

Geometric Measure Theory Notes

My two primary sources are [Mag12] and [Sim14]. Monica Torres also has very help notes on her webpage [here](#).

1 Lebesgue equals Hausdorff (3.9.23)

We follow (Thm 2.9, [Sim14]). Recall the definitions of Lebesgue and Hausdorff measures.

$$\mathcal{L}^n(A) = |A| := \inf \left\{ \sum_{j=1}^{\infty} |R_j| : R_j \text{ is a open rectangle, } A \subset \cup_{j=1}^{\infty} R_j \right\},$$

$$\mathcal{H}_{\delta}^n(A) := \inf \left\{ \sum_{j=1}^{\infty} \omega_n \left(\frac{\text{diam} C_j}{2} \right)^n : \text{diam}(C_j) < \delta, A \subset \cup_{j=1}^{\infty} C_j \right\},$$

and $\mathcal{H}^n(A) := \lim_{\delta \searrow 0} \mathcal{H}_{\delta}^n(A)$.

Theorem 1.1. *For every $\delta > 0$ and $A \subset \mathbb{R}^n$,*

$$\mathcal{H}^n(A) = \mathcal{H}_{\delta}^n(A) = |A|.$$

Proof. Taking $\delta \searrow 0$, it suffices to show $\mathcal{H}_{\delta}^n = \mathcal{L}^n$. Since taking closure does not affect diameter, we may assume C_k are closed. Note also $|E| = 0 \implies \mathcal{H}_{\delta}^n(E) = 0$ since we may inscribe a ball B_j with diameter $< \delta$ in each rectangle R_j .

$(\mathcal{H}_{\delta}^n \leq \mathcal{L}^n)$ The idea here is to “uniformly eat up” all the measure A with finitely many pairwise disjoint balls, then iterate this algorithm *ad infinitum*.¹ Fix an arbitrary cover $\{R_j\}$ of A by open rectangles.

Step $k = 1$. For each j , consider a disjoint family of cubes $\{I_k\}$ ² with $\text{diam}(I_k) < \delta$ such that the interiors of I_k are pairwise disjoint and $\cup I_k = R_j$. This is possible since R_j is an open set (Thm 1.4, [SS05]). For each k , inscribe a *closed* ball B_k into I_k such that $\text{diam}(B_k) > \frac{1}{2}s_k$ where s_k is the side length of I_k [Figure 1]. This is obviously not sharp, but it doesn’t matter. What does matter is that the most measure we’ve left off out is

$$|I_k - B_k| \leq s_k^n - \omega_n \left(\frac{s_k}{4} \right)^n = \left(1 - \frac{\omega_n}{4^n} \right) s_k^n.$$

¹i.e. Step 1 leaves $\frac{1}{2}$ the measure, step 2 leaves $\frac{1}{4}$ the measure, etc (these are not the correct constants, but the idea is right).

² I_k depends on j also, which we suppress from the notation. Note that I_k^j may intersect $I_k^{j'}$ for $j \neq j'$ - the pairwise disjoint condition is with respect to a fixed rectangle.

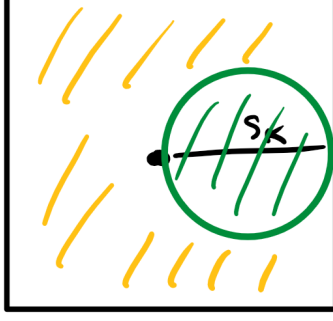


Figure 1: B_k must be bigger than the green ball.

Note the constant in front of s_k is uniform in k and strictly smaller than 1. Therefore,

$$|R_j - \cup_k B_k| = |\cup_k I_k - B_k| \leq (1 - \frac{\omega_n}{4^n}) \sum_k s^k = (1 - \frac{\omega_n}{4^n}) |R_j|.$$

Thus, for each j , we may choose finitely many ball B_j^1, \dots, B_j^N such that the same inequality holds.

Step $k \geq 2$. For $k = 2$, we repeat the above argument but for $R_j - \cup_{k=1}^N B_j^k$ instead of R_j , which is *again an open set*. Repeat this construction for $k > 2$.

