Abstract. We show that a divergence-free measure on the plane is a continuous sum of unit tangent vector fields on rectifiable Jordan curves. This loop decomposition is more precise than the general decomposition in terms of elementary solenoids given by S.K. Smirnov when applied to the planar case. The proof involves extending the Fleming-Rishel formula to homogeneous BV functions (in any dimension), and establishing for such functions approximate continuity of measure theoretic connected components of suplevel sets as functions of the level. We apply these results to inverse potential problems whose source term is the divergence of some unknown (vector-valued) measure. A prototypical case is that of inverse magnetization problems where magnetizations are modeled by $\mathbb{R}^3$-valued Borel measures. We investigate methods for recovering a magnetization $\mu$ by penalizing the measure theoretic total variation norm $\|\mu\|_{TV}$. In particular, we show that if a magnetization is supported in a plane, then $TV$-regularization schemes always have a unique minimizer, even in the presence of noise. It is further shown that $TV$-norm minimization (among magnetizations generating the same field) uniquely recovers planar magnetizations in the following cases: when the magnetization is carried by a collection of sufficiently separated line segments and a set that is purely 1-rectifiable, or when a superset of the support is tree-like. We note that such magnetizations can be recovered via $TV$-regularization schemes in the zero noise limit by taking the regularization parameter to zero. This suggests definitions of sparsity in the present infinite dimensional context, that generate results akin to compressed sensing.

1. Introduction

This paper deals with the structure of finite divergence-free measures in the plane, and applications thereof to inverse magnetization problems on thin plates. These are prototypical of inverse potential problems with source term in divergence form, and have been the main motivation of the authors to develop a purely measure-geometric result like Theorem 4.5. The latter asserts that a planar divergence-free measure can be decomposed as a superposition of elementary “loops”; i.e., unit tangent vector fields on rectifiable Jordan curves. This result is more precise than the general structure theorem for solenoids given by Smirnov in [27] (valid in any dimension), and is hinted at on page 843 of that reference. Because divergence-free distributions in the plane are rotations by $\pi/2$ of distributional gradients, one is quickly left to decompose gradients of “homogeneous” $BV$-functions; i.e., locally integrable functions whose partial derivatives are finite measures. To do this, we combine a version of the co-area formula for homogeneous $BV$-functions (Theorem 3.6) with a decomposition into Jordan curves of the measure-theoretic boundary of planar sets of finite perimeter given in [1]. The latter is a special case of the decomposition of 1-dimensional integral currents into indecomposable elements [14, 4.2.25], in which the pattern of orientations has special structure. To handle measurability issues in the integral expressing the decomposition of a divergence-free measure as a superposition of loops, we also establish (in any dimension) an approximate continuity property of measure-theoretic connected components of suplevel sets for homogeneous $BV$-functions (Theorem 3.9), which is interesting in its own right.

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The loop decomposition of planar divergence-free measures has interesting applications to inverse magnetization problems for thin plates, when magnetizations are modelled by $\mathbb{R}^3$-valued measures supported on a set $S$ (in the thin plate case, $S \subset \mathbb{R}^2$). Then, the inverse magnetization problem consists in recovering such a measure, say $\mu$, from knowledge of the magnetic field $b(\mu)$ that it generates, see Section 1.1 for details. Magnetizations supported in a plane generate the zero magnetic field if and only if they are tangent to that plane and divergence-free there (see Lemma 2.1). Thus, the kernel of the forward operator mapping $\mu$ to $b(\mu)$ consists precisely of planar divergence-free measures in this case. The loop decomposition gives insight on the structure of this kernel, enabling us to give sufficient conditions for a magnetization to be $TV$-minimal on $S$; i.e., the magnetization has minimum total variation among those magnetizations supported on $S$ that generate the same field. When a $TV$-minimal magnetization on $S$ is unique among magnetizations generating the same field, we call it strictly $TV$-minimal on $S$. By standard regularization theory, strictly $TV$-minimal magnetizations can be recovered by solving a sequence of minimization problems for the so-called regularizing functional, which is the sum of the quadratic residuals and a penalty term consisting of the product of a regularization parameter $\lambda > 0$ and the total variation of the unknown, see (4). Then, any sequence of minimizers of the regularizing functional converges weak-* to the strictly $TV$-minimal measure generating the data (when it exists), as the regularization parameter and the noise tend jointly to zero in a suitable manner, see e.g. [7]. In short: regularizing schemes that penalize the total variation are consistent to recover strictly $TV$-minimal magnetizations, and thus, any assumption ensuring strict $TV$-minimality gives rise to a consistency result. For the larger class of magnetizations supported on a slender set $S$ (see Section 1.1 for a definition), such a consistency result is obtained in [5] Theorem 2.6 by showing, using reference [27], that magnetizations supported on a purely 1-rectifiable set are strictly $TV$-minimal. Specializing to the case of planar $S$ will allow us to obtain more general conditions, proving for instance that magnetizations carried by the union of a purely 1-rectifiable set and a collection of sufficiently separated line segments are strictly $TV$-minimal (Corollary 5.4 and Theorem 5.2).

The results just mentioned are reminiscent of compressed sensing, where underdetermined systems of linear equations in $\mathbb{R}^n$ are approximately solved by minimizing the residuals while penalizing the $l^1$-norm. This favors the recovery of sparse solutions (i.e. solutions having a large number of zero components) when they exist, see e.g. [16]. In this connection, the gist of [5] Theorem 2.6 and its sharpening described above for the planar case is to introduce notions of “sparsity” in the present, infinite-dimensional context. This warrants the use of regularizing schemes that penalize the total variation (a natural analog of the $l^1$-norm), in order to recover sparse magnetizations.

Our second application of the loop decomposition to inverse magnetization problems on thin plates is to prove that, for each value of the regularization parameter, the minimizer of the regularizing functional is unique (Theorem 5.7). This result is important for algorithmic approaches to the inverse magnetization problem, because it tells us that for every choice of the regularization parameter there is a unique estimate of the unknown magnetization based on the regularization scheme [5]. It is also surprising, for in the case that a magnetization is $TV$-minimal, but not strictly $TV$ minimal, one would rather expect the regularizing functional to have several minimizers, at least for small values of the regularization parameter.

To conclude this introduction, let us stress that magnetizations supported in a plane are commonly considered in paleomagnetic studies, where thin slabs of rock are modeled by planar regions [1, 21, 28, 22]. It would be interesting to carry over the contents of the present paper to more general slender surfaces in $\mathbb{R}^3$ than the plane, as the results could apply to other situations in geosciences or medical imaging. In practice, the development of numerically effective algorithms for...
these inverse problem raises delicate issues of discretization. Such considerations are not addressed in this paper, but will be taken up in future work.

1.1. Background and Overview of Results. Let us first describe the inverse magnetization problem, which serves as a motivation for the results to come. For a closed subset $S \subset \mathbb{R}^3$, let $\mathcal{M}(S)$ denote the space of finite signed Borel measures supported on $S$. We shall use the space $\mathcal{M}(S)^3$ of $\mathbb{R}^3$-valued measures supported on $S$ to model physical magnetizations distributed on $S$ and shall often use “magnetization on $S$” interchangeably with “element of $\mathcal{M}(S)^3$”. For $\mu \in \mathcal{M}(S)^3$, we let $|\mu|$ denote the total variation measure of $\mu$. The latter is a positive measure, and we put $\|\mu\|_{TV} := |\mu|(\mathbb{R}^3)$ for the total variation of $\mu$, see Section 1.2.

The magnetic field $b(\mu)$ generated by a magnetization $\mu \in \mathcal{M}(S)^3$ is defined, at a point $x$ not in the support of $\mu$, in terms of the scalar magnetic potential $\Phi(\mu)$ by (see \cite{19}):

$$b(\mu)(x) = -\mu_0 \nabla \Phi(\mu)(x), \quad x \notin \text{supp } \mu,$$

where $\mu_0$ is the magnetic constant and $\nabla$ indicates the gradient. Here, $\Phi(\mu)(x)$ is given by

$$\Phi(\mu)(x) := \frac{1}{4\pi} \int \nabla_y \frac{1}{|x-y|} \cdot d\mu(y) = \frac{1}{4\pi} \int \frac{x-y}{|x-y|^3} \cdot d\mu(y),$$

where, for $x,y \in \mathbb{R}^3$, $x \cdot y$ and $|x|$ denote the Euclidean scalar product and norm and $\nabla_y$ the gradient with respect to $y$. Clearly, $\Phi(\mu)$ and the components of $b(\mu)$ are harmonic functions on $\mathbb{R}^3 \setminus S$. Moreover, formula (2) defines $\Phi(\mu)$ on the whole of $\mathbb{R}^3$ as a member of $L^2(\mathbb{R}^3) + L^1(\mathbb{R}^3)$ (see \cite{5} Proposition 2.1)) so that $b(\mu)$, initially defined on $\mathbb{R}^3 \setminus S$, extends to a $\mathbb{R}^3$-valued divergence-free distribution on $\mathbb{R}^3$. Indeed, we may write

$$\Delta \Phi = \nabla \cdot \mu \quad \text{and} \quad b(\mu) = \mu_0 (\mu - \nabla \Phi(\mu)),$$

where $\nabla \cdot \mu$ indicates the divergence of $\mu$. Note that (2) yields a Helmholtz-Hodge decomposition of $\mu$, as the sum of a gradient and a divergence-free distribution. However, neither term is a measure in general but rather a distribution of order $-1$.

The inverse magnetization problem is to recover $\mu$ from measurements of $b(\mu)$ taken on a set $Q \subset \mathbb{R}^3 \setminus S$ which, due to the oriented nature of sensors (coils), are usually observed in one direction only, say along some unit vector $v \in \mathbb{R}^3$. We assume for simplicity that $v$ is the same at each measurement point. For instance, it is so in usual Scanning Magnetic Microscopy experiments (SMM) where data consist of point-wise values of the normal component of the magnetic field on a planar region not intersecting $S$, see \cite{21, 22, 23}. Geometric conditions on $Q$, $S$ and $v$, ensuring that such measurements suffice to determine $b(\mu)$ in the entire region $\mathbb{R}^3 \setminus S$, are given in \cite{5} Lemma 2.3], and recalled for convenience when $S$ is planar in Section 5.2 further below. In the remainder of this introduction, we assume that these assumptions are satisfied.

Still, the mapping $\mu \to b(\mu)$ is generally not injective, which is a major difficulty with this inverse problem. In this connection, we say that $\mu, \nu \in \mathcal{M}(S)^3$ are $S$-equivalent if $b(\mu)$ and $b(\nu)$ agree on $\mathbb{R}^3 \setminus S$. A magnetization $\mu$ is said to be $S$-silent if $\mu$ is $S$-equivalent to the zero magnetization; i.e., if $b(\mu)$ vanishes on $\mathbb{R}^3 \setminus S$.

Since no nonzero harmonic function lies in $L^2(\mathbb{R}^3) + L^1(\mathbb{R}^3)$, it follows from (3) that a divergence-free magnetization is $S$-silent. A partial converse is given in \cite{5} Theorem 2.2], namely a $S$-silent magnetization is divergence-free provided that $S$ is slender, meaning it has Lebesgue measure zero and each connected component of $\mathbb{R}^3 \setminus S$ has infinite Lebesgue measure. The slenderness assumption is a strong one: for instance it rules out the case where $S$ is a volumic sample or a closed surface. However, it is satisfied in important special cases, for example in paleomagnetic studies, as mentioned already, or in Geomagnetism where some regions of the Earth’s crust are
assumed to be non-magnetic (or much less magnetic) than the others \cite{17}, or even in Magneto-
Encephalography where sources are often considered to lie on the surface of the encephalon (which is
closed and therefore not slender) but their support should arguably leave out the brain stem
connecting to the spinal cord (therefore the support is contained in a slender set).

In \cite{27}, Smirnov describes divergence-free measures in $\mathbb{R}^n$, also known as solenoids, in terms of
integrals of elementary components that are absolutely continuous with respect to 1-dimensional
Hausdorff measure $\mathcal{H}^1$. Consequently, if $S$ is slender and $\mu \in \mathcal{M}(S)^3$ is such that there is a purely
1-unrectifiable set (i.e., whose intersection with any 1-rectifiable set has $\mathcal{H}^1$- measure zero, see
\cite{23}) of full $|\mu|$ measure, then $\mu$ is mutually singular to every $S$-silent magnetization and so has
minimum total variation amongst all magnetizations that are $S$-equivalent to $\mu$. This observation
led the authors in \cite{5} to consider the following extremal problem involving the quantity $M_S(\mu)$,
declared for $\mu \in \mathcal{M}(S)^3$ by
\[ M_S(\mu) := \inf \{ \| \nu \|_{TV} : \nu \text{ is } S\text{-equivalent to } \mu \}. \]

**Extremal Problem 1.** Given $\mu_0 \in \mathcal{M}(S)^3$, find $\mu$ that is $S$-equivalent to $\mu_0$ satisfying
\[ \| \mu \|_{TV} = M_S(\mu_0). \]

A solution to Extremal Problem 1 is, by definition, $TV$-minimal on $S$ and is strictly $TV$-minimal
on $S$ if this solution is unique. When $S \subset \mathbb{R}^3$ is slender and $\mu_0 \in \mathcal{M}(S)^3$, we find that $\mu_0$ is strictly
$TV$-minimal on $S$ for the three cases listed below. Here case (a) is essentially \cite{5} Theorem 2.6 and
a special case of Theorem 5.2 to come, while (b) is contained in \cite{5} Theorem 2.11 and (c) follows
from Corollary 5.4 further below.

(a) there is a purely 1-unrectifiable set of full $|\mu_0|$ measure;
(b) the set $S$ is a finite disjoint union of compact sets $S_1, \ldots, S_k$ and
\[ \mu_0|_{S_i} = u_i|\mu_0||_{S_i}, \]
for some set of unit vectors $u_1, \ldots, u_k \in \mathbb{R}^3$, in which case we say $\mu_0$ is piecewise unidirectional;
(c) $\mu_0$ has a carrier contained in a countable union of coplanar disjoint line segments $L_k$ such
that the distance from any $L_k$ to any $L_j, j \neq k$, is greater than or equal to $\mathcal{H}^1(L_k)$.

Corollary 5.4 also implies that (a) can be combined (c), namely if a measure satisfies (c) and we
add to it a measure on $S$ carried by a purely 1-unrectifiable set, then we get a measure which is
strictly $TV$-minimal again.

Now, for $\rho$ a positive measure on $Q$, let $A : \mathcal{M}(S)^3 \to L^2(Q, \rho)$ be the forward operator mapping
$\mu$ to the restriction of $b(\mu) \cdot v$ on $Q$ (see \cite{55}). The measure $\rho$ does not play a significant role
in what follows (e.g., it could be chosen to be Lebesgue measure on $Q$), but it is important for
practical applications. To recover solutions of Extremal Problem 1 knowing the restriction $f$ of
$b(\mu_0) \cdot v$ to $Q$, the theory of regularization for convex problems \cite{27} suggests to minimize with
respect to $\mu \in \mathcal{M}(S)^3$ the functional
\[ F_{f,\lambda}(\mu) := \| f - A\mu \|^2_{L^2(Q, \rho)} + \lambda \| \mu \|_{TV} \]
for some suitable value of the regularization parameter $\lambda > 0$. That is, we consider:

**Extremal Problem 2.** Given $f \in L^2(Q)$ and $\lambda > 0$, find $\mu_\lambda \in \mathcal{M}(S)^3$ such that
\[ F_{f,\lambda}(\mu_\lambda) = \inf_{\mu \in \mathcal{M}(S)^3} F_{f,\lambda}(\mu). \]
When $Q$ and $S$ are positively separated, the existence of at least one minimizer is a consequence of the weak-* compactness of the unit ball in $\mathcal{M}(S)^3$ see e.g. [6, Proposition 3.6]. Solving Extremal Problem 2 is a particular regularization scheme for the Inverse Magnetization Problem, namely one that penalizes the total variation of the unknown.

It is standard that if $f = A\mu_0$ and $\lambda_n \to 0$, then any subsequence of $\mu_{\lambda_n}$ has a subsequence converging weak-* to a solution of Extremal Problem 1. To account for measurement noise, one usually replaces $f$ by $f_n = A\mu_0 + \epsilon_n$, and then the same result holds for a sequence $\mu_n$ minimizing (1) with $f = f_n$ and $\lambda = \lambda_n$, provided that both $\lambda_n$ and $\|\epsilon_n\|_{L^2(\rho)}$ tend to 0, see [7, Theorems 2&5] or [18, Theorems 3.5&4.4]. In particular, if $\mu_0$ is the unique solution of Extremal Problem 1, then we get weak-* convergence of $\mu_n$ to $\mu_0$. A stronger result, involving weak-* convergence of the total variation measure $|\mu_n|$, can be found in [5, Theorem 4.3]. To recap, we have a consistency property asserting that a magnetization meeting a certain assumptions (e.g. either (a), (b) or (c) above) can be approximately recovered via the regularization scheme (5), when the noise is small and the regularization parameter $\lambda$ is chosen small but still larger than the square of the noise (the so-called Morozov discrepancy principle). Note that [5] may a priori have several minimizers, for the total variation norm is not strictly convex and the kernel of $A$ is nontrivial, whence the objective function (1) is not strictly convex either as is easy to see.

In Section 5 we analyze Extremal Problems 1 and 2 further in the case where $S$ is contained in a plane. We prove that $\mu = \mu_0$ is the unique solution to Extremal Problem 1 in case (c) listed above (Theorem 5.3), and also that Extremal Problem 2 has a unique solution for any data (Theorem 5.7).

Both results depend on Theorem 4.3 asserting that two-dimensional divergence-free measures can be decomposed into loops, i.e. contour integrations along rectifiable Jordan curves. The proof of the latter occupies Section 4 after some preparation in Section 3 which develops a co-area formula for homogeneous $BV$-functions and approximate continuity of suplevel sets thereof. Section 2 describes relevant results from [27], while Appendix A gathers technical facts connected to the latter.

1.2. Notation. We conclude this section with some notation and definitions regarding measures and distributions. For a vector $x$ in the Euclidean space $\mathbb{R}^n$ (we mainly deal with $n = 2$ or 3), we denote the $j$-th component of $x$ by $x_j$ and the partial derivative with respect to $x_j$ by $\partial x_j$. By default, we consider vectors as column vectors; e.g., for $x \in \mathbb{R}^3$ we write $x = (x_1, x_2, x_3)^T$ where "$^T$" denotes “transpose”. We write $\mathbb{N}$ for the nonnegative integers, $\mathbb{N}^*$ for the positive integers, and $\mathbb{R}^+$ for the nonnegative real numbers. We use bold symbols to represent vector-valued functions and measures, and the corresponding nonbold symbols with subscripts to denote the respective components; e.g., $\mu = (\mu_1, \mu_2, \mu_3)^T$ or $b(\mu) = (b_1(\mu), b_2(\mu), b_3(\mu))^T$. For $x \in \mathbb{R}^n$ and $R > 0$, we let $B(x, R)$ denote the open ball centered at $x$ with radius $R$, and $S(x, R)$ the boundary sphere. This notation does not show dependence on $n$, but no confusion should arise. We denote by $\mathcal{M}(E)$ the space of finite signed measures on $E \subset \mathbb{R}^n$.

We write $\chi_E$ for the characteristic function of a set $E$ and $\delta_x$ for the Dirac delta measure at $x$. Given a $\mathbb{R}^m$-valued measure in $\mu \in \mathcal{M}(\mathbb{R}^n)^m$ and a Borel set $E \subset \mathbb{R}^n$, we denote by $\mu|_E$ the measure obtained by restricting $\mu$ to $E$ (i.e. for every Borel set $B \subset \mathbb{R}^n$, $\mu|_E(B) := \mu(E \cap B)$).

For $\mu \in \mathcal{M}(\mathbb{R}^n)^m$, the total variation measure $|\mu|$ is defined on Borel sets $B \subset \mathbb{R}^n$ by

$$|\mu|(B) := \sup_{\mathcal{P}} \sum_{P \in \mathcal{P}} |\mu(P)|,$$

where $\mathcal{P}$ denotes a finite partition of $B$. This is a metric on $\mathcal{M}(\mathbb{R}^n)^m$, and it is the unique function satisfying the properties of a total variation. For vectors $\mu \in \mathcal{M}(\mathbb{R}^n)^m$, this metric is the total variation metric.

The function $\mu \mapsto \mu(B)$ is lower semi-continuous with respect to the total variation metric. For $\mu \in \mathcal{M}(\mathbb{R}^n)^m$, $\mu|_E(B)$ is the measure obtained by restricting $\mu$ to $E$.

In particular, if $\mu$ is a measure on $\mathbb{R}^n$, we denote by $\mu|_E$ the restriction of $\mu$ to $E$. For a Borel set $B \subset \mathbb{R}^n$, we define $\mu(B) := \mu|_B(B)$.

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where the supremum is taken over all finite Borel partitions $P$ of $B$. The total variation norm of $\mu$ is then defined as

$$\|\mu\|_{TV} := |\mu|(\mathbb{R}^n).$$

The support of $\mu$ (i.e., the complement of the largest open set $U$ such that $|\mu|(U) = 0$) is denoted as $\text{supp} \mu$. Since $|\mu|$ is a Radon measure, the Radon-Nikodym derivative $u_\mu := d\mu/d|\mu|$ exists as a $\mathbb{R}^m$-valued $|\mu|$-integrable function and it satisfies $|u_\mu| = 1$ a.e. with respect to $|\mu|$.

For $\Omega \subset \mathbb{R}^n$ an open set, we denote by $C_c(\Omega, \mathbb{R}^m)$ the space of $\mathbb{R}^m$-valued continuous functions on $\mathbb{R}^n$ vanishing at infinity.

We shall identify $\mu \in \mathcal{M}(\mathbb{R}^n)^m$ with the linear form on $C_c(\mathbb{R}^n, \mathbb{R}^m)$ given by

$$\langle \mu, f \rangle := \int f \cdot d\mu, \quad f \in C_c(\mathbb{R}^n, \mathbb{R}^m).$$

The norm of the functional $\|\mu\|_{TV}$. More generally, for $\Omega \subset \mathbb{R}^n$ an open set, it follows from Lusin’s theorem [24] Cor. to Theorem 2.23, applied to the restriction of $u_\mu$ to “large” compact sets in $\Omega$, and from the dominated convergence theorem that

$$|\mu|(\Omega) = \sup \{ \langle \mu, \varphi \rangle, \varphi \in C_c(\Omega, \mathbb{R}^m), |\varphi| \leq 1 \}.$$

The functional $\mathcal{M}$ extends naturally with the same norm to the Banach space $C_0(\mathbb{R}^n, \mathbb{R}^m)$ of $\mathbb{R}^m$-valued continuous functions on $\mathbb{R}^n$ vanishing at infinity.

At places, we also identify $\mu$ with the restriction of $\mathcal{M}$ to $C^\infty(\mathbb{R}^n, \mathbb{R}^m)$, the space of $C^\infty$-smooth functions with compact support, equipped with the usual topology of test functions [25]. We refer to a continuous linear functional on $C^\infty(\mathbb{R}^n, \mathbb{R}^m)$ as being a distribution, and put $\partial_{x_i}$ to mean distributional derivative with respect to the variable $x_i$.

We denote Lebesgue measure on $\mathbb{R}^n$ by $\mathcal{L}_n$ and $d$-dimensional Hausdorff measure by $\mathcal{H}^d$, see [11] for the definitions. We normalize $\mathcal{H}^d$ for $d = 1$ and 2 so that it coincides with arclength and surface area for smooth curves and surfaces, and more generally that it agrees with $d$-dimensional volume for nice $d$-dimensional subsets of $\mathbb{R}^n$. We denote the Hausdorff dimension of a set $E$ by $\text{dim}_H(E)$. We say that $E \subset \mathbb{R}^n$ is $m$-rectifiable if it is the countable union of images of Lipschitz functions from $\mathbb{R}^m$ to $\mathbb{R}^n$, up to a set of $\mathcal{H}^m$-measure zero, see [24] Def. 15.3.

For $E \subset \mathbb{R}^n$ a measurable set and $1 \leq p \leq \infty$, we write $L^p(E)$ for the familiar Lebesgue space of (equivalence classes of $\mathcal{L}_n$-a.e. coinciding) real-valued measurable functions on $E$ whose $p$-th power is integrable, with norm $\|g\|_{L^p(E)} = (\int_E |g|^p d\mathcal{L}_n)^{1/p}$ (ess. sup$_E |g|$ if $p = \infty$). If $E$ is open, we set $L^1_{\text{loc}}(E)$ to consist of functions $f$ whose restriction $f|_K$ to $K$ lies in $L^1(K)$, for every compact $K \subset E$. Since $E = \bigcup K_n$ with $K_n$ compact, $L^1_{\text{loc}}(E)$ is a Fréchet space for the distance $d_1(f, g) = \sum_n 2^{-n}\|f - g\|_{L^1(K_n)}/(1 + \|f - g\|_{L^1(K_n)})$. For $\nu \in \mathcal{M}(\mathbb{R}^n)$ a positive measure different from $\mathcal{L}_n$, we put $L^1[\nu]$ for the space of real-valued integrable functions against $\nu$.

