ}(u) \leq \text{sd}_+^{\varepsilon, \phi^\circ}(u) \leq \text{sd}^<(u). \tag{4.32}$$

three sd

Thus, between the many possible choices we could have performed in (4.5), it turns out that $\text{sd}^<$ is the “maximal” one, while sd^{\leq} is the “minimal”. Indeed, let us show that $\text{sd}_-^{\varepsilon, \phi^\circ}(u) \leq \text{sd}_+^{\varepsilon, \phi^\circ}(u)$. By definition (4.5) and (4.9), (4.11) for every $i \in \{u \geq 0\}$ it holds

$$(\text{sd}_-^{\varepsilon, \phi^\circ}(u))_i = \inf_{j \in \{u \leq 0\}} \{(d_-^{\varepsilon, \phi^\circ}(u))_j + \phi^\circ(i - j)\} \leq \inf_{j \in \{u \leq 0\}} \{u_j + \phi^\circ(i - j)\} = (\text{sd}_+^{\varepsilon, \phi^\circ}(u))_i.$$

Reasoning analogously, for every $i \in \{u \leq 0\}$ it holds

$$(\text{sd}_+^{\varepsilon, \phi^\circ}(u))_i = \sup_{j \in \{u \geq 0\}} \{(d_+^{\varepsilon, \phi^\circ}(u))_j - \phi^\circ(i - j)\} \geq \sup_{j \in \{u \geq 0\}} \{u_j - \phi^\circ(i - j)\} = (\text{sd}_-^{\varepsilon, \phi^\circ}(u))_i.$$

Furthermore, for any two $(1, \phi^\circ)$ -Lipschitz functions $u, u' \in X_\varepsilon$, if $u \leq u' - s$ for $s > 0$ then

$$\text{sd}^<(u) \leq \text{sd}^<(u') - s.$$

In particular, this implies that for any $(1, \phi^\circ)$ -Lipschitz function $u \in X_\varepsilon$ and $s' > s$ then

$$\text{sd}^{\varepsilon, \phi^\circ}(u - s) \leq \text{sd}^{\varepsilon, \phi^\circ}(u - s') + s' - s.$$

Fix $u_0 \in X_\varepsilon$ is a $(1, \phi^\circ)$ -Lipschitz function. Using the properties above and standard arguments, one can see that for all but countably many $s \in \mathbb{R}$ the discrete evolutions starting from $\{u_0 \leq s\}$ and corresponding to the three possible choices of distances in (4.32) coincide.

sec:Wulff

4.3. Discrete evolution of Wulff shapes. In this section we provide some control on the evolution speed of discrete Wulff shapes. The first result estimates the solution of (4.26) for the distance to the Wulff shape.

Lemma 4.10. *There exists a constant $C = C(\phi) > 0$ with the following property. If u is the solution of (4.26) with $g = \phi^\circ$, then $u \leq \phi^h$, where $\phi^h \in X_\varepsilon$ is defined as*

$$(4.33) \quad \phi_i^h := \begin{cases} \phi^\circ(i) + \frac{Ch}{\phi^\circ(i)} & \text{if } \phi^\circ(i) \geq C(\sqrt{h} \vee \varepsilon) \\ C(\sqrt{h} \vee \varepsilon) + \frac{Ch}{\sqrt{h} \vee \varepsilon} & \text{otherwise.} \end{cases}$$

phi h

The proof of Lemma 4.10, based on the construction of a calibration, is postponed to Appendix A. We now prove a useful lemma used to estimate the redistancing step in our algorithm for functions of the form of (4.33).

lemma sd po-R

Lemma 4.11. *Let $R \geq \delta > 0$ and set*

$$u := (\phi^\circ - R) \vee (\delta/2 - R).$$

Then, for ε small enough depending on δ it holds

$$(4.34) \quad \text{sd}^{\varepsilon, \phi^\circ}(u) \leq \phi^\circ - R + \hat{c}\varepsilon \quad \text{in } \varepsilon\mathbb{Z}^N,$$

for a suitable positive constant \hat{c} , depending on ϕ . Furthermore, if we assume (B.1), it holds

$$(4.35) \quad \text{sd}^{\varepsilon, \phi^\circ}(u) \leq \phi^\circ - R \quad \text{in } \varepsilon\mathbb{Z}^N.$$

sd po-R

Proof. By (4.32), it is sufficient to prove the claim for $\text{sd}_+^{\varepsilon, \phi^\circ}$. We start showing that $d_+^{\varepsilon, \phi^\circ}(u) = u$, noting that by (4.11) it suffices to prove $d_+^{\varepsilon, \phi^\circ}(u) \leq u$ in $\{u \geq 0\} = \{\phi^\circ \geq R\}$. Assuming (B.1), given $i \in \{u \geq 0\}$ we note that $\phi^\circ(i) \geq R$ thus by Lemma B.1 there exists $j \in \mathcal{W}_R \setminus \mathcal{W}_{R-2\varepsilon\ell_1}$ satisfying

$$\phi^\circ(j) + \phi^\circ(i - j) = \phi^\circ(i).$$

Taking $\varepsilon = \varepsilon(\delta)$ we can ensure that $R - 2\varepsilon\ell_1 \geq \delta/2$, so that $j \in (\mathcal{W}_R \setminus \mathcal{W}_{\delta/2}) \cap \varepsilon\mathbb{Z}^N$. By definition (4.5) and the equation above we conclude that

$$d_+^{\varepsilon, \phi^\circ}(u) \leq u_j + \phi^\circ(i - j) = \phi^\circ(j) - R + \phi^\circ(i - j) = \phi^\circ(i) - R,$$

hence we have shown that $d_+^{\varepsilon, \phi^\circ}(u) = u$. Finally, from the definition (4.5) and since $d_+^{\varepsilon, \phi^\circ}(u) = u = \phi^\circ - R$ on $\{u \geq 0\}$, we conclude by the triangular inequality that $\text{sd}_+^{\varepsilon, \phi^\circ}(u) \leq \phi^\circ - R$. All in all, we have obtained (4.35).

If instead (B.1) does not hold, using the first part of Lemma B.1 and reasoning as above, one concludes that

$$\text{sd}_+^{\varepsilon, \phi^\circ}(u) \leq \phi^\circ - R + \hat{c}\varepsilon,$$

for a positive constant \hat{c} , and then the conclusion follows. \square

Combining the two results above we can provide a bound on the evolution speed of Wulff shapes in the algorithm (4.28).

Proposition 4.12. *Assume either $\varepsilon \leq O(h)$ or that (B.1) holds. For every $\delta > 0$ there exist ε_0, h_0, c_0 positive constants depending on δ with the following property. If $R \geq \delta$, $\varepsilon \leq \varepsilon_0$ and $h \leq h_0$, then the discrete evolution of \mathcal{W}_R defined in (4.28), denoted $\mathcal{W}^h(t)$, satisfies*

$$(4.36) \quad \mathcal{W}^h(t) \supseteq (\mathcal{W}_{R-c_0(t+\varepsilon)}) \cap \varepsilon \mathbb{Z}^N,$$

as long as $R - c_0(t + \varepsilon) \geq \delta/2$.

Proof. Let $\hat{\mathcal{W}}^h(t)$ be the open discrete evolution (see Remark 4.7) starting from the closure of \mathcal{W}_R , for some $R > 0$ and let $v^h(t)$ be the associated function as in the third equation in (4.29). Using the definition of $v^{h,0}$, (4.10) and the first definition in (4.5), it is easy to see that

$$(4.37) \quad (\text{sd}_-^{\varepsilon, \phi^\circ}(v^{h,0}))_0 = (d_-^{\varepsilon, \phi^\circ}(v^{h,0}))_0 \leq -R + c_\phi \varepsilon.$$

On the other hand, consider $i \in \{v^{h,0} \geq 0\}$ and let $x' \in \partial \mathcal{W}_R$ be such that

$$\phi^\circ(i - x') = \phi^\circ(i) - \phi^\circ(x') = \phi^\circ(i) - R.$$

Since there exists $j' \in \{v^{h,0} \leq 0\}$ such that $\phi^\circ(j' - x') \leq c_\phi \varepsilon$, then by triangular inequality

$$\phi^\circ(i - j') \leq \phi^\circ(i) - R + c_\phi \varepsilon.$$

Thus, using again definition (4.5), we get

$$(d_+^{\varepsilon, \phi^\circ}(v^{h,0}))_i \leq \inf_{j \in \{v^{h,0} \leq 0\}} \phi^\circ(i - j) \leq \phi^\circ(i) - R + c_\phi \varepsilon,$$

which implies

$$(4.38) \quad (\text{sd}_+^{\varepsilon, \phi^\circ}(v^{h,0}))_0 \leq \sup_{j \in \{v^{h,0} \geq 0\}} (d_+^{\varepsilon, \phi^\circ}(v^{h,0}))_j - \phi^\circ(j) \leq -R + c_\phi \varepsilon.$$

Therefore, since $\text{sd}^{\varepsilon, \phi^\circ}(v^{h,0})$ is a $(1, \phi^\circ)$ -Lipschitz function, from (4.37), (4.38) we get that

$$\text{sd}^{\varepsilon, \phi^\circ}(v^{h,0}) \leq \phi^\circ - R + c_\phi \varepsilon \quad \text{in } \varepsilon \mathbb{Z}^N.$$

By comparison and Lemma 4.10 we obtain

$$(4.39) \quad v^h(h) \leq \phi^h - R + c_\phi \varepsilon,$$

where $\phi^h \in X_\varepsilon$ is defined in (4.33). Considering $R \geq \delta$ and $h = h(\delta), \varepsilon = \varepsilon(\delta)$ small enough, the equation above implies that

$$(4.40) \quad v^h(h) \leq (\phi^\circ - R + c_0 h + c_\phi \varepsilon) \vee \left(\frac{\delta}{2} - R \right)$$

where $c_0 = 4C/\delta$, with C the same as in (4.33). Assume first (B.1). From Lemma 4.11, with R replaced by $R - c_0 h - c_\phi \varepsilon$, we get

$$(4.41) \quad \text{sd}^{\varepsilon, \phi^\circ}(v^h(h)) \leq \phi^\circ - R + c_0 h + c_\phi \varepsilon,$$

therefore by comparison and Lemma 4.10 we get

$$v^h(2h) \leq \phi^h - R + c_0 h + c_\phi \varepsilon,$$

which, reasoning as above, implies for $\varepsilon(\delta), h(\delta)$ small

$$v^h(2h) \leq (\phi^\circ - R + 2c_0 h + c_\phi \varepsilon) \vee \left(\frac{\delta}{2} - R \right).$$

Hence, we can iterate the argument to conclude that

est speed vh

$$(4.42) \quad v^h(t) \leq (\phi^\circ - R + c_0 t + c_\phi \varepsilon) \vee \left(\frac{\delta}{2} - R \right),$$

as long as $R - c_0 t - c_\phi \varepsilon \geq \delta/2$ and ε, h are sufficiently small. In particular, this implies (4.36) (possibly changing the value of c_0).