In total, for each j we get a countable disjoint collection of balls $\{B_j^k\}$ of R_j with radius $< \delta$ such that $|R_j - \cup_k B_j^k| = 0$, so $\mathcal{H}_\delta^n(R_j - \cup_k B_j^k) = 0$. Therefore,

$$\mathcal{H}_\delta^n(R_j) = \mathcal{H}_\delta^n(\cup_k B_j^k) \leq \sum_{k=1}^{\infty} \omega_n \left(\frac{\text{diam} B_j^k}{2} \right)^n = \sum_{k=1}^{\infty} |B_j^k| = |R_j|.$$

Thus

$$\mathcal{H}_\delta^n(A) \leq \sum_{j=1}^{\infty} \mathcal{H}_\delta^n(R_j) \leq \sum_{j=1}^{\infty} |R_j|,$$

and since R_j was an arbitrary cover, the result is shown.

($\mathcal{H}_\delta^n \geq \mathcal{L}^n$) The idea here is to use *Steiner symmetrization* to prove the isodiametric inequality.

Lemma 1.2. *For any $A \subset \mathbb{R}^n$,*

$$|A| \leq \omega_n \left(\frac{\text{diam} A}{2} \right)^n.$$

The proof is easy but irrelevant. What matters is the moral of the story - if we're out looking for compact sets in infinite dimensional space, the strong topology is not the correct one to look in. Even the most basic candidate for a compact set is not compact, so there are way too many open sets. We need a coarser topology.

Look not in V , but in its dual V^* together with its unit ball B^* defined by the operator norm. We see

$$B^* := \{\mu : V \rightarrow \mathbb{R} : |\mu(\phi)| \leq \|\phi\|\} = \{L : V \rightarrow \mathbb{R} : |\mu(\phi)| \leq 1 \text{ for } \|\phi\| \leq 1\}.$$

In other words, $\mu : B \rightarrow [-1, 1]$ and so $\mu \in [-1, 1]^B$; in other words, B^* canonically sits inside $[-1, 1]^B$, so it is compact in the subspace topology by Tychonoff's. However, the subspace topology agrees does *not* agree with the topology induced by the operator norm. The subspace topology oversees only that the evaluation pairing between V, V^* is continuous, and so it agrees with the weak star topology. That is, a sequence $\{\mu_i\}$ in V^* converges weak-* to μ iff for every $\phi \in V$,

$$\mu_i \xrightarrow{*} \mu \iff \langle \phi, \mu_i \rangle \rightarrow \langle \phi, \mu \rangle,$$

where $\langle -, - \rangle$ denotes the evaluation pairing. This is known as *Banach-Alaoglu* and will serve as the backbone functional analysis tool for the compactness result for the space of Radon measures (which by RRT is dual to $V = C_c$ with a mildly strange topology). Truthfully, it's important that we have the sequential version of Banach-Alaoglu - this is true if V is *separable* (counterexamples exist otherwise) which is true in our case. ☹ ————— 🎉🎉🎉🎉🎉

Theorem 3.2. *Given a sequence $\{\mu_i\}$ of Radon measures which are locally uniformly bounded, i.e. for $K \subset \mathbb{R}^n$ compact*

$$\sup_i \mu_i(K) < \infty,$$

then there exists a subsequence, upon reindexing, $\{\mu_k\}$ which weak- converge to a Radon measure. That is, by RRT,*

$$\int_K \phi d\mu_i \rightarrow \int_K \phi d\mu,$$

for each $\phi \in C_c(\mathbb{R}^n)$.

Proof. The idea is basically sequential Banach-Alaoglu and RRT. We first give a construction of $\{\mu_k\}$ via a diagonalization procedure. Consider an exhaustion of \mathbb{R}^n by balls $\{B_j\}$ centered at 0. Define functionals

$$F_{i,j}(\phi) := \int_{B_j} \phi d\mu_i,$$

for $\phi \in C_c(B_j)$. Linearity of $F_{i,j}$ is clear, and boundedness follows from the local uniformity assumption as

$$|F_{i,j}(\phi)| \leq \sup \phi \cdot \mu_i(B_j) \leq C \sup \phi,$$


where $C = C(j)$. By sequential Banach-Alaoglu, there is a functional $F_j : C_c(B_j) \rightarrow \mathbb{R}$ and a subsequence $\{F_{i',j}\}$ such that $F_{i',j} \xrightarrow{*} F_j$. By extracting subsequences subsequently, then selecting the diagonal subsequence, we extract the desired $\{\mu_k\}$ upon relabeling. We claim that $F = \lim_k \mu_k$. By construction, this limit is well-defined. Furthermore, by RRT we have