We are particularly concerned with magnetizations supported on $\mathbb{R}^2 \times \{0\} \subset \mathbb{R}^3$ and hence, with a slight abuse of notation, given $S \subset \mathbb{R}^2$ and $\mu \in \mathcal{M}(S \times \{0\})^3$, we shall identify $S$ with $S \times \{0\} \subset \mathbb{R}^3$ and $\mu$ with $\mu |(\mathbb{R}^2 \times \{0\})$. In addition, we let $\mathfrak{R}$ denote the rotation by $\pi/2$ in $\mathbb{R}^2$; i.e., $\mathfrak{R}(x_1, x_2)^T = (-x_2, x_1)^T$.

For an open set $\Omega \subset \mathbb{R}^n$, recall the space $BV(\Omega)$ of functions of bounded variation comprised of functions in $L^1(\Omega)$ whose distributional derivatives are signed measures on $\Omega$ (see, [24]). We let $BV_{\text{loc}}(\Omega)$ denote the space of functions whose restriction to any relatively compact open subset $\Omega_1$ of $\Omega$ lies in $BV(\Omega_1)$. We define the space $BV(\Omega)$ of “homogeneous” BV-functions to consist of
locally integrable functions whose distributional derivatives are finite signed measures on \( \Omega \). Note that \( \phi \in BV(\Omega) \) if and only if it is a distribution on \( \Omega \) such that \( \nabla \phi \in M(\Omega)^n \), by [10] Theorem 6.7.7. If \( \phi \in BV(\Omega) \), we see from (9) by mollification that

\[
\|
\nabla \phi \n\|_{TV} = \sup_{\psi \in C_c^1(\Omega, \mathbb{R}^n), |\psi| \leq 1} \int \psi \cdot d(\nabla \phi) = \sup_{\psi \in C_c^1(\Omega, \mathbb{R}^n), |\psi| \leq 1} \int \phi \nabla \cdot \psi \, d\mathcal{L}_2,
\]

where \( C_c^1(\Omega, \mathbb{R}^n) \) denotes the space of \( \mathbb{R}^n \)-valued continuously differentiable functions with compact support in \( \Omega \), see [11, Ch. 5].

2. Divergence-free measures on \( \mathbb{R}^n \)

We recall in this section the decomposition of divergence-free measures into elementary components obtained in [27]. We also point at additional properties of the elementary components, the proofs of which are appended in Appendix A to streamline the exposition.

2.1. Curves as measures. For \( a < b \) two real numbers, we call a Lipschitz mapping \( \gamma : [a, b] \to \mathbb{R}^n \) a \textit{parametrized rectifiable curve}, while the image \( \Gamma := \gamma([a, b]) \) is simply termed a (non-parametrized) \textit{rectifiable curve}. By Rademacher’s Theorem (see [11]), \( \gamma \) is differentiable a.e. on \( [a, b] \). Note that \( \gamma \) needs not be injective, i.e. the curve needs not be simple. If we let \( N(\gamma, x) \) be the cardinality (finite or infinite) of the preimage \( \gamma^{-1}(x) \), then the length \( \ell(\gamma) \) of \( \gamma \) is

\[
\ell(\gamma) := \int_a^b |\gamma'(t)| \, dt = \int N(\gamma, x) \, d\mathcal{H}^1(x),
\]

where the second equality follows from the area formula [14, 3.2.3]. In particular, \( \mathcal{H}^1(\Gamma) < \infty \) and \( \mathcal{H}^1 \)-almost every \( x \in \Gamma \) is attained only finitely many times by \( \gamma \). Observe that \( \ell(\gamma) \neq \mathcal{H}^1(\Gamma) \) in general. When \( |\gamma'(t)| = 1 \) a.e. on \([a, b]\), we call \( \gamma \) a unit speed parametrization. This means that \( \gamma \) parametrizes \( \Gamma \) (non injectively perhaps) by percursed arclength.

If \( \gamma \) is injective on \([a, b]\) and \( \gamma(a) = \gamma(b) \), we say that \( \gamma \) is a parametrized rectifiable Jordan curve and \( \Gamma \) a rectifiable Jordan curve; in this case \( \ell(\gamma) = \mathcal{H}^1(\Gamma) \). Given a Jordan curve \( \Upsilon \) (i.e. the image of a circle by an injective continuous map) such that \( \mathcal{H}^1(\Upsilon) < \infty \), one can easily construct a unit speed parametrization \( \gamma : [0, \mathcal{H}^1(\Upsilon)] \to \Upsilon \) which is injective on \([0, \mathcal{H}^1(\Upsilon)]\) with \( \gamma(0) = \gamma(\mathcal{H}^1(\Upsilon)) \). Thus, a Jordan curve \( \Upsilon \) is rectifiable if and only if \( \mathcal{H}^1(\Upsilon) < \infty \).

For \( \gamma : [a, b] \to \mathbb{R}^n \) a parametrized rectifiable curve, we define \( R_\gamma \in M(\mathbb{R}^n)^n \) by

\[
\langle R_\gamma, g \rangle := \int_a^b g(\gamma(t)) \cdot \gamma'(t) \, dt = \int_{\Gamma} \left( \sum_{t \in \gamma^{-1}(x)} g(x) \cdot \gamma'(t) \right) \, d\mathcal{H}^1(x), \quad g \in C_0(\mathbb{R}^n)^n,
\]

where the second equality follows from the area formula. Clearly, \( R_\gamma \) is supported on \( \Gamma \) and \( \|R_\gamma\|_{TV} \leq \ell(\gamma) \). If we define \( \psi : [a, b] \to [0, \ell(\gamma)] \) by \( \psi(t) = \int_a^t |\gamma'(\tau)| \, d\tau \), then \( \psi \) is Lipschitz with \( \psi'(t) = |\gamma'(t)| \) a.e. and there is a unit speed parametrization \( \tilde{\gamma} : [0, \ell(\gamma)] \to \Gamma \) such that \( \gamma = \tilde{\gamma} \circ \psi \), by the chain rule and Sard’s theorem for Lipschitz functions (see [23, Theorem 7.4]). Moreover, we see from the area formula that \( R_\gamma = R_{\tilde{\gamma}} \), so we assume unless otherwise stated that parametrized rectifiable curves are unit speed parametrizations.

By Lemma [A.1] \( R_\gamma \) is absolutely continuous with respect to \( \mathcal{H}^1|_\Gamma \) and has Radon-Nykodim derivative \( dR_\gamma / d(\mathcal{H}^1|_\Gamma)(x) = \sum_{t \in \gamma^{-1}(x)} \gamma'(t) \) at \( \mathcal{H}^1 \)-a.e. \( x \in \Gamma \). Hence, for every Borel set
$B \subset \mathbb{R}^n$, we have that

$$R_\gamma(B) = \int_{\Gamma \cap B} \left( \sum_{t \in \gamma^{-1}(x)} \gamma'(t) \right) d\mathcal{H}^{1}(x), \quad |R_\gamma|(B) = \int_{\Gamma \cap B} \left| \sum_{t \in \gamma^{-1}(x)} \gamma'(t) \right| d\mathcal{H}^{1}(x).$$

It may happen that $\|R_\gamma\|_{TV} < \ell(\gamma)$, because cancellation can occur in (12). To discard such cases, we consider for each $\ell > 0$ the collection $\mathcal{C}_\ell$ of those $R_\gamma$ associated to a parametrized rectifiable curve $\gamma$ of length $\ell$ that satisfy $\|R_\gamma\|_{TV} = \ell$. By Lemma A.2 we have that $R_\gamma \in \mathcal{C}_\ell$ if and only if $\Gamma$ has a well defined (oriented) unit tangent $\tau(x)$ at $\mathcal{H}^{1}$-a.e. $x$, given by $\gamma'(t)$ for any $t$ such that $\gamma(t) = x$. In this case, we note that (13) can be rewritten as

$$R_\gamma(B) = \int_{\Gamma \cap B} N(\gamma, x) \tau(x) d\mathcal{H}^{1}(x), \quad |R_\gamma|(B) = \int_{\Gamma \cap B} N(\gamma, x) d\mathcal{H}^{1}(x).$$

2.2. Decomposition of solenoids into curves. Since $\mathcal{M}(\mathbb{R}^n)^n$ is dual to $C_c(\mathbb{R}^n, \mathbb{R}^n)$ which is separable, the closed ball $B_\ell \subset \mathcal{M}(\mathbb{R}^n)^n$ centered at 0 of radius $\ell$ is a compact metrizable space when endowed with the weak-* topology. In particular, $\mathcal{C}_\ell$ equipped with the weak-* topology is a (non complete) metric space. Now, suppose that $\mu \in \mathcal{M}(\mathbb{R}^n)^n$ is a solenoid, i.e. that $\nabla \cdot \mu = 0$ (as a distribution). Then, it follows from [27] Theorem A that $\mu$ can be decomposed into elements from $\mathcal{C}_\ell$, meaning there is a positive finite Borel measure $\rho$ on $\mathcal{C}_\ell$ such that, for $\rho$-a.e. $\gamma$, the measure $R_\gamma$ is supported in $\supp \rho$ and

$$\langle \mu, g \rangle = \int_{\mathcal{C}_\ell} \langle R_\gamma, g \rangle d\rho(\gamma), \quad \langle |\mu|, \varphi \rangle = \int_{\mathcal{C}_\ell} \langle |R_\gamma|, \varphi \rangle d\rho(\gamma),$$

for all $g \in C_c(\mathbb{R}^n, \mathbb{R}^n)$ and $\varphi \in C_c(\mathbb{R}^n)$. Of course, by mollification, it is clear that (15) more generally holds for $g \in C_c(\mathbb{R}^n, \mathbb{R}^n)$ and $\varphi \in C_c(\mathbb{R}^n)$. By Lemma A.3 the two equalities in Equation (15) amount to say that, for each Borel set $B \subset \mathbb{R}^n$,

$$\mu(B) = \int_{\mathcal{C}_\ell} R_\gamma(B) d\rho(\gamma), \quad |\mu|(B) = \int_{\mathcal{C}_\ell} |R_\gamma|(B) d\rho(\gamma).$$

We note that (16) was used in the proof of [5] Theorem 2.6] without further justification.

The representation (15) is far from unique: for instance $\ell > 0$ was arbitrary. Moreover, the $R_\gamma$ need not be divergence-free even though $\mu$ is, i.e. the solenoid $\mu$ gets decomposed via (15) into elementary components $R_\gamma$ which may not be solenoids. In this connection, observe that $\nabla \cdot R_\gamma = \delta_{\gamma(b)} - \delta_{\gamma(a)}$ which vanishes only if $\gamma$ is a closed parametrized curve. In the next section, we discuss a more subtle decomposition of $\mu$, this time into divergence-free components, which is established in [27] Theorem B. In a sense, it is obtained by letting $\ell \to \infty$ in (15).

2.3. Decomposition of solenoids into elementary solenoids. In the terminology of [27], an elementary solenoid $T_f$ is a $\mathbb{R}^n$-valued measure associated to a Lipschitz function $f : \mathbb{R} \to \mathbb{R}^n$ with $|f'(t)| \leq 1$, acting on $\varphi \in C_c(\mathbb{R}^n)^n$ by the formula:

$$T_f(\varphi) = \lim_{s \to +\infty} \frac{1}{2s} \int_{-s}^{s} \varphi(f(t)) \cdot f'(t) dt,$$

where the existence of the limit is assumed for every $\varphi$ (for instance, it will exist if $f$ is periodic or quasi-periodic). In addition, it is required that $f(\mathbb{R}) \subset \operatorname{supp} T_f$ and that $\|T_f\|_{TV} = 1$. Letting $f_s := f|_{[-s, s]}$, we get with the notation of Section 2.1 that $T = *\lim R_{f_s}/(2s)$ as $s \to +\infty$, where $*\lim$ indicates the weak-*$\lim$ limit. It is clear from (17) that $\operatorname{supp} T_f \subset (\check{f}(\mathbb{R}))$, therefore the condition that $f(\mathbb{R}) \subset \operatorname{supp} T_f$ really means that $\operatorname{supp} T_f = \check{f}(\mathbb{R})$. Also, by Lemma A.3 we assume without
loss of generality that $|f'(t)| = 1$ a.e. on $\mathbb{R}$ in the definition of $T_f$. It is straightforward to check that $\nabla \cdot T_f = 0$, since $T_f(\nabla \Psi) = \lim_s (\Psi(f(s) - \Psi(f(-s))) / s = 0$ for any $\Psi \in C^1_0(\mathbb{R}^n)$. Hence, $T_f$ is indeed a solenoid. We denote by $\mathcal{S}(\mathbb{R}^n)$ the set of elementary solenoids on $\mathbb{R}^n$. Since it is contained in $B_1$, the set $\mathcal{S}(\mathbb{R}^n)$ is a metric space when endowed with the weak-$*$ topology.

It is more difficult to describe members of $\mathcal{S}(\mathbb{R}^n)$ than members of $\mathcal{C}_f$, but still their structure is reminiscent of (13) as we now indicate. Indeed, putting $\Gamma_s = f([-s, s])$ and $N(f, x, s)$ for the cardinality (finite or infinite) of those $t \in [-s, s]$ such that $f(t) = x$, let us define the normalized arclength of the parametrization $f_s : [-s, s] \to \mathbb{R}^n$ to be the measure on $\mathbb{R}^n$ given by

$$d\nu_s(x) := \frac{N(f, x, s)}{2s} d(\mathcal{H}^1 | \Gamma_s)(x).$$

From (11), we see that $\nu_s$ is a probability measure for each $s > 0$, and by Lemma A.3 the family $(\nu_s)_{s>0}$ converges weak-$*$, as $s \to +\infty$, to the probability measure $|T_f|$. Moreover, the Radon-Nykodim derivative $u_{T_f}$ extrapolates, in a sense made precise in that lemma, a limit of averaged tangents to $f(\mathbb{R})$. For instance, if $g_k$ is a sequence in $C_c(\mathbb{R}^n)$ such that $|g_k| \leq 1$ and $\lim_k g_k(x) = u_{T_f}(x)$ for $|T_f|$-a.e. $x \in \mathbb{R}^n$ (such a sequence exists by Lusin’s theorem), then to any real sequence $s_k \to +\infty$ there is a subsequence $s_j(k)$ such that (compare (95)):

$$\lim_{k \to \infty} \int \left| g_k(x) - \frac{\sum_{t \in f^{-1}(x), |t| \leq s_j(k)} f'(t)}{N(f, x, s_j(k))} \right|^2 d\nu_s(x) = 0.$$

A typical example is obtained when $f$ is a line winding on a torus with irrational slope. Then $|T_f|$ is the normalized area measure and $u_{T_f}$ is a continuous tangential vector field on the torus.

It is shown in [27] Theorem B that each $\mu \in \mathcal{M}(\mathbb{R}^k)^k$ with $\nabla \cdot \mu = 0$ can be expressed as

$$\langle \mu, \varphi \rangle = \int_{\mathcal{S}(\mathbb{R}^k)} \langle T, \varphi \rangle d\rho(T), \quad \varphi \in C_c(\mathbb{R}^n, \mathbb{R}^n),$$

for some positive Borel measure $\rho = \rho(\mu)$ on $\mathcal{S}(\mathbb{R}^k)$, in such a way that

$$\langle |\mu|, \varphi \rangle = \int_{\mathcal{S}(\mathbb{R}^k)} \langle |T|, \varphi \rangle d\rho(T).$$

Arguing as in Lemma A.3 one sees that (19) and (20) together are equivalent to

$$\mu(B) = \int_{\mathcal{S}(\mathbb{R}^k)} T(B) d\rho(T), \quad |\mu|(B) = \int_{\mathcal{S}(\mathbb{R}^k)} |T|(B) d\rho(T)$$

for every Borel set $B$, in particular supp $\mu$ is the restriction $\mu_0$ of $\mu$ to $\mathcal{S}(\mathbb{R}^k)$. In [27], the relations (19) and (20) are summarized by saying that a divergence-free measure can be completely decomposed into elementary solenoids.

It is not easy to describe in general those functions $f$ giving rise to a well-defined measure $T_f$ via (17). In dimension 3 already, these can have rather complex behaviour, see examples in [27] Sec. 1.3. However, in dimension 2, the decomposition (19) can be achieved using periodic $f$ parametrizing rectifiable Jordan curves: this follows from Theorem 4.3 in Section 4. In this connection, we note that if $f : \mathbb{R} \to \mathbb{R}^n$ satisfies $|f'| = 1$ a.e. and is periodic of period $L > 0$, then the limit in (17) does exist and in fact $T_f = R_\gamma / L$, where $\gamma : [0, L] \to \mathbb{R}^n$ is the restriction of $f_{[0,L]}$. Clearly then, we have that $\sup p T_f = \gamma([0, L]) = f(\mathbb{R})$, and in order that $T_f$ be an elementary solenoid it is necessary and sufficient that $|T_f| TV = 1$. This amounts to require that $\|R_\gamma\| TV = L$ or, equivalently, that $R_\gamma \in C_L$. By the discussion after (13), this is the case when $\gamma([0, L])$ is a rectifiable Jordan curve.
\( \mathbb{R}^3 \)-valued solenoids with planar support are of particular significance for our applications. The following elementary lemma, essentially contained in \([1]\), gives simple characterizations of such solenoids. We include a proof for the convenience of the reader. Recall the definition of \(BV\) and the notation \(\mathfrak{R}\) for the rotation by \(\pi/2\) in \(\mathbb{R}^2\).

**Lemma 2.1.** Let \( S \subset \mathbb{R}^2 \times \{0\} \) be closed, \( \mu = (\mu_1, \mu_2, \mu_3)^T \in \mathcal{M}(S)^3 \), and \( \mu_T = (\mu_1, \mu_2)^T \). The following are equivalent:

(a) \( \nabla \cdot \mu = 0 \) in the distributional sense on \( \mathbb{R}^3 \).
(b) \( \mu_3 = 0 \) and \( \nabla \cdot \mu_T = 0 \) in the distributional sense on \( \mathbb{R}^2 \).
(c) \( \mu_3 = 0 \) and \( \mu_T = \mathfrak{R} \nabla \phi = (-\partial_{x_2} \phi, \partial_{x_1} \phi)^T \) for some \( \phi \in BV(\mathbb{R}^2) \).

**Proof.** Since \( \mu \) has support contained in \( \mathbb{R}^2 \times \{0\} \), it can be written in tensor product form as \( \mu = (\mu|\mathbb{R}^2) \otimes \delta_{x_3=0} \) and thus \( \nabla \cdot \mu = (\nabla \cdot \mu_T) \otimes \delta_{x_3=0} + \mu_3 \otimes \delta'_{x_3=0} \), where \( \delta_{x_3=0} \) is the Dirac mass at zero on \( \mathbb{R} \) in the variable \( x_3 \) and \( \delta'_{x_3=0} \) its distributional derivative. Hence (b) implies that \( \nabla \cdot \mu = 0 \) and therefore (b) \( \Rightarrow \) (a). Next, for any \( \phi \in C_c^{\infty}(\mathbb{R}^2) \), let \( \phi_0, \phi_1 \in C_c^{\infty}(\mathbb{R}^2) \) be given by \( \phi_0(x_1, x_2) = \phi(x_1, x_2, 0) \) and \( \phi_1(x_1, x_2) = \partial_{x_3} \phi(x_1, x_2, 0) \). By the definition of distributional derivatives, we get that

\[
(\nabla \cdot \mu, \phi) = -\langle \mu_1, \partial_{x_1} \phi_0 \rangle - \langle \mu_2, \partial_{x_2} \phi_0 \rangle - \langle \mu_3, \phi_1 \rangle.
\]

Pick \( \phi \) of the form \( \phi(x_1, x_2, x_3) = \psi(x_1, x_2) \eta(x_3) \) where \( \psi \in C_c^{\infty}(\mathbb{R}^2) \) and \( \eta \in C_c^{\infty}(\mathbb{R}) \). First, letting \( \eta \) be such that \( \eta(0) = 1 \) and \( \eta'(0) = 0 \), we deduce from (22) that if \( \nabla \cdot \mu = 0 \) then \( \nabla \cdot \mu_T = 0 \). Second, letting \( \eta \) be such that \( \eta(0) = 0 \) and \( \eta'(0) = 1 \), we deduce from (22) again that if \( \nabla \cdot \mu = 0 \) then \( \mu_3 = 0 \). Hence, (a) \( \Rightarrow \) (b).

Suppose now that (b) holds. Then \( (\mu_2, \mu_1)^T \) satisfies the Schwartz rule when viewed as a \( \mathbb{R}^2 \)-valued distribution on \( \mathbb{R}^2 \); i.e, \( \partial_{x_2}(-\mu_2) = \partial_{x_1} \mu_1 \). Therefore, \( \mathfrak{R} \mu_T = (-\mu_2, \mu_1)^T \) is the gradient of a scalar valued distribution \( \Psi \) (see, \([20]\)). Since the components of \( \nabla \Psi \) are finite signed measures, \( \Psi \in BV_{\text{loc}}(\mathbb{R}^n) \) so that in fact \( \Psi \in BV(\mathbb{R}^2) \). Thus, (c) holds with \( \phi = -\Psi \) and we get that (b) \( \Rightarrow \) (c). In the other direction if \( \mu_T = (-\partial_{x_2} \phi, \partial_{x_1} \phi)^T \) for some distribution \( \phi \), then \( \nabla \cdot \mu_T = -\partial_{x_1} \partial_{x_2} \phi + \partial_{x_2} \partial_{x_1} \phi = 0 \) so that (c) \( \Rightarrow \) (b). \( \square \)

Lemma 2.1 entails that decomposing solenoids in the plane is equivalent, up to a rotation, to decomposing gradients. As surmised in \([27]\), the latter can be achieved via the co-area formula and the decomposition of the measure-theoretical boundary of sets of finite perimeter in \( \mathbb{R}^2 \) into rectifiable Jordan curves. In Section 3 to come, we derive a version of the co-area formula that applies to \(BV\)-functions (not just \(BV\)-functions), as we could not locate one in the literature; we also establish approximate continuity of \( M \)-connected components of sup-level sets of \(BV\)-functions (see Proposition 3.8 and Theorem 3.9), which is of independent interest and needed to handle measurability issues in the loop decomposition of planar divergence-free measures (see Proposition 4.6). Though we later lean on the planar case, it would be artificial to restrict to \( \mathbb{R}^2 \) in Section 3 and we shall present the material in \( \mathbb{R}^n \).

3. **Sup-level sets of functions in \(BV(\mathbb{R}^n)\) and the Co-area formula**

We begin with a summability property of homogeneous \(BV\)-functions.

**Lemma 3.1.** If \( \phi \in BV(\mathbb{R}^n) \) with \( n \geq 2 \), there is \( p \in \mathbb{R} \) such that \( \phi - p \in L^{n/(n-1)}(\mathbb{R}^n) \).

**Proof.** As noted in Section 12, \( \phi \) lies in \(BV_{\text{loc}}(\mathbb{R}^n)\). Thus, by localization and the Poincaré inequality for BV functions \([11\, \text{Theorem 5.10}]\), there is a constant \( K \) such that, for all open balls
\[ \mathbb{B} \subset \mathbb{R}^n, \]
\[ \| \phi - (\phi)_{\mathbb{B}} \|_{L^n/(n-1)(\mathbb{B})} \leq \mathcal{K} \| \nabla \phi \|_{TV}, \]
where \((\phi)_{\mathbb{B}} = \left( \int_{\mathbb{B}} \phi \, d\mathcal{L}_n \right) / \mathcal{L}_n(\mathbb{B})\) is the mean of \(\phi\) on \(\mathbb{B}\). Hence, for \(k, m \in \mathbb{N}\) with \(k < m\),
\[ (23) \quad \kappa_1^{(n-1)/n} k^{-1} n \| (\phi)_{\mathbb{B}(0,m)} - (\phi)_{\mathbb{B}(0,k)} \| \leq \| (\phi)_{\mathbb{B}(0,m)} - (\phi)_{\mathbb{B}(0,k)} \|_{L^n/(n-1)(\mathbb{B}(0,k))} \]
so that
\[ (24) \quad \partial_M E := \left\{ x \in \mathbb{R}^n : \limsup_{\rho \to 0} \frac{\mathcal{L}_n(\mathbb{B}(x, \rho) \cap E)}{\mathcal{L}_n(\mathbb{B}(x, \rho))} > 0 \text{ and } \limsup_{\rho \to 0} \frac{\mathcal{L}_n(\mathbb{B}(x, \rho) \setminus E)}{\mathcal{L}_n(\mathbb{B}(x, \rho))} > 0 \right\}. \]
Next, we collect several definitions and properties that are central to what follows. For \(E \subset \mathbb{R}^n\) a Borel set, the measure-theoretical boundary of \(E\) is the set \(\partial_M E\) defined by
\[ (25) \quad |\nabla \chi_E| = \mathcal{H}^{n-1}(\partial_M E), \]
and \(\| \nabla \chi_E \|_{TV} = \mathcal{H}^{n-1}(\partial_M E)\) is called the perimeter of \(E\), denoted as \(\mathcal{P}(E)\). The identity \((25)\) can be obtained by combining \([11] \text{ Theorem } 5.15 \ (\text{iii})\), which says that \((25)\) holds if \(\partial_M E\) gets replaced by the so-called reduced boundary of \(E\), with \([11] \text{ Lemma } 5.5\), asserting that \(\partial_M E\) differs from the reduced boundary by a set of \(\mathcal{H}^{n-1}\)-measure zero (see also \([3] \text{ Theorem } 10.3.2\)).

