ON THE TOTAL SURFACE AREA OF POTATO PACKINGS

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ABSTRACT. We prove that if we fill without gaps a bag with infinitely many potatoes, in such a way that they touch each other in few points, then the total surface area of the potatoes must be infinite. In this context potatoes are measurable subsets of the Euclidean space, the bag is any open set of the same space. As we show, this result also holds in the general context of doubling (even locally) metric measure spaces satisfying Poincaré inequality, in particular in smooth Riemannian manifolds and even in some sub-Riemannian spaces.

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INTRODUCTION

In this note we prove the following curious fact: if we fill without gaps a bag (modeled, say, by an arbitrary open connected subset of $\mathbb{R}^d$) with potatoes (modeled, in this case, by open sets of finite perimeter), in such a way that the potatoes touch each other in a single point (more generally in a set of zero surface measure), see Figure 1, then the total surface area of the potatoes is infinite. We show that this very simple result is in fact true for a fairly large class of metric measure spaces, where the perimeter of a set can be naturally defined.

This result implies in particular that the residual set (the complement of the union of the potatoes) has Hausdorff dimension at least $d - 1$. Theorem 1.4(ii) from [14] shows that this statement is sharp: in fact it proves the existence of a packing of a planar convex set by planar strictly convex sets for which the dimension of the residual set is exactly 1.
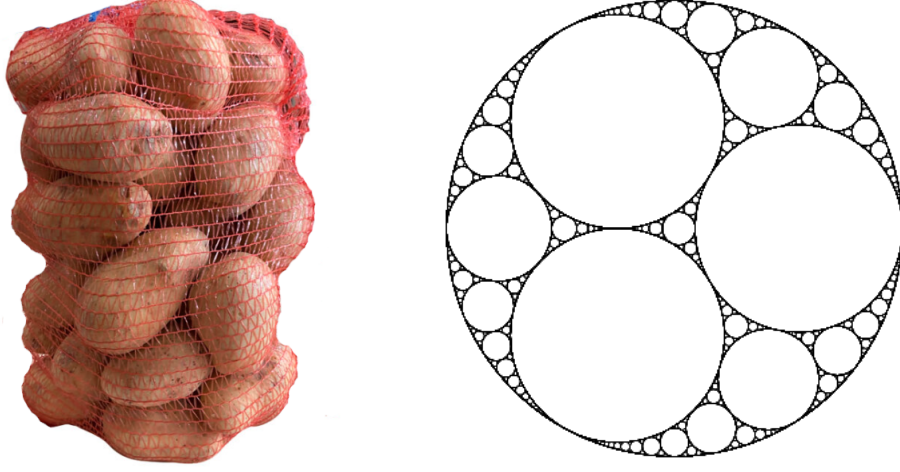
FIGURE 1. On the left-hand side: a potato bag. On the right-hand side: an Apollonian gasket.

In this way we generalise the results of [14], dedicated to packing of convex sets, which in their turn generalise those from the series of papers [12, 10, 11, 13] and [15] dedicated to packings of spheres.

1. NOTATION AND PRELIMINARY RESULTS

We will consider here metric measure spaces $(X, \mathrm{d}, \mathfrak{m})$ where X is a nonempty set equipped with a distance d and a σ-finite Borel measure $\mathfrak{m}$ with $\mathfrak{m}(X) \neq 0$. We say that a function F defined on the borel sets of a metric space X with values in $[0, +\infty]$ is a *perimeter-like evaluation* if it satisfies the following properties:

(0) $F(\emptyset) = 0$;
(T) $F(A) \geq \limsup_n F(A_n)$ whenever $A_n \subset A$ and $F(A \setminus A_n) \to 0$;
(C) $F(X \setminus A) = F(A)$;
(L) $F(A) \leq \liminf_n F(A_n)$ if $\lim_n \mathfrak{m}(A_n \triangle A) = 0$ (one says that F is lower semicontinuous with respect to $L^1(X, \mathfrak{m})$ convergence of sets);
(Z) if $\mathfrak{m}(A \triangle B) = 0$ then $F(A) = F(B)$.