If instead (B.1) does not hold and $\varepsilon \leq O(h)$, we obtain (4.39), (4.40) in the same way. Then, using the first part of Lemma 4.11 we get

$$(4.43) \quad \text{sd}^{\varepsilon, \phi^\circ}(v^h(h)) \leq \phi^\circ - R + c_0 h + \hat{c}\varepsilon + c_\phi \varepsilon,$$

then iterating we get

$$v^h(kh) \leq (\phi^\circ - R + k c_0 h + k \hat{c}\varepsilon + c_\phi \varepsilon) \vee \left(\frac{\delta}{2} - R \right),$$

hence, recalling that $\varepsilon \leq O(h)$ we conclude (4.42) and (4.36), as long as $R - c_0 t - c_\phi \varepsilon \geq \delta/2$, with ε, h sufficiently small and possibly changing the value of c_0 . \square

As a corollary of the previous result, we deduce an estimate of the evolution of the distance function \hat{d}^h at distance from the evolving boundary, which we show next.

lm:bound dist

Corollary 4.13. *Let $E_0 \subseteq \mathbb{R}^N$ be a closed set and consider the discrete evolution defined in (4.29). Assume either that $\varepsilon \leq O(h)$ or that (B.1) holds. Then, for every $\delta > 0$ there exist $c_0 = c_0(\delta) > 0$, $h_0 = h_0(\delta) > 0$ and $\varepsilon_0 = \varepsilon_0(\delta)$ such that the following holds. If $\hat{d}^h(x, t) \geq \delta$, then for $s \geq t$,*

bound dist+

$$(4.44) \quad \hat{d}^h(x, s) \geq \hat{d}^h(x, t) - c_0(s - t + \varepsilon + h)$$

provided $0 < h \leq h_0$, $0 < \varepsilon < \varepsilon_0$ and as long as $\hat{d}^h(x, t) - c_0(s - t + \varepsilon + h) \geq \delta/2$. Similarly, if $\hat{d}^h(x, t) \leq -\delta$, then for $s \geq t$,

bound dist-

$$(4.45) \quad \hat{d}^h(x, s) \leq \hat{d}^h(x, t) + c_0(s - t + \varepsilon + h)$$

provided $0 < h \leq h_0$ and as long as $\hat{d}^h(x, t) + c_0(s - t + \varepsilon + h) \leq -\delta/2$.

Proof. As usual, in this proof we denote by c_ϕ a positive constant depending on ϕ whose value may change from line to line and also within the same line.

Assume $\hat{d}^h(x, t) \geq \delta$. Without loss of generality we may assume $t \in [0, T_h^*)$ so that $\hat{d}^h(x, t)$ is finite. Denote by $x_\varepsilon \in \varepsilon \mathbb{Z}^N$ such that $x \in x_\varepsilon + [0, \varepsilon)^N$. Note that there exists a constant $c_\phi > 0$ such that, setting $R := \hat{d}^h(x, t) - c_\phi \varepsilon$, one has $(\mathcal{W}_R(x_\varepsilon))^{h,0} \cap E^h(t) = \emptyset$ and $R > \delta/2$ (if ε, h are sufficiently small, depending on δ). By the avoidance principle stated in Remark 4.8, we deduce that the open discrete evolution of $\mathcal{W}_R(x_\varepsilon)$, which we denote by $F(\tau)$, lies outside $E^h([\frac{t}{h}]h + \tau)$ for all $\tau \geq 0$. By Proposition 4.12 we deduce

incl wulff

$$(4.46) \quad F(\tau) \supseteq \mathcal{W}_{R-c_0(\tau+\varepsilon)}(x_\varepsilon) \cap \varepsilon \mathbb{Z}^N,$$

provided that $R - c_0(\tau + \varepsilon) \geq \delta/2$. Note that in particular

$$(\mathcal{W}_{R-c_0(\tau+h+\varepsilon)}(x_\varepsilon) \cap \varepsilon \mathbb{Z}^N) \subseteq (\varepsilon \mathbb{Z}^N \setminus E^h(t + \tau)),$$

as long as $R - c_0(\tau + h + \varepsilon) \geq \delta/2$. In turn, we get

$$(4.47) \quad \hat{d}^h(x_\varepsilon, t + \tau) \geq R - c_0(\tau + h + \varepsilon),$$

provided $R - c_0(\tau + h + \varepsilon) \geq \delta/2$ (for a possibly larger value of c_0). Recalling the definition of R and x_ε and possibly increasing the value of c_0 , we infer

$$(4.48) \quad \hat{d}^h(x, t + \tau) \geq \hat{d}^h(x, t) - c_0(\tau + h + \varepsilon)$$

as long as $\widehat{d}^h(x, t) - c_0(\tau + h + \varepsilon) \geq \delta$. The case $\widehat{d}^h(x, t) \leq -\delta$ is analogous. \square

5. CONVERGENCE OF THE SCHEME

sec:conv

We now are ready to study the convergence of the scheme as $\varepsilon \rightarrow 0, h \rightarrow 0$. Recall that we assumed that $\varepsilon = \varepsilon(h)$ goes to 0 as $h \rightarrow 0$. In this section we assume that either $\varepsilon \leq O(h)$ or that (B.1) holds. Let $E^h(\cdot)$ be the discrete evolution defined in (4.29) and recall that $\widehat{E}^h(\cdot) = E^h(\cdot) + [0, \varepsilon]^N$. We introduce the closed space-time tubes

tubidiscreti

$$(5.1) \quad \overline{E}^h := \text{cl}(\{(x, t) \in \mathbb{R}^N \times [0, +\infty) : x \in \widehat{E}^h(t)\})$$

where the closure is in space-time. Then, there exist A, E open and closed (respectively) subsets of $\mathbb{R}^N \times [0, +\infty)$, with $A \subseteq E$, and a subsequence $h_k \rightarrow 0$ such that

$$\overline{E}^{h_k} \xrightarrow{\mathcal{K}} E \quad \text{and} \quad \mathbb{R}^N \times [0, +\infty) \setminus \text{int}(\overline{E}^{h_k}) \xrightarrow{\mathcal{K}} \mathbb{R}^N \times [0, +\infty) \setminus A,$$

where interior, and Kuratowski convergence are meant in space-time. Let $E(t)$ and $A(t)$ be the t -time slice of E and A , respectively.

Note that if $E(t) = \emptyset$ for some $t \geq 0$, then (4.44) implies $E(s) = \emptyset$ for all $s \geq t$ so that we can define, as in Definition 2.1, the extinction time T^* of E . In the same fashion one can define the extinction time T'^* of $\mathbb{R}^N \times [0, +\infty) \setminus A$ (notice that at least one between T^* and T'^* is $+\infty$). Possibly extracting a further (not relabelled) subsequence and arguing exactly as in [22, Proof of Proposition 4.4] (and relying on the bounds (4.44) and (4.45)), one can in fact show the following result.

prop:E

Proposition 5.1. *There exists a countable set $\mathcal{N} \subseteq (0, +\infty)$ such that $\widehat{d}^{h_k}(\cdot, t)^+ \rightarrow \text{dist}^{\phi^\circ}(\cdot, E(t))$ and $\widehat{d}^{h_k}(\cdot, t)^- \rightarrow \text{dist}^{\phi^\circ}(\cdot, \mathbb{R}^N \setminus A(t))$ locally uniformly for all $t \in (0, +\infty) \setminus \mathcal{N}$. Moreover, E and $\mathbb{R}^N \times [0, +\infty) \setminus A$ satisfy the continuity properties (b) and (c) of Definition 2.1. In addition, if $T^* > 0$, then $\{\widehat{d}^{h_k}\}$ is locally uniformly bounded in $\mathbb{R}^N \times (0, T^*) \setminus E$ and analogously $\{\widehat{d}^{h_k}\}$ is locally uniformly bounded in $\mathbb{R}^N \times (0, T'^*) \cap A$ if $T'^* > 0$. Finally, $E(0) = E_0$ and $A(0) = \text{int}(E_0)$.*

themthm

Theorem 5.2. *The set E is a superflow in the sense of Definition 2.1 with initial datum E_0 , while A is a subflow with initial datum E_0 .*

The proof of this result follows the main lines of the proof of [22, Theorem 4.5]. One important difference with respect to the local, continuous setting is that the variable z^{h_k} is defined on the edges (i, j) between the vertices $i, j \in \varepsilon\mathbb{Z}^N$ and it is therefore unclear how to pass to the limit in this variable to obtain the limiting vector field $z(x, t)$. In order to do so, we associate with the discrete vector field $z_{ij}^h(t) \in Y_\varepsilon$ a vector field $\mathbf{z}^h(\cdot, t)$ in \mathbb{R}^N defined as follows:

$$(5.2) \quad \mathbf{z}^h(x, t) := \frac{1}{\varepsilon} \sum_{j \in \varepsilon\mathbb{Z}^N} z_{ij}^h(t)(i - j),$$

where $i \in \varepsilon\mathbb{Z}^N$ is such that $x \in i + [0, \varepsilon)^N$. Recall that we can take $z_{ij}^h(t)$ and thus $\mathbf{z}^h(\cdot, t)$ identically zero for $t \geq \min\{T_h^*, T_h'^*\}$. First, we show the following:

lemma phi circ

Lemma 5.3. *The vector field \mathbf{z}^h satisfies*

$$(5.3) \quad \phi^\circ(\mathbf{z}^h) \leq 1.$$

Proof. Take $v \neq 0$ in \mathbb{R}^N . Recalling that $\phi(v) = \sum_{\ell \in \mathbb{Z}^N} \beta(\ell) |v \cdot \ell|$, one has for any $x \in \mathbb{R}^N$ and $i \in \varepsilon \mathbb{Z}^N$ such that $x \in i + [0, \varepsilon)^N$

$$(5.4) \quad \mathbf{z}^h(x, t) \cdot v = \frac{1}{\varepsilon} \sum_{j \in \varepsilon \mathbb{Z}^N} z_{ij}^h(t) (i - j) \cdot v = \sum_{\ell \in \mathbb{Z}^N} z_{i, i+\varepsilon \ell}^h(t) \ell \cdot v \leq \phi(v),$$

where we used that $|z_{i, i+\varepsilon \ell}^h(t)| \leq \beta(\ell)$. \square

Hence, being globally bounded, this vector field is weakly-* compact in $L^\infty(\mathbb{R}^N \times (0, T); \mathbb{R}^N)$ for any $T > 0$. The following lemma establishes a relationship between the divergence of its limits and the limits of the discrete divergences of z^h .