It follows from \((23)\) that \(\{ (\phi)_{\mathbb{B}(0,k)} \}_{k \in \mathbb{N}}\) is a Cauchy sequence, converging to some \(p \in \mathbb{R}\), and also that for every \(k \in \mathbb{N}\):
\[ |(\phi)_{\mathbb{B}(0,k)} - p| \leq 2 \mathcal{K} \| \nabla \phi \|_{TV} k^{(n-1)/n}, \]
so that
\[ \| \phi - p \|_{L^n/(n-1)(\mathbb{B}(0,k))} \leq \| \phi - (\phi)_{\mathbb{B}(0,k)} \|_{L^n/(n-1)(\mathbb{B}(0,k))} + \| p - (\phi)_{\mathbb{B}(0,k)} \|_{L^n/(n-1)(\mathbb{B}(0,k))} \leq 3 \mathcal{K} \| \nabla \phi \|_{TV} < \infty. \]
Therefore \(\phi - p \in L^n/(n-1)(\mathbb{R}^n)\), as desired. \(\square\)

Note that for any set \(E\), \(\partial_M E\) is a subset of the topological boundary of \(E\).

A measurable set \(E \subset \mathbb{R}^n\) such that \(\nabla \chi_E \in \mathcal{M}(\mathbb{R}^n)^n\) is said to be of finite perimeter.\(^1\) For such a set it holds that
\[ (25) \quad |\nabla \chi_E| = \mathcal{H}^{n-1}(\partial_M E), \]
and \(\| \nabla \chi_E \|_{TV} = \mathcal{H}^{n-1}(\partial_M E)\) is called the perimeter of \(E\), denoted as \(\mathcal{P}(E)\). The identity \((25)\) can be obtained by combining \([11] \text{ Theorem } 5.15 \ (\text{iii})\), which says that \((25)\) holds if \(\partial_M E\) gets replaced by the so-called reduced boundary of \(E\), with \([11] \text{ Lemma } 5.5\), asserting that \(\partial_M E\) differs from the reduced boundary by a set of \(\mathcal{H}^{n-1}\)-measure zero (see also \[3 \text{ Theorem } 10.3.2\]).

It follows from \((25)\) that a set of finite perimeter has a measure-theoretical boundary of finite \(\mathcal{H}^{n-1}\)-measure. In contrast, its Euclidean boundary can be much larger and even have positive \(\mathcal{L}_n\)-measure, as the following example shows when \(n = 2\).

\textbf{Example 3.1.} Let \(E_1 = \mathbb{B}(0,1) \subset \mathbb{R}^2\) and \(\{ q_j \}_{j \in \mathbb{N}}\) be a sequence of all points in \(E_1\) with rational coordinates. Having defined inductively a closed set \(E_n\) for \(n \geq 1\), let \(j_n\) be the smallest integer such that \(q_{j_n}\) lies interior to \(E_n\) and set \(B_n\) to be the largest open ball centered at \(q_{j_n}\) contained in \(E_n\), with radius \(r_n \leq 2^{-n}\) (at some steps \(B_n\) could be empty). Then, define \(E_{n+1} = E_n \setminus B_n\) which must be a closed set with nonempty interior, otherwise a finite union of balls of total \(\mathcal{L}_2\)-measure less than \(\pi/3\) would cover \(\mathbb{B}(0,1)\). Hence, the process can continue indefinitely, and we let \(E = \bigcap E_n\) which is a closed set.

\(^1\)In \([3 \ [11 \ [29]\), the definition is that \(\chi_E \in BV(\mathbb{R}^n)\). The present definition means that \(\chi_E \in BV(\mathbb{R}^n)\) and, in view of Lemma \([3 \ [1]\), amounts to requiring that either \(\chi_E\) or \(\chi_{\mathbb{R}^n \setminus E}\) lies in \(BV(\mathbb{R}^n)\).
Clearly $E$ has no interior, for all the $q_j$ have been excised out in the process; therefore its Euclidean boundary is $E$ itself. Moreover, $L_2(E) \geq \pi - \pi \sum_{n=1}^{\infty} r_n^2 \geq \pi (1 - \sum_{n=1}^{\infty} 4^{-n}) > 0$.

Now, by the standard Green formula, each $E_n$ is of finite perimeter, because it is a finitely connected set with piecewise smooth boundary. Thus, $\{\chi_{E_n}\}$ is a nonincreasing sequence of $BV$-functions and their point-wise limit $\chi_E$ is integrable. Also, by [25], it holds that $\|\nabla \chi_{E_n}\|_{TV} \leq 2\pi \sum_{n=0}^{\infty} r_n \leq 4\pi$, therefore we can use [29, Remark 5.2.2] to the effect that $\chi_E \in BV(\mathbb{R}^2)$, i.e. $E$ is a set of finite perimeter with Euclidean boundary of positive $L_2$-measure, as announced.

For any $E \subset \mathbb{R}^n$ of finite perimeter, we define the generalized unit inner normal $\nu_E$ to $\partial M E$ as the Radon-Nikodym derivative $u \chi_E$ which is but $d\chi_E/\partial M E$, by [25]. The Radon Nikodym Theorem then gives us the following version of the Gauss-Green formula:

**Lemma 3.2.** Let $E \subset \mathbb{R}^n$ be a set of finite perimeter. Then, for each Borel set $B \subset \mathbb{R}^n$,

$$\nabla \chi_E(B) = \int_B \nu_E \, d(H^{n-1}(\partial M E))$$

or, equivalently, $d\chi_E = \nu_E d(H^{n-1}(\partial M E))$ as measures on $\mathbb{R}^n$.

The connection with the classical Gauss-Green formula becomes transparent in the distributional version of (26), namely:

$$\int \chi_E \nabla \varphi \, d\mathcal{L}_n = - \int \varphi \cdot \nu_E \, d(H^{n-1}(\partial M E)), \quad \varphi \in C^1_c(\mathbb{R}^n, \mathbb{R}^n).$$

The identity (27) was initially proven in the works [8, 9] and [12, 13]. See also [11, Theorem 5.16] and [3, Theorem 10.3.2]. Note that if $E$ has finite perimeter, then so does $\mathbb{R}^n \setminus E$ and we have that $\nu_{\mathbb{R}^n \setminus E} = -\nu_E$.

**Remark.** When $n = 2$, we get in particular from (27) that $\nu_E$ coincides with the usual, differential-geometric inner unit normal to the boundary of $E \subset \mathbb{R}^2$ when the latter is a rectifiable Jordan curve, since in this case Green’s formula is valid for both definitions of the normal (see [2, Theorem 10–43] for a suitable version of the Green formula here). Actually, we will see in Lemma 4.3 that the measure-theoretical boundary of any planar set of finite perimeter is comprised of a countable union of rectifiable Jordan curves, up to a set of $H^1$-measure zero. Thus, both notions of inner unit normal coincide $H^1$-a.e. on the measure-theoretical boundary of such a set.

Whenever $\phi \in BV(\mathbb{R}^n)$, the suplevel sets

$$E_t := \{ x \in \mathbb{R}^n \mid \phi(x) > t \}$$

have finite perimeter for a.e. $t \in \mathbb{R}$ [11, Theorem 5.9]. Of course, the set $E_t$, as well as a number of subsequent sets in $\mathbb{R}^n$ that we will consider, is defined up to a set of $\mathcal{L}_n$-measure zero only, but which representative is chosen will be irrelevant for our purposes. Hereafter, we abbreviate the sentence “up to a set of $\mathcal{L}_n$-measure zero” by “mod-$\mathcal{L}_n$”, and similarly for $H^{n-1}$. The sup-level sets are a key ingredient of the co-area formula for $BV$-functions. In Theorem 3.6 to come, we give a version of this formula for homogeneous $BV$-functions (i.e. a Fleming-Rishel formula for $BV(\mathbb{R}^n)$). First, we need a couple of lemmas that will be used in the proof. We mention that these lemmas, as well as Theorem 3.6 itself, seem difficult to find in the literature.

If $\psi$ is a measurable function on a real interval $(a, b)$, its essential variation is defined as

$$\text{ess}V^b_a(\psi) := \sup \left\{ \sum_{i=1}^{k} |\psi(t_i) - \psi(t_{i-1})| \right\},$$
where the supremum is taken over all finite partitions $a < t_0 < t_1 < \cdots < t_k < b$ such that each $t_i$ is a point of approximate continuity of $\psi$, i.e. a point $x$ where $\psi$ is continuous on a set of density 1 at $x$. Approximate continuity points are of full $L^1$-measure on $(a, b)$ \[1\] Theorem 1.37). For instance, if $\psi \in L^1((a, b))$, Lebesgue points are approximate continuity points \[20\] Remark 4.4.5).

For $1 \leq i \leq n$ and $x = (x_1, \ldots, x_n)^T \in \mathbb{R}^n$, we let $\tilde{x}_i \in \mathbb{R}^{n-1}$ be the vector obtained by deleting $x_i$ from the list of components. For $\phi : \mathbb{R}^n \to \mathbb{R}$, we define the partial map $\phi_{\tilde{x}_i} : \mathbb{R} \to \mathbb{R}$ by $\phi_{\tilde{x}_i}(t) := \phi(x_1, \ldots, x_{i-1}, t, x_{i+1}, \ldots, x_n)$.

It follows from \[29\] Theorem 5.3.5] that if $\phi \in L^1_{\text{loc}}(\mathbb{R}^n)$, then $\phi \in BV_{\text{loc}}(\mathbb{R}^n)$ if and only if, for every bounded open rectangle $\Omega = (a_1, b_1) \times \cdots \times (a_n, b_n) \subset \mathbb{R}^n$, with partial rectangles

$$
\hat{\Omega}_i = (a_1, b_1) \times \cdots \times (a_{i-1}, b_{i-1}) \times (a_{i+1}, b_{i+1}) \times \cdots \times (a_n, b_n) \subset \mathbb{R}^{n-1}, \quad 1 \leq i \leq n,
$$

it holds that

$$
\int_{\hat{\Omega}_i} \text{ess} V^b_{\alpha i}(\phi_{\tilde{x}_i}) \, d\tilde{x}_i < \infty \quad \text{for } 1 \leq i \leq n.
$$

Moreover, if $\Omega'$ another bounded open rectangle such that $\overline{\Omega} \subset \Omega'$, the proofs of \[29\] Theorem 5.3.1] and \[29\] Theorem 5.3.5] show that

$$
|\partial x_i(\phi)(\Omega)| \leq \int_{\hat{\Omega}_i} \text{ess} V^b_{\alpha i}(\phi_{\tilde{x}_i}) \, d\tilde{x}_i \leq |\partial x_i(\phi)(\Omega')|.
$$

**Lemma 3.3.** If $\phi \in BV_{\text{loc}}(\mathbb{R}^n)$, then $\phi^+ = \max\{\phi, 0\}$ and $\phi^- = \max\{-\phi, 0\}$ belong to $BV_{\text{loc}}(\mathbb{R}^n)$. Furthermore, if $\Omega, \Omega'$, are two bounded open rectangles such that $\overline{\Omega} \subset \Omega'$, then

$$
|\nabla \phi^+|(\Omega) \leq \sqrt{n} |\nabla \phi|(\Omega').
$$

**Proof.** By \[30\] and \[31\], it is enough to prove that if $\psi$ is a real integrable function on a real interval $(a, b)$, then $\text{ess} V^b_{\alpha i}(\psi) \geq \text{ess} V^b_{\alpha i}(\psi^+)$. Consider a sum $\sum_{i=1}^k |\psi^+(t_i) - \psi^+(t_{i-1})|$ where the $t_i$ are approximate continuity points of $\psi^+$, and assume without loss of generality that $\psi^+$ does not vanish at two consecutive $t_i$. If $\psi^+(t_i) > 0$, then $t_i$ is an approximate continuity point of $\psi$ and $\psi^+(t_i) = \psi(t_i)$. If on the contrary $\psi^+(t_i) = 0$, then either we can find a Lebesgue point $\tau_i$ of $\psi$ in $(t_{i-1}, t_{i+1})$ with $\psi(\tau_i) < 0$ (we set $t_{-1} = a$ and $t_{k+1} = b$), in which case $|\psi(\tau_i) - \psi(t_{i+1})| > |\psi^+(t_i) - \psi^+(t_{i+1})|$ and $|\psi(\tau_i) - \psi(t_{i-1})| > |\psi^+(t_i) - \psi^+(t_{i-1})|$ (if $i = 1$ or $k$ we ignore the inequality involving $a$ or $b$), or else $\psi = \psi^+$ a.e. in $(t_{i-1}, t_{i+1})$ and in particular $t_i$ is an approximate continuity point of $\psi$ with $\psi(t_i) = 0$. Altogether, replacing $\psi^+(t_i)$ by $\psi(t_i)$ or by $\psi(\tau_i)$ at those $i$ such that $\psi^+(t_i) = 0$, and $\tau_i$ can be found as above, we form a sum of the type indicated in \[29\] which is no less that $\sum_{i=1}^k |\psi^+(t_i) - \psi^+(t_{i-1})|$. This achieves the proof. \[\square\]

**Lemma 3.4.** If $\phi \in BV(\mathbb{R}^n)$, then its sup-level set $E_t$ has finite perimeter for a.e. $t \in \mathbb{R}$.

**Proof.** By Lemma \[31\] we may assume that $\phi \in L^{n/(n-1)}(\mathbb{R}^n)$. Then, for any $s > 0$, we have that $L_n(E_s) < \infty$. By Lemma \[32\], the function $\tilde{\phi}$ which is $\phi - s$ on $E_s$ and 0 elsewhere lies in $BV_{\text{loc}}(\mathbb{R}^n)$, and since $\tilde{\phi}$ is integrable by Hölder’s inequality inequality, it belongs to $BV(\mathbb{R}^n)$. Now, for every $t > s$, $E_t$ is the sup-level set of $\tilde{\phi}$ at level $t - s$, and hence, for a.e. $t > s$ it has finite perimeter. So, if we consider a sequence $s_n \to 0$, we find by countable additivity of sets of measure zero that $E_t$ has finite perimeter for a.e. $t > 0$.

Analogously, for any $s < 0$, the function $\tilde{\phi}$ which is $\phi - s$ on $\mathbb{R}^n \setminus E_s$ and zero elsewhere, lies in $BV(\mathbb{R}^n)$ and its sup-level set at level $t - s$ coincides with $E_t$ for any $t < s$. Hence, for a.e. $t < 0$, $E_t$ has finite perimeter as well. \[\square\]
Lemma 3.4 implies that for a.e. \( t \in \mathbb{R} \) and \( E_t \) as in (28), the measures \( \nabla \chi_{E_t} \) and \( |\nabla \chi_{E_t}| \) are well defined in \( \mathcal{M}(\mathbb{R}^n)^n \) and \( \mathcal{M}(\mathbb{R}^n) \), respectively. Since the mapping from \( \mathbb{R}^n \times \mathbb{R} \) into \( \mathbb{R} \) defined by \( (x,t) \to \chi_{E_t}(x) \) is clearly measurable, we see as in [11] Lemma 5.1 that for each Borel set \( B \subset \mathbb{R}^n \) the map \( t \to |\nabla \chi_{E_t}(B) | \) is Lebesgue measurable, from which it follows easily, on approximating the components of \( \nu_{E_t} \) by simple functions pointwise almost everywhere with respect to \( |\nabla \chi_{E_t}| \), that \( t \to |\nabla \chi_{E_t}(B) | \) is measurable as well. Thus, the integrals in the next lemma and theorem do indeed make sense. When \( \phi \in BV(\mathbb{R}^n) \), Lemma 3.5 below can be found in [3] Theorem 10.3.3 and is known as the Fleming-Rishel formula, see [15]. In the statement, it is understood that if \( \nu \) is a positive measure and \( f \) a real-valued \( \nu \)-measurable function, then \( f \) is \( \nu \)-integrable if at least one of the functions \( f^+ := \max \{ f, 0 \} \) and \( f^- := \min \{ f, 0 \} \) has finite integral against \( \nu \).

**Lemma 3.5.** If \( \phi \in BV(\mathbb{R}^n) \), and if for \( t \in \mathbb{R} \) we define \( E_t \) as in (28), then

\[
\int f d|\nabla \phi| = \int_{-\infty}^{\infty} \int f d|\nabla \chi_{E_t}| dt \quad \text{for each } |\nabla \phi| \text{-integrable Borel function } f.
\]

Moreover, it holds that

\[
\int \varphi \cdot d(\nabla \phi) = \int_{-\infty}^{\infty} \int \varphi \cdot d(\nabla \chi_{E_t}) dt \quad \text{for each } \varphi \in C^1_c(\mathbb{R}^n, \mathbb{R}^n).
\]

**Proof.** By Lemma 3.4 we may assume that \( \phi \in L^{n/(n-1)}(\mathbb{R}^n) \). Arguing as in the proof of Lemma 3.3 the function \( \phi_k \) equal to \( \phi - 1/k \) on \( E_{1/k} \), to \( \phi + 1/k \) on \( \mathbb{R}^2 \setminus E_{1/k} \), and to zero elsewhere belongs to \( BV(\mathbb{R}^n) \) for each integer \( k \geq 1 \). Denoting by \( E^k \) the sup-level sets of \( \phi_k \) and applying [3] Theorem 10.3.3 to the latter, we get that (33) and (34) hold with \( \phi_k \) instead of \( \phi \) and \( E_t \) replaced by \( E^k_t \). By inspection, these equalities can be rewritten as

\[
\int f d|\nabla \phi_k| = \int_{-\infty}^{-1/k} \int f d|\nabla \chi_{E^k_t}| dt + \int_{1/k}^{\infty} \int f d|\nabla \chi_{E^k_t}| dt
\]

and

\[
\int \varphi \cdot d(\nabla \phi_k) = \int_{-\infty}^{-1/k} \int \varphi \cdot d(\nabla \chi_{E^k_t}) dt + \int_{1/k}^{\infty} \int \varphi \cdot d(\nabla \chi_{E^k_t}) dt.
\]

On the one hand, since \( \phi_k \) converges pointwise to \( \phi \) as \( k \to \infty \) and \( |\phi_k| \leq |\phi| \) while \( \phi \in L^1_{loc}(\mathbb{R}^n) \), we get by dominated convergence that for each \( \varphi \in (C^1_c(\mathbb{R}^n))^n \)

\[
\lim_{k \to \infty} \int \varphi \cdot d(\nabla \phi_k) = - \lim_{k \to \infty} \int \phi_k \nabla \cdot \varphi = - \int \varphi \nabla \cdot \varphi = \int \varphi \cdot d(\nabla \phi).
\]

On the other hand, since \( \phi_k = (\phi - 1/k)^+ + (\phi + 1/k)^- \), we have that \( \|\nabla \phi_k\|_{TV} \leq 2\sqrt{n}\|\nabla \phi\|_{TV} \) for each \( k \), by (32). Thus, choosing \( f \equiv 1 \) in (35), we see that \( t \to \|\nabla \chi_{E^k_t}\|_{TV} \) is integrable over \( \mathbb{R} \). Now, taking into account (37) and the fact that \( \int \varphi \cdot d(\nabla \chi_{E_t}) \leq \sup |\varphi||\nabla \chi_{E_t}|_{TV} \), we obtain (34) on applying the dominated convergence theorem to the right hand side of (36).

Next, pick \( \varepsilon > 0 \) and \( k_\varepsilon \) so large that

\[
\int_{-1/k}^{1/k} \|\nabla \chi_{E^k_t}\|_{TV} dt < \varepsilon, \quad k \geq k_\varepsilon.
\]

Let \( \Omega \subset \mathbb{R}^n \) be open and choose \( \varphi_k \in C^1_c(\Omega)^n \) with \( |\varphi_k| \leq 1 \) such that (see (10))

\[
\int \varphi_k \cdot d\nabla \phi_k \geq \|\nabla \phi_k\|_{TV} - \varepsilon.
\]
If we fix \( k \geq k_\varepsilon \), we get by (37) and (36) that
\[
\| (\nabla \phi) |\Omega \|_{TV} \geq \int \varphi_k \cdot d\nabla \phi = \lim_{m \to \infty} \int \varphi_k \cdot d\nabla \phi_m
\]
\[
= \lim_{m \to \infty} \left( \int_{-1/m}^{1/m} \int \varphi_k \cdot d(\nabla \chi_{E_t}) \, dt + \int_{1/m}^{\infty} \int \varphi_k \cdot d(\nabla \chi_{E_t}) \, dt \right)
\]
\[
\geq \int_{-1/k}^{-1/k} \int \varphi_k \cdot d(\nabla \chi_{E_t}) \, dt + \int_{1/k}^{\infty} \int \varphi_k \cdot d(\nabla \chi_{E_t}) \, dt - \varepsilon
\]
where the second inequality uses (38) and the last uses (39). As \( \varepsilon \) was arbitrary and the above inequality holds for all \( k \geq k_\varepsilon \), we deduce that
\[
\| (\nabla \phi) |\Omega \|_{TV} \geq \limsup_k \| (\nabla \phi_k) |\Omega \|_{TV}.
\]
However, from [29, Theorem 5.2.1] we know that \( \| \nabla \phi |\Omega \|_{TV} \leq \liminf_k \| (\nabla \phi_k) |\Omega \|_{TV} \) because \( \phi_k \to \phi \) in \( L_{loc}^1(\mathbb{R}^n) \). Hence, we get for any open set \( \Omega \subset \mathbb{R}^n \) that
\[
(40) \quad \lim_{k \to \infty} \| \nabla \phi_k |\Omega \| = \| \nabla \phi |\Omega \|
\]
which implies, on applying the monotone convergence theorem to the right hand side of (35), that (33) holds when \( f = \chi_B \). Thus, if we restrict to \( f \) of the form \( \chi_B \) where \( B \) ranges over Borel sets, the two sides of (33) define finite positive Borel measures on \( \mathbb{R}^n \) which coincide on open sets, therefore they are one and the same Borel measure, by regularity. Consequently (33) holds for simple functions \( f \), therefore also for positive Borel functions by monotone convergence. The case of \( |\nabla \Phi| \)-integrable Borel functions follows from this.

We next obtain a version of the co-area (or Fleming-Rishel) formula for \( BV \)-functions.

**Theorem 3.6.** Suppose \( \phi \in BV(\mathbb{R}^n) \) and let \( E_t \) be as in (28). Then, for any Borel set \( B \subset \mathbb{R}^n \), \( g \in L^1[d|\nabla \phi|] \) and \( h \in L^1[d|\nabla \phi|] \), it holds that
\[
(\text{a}) \quad |\nabla \phi| (B) = \int_{-\infty}^{\infty} |\nabla \chi_{E_t}| (B) \, dt = \int_{-\infty}^{\infty} \mathcal{H}^{n-1}(\partial_M E_t \cap B) \, dt,
\]
\[
(\text{b}) \quad \int B h \, d(\nabla \phi) = \int_{-\infty}^{\infty} \int_B h \, d(\nabla \chi_{E_t}) \, dt = \int_{-\infty}^{\infty} \int_B h \, d(\mathcal{H}^{n-1}(\partial_M E_t)) \, dt,
\]
\[
(\text{c}) \quad \nabla \phi (B) = \int_{-\infty}^{\infty} \nabla \chi_{E_t} (B) \, dt = \int_{-\infty}^{\infty} \int_B \nu_E, d(\mathcal{H}^{n-1}(\partial_M E_t)) \, dt,
\]
\[
(\text{d}) \quad \int_B g \cdot d(\nabla \phi) = \int_{-\infty}^{\infty} \int_B g \cdot d(\nabla \chi_{E_t}) \, dt = \int_{-\infty}^{\infty} \int_B g \cdot \nu_E, d(\mathcal{H}^{n-1}(\partial_M E_t)) \, dt,
\]
where in (b) the function \( h \) lies in both \( L^1[d|\nabla \chi_{E_t}|] \) and \( L^1[d\mathcal{H}^{n-1}(\partial_M E_t)] \) for a.e. \( t \) and in (d) the functions \( g \) and \( g \cdot \nu_E \) lie in \( L^1[d|\nabla \chi_{E_t}|] \) and \( L^1[d\mathcal{H}^{n-1}(\partial_M E)] \), respectively, for a.e. \( t \).

**Proof.** Taking \( f = \chi_B \) in (33) implies the first equality in (a), and the second one is just the combination with (25). To show the first equality in (c), we apply Lusin’s theorem to the effect that \( \chi_B \) is the bounded pointwise limit of a sequence \( \varphi_k \in C_c(\mathbb{R}^n) \), except on a Borel set \( E \) of \( |\nabla \phi| \)-measure zero. From the first equality in (a) we get \( |\nabla \chi_{E_t}| (E) = 0 \) for a.e. \( t \), and for such \( t \) it holds by dominated convergence that if we pick \( v \in \mathbb{R}^n \), then \( \lim_k \int \varphi_k \cdot d(\nabla \chi_{E_t}) = v \cdot \nabla (\chi_{E_t})(B) \).

Since \( v \) is arbitrary in \( \mathbb{R}^n \), the first equality in (c) now follows from (44), applied with \( \varphi = \varphi_k v \).
by invoking the dominated convergence theorem when \( k \to \infty \) in \( L^1[|d\nabla \phi|] \) on the left hand side, and in \( L^1(\mathbb{R}) \) on the right hand side. The second equality in (c) ensues from (24).

Next, (a) yields (b) for simple functions, and the case of \( C_c(\mathbb{R}^n) \)-functions follows by uniform approximation, using (a). The case of bounded \( |\nabla \phi| \)-measurable functions can now be obtained from Lusin’s Theorem and dominated convergence, using (a) to ascertain that a Borel set \( B \) such that \(|\nabla \phi|(B) = 0\) has \(|\nabla \chi_E| (B) = 0\) and \( H^{n-1} |\partial_M E_t(B) = 0\) for a.e. \( t \). The general case follows by monotone convergence. That (c) implies (d) follows similarly, proceeding componentwise to pass from continuous \( g \) to the case where \( g \in L^1[|d\nabla \phi|] \) (compare the proof of Lemma A.3).