Lemma 1.1. *The property (T) is valid if, for some $c > 0$, one has*

(T') $F(A) \geq F(A \setminus B) - cF(B)$ *whenever $B \subset A$.*

Proof. Just notice that

$$F(A) = F(A_n \cup (A \setminus A_n))$$
$$\geq F(A_n) - cF(A \setminus A_n) \qquad \text{by } (T')$$

and if $F(A \setminus A_n) \to 0$, then we have (T). $\square$

For a fairly general class of metric measure spaces, namely those with a doubling measure and satisfying the Poincaré inequality, a perimeter functional has been defined in [16, 3, 4]. We refer to the monograph [8] and references therein for a

detailed discussion of such spaces. Here we just recall the basic definitions. A measure $\mathfrak{m}$ is said *doubling*, provided there is a $C_D \geq 1$ such that

$$\mathfrak{m}(B_{2r}(x)) \leq C_D \mathfrak{m}(B_r(x)), \qquad \text{for all } x \in X, r \in (0, R).$$

We will shortly say that $(X, \mathrm{d}, \mathfrak{m})$ is a doubling space.

We say that a metric measure space $(X, \mathrm{d}, \mathfrak{m})$ supports a *weak* $(1, 1)$ *Poincaré* inequality, provided there is $\tau_P \geq 1$, and a constant $C_P > 0$ such that, for any locally Lipschitz function $f : X \to \mathbb{R}$, one has

$$\fint_{B_r(x)} |f - f_{x,r}| \, d\mathfrak{m} \leq C_P r \fint_{B_{\tau_P r}(x)} \mathrm{Lip}(f) \, d\mathfrak{m}, \qquad \text{for all } x \in X, r > 0,$$

where $f_{x,r} := \fint_{B_r(x)} f \, d\mathfrak{m}$ and $Lip(f)$ stands for the Lipschitz constant of f over $B_{\tau_P r}(x)$. Actually, this is usually formulated with *upper gradients* (see [7]), rather than with local Lipschitz constant. However, if $(X, \mathrm{d}, \mathfrak{m})$ is doubling, the two formulations are equivalent [9].

Definition 1.2. A PI-space is a metric measure space $(X, \mathrm{d}, \mathfrak{m})$ that is doubling and supports a weak $(1, 1)$-local Poincaré inequality.

The perimeter functional in a PI-space has been defined in [16, 3] (see also [4]) as a natural generalization of the classical Euclidean perimeter in $\mathbb{R}^d$ (see [6]). Note that, like in the classical Euclidean case $\mathbb{R}^d$ where the perimeter is the $(d-1)$-dimensional Hausdorff measure of the essential boundary, also in PI-spaces the perimeter of a set E is a measure of the essential boundary $\partial^e E$ of E, defined in [3], and is absolutely continuous with respect to the so-called codimension one Hausdorff measure $\mathcal{H}^{-1}$, with a Borel density $\theta_E : X \to [\alpha, \beta]$ where α and β are two positive constants depending only on the constants C_D, C_P, τ_P of the space [4]. In particular, one has the integral representation

$$P(E) = \int_{\partial^e E} \theta_E(x) \, d\mathcal{H}^{-1}(x).$$

We refer to [4, 5] where this notion has been further studied. It is important to know that this includes many classical examples, like for instance

(1) the Euclidean space $X = \mathbb{R}^d$ (or X open subset of $\mathbb{R}^d$) with the Lebesgue measure (in this case $\mathcal{H}^{-1}$ is the classical $(d-1)$-dimensional Hausdorff measure and $\partial^e E$ is equivalent to the reduced boundary of E as defined by De Giorgi),

(2) X a finite dimensional space equipped with any anisotropic norm and the Lebesgue measure, or even some of the so-called RCD metric measure spaces,

(3) X a Heisenberg group of any dimension, or even some of the more general Carnot groups.

Lemma 1.3. *Let* $(X, \mathrm{d}, \mathfrak{m})$ *be a PI space. Then the perimeter functional P is a perimeter-like evaluation, i.e. it satisfies all the properties (0), (T), (C), (L), and (Z).*

Proof. Property (0) follows from $\partial^e \emptyset = \emptyset$. Property (T'), with $c = 1$, is shown in [2, eq. (4.1)]. Proposition 1.7 (i), (ii), and (vi) in [4] shows (Z), (L), and (C) respectively. $\square$

2. Main result

We start with the following auxiliary statement.