Lemma 5.4. *Assume that $\mathbf{z}^{h_k} \xrightarrow{*} z$ in $L^\infty(\mathbb{R}^N \times (0, T); \mathbb{R}^N)$ along a subsequence $h_k \rightarrow 0$. Then, for every $\varphi \in C^\infty(\mathbb{R}^N \times (0, T))$ and $\eta \in C_c^\infty(\mathbb{R}^N \times (0, T))$ it holds*

$$\lim_{k \rightarrow \infty} \left(\varepsilon_k^N \int \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) \frac{\varphi(i, t) - \varphi(j, t)}{\varepsilon_k} dt \right) = \iint \eta z \cdot \nabla \varphi \, dx \, dt.$$

Proof. Let $\varphi \in C^\infty(\mathbb{R}^N \times (0, T))$ and $\eta \in C_c^\infty(\mathbb{R}^N \times (0, T))$ and denote $S(t) = \text{supp}(\eta(t))$ and $Q_k := [0, \varepsilon_k)^N$. We have

$$(5.5) \quad \varepsilon_k^N \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) \frac{\varphi(i, t) - \varphi(j, t)}{\varepsilon_k} = \varepsilon_k^N \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} \frac{z_{ij}^{h_k}(t)}{\varepsilon_k} \eta(i, t) \nabla \varphi(x_{ij}) \cdot (i - j),$$

where x_{ij} belongs to the segment between i and j . Furthermore we have

$$\left| \varepsilon_k^N \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) \frac{\varphi(i, t) - \varphi(j, t)}{\varepsilon_k} - \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} \frac{z_{ij}^{h_k}(t)}{\varepsilon_k} \int_{i+Q_k} \eta \nabla \varphi \cdot (i - j) \, dx \right|$$

$$(5.6) \quad \leq \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} \frac{\alpha_{ij}^{\varepsilon_k}}{\varepsilon_k} |\eta(i, t)| \int_{i+Q_k} |(\nabla \varphi(x_{ij}, t) - \nabla \varphi(x, t)) \cdot (i - j)| \, dx + O(\varepsilon_k^N) \\ \leq 2 \|\eta\|_\infty \sum_{i \in S(t) \cap \varepsilon_k \mathbb{Z}^N} \sum_{j \in \varepsilon_k \mathbb{Z}^N} \frac{\alpha_{ij}^{\varepsilon_k}}{\varepsilon_k} \int_{i+Q_k} |(\nabla \varphi(x_{ij}, t) - \nabla \varphi(x, t)) \cdot (i - j)| \, dx + O(\varepsilon_k^N)$$

$$(5.7) \quad \leq c \varepsilon_k^N \sum_{i \in S(t) \cap \varepsilon_k \mathbb{Z}^N} \sum_{j \in \varepsilon_k \mathbb{Z}^N} \frac{\alpha_{ij}^{\varepsilon_k}}{\varepsilon_k} |i - j|^2 + O(\varepsilon_k^N) \\ = c \varepsilon_k^{N+1} \sum_{\substack{i \in \mathbb{Z}^N \\ \varepsilon_k i \in S(t)}} \sum_{j \in \mathbb{Z}^N} \alpha_{ij} |i - j|^2 + O(\varepsilon_k^N) \\ \leq c \varepsilon_k^{N+1} \left(\sum_{\ell \in \mathbb{Z}^N} \beta(\ell) |\ell|^2 \right) (\#S(t) \cap \varepsilon_k \mathbb{Z}^N) + O(\varepsilon_k^N)$$

$$(5.8) \quad \leq c \varepsilon_k \sum_{\ell \in \mathbb{Z}^N} \beta(\ell) |\ell|^2 + O(\varepsilon_k^N)$$

where in (5.6) we used the Lipschitz property of η and (4.2), while in (5.7) we used the Lipschitz property of $\nabla \varphi$ and $|x_{ij} - x| \leq (1 + \sqrt{N})|i - j|$ for $i \neq j$ and $x \in i + Q_k$, and finally in (5.8) we used that $\#(S(t) \cap \varepsilon \mathbb{Z}^N) = O(\varepsilon_k^{-N})$, which holds locally uniformly in time. Moreover, note that the estimate provided above is uniform as t varies in compact subsets of $(0, T)$. Recalling (4.2), we conclude integrating in time and sending $k \rightarrow \infty$. \square

At this point, we may proceed with the proof of Theorem 5.2.

Proof of Theorem 5.2. As usual, in this proof we denote by c_ϕ a positive constant depending on ϕ whose value may change from line to line and also within the same line.

We only show that E is a superflow, as the subflow property of A can be proven analogously. Points (a), (b) and (c) of Definition 2.1 follow from Proposition 5.1. We are left with showing (d). Without loss of generality we may assume $T^* > 0$ (which follows from Corollary 4.13 if the initial set is not trivial). Note also that by Proposition 5.1 we have $\liminf_k T_{h_k}^* \geq T^*$.

Step 1: (Proof of (2.1)). For $(x, t) \in \mathbb{R}^N \times (0, T^*) \setminus E$ we set $d(x, t) := \text{dist}^{\phi^\circ}(\cdot, E(t))$. By Lemma 4.2 and Proposition 5.1 we have

conv1

$$(5.9) \quad \sup_{\varepsilon_k \mathbb{Z}^N \cap K} |d^{h_k}(t) - d(\cdot, t)| \rightarrow 0 \text{ as } k \rightarrow \infty \text{ for } t \in (0, T^*) \setminus \mathcal{N} \text{ and for any compact } K \subseteq \mathbb{R}^N \setminus E(t).$$

Moreover, d^{h_k} and d are locally uniformly bounded in $\mathbb{R}^N \times (0, T^*) \setminus E$. Set $\mathbf{z}^{h_k}(\cdot, t) := 0$ for $t > T_{h_k}^*$ if $T_{h_k}^* < T^*$. Extracting a further subsequence, if needed, and recalling Lemma 5.3, we may assume that \mathbf{z}^{h_k} converges weakly-* in $L^\infty(\mathbb{R}^N \times (0, T^*); \mathbb{R}^N)$ to some vector-field z satisfying

subdiff 0

$$(5.10) \quad \phi^\circ(z) \leq 1$$

almost everywhere. Recall that by (4.30) we have $u^{h_k}(t) \leq d^{h_k}(t)$ in $\varepsilon_k \mathbb{Z}^N \setminus E^{h_k}(t)$; i.e., in the region where $d^{h_k}(t)$ is nonnegative. Combining with (4.28) (and recalling (4.29)) we infer that for $t < T_{h_k}^*$ it holds

eq:ineqdisc

$$(5.11) \quad -D_{\varepsilon_k}^* z^{h_k}(t + h_k) \leq \frac{d^{h_k}(t + h_k) - d^{h_k}(t)}{h_k} \quad \text{in } \varepsilon_k \mathbb{Z}^N \setminus E^{h_k}(t).$$

Consider a nonnegative test function $\varphi \in C_c^\infty((\mathbb{R}^N \times (0, T^*)) \setminus E)$. If k is large enough, then the distance of the support of φ from \overline{E}^{h_k} is bounded away from zero. In particular, d^{h_k} is finite and positive on $\text{supp } \varphi$. We deduce from (5.11) that

$$\begin{aligned} & \varepsilon_k^N \int \sum_{i \in \varepsilon_k \mathbb{Z}^N} \varphi(i, t) \left(\frac{d_i^{h_k}(t + h_k) - d_i^{h_k}(t)}{h_k} + (D_{\varepsilon_k}^* z^{h_k}(t + h_k))_i \right) dt \\ &= -\varepsilon_k^N \int \sum_{i \in \varepsilon_k \mathbb{Z}^N} \frac{\varphi(i, t) - \varphi(i, t - h_k)}{h_k} d_i^{h_k}(t) dt + \varepsilon_k^N \int \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} \frac{z_{ij}^{h_k}(t + h_k) - z_{ji}^{h_k}(t + h_k)}{h_k} \varphi(i, t) dt \end{aligned}$$

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$$(5.12) \quad = -\varepsilon_k^N \int \sum_{i \in \varepsilon_k \mathbb{Z}^N} \frac{\varphi(i, t) - \varphi(i, t - h_k)}{h_k} d_i^{h_k}(t) dt + \varepsilon_k^N \int \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t + h_k) \frac{\varphi(i, t) - \varphi(j, t)}{h_k} dt \geq 0.$$

It is easy to check that the first integral in (5.12) converges to $-\iint d \partial_t \varphi dx dt$ as $k \rightarrow \infty$ thanks to (5.9) and since d^{h_k}, d are uniformly bounded. Recalling that \mathbf{z}^{h_k} converges weakly-* in $L^\infty(\mathbb{R}^N \times (0, T^*))$ to z , we use Lemma 5.4 to conclude that the second integral in (5.12) converges to $\iint z \cdot \nabla \varphi dx dt$. We thus conclude (2.1).

Step 2: (Convergence of u^{h_k} to d). Firstly, we establish an upper bound for $-D_{\varepsilon_k}^* z_{h_k}$ away from E^{h_k} . We start by noting that definition (4.5) implies

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$$(5.13) \quad \text{sd}^{\varepsilon, \phi^\circ}(u) \leq \frac{1}{2} \left((d_-^{\varepsilon, \phi^\circ}(u))_j + u_\ell + \phi^\circ(\cdot - j) + \phi^\circ(\cdot - \ell) \right) \quad \text{in } \varepsilon \mathbb{Z}^N \setminus \{u \leq 0\},$$

for every $(1, \phi^\circ)$ -Lipschitz function $u \in X_\varepsilon$ and $j, \ell \in \{u \leq 0\}$. Therefore, specifying the inequality above for $u^{h_k}(t)$, by the comparison principle and Lemma 4.10 we conclude

$$(5.14) \quad u_i^{h_k}(t + h_k) \leq \frac{1}{2} \left(\phi_{i-j}^{h_k} + \phi_{i-\ell}^{h_k} + (d_-^{\varepsilon, \phi^\circ}(u^{h_k}(t)))_j + u_\ell^{h_k}(t) \right), \quad \forall i \in \varepsilon_k \mathbb{Z}^N \setminus E^{h_k}(t),$$

where $j, \ell \in E^{h_k}(t)$. If $\widehat{d}^{h_k}(i, t) \geq R > 0$, recalling the definition of ϕ^h , we get

$$\text{ineq div:1} \quad (5.15) \quad u_i^{h_k}(t + h_k) \leq \frac{1}{2} \left(\phi^\circ(i - j) + \phi^\circ(i - \ell) + (d_-^{\varepsilon, \phi^\circ}(u^{h_k}(t)))_j + u_\ell^{h_k}(t) \right) + \frac{Ch_k}{R - c_\phi \varepsilon},$$

for all $i \in \varepsilon_k \mathbb{Z}^N \setminus E^{h_k}(t)$. Infimizing in j, ℓ over $E^{h_k}(t)$ in (5.15) and using again (4.5) and (4.11), we conclude

$$\text{eq:iterk} \quad (5.16) \quad u_i^{h_k}(t + h_k) \leq d_i^{h_k}(t) + h_k \frac{C}{R - c_\phi \varepsilon_k} \leq d_i^{h_k}(t) + h_k \frac{C}{R}.$$

provided h_k, ε_k are small enough depending on R , and for a possibly larger value of C . As a consequence of (5.16), we obtain

$$\text{numero} \quad (5.17) \quad -D_{\varepsilon_k}^* z^{h_k}(t + h_k) \leq \frac{C}{R} \quad \text{in } \{\widehat{d}^{h_k}(\cdot, t) \geq R\} \cap \varepsilon_k \mathbb{Z}^N.$$