With this version of the co-area formula it is now possible to give a description of the “measure theoretical discontinuities” of \( BV \)-functions. For a Borel function \( f \) on \( \mathbb{R}^n \) and any \( x \in \mathbb{R}^n \) we define (see [11, Def. 5.8, 5.9]):

\[
\begin{align*}
    f^{\sup}(x) &:= \text{ap lim sup}_{y \to x} f(y) = \inf \left\{ t \mid \lim_{r \to 0} \frac{\mathcal{L}_n(\mathbb{B}(x,r) \cap \{ \phi > t \})}{\mathcal{L}_n(\mathbb{B}(x,r))} = 0 \right\}, \\
    f^{\inf}(x) &:= \text{ap lim inf}_{y \to x} f(y) = \sup \left\{ t \mid \lim_{r \to 0} \frac{\mathcal{L}_n(\mathbb{B}(x,r) \cap \{ \phi < t \})}{\mathcal{L}_n(\mathbb{B}(x,r))} = 0 \right\}, \\
    J(f) &:= \left\{ x \mid f^{\inf}(x) < f^{\sup}(x) \right\}. 
\end{align*}
\]

Lemma 3.7. Given \( \phi \in BV(\mathbb{R}^n) \), the set \( J(\phi) \) is \((n-1)\)-rectifiable. Furthermore, \( \nabla \phi | J(\phi) \) is absolutely continuous with respect to \( H^1 \) and, with \( E_t \) as in (23), its Radon-Nykodim derivative satisfies for a.e. \( t \in \mathbb{R} \) and \( H^{n-1} \cdot \text{a.e. } x \in \partial_M E_t \cap J \cdot d\nabla \phi / dH^{n-1} = (f^{\sup} - f^{\inf}) \nu_{E_t} \).

Proof. The first assertion of the lemma follows by arguing as in the proof of [11, Theorem 5.17], using the co-area formula from Theorem 3.6. For \( \Omega \subset \mathbb{R}^n \) an arbitrary bounded open set, the restriction \( \phi|\Omega \) lies in \( BV(\Omega) \). By [3, Remark 10.3.4, Theorem 10.4.1] we obtain the second assertion when \( \phi \) gets replaced with \( \phi|\Omega \) and \( E_t \) by \( E_t' := E_t \cap \Omega \) (the \( t \)-superlevel set of \( \phi|\Omega \)). As \( \Omega \) is arbitrary, the result for \( \phi \) now follows by noticing that \( (\nabla \phi)|\Omega = \nabla (\phi|\Omega) \) and that for each \( t \) such that \( \partial_M E_t \) has finite perimeter in \( \mathbb{R}^n \) and intersects \( \Omega \), then \( \nu_{E_t} = \nu_{E_t'} \) on \( \Omega \).

Our next result relies on the work in [1]. Recall that a set \( E \subset \mathbb{R}^n \) with finite perimeter is called indecomposable if it cannot be partitioned as \( E = F_1 \cup F_2 \) with \( \mathcal{L}_n(F_i) > 0 \) for \( i = 1, 2 \) and \( \mathcal{P}(F_1) + \mathcal{P}(F_2) = \mathcal{P}(E) \). Every set \( E \) of finite perimeter can be partitioned as a countable union \( \cup_i C_i \), where the \( C_i \) are indecomposable with \( \mathcal{L}_n(C_i) > 0 \) for each \( i \) and \( \sum_i \mathcal{P}(C_i) = \mathcal{P}(E) \). Such a partition is unique mod-\( \mathcal{L}_n \), and the \( C_i \) are called the \( M \)-connected components of \( E \); moreover, if \( F \subset E \) and \( F \) is indecomposable, then \( F \subset C_i \) mod-\( \mathcal{L}_n \) for some \( i \), see [1, Theorem 1].

There is no natural way to order the \( M \)-connected components of a set \( E \) of finite perimeter, but we can enumerate them so that their \( \mathcal{L}_n \)-measures are nonincreasing; of course, several orderings with this property will exist if distinct components have the same measure. Also, if \( E \) has finitely many \( M \)-connected components, it is convenient to append to them a countable infinity of spurious components having \( \mathcal{L}_n \)-measure zero (therefore also zero perimeter). This will allow us to consistently index the \( M \)-connected components over \( \mathbb{N} \), regardless whether the set under consideration has finitely many nontrivial components or not.

Formally, let \( \mathcal{S} \) be the set of sequences \((F_i)_{i \in \mathbb{N}}\) of subsets of \( \mathbb{R}^n \) mod-\( \mathcal{L}_n \) such that \( \mathcal{L}_n(F_i) \geq \mathcal{L}_n(F_{i+1}) \) and \( \lim_i \mathcal{L}_n(F_i) = 0 \). We say that two elements \((F_i)_{i \in \mathbb{N}}, (F'_i)_{i \in \mathbb{N}}\) of \( \mathcal{S} \) are equivalent if there is bijection \( \sigma : \mathbb{N} \to \mathbb{N} \) such that \( F_{\sigma(i)} = F'_i \) for all \( i \) mod \( \mathcal{L}_n \). We denote by \( \tilde{\mathcal{S}} \) the set of equivalence classes. For \( E \) a set of finite perimeter and \( C_0, C_1, C_2, \ldots \) a list of its \( M \)-connected
components, arranged so that their $\mathcal{L}_n$ measures are nonincreasing, we consider $(C_i)_{i \in \mathbb{N}}$ as (a representative of) an element of $\mathcal{S}$. If $\mathcal{L}_n(E) < \infty$, then clearly $\mathcal{L}_n(C_i) < \infty$ for all $i$, and if $\mathcal{L}_n(E) = \infty$, then $C_0$ is the only component with infinite $\mathcal{L}_n$-measure [1, Rem. 1]. In particular, since $\sum_i \mathcal{P}(C_i) = \mathcal{P}(E)$, we have indeed that $\lim_i \mathcal{L}_n(C_i) = 0$, by the isoperimetric inequality (see e.g. [11, Theorem 5.11]). Of course, $(C_i)_{i \in \mathbb{N}}$ is a rather special element of $\mathcal{S}$, because the $C_i$ are pairwise disjoint mod-$\mathcal{L}_n$ and the $\partial_M C_i$ are pairwise disjoint mod-$\mathcal{H}^{n-1}$ (see [11, Proposition 3])

We now record an extremal property of $M$-connected components. Fix $\alpha \in (1, n/(n - 1))$ and, for any measurable set $F \subset \mathbb{R}^n$, set $G(F) := \int_F e^{-|x|^2} dx \alpha$. If $E$ has finite perimeter, then its $M$-connected components are the unique solution of

$$\max \left\{ \sum_{i \in \mathbb{N}} G(F_i) : (F_i)_{i \in \mathbb{N}} \in \mathcal{S}, \text{ the } F_i \text{ partition } E, \sum_{i \in \mathbb{N}} \mathcal{P}(F_i) \leq \mathcal{P}(E) \right\},$$

see the proof of [1, Theorem 1].

Recall the notion of local convergence in measure for sets of finite perimeter, which is just the $L_{loc}$-convergence of their characteristic function. Any sequence of sets with uniformly bounded perimeters has a subsequence converging locally in measure, and the perimeter is lower semi-continuous for this type of convergence, see e.g. [20, Proposition 3.6 & Theorem 3.7].

**Proposition 3.8.** Let $\phi \in BV(\mathbb{R}^n)$ and $E_t$ be as in [28]. For $t$ such that $E_t$ has finite perimeter, let $(C_{i0}^t, C_{i1}^t, C_{i2}^t, \cdots) \in \mathcal{S}$ be (a representative of) the $M$-connected components of $E_t$. To each $\eta > 0$, there is a $\sigma$-compact set $\Sigma_\eta \subset \mathbb{R}$, with $\mathcal{L}_1(\mathbb{R} \setminus \Sigma_\eta) < \eta$, having the following properties.

(i) For each $t \in \Sigma_\eta$, it holds that $E_t$ has finite perimeter.

(ii) If $(t_m)_{m \geq 1}$ is a sequence in $\Sigma_\eta$ converging to $t_0 \in \Sigma_\eta$, there is a subsequence $(t_{m_j})$ such that $C_{i_{m_j}}^t$ converges locally in measure, for fixed $i$ as $j \to \infty$, to a set $F_i \subset \mathbb{R}^n$ of finite perimeter, and the sequence $(F_0, F_1, F_2, \cdots)$ is equivalent to $(C_{i0}^0, C_{i1}^0, C_{i2}^0, \cdots)$ in $\mathcal{S}$.

(iii) It holds that $\lim_j \mathcal{L}_n((C_{i_{m_j}}^t \setminus F_i) \cup (F_i \setminus C_{i_{m_j}}^t)) = 0$ and $\lim_j \mathcal{P}(C_{i_{m_j}}^t) = \mathcal{P}(F_i)$ for each $i$.

(iv) One has the limiting relations:

$$\lim_{p \to \infty} \limsup_{j} \sum_{i \geq p} \mathcal{P}(C_{i_{m_j}}^t) = 0, \quad \text{and} \quad \lim_{p \to \infty} \limsup_{j} \sup_{i \geq p} \mathcal{L}_n(C_{i_{m_j}}^t) = 0.$$

**Proof.** By Lemma 3.11 we may assume that $\phi \in L^{n/(n-1)}(\mathbb{R}^n)$. For $t \in \mathbb{R}$, let us define $M(t) := \lim_{t \to 0} \mathcal{L}_n(\{x: t - \epsilon < \phi(x) \leq t + \epsilon\})$. If we fix $k \in \mathbb{N}^*$, every finite sequence $t_1, \cdots, t_\ell$ with $1/k < t_1 < t_2 < \cdots < t_\ell$ is such that $M(t_i) \leq k^{n/(n-1)} \|\phi\|_{L^{n/(n-1)}(\mathbb{R}^n)}$. Hence, the set of $t > 0$ such that $M(t) > 0$ is at most countable, and the same holds for $t < 0$. Let $N \subset \mathbb{R}$ be a countable set with $0 \in N$ such that $M(t) = 0$ for $t \notin N$. Let further $Z \subset \mathbb{R}$ be a Borel set of measure zero such that $E_t$ has finite perimeter for $t \notin Z$, see Lemma 3.4. It follows from Theorem 3.6 (a) that the map $t \mapsto \mathcal{P}(E_t)$ is integrable on $\mathbb{R}$ and therefore, by Lusin’s theorem and the regularity of $\mathcal{L}_1$, for each integer $k \geq 1$ we can find a compact set $K_k \subset [-k, k]$, with $K_k \cap (Z \cup N) = \emptyset$ and $\mathcal{L}_1([-k, k] \setminus K_k) < 1/k^2$, such that $t \mapsto \mathcal{P}(E_t)$ is continuous $K_k \to \mathbb{R}$. Define $\Sigma := \cup_{k \neq k'} (K_k \cap K_{k'})$, and observe that it is a $\sigma$-compact set such that $\mathcal{L}_1(\mathbb{R} \setminus \Sigma) = 0$, because a.e. $t \in \mathbb{R}$ belongs to only finitely many sets $[-k, k] \setminus K_k$, by the Borel-Cantelli lemma; hence, a.e. $t$ belongs to all but finitely many $K_k$, and therefore also to $\Sigma$.

We claim that the restriction of $t \mapsto \mathcal{P}(E_t)$ to $\Sigma$ is continuous. Otherwise indeed, there would be a sequence $t_m$ in $\Sigma$, converging to $t_0 \in \Sigma$, such that

$$|\mathcal{P}(E_{t_m}) - \mathcal{P}(E_{t_0})| > \epsilon > 0 \quad \text{for all } m.$$
Since by construction \( t \mapsto \mathcal{P}(E_t) \) is continuous on \( K_k \) which is compact, it would imply that each \( K_k \) contains at most finitely many \( t_m \), for if not a subsequence \( t_{m_j} \) would converge in some \( K_{k_0} \) to a number \( t \in K_{k_0} \), which can be none but \( t_0 \), and \( \mathcal{P}(E_{t_{m_j}}) \) would converge to \( \mathcal{P}(E_{t_0}) \) which is impossible by (14). Hence, replacing \( (t_m) \) with a subsequence if necessary, we may assume that each \( t_m \) belongs to at most one \( K_k \). However, by definition of \( \Sigma \), \( t_m \) must belong to two of them at least, a contradiction which proves the claim.

Let \( N_1 \) denote the norm of \( t \mapsto \mathcal{P}(E_t) \) in \( L^1(\mathbb{R}) \), and set \( \Sigma_\eta := \{ t \in \Sigma, \mathcal{P}(E_t) \leq N_1/\eta \} \). By construction, \( \Sigma_\eta \) is \( \sigma \)-compact and \( \mathcal{L}_1(\mathbb{R} \setminus \Sigma_\eta) < \eta \). Note that \( \Sigma_\eta \cap Z = 0 \), therefore (i) holds.

Now, let \( t_m \to t_0 \) in \( \Sigma_\eta \). As \( t_0 \neq 0 \) (for \( 0 \notin \Sigma_\eta \)) and \( \phi \in L^{n/(n-1)}(\mathbb{R}^n) \), either \( t_0 > 0 \) in which case \( \mathcal{L}_n(E_{t_0}) < \infty \), or else \( t_0 < 0 \) in which case \( \mathcal{L}_n(E_{t_0}) = \infty \). In the former (resp. latter) case, we may assume that \( t_m > 0 \) (resp. \( t_m < 0 \)), and then \( \mathcal{L}_n(E_{t_{m_j}}) < \infty \) (resp. \( \mathcal{L}_n(E_{t_{m_j}}) = \infty \)) for all \( m \). By the boundedness of \( t_m \mapsto \mathcal{P}(E_{t_{m_j}}) = \sum_i \mathcal{P}(C_i^{t_{m_j}}) \) (since \( t \mapsto \mathcal{P}(E_t) \) is bounded on \( \Sigma_\eta \) by construction), we get that \( \mathcal{P}(C_i^{t_{m_j}}) \) is bounded independently of \( i \) and \( m \), hence for each \( i \) some subsequence \( C_i^{t_{m_j}} \) converges locally in measure to a set \( F_i \) of finite perimeter. Using a diagonal argument, we may assume that \( t_{m_j}^{(i)} = t_{m_j} \) is independent of \( i \), and that \( C_i^{t_{m_j}} \) converges locally in measure to \( F_i \) for each \( i \geq 0 \). Next, recall from (42) the definition of \( G \) and let us prove that

\[
\lim_{p \to \infty} \limsup_{j} \sum_{i=p}^{\infty} G(C_i^{t_{m_j}}) = 0.
\]

For this, we adapt the argument of (11) proof of Eqn. (12): from the isoperimetric inequality (recall \( \mathcal{L}_n(C_i^{t_{m_j}}) < \infty \) for \( i \geq 1 \)) and the subadditivity of perimeter, we get for each \( p \geq 1 \) and some dimensional constant \( \gamma_n \) that

\[
p^{\frac{n-1}{\alpha}} \mathcal{L}_n^{\frac{n-1}{n}}(C_i^{t_{m_j}}) \leq \mathcal{L}_n^{\frac{n-1}{n}} \left( \bigcup_{i=1}^{p} C_i^{t_{m_j}} \right) \leq \gamma_n \sum_{i=1}^{p} \mathcal{P}(C_i^{t_{m_j}}) \leq \gamma_n \mathcal{P}(E_{t_{m_j}}),
\]

where the first inequality is because \( \mathcal{L}_n(C_i^{t_{m_j}}) \) does not increase with \( i \) and the \( C_i^{t_{m_j}} \) are disjoint mod-\( \mathcal{L}_n \). Since \( e^{-|x|^2} \leq 1 \) and \( \alpha < n/(n-1) \), we deduce from (46) and the isoperimetric inequality again that

\[
\sum_{i=p}^{\infty} G(C_i^{t_{m_j}}) = \sum_{i=p}^{\infty} \mathcal{L}_n^{\frac{1}{n}}(C_i^{t_{m_j}}) \leq \left( \frac{\gamma_n \mathcal{P}(E_{t_{m_j}})}{p^{\frac{1}{\alpha} \frac{(n-1)}{n}}} \right) \frac{1}{\alpha(n-1)} \sum_{i=p}^{\infty} \mathcal{L}_n^{\frac{n-1}{n}}(C_i^{t_{m_j}})
\]

\[
\leq \left( \frac{\gamma_n \mathcal{P}(E_{t_{m_j}})}{p^{\frac{1}{\alpha} \frac{(n-1)}{n}}} \right) \frac{1}{\alpha(n-1)} \sum_{i=p}^{\infty} \gamma_n \mathcal{P}(C_i^{t_{m_j}}) \leq \left( \frac{\gamma_n \mathcal{P}(E_{t_{m_j}})}{p^{\frac{1}{\alpha} \frac{(n-1)}{n}}} \right) \frac{1}{\alpha(n-1)} \frac{\gamma_n \mathcal{P}(E_{t_{m_j}})}{p^{\frac{1}{\alpha} \frac{(n-1)}{n}}} ,
\]

from which (45) follows because \( \mathcal{P}(E_{t_{m_j}}) \) is bounded independently of \( m \). Observe also that \( G(C_i^{t_{m_j}}) \to G(F_i) \) for fixed \( i \) as \( m \to \infty \), because \( x \mapsto e^{-|x|^2} \) is summable and so a 3-\( \varepsilon \) argument reduces the issue to \( L^1_{loc} \)-convergence of \( e^{-|x|^2} \chi_{C_i^{t_{m_j}}}(x) \) to \( e^{-|x|^2} \chi_{F_i}(x) \), which follows from local convergence in measure of \( C_i^{t_{m_j}} \) to \( F_i \). Now, by (45), for every \( \varepsilon > 0 \) there is a \( p > 0 \) such that
\[
\limsup_{i=p} \sum_{i=0}^{\infty} G(C^t_{i}) < \epsilon. \text{ Thus}
\]
\[
\sum_i G(F_i) \leq \liminf_{j \to \infty} \sum_i G(C^t_{i}) \leq \lim_{j \to \infty} \sum_{i=0}^{p} G(C^t_{i}) + \epsilon = \sum_{i=0}^{p} G(F_i) + \epsilon \leq \sum_i G(F_i) + \epsilon,
\]
where the first inequality follows from Fatou’s lemma (for series). Since \( \epsilon \) was arbitrary, we get
\[
\lim_{j \to \infty} \sum_i G(C^t_{i}) = \sum_i G(F_i).
\]

Because the \( C^t_{i} \) are pairwise disjoint mod-\( \mathcal{L}_n \), so are the \( F_i \). Moreover, since \( t_0 \notin N \) by definition of \( \Sigma_{\eta} \), we have that
\[
\lim_{t \to t_0} \mathcal{L}_n \left( (E_t \setminus E_{t_0}) \cup (E_{t_0} \setminus E_t) \right) = 0,
\]
implying by local convergence in measure that \( F_i \subset E_{t_0} \mod-\mathcal{L}_n \) for each \( i \). In addition, as \( \alpha > 1 \), we see that \( \text{a fortiori} \) implies
\[
\sum_i \int_{F_i} e^{-|x|^2} \, dx = \lim_{j \to \infty} \sum_i \int_{C^t_{i}} e^{-|x|^2} \, dx = \lim_{j \to \infty} \int_{E_{t_0}} e^{-|x|^2} \, dx = \int_{E_{t_0}} e^{-|x|^2} \, dx,
\]
where the last equality follows from \( [15] \). Thus, as \( e^{-|x|^2} > 0 \) for all \( x \), we get \( \mathcal{L}_n(E_{t_0} \setminus \cup_i F_i) = 0 \), whence the \( F_i \) partition \( E_{t_0} \mod-\mathcal{L}_n \). Also, by the lower semi-continuity of perimeter with respect to local convergence in measure, we get that
\[
\sum_i \mathcal{P}(F_i) \leq \lim_j \sum_i \mathcal{P}(C^t_{i}) = \lim_j \mathcal{P}(E_{t_0}) = \mathcal{P}(E_{t_0}),
\]
where the last equality comes from the continuity of \( t \mapsto \mathcal{P}(E_t) \) on \( \Sigma_{\eta} \). Therefore, by the maximizing property \( [12] \) of \( M \)-connected components, it holds that
\[
\sum_i G(F_i) \leq \sum_i G(C_{i}^{t_0}).
\]

We claim that in fact \( \sum_i G(F_i) = \sum_i G(C_{i}^{t_0}) \). To show this, it is enough to consider separately the two cases where \( t_{m_j} \to t_0 \) from above and from below. Assume first that \( t_{m_j} > t_0 \) for all \( j \), whence \( E_{t_{m_j}} \subset E_{t_0} \). Set \( F_{i}^{t_{m_j}} := E_{t_{m_j}} \cap C_{i}^{t_0} \) and observe that the \( (F_{i}^{t_{m_j}})_{i \in N} \) are disjoint mod-\( \mathcal{L}_n \) and form a partition of \( E_{t_{m_j}} \mod-\mathcal{L}_n \). As \( \partial_M F_{i}^{t_{m_j}} \subset \partial_M E_{t_{m_j}} \cup \partial_M C_{i}^{t_0} \) by definition \( [21] \), and because each point of \( \partial_M F_{i}^{t_{m_j}} \setminus \partial_M C_{i}^{t_0} \) is clearly a density point of \( C_{i}^{t_0} \), we get since the sets of density points of the \( C_{i}^{t_0} \) are pairwise disjoint while \( H^{n-1}(\partial_M C_{i}^{t_0} \cap \partial_M C_{i}^{t_0}) = 0 \) for \( i_1 \neq i_2 \) (see \( [1] \) Proposition 3)) that the \( \partial_M F_{i}^{t_{m_j}} \) are pairwise disjoint mod-\( H^{n-1} \). Hence, by \( [1] \) Proposition 3 again, it holds that \( \mathcal{P}(E_{t_{m_j}}) = \sum_i \mathcal{P}(F_{i}^{t_{m_j}}) \) and so the \( F_{i}^{t_{m_j}} \) are candidate maximizers in \( [12] \) if we put \( E = E_{t_{m_j}} \) there. However, as \( \mathcal{L}_n(E_{t_0} \setminus E_{t_{m_j}}) \to 0 \) by \( [18] \), it holds that \( \sum_i \mathcal{L}_n(C_{i}^{t_0} \setminus F_{i}^{t_{m_j}}) \to 0 \) when \( j \to \infty \), and since \( e^{-|x|^2} \) is summable we get by dominated convergence that
\[
\sum_i G(C_{i}^{t_0}) = \lim_j \sum_i G(F_{i}^{t_{m_j}}) \leq \lim_j \sum_i G(C_{i}^{t_{m_j}}),
\]
where the last inequality comes from the maximizing character of the \( \{C_i^{L,m_j}\} \) in (42) when \( E = E_{t_{m_j}} \). The claim in this case now follows from (51), (50) and (47). Assume next that \( t_{m_j} < t_0 \) for all \( j \), whence \( E_{t_{m_j}} \supset E_{t_0} \). Since \( C_i^{L} \) is indecomposable and \( C_i^{L} \subset E_{t_{m_j}} \), it holds that \( C_i^{L} \subset C_i^{L,m_j} \) modulo \( \mathcal{L}_n \) for some \( \ell_i \), by [1] Theorem 1. Obviously then, \( \sum_i G(C_i^{L}) \leq \sum_i G(C_i^{L,m_j}) \), and in view of (47), (50) this proves the claim in all cases.

From the claim, we deduce by uniqueness of a maximizer in (42) that \((F_i)_{i \in \mathbb{N}} \) and \((C_i^{L})_{i \in \mathbb{N}} \) are equivalent in \( \hat{S} \), thereby proving (ii). In particular \( \sum_i \mathcal{P}(F_i) = \mathcal{P}(E_{t_0}) \), and since \( \lim_{j \to \infty} \mathcal{P}(C_{i,j}^{L}) \geq \mathcal{P}(F_i) \) for each \( i \) by lower semi-continuity of the perimeter under local convergence in measure, we deduce from (49) that \( \lim_{j \to \infty} \mathcal{P}(C_{i,j}^{L}) = \mathcal{P}(F_i) \), thereby proving the second half of (iii). To prove the first half, observe that if \( t_{m_j} > t_0 \) then \( E_{t_{m_j}} \subset E_{t_0} \). Therefore \( C_i^{L,m_j} \), which is indecomposable, must be included in \( C_i^{L} \) for some \( \ell = \ell(i,j) \). But for \( j \) large enough \( C_i^{L,m_j} \) can be none but \( F_i \), and so \( \lim_{j \to \infty} \mathcal{L}_n(F_i \setminus C_i^{L,m_j}) \leq \lim_{j \to \infty} \mathcal{L}_n(E_{t_0} \setminus E_{t_{m_j}}) = 0 \), by (48). If on the contrary \( t_{m_j} < t_0 \), then \( E_{t_{m_j}} \supset E_{t_0} \) and each \( C_i^{L,m_j} \), which is indecomposable, must be included in \( C_i^{L} \) for some \( i = i(\ell,j) \). Necessarily then, it holds that \( C_i^{L} = F_i \), and so \( \lim_{j \to \infty} \mathcal{L}_n(C_i^{L,m_j} \setminus F_i) \leq \lim_{j \to \infty} \mathcal{L}_n(E_{t_{m_j}} \setminus E_{t_0}) = 0 \), by (48) again. Since every \( F_i \) is a \( C_i^{L} \) for some \( \ell = \ell(i) \), this proves (iii).