Proposition 2.1. *If F satisfies properties (0), (C), and the family of sets E_k, $k \in \mathbb{N}$ is such that $\bigcup E_i = X$, and*

$$F\left(\bigcup_j E_j\right) \geq \sum_j F(E_j)$$

then $F(E_i) = 0$ for all $i \in \mathbb{N}$.

If, additionally, F satisfies (Z) then the same holds true if $\mathfrak{m}(X \setminus \bigcup E_i) = 0$ rather than $\bigcup E_i = X$.

Proof. One has

$$
\begin{aligned}
0 = F(\emptyset) && \text{by (0)} \\
= F(X) && \text{by (C)} \\
= F\left(\bigcup E_i\right) && \text{by assumption} \\
\geq \sum_i F(E_i) && \text{by assumption}
\end{aligned}
$$

hence $F(E_i) = 0$ for all $i \in \mathbb{N}$.

If, additionally, F satisfies (Z), and $\mathfrak{m}(X \setminus \bigcup E_i) = 0$ one has

$$
\begin{aligned}
0 = F(\emptyset) = F(X) \\
= F\left(X \setminus \bigcup E_i\right) && \text{by (Z)} \\
= F\left(\bigcup E_j\right) && \text{by (C)} \\
\geq \sum F(E_j) && \text{by assumption}
\end{aligned}
$$

so that $F(E_j) = 0$ for all j.   □

The Theorem below is the main tecnical result which will be further translated into corollaries adapted to applications.

Theorem 2.2. *If F satisfies properties (0), (C), (T), (L) and the family of sets E_k, $k \in \mathbb{N}$ is such that $F(E_i \cup E_j) = F(E_i) + F(E_j)$ for $i \neq j$, $\bigcup_{i=0}^{+\infty} E_i = X$, and $\mathfrak{m}\left(\bigcup_{i=1}^{+\infty} E_i\right) < +\infty$, then either $\sum_{i=0}^{+\infty} F(E_i) = +\infty$ or $F(E_i) = 0$ for all $i \in \mathbb{N}$.*

If, additionally, F satisfies (Z) then the same holds true if $\mathfrak{m}(X \setminus \bigcup_{i=0}^{+\infty} E_i) = 0$ for all $i \neq j$, in place of $\bigcup E_i = X$.

Proof. Let

$$T_n := \bigcup_{i=n+1}^{+\infty} E_j, \qquad T_n^m := \bigcup_{i=n+1}^{m} E_j.$$

Clearly $T_n^m \nearrow T_n$ as $m \to +\infty$, hence $\lim_m \mathfrak{m}(T_n^m) = \mathfrak{m}(T_n)$. Since $\mathfrak{m}(T_n) \leq \mathfrak{m}\left(\bigcup_{i=1}^{+\infty} E_i\right) < +\infty$ then we have that $\mathfrak{m}(T_n^m \triangle T_n) \to 0$ as $m \to +\infty$. Therefore

$$
\begin{aligned}
F(T_n) &\leq \liminf_m F(T_n^m) && \text{by (L)} \\
&= \liminf_m \sum_{i=n+1}^{m} F(E_i) && \text{by assumption} \\
&= \sum_{i=n+1}^{+\infty} F(E_i).
\end{aligned}
$$

(1)

If $\sum_{i=1}^{+\infty} F(E_i) = +\infty$ the proof is concluded. Otherwise the righthand side of (1) is the remainder of a convergent number series and hence $F(T_n) \to 0$ as $n \to +\infty$. We have then

$$
\begin{aligned}
F\left(\bigcup_{i=0}^{+\infty} E_i\right) &\geq \limsup_n F\left(\bigcup_{i=0}^{n} E_i\right) && \text{by (T)} \\
&= \lim_n \sum_{i=0}^{n} F(E_i) && \text{by assumption} \\
&= \sum_{i=0}^{+\infty} F(E_i).
\end{aligned}
$$

The proof is then concluded using the previous proposition. $\qquad\square$

3. Some applications

Combining Theorem 2.2 with Lemma 1.3 we obtain the following result.