Using again Lemma 5.4 and the convergences of E_{h_k} and d_{h_k} it follows that

$$\text{div} z \leq \frac{C}{R} \quad \text{in } \{(x, t) \in \mathbb{R}^N \times (0, T^*) : d(x, t) > R\}$$

in the sense of distributions. Hence $\text{div} z$ is a Radon measure in $\mathbb{R}^N \times (0, T^*) \setminus E$, and $(\text{div} z)^+ \in L^\infty(\{(x, t) \in \mathbb{R}^N \times (0, T^*) : d(x, t) \geq \delta\})$ for every $\delta > 0$.

On the other hand, note that for every $i \in \varepsilon_k \mathbb{Z}^N$ it holds

$$d^{h_k}(t) \geq d_i^{h_k}(t) - \phi^\circ(\cdot - i).$$

Thus, by Lemma 4.10 and by comparison as before, we get

$$u_i^{h_k}(t + h_k) \geq d_i^{h_k}(t) - \phi_0^{h_k} = d_i^{h_k}(t) - (C + 1)\sqrt{h_k}.$$

Combining the above inequality with (5.16), we deduce for all $t \in (0, T^*) \setminus \mathcal{N}$ and any $\delta > 0$ that

$$\sup_{\{\widehat{d}_{h_k}(\cdot, t) \geq \delta\} \cap \varepsilon_k \mathbb{Z}^N} |u^{h_k}(t + h_k) - d^{h_k}(t)| \leq \sqrt{h_k}(C + 2),$$

provided that k is large enough. In particular, recalling also (5.9), we deduce that

$$\text{elleuno} \quad (5.18) \quad \sup_{\varepsilon_k \mathbb{Z}^N \cap K} |u^{h_k}(t) - d(\cdot, t)| \rightarrow 0 \text{ as } k \rightarrow \infty \text{ for } t \in (0, T^*) \setminus \mathcal{N} \text{ and for any compact } K \subseteq \mathbb{R}^N \setminus E(t),$$

also with the sequence $\{u^{h_k}\}$ locally (in space and time) uniformly bounded.

Step 3: (The subdifferential inclusion). It remains to show that

$$\text{conv subdiff} \quad (5.19) \quad z \in \partial \phi(\nabla d) \quad \text{a.e. in } \mathbb{R}^N \times (0, T^*) \setminus E.$$

Recall that $\xi \in \partial \phi(\eta)$ if and only if $\xi \in \{v : \phi^\circ(v) \leq 1, v \cdot \eta \geq \phi(\eta)\}$. Since one inequality has been proved in (5.10), we show the other one. Consider a test function $\eta \geq 0$, $\eta \in C_c^\infty((\mathbb{R}^N \times (0, T^*)) \setminus E)$. Let $\sigma > 0$ and set $d_\sigma \in C^\infty(\mathbb{R}^N \times (0, T^*))$ as $d_\sigma = d * \rho_\sigma$, where ρ_σ are space-time mollifiers. Obviously

$$\begin{aligned} \text{eq rewr} \quad (5.20) \quad \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) (u_i^{h_k}(t) - u_j^{h_k}(t)) &= \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) (d_\sigma(i, t) - d_\sigma(j, t)) \\ &+ \sum_{i, j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) \left(u_i^{h_k}(t) - d_\sigma(i, t) - u_j^{h_k}(t) + d_\sigma(j, t) \right). \end{aligned}$$

In turn, Lemma 5.4 implies that

$$\text{eq rewr 1} \quad (5.21) \quad \lim_{k \rightarrow \infty} \varepsilon_k^N \int \left(\sum_{i, j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) \frac{d_\sigma(i, t) - d_\sigma(j, t)}{\varepsilon_k} \right) dt = \iint z \cdot \nabla d_\sigma \eta \, dx \, dt.$$

Let us thus show that

$$\boxed{\text{error term 1}} \quad (5.22) \quad \lim_{\sigma \rightarrow 0} \lim_{k \rightarrow \infty} \varepsilon_k^N \int \sum_{i,j \in \varepsilon_k \mathbb{Z}^N} \left(z_{ij}^{h_k}(t) \eta(i, t) \frac{u_i^{h_k}(t) - d_\sigma(i, t) - u_j^{h_k}(t) - d_\sigma(j, t)}{\varepsilon_k} \right) dt = 0,$$

We set for every $t \in (0, T_h^*)$ and $\sigma > 0$

$$m_{k,\sigma}(t) := \min_{i \in \text{supp}(\eta) \cap \varepsilon_k \mathbb{Z}^N} (u_i^{h_k}(t) - d_\sigma(i, t)),$$

$$M_{k,\sigma}(t) := \max_{i \in \text{supp}(\eta) \cap \varepsilon_k \mathbb{Z}^N} (u_i^{h_k}(t) - d_\sigma(i, t)).$$

The convergence (5.18) implies that these quantities are uniformly bounded and

$$\boxed{\text{mek}} \quad (5.23) \quad \lim_{\sigma \rightarrow 0} \lim_{k \rightarrow +\infty} m_{k,\sigma}(t) = 0, \quad \lim_{\sigma \rightarrow 0} \lim_{k \rightarrow +\infty} M_{k,\sigma}(t) = 0,$$

uniformly for all $t \notin \mathcal{N}$. For all times $t \in (0, T^*) \setminus \mathcal{N}$ it holds

$$\begin{aligned} & \varepsilon_k^N \sum_{i,j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) \frac{u_i^{h_k}(t) - d_\sigma(i, t) - u_j^{h_k}(t) + d_\sigma(j, t)}{\varepsilon_k} \\ &= \varepsilon_k^N \sum_{i,j \in \varepsilon_k \mathbb{Z}^N} z_{ij}^{h_k}(t) \eta(i, t) \frac{(u_i^{h_k}(t) - d_\sigma(i, t) - m_{k,\sigma}(t)) - (u_j^{h_k}(t) - d_\sigma(j, t) - m_{k,\sigma}(t))}{\varepsilon_k} \\ \boxed{\text{eq err 1}} \quad (5.24) \quad &= \varepsilon_k^N \sum_{i \in \varepsilon_k \mathbb{Z}^N} (u_i^{h_k}(t) - d_\sigma(i, t) - m_{k,\sigma}(t)) \sum_{j \in \varepsilon_k \mathbb{Z}^N} \left(\frac{z_{ij}^{h_k}(t) - z_{ji}^{h_k}(t)}{\varepsilon_k} \eta(i, t) + z_{ji}^{h_k}(t) \frac{\eta(i, t) - \eta(j, t)}{\varepsilon_k} \right). \end{aligned}$$

For k large enough, since the support of η is at positive distance from E , by the bound (5.17) one has $D_{\varepsilon_k}^* z^{h_k}(t) \geq -c(\delta)$ on the support for h_k small enough. Thus it holds

$$\begin{aligned} & \varepsilon_k^N \sum_{i \in \varepsilon_k \mathbb{Z}^N} (u_i^{h_k}(t) - d_\sigma(i, t) - m_{k,\sigma}(t)) \eta(i, t) \sum_{j \in \varepsilon_k \mathbb{Z}^N} \frac{z_{ij}^{h_k}(t) - z_{ji}^{h_k}(t)}{\varepsilon_k} \\ & \geq -c(\delta) \varepsilon_k^N \sum_{i \in \varepsilon_k \mathbb{Z}^N} (u_i^{h_k}(t) - d_\sigma(i, t) - m_{k,\sigma}(t)) \eta(i, t). \end{aligned}$$

Recalling that $\#(\text{supp}(\eta) \cap \varepsilon_k \mathbb{Z}^N) = O(h_k^{-N})$ uniformly in time, by uniform convergence and (5.18) we conclude that

$$\boxed{\text{eq err 2}} \quad (5.25) \quad \lim_{\sigma \rightarrow 0} \liminf_{k \rightarrow \infty} \varepsilon_k^N \int \sum_{i \in \varepsilon_k \mathbb{Z}^N} (u_i^{h_k}(t) - d_\sigma(i, t) - m_{\varepsilon,k}(t)) \eta(i, t) \sum_{j \in \varepsilon_k \mathbb{Z}^N} \frac{z_{ij}^{h_k}(t) - z_{ji}^{h_k}(t)}{\varepsilon_k} dt \geq 0.$$

The other term in (5.24) can be estimated using the Lipschitz constant of η :

$$\begin{aligned} & \left| \int \sum_{i,j \in \varepsilon_k \mathbb{Z}^N} \varepsilon_k^N (u_i^{h_k}(t) - d_\sigma(i, t) - m_{\varepsilon,k}(t)) z_{ji}^{h_k}(t) \frac{\eta(i, t) - \eta(j, t)}{\varepsilon_k} dt \right| \\ & \leq \|\nabla \eta\|_\infty \varepsilon_k^N \int \sum_{i,j \in \varepsilon_k \mathbb{Z}^N} (u_i^{h_k}(t) - d_\sigma(i, t) - m_{\varepsilon,k}(t)) \alpha_{ji}^{h_k} \frac{|i - j|}{\varepsilon_k} dt \rightarrow 0 \end{aligned}$$

letting first $k \rightarrow +\infty$ and then $\sigma \rightarrow 0$, thanks to (5.18) and (5.23). Note now that adding and subtracting $M_{\varepsilon,k}(t)$ to (5.22) instead of $m_{\varepsilon,k}(t)$ and reasoning as above, one proves that

eq err 4

$$(5.26) \quad \lim_{\sigma \rightarrow 0} \limsup_{k \rightarrow \infty} \varepsilon_k^N \int \left(\sum_{i \in \varepsilon_k \mathbb{Z}^N} ((u_i^{h_k}(t) - d_\sigma(i, t) - M_{\varepsilon,k}(t)) \eta(i, t) \sum_{j \in \varepsilon_k \mathbb{Z}^N} \frac{z_{ij}^{h_k}(t) - z_{ji}^{h_k}(t)}{\varepsilon_k}) \right) dt \leq 0,$$

$$\lim_{\varepsilon \rightarrow 0} \lim_{k \rightarrow \infty} \varepsilon_k^N \int \left| \sum_{i,j \in \varepsilon_k \mathbb{Z}^N} ((u_i^{h_k}(t) - d_\sigma(i, t) - M_{\varepsilon,k}(t)) z_{ji}^{h_k}(t) \frac{\eta(i, t) - \eta(j, t)}{\varepsilon_k}) \right| dt = 0.$$

Combining (5.24), (5.25) and (5.26), we conclude (5.22).