To establish (iv), note since \( \sum_{i=0}^{\infty} \mathcal{P}(C_i^{L}) < \infty \) that to each \( \varepsilon > 0 \) there is \( i_0 \geq 1 \) with \( \sum_{i=i_0}^{\infty} \mathcal{P}(C_i^{L}) < \varepsilon \). Then, by lower-semi-continuity of the perimeter with respect to local convergence in measure, there is \( j_0 = j_0(i_0) \) so large that

\[
\sum_{i=0}^{i_0-1} \mathcal{P}(C_i^{L,m_j}) > \sum_{i=0}^{i_0-1} \mathcal{P}(C_i^{L}) - \varepsilon, \quad j \geq j_0,
\]

and since \( \lim_{j} \sum_i \mathcal{P}(C_i^{L,m_j}) = \sum_i \mathcal{P}(C_i^{L}) \) by (49), we get for \( j \) large enough that \( \sum_{i=i_0}^{\infty} \mathcal{P}(C_i^{L,m_j}) \leq \varepsilon \). As \( \varepsilon \) was arbitrary, this gives us the first limit in (43), which implies the second by the isoperimetric inequality because \( \mathcal{L}_n(C_i^{L,m_j}) < \infty \) for \( i \geq 1 \).

We equip \( \hat{S} \) with the distance \( d_{\hat{S}}(E_i, (E'_i)) = \sup d_1 (\chi_{E_i}, \chi_{E'_i}) \), where \( d_1 \) is a distance function on \( L^1_{loc}(\mathbb{R}^n) \), and we endow \( \hat{S} \) with the quotient topology (i.e. the coarsest topology such that the canonical map \( S \to \hat{S} \) is continuous). Then, Proposition 3.8 may be construed as an approximate continuity result of the \( M \)-connected components of the suplevel sets of a homogeneous \( BV \)-function with respect to the level. Recall that a map \( \psi : \mathbb{R} \to \mathcal{E} \), with \( \mathcal{E} \) a topological space, is approximately continuous at \( t_0 \in \mathbb{R} \) if, for every neighborhood \( V \subset \mathcal{E} \) of \( \psi(t_0) \), it holds that

\[
\lim_{r \to 0} \frac{\mathcal{L}_1 \left( \{ t : |t - t_0| < r, \psi(t) \notin V \} \right)}{r} = 0.
\]

**Theorem 3.9.** Let \( \phi \in BV(\mathbb{R}^n) \) and \( E_t \) its suplevel set at level \( t \), cf. (28). Then, the map \( \psi : \mathbb{R} \to \hat{S} \) sending \( t \) to the \( M \)-connected components of \( E_t \) is approximately continuous \( \mathcal{L}_1 \)-a.e.

**Proof.** It follows from assertions (ii), (iv) of Proposition 3.8 and from the definition of the quotient topology that \( \psi \) is continuous on \( \Sigma_\eta \) for each \( \eta > 0 \). So, when \( t_0 \) is a density point of \( \Sigma_\eta \) for some \( \eta > 0 \), then (52) holds. But if \( D_\eta \) denotes the set of such density points, then \( \mathbb{R} \setminus (\bigcup_{k \geq 1} D_{1/k^2}) \) has measure zero, by the Borel-Cantelli lemma. Hence (52) holds a.e. \( \square \)
4. LOOP DECOMPOSITION OF DIVERGENCE-FREE PLANAR MEASURES

In this section, we make use of Theorem 3.6 and Proposition 3.8 when \( n = 2 \) to decompose gradients of functions in \( BV(\mathbb{R}^2) \) as a continuous sum of measures of the form (20), with \( \partial_M E \) a rectifiable Jordan curve. The results in this section, up to and including Proposition 4.4, could be developed in an analogous way for \( n \geq 3 \), replacing Jordan curves with Jordan boundaries (see [1]). However, we stick with \( n = 2 \) since our main application, stated in Theorem 4.5, is to describe divergence-free vector fields whereas the connection with gradients, stated in Lemma 2.1, only works in the plane.

**Lemma 4.1.** Let \( E, F \subset \mathbb{R}^2 \) be sets of finite perimeter such that \( \mathcal{L}_2(E \setminus F) = 0 \). Then for \( \mathcal{H}^1 \)-a.e. \( x \in \partial_M E \cap \partial_M F \), it holds that \( \nu_F(x) = \nu_E(x) \).

**Proof.** Given \( \epsilon > 0 \), \( x, v \in \mathbb{R}^2 \) with \( v \neq 0 \) and \( G \subset \mathbb{R}^2 \), define the half-disk
\[
H_\epsilon(x, v) := \{ y \in \mathbb{B}(\epsilon, x) : (y - x) \cdot v > 0 \},
\]
and let
\[
L_G(x, v) := \lim_{\epsilon \to 0} \frac{\mathcal{L}_2(H_\epsilon(x, v) \cap G)}{\mathcal{L}_2(H_\epsilon(x, v))} = \lim_{\epsilon \to 0} \frac{2\mathcal{L}_2(H_\epsilon(x, v) \cap G)}{\pi \epsilon^2}
\]
whenever the limit exists. Assume \( G \) has finite perimeter. Then, for \( \mathcal{H}^1 \)-a.e. \( x \in \partial_M G \), \( \nu_G(x) \) is the unique unit vector that satisfies
\[
L_G(x, \nu_G(x)) = 1 \quad \text{and} \quad L_G(x, -\nu_G(x)) = 0,
\]
(see [3] Proposition 10.3.4 and Theorem 10.3.2 or [29] Thm. 5.6.5). Since \( E \) is included in \( F \) except for a set of \( \mathcal{L}_2 \)-measure zero, clearly \( L_E(x, -\nu_F(x)) = 0 \) for \( \mathcal{H}^1 \)-a.e. \( x \in \partial_M F \). Let \( Z \subset \partial_M F \) be the set consisting of such \( x \). Moreover, \( L_E(x, \nu_E(x)) = 1 \) for \( \mathcal{H}^1 \)-a.e. \( x \in \partial_M E \), and we let \( Y \subset \partial_M F \) be the set consisting of such \( x \). Now, if for \( x \in X \cap Y \) we had \( \nu_E \neq \nu_F \), the truncated positive cone \( C_\epsilon := H_\epsilon(x, -\nu_F) \cap H_\epsilon(x, \nu_E) \) would have strictly positive angle, say \( \theta \), and since
\[
\limsup_{\epsilon \to 0} \frac{2\mathcal{L}_2(H_\epsilon(x, \nu_E) \cap E \cap C_\epsilon)}{\pi \epsilon^2} = \limsup_{\epsilon \to 0} \frac{2\mathcal{L}_2(E \cap C_\epsilon)}{\pi \epsilon^2} \leq L_E(x, -\nu_F) = 0,
\]
we would have that
\[
L_E(x, \nu_E) = \lim_{\epsilon \to 0} \frac{\mathcal{L}_2(H_\epsilon(x, \nu_E) \cap (E \setminus C_\epsilon))}{\mathcal{L}_2(H_\epsilon(x, \nu_E))} \leq \limsup_{\epsilon \to 0} \frac{\mathcal{L}_2(H_\epsilon(x, \nu_E) \setminus C_\epsilon)}{\mathcal{L}_2(H_\epsilon(x, \nu_E))} \leq 1 - \frac{\theta}{\pi},
\]
a contradiction. \( \square \)

Let us make one more piece of notation: for \( \Gamma \subset \mathbb{R}^2 \) a Jordan curve, we denote by \( \text{int}(\Gamma) \) (resp. \( \text{ext}(\Gamma) \)) the bounded (resp. unbounded) connected component of \( \mathbb{R}^2 \setminus \Gamma \).

**Lemma 4.2.** If \( \Gamma \subset \mathbb{R}^2 \) is a rectifiable Jordan curve, then \( \partial_M(\text{int}(\Gamma)) = \Gamma \mod\mathcal{H}^1 \).

**Proof.** Clearly \( \partial_M(\text{int}(\Gamma)) \) is a subset of the topological boundary of \( \text{int}(\Gamma) \) which is \( \Gamma \). Now, by [1] Proposition 2 & Theorem 7, \( \partial_M(\text{int}(\Gamma)) \) is equal to a rectifiable Jordan curve \( \tilde{\Gamma} \mod\mathcal{H}^1 \).

Thus, \( \mathcal{H}^1(\tilde{\Gamma} \setminus \Gamma) = 0 \) whence \( \tilde{\Gamma} \cap \Gamma \) is dense in \( \tilde{\Gamma} \), and so \( \tilde{\Gamma} \subset \Gamma \) by compactness of \( \Gamma \). Therefore, by the Jordan curve theorem, \( \tilde{\Gamma} = \Gamma \) which implies our lemma. \( \square \)

The next lemma elaborates on [1] Corollary 1].
Lemma 4.3. The measure-theoretical boundary of a set \( E \subset \mathbb{R}^2 \) of finite perimeter decomposes \( \text{mod-}\mathcal{H}^1 \) as the union of two countable families of rectifiable Jordan curves \( \{\Gamma_k^+\}_{k \in K} \) and \( \{\Gamma_j^-\}_{j \in J} \), with \( K, J \subset \{1, 2, 3 \cdots \} \), such that
\[
\nabla \chi_E = \sum_{k \in K} \nabla \chi_{\text{int}(\Gamma_k^+)} - \sum_{j \in J} \nabla \chi_{\text{int}(\Gamma_j^-)}
\]
\[
\mathcal{H}^1\left(\partial_M E\right) = \sum_{k \in K} \mathcal{H}^1(\Gamma_k^+) + \sum_{j \in J} \mathcal{H}^1(\Gamma_j^-).
\]

Moreover, if we let
\[
I_k := \{j \in J : \text{int}(\Gamma_j^-) \subset \text{int}(\Gamma_k^+)\}
\]
and \( Y_k = \text{int}(\Gamma_k^+) \setminus \bigcup_{j \in I_k} \text{int}(\Gamma_j^-) \),
as well as
\[
Y_0 := \bigcap_{j \in J} \text{ext}(\Gamma_j^-) \text{ if } \mathcal{L}_2(E) = \infty \text{ and } Y_0 := \emptyset \text{ otherwise},
\]
then the \( Y_k \) for \( k \in K \), together with \( Y_0 \) if nonempty, are the \( M \)-connected components of \( E \). In particular, it holds that
\[
E = \left( \bigcup_{k \in K} Y_k \right) \cup Y_0 \quad \text{mod-}\mathcal{L}_2.
\]

In addition, if we put
\[
I_\infty := \{j \in J : \text{there is no } k \in K \text{ such that } \text{int}(\Gamma_k^+) \supset \text{int}(\Gamma_j^-)\},
\]
along with
\[
I_\infty := \{j \in J : \text{there is no } k \in K \text{ such that } \text{int}(\Gamma_k^+) \supset \text{int}(\Gamma_j^-)\},
\]
then \( I_\infty \neq \emptyset \) if and only if \( \mathcal{L}_2(E) = \infty \) and each \( j \in J \) belongs to \( I_k \) for some unique \( k \) or else to \( I_\infty \). Furthermore, for each \( k \in K \), the sets \( \{\text{int}(\Gamma_j^-)\}_{j \in I_k} \) together with \( \text{ext}(\Gamma_k^+) \) are the \( M \)-connected components of \( \mathbb{R}^2 \setminus Y_k \), and if \( \mathcal{L}_2(E) = \infty \) then the \( \{\text{int}(\Gamma_j^-)\}_{j \in I_\infty} \) are the \( M \)-connected components of \( \mathbb{R}^2 \setminus Y_0 \).

Proof. By [1 Corollary 1], there exists two families \( \{\Gamma_k^+\}_{k \in K} \) and \( \{\Gamma_j^-\}_{j \in J} \) of countably many rectifiable Jordan curves (we can always take \( K, J \subset \{1, 2, 3 \cdots \} \)), satisfying:

(a) \( \partial_M E = \bigcup_k \Gamma_k^+ \cup \bigcup_j \Gamma_j^- \text{ mod-}\mathcal{H}^1 \),
(b) For any two \( \text{int}(\Gamma_k^+) \) and \( \text{int}(\Gamma_j^-) \) either one is contained in the other or they are disjoint.
   Similarly, for any two \( \text{int}(\Gamma_j^-) \) and \( \text{int}(\Gamma_i^-) \) either one is contained in the other or they are disjoint.
(c) \( \mathcal{H}^1(\partial_M E) = \sum_k \mathcal{H}^1(\Gamma_k^+) + \sum_j \mathcal{H}^1(\Gamma_j^-) \), in particular the curves are disjoint mod-\( \mathcal{H}^1 \).
(d) If \( l \neq k \) and \( \text{int}(\Gamma_k^+) \subset \text{int}(\Gamma_l^+) \) then there exists a \( \text{int}(\Gamma_j^-) \) with the property that \( \text{int}(\Gamma_k^+) \subset \text{int}(\Gamma_j^-) \subset \text{int}(\Gamma_l^+) \). Analogously, if \( j \neq i \) and \( \text{int}(\Gamma_j^-) \subset \text{int}(\Gamma_i^-) \) then there exists a \( \text{int}(\Gamma_k^+) \) such that \( \text{int}(\Gamma_j^-) \subset \text{int}(\Gamma_k^+) \subset \text{int}(\Gamma_i^-) \).
(e) The \( Y_k \) defined in (56), along with \( Y_0 \) defined in (57) if nonempty, are the \( M \)-connected components of \( E \), in particular (58) holds. Note that if \( \mathcal{L}_2(E) = \infty \), then \( Y_0 \) is the \( M \)-connected component of infinite \( \mathcal{L}_2 \)-measure. Note also that \( \mathcal{L}_2(E) = \infty \) (equivalently:

\(^2\text{In [1 Cor. 1], the set } Y_0 \text{ is not introduced, but an abstract “Jordan curve” } \Gamma_{\infty}^+, \text{ reducing to the point at } \infty \text{ (i.e. having zero length and interior } \mathbb{R}^2 \text{), is allowed in case } \mathcal{L}_2(E) = \infty, \text{ so that } Y_0 \text{ corresponds to } \text{int}(\Gamma_{\infty}^+) \setminus \bigcup_j \text{int}(\Gamma_j^-). \)
Thus, the set \( \partial_j(\Gamma_j^+) \) (not contained in any \( \text{int}(\Gamma_k^+) \)), that is: if and only if \( I_\infty \neq \emptyset \).

It remains for us to show that this decomposition satisfies (54) and that the last two assertions after (60) do hold. In view of (27) and (55), it is enough for (54) to hold that

(i) for any \( k \in K \), \( \nabla \lambda_E[\Gamma_k^+] = \nabla \lambda_{\text{int}(\Gamma_k^+)} \),

(ii) for any \( j \in J \), \( \nabla \lambda_E[\Gamma_j^-] = -\nabla \lambda_{\text{int}(\Gamma_j^-)} \).

To obtain (i) and (ii), we will prove that for each \( k_0 \in K \) (resp. \( j_0 \in J \)) and \( \mathcal{H}^1 \text{-a.e. } x \in \Gamma_{k_0}^+ \) (resp. \( \Gamma_{j_0}^- \)), we have \( \nu_E(x) = \nu_{\text{int}(\Gamma_{k_0}^+)}(x) \) (resp. \( \nu_E(x) = -\nu_{\text{int}(\Gamma_{j_0}^-)}(x) \)).

Fix \( k_0 \in K \) and let \( F_{k_0} := \text{int}(\Gamma_{k_0}^+) \cap E \). Define \( \tilde{K} := \{ k \in K : \text{int}(\Gamma_k^+) \subset \text{int}(\Gamma_{k_0}^+) \} \) and \( \tilde{J} := \bigcup_{k \in \tilde{K}} I_k \). The pair of families of rectifiable Jordan curves \( \{ \Gamma_k^+ \}_{k \in \tilde{K}}, \{ \Gamma_j^- \}_{j \in \tilde{J}} \) a fortiori meets properties (b) and (d) above when the indices \( k, l \) and \( j, i \) range over \( \tilde{K} \) and \( \tilde{J} \), respectively. Also, by (c), these families are such that

(f) each two different Jordan curves are disjoint mod-\( \mathcal{H}^1 \),

(g) \( \sum_k \mathcal{H}^1(\Gamma_k) + \sum_j \mathcal{H}^1(\Gamma_j^-) < \infty, k \in \tilde{K}, j \in \tilde{J} \).

Moreover, we get from (b) and (58) that

(h) \( F_{k_0} = \bigcup_{k \in \tilde{K}} Y_k \) mod-\( \mathcal{L}^2 \).

Properties (b), (d), (f), (g) and (h) show that \( F_{k_0}, \{ \Gamma_k^+ \}_{k \in \tilde{K}}, \{ \Gamma_j^- \}_{j \in \tilde{J}} \) satisfy the assumptions of [1, Theorem 5]. The latter implies that \( F_{k_0} \) has finite perimeter and that \( \partial_M F_{k_0} = \bigcup_{k \in \tilde{K}} \Gamma_k^+ \bigcup \bigcup_{j \in \tilde{J}} \Gamma_j^- \) mod-\( \mathcal{H}^1 \). Applying Lemma 4.1 twice, we now get that \( \nu_E(x) = \nu_{F_{k_0}}(x) = \nu_{\text{int}(\Gamma_{k_0}^+)}(x) \) for \( \mathcal{H}^1 \text{-a.e. } x \in \partial_M F_{k_0} \cap \partial_M E \cap \partial_M \text{int}(\Gamma_{k_0}^+) \), and by Lemma 4.2 this intersection reduces to \( \text{int}(\Gamma_{k_0}^+) \) mod-\( \mathcal{H}^1 \). This proves (i).

To prove (ii), pick \( j_0 \in J \) and assume first that \( j_0 \notin I_\infty \), so there is \( k_0 \in K \) such that \( \text{int}(\Gamma_{k_0}^+) \supset \text{int}(\Gamma_{j_0}^-) \). As there is no infinite sequence \( \text{int}(\Gamma_{\ell_i}^+) \supset \text{int}(\Gamma_{\ell_i}^-) \supset \cdots \) each element of which contains \( \text{int}(\Gamma_{j_0}^-) \) (otherwise the isoperimetric inequality would imply that \( \pi^{1/2} \mathcal{H}^1(\Gamma_{\ell_i}^+) \geq \mathcal{L}^2(\text{int}(\Gamma_{\ell_i}^-)) > 0 \) for all \( i \) and this would contradict (g)), we may choose \( k_0 \) so that \( \text{int}(\Gamma_{k_0}^+) \) is smallest with the property that \( \text{int}(\Gamma_{k_0}^+) \supset \text{int}(\Gamma_{j_0}^-) \) or, equivalently, such that \( j_0 \in I_{k_0} \) defined in (59). Note that such a \( k_0 \) is unique, by (b), thereby proving in passing the next-to-last assertion after (60).

Now, the sets \( \{ \text{int}(\Gamma_{j}^-) \}_{j \in I_{k_0}} \) are disjoint, by (b) and (d). Moreover, for each \( i \in I_{k_0} \), there is \( j \in I_{k_0} \) such that \( \text{int}(\Gamma_{j}^-) \subset \text{int}(\Gamma_{i}^-) \), because of (d) and the fact that there is no infinite sequence \( \text{int}(\Gamma_{i_1}^-) \subset \text{int}(\Gamma_{i_2}^-) \subset \cdots \), by (c) and the isoperimetric inequality again. In particular, we have that

\[
Y_{k_0} = \text{int}(\Gamma_{k_0}^+) \setminus \bigcup_{j \in I_{k_0}} \text{int}(\Gamma_j^-).
\]

Thus, the set \( Y_{k_0} \) and the pair of families of curves \( \{ \Gamma_{i_1}^- \}, \{ \Gamma_j^- \}_{j \in I_{k_0}} \) (the first family has only one element) satisfy the assumptions of [1, Theorem 5], to the effect that

\[
\partial_{\text{M}} Y_{k_0} = \Gamma_{k_0}^+ \cup \bigcup_{j \in I_{k_0}} \Gamma_j^- \text{ mod-} \mathcal{H}^1.
\]
In another connection, if we define $F_{k_0}$ as before, we get from the first part of the proof and Lemma 4.1 that

$$\Gamma_{j_0}^- \subset \partial_M F_{k_0} \cap \partial_M E \quad \text{and} \quad \nu_E(x) = \nu_{F_{k_0}}(x), \quad \mathcal{H}^1\text{-a.e. } x \in \Gamma_{j_0}^-.$$  

Moreover, (h) implies that $F_{k_0} \supset Y_{k_0}$ mod-$\mathcal{L}_2$, and (63), (62) that $\Gamma_{j_0}^- \subset \partial_M F_{k_0} \cap \partial_M Y_{k_0}$ mod-$\mathcal{H}^1$, therefore we conclude from Lemma 4.1 that

$$\nu_{F_{k_0}}(x) = \nu_{Y_{k_0}}(x), \quad \mathcal{H}^1\text{-a.e. } x \in \Gamma_{j_0}^-.$$  

Besides, since $Y_{k_0} \subset \text{ext}(\Gamma_{j_0}^-)$ by (65), while $\Gamma_{j_0}^- \subset \partial_M Y_{k_0} \cap \partial_M \text{ext}(\Gamma_{j_0}^-)$ mod-$\mathcal{H}^1$ by (62) and Lemma 4.2, we get from Lemma 4.1 again that

$$\nu_{Y_{k_0}}(x) = \nu_{\text{ext}(\Gamma_{j_0}^-)}(x) = -\nu_{\text{int}(\Gamma_{j_0}^-)}(x), \quad \mathcal{H}^1\text{-a.e. } x \in \Gamma_{j_0}^-.$$  

The conjunction of (63), (65) and (67) proves (ii) when $j_0 \notin I_\infty$. Next, assume that $j_0 \in I_\infty$; in particular $I_\infty \neq \emptyset$ so that $Y_0 \neq \emptyset$, where $Y_0$ was defined in (57). If we define

$$\tilde{I} := \{i \in J : \text{there is no } j \in J \text{ such that } \text{int}(\Gamma_j^-) \supset \text{int}(\Gamma_i^-)\},$$  

we obviously have that $Y_0 = \bigcap_{i \in \tilde{I}} \text{ext}(\Gamma_i^-)$. Note that the sets $\{\text{int}(\Gamma_i^-)\}_{i \in \tilde{I}}$ are disjoint, by (b). Thus, if we let $\tilde{T}_i^+ := \Gamma_i^-$, we get in view of (c) that the set $\mathbb{R}^2 \setminus Y_0 = \bigcup_{i \in \tilde{I}} \text{int}(\tilde{T}_i^+)$ together with the pair of families of rectifiable Jordan curves $\{\tilde{T}_i^+, i \in \tilde{I}\}$, $\emptyset$ (i.e. the second family is empty), satisfy the assumptions of [1, Theorem 5]. The latter implies that

$$\partial_M(\mathbb{R}^2 \setminus Y_0) = \bigcup_{i \in \tilde{I}} \Gamma_i^-,$$  

and since $j_0 \in \tilde{I}$, by (d), we get from Lemma 4.1 that $\nu_{\text{int}(\Gamma_{j_0}^-)}(x) = \nu_{\mathbb{R}^2 \setminus Y_0}(x) = -\nu_{Y_0}(x)$ for $\mathcal{H}^1$-a.e. $x \in \Gamma_{j_0}^-$. As $Y_0 \subset E$ and $\Gamma_{j_0}^- \subset \partial_M E \cap \partial_M Y_0$, by (67), another application of Lemma 4.1 yields that $\nu_{Y_0}(x) = \nu_E(x)$ for $\mathcal{H}^1$-a.e. $x \in \Gamma_{j_0}^-$, thereby establishing (ii) in this case as well.