Theorem 3.1. *Let $(X, \mathrm{d}, \mathfrak{m})$ be a PI space. Let E_k, $k \in \mathbb{N}$, be a sequence of Borel subsets of X such that*

(i) $\mathfrak{m}(E_k \cap E_j) = 0$ *for $k \neq j$;*
(ii) $\mathfrak{m}\left(X \setminus \bigcup E_k\right) = 0$;
(iii) $\mathcal{H}^{-1}(\partial^e E_k \cap \partial^e E_j) = 0$ *for all $k \neq j$.*
(iv) $\mathfrak{m}(E_0) > 0$ *and $\mathfrak{m}(E_1) > 0$.*

Then

$$
\sum_k P(E_k) = +\infty.
$$

Proof. Conditions (i) and (iii) imply

$$
P(E_k \cup E_j) = P(E_k) + P(E_j)
$$

in view of Lemma 2.3(ii) in [4]. The assumptions of Theorem 2.2 are therefore satisfied by P in view of Lemma 1.3. Hence by Theorem 2.2 we conclude that either $\sum P(E_k) = +\infty$ or $P(E_k) = 0$ for all k. But the latter option is excluded by (iv) in view of the relative isoperimetric inequality for PI spaces, provided in [16]. $\qquad\square$

Corollary 3.2. *Let $\mathfrak{m}$ be the Lebesgue measure on $\mathbb{R}^d$. Let $\mathcal{F}$ be a family of at least two measurable nonempty subsets of $\mathbb{R}^d$, each with positive volume $\mathfrak{m}$ and kissing each other on sets of zero $\mathcal{H}^{d-1}$ measure, i.e.*

(2)
$$
\mathcal{H}^{d-1}(\bar{A} \cap \bar{B}) = 0, \qquad \text{for every } A, B \in \mathcal{F}, A \neq B.
$$

In particular this assumption is satisfied if the sets in $\mathcal{F}$ are strictly convex and their interiors are not intersecting.

Let $B \subset \mathbb{R}^d$ be an open ball. If $\sum_{E \in \mathcal{F}} \mathcal{H}^{d-1}(\partial E \cap B) < +\infty$, then either there exists a set $E \in \mathcal{F}$ such that

$$\mathfrak{m}(B \setminus E) = 0$$

or

$$\mathfrak{m}\left(B \setminus \bigcup_{E \in \mathcal{F}} E\right) > 0,$$

i.e. there is a subset of B with positive measure which is not covered by the union of $\mathcal{F}$.

In particular if $\Omega \subset \mathbb{R}^d$ is an open set and all $E \in \mathcal{F}$ are open nonempty subsets of Ω, regular in the sense that they coincide with the interior of their closure, satisfying (2) and

$$(3) \qquad \mathfrak{m}\left(\Omega \setminus \bigcup_{E \in \mathcal{F}} E\right) = 0,$$

then given any $x \in \Omega \cap \bigcup_{E \in \mathcal{F}} \partial E$ and B an open ball centered at x, one has

$$(4) \qquad \sum_{E \in \mathcal{F}} \mathcal{H}^{d-1}(\partial E \cap B) = +\infty.$$

If, moreover, Ω is connected, this implies in particular

$$(5) \qquad \sum_{E \in \mathcal{F}} \mathcal{H}^{d-1}(\partial E \cap \Omega) = +\infty.$$

Proof. We apply Theorem 3.1 with $X := B$, equipped with the Euclidean distance, and P is the usual Euclidean (Caccioppoli) perimeter relative to B. Clearly, the doubling condition holds for B and, since B is connected, the Poincaré inequality is satisfied and $X = B$ is a PI space. Then, the De Giorgi reduced boundary $\partial^* E$ of a Borel set $E \subset \mathbb{R}^d$ satisfies $\partial^* E \subset \partial^e E$ and $\mathcal{H}^{d-1}(\partial^e E) = \mathcal{H}^{d-1}(\partial^* E)$. Notice that $\mathcal{H}^{d-1}$ coincides with the spherical Hausdorff measure $\mathcal{S}^{d-1}$ on rectifiable sets, and (see the Example "weighted spaces" in Section 7 of [3]) $\mathcal{H}^{d-1}$ coincides, up to a multiplicative constant, with $\mathcal{S}^{d-1}$.