Integrating in time (5.20) and combining (5.21) and (5.22), since $\nabla d_\sigma = \rho_\sigma * \nabla d \rightarrow \nabla d$ pointwise a.e. and are uniformly bounded in $L^\infty(\mathbb{R}^N \times (0, T^*); \mathbb{R}^N)$, it holds

$$\lim_{k \rightarrow \infty} \varepsilon_k^N \int \left(\sum_{i,j \in \varepsilon_k \mathbb{Z}^N} \eta(i, t) z_{ij}^{h_k}(t) \frac{u_i^{h_k}(t) - u_j^{h_k}(t)}{\varepsilon_k} \right) dt = \iint z \cdot \nabla d \eta dx dt.$$

The convergence above can be paired with the lower semicontinuity of the Γ -convergence of the discrete total variations (which follows from an adaptation of classical arguments, see e.g. [19]) and $z_{ij}^\varepsilon(u_i^\varepsilon - u_j^\varepsilon) = \alpha_{ij}^\varepsilon |u_i^\varepsilon - u_j^\varepsilon|$ to obtain

$$\begin{aligned} \iint \phi(\nabla d) \eta &\leq \liminf_{k \rightarrow \infty} \varepsilon_k^N \int \left(\sum_{i,j \in \varepsilon_k \mathbb{Z}^N} \eta(i, t) \alpha_{ij}^{h_k} \frac{|u_i^{h_k}(t) - u_j^{h_k}(t)|}{\varepsilon_k} \right) dt \\ &= \liminf_{k \rightarrow \infty} \varepsilon_k^N \int \left(\sum_{i,j \in \varepsilon_k \mathbb{Z}^N} \eta(i, t) z_{ij}^{h_k}(t) \frac{u_i^{h_k}(t) - u_j^{h_k}(t)}{\varepsilon_k} \right) dt = \iint z \cdot \nabla d \eta, \end{aligned}$$

which shows that $\phi(\nabla d) = z \cdot \nabla d$ a.e. on the support of η , from which we deduce (5.19). \square

We conclude this section by observing that the discrete scheme converges to the unique weak flow (in the sense of Definition 2.1) starting from E_0 for “generic” initial data E_0 , i.e. whenever fattening does not occur. More precisely, we have the following Corollary.

Corollary 5.5. *Let $u_0 \in \text{UC}(\mathbb{R}^N)$ and for every $\lambda \in \mathbb{R}$ let \overline{E}_λ^h be the closed space-time tube of the h -discrete evolution starting from $\{u_0 \leq \lambda\}$; i.e., as in (5.1) with $E_0 = \{u_0 \leq \lambda\}$. Then, there exists a countable set \mathcal{N} such that for all $\lambda \in \mathbb{R}^N \setminus \mathcal{N}$*

$$\overline{E}_\lambda^h \xrightarrow{\mathcal{K}} E_\lambda \quad \text{in } \mathbb{R}^N \times [0, +\infty)$$

as $h \rightarrow 0$, where E_λ is the unique weak flow in the sense of Definition 2.1 starting from $\{u_0 \leq \lambda\}$.

Proof. It follows by combining Theorems 5.2 and 2.5. \square

sec:Num

6. NUMERICAL EXPERIMENTS

We show some numerical experiments to illustrate our results, in dimension 2 (an implementation in 3D is currently being developed). We follow the implementation described in [18] (see also [17]), except that now the distance is properly computed using the inf/sup-convolution formulas (4.5). The (exact) numerical resolution of the discrete ROF functional is computed using Hochbaum’s parametric maximum flow algorithm [36, 37], implemented upon the maxflow/mincut implementation of Boykov and Kolmogorov [8]. This particular algorithm has the advantage to provide an *exact* solution of the ROF problem, up to computer precision. Other implementations

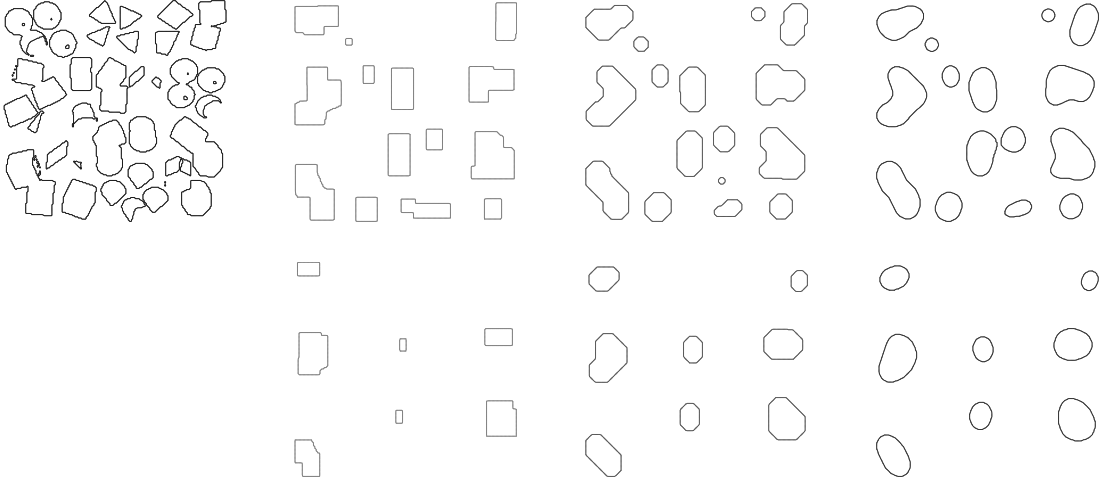


FIGURE 1. An initial datum and evolutions for square, octagonal and “almost isotropic” anisotropies, at two different times.

fig:shapes

of the algorithm yielding approximate minimizers have been considered for instance in [16, 44], of course they work in practice and allow to address more (an)isotropies than the current work, yet the joint convergence as $\varepsilon = h \rightarrow 0$ is not clear in these contexts. For numerical speedup, the infimum and supremum of definition (4.5) are computed only in a neighborhood of fixed size and not on the whole grid. We expect this to yield, in general, an error of order $C\varepsilon$ with C getting smaller as the width of the strip increases, however we observe that Corollary B.2 in Appendix B justifies this restriction (showing that $C = 0$) in some cases, notably the case $\phi = \|\cdot\|_{\ell^1}$, $\phi^\circ = \|\cdot\|_{\ell^\infty}$, see Fig. 2, left, for which the sup/inf are in fact min/max which are reached very close to the evolving boundary (as one can chose $\ell_1 = 1$ in Lemma B.1). Similarly, the ROF minimization is only performed in a neighborhood of the boundary (one can show that this does not affect the solution in a smaller neighborhood, hence the overall error is the same as when computing the distance in a strip only).

The code is available at <https://plmlab.math.cnrs.fr/chambolle/discretocrystals/> (implemented in C/C++ and running on GNU/linux with gcc).

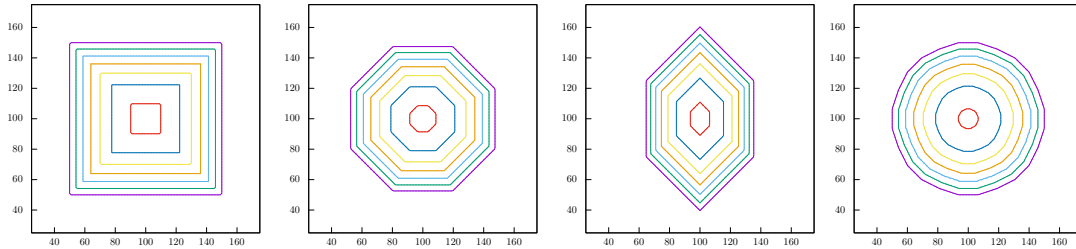


FIGURE 2. Wulff shapes of initial radius $R_0 = 50$ evolved at times $t = 0, 200, 400, \dots, 1200$ for four different anisotropies (square, octagon, diamond and “almost isotropic”).

fig:Wulffshapes

Figure 1 shows three examples of flows from the same starting set, composed of random shapes. The anisotropies are square (nearest neighbours interactions), octagonal (next nearest neighbours, weighted so that the corresponding Wulff shape is a regular octagon), and “almost isotropic”,

which is generated by the interactions in the 12 directions $e \in \{(0, \pm 1), (\pm 1, 0), (\pm 1, \pm 2), (\pm 1, \pm 3)\}$ weighted so that the Wulff shape is a polygon with 24 facets of equal lengths. This is obtained by setting the weights in the discrete total variation as $.131/\text{length}(e)$ for each direction e , so that the total perimeter of the unit Wulff shape is $24 \times (2 \times .131) \approx 2\pi$, in the hope that the corresponding crystalline curvature will be close to the Euclidean one.