To prove the last assertion after (60), pick $k \in K$ and observe from (b) and (d) that the sets $\text{ext}(\Gamma_k^+) = \{\text{int}(\Gamma_{j_0}^-)\}_{i \in \tilde{I}}$ are pairwise disjoint, while $\mathbb{R}^2 \setminus Y_k$ is their union. These sets are indecomposable, by Lemma 4.2 and [1, Theorem 2], and since their measure-theoretical boundaries are pairwise disjoint mod-$\mathcal{H}^1$, because of (c), we deduce from [1, Proposition 3] that their perimeters add up to $\mathcal{P}(\mathbb{R}^2 \setminus Y_k)$. Hence, they are indeed the $M$-connected components of $\mathbb{R}^2 \setminus Y_k$. If $\mathcal{L}_2(E) = \infty$, so that $Y_0 \neq \emptyset$, a similar reasoning on (67) shows that the $\{\text{int}(\Gamma_{j_0}^-)\}_{i \in \tilde{I}}$ are the $M$-connected components of $\mathbb{R}^2 \setminus Y_0$, and it remains for us to prove that $\tilde{I} = I_\infty$. From (d), we know that $I_\infty \subset \tilde{I}$. Conversely, if $j \in J$ and $j \notin I_\infty$, we showed earlier there is a unique $k_0 \in K$ such that $j \in I_{k_0}$. We also know that $Y_{k_0}$ is a $M$-connected component of $E$, therefore it is indecomposable and disjoint mod-$\mathcal{L}_2$ from $Y_0$ which is another such component. Consequently, by (67), we have that $Y_{k_0} \subset \bigcup_{i \in \tilde{I}} \text{int}(\Gamma_i^--) \setminus \mathcal{L}_2$. As the $\{\text{int}(\Gamma_{i_0}^-)\}_{i_0 \in \tilde{I}}$ are the $M$-connected components of $\mathbb{R}^2 \setminus Y_0$ and $Y_{k_0}$ is indecomposable, we get that $Y_{k_0} \subset \text{int}(\Gamma_{i_0}^-) \setminus \mathcal{L}_2$ for some $i_0 \in \tilde{I}$. It implies easily that $\mathcal{H}^1$-a.e. point of $\partial_M Y_{k_0}$ is not a density point of $\text{ext}(\Gamma_{i_0}^-)$. A fortiori then, by (62), $\hat{\Gamma}_j^- \subset \overline{\text{int}(\Gamma_{i_0}^-)}$ mod-$\mathcal{H}^1$ where the bar indicates Euclidean closure. Since $\hat{\Gamma}_j^-$ is a closed curve we get in fact that $\Gamma_{j_0}^- \subset \text{int}(\Gamma_{i_0}^-)$, and by the Jordan curve theorem it follows that $\text{int}(\hat{\Gamma}_j^-) \subset \text{int}(\Gamma_{i_0}^-)$, whence $j \notin \tilde{I}$. The proof is now complete. \qed
Lemma 4.3 tells us that the measure-theoretical boundary of a set $E$ of finite perimeter consists of two countable families of Jordan curves, namely $\{\Gamma^+_k\}_{k \in K}$ and $\{\Gamma^-_j\}_{j \in J}$, such that the $\text{int} \Gamma^-_j$ and the $\text{ext} \Gamma^+_k$ are the $M$-connected components of the complements of the $M$-connected components of $E$. This will allow us to put a structure on these Jordan curves. More precisely, recall from Section 3 that we put $E$ of finite perimeter may be regarded as a member of $\tilde{S}$, a representative of which is obtained in $S$ by arranging the $M$-connected components in nonincreasing measure, and appending to them infinitely many copies of the emptyset if these components are finite in number. For $S \in S$, say $S = (F_0, F_1, F_2, \cdots)$, we let for simplicity $U_S = \cup_j F_j$, and we let $T$ be the subset of $S^\mathbb{N}$ consisting of sequences $(S_0, S_1, S_2, \cdots)$ such that $(\mathbb{R}^2 \setminus \cup S_0, \mathbb{R}^2 \setminus \cup S_1, \mathbb{R}^2 \setminus \cup S_2, \cdots)$ also lies in $S$. We say that two elements $(S_i)_{i \in \mathbb{N}}$ and $(S'_i)_{i \in \mathbb{N}}$ of $T$ are equivalent if there is a permutation $\sigma : \mathbb{N} \rightarrow \mathbb{N}$ such that $(S_0, S_1, S_2, \cdots)$ represent the same element in $\tilde{S}$. We call $\tilde{T}$ the set of equivalence classes.

With the notation of Lemma 4.3 let $K$ be ordered so that the $\mathcal{L}_2(Y_k), k \in K$, are nonincreasing, and append to the sequence $Y_k$ infinitely many copies of the empty set if $K$ is finite. We define a particular element $S = (S_0, S_1, S_2, \cdots)$ of $T$ as follows. Let $S_0 = (\emptyset, \emptyset, \cdots)$ if $\mathcal{L}_2(E) < \infty$, otherwise let $S_0$ be a representative in $S$ of the $M$-connected components of $\mathbb{R}^2 \setminus Y_0$. Let further $S_k$, for $k \geq 1$, be a representative in $S$ of the $M$-connected components of $\mathbb{R}^2 \setminus Y_k$. Note that $(\mathbb{R}^2 \setminus \cup S_0, \mathbb{R}^2 \setminus \cup S_1, \mathbb{R}^2 \setminus \cup S_2, \cdots)$ is equal to $(Y_0, Y_1, \cdots)$ if $\mathcal{L}_2(E) = \infty$ and to $(\mathbb{R}^2 \setminus Y_1, Y_1, \cdots)$ if $\mathcal{L}_2(E) < \infty$, so it is an element of $S$. Hence, $S := (S_0, S_1, S_2, \cdots)$ belongs to $T$, and if for $k \geq 0$ we write $S_k = (S_{k,0}, S_{k,1}, \cdots)$, where the $S_{k,j}$ are sets of finite perimeter mod-$\mathcal{L}_2$ constitutive of $S_k \in S$, then: (i) for $k \geq 1$ we have $S_{k,1} = \text{ext}(\Gamma^+_k)$ while $(S_{k,j})_{j \geq 2}$ enumerates the $(\text{int}(\Gamma^-_j))_{j \in I_k}$ in nonincreasing $\mathcal{L}_2$-measure, with infinitely many copies of the empty set appended when $I_k$ is finite; (ii) if $\mathcal{L}_2(E) = \infty$ then $(S_{0,j})_{j \in \mathbb{N}}$ enumerates the $(\text{int}(\Gamma^-_j))_{j \in I_\infty}$ in nonincreasing $\mathcal{L}_2$-measure, with infinitely many copies of the empty set appended when $I_\infty$ is finite, and if $\mathcal{L}_2(E) < \infty$ then $S_{0,j} = \emptyset$ for all $j$. Altogether, the families $\{(\text{ext}(\Gamma^+_k))_{k \in K}\}, \{(\text{int}(\Gamma^-_j))_{j \in J}\}$, padded with copies of the empty set if needed and arranged in the previously described structure as entries of the infinite array $(S_{k,j}), 0 \leq k, j \leq \infty$, define some $S \in T$. Of course, $S$ depends on the ordering we chose to enumerate the $Y_k$ and the $M$-connected components of the $\mathbb{R}^2 \setminus Y_k$, if there are several orderings making their $\mathcal{L}_2$-measures nonincreasing. However, the equivalence class $\tilde{S} \in \tilde{T}$ is independent of such choices.

We orient the $\Gamma^+_k$ counterclockwise and the $\Gamma^-_j$ clockwise. This allows us to regard $\Gamma^+_k$ (resp. $\Gamma^-_j$) as the image of a unique parametrized Jordan curve $\gamma^+_k$ (resp. $\gamma^-_j$). We shall identify $\text{ext}(\Gamma^+_k)$ (resp. $\text{int}(\Gamma^-_j)$) with $\gamma^+_k$ (resp. $\gamma^-_j$), and we regard the emptyset as a degenerate curve reducing to a point. This way, the sets $S_{k,j}$ defined above can be viewed as parametrized rectifiable Jordan curves, and the latter can in turn be considered as measures if we regard a parametrized Jordan curve $\gamma$ as the member $R_\gamma$ of $\mathcal{M}(\mathbb{R}^2)^2$ defined in (12). Here, a degenerate curve has constant parametrization and therefore corresponds to the zero measure. Recall also from Section 2.3 that if $\gamma$ is a parametrized rectifiable Jordan curve of length $L > 0$ and $\hat{\gamma} : \mathbb{R} \rightarrow \mathbb{R}^2$ is the periodic extension of $\gamma$, then $\hat{\gamma}$ defines via (17) the elementary solenoid $\mathbf{T}_{\hat{\gamma}} = R_\gamma/L$, and in the degenerate case where $\gamma$ reduces to a point, we define $\mathbf{T}_{\hat{\gamma}} = 0$.

**Proposition 4.4.** Let $\phi \in \hat{BV}(\mathbb{R}^2)$ and $E_t$ be as in (28). For $t$ such that $E_t$ has finite perimeter, let $S^t := (S^t_0, S^t_1, S^t_2, \cdots) \in T$ be constructed as indicated above from the curves $\{(\Gamma^+_k)_{k \in K}\}, \{(\Gamma^-_j)_{j \in J}\}$
obtained by applying Lemma 4.3 to \( E_t \). Write \( S_k(t) = (S_{k,0}^t, S_{k,1}^t, \ldots) \) for the components of \( S_k^t \in \mathcal{S} \). As we just explained, each \( S_{k,j}^t \) is a parametrized Jordan curve \( \gamma_{k,j}^t \) with image \( \Gamma_{k,j}^t \).

To each \( \eta > 0 \), there is a \( \sigma \)-compact set \( \Sigma_\eta \subset \mathbb{R} \), with \( L_1(\mathbb{R} \setminus \Sigma_\eta) < \eta \), such that:

(i) For each \( t \in \Sigma_\eta \), it holds that \( E_t \) has finite perimeter.
(ii) For each sequence \( (t_m)_m \geq 1 \) in \( \Sigma_\eta \) converging to \( t_0 \in \Sigma_\eta \), there is a subsequence \( t_{m_k} \) such that \( R_{\gamma_{k,j}}^{t_{m_k}} \) converges weak-* as \( k \to \infty \), for fixed \( k,j \), to \( R_{\gamma_{k,j}}^{t_{0}} \) for some parametrized Jordan curve \( \gamma_{k,j} \) with image \( \Gamma_{k,j} \). Moreover, \( (\gamma_{k,j})_{k,j} \in \mathbb{N} \) is equivalent to \( S_{k,j}^t \) in \( T \).
(iii) We have the limiting relation \( \lim_{k,j} \mathcal{H}^1(\Gamma_{k,j}^t) = \mathcal{H}^1(\Gamma_{k,j}) \) for each \( k,j \).
(iv) It holds that \( T_{\gamma_{k,j}}^{t_{m_k}} \) converges weak-* as \( \ell \to \infty \), for fixed \( k,j \), to \( T_{\gamma_{k,j}}^{t_{0}} \).

Proof. We adopt the notation of Lemma 4.3 for the decomposition of \( E_t \), only with an extra-superscript \( t \) to keep track of the level; e.g., as in \( Y_k^t \). By Lemma 4.1, we may assume that \( \phi \in L^2(\mathbb{R}^2) \), so that \( L_2(E_t) = \infty \) when \( t < 0 \) and \( L_2(E_t) < \infty \) when \( t > 0 \). To avoid bookkeeping with indices, we give the proof when \( t_0 < 0 \) only, as the case where \( t_0 > 0 \) is similar but simpler. Thus, we may assume that \( t_m < 0 \) for all \( m \). With \( \Sigma_\eta \) as in Proposition 5.8, we know from the latter that (i) holds and that, for some subsequence \( t_{m_k} \), the \( Y_{k,m_k}^t \) converge locally in measure for fixed \( k \) as \( i \to \infty \), to some \( F_k \) such that \( (F_k)_{k \geq 0} \) is equivalent to \( (Y_k^{t_0})_{k \geq 0} \) in \( \mathcal{S} \). Moreover, we know from (iii) of this proposition that \( \lim_{k} L_n((Y_{k,m_k}^t \setminus F_k) \cup (F_k \setminus Y_{k,m_k}^t)) = 0 \) and that \( \lim_{k} \mathcal{P}(Y_{k,m_k}^t) = \mathcal{P}(F_k) \) for each \( k \). Equivalently, the \( \mathbb{R}^2 \setminus Y_{k,m_k}^t \) converge locally in measure to \( \mathbb{R}^2 \setminus F_k \) as \( k \to \infty \) and \( \lim_{k} L_n((\mathbb{R}^2 \setminus Y_{k,m_k}^t) \setminus (\mathbb{R}^2 \setminus F_k) \cup ((\mathbb{R}^2 \setminus F_k) \setminus (\mathbb{R}^2 \setminus Y_{k,m_k}^t))) = 0 \), while \( \lim_{k} \mathcal{P}(\mathbb{R}^2 \setminus Y_{k,m_k}^t) = \mathcal{P}(\mathbb{R}^2 \setminus F_k) \) for each \( k \). This is all we need to apply the proof of Proposition 5.8 to \( \mathbb{R}^2 \setminus Y_{k,m_k}^t \) instead of \( E_{t_{m_k}} \), to the effect that for each \( k \geq 0 \) there is a subsequence \( t_{m_{k,l}}(k) \) of \( t_{m_k} \) such that \( S_{k,j}^{t_{m_{k,l}}} \) converges locally in measure to some \( C_{k,j} \), where \( (C_{k,j})_{k,j} \in \mathbb{N} \) is equivalent to \( S_k^t \) in \( \mathcal{S} \). Using a diagonal argument, we can make \( t_{m_{k,l}}(k) \) independent of \( k \) and we rename it as \( t_{m_{k,l}} \) for simplicity. By construction, we may write for \( k = 0 \) or \( j = 1 \) that \( C_{k,j} = \text{int}(\Gamma_{k,j}) \mod L_2 \) with \( \Gamma_{k,j} = \Gamma_{k,j}^{t_{0}} \) for some \( l = l(k,i) \), while for \( k \geq 1 \) we have \( C_{k,0} = \text{ext}(\Gamma_{k,0}) \mod L_2 \) with \( \Gamma_{k,0} = \Gamma_{k,0}^{t_{0}} \). Moreover, we know from the proof of Proposition 5.8 point (iii) that \( \lim_{k} \mathcal{P}(S_{k,j}^{t_{m_{k,l}}}) = \mathcal{P}(C_{k,j}) \) or, equivalently, that \( \lim_{k} \mathcal{H}^1(\Gamma_{k,j}^{t_{m_k}}) = \mathcal{H}^1(\Gamma_{k,j}) \), which proves (iii). Now, if we let \( \gamma_{k,j} \) be a parametrization of \( \Gamma_{k,j} \) and \( \gamma_{k,j}^{t_{m_k}} \) be a parametrization of \( \Gamma_{k,j}^{t_{m_k}} \), oriented clockwise for \( j \geq 1 \) or \( k = 0 \) and counterclockwise when \( j = 0 \) and \( k \geq 1 \), it follows from (27) and a mollification argument, since \( \mathcal{H}^1(\Gamma_{k,j}^{t_{m_k}}) \) is bounded for fixed \( k,j \) as \( \ell \to \infty \), that \( \gamma_{k,j}^{t_{m_k}} \) converges weak-* to \( \gamma_{k,j} \). Applying pointwise a rotation by \( \pi/2 \), this is tantamount to say that \( R_{\gamma_{k,j}}^{t_{m_k}} \) converges weak-* to \( R_{\gamma_{k,j}}^{t_{0}} \), thereby proving (ii). Note that when \( \mathcal{H}^1(\Gamma_{k,j}) > 0 \), then the assertion of item (iv) follows immediately from items (ii) and (iii). Now suppose \( \mathcal{H}^1(\Gamma_{k,j}) = 0 \). Let \( f \in C_c(\mathbb{R}^2) \) and \( \epsilon > 0 \). By uniform continuity, there is some \( \delta > 0 \) such that \( |f(x) - f(y)| < \epsilon \) whenever \( |x - y| < \delta \). Let \( L_\ell \) be such that \( \text{diam}(\Gamma_{k,j}^{t_{m_k}}) < \delta \) for \( \ell \geq L_\ell \). Since \( R_{\gamma_{k,j}}^{t_{m_k}} \) is divergence free for all \( j,k,\ell \), it annihilates constant functions. Thus, for \( x_\ell \in \Gamma_{k,j}^{t_{m_k}} \), we have

\[
|\langle f, R_{\gamma_{k,j}}^{t_{m_k}} \rangle| = |\langle f - f(x_\ell), R_{\gamma_{k,j}}^{t_{m_k}} \rangle| \leq \epsilon \mathcal{H}^1(\Gamma_{k,j}^{t_{m_k}}),
\]
which verifies (iv) in this case.

In the discussion before Proposition 4.4, we identified the curves \( \{ \Gamma_k^+ \}_{k \in K} \) and \( \{ \Gamma_j^- \}_{j \in J} \) forming the measure-theoretical boundary of a set of finite perimeter with (the equivalence classes of) an element of \( T \) of the form \( S = (S_{k,j})_{k,j \in \mathbb{N}} \) where \( S_{k,j} \) is (the interior of) a (possibly degenerate) Jordan curve oriented clockwise for \( j \geq 1 \) or \( k = 0 \), while \( S_{k,0} \) is (the exterior of) a Jordan curve oriented counterclockwise when \( k \geq 1 \). We let \( \mathcal{C} \subset T \) denote the set of such elements, and \( \hat{\mathcal{C}} \) the set of equivalence classes. Recalling that \( \mathcal{M}(\mathbb{R}^2)^2 \) equipped with the weak-* topology is a metric space, say with distance \( d_w \), we endow \( \mathcal{C} \) with the distance \( d_C ((S_{k,j}), (S'_{k,j})) := \sup_{k,j} d_w (S_{k,j}, S'_{k,j}) \) and \( \hat{\mathcal{C}} \) with the quotient topology. We also find it more convenient to enumerate with a single index the curves \( S_{k,j} \) constitutive of \( S \in \mathcal{C} \): for this, we choose a bijection \( \sigma : \mathbb{N}^2 \to \mathbb{N} \) and we write \( \Gamma_{\sigma(k,j)} := S_{k,j} \). The orientation of the corresponding parametrized curve \( \gamma_{\sigma(i,j)} \) will depend on the choice of \( \sigma \), and so do the permutations defining equivalence classes in \( \hat{\mathcal{C}} \), but our results will not. We can now state the representation theorem for divergence-free measures in the plane:

**Theorem 4.5.** Let \( \nu \in \mathcal{M}(\mathbb{S})^2 \) be divergence-free in \( \mathbb{R}^2 \). Then, there exists \( G \subset \mathbb{R} \) with \( L_1(\mathbb{R} \setminus G) = 0 \) such that, for \( t \in G \), there is a countable collection of (possibly degenerate) parametrized rectifiable Jordan curves \( \{ \gamma_n^i \}_{n \in \mathbb{N}} \) with images \( \Gamma^i_n \) such that:

(i) the \( \Gamma^i_n \) are disjoint up to a set of \( H^1 \)-measure zero and \( \Gamma^i_n \subset \text{supp} \nu \) for each \( n \);

(ii) the union \( \bigcup_n \Gamma^i_n \) is, up to a set of \( H^1 \)-measure zero, the measure-theoretical boundary \( \partial_M \Omega(t) \) of a set \( \Omega(t) \subset \mathbb{R}^2 \) of finite perimeter;

(iii) \( \Omega(t_1) \supset \Omega(t_2) \) if \( t_1 < t_2 \), and the mapping \( t \mapsto (\gamma_n^i)_{n \in \mathbb{N}} \) from \( \mathbb{R} \) to \( \hat{\mathcal{C}} \) is approximately continuous for a.e. \( t \);

(iv) For any Borel set \( B \subset \mathbb{R}^2 \), \( g \in L^1[d|\nu|^2] \) and \( h \in L^1[d|\nu|] \), it holds that

\[
\nu(B) = \int \sum_{n \in \mathbb{N}} \left( \int_B \tau^i_n \, d \left( H^1[\Gamma^i_n] \right) \right) dt,
\]

where \( \tau^i_n = (\gamma_n^i)'/|\gamma_n^i'| \) is the unit tangent vector field to \( \Gamma^i_n \) oriented by \( \gamma_n^i \),

\[
|\nu|(B) = \int \mathcal{H}^1(\partial_M \Omega(t) \cap B) dt = \int \left( \sum_{n \in \mathbb{N}} \mathcal{H}^1(\Gamma^i_n \cap B) \right) dt,
\]

\[
\int g \cdot d\nu = \int \sum_{n \in \mathbb{N}} \left( \int \mathcal{H}^1[\Gamma^i_n] \right) dt,
\]

and

\[
\int h d|\nu| = \int \sum_{n \in \mathbb{N}} \left( \int h \, d \left( H^1[\Gamma^i_n] \right) \right) dt,
\]

where the inner integrals on the right handsides of (70) and (71) are well defined for a.e. \( t \in \mathbb{R} \).

(v) The set \( J := \bigcup_{t_1, t_2 \in G} \Gamma_{n_1}^{i_1} \cap \Gamma_{n_2}^{i_2} \) is 1-rectifiable in \( \mathbb{R}^2 \) and \( \nu |_J \) is absolutely continuous with respect to \( \mathcal{H}^1 \); for a.e. \( t \in G \), \( u_\nu(x) = \tau^i_n(x) \) for \( \mathcal{H}^1 \)-a.e. \( x \in J \cap \partial_M \Omega(t) \). More generally, it holds for a.e. \( t \in G \) and every \( n \in \mathbb{N} \) that \( u_\nu(x) = \tau^i_n(x) \) for \( \mathcal{H}^1 \)-a.e. \( x \in \Gamma^i_n \).

**Proof.** By Lemmas 2.1 and 3.3, we have \( \nu(B) = \nabla \phi(B) \) for some \( \phi \in BV(\mathbb{R}^2) \). Defining \( E_t \) as in (28), we get from Lemma 3.4 that it has finite perimeter for a.e. \( t \). We let \( G \) be the set of
such $t$, and for $t \in G$ we let $\{\gamma^t_n\}_{n \in \mathbb{N}}$ be a representative in $C$ of the element of $\tilde{C}$ corresponding to the family of curves $(\gamma^t_{k,j}) \in T$ appearing in Proposition 4.4; see discussion after the proof of that proposition. If we set $\Omega(t) = E_t$, then $(ii)$ and the first assertion in $(i)$ come from Lemma 4.3; the first assertion in $(iii)$ is obvious and the second on approximate continuity follows from Proposition 4.4 much like Theorem 3.9 did from Proposition 3.8. Recalling definition (13), we see that Theorem 4.6 and the remark after Lemma 3.2 together imply $(iv)$, where it should be noted that equations (68) through (71) only depend on the equivalence class of $\{\gamma^t_n\}_{n \in \mathbb{N}}$ in $\tilde{C}$. Since (69) implies that $H^1(\Gamma_n(t) \setminus \supp \nu) = 0$ for a.e. $t \in G$ the second half of $(i)$ holds.

Observing that $\bigcup_{n \in \mathbb{N}} \Gamma^t_n = \partial_M E_1 \mod H^1$, we see for each $t \in G$ that every $x \in J$ lies in $\partial_M (\mathbb{R}^2 \setminus E_{t_1}) \cap \partial_M E_{t_2}$ for some $t_1 < t_2$. Remembering the definitions in (11), this implies that, for every $x \in J$, $\phi^{\inf}(x) \leq t_1 < t_2 \leq \phi^{\sup}(x)$. Hence, by Lemma 3.7 $J \subset J(\varphi)$ and the first two assertions of $(v)$ follow. Now, evaluating $\|\nu\|$ with (69) and integrating (70) against $u_\nu$ we get,

$$
\int_{\mathbb{R}} \left( \sum_{n \in \mathbb{N}} H^1(\Gamma^t_n) \right) dt = \|\nu\| = \int \left( \sum_{n \in \mathbb{N}} \int \nu_\mathcal{L} \cdot \tau^t_n d(H^1|\Gamma^t_n) \right) dt,
$$

and noting that $u_\nu \cdot \tau^t_n \leq 1$, with equality only when $u_\nu = \tau^t_n$, gives us the last assertion of $(v)$. 

Decomposition (66)–(69) is a special case of (21), as we now show.

**Proposition 4.6.** Let $\nu \in \mathcal{M}(S)^2$ be divergence-free in $\mathbb{R}^2$, with $G$, $\{\gamma^t_n\}_{n \in \mathbb{N}}$ and $\Gamma^t_n$ as in Theorem 4.3; take $\tilde{\gamma}^t_n$ to be the periodic extension to $\mathbb{R}$ of $\gamma^t_n$. If we set

$$(72) \quad \rho(\mathcal{B}) := \int_{\mathbb{R}} \sum_{n \in \mathbb{N}} H^1(\Gamma^t_n) \delta_{T_{\tilde{\gamma}^t_n}}(\mathcal{B}) dt \quad \text{for every Borel } \mathcal{B} \subset \mathcal{G}(\mathbb{R}^2),$$

then the integral exists and $\rho$ defines a Borel measure on $\mathcal{G}(\mathbb{R}^2)$ such that (21) holds with $\mu = \nu$.

**Proof.** As in Section 2.2 let $B_1$ denote the unit ball in $\mathcal{M}(\mathbb{R}^2)^2$ with the weak-* topology. Let $\mathcal{B} \subset B_1$ be Borel, and $F : \mathbb{R} \to \mathbb{R}$ denote the integrand in (72). Recall from Proposition 4.3 the $\sigma$-compact sets $\Sigma_\eta$ such that $L^1(\mathbb{R} \setminus \Sigma_n) < \eta$ for $\eta > 0$. By the Borel-Cantelli lemma, $\Sigma_0 := \bigcup_{j \in \mathbb{N}} \Sigma_{1/j^2}$ is $\sigma$-compact such that $L^1(\mathbb{R} \setminus \Sigma_0) = 0$. Hence, if $F|\Sigma_\eta$ is a Borel function, then $F$ is also Borel. We will show that $F|\Sigma_\eta$ is Borel by writing it as a composition of Borel functions.

Let $Q := \ell_1(\mathbb{N}) \times B^1_\mathcal{N}$ where $B^1_\mathcal{N}$ is given the product topology, and $\bar{Q}$ denote the quotient space under the relation $(a_n, \mu_n) \sim (b_n, \nu_n)$ if and only if there is a bijection $\sigma : \mathbb{N} \to \mathbb{N}$ such that $b_{\sigma(n)} = a_n$ and $\nu_{\sigma(n)} = \mu_n$. We endow $\bar{Q}$ with the quotient topology. Define $f_1 : \Sigma_\eta \to \bar{Q}$ by $f_1(t) := [(H^1(\Gamma^t_n), T_{\tilde{\gamma}^t_n})]$, where the bracket represents the equivalence class; note that indeed $\sum_n H^1(\Gamma^t_n) < \infty$, because this sum is $P(E_t)$ which is uniformly bounded on $\Sigma_\eta$ by construction, see proof of Proposition 3.3. By points (iii) and (iv) of Proposition 4.4, $f_1$ is continuous (observe that $\sim$ takes quotient by all permutations, not just those used to define $T$, which does not affect continuity). Now let $f_2 : Q \to \mathbb{R}$ be defined by $f_2(a_n, \mu_n) := \sum_n a_n \chi_\mathcal{N}(\mu_n)$. Clearly, $f_2$ is Borel since it is the limit of Borel functions, and since it is invariant under permutations on $n$ the quotient map $f_2 : \bar{Q} \to \mathbb{R}$ is well-defined and Borel.