If there exists $E \in \mathcal{F}$ such that $\mathfrak{m}(B \setminus E) = 0$ or, if $\mathfrak{m}(B \setminus \bigcup_{E \in \mathcal{F}} E) > 0$ there is nothing to prove. Otherwise there should be at least two different sets E_0, E_1 in $\mathcal{F}$ such that $\mathfrak{m}(B \cap E_0) > 0$ and $\mathfrak{m}(B \cap E_1) > 0$. Enumerate now all the sets of $\mathcal{F}$ as E_k, $k \in \mathbb{N}$ (clearly $\mathcal{F}$ is at most countable since each set is assumed to have positive measure, and in the case that $\mathcal{F}$ is finite we can complete the sequence with empty sets). Notice that $\mathcal{H}^{d-1}(\partial^e E_k \cap \partial^e E_j) = 0$ for all $k \neq j$ and $\mathfrak{m}(E_k \cap E_j) = 0$ since $\mathcal{H}^{d-1}(\bar{E}_k \cap \bar{E}_j) = 0$.

Therefore, we can apply Theorem 3.1 to the sequence $E_k \cap B$ to get $\sum_k P(E_k, B) = +\infty$ hence

$$\sum_k \mathcal{H}^{d-1}(\partial E_k \cap B) \geq \sum_k \mathcal{H}^{d-1}(\partial^* E_k \cap B) = \sum_k P(E_k, B) = +\infty,$$

showing the first claim.

In the particular case when $\mathfrak{m}(\Omega \setminus \bigcup_{E \in \mathcal{F}} E) = 0$ for some open $\Omega \subset \mathbb{R}^d$, taking x and B as in the statement, we consider a ball $B' \subset B$ centered at x such that $B' \subset \Omega$. Then, for every $E \in \mathcal{F}$ either $E \cap B' = \emptyset$ or $E \cap B' \neq \emptyset$. In the latter case

one has $\partial E \cap B' \neq \emptyset$ since otherwise we would have $B' \subset E$ which contradicts the choice of the center x and the fact that all the sets in $\mathcal{F}$ are disjoint. The regularity assumption implies that the interior of $B' \setminus E$ is nonempty, hence $\mathfrak{m}(B' \setminus E) > 0$. Therefore we have shown that $\mathfrak{m}(B' \setminus E) > 0$ for every $E \in \mathcal{F}$ and hence by the previous claim with B' in place of B, one has

$$\sum_{E \in \mathcal{F}} \mathcal{H}^{d-1}(\partial E \cap B) \geq \sum_{E \in \mathcal{F}} \mathcal{H}^{d-1}(\partial E \cap B') = +\infty$$

as claimed. If Ω is also connected, then since $\mathcal{F}$ has at least two elements, we obtain that $\bigcup_{E \in \mathcal{F}} \partial E \cap \Omega$ is not empty. Finally, from (4) one has

$$\sum_{E \in \mathcal{F}} \mathcal{H}^{d-1}(\partial E \cap \Omega) = +\infty,$$

proving the last claim. $\qquad\square$

Remark 3.3. It is clear from the proof that the statement of Corollary 3.2 holds under the slightly weaker assumption that $\mathcal{H}^{d-1}(\partial^* A \cap \partial^* B) = 0$ for all $A, B \in \mathcal{F}$ instead of $\mathcal{H}^{d-1}(\bar{A} \cap \bar{B}) = 0$, where ∂^* stands for the reduced boundary in the sense of De Giorgi.

Remark 3.4. Corollary 3.2 is valid in any metric measure space $(X, \mathrm{d}, \mathfrak{m})$ satisfying the Poincaré inequality where for every $x \in X$ there is an open ball $U \subset X$ containing x such that $(U, \mathrm{d}, \mathfrak{m})$ is doubling. In particular, it is valid in any C^2 smooth Riemannian manifold. Indeed it is enough to rewrite word-to-word the proof of Corollary 3.2 with balls $B \subset U$. In the case when X a C^2 smooth Riemannian manifold it is enough to note that over every ball U the curvature of X is bounded hence $(U, \mathrm{d}, \mathfrak{m})$ is doubling (in fact it is enough for this purpose that the curvature be bounded from below).