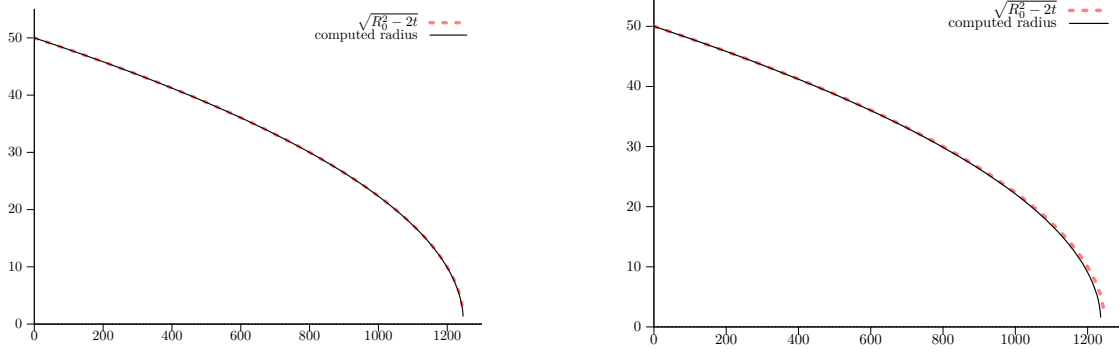


FIGURE 3. Evolution of the radius for the square (left) and octogonal (right) anisotropies.

fig:radiiSqOc

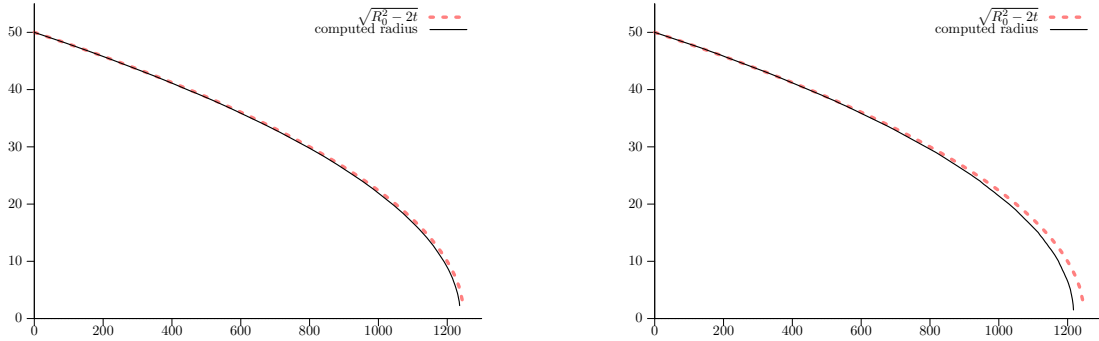


FIGURE 4. Evolution of the radius for the diamond (left) and “almost isotropic” (right) anisotropies.

fig:radiiDiIs

Then, we estimate the decay of the radius of an initial Wulff shape $\mathcal{W}_{R_0} = \{\phi \leq R_0\}$ along the evolution, up to extinction. In our experiment, $R_0 = 50$. It is well known that the solution is the Wulff shape of radius $R(t) = \sqrt{R_0^2 - 2(N-1)t}$ (where here $N = 2$). The evolutions are depicted in Figure 2. We use the same anisotropies as in figure 1, with additionally a “diamond” Wulff shape generated by the directions $(0, \pm 1), (\pm 1, \pm 2)$ and with sides of equal lengths. In all cases, the weights have been calibrated so that the perimeters of the Wulff shapes are $6.28 \approx 2\pi$.

The plots in Figure 4 show that the decay of the radii is remarkably close to the theoretical prediction, even if this is less precise when more directions of interactions are involved, near extinction. This might be due in part to the fact that the computation of the distance through truncated variants of (4.5) become less precise.

Finally, we perform the same experiment with varying ε and h . We observe that the results look remarkably close even if, at low resolution, the error becomes huge when the size of the Wulff shape is of the order of the discretization. Figure 5 shows the shapes. Observe that the shape at time $t = 49$ is only computed for $\varepsilon = 0.1$ and $h = 0.1$ (the shape vanishes before for the two other

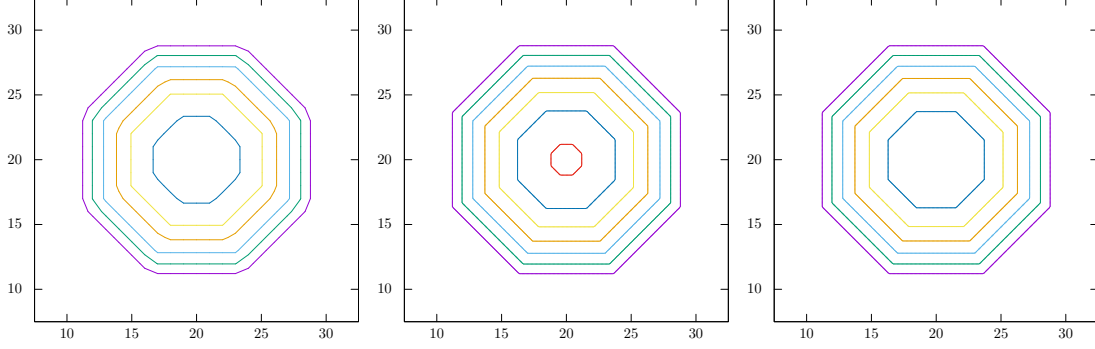
FIGURE 5. Evolution of an initial octagon with $R_0 = 10$ at times $0, 7, 14, \dots$ Left: $\varepsilon = 1$, $h = 0.1$, middle: $\varepsilon = 0.1$, $h = 0.1$, right: $\varepsilon = 0.1$, $h = 0.5$.

fig:octos

experiments). On the other hand, this computation took more than one hour, while the case $\varepsilon = 1$ took less than a minute and the case $\varepsilon = 0.1$, $h = 0.5$ a bit less than an hour. Figure 6 shows the decay of the radii, which should be $\sqrt{R_0^2 - 2t}$ for $R_0 = 10$ and $t \in [0, 50]$.

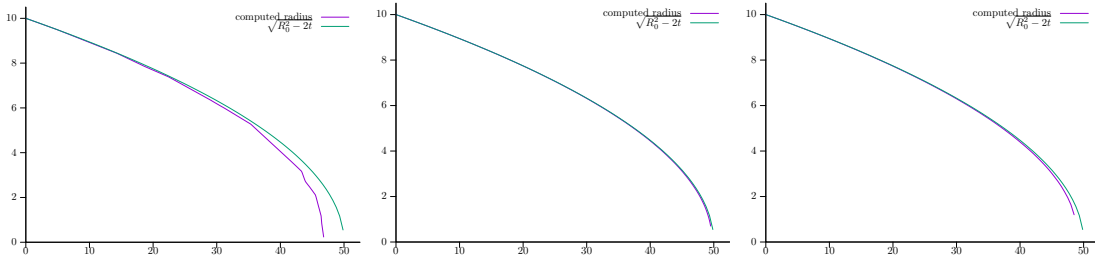
FIGURE 6. Evolution of the radius for an initial octagon with $R_0 = 10$ until the vanishing time $t = 50$. Left: $\varepsilon = 1$, $h = 0.1$, middle: $\varepsilon = 0.1$, $h = 0.1$, right: $\varepsilon = 0.1$, $h = 0.5$.

fig:radiiOcto

sec:proofscsv

APPENDIX A. PROOF OF LEMMA 4.10

We build here a supersolution to Problem (4.26) when $g = \phi^\circ$. Let us first recall some notation and results concerning zonotopes (see e.g. [41]). Recall that $\mathcal{E} = \{\pm e_k\}_{k=1}^m \subseteq \mathbb{Z}^N$ where, without loss of generality, the vectors e_1, \dots, e_m span the whole \mathbb{R}^N . Given a non-negative interaction function $\beta \in X$, we assume that $\beta = 0$ on $\mathbb{Z}^N \setminus \mathcal{E}$ and that $\beta(-i) = \beta(i)$ for every $i \in \mathbb{Z}^N$. The anisotropy ϕ associated to β , as defined in (1.5), is such that its 1-Wulff shape $\mathcal{W}_1 \subseteq \mathbb{R}^N$ is a zonotope, which can be expressed as the Minkowski sum

$$\mathcal{W}_1 = \sum_{e \in \mathcal{E}} \beta(e)[-e, e] = \sum_{k=1}^m 2\beta(e_k)[-e_k, e_k],$$

where $[-e, e] \subseteq \mathbb{R}$ denotes the closed segment from $-e$ to e . Alternatively, one can define the zonotope \mathcal{W}_1 as the image of a cube under an affine map. Indeed, it holds

$$(A.1) \quad \mathcal{W}_1 = V(Q^{(m)})$$

where $V = (2\beta(e_1)e_1, \dots, 2\beta(e_m)e_m) \in \mathbb{R}^{N \times m}$ and $Q^{(m)} = [-1, 1]^m$. Since the set \mathcal{E} is uniquely defined up to sign changes, the matrix V is also uniquely determined up to permutations of columns or sign changes.

def proj cube

Note that by definition of zonotope any element $x \in \mathcal{W}_\ell$ for $\ell > 0$ can be written as

$$x = \ell \sum_{k=1}^m 2\beta(e_k) \lambda_k e_k,$$

for suitable coefficients $|\lambda_k| \leq 1$. We note that (the closure of) a facet F (of non-zero dimension) of the zonotope \mathcal{W}_ℓ can be described in the following form:

formula facet

$$(A.2) \quad F = \ell \sum_{j=1}^r 2\beta(e_{\sigma(j)}) [-e_{\sigma(j)}, e_{\sigma(j)}] + \ell \sum_{j=r+1}^m 2\beta(e_{\sigma(j)}) \varepsilon_{\sigma(j)} e_{\sigma(j)},$$

where σ is a permutation of $\{1, \dots, m\}$, $1 \leq r \leq m$ and $|\varepsilon_j| = 1$. Moreover (see [41, page 206] for details) the vectors $e_{\sigma(1)}, \dots, e_{\sigma(r)}$ uniquely identify

$$\{e \in \mathcal{E} : e \parallel F\},$$

and r is uniquely defined as the number of vectors in the family \mathcal{E} which are parallel to the facet F . Analogously, any vertex v of the zonotope \mathcal{W}_ℓ is of the form

formula vertex

$$(A.3) \quad v = \ell \sum_{j=1}^m 2\beta(e_{\sigma(j)}) \varepsilon_{\sigma(j)} e_{\sigma(j)},$$

where $\varepsilon_j \in \{\pm 1\}$ for every $j = 1, \dots, m$ and σ is a permutation of $\{1, \dots, m\}$. Note however that not every point of this form is a vertex of the zonotope.

lemma zonotopes

Lemma A.1. *There exists $\ell_0 > 0$ such that for every $\varepsilon > 0$ and every $\ell \geq \ell_0$, if $i \in \varepsilon \mathbb{Z}^N$ belongs to $\partial \mathcal{W}_{\varepsilon \ell}$, then for each $k \in \{1, \dots, m\}$ either one of the following holds:*

- i) *neither $i + \varepsilon e_k$ nor $i - \varepsilon e_k$ belong to $\partial \mathcal{W}_{\varepsilon \ell}$. In this case it holds either $\phi^\circ(i + \varepsilon e_k) > \phi^\circ(i) > \phi^\circ(i - \varepsilon e_k)$ or $\phi^\circ(i - \varepsilon e_k) > \phi^\circ(i) > \phi^\circ(i + \varepsilon e_k)$;*
- ii) *one between $i \pm \varepsilon e_k$ belongs to $\partial \mathcal{W}_{\varepsilon \ell}$. In this case $\phi^\circ(i \pm \varepsilon e_k) \geq \ell$ and it holds*

length

$$(A.4) \quad \#((i + \varepsilon \mathbb{Z} e_k) \cap \partial \mathcal{W}_{\varepsilon \ell}) \geq 2[\ell/\ell_0].$$

Proof. By scaling, it suffices to prove the result in the case $\varepsilon = 1$. We take ℓ_0 such that

choice ell0

$$(A.5) \quad \ell_0 \geq \max_{k=1, \dots, m} \frac{1}{2\beta(e_k)}$$

and remark that $\ell_0 \in (0, +\infty)$. Note that the choice (A.5) implies for every $j = 1, \dots, m$ that

$$|[-2\ell\beta(e_j)e_j, 2\ell\beta(e_j)e_j]| = 4\ell\beta(e_j)|e_j| \geq 2\frac{\ell}{\ell_0}|e_j|.$$

We then fix $i \in \partial \mathcal{W}_\ell \cap \mathbb{Z}^N$ and $e_k \in \mathcal{E}$. We have to distinguish two cases.