Altogether, $F|\Sigma_\eta = f_2 \circ f_1$, is Borel and so is $F$. Hence, since $F$ is nonnegative and its integral is bounded by $\int_{\mathbb{R}} \sum_{n \in \mathbb{N}} H^1(\Gamma^t_n) = \|\nu\|$, the set function $\rho$ given by (72) defines a Borel measure on $B_1$. By restriction $\rho$ defines a Borel measure on $\mathcal{G}(\mathbb{R}^2)$. Finally we will show that the left equation of (21) holds, the proof for the right one is similar. Let $B \subset \mathbb{R}^2$ be Borel, $\{a_i\}_{i=0}^n$ be a partition of $[-1,1]$, $(T_1, T_2)$ be the components of $T$, for $i < n$ and $j = 1, 2$, $\mathcal{T}_i := \{T \in \mathcal{G}(\mathbb{R}^2) : a_{i-1} \leq f_3(T) \leq a_i\}$ be
$T_j(B) < a_i$, $\mathcal{A}_i' := \{ T \in \mathcal{G}(\mathbb{R}^2) | a_{n-1} \leq T_j(B) \leq 1 \}$, $M_j = \sum_i a_i \rho(\mathcal{A}_i')$ and $m_j = \sum_i a_{i-1} \rho(\mathcal{A}_i')$. Then

$$m_j = \sum_i a_{i-1} \int_{\mathbb{R}} \sum_{n \in \mathbb{N}} \mathcal{H}^1(\Gamma_n') \delta_{T_n'}(\mathcal{A}_i') dt \leq \int_{\mathbb{R}} \sum_i a_{i} T_n' \in \mathcal{A}_i \mathcal{H}^1(\Gamma_n')(T_n')_j(B) dt,$$

where the right-hand side of this equation is equal to $(\nu(B))_j$ in view of (68), Fubini’s theorem and the fact that the $\mathcal{A}_i'$’s form a partition of $\mathcal{G}(\mathbb{R}^2)$. Analogously $(\nu(B))_j \leq M_j$, hence, taking the limit as $\max\{a_i - a_{i-1}\} \to 0$ and using $\rho(\mathcal{G}(\mathbb{R}^2)) = \|\nu\| < \infty$, we get (21).

Theorem (iii) asserts approximate continuity of $\partial_M \Omega(t)$ with respect to $t$ in the weak-* sense. Still, the $\Omega(t)$ could all have different topologies as can be seen from the following example.

Example 4.1. We will generate a $BV$ function $\varphi_\infty$, valued in $[0, 1]$, whose suplevel sets $E_t$ all have different topologies. Then, $\nu := \mathcal{G} \varphi_\infty$ is divergence-free and $\Omega(t) = E_t$ in Theorem 15 thereby yielding an example with the aforementioned property.

We construct $\varphi_\infty$ as the limit of a bounded increasing sequence $(\varphi_m)$ of $BV$ functions. Let us first define a family of sets of finite perimeter that we will use to construct the $\varphi_m$. For any two integers $m$ and $n$ such that $m \geq 0$ and $1 \leq n \leq 2^m$, define the set $b(n, m) \subset \mathbb{R}^2$ to be the closed ball around the point $(n, m)$ with perimeter $2^{-2m-1}$ (thus, radius $2^{-2m-2}/\pi$) minus $2^m$ pairwise disjoint nonempty open balls contained in this closed ball. We pick the sum of the perimeters of this $2^m$ open balls to be strictly less than $2^{-2m-1}$. Note that the $(n, m)$ are pairwise disjoint. Define $\varphi_0 := \frac{1}{2} \chi_{b(1,0)}$ and, for $m > 0$, $\varphi_m := \varphi_{m-1} + \sum_{k=1}^{2^m} \frac{2^m - 1}{2^m+1} \chi_{b(k,m)}$. Then $\|\nabla \varphi_0\|_{TV} < 1/2$, moreover for $m > 0$:

$$\|\nabla \varphi_m\|_{TV} = \|\nabla \varphi_{m-1}\|_{TV} + \sum_{k=1}^{2^m} \frac{2^m - 1}{2^m+1} \|\nabla \chi_{b(k,m)}\|_{TV}$$

$$< \|\nabla \varphi_{m-1}\|_{TV} + \sum_{k=1}^{2^m} \frac{2^m - 1}{2^m+1} (2^{-2m-1} + 2^{-2m-1})$$

$$= \|\nabla \varphi_{m-1}\|_{TV} + \frac{2^{2m}}{2^{2m+1}},$$

and hence, $\|\nabla \varphi_m\|_{TV} < 1$ for every $m$. Thus, $\varphi_\infty$, the pointwise limit of the nondecreasing sequence of functions $\{\varphi_m\}_m$, is a BV function (see 29 Theorem 5.2.1).

Now, for $m, n, p, q$ some integers such that $1 \leq n \leq 2^m$ and $1 \leq p \leq 2^q$, it is clear that $b(n, m)$ is topologically equivalent to $b(p, q)$ if and only if $q = m$. Hence, with the notation of Theorem 15 we see that given $s, t \in (0, 1)$, the sets $\Omega(t)$ and $\Omega(s)$ can be topologically equivalent only if they contain, for each fixed $m$, the same number of sets from the family $\{b(n, m)\}_{n=1}^{2^m}$. However if $s < t$ then there exist two positive integers $m$ and $n$ such that $s < \frac{2m - 1}{2^{2m+1}} < t$, thus $b(n, m) \subset \Omega(s) \setminus \Omega(t)$ and therefore $\Omega(t)$ is not topologically equivalent to $\Omega(s)$.

5. Applications to Inverse Magnetization Problems

5.1. Solutions to Extremal Problem 1. For $\mu, \nu \in M(\mathbb{R}^3)$ with $f_\mu$ to denote the Radon-Nikodym derivative of $\mu$ with respect to $|\nu|$, we define for $|\nu|$-a.e. $x$:

$$w_\nu^\nu(x) := \begin{cases} \frac{f_\mu(x)}{f_\mu(x)}, & f_\mu(x) \neq 0, \\ u_\nu(x), & f_\mu(x) = 0. \end{cases}$$

(73)
We put $E = f^{-1}_\mu(0)$ and observe that

$$
\int w_\mu^\nu \cdot d\nu = \int_{E^c} w_\mu^\nu \cdot u_\nu \, d|\nu| + |\nu|(E). \tag{74}
$$

The next lemma provides a variational characterization of solutions to Extremal Problem 1.

**Lemma 5.1.** Let $S \subset \mathbb{R}^3$ be closed and suppose $\mu, \nu \in \mathcal{M}(S)^3$, with $w_\mu^\nu$ and $E$ as above. Then

$$
||\mu||_{TV} \leq ||\mu + t\nu||_{TV}, \text{ for every } t > 0,
$$

if and only if

$$
\int w_\mu^\nu \cdot d\nu \geq 0. \tag{76}
$$

Hence, $||\mu||_{TV} = M_S(\mu)$ if and only if (76) holds for every $S$-silent $\nu \in \mathcal{M}(S)^3$. The inequality (75) is strict for every $t > 0$ if the inequality (76) is strict.

**Proof.** Let $\mu_s$ denote the singular part of $\mu$ with respect to $|\nu|$. Then, for $\epsilon > 0$,

$$
||\mu + \epsilon\nu||_{TV} = \int |f_\mu + \epsilon u_\nu| \, d|\nu| + ||\mu_s||_{TV}
$$

$$
= \int_{E^c} |f_\mu + \epsilon u_\nu| \, d|\nu| + \epsilon|\nu|(E) + ||\mu_s||_{TV}
$$

$$
= ||\mu||_{TV} + \epsilon \left( \int_{E^c} w_\mu^\nu \cdot u_\nu \, d|\nu| + |\nu|(E) \right) + o(\epsilon)
$$

$$
= ||\mu||_{TV} + \epsilon \int w_\mu^\nu \cdot d\nu + o(\epsilon), \tag{77}
$$

where the above used that for $a, b \in \mathbb{R}^3$, $a \neq 0$ and $|b| = 1$ (with $a = f_\mu$ and $b = u_\nu$),

$$
|a + \epsilon b| = |a| \left( 1 + 2\epsilon \frac{a \cdot b}{|a|^2} + \epsilon^2 \frac{|b|^2}{|a|^2} \right)^{1/2} = |a| + \epsilon \frac{a}{|a|} \cdot b + \frac{1}{|a|} O(\epsilon^2),
$$

together with $|\nu|(\{x : 0 < |f_\mu(x)| < \epsilon\}) = o(1)$ as $\epsilon \to 0$. Using the convexity of the TV-norm we have for $0 < \epsilon \leq 1$ and $t > 0$:

$$
||\mu + t\epsilon\nu||_{TV} = ||(1 - \epsilon)\mu + \epsilon(\mu + t\nu)||_{TV} \leq (1 - \epsilon)||\mu||_{TV} + \epsilon||\mu + t\nu||_{TV},
$$

which implies

$$
\frac{t||\mu + \epsilon t\nu||_{TV} - ||\mu||_{TV}}{t\epsilon} \leq ||\mu + t\nu||_{TV} - ||\mu||_{TV}. \tag{78}
$$

If (76) holds, then it follows in view of (77) (with $t\epsilon$ instead of $\epsilon$) that the limit of the left-hand side of (78) is nonnegative when $\epsilon \to 0^+$, which implies (75). Conversely, if (75) holds then the left hand side of (78) is nonnegative and using (77) we can take the limit as $\epsilon \to 0^+$ to obtain (76). That the inequality (75) is strict for every $t > 0$ when the inequality (76) is strict follows immediately from the above computations. \hfill \square

We say that $\mu \in \mathcal{M}(S)^3$ is carried by a set if that set has full $|\mu|$-measure; i.e., the complement has $|\mu|$-measure zero. Recall that a set $B \subset \mathbb{R}^n$ is purely 1-unrectifiable if $\mathcal{H}^1(E \cap B) = 0$ for every 1-rectifiable set $E$. Clearly a set of $\mathcal{H}^1$-measure zero is purely 1-unrectifiable.
Theorem 5.2. Let $S \subset \mathbb{R}^3$ be slender and closed and suppose $\tilde{\mu} \in \mathcal{M}(S)^3$ is carried by a purely 1-rectifiable set. Then $\tilde{\mu}$ is strictly TV-minimal. Moreover, if $\mu \in \mathcal{M}(S)^3$ is TV-minimal on $S$, then so is $\mu + \tilde{\mu}$.

Proof. Since $S$ is slender, any $S$-silent magnetization $\nu$ is divergence-free. From the decomposition (16), we then have that $\nu$ and $\tilde{\mu}$ are mutually singular since the latter is carried by a purely 1-rectifiable set, showing that $\tilde{\mu}$ is strictly TV-minimal.

Next suppose $\mu \in \mathcal{M}(S)^3$ satisfies $\|\mu\|_{TV} = M_S(\mu)$ and $\nu \in \mathcal{M}(S)^3$ be $S$-silent. Since $\nu$ and $\tilde{\mu}$ are mutually singular, $d\tilde{\mu}/d\nu| = 0$ and thus, recalling definition (79), we see that $w^\nu_{t\mu} = w^\nu_{t\mu + \tilde{\mu}}$ $\nu$-a.e. Lemma 5.1 then implies $\|\mu + \tilde{\mu}\|_{TV} = M_S(\mu + \tilde{\mu})$.

The first assertion of Theorem 5.2 sharpens Theorem 2.6 of [5] stating that a magnetization supported on a purely 1-rectifiable set is strictly TV-minimal. In the case that $S$ is planar, this result can be strengthened by the following theorem.

Theorem 5.3. Let $S \subset \mathbb{R}^2 \times \{0\}$ be closed and suppose $\mu$ is a magnetization carried by a Borel set $Z \subset S$ that satisfies

$$\mathcal{H}^1(\Gamma \cap Z) \leq \mathcal{H}^1(\Gamma \setminus Z),$$

for any rectifiable Jordan curve $\Gamma \subset S$. Then $\mu$ is TV-minimal on $S$. If $\nu \in \mathcal{M}(S)^3$ is $S$-silent and $\|\mu + \nu\|_{TV} = \|\mu\|_{TV}$, then equality holds in (79) when $\Gamma = \Gamma_t$ for almost every $t$ and every $n \in \mathbb{N}$ in the loop decomposition of $\nu$. In particular, $\mu$ is strictly TV-minimal on $S$ if the inequality (79) is strict for every nondegenerate $\Gamma \subset S$, and then $\mu + \tilde{\mu}$ is also strictly TV-minimal when $\tilde{\mu}$ is carried by a purely 1-rectifiable set.

Proof. Let $\nu$ be an $S$-silent magnetization with $f_{\nu}^\mu$, $w_{\nu}^\mu$ as in (73), and loop decompositions $\{\Gamma_t\}$ and recall $E = f_{\nu}^{-1}(0)$. Also let $\mu_\nu$ denote the singular part of $\mu$ with respect to $|\nu|$. By Lemma 2.4, $\nu = (\nu_T, 0)$ where $\nu_T \in \mathcal{M}(S)^2$ is divergence-free. For $t \in \mathbb{R}$ and $n \in \mathbb{N}$, let $\Gamma_t$ and $\tau_t$ be as in Theorem 4.5 from the decomposition of $\nu_T$.

By assertion (v) of Theorem 4.5 we know for a.e. $t \in \mathbb{R}$ and for every $n \in \mathbb{N}$ that $u_{\nu}(x) = (\tau_n^{-1}(x), 0)$ for $\mathcal{H}^1$-a.e. $x \in \Gamma_t$. Note also that by (iv) of Theorem 4.5 $w_{\nu}^\mu \cdot (\tau_t, 0)$ is $\mathcal{H}^1$-integrable on $\Gamma_t$ for every $n \in \mathbb{N}$ and a.e. $t \in \mathbb{R}$. Now, for every such $t$,

$$\int_{\Gamma_t} w_{\nu}^\mu \cdot (\tau_t, 0) d\mathcal{H}^1 = \int_{\Gamma_t \cap E^c} w_{\nu}^\mu \cdot (\tau_t, 0) d\mathcal{H}^1 + \int_{\Gamma_t \cap E} u_{\nu} \cdot (\tau_t, 0) d\mathcal{H}^1$$

$$= \int_{\Gamma_t \cap E^c} w_{\nu}^\mu \cdot (\tau_t, 0) d\mathcal{H}^1 + \mathcal{H}^1(\Gamma_t \cap E)$$

$$\geq -\mathcal{H}^1(\Gamma_t \cap E^c) + \mathcal{H}^1(\Gamma_t \cap E).$$

From (71) we have

$$0 = \int_{Z^c} |f_{\nu}| d|\nu| = \int_{E^c} \sum_{n \in \mathbb{N}} \left( \int_{Z^c} |f_{\nu}| d(\mathcal{H}^1|_{\Gamma_t}^n) \right) dt.$$

Observing that $|f_{\nu}(x)| > 0$ for $x \in E^c$, the above equation implies that the $L_1$-measure of

$$T_0 := \{ t \in \mathbb{R} \mid \exists n \in \mathbb{N} : \mathcal{H}^1(\Gamma_t \cap E^c \cap Z^c) \neq 0 \}$$

is zero; that is, $\mathcal{H}^1(\Gamma_t \cap E^c \cap Z^c) = 0$ for a.e. $t$. Thus, by (80) we get

$$\int_{\Gamma_t} w_{\nu}^\mu \cdot (\tau_t, 0) d\mathcal{H}^1 \geq -\mathcal{H}^1(\Gamma_t \cap Z) + \mathcal{H}^1(\Gamma_t \setminus Z) \geq 0,$$
where the last inequality follows from the condition (79). Therefore, by (80),
\[
\int_{\mathbb{R}^2} w_\mu \cdot d\nu = \int_{\mathbb{R}} \sum_{n \in \mathbb{N}^2} \left( \int_{\mathbb{R}^2} w_\mu \cdot (\tau_n^j, 0) d(\mathcal{H}^1(\Gamma_n^j)) \right) dt \geq 0,
\]
and, hence, Lemma 5.1 gives us \(\|\mu\|_{TV} \leq \|\mu + \nu\|_{TV}\). Moreover, if there is a set of positive measure \(E \subset \mathbb{R}\) such that for every \(t \in E\) there exists an \(n\) for which the rightmost inequality in (81) is strict, then the inequality in (82) is also strict. Finally, (79) is invariant upon adding a purely 1-rectifiable set to \(Z\).

**Corollary 5.4.** Let \(S \subset \mathbb{R}^2 \times \{0\}\) be closed and suppose \(\mu\) is a magnetization carried by a Borel set \(Z \subset S\) that is contained in a purely 1-rectifiable set plus a countable union \(\bigcup_{k \in K} L_k\) where the \(L_k\) are disjoint line segments such that the distance from any \(L_k\) to any \(L_j, j \neq k\), is greater than or equal to the length of \(L_k\). Then (79) holds for any rectifiable Jordan curve \(\Gamma\), and thus \(\mu\) is TV-minimal on \(S\). Moreover, if the distance from any \(L_k\) to any \(L_j, j \neq k\), is strictly greater than the length of \(L_k\), then (79) is strict and \(\mu\) is strictly TV-minimal on \(S\).

**Proof.** By the last assertion of Theorem 5.3 it is enough to assume \(Z\) is contained in a countable union of line segments with the aforementioned properties. Let \(\Gamma\) be a rectifiable Jordan curve oriented by a parametrization \(\tau\). Without loss of generality we may assume that \(Z \cap L_k \neq \emptyset\) for all \(k \in K\). If \(K = \{1\}\) is a singleton, then (since \(L_1\) is a line segment)
\[
\mathcal{H}^1(\Gamma \cap Z) \leq \mathcal{H}^1(\Gamma \cap L_1) < \mathcal{H}^1(\Gamma \setminus L_1) \leq \mathcal{H}^1(\Gamma \setminus Z).
\]
Otherwise, for each \(k \in K\) there is some directed sub-arc \(\Gamma_k \subset \Gamma\) with initial point in \(L_k\), endpoint in some \(L_j\) for \(j \neq k\), and interior in the complement of \(\bigcup_{\ell \neq k} L_\ell\). Note that for \(j \neq k\), the interiors of \(\Gamma_k\) and \(\Gamma_j\) are disjoint, and that \(\mathcal{H}^1(\Gamma \cap L_k) \leq \mathcal{H}^1(\Gamma_k)\) by assumption. Also note that this inequality is strict under the final assumption. Thus,
\[
\mathcal{H}^1(\Gamma \cap Z) \leq \sum_{k \in K} \mathcal{H}^1(\Gamma \cap L_k) \leq \sum_{k \in K} \mathcal{H}^1(\Gamma_k) \leq \mathcal{H}^1(\Gamma \setminus Z),
\]
where the second inequality is strict under the last assumption. □

We next characterize the space of S-silent magnetizations when \(S\) contains only a finite number of Jordan curves. First we consider the class of closed \(S \subset \mathbb{R}^2\) that contain no rectifiable Jordan curve at all, and hence, cannot hold nontrivial silent magnetizations. We call such \(S\) tree-like. Note that any closed purely 1-rectifiable set is tree-like, but the converse is not true. We also note that a tree-like set may contain a Jordan curve, such as the Koch curve, which is not rectifiable. As a consequence of Theorem 5.3 we obtain the following result.

**Lemma 5.5.** Let \(S\) be a closed subset of \(\mathbb{R}^2 \times \{0\}\). If \(\mu \in M(S)^3\) is nonzero and \(S\)-silent, then the support of \(\mu\) contains a rectifiable Jordan curve. Hence, if \(S\) is tree-like the only \(S\)-silent magnetization is the zero magnetization.

**Proof.** Since \(S \subset \mathbb{R}^2 \times \{0\}\), it is slender and hence \(S\)-silent magnetizations are divergence free. The lemma now follows from Theorem 4.5. □

For a closed set \(S \subset \mathbb{R}^2 \times \{0\}\), let \(\Sigma(S)\) denote the linear subspace of \(M(S)^3\) consisting of \(S\)-silent sources. The previous lemma shows that \(\Sigma(S)\) is the trivial subspace when \(S\) is tree-like. The next theorem provides sufficient conditions that \(\Sigma(S)\) is finite dimensional and generalizes the second assertion of Lemma 5.5 when \(\mathcal{H}^1(S)\) is finite.
Theorem 5.6. Let $S \subset \mathbb{R}^2 \times \{0\}$ be closed with empty interior. If the number $n$ of bounded connected components of $\mathbb{R}^2 \times \{0\} \setminus S$ is finite, then the dimension of $\Sigma(S)$ is less than or equal to $n$. Furthermore, the dimension is equal to $n$ if $H^1(S)$ is finite.

Proof. Let $S' \subset S$ be the union of all rectifiable Jordan curves contained in $S$ and let $m$ be the number of bounded connected components of $\mathbb{R}^2 \setminus S'$. Since $(\mathbb{R}^2 \setminus S) \cup (S \setminus S') = (\mathbb{R}^2 \setminus S')$ and the set $S \setminus S'$ is a subset of the topological boundary of $\mathbb{R}^2 \setminus S$, then $n \geq m$. From Theorem 4.5 it follows that $\Sigma(S) = \Sigma(S')$, thus showing that $\dim \Sigma(S') = m$ will prove our theorem.

Let $\{E_i\}_{i=1}^m$ be the family of bounded connected components of $\mathbb{R}^2 \setminus S'$. Note that each $E_i$ is of finite perimeter since $H^1(S')$ is finite. Let $\ell_i := \Re \nabla \chi_{E_i}$ for $i = 1, \ldots, m$. By Lemma 2.1 each $\ell_i$ is $S'$-silent. To show that $\{\ell_i\}_{i=1}^m$ generates $\Sigma(S')$, it is sufficient by Theorem 4.5 to prove that for any rectifiable Jordan curve $\Gamma \subset S'$ with arclength parametrization $\gamma$, the magnetization $R_\gamma$ defined by (12) is in the span of the $\ell_i$'s.

Using the Jordan curve theorem we can see that for any $E_i$ such that $\text{int}(\Gamma) \cap E_i \neq \emptyset$ we have that $E_i \subset \text{int}(\Gamma)$. Hence there exists a $J \subset \{1, \ldots, m\}$ such that $\bigcup_{i \in J} E_i \subset \text{int}(\Gamma) \subset S' \cup \bigcup_{i \in J} E_i$ and since $L_2(S') = 0$, then

$$
R_\gamma = \Re \nabla \chi_{\text{int}(\Gamma)} = \Re \nabla \chi_{\bigcup_{i \in J} E_i}
$$

where the first equality comes from the remark after Lemma 3.2, equation (26), and Lemma 4.2.

To show linearly independence, assume that $\sum_{i=1}^m c_i \ell_i = 0$ where $c_i \in \mathbb{R}$, $i = 1, \ldots, m$. Since $0 = \sum_{i=1}^m c_i \Re \nabla \chi_{E_i} = \Re \nabla \left(\sum_{i=1}^m c_i \chi_{E_i}\right)$, thus $\sum_{i=1}^m c_i \chi_{E_i}$ is a constant but since the $E_i$'s are bounded and disjoint then each $c_i = 0$ and hence the $\ell_i$'s are indeed linearly independent. $\square$

5.2. Regularization by penalizing the total variation. Let $S \subset \mathbb{R}^2 \times \{0\}$ and $Q \subset \mathbb{R}^3$ be closed and positively separated. For $\mu \in \mathcal{M}(S)^3$ and $v$ a unit vector in $\mathbb{R}^3$, the component of the magnetic field $b(\mu)$ in the direction $v$ at $x \notin S$ is given, in view of (1), by

$$
b_v(\mu)(x) := v \cdot b(\mu)(x) = -\frac{\mu_0}{4\pi} \int K_v(x - y) \cdot d\mu(y),
$$

where

$$
K_v(x) = \frac{v}{|x|^3} - 3x \frac{v \cdot x}{|x|^5} = \nabla \left(\frac{v \cdot x}{|x|^2}\right).
$$

Consider a finite, positive Borel measure $\rho$ with support contained in $Q$ and let $A : \mathcal{M}(S)^3 \to L^2(Q, \rho)$ be the so-called forward operator defined by

$$
A(\mu)(x) := b_v(\mu)(x), \quad x \in Q.
$$

The adjoint operator $A^*$ is then given by (see [5, Section 3])

$$
A^*(\Psi)(x) := -\mu_0 \nabla (\nabla U^{\rho} \cdot v)(x), \quad U^{\rho} \Psi(x) = -\frac{1}{4\pi} \int \frac{\Psi(y)}{|x - y|} d\rho(y).
$$

Since $Q$ and $S$ are positively separated it follows from the harmonicity of $K_v$ that $A^*(\Psi) \in C_0(S)^3$ and thus $A^* : (L^2(Q, \rho))^* \sim L^2(Q, \rho) \to C_0(S)^3 \subset (\mathcal{M}(S)^3)^*$. Note the kernel of the forward operator $A$ contains all S-silent magnetizations. In the case this kernel consists exactly of S-silent magnetizations, we say that $A$ is $S$-sufficient. It follows from [5, Lemma 2.3] and the discussion thereafter that $A$ is $S$-sufficient when $S \subset \mathbb{R}^2 \times \{0\}$ and $Q \subset \mathbb{R}^3$ are positively separated closed sets and for some complete real analytic surface $A \subset \mathbb{R}^3 \setminus S$ we have:
(a) $S$ and $A$ are positively separated;
(b) $S$ lies entirely within one connected component of $\mathbb{R}^3 \setminus A$;
(c) $Q \cap A$ has Hausdorff dimension strictly greater than 1 in each connected component of $\mathbb{R}^3 \setminus S$;
(d) $\text{supp } \rho = Q$.