Remark 3.5. An alternative proof of Corollary 3.2 for a family $\mathcal{F}$ of strictly convex sets could proceed as follows:

- For the planar case $d = 2$ one uses the coarea inequality to state that if the total perimeter of the sets in the family is finite then almost every line (in fact every except a countable number of lines), say horizontal, intersects the boundary of the sets in a set of finite $\mathcal{H}^0$ measure (i.e. in a finite set). On the other hand if the sets of $\mathcal{F}$ are assumed to be strictly convex then the lines intersecting only a finite number of sets in the family should be at most countable: in fact, the intersection of a convex set with a line is a line segment, and hence if the line intersects only a finite number of sets, then each point of its intersection with the boundary of some set of $\mathcal{F}$ is a point of intersection between two different sets of $\mathcal{F}$, which are countably many in total. This contradiction shows that the total perimeter of the sets in the family is infinite for planar packing of strictly convex sets (even in the case when the ambient set is not convex).
- For the general space dimension $d \geq 2$, again assuming that the total perimeter of the packing is finite, by coarea inequality we have that the intersection of almost every hyperplane, say, horizontal, with the boundary of the sets in the family, has finite $\mathcal{H}^{d-2}$ measure. If the ambient set is convex, then inside every such hyperplane we have a packing of a convex set by strictly convex sets. Proceeding by backward induction on the dimension

we arrive at a contradiction. Convexity of the ambient set is clearly essential for the argument to work in the case $d > 2$.

Remark 3.6. Under the assumptions of Corollary 3.2, if Ω is connected and every set in $\mathcal{F}$ is regular in the sense of this Corollary, reasoning as in Remark 3.5 one can prove that

$$(6) \qquad \sum_{E \in \mathcal{F}} (\mathrm{diam}E)^{d-1} = +\infty,$$

where $\mathrm{diam}E$ denotes the diameter of E. Indeed, since Ω is connected, we can choose a ball $B \subset \Omega$ such that $V := \bigcup_{E \in \mathcal{F}} \partial E \cap B$ is nonempty. Notice that, if $x \in \partial E$ for some $E \in \mathcal{F}$, then every neighborhood of x intersects at least two sets in $\mathcal{F}$. Therefore, up to a suitable rotation, we can assume that there exists a set L_1 of positive measure of lines ℓ parallel to the first coordinate direction e_1, which intersect in B at least two sets of $\mathcal{F}$ (hence they also intersect the set V). Here by measure of the set of lines L_1 we mean the $\mathcal{L}^{d-1}$ measure of its orthogonal projections on the hyperplane $e_1^\perp$ perpendicular to e_1. In particular $\mathcal{L}^{d-1}(p_1(V)) > 0$, where p_1 denotes the orthogonal projection on $e_1^\perp$. Since

$$\mathcal{L}^{d-1}(p_1(\bar{E})) \leq \omega_{d-1}\mathrm{diam}(p_1(\bar{E}))^{d-1} \leq \omega_{d-1}(\mathrm{diam}\bar{E})^{d-1} = \omega_{d-1}(\mathrm{diam}E)^{d-1},$$

if (6) is not satisfied, then, for every $\varepsilon > 0$, there is a cofinite subfamily $\mathcal{F}_\varepsilon \subset \mathcal{F}$ such that

$$\sum_{E \in \mathcal{F}_\varepsilon} \mathcal{L}^{d-1}(p_1(\bar{E})) < \varepsilon.$$

This implies that there exists a set $L_2 \subset L_1$ of positive measure of lines ℓ which do not intersect the closures of the sets in $\mathcal{F}_\varepsilon$, but intersect at least two sets in $\mathcal{F} \setminus \mathcal{F}_\varepsilon$. Notice that $\ell \cap B \subset \bigcup_{E \in \mathcal{F} \setminus \mathcal{F}_\varepsilon} \bar{E}$ for almost every line ℓ parallel to e_1, since otherwise, by Fubini Theorem, the volume of $B \setminus \bigcup_{E \in \mathcal{F}} \bar{E}$ would be strictly positive, contradicting (3). As a consequence, for almost every line $\ell \in L_2$, since $\ell \cap B$ is connected, there exist two sets U, W in $\mathcal{F} \setminus \mathcal{F}_\varepsilon$, possibly depending on ℓ, such that $\ell \cap B \cap \partial U \cap \partial W$ is nonempty (otherwise $\ell \cap B$ would be a union of a finite disjoint family of relatively closed sets). Finally, since the family $\mathcal{F} \setminus \mathcal{F}_\varepsilon$ is finite, we can find two sets E_1, E_2 in $\mathcal{F} \setminus \mathcal{F}_\varepsilon$ and a subset $L_3 \subset L_2$ of positive measure such that $\ell \cap B \cap \partial E_1 \cap \partial E_2$ is nonempty for every $\ell \in L_3$, contradicting (2).

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