Case 1. There exists a facet $F \ni i$ of \mathcal{W}_ℓ such that $e_k \parallel F$. By (A.2) we then see that

$$i \in 2\ell\beta(e_k)[-e_k, e_k] + j,$$

where $j \in F$. This implies in particular that $\{n \in \mathbb{Z} : i + ne_k \in F\}$ is an interval of \mathbb{Z} containing 0. Furthermore, by the assumption (A.5), it contains at least $[2\ell|e_k|/\ell_0]$ points and we conclude (A.4). Since i and one between $i \pm e_k$ belong to $\partial \mathcal{W}_\ell$, then $\phi^\circ(i \pm e_k) \geq \ell$ by convexity.

Case 2. For every facet $F \ni i$ of \mathcal{W}_ℓ it holds $e_k \not\parallel F$. Let us fix a facet $F \ni i$ and note that by (A.2) and up to relabelling the indexes, it holds

$$i \in \ell \sum_{j=1}^r 2\beta(e_j)[-e_j, e_j] + \ell \sum_{j=r+1}^m 2\beta(e_j) \varepsilon_j e_j,$$

with $k > r$ and $|\varepsilon_j| = 1$ for $j = r+1, \dots, m$. Recalling (A.1), we see that

$$i - \varepsilon_k e_k = \ell V(y - \frac{\varepsilon_k}{\ell \beta(e_k)} \tilde{e}_k),$$

where $\tilde{e}_1, \dots, \tilde{e}_m$ denotes the canonical base of \mathbb{R}^m and $y \in \sum_{j=1}^r [-\tilde{e}_j, \tilde{e}_j] + \sum_{j=r+1}^m \varepsilon_j \tilde{e}_j \subseteq \partial Q^{(m)}$. By the choice (A.5) and since $k > r$, one deduces that $y - \frac{\varepsilon_k}{\ell \beta(e_k)} \tilde{e}_k \in Q^{(m)}$, thus $i - \varepsilon_k e_k \in \overline{W}_\ell$. Since then $e_k \nparallel F$ for any facet containing i , it must hold $\phi^\circ(i - \varepsilon_k e_k) < \ell$. By convexity one easily concludes that $\phi^\circ(i + \varepsilon_k e_k) > \ell$, which shows i). \square

We now define a calibration z_{ij} for every $(i, j) \in (\{\phi^\circ > \varepsilon \ell_0\} \cap \varepsilon \mathbb{Z}^N) \times \varepsilon \mathbb{Z}^N$. Fix $i \in \varepsilon \mathbb{Z}^N$ with $\phi^\circ(i) > \varepsilon \ell_0$. In the following we write $i \sim j$ if $\frac{i-j}{\varepsilon} \in \mathcal{E}$. We start defining

$$\text{def z 1} \quad (A.6) \quad z_{ij} = \begin{cases} 0 & \text{if } j \not\sim i \\ -\beta(e_k) & \text{if } j = i \pm \varepsilon e_k \text{ and } \phi^\circ(j) > \phi^\circ(i) \\ \beta(e_k) & \text{if } j = i \pm \varepsilon e_k \text{ and } \phi^\circ(j) < \phi^\circ(i). \end{cases}$$

In particular, this definition covers case i) in Lemma A.1. Assume then that there exists $j \sim i$ with $\phi^\circ(j) = \phi^\circ(i)$ and $\frac{j-i}{\varepsilon} = e_k \in \mathcal{E}$. Since $i \in \varepsilon \mathbb{Z}^N$ and $e_k \in \mathcal{E}$ fall in case ii) of Lemma A.1, there exists an interval $[-\underline{n}, \bar{n}] \cap \mathbb{Z}$ for $\underline{n}, \bar{n} \in \mathbb{N}$ such that

$$(i + \varepsilon \mathbb{Z} e_k) \cap \partial W_{\phi^\circ(i)}^{\phi^\circ} = i + ([-\underline{n}, \bar{n}] \cap \mathbb{Z}) \varepsilon e_k$$

and moreover

$$\text{length2} \quad (A.7) \quad \#([-\underline{n}, \bar{n}] \cap \mathbb{Z}) \geq 2[\phi^\circ(i)/(\varepsilon \ell_0)].$$

Thus, we define z_{ij} as a linear interpolation of the values assumed at the extremal points of $i + [-\underline{n}, \bar{n}] \varepsilon e_k$ as

$$\text{def z 2} \quad (A.8) \quad \begin{aligned} z_{i+t\varepsilon e_k, i+(t+1)\varepsilon e_k} &:= \beta(e_k) \left(1 - 2 \frac{t + \underline{n} + 1}{\underline{n} + \bar{n} + 1} \right) \quad \forall t \in [-\underline{n} - 1, \bar{n}] \cap \mathbb{Z}, \\ z_{i+t\varepsilon e_k, i+(t-1)\varepsilon e_k} &:= \beta(e_k) \left(1 - 2 \frac{-t + \underline{n} + 1}{\underline{n} + \bar{n} + 1} \right) \quad \forall t \in [-\underline{n}, \bar{n} + 1] \cap \mathbb{Z}. \end{aligned}$$

By definition one easily sees that

$$\text{subdiff z} \quad (A.9) \quad |z_{ij}| \leq \alpha_{ij}^\varepsilon, \quad z_{ij}(\phi^\circ(i) - \phi^\circ(j)) = \alpha_{ij}^\varepsilon |\phi^\circ(i) - \phi^\circ(j)|.$$

We now show how to bound the divergence $(D_\varepsilon^* z)_i$. Assume that $\phi^\circ(i + \varepsilon e_k) = \phi^\circ(i)$ or that $\phi^\circ(i - \varepsilon e_k) = \phi^\circ(i)$. Then by definition (A.8) and by (A.7) one deduces

$$\text{div1} \quad (A.10) \quad z_{i, i+\varepsilon e_k} + z_{i, i-\varepsilon e_k} - z_{i+\varepsilon e_k, i} - z_{i-\varepsilon e_k, i} = -\frac{4\beta(e_k)}{\underline{n} + \bar{n} + 1} \geq -\frac{2\beta(e_k)}{[\phi^\circ(i)/(\varepsilon \ell_0)]} \geq -\frac{C\varepsilon}{\phi^\circ(i)},$$

and similarly if $\phi^\circ(i - \varepsilon e_k) = \phi^\circ(i)$. If instead $\phi^\circ(i \pm \varepsilon e_k) \neq \phi^\circ(i)$ and $\phi^\circ(i \pm \varepsilon e_k) \geq \varepsilon \ell_0$, one sees that

$$\text{div2} \quad (A.11) \quad z_{i, i+\varepsilon e_k} + z_{i, i-\varepsilon e_k} = 0 \text{ and } z_{i+\varepsilon e_k, i} + z_{i-\varepsilon e_k, i} = 0$$

Combining (A.10) and (A.11) and recalling (4.2) we conclude that if $\phi^\circ(i) \geq \ell_1 \varepsilon$ then

$$\text{bound div big d} \quad (A.12) \quad h(D_\varepsilon^* z)_i \geq -\frac{c_\phi h}{\phi^\circ(i)}$$

for a suitable positive constant c_ϕ depending on ϕ .

We now illustrate a procedure that allows to extend the calibration above to $\varepsilon\mathbb{Z}^N \times \varepsilon\mathbb{Z}^N$. We set $C > 1$ a sufficiently big constant and define a function $v \in X_\varepsilon$ setting

$$\boxed{\text{def v}} \quad (\text{A.13}) \quad v := \begin{cases} \phi^\circ + \frac{Ch}{\phi^\circ} & \text{on } \{\phi^\circ \geq C(\sqrt{h} \vee \varepsilon)\} \cap \varepsilon\mathbb{Z}^N \\ C(\sqrt{h} \vee \varepsilon) + \frac{h}{\sqrt{h} \vee \varepsilon} & \text{on } \{\phi^\circ < C(\sqrt{h} \vee \varepsilon)\} \cap \varepsilon\mathbb{Z}^N \end{cases}.$$

A calibration $w \in Y_\varepsilon$ can be defined setting for $i, j \in \varepsilon\mathbb{Z}^N$

$$\boxed{\text{def z 3}} \quad (\text{A.14}) \quad w_{ij} := \begin{cases} z_{ij} & \text{if } \phi^\circ(i) \geq 2\sqrt{C}(\sqrt{h} \vee \varepsilon) \\ -\alpha_{ij}^\varepsilon & \text{if } \phi^\circ(i) < 2\sqrt{C}(\sqrt{h} \vee \varepsilon) \end{cases}.$$

Since $x \mapsto x + Chx^{-1}$ is strictly monotone in the region $\{x \geq \sqrt{Ch}\}$, we can employ (A.9) to prove that, for every $i, j \in \varepsilon\mathbb{Z}^N$ with $\phi^\circ(i) \geq C(\sqrt{h} \vee \varepsilon)$, it holds

$$\boxed{\text{eq subdiff v}} \quad (\text{A.15}) \quad w_{ij}(v_i - v_j) = \alpha_{ij}^\varepsilon |v_i - v_j|, \quad |w_{ij}| \leq \alpha_{ij}^\varepsilon.$$

Moreover, taking C large enough ensures that whenever $j \sim i$, then

$$\boxed{\text{choice C}} \quad (\text{A.16}) \quad \begin{aligned} \phi^\circ(i) \leq 2\sqrt{C}(\sqrt{h} \vee \varepsilon) &\implies \phi^\circ(j) \leq C(\sqrt{h} \vee \varepsilon) \\ \phi^\circ(i) \geq 2\sqrt{C}(\sqrt{h} \vee \varepsilon) &\implies \phi^\circ(j) \geq \sqrt{C}(\sqrt{h} \vee \varepsilon) \end{aligned}.$$

Thus, equation (A.15) can be directly checked in the case $\phi^\circ(i) \leq 2\sqrt{C}(\sqrt{h} \vee \varepsilon)$ using the definition (A.14).