For $\mu \in \mathcal{M}(S)^3$, $f \in L^2(Q, \rho)$, and $\lambda > 0$, recall from (4) the definition of $\mathcal{F}_{f, \lambda}$, and from (5) the notation $\mu_\lambda \in \mathcal{M}(S)^3$ to designate a minimizer of $\mathcal{F}_{f, \lambda}$. As a second application of our results in Section 4.5 we prove:

**Theorem 5.7.** Let $S$ be a closed subset of $\mathbb{R}^2 \times \{0\}$, $Q \subset \mathbb{R}^3$ be a closed set and $\rho \in \mathcal{M}(Q)$ be such that the forward operator $A$ defined in (55) is $S$-sufficient. For $f \in L^2(Q, \rho)$ and $\lambda > 0$, the solution to (5) is unique.

*Proof.* It is well known (see e.g. [6, Proposition 3.6]) that $\mu_\lambda \in \mathcal{M}(S)^3$ is a minimizer of $\mathcal{F}_{f, \lambda}$ if and only if:

\[
A^*(f - A\mu_\lambda) = A^*(f - A\mu_\lambda)| = \frac{\lambda}{\lambda} u_\mu_\lambda \text{ a.e. and } |A^*(f - A\mu_\lambda)| \leq \frac{\lambda}{\lambda} \text{ everywhere on } S.
\]

Moreover, it follows from the strict convexity of the $L^2$-norm that $\mu'_\lambda \in \mathcal{M}(S)^3$ is another solution if and only if $A(\mu'_\lambda - \mu_\lambda) = 0$.

Assume for a contradiction that $\mu_\lambda$ and $\mu'_\lambda$ are two distinct minimizers in (55) and let $\mu := \mu'_\lambda - \mu_\lambda$. As $\mu'_\lambda - \mu_\lambda = \mu$ is absolutely continuous with respect to $|\mu|$, the Lebesgue decompositions of $\mu_\lambda$ and $\mu'_\lambda$ with respect to $|\mu|$ must have the same singular term. That is, these decompositions are necessarily of the form

\[
d\mu_\lambda = \gamma d|\mu| + d\nu, \quad d\mu'_\lambda = \gamma' d|\mu| + d\nu',
\]

where $|\nu|$ is singular with respect to $|\mu|$ and $\gamma, \gamma'$ are $|\mu|$-integrable $\mathbb{R}^3$-valued functions.

Put for simplicity $\psi = (2/\lambda)(f - A(\mu_\lambda)) = (2/\lambda)(f - A(\mu'_\lambda))$. Thanks to (87) we know that $u_{\mu_\lambda} = A^*\psi$ and $u_{\mu'_\lambda} = A^*\psi$, $\mu_\lambda$ and $\mu'_\lambda$-a.e. respectively. Now, since $d|\mu_\lambda| = |\gamma|d|\mu| + d\nu$ and $d|\mu'_\lambda| = |\gamma'|d|\mu| + d\nu'$, we have that

\[
u' d|\mu| = d\mu = u_{\mu_\lambda}d|\mu_\lambda| - u_{\mu_\lambda}d|\mu_\lambda| = A^*\psi d|\mu_\lambda| - A^*\psi d|\mu_\lambda| = A^*\psi(|\gamma'| - |\gamma|)d|\mu|.
\]

Therefore $u_\mu = A^*\psi(|\gamma'| - |\gamma|)$ at $|\mu|$-a.e point, and since $|A^*\psi| = 1$ on the supports of $\mu_\lambda$ and $\mu'_\lambda$, it holds that $u_\mu(x) = \pm_x A^*\psi(x)$ for $|\mu|$-a.e. $x$, where the choice of sign $\pm_x$ has a subscript $x$ to indicate that it may vary with $x$.

From the $S$-sufficiency of $A$ we know that $\mu$ is $S$-silent. Also, by [5, Corollary 4.2] (take $B = \mathbb{R}^2 \times \{0\}$ there), the supports of $\mu_\lambda$ and $\mu'_\lambda$ are contained in a finite collection of points and analytic arcs. In particular, there are only finitely many rectifiable Jordan curves contained in the support of $\mu$ and they are all piecewise analytic. Thus, applying Theorem 4.5 to $\mu$, we find there are finitely many piecewise analytic oriented Jordan curves $\Gamma_1, \cdots, \Gamma_N$ with respective unit tangent vector fields $\tau_1, \cdots, \tau_n$, and strictly positive real numbers $a_1, \cdots, a_N$ such that $\tau_m = \tau_n$ on $\Gamma_m \cap \Gamma_n$, $\mathcal{H}^1$-a.e. and

\[
d\mu = \sum_{n=1}^N a_n \tau_n d(\mathcal{H}^1|\Gamma_n).
\]

In particular, $d|\mu| = \sum_{n=1}^N a_n d(\mathcal{H}^1|\Gamma_n)$ and $\tau_n(x) = u_\mu(x) = \pm_x A^*\psi(x)$, for $|\mu|$-a.e. $x$, hence $\mathcal{H}^1$-a.e., on $\Gamma_n$. 

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Fix $n$ and let $E$ be an analytic sub-arc of $\Gamma_n$. Being the unit tangent to an oriented analytic arc, $\tau_n(x)$ must be an analytic function of $x \in E$, and so is $A^* \psi(x)$ by the real analyticity of $A^* \psi$, cf. (86). Hence, either $\tau_n = A^* \psi$ or $\tau_n = -A^* \psi$ everywhere on $E$. Therefore, $E$ is a subset of a trajectory of the autonomous differential equation $\dot{x} = A^* \psi(x)$. Moreover, since $E$ is bounded and perused at unit speed, the corresponding trajectory extends beyond the endpoints of $E$, and since two distinct trajectories cannot intersect we conclude that $\Gamma_n$ is smooth and constitutes a single, periodic trajectory. This, however, is impossible because $A^* \psi$ is a gradient vector field, by (86). 

When $S$ is planar and EP-1 has a unique solution, Theorem 4.3 from [3] and Theorem 5.7 together imply the following corollary.

**Corollary 5.8.** Let $S \subset \mathbb{R}^2 \times \{0\}$ be closed, the forward operator $A$ be $S$-sufficient, and $\mu_0 \in \mathcal{M}(S)^3$. Set $f = A\mu_0$ and, for $e \in L^2(Q, \rho)$, set $f_e := f + e$. For $\lambda > 0$, there is a unique minimizer $\mu_{\lambda,e}$ of (4) where $f$ gets replaced by $f_e$.

If $\|\mu\|_{TV} > \|\mu_0\|_{TV}$ for any magnetization $\mu$ that is $S$-equivalent to $\mu_0$, then $\mu_{\lambda,e}$ (resp. $|\mu_{\lambda,e}|$) converges to $\mu_0$ (resp. $|\mu_0|$) in the narrow sense as $\lambda \to 0$ and $\|e\|_{L^2(Q)}/\sqrt{\lambda} \to 0$.

Theorems 5.2 and 5.3, Corollary 5.4, and Lemma 5.5 give sufficient conditions for the uniqueness of solutions to EP-1. Hence, if $\mu_0 \in \mathcal{M}(S)^3$ is carried by a set $Z \subset S \subset \mathbb{R}^2 \times \{0\}$, then we may apply the above corollary under the following conditions:

(a) $\mathcal{H}^1(\Gamma \cap Z) < \mathcal{H}^1(\Gamma \setminus Z)$ for any rectifiable Jordan curve $\Gamma \subset S$, or
(b) $Z \subset W \cup \bigcup_{k \in K} L_k$ where $W \subset S$ is purely 1-rectifiable and the $L_k$ are disjoint line segments such that the distance from any $L_k$ to any $L_j$, $j \neq k$, is greater than the length of $L_k$, or
(c) $S$ is tree-like.

In particular, it follows from condition (b) that Corollary 5.8 applies when $\mu_0$ is carried by a countable collection of points and sufficiently separated line segments.

We conclude with an example.

**Example 5.1.** Let $v_0 = v_1 = (0,0), v_2 = (1,0), v_2 = (1,1)$, and $v_3 = (0,1)$ denote the vertices of the unit square $[0,1]^2$ and let $\gamma_i$ denote the arclength parametrization of the directed line segment from $v_i$ to $v_{i+1}$ for $i = 0, 1, 2, 3$. Let $\mu_0 = R\gamma_0 + R\gamma_2$, and $\mu_1 = -R\gamma_1 - R\gamma_2$, and let $S$ be any closed set that contains the unit square (e.g. $S = \mathbb{R}^2$). By Corollary 5.4 both $\mu_0$ and $\mu_1$ are TV-minimal on $S$. However, $\mu_0$ and $\mu_1$ are not strictly TV-minimal since $\mu_0 - \mu_1$ is the loop around $[0,1]^2$, showing that $\mu_0$ and $\mu_1$ are $S$-equivalent. Clearly, any convex combination $(1 - \alpha)\mu_0 + \alpha\mu_1$, $\alpha \in [0,1]$, is also $S$-equivalent to $\mu_0$ and TV-minimal on $S$. In fact, any TV-minimal magnetization is of this form. Indeed, taking $\mu = \mu_0$ and $Z = \text{supp } \mu_0$, in (29), the only $\Gamma$ that makes this inequality an equality is the boundary of $[0,1]$. Hence, by Theorem 5.3, any TV-minimal magnetization is of the form $\mu_0 + s(\mu_1 - \mu_0)$ for some $s \in \mathbb{R}$. Then minimality of the total variation forces $0 \leq s \leq 1$.

If we take $Q = [0,1]^2 \times \{1\}$ and $\rho = L^2(Q)$ then the forward operator $A$ is $S$-sufficient. With the notation of Corollary 5.8, we get since $\mathcal{R}\mu_0 = \mu_1$ that if $e = \mathcal{R}e$ then $\mathcal{R}f_e = f_e$. In this case, we get from Theorem 5.7 that $\mathcal{R}\mu_{\lambda,e} = \mu_{\lambda,e}$ for every $\lambda > 0$. Now, we know that any weak* limit of minimizers of EP-2 is TV-minimal, provided that both $\lambda$ and $\|e\lambda^{-1/2}\|_{L^2(Q, \rho)}$ tend to 0 (see [7] Theorems 2&5)). Because the limit should also be invariant under $\mathcal{R}$, it must be equal to $(\mu_0 + \mu_1)/2$. In particular, we get global weak* convergence of $\mu_{\lambda,e}$ and $|\mu_{\lambda,e}|$ for this example, as long as the noise $e$ has the same symmetry as the data.
APPENDIX A.

In this appendix we gather several technical results (particularly Lemma A.3) concerning the Smirnov decomposition that are needed in Section 2.

**Lemma A.1.** Let \( \gamma : [a, b] \to \mathbb{R}^n \) be a parametrized rectifiable curve, \( \Gamma = \gamma([a, b]) \) its image and \( R_\gamma \) the \( \mathbb{R}^n \)-valued measure defined by (12). Then, \( R_\gamma \) is absolutely continuous with respect to \( \mathcal{H}^1|\Gamma \), and its Radon-Nikodym derivative is given by

\[
dR_\gamma / d\mathcal{H}^1|\Gamma(x) = \sum_{t \in \gamma^{-1}(x)} \gamma'(t), \quad \mathcal{H}^1\text{-a.e. } x \in \Gamma.
\]

**Proof.** As \( |R_\gamma| \) is regular (being a finite Borel measure on \( \mathbb{R}^n \)), for any open set \( V \subset \mathbb{R}^n \) we have that

\[(88) \quad |R_\gamma|(V) = \sup\{|\langle R_\gamma, \varphi \rangle|, \varphi \in C_c(V, \mathbb{R}^n), |\varphi| \leq 1\} \leq \int_{\Gamma \cap V} N(\gamma, x) d\mathcal{H}^1(x).\]

Now, \( \mathcal{H}^1|\Gamma \) is also regular, since it is finite and every open set in \( \Gamma \) is \( \sigma \)-compact, see [21, Theorem 2.18]. In particular, if \( B \subset \mathbb{R}^n \) is a Borel set such that \( \mathcal{H}^1(B \cap \Gamma) = 0 \), then there is a decreasing sequence \( V_k \) of open sets in \( \mathbb{R}^n \) with \( V_k \supset B \cap \Gamma \) and \( \mathcal{H}^1(V_k \cap \Gamma) = 0 \). Hence, we obtain from (88), (11) and the dominated convergence theorem that

\[
|R_\gamma|(B) = |R_\gamma|(B \cap \Gamma) \leq \liminf_k |R_\gamma|(V_k) \leq \lim_k \int_{\Gamma \cap V_k} N(\gamma, x) d\mathcal{H}^1(x) = 0.
\]

Thus, \( |R_\gamma| \) and a fortiori \( R_\gamma \) are absolutely continuous with respect to \( \mathcal{H}^1|\Gamma \). Next, it holds for any Borel set \( B \subset \mathbb{R}^n \) that the characteristic function \( \chi_B|\Gamma \) is the bounded pointwise limit \( \mathcal{H}^1|\Gamma \)-a.e. (and thus \( |R_\gamma| \)-a.e. by what precedes) of a sequence of continuous functions \( g_k : \Gamma \to \mathbb{R} \) by Lusin’s theorem. Since \( g_k \) is the restriction to \( \Gamma \) of some \( f_k \in C_c(\mathbb{R}^n) \) with \( \sup |f_k| = \sup |g_k| \) by the Tietze extension theorem (for \( \Gamma \) is compact), we get from (12) that for any \( v \in \mathbb{R}^n \)

\[
\langle R_\gamma, f_k v \rangle = v \cdot \int_{\Gamma} f_k \left( \sum_{t \in \gamma^{-1}(x)} \gamma'(t) \right) d\mathcal{H}^1(x)
\]

and, applying the dominated convergence theorem to both sides when \( k \to \infty \), we conclude since \( v \) was arbitrary that

\[
R_\gamma(B) = \int_{\Gamma \cap B} \left( \sum_{t \in \gamma^{-1}(x)} \gamma'(t) \right) d\mathcal{H}^1(x). \tag{89}
\]

**Lemma A.2.** Let \( \gamma : [a, b] \to \mathbb{R}^n \) be a unit speed parametrization, \( \Gamma = \gamma([a, b]) \) its image and \( R_\gamma \) the \( \mathbb{R}^n \)-valued measure defined by (12). Then, \( \|R_\gamma\|_{TV} = \ell(\gamma) \) if and only if, for \( \mathcal{H}^1\text{-a.e. } x \in \Gamma \), we have that \( \gamma'(t) \) is independent of \( t \in \gamma^{-1}(x) \).

**Proof.** If \( \|R_\gamma\|_{TV} = \ell(\gamma) \), there is a sequence of continuous functions \( g_k \in C_c(\mathbb{R}^n, \mathbb{R}^n) \), with \( |g_k| \leq 1 \), such that

\[
\ell(\gamma) = \lim_{k \to \infty} \langle R_\gamma, g_k \rangle = \lim_{k \to \infty} \int_{\Gamma} \left( \sum_{t \in \gamma^{-1}(x)} g_k(x) \cdot \gamma'(t) \right) d\mathcal{H}^1(x). \tag{89}
\]
As \(|g_k(\gamma(t))| \leq 1 = |\gamma'(t)|\), we see from (11), (59) and the definition of \(N(\gamma, x)\) that for some subsequence \(k(k)\) and \(H^1\)-a.e. \(x \in \Gamma\), we have \(\lim_{k} g_{k(k)}(x) \cdot \gamma'(t) = 1\) for all \(t\) such that \(\gamma(t) = x\). In particular, \(\gamma'(t)\) is independent of \(t \in \gamma^{-1}(x)\) for \(H^1\)-a.e. \(x\). Conversely, if the latter property hold, we get from (13) and (11) that \(|R_\gamma|(|R^n|) = \ell(\gamma)|.

\[\text{Lemma A.3. Let } \mu \in \mathcal{M}(\mathbb{R}^n) \text{ and } \rho \text{ be a finite positive Borel measure on } C_\ell \text{ for some } \ell > 0. \text{ Then, } (15) \text{ holds if and only if } (16) \text{ does.}\]

\[\text{Proof. Assume that } (15) \text{ holds, and let } V \subset \mathbb{R}^n \text{ be open. Let } \varphi_k \in C_c(V) \text{ be a sequence of nonnegative functions increasing to } \chi_V; \text{ such a sequence is easily constructed using Urysohn's lemma and the } \sigma\text{-compactness of } V. \text{ Applying the second identity in } (15) \text{ to } \varphi_k, \text{ we get by monotone convergence that}\]

\[
(90) \quad |\mu|(V) = \lim_{k \to +\infty} \langle |\mu|, \varphi_k \rangle = \lim_{k \to +\infty} \int \langle |R_\gamma|, \varphi_k \rangle d\rho(R_\gamma) = \int |R_\gamma|(V) d\rho(R_\gamma).
\]

Hence, \(|\mu|\) and \(\int |R_\gamma| d\rho\) coincide on open sets. In particular, we get for \(V = \mathbb{R}^n\) that

\[
(91) \quad \|\mu\|_{TV} = \int_{C_\ell} \|R_\gamma\|_{TV} d\rho(R_\gamma).
\]

Moreover, as \(|\mu|\) is regular, we see from (90) that for any Borel set \(B \subset \mathbb{R}^n:\)

\[
(92) \quad |\mu|(B) = \inf \{|\mu|(V), B \subset V \text{ open} \} = \inf_V \int \langle |R_\gamma|(V) d\rho(R_\gamma) \geq \int_{C_\ell} |R_\gamma|(B) d\rho(R_\gamma).
\]

The conjunction of (91) and (92) implies the second equality in (16).

To obtain the first equality in (16), apply Lusin’s theorem to the effect that \(\chi_B\) is the bounded pointwise limit of a sequence \(f_k \in C_c(\mathbb{R}^n)\), except on a Borel set \(E\) of \(|\mu|\)-measure zero. From the second equality in (16), it follows that \(|R_\gamma|(E) = 0\) for \(\rho\)-a.e. \(R_\gamma \in C_\ell\). Thus, if we set \(R_\gamma = (m_1, \ldots, m_n)^T\) to indicate the components of \(R_\gamma\) in \(\mathcal{M}(\mathbb{R}^n)\), we get a fortiori that \(|m_j|(E) = 0\) for \(\rho\)-a.e. \(R_\gamma\). So, picking \(v = (v_1, \ldots, v_n)^T \in \mathbb{R}^n\), we deduce for such \(R_\gamma\) on applying the dominated convergence theorem component-wise that

\[
(93) \quad \lim_{k} \langle R_\gamma, f_k v \rangle = \sum_{j=1}^{n} v_j \lim_{k} \int f_k dm_j = \sum_{j=1}^{n} v_j \int \chi_B dm_j = v \cdot R_\gamma(B).
\]

Since \(v\) was arbitrary, we can now show the first equality in (16) from the first equation in (15), applied with \(g = f_k v\), by invoking the dominated convergence theorem when \(k \to \infty\), in \(L^1[|d|\mu|]\) on the left hand side and in \(L^1[|d|\rho|]\) on the right hand side.

Conversely, if (16) holds, sets of \(|\mu|\)-measure zero have \(|R_\gamma|\)-measure zero for \(\rho\)-a.e. \(R_\gamma\), moreover \(|\mu|\) and \(\int |R_\gamma| d\rho\) (resp. \(|\mu|\) and \(\int R_\gamma d\rho\)) have the same integral on simple functions, hence also on \(L^1[|d|\mu|]\) (resp. \(L^1[|d|\mu|]|n)\). This is logically stronger than (15). \(\square\)

\[\text{Lemma A.4. Let } T_\ell \text{ be an elementary solenoid as in (17). Then, there is a Lipschitz map } g : \mathbb{R} \to \mathbb{R}^n \text{ with } |g'(t)| = 1 \text{ a.e. such that } T_\ell = T_\ell \text{ is an elementary solenoid with } T_\ell = T_\ell g.\]

\[\text{Proof. Recall from Section2.3 that } T = \star \lim_{s \to +\infty} R_{T_\ell}/s \text{ as } s \to +\infty, \text{ where we have set } f_s = f_{[-s,s]}. \text{ As the TV-norm of the weak* limit cannot exceed the limit of the TV-norms, we get since } |T(t)| \leq 1 \text{ that}\]

\[
(94) \quad 1 = \|T_\ell\|_{TV} \leq \lim inf_{s \to +\infty} \frac{1}{2s} \|R_{T_\ell}\|_{TV} \leq \lim inf_{s \to +\infty} \frac{1}{2s} \int_{-s}^{s} |T'(t)| dt \leq 1.
\]
Thus, \( \frac{1}{\lambda} \int_{\mathbf{s}}^{\mathbf{s}^*} |f'(t)| dt \to 1 \) as \( \mathbf{s} \to +\infty \) and therefore, reparametrizing \( f \) by unit speed like we did for \( \gamma \) after \((12)\), we obtain the desired function \( g \).

\( \square \)

**Lemma A.5.** Let \( T_f \) be an elementary solenoid as in \((17)\) and \( \Gamma_s = f([-s, s]) \). Then, the family \( \{\nu_s\}_{s > 0} \) of normalized arclengths on \( \Gamma_s \), defined in \((18)\), converges weak-* to the probability measure \( |T_f| \). Moreover, if \( \varphi_j \in C_c(\mathbb{R}^n, \mathbb{R}^n) \) is a sequence of continuous functions, with \( |\varphi_j| \leq 1 \), such that \( \langle T_f, \varphi_j \rangle \to 1 \) as \( j \to \infty \), then

\[
\lim_{j \to \infty} \limsup_{s \to +\infty} \int \varphi_j(x) = \frac{\sum_{t \in f^{-1}(x), |t| \leq s} f'(t)}{2s} \cdot \nu_s = 0.
\]

**Proof.** The family \( \{\nu_s\}_{s > 0} \) has at least one weak-* accumulation point as \( s \to +\infty \), say \( \nu \). Let \( s_k \) be a sequence of positive real numbers tending to \( +\infty \) and such that \( \nu_{s_k} \) converges weak-* to \( \nu \).

For \( V \subset \mathbb{R}^n \) an open set, we get by \((9)\) that

\[
|T_f|(V) = \sup \{\langle T_f, \varphi \rangle, \varphi \in C_c(V, \mathbb{R}^n), |\varphi| \leq 1\} = \lim_{s \to +\infty} \int_{\Gamma_s} \varphi(x) \cdot \frac{\sum_{t \in f^{-1}(x), |t| \leq s} f'(t)}{2s} \cdot dH^1(x)
\]

\[
\leq \sup_{\varphi} \liminf_{k \to +\infty} \int_{\Gamma_{s_k}} \varphi(x) \cdot \frac{\sum_{t \in f^{-1}(x), |t| \leq s_k} f'(t)}{2s_k} \cdot dH^1(x)
\]

\[
\leq \sup_{\varphi} \lim_{k \to +\infty} \int_{\Gamma_{s_k}} \varphi(x) \cdot \frac{N(f, x, s_k)}{2s_k} \cdot dH^1(x) = \sup_{\varphi} \langle \nu, |\varphi| \rangle \leq \nu(V).
\]

Thus, by regularity, \( |T_f|(B) \leq \nu(B) \) for any Borel set \( B \subset \mathbb{R}^n \), and since \( |T_f| \) is a probability measure (by definition of an elementary solenoid) while \( \|\nu\|_{TV} \leq 1 \) by the Banach-Alaoglu theorem, we conclude that \( |T_f| = \nu \). This proves the first assertion.

Next, if \( \varphi \in C_c(\mathbb{R}^n, \mathbb{R}^n) \), \( |\varphi| \leq 1 \), is such that \( \langle T_f, \varphi \rangle > 1 - \varepsilon \) for some \( \varepsilon \in (0, 1) \), then it follows from \((13)\) and the definition of \( T_f \) that for \( s > s_0 = s_0(\varphi) \) large enough:

\[
1 - \varepsilon < \int_{\Gamma_s} \varphi(x) \cdot \frac{\sum_{t \in f^{-1}(x), |t| \leq s} f'(t)}{2s} \cdot dH^1(x) = \int \varphi(x) \cdot \frac{\sum_{t \in f^{-1}(x), |t| \leq s} f'(t)}{N(f, x, s)} \cdot d\nu_s(x).
\]

Because \( \sum_{t \in f^{-1}(x), |t| \leq s} f'(t) \leq N(f, x, s) \), the above inequality entails that

\[
\int \varphi(x) - \frac{\sum_{t \in f^{-1}(x), |t| \leq s} f'(t)}{N(f, x, s)} \cdot d\nu_s < 2\varepsilon,
\]

which implies \((95)\).

\( \square \)

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