Note now that definition (A.14) implies $D_\varepsilon^* w = 0$ in the region $\{\phi^\circ < 2\sqrt{C}(\sqrt{h} \vee \varepsilon)\}$ thus we assume $\phi^\circ(i) \geq 2\sqrt{C}(\sqrt{h} \vee \varepsilon)$ and estimate $(D_\varepsilon^* w)_i$. If $\phi^\circ(i - \varepsilon e_k) < 2\sqrt{C}(\sqrt{h} \vee \varepsilon)$ by convexity $\phi^\circ(i + \varepsilon e_k) > 2\sqrt{C}(\sqrt{h} \vee \varepsilon)$, thus by definition (A.14) we get

$$z_{i,i+\varepsilon e_k} - z_{i+\varepsilon e_k,i} + z_{i,i-\varepsilon e_k} - z_{i-\varepsilon e_k,i} = -\beta(e_k) - \beta(e_k) + \beta(e_k) - (-\beta(e_k)) = 0.$$

The symmetric case is analogous. On the other hand, if every $j \sim i$ is in $\{\phi^\circ \geq 2\sqrt{C}(\sqrt{h} \vee \varepsilon)\}$ equation (A.12) holds. Therefore, we have shown

$$\boxed{\text{bound div w}} \quad (\text{A.17}) \quad hD_\varepsilon^* w \geq -\frac{c_\phi h}{\phi^\circ} \chi_{\{\phi^\circ \geq \sqrt{C}(\sqrt{h} \vee \varepsilon)\}}.$$

By a direct computation, using (A.17) and assuming the $C > c_\phi$, we see that the pair (v, w) defined above satisfies

$$\begin{cases} hD_\varepsilon^* w + v \geq \phi^\circ \\ w_{ij}(v_i - v_j) = \alpha_{ij}^\varepsilon |v_i - v_j|, \quad |w_{ij}| \leq \alpha_{ij}^\varepsilon. \end{cases}$$

Recalling the comparison result in Theorem 3.3, we conclude that the solution u to (3.4) satisfies $u \leq v$ in $\varepsilon\mathbb{Z}^N$.

APPENDIX B. A REMARK ON THE INF/SUP-CONVOLUTION FORMULAS (4.5)

app:finite

In this section we show that in some particular cases, the inf,sup in the definition (4.5) can be replaced by min,max and that this minimization/maximization procedure can be made in a fixed neighborhood of the point considered. Yet, our proof also shows that this neighborhood can become very large, depending on the weights of the interaction, and it seems that we cannot expect in general cases that the min,max are actually reached.

We introduce the following condition. There exists $\ell_\phi > 0$ such that for every $\varepsilon_k \in \{0, \pm 1\}$ for $k = 1, \dots, m$, there exists $\ell \leq \ell_\phi$ such that

$$\text{ational zonotope} \quad (\text{B.1}) \quad \ell \sum_{k=1}^m 2\beta(e_k) \varepsilon_k e_k \in \mathbb{Z}^N.$$

Note that this condition is satisfied if $\beta(e_k)/\beta(e_{k'}) \in \mathbb{Q}$ for all $k, k' = 1, \dots, m$.

lemma neigh

Lemma B.1. *There exists $\ell_1 > 0$ with the following property. For any $i \in \varepsilon \mathbb{Z}^N$ with $\phi^\circ(i) \geq \varepsilon \ell_1$ there exists $j \in \varepsilon \mathbb{Z}^N \setminus \{0\}$ with $\phi^\circ(j) < \phi^\circ(i)$ and satisfying*

$$\text{additive s dl} \quad (\text{B.2}) \quad \phi^\circ(i) \geq \phi^\circ(j) + \phi^\circ(i - j) - c_\phi \varepsilon.$$

If (B.1) holds, for any $i \in \varepsilon \mathbb{Z}^N$ with $\phi^\circ(i) \geq 2\varepsilon \ell_1$ there exists $j \in (\mathcal{W}_{\varepsilon \ell_1} \setminus \{0\}) \cap \varepsilon \mathbb{Z}^N$ such that

$$\text{additive sd} \quad (\text{B.3}) \quad \phi^\circ(i) = \phi^\circ(j) + \phi^\circ(i - j).$$

Moreover, for every $R \in (2\varepsilon \ell_1, \phi^\circ(i))$ there exists $j \in \mathcal{W}_R \setminus \mathcal{W}_{R-2\varepsilon \ell_1}$ such that (B.3) holds.

Proof. By scaling we prove the result in the case $\varepsilon = 1$. Given $i \in \mathbb{Z}^N \setminus \{0\}$, inequality (B.2) follows easily choosing $\ell_1 \geq 2$, considering $\sigma i \in \mathbb{R}^N \setminus \{0\}$ for an appropriate $\sigma \in (0, 1)$ and $j \in \mathbb{Z}^N$ so that $\sigma i \in (j + [0, 1]^N)$.

We now assume (B.1) and denote by ℓ_ϕ the radius associated to ϕ . We then choose $\ell_1 = \ell_\phi$. Let us fix $i \in \mathbb{Z}^N$ with $\phi^\circ(i) = \ell \geq 2\ell_1$. By (A.2) there exist $r > 0$, ε_k, λ_k with $|\varepsilon_k| = 1$ and $|\lambda_k| < 1$ such that

$$i = \ell \left(\sum_{k=1}^r 2\beta(e_k) \varepsilon_k e_k + \sum_{k=r+1}^m \lambda_k 2\beta(e_k) e_k \right).$$

Let us denote the point

$$v = \sum_{k=1}^r 2\beta(e_k) \varepsilon_k e_k \in \partial \mathcal{W}_1,$$

and define the function sign by $\text{sign}(x) = x/|x|$ if $x \neq 0$ and 0 otherwise. For any $\ell' \leq \ell_\phi$ we rewrite i as follows

$$\begin{aligned} i &= \ell' \left(v + \sum_{k=r+1}^m 2\beta(e_k) \text{sign}(\lambda_k) e_k \right) + (\ell - \ell') \left(v + \sum_{k=r+1}^m 2\beta(e_k) \left(\frac{\ell}{\ell - \ell'} \lambda_k - \frac{\ell'}{\ell - \ell'} \text{sign}(\lambda_k) \right) e_k \right) \\ &=: \ell' w + (\ell - \ell') \left(v + \sum_{k=r+1}^m 2\beta(e_k) \lambda'_k e_k \right). \end{aligned}$$

Notice that, since $\ell \geq 2\ell'$ and $|\lambda_k| \leq 1$ it holds $|\lambda'_k| \leq 1$, thus by formula (A.2) we get

$$v + \sum_{k=r+1}^m 2\beta(e_k) \lambda'_k e_k \in \partial \mathcal{W}_1$$

and therefore $\phi^\circ(i - \ell' w) = \ell - \ell'$. We conclude noting that by the hypothesis (B.1) we can choose $\ell' \leq \ell_1$ so that $\ell' w \in \mathbb{Z}^N$, which implies (B.3) since $\phi^\circ(\ell' w) = \ell'$.

We now prove the last assertion. Since $\phi^\circ(i) \geq 2\ell_1$, by the previous result there exists $j_0 \in (\mathcal{W}_{\ell_1} \setminus \{0\})$ so that $\phi^\circ(i) = \phi^\circ(j_0) + \phi^\circ(i - j_0)$. Now, if $R - 2\ell_1 \leq \phi^\circ(j_0)$ we conclude. If not, then $\phi^\circ(i - j_0) \geq 2\ell_1$ by (B.3), and thus we can find $k_0 \in (\mathcal{W}_{\ell_1} \setminus \{0\})$ so that

$$\text{induct0} \quad (\text{B.4}) \quad \phi^\circ(i - j_0) = \phi^\circ(k_0) + \phi^\circ(i - j_0 - k_0).$$

Denoting $j_1 = j_0 + k_0$, on one hand (B.4) implies

$$\text{induct1} \quad (\text{B.5}) \quad \phi^\circ(i) = \phi^\circ(j_0) + \phi^\circ(j_1 - j_0) + \phi^\circ(i - j_1) \geq \phi^\circ(j_1) + \phi^\circ(i - j_1)$$

thus equality holds instead. If $\phi^\circ(j_1) \geq R - 2\ell_1$ we conclude, if not (B.5) yields $\phi^\circ(i - j_1) \geq 2\ell_1$ and we can iterate. Recalling that $\phi^\circ \geq c_\phi > 0$ on $\varepsilon\mathbb{Z}^N \setminus \{0\}$, it is clear that after a finite number of iterations the process stops, and one can check that the required properties are satisfied. \square

By the previous lemma it is easy to prove the following result.

cor neigh

Corollary B.2. *Let $u \in X$ be a $(1, \phi)$ -Lipschitz function and ℓ_1 as in Lemma B.1. Then, for all $i \in \varepsilon\mathbb{Z}^N$ it holds*

$$\sup_{j \in \{u \geq 0\}} \{u_j - \phi^\circ(i - j)\} = \max_{j \in \{u \geq 0\}} \{u_j - \phi^\circ(i - j)\}.$$

In addition, if $i \in \{u \leq 0\}$, the maximum is reached in a point in $(\{u \leq 0\} + \mathcal{W}_{2\varepsilon\ell_1}) \cap \varepsilon\mathbb{Z}^N$.

Proof. It is enough to consider $i \in \{u < 0\} \cap \varepsilon\mathbb{Z}^N$. Let us denote $F = (\{u \leq 0\} + \mathcal{W}_{2\varepsilon\ell_1}) \cap \{u > 0\}$. Firstly, by a variant of the argument by iteration employed in the proof of Lemma B.1, one can prove that

sup=sup'

$$(B.6) \quad \sup_{j \in \{u \geq 0\}} \{u_j - \phi^\circ(i - j)\} = \sup_{j \in F} \{u_j - \phi^\circ(i - j)\}.$$

On the other hand, take a point $j_0 \in \{u > 0\}$. If $j \in F$ satisfies $u_j - \phi^\circ(i - j) \geq u_{j_0} - \phi^\circ(i - j_0)$, since $u \leq 2\varepsilon\ell_1$ in F (as u is $(1, \phi^\circ)$ -Lipschitz) we obtain

$$2\varepsilon\ell_1 + \phi^\circ(i - j_0) \geq \phi^\circ(i - j),$$

which implies that the sup in (B.6) is indeed a max. \square

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