$$F(\phi) := \int_{\mathbb{R}^n} \phi d\mu,$$

for some Radon measure μ . For $\phi \in C_c(\mathbb{R}^n)$, take $\text{spt}\phi \subset B_j$. Linearity follows since $F(\phi) = F_j(\phi)$, and F_j is linear. Boundedness follows from

$$|F(\phi)| \leq \sup \phi \cdot \mu(B_j) \leq C \sup \phi.$$

Here $C = C(j)$; nonetheless the weird topology we put on $C_C(\mathbb{R}^n)$ allows us to consider F as a bounded functional. ■

A similar statement holds for \mathbb{R}^m -valued measures by applying the above to the positive and negative part of each component to extract an \mathbb{R}^m -valued measure. 

We very briefly discuss regularization. The basic theory of regularization of functions extends to measures as one expects. Given a Radon measure μ , define the function $\mu_\epsilon := \rho_\epsilon * \mu$ as

$$\mu_\epsilon(x) := \int_{\mathbb{R}^n} \rho_\epsilon(x - y) d\mu(y),$$

where ρ is a *regularization kernel*. One then makes this a measure by considering it as a density wrt the Lebesgue measure $\mu_\epsilon(x)dx$. The basic proposition that holds here is the following.

Proposition 3.3. *With the above notation, and $B_\epsilon(E)$ the ϵ -ball (neighborhood) of E ,*

1. $\mu_\epsilon \xrightarrow{*} \mu$,
2. $|\mu_\epsilon| \xrightarrow{*} |\mu|$,
3. $|\mu_\epsilon|(E) \leq \mu(B_\epsilon(E))$.

Proof. The one word proof of 1 and 3 is Fubini's. 2 is more complicated, requiring an exercise we skipped. ■

4 Area Formula I (6.1.23)

For $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ an *injective, Lipschitz* function (throughout the section, $n \leq m$), set the *Jacobian* of f to be

$$Jf(x) := \begin{cases} \sqrt{\det(\nabla f(x)^* \nabla f(x))} & f \text{ is differentiable} \\ \infty & f \text{ is not differentiable.} \end{cases}$$

By Rademacher's theorem, Jf is integrable, and the area formula (in the case without considering multiplicity) calculates for Lebesgue measurable E the measures of images in terms of Jf as

$$\mathcal{H}^n(f(E)) = \int_E Jf(x) \, dx. \tag{1}$$

A useful consequence is the following.

Theorem 4.1. *If $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is an injective, Lipschitz function, and $g : \mathbb{R}^m \rightarrow [-\infty, \infty]$ is Borel and if $g \geq 0$ or $g \in L^1(\mathbb{R}^m, \mathcal{H}^n \llcorner f(\mathbb{R}^n))$, then $g \circ f$ is Borel and*

$$\int_{f(\mathbb{R}^n)} g \, d\mathcal{H}^n = \int_{\mathbb{R}^n} g(f(x)) Jf(x) \, dx.$$

There are two obvious requirements that need to hold for the above formula to be true. First, if $E := \{x \in \mathbb{R}^n : Jf(x) = 0\}$, then $\mathcal{H}^n(f(E)) = 0$ (injectivity is dropped for this statement). This is the content of Proposition 8.7. The second is that under the above assumptions, $f(E)$ had better be \mathcal{H}^n measurable.

Proposition 4.2. *If E is Lebesgue measurable in \mathbb{R}^n and $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is an injective Lipschitz function, then $f(E)$ is \mathcal{H}^n measurable in \mathbb{R}^m .*

Proof. Assume E is bounded, and exhaust E by a sequence of compact sets $\{K_i\}$ wrt \mathcal{L}^n , so $|E - \cup K_i| = 0$. Since f is Lipschitz, it's continuous and so $f(K_i)$ is compact and $\cup f(K_i)$ is Borel. Then,

$$\mathcal{H}^n(f(E) - \cup f(K_i)) = \mathcal{H}^n(f(E - \cup K_i)) \leq \text{Lip} f^n \cdot \mathcal{H}^n(E - \cup K_i) = \text{Lip} f^n \cdot |E - \cup K_i| = 0.$$

Note that injectivity is used in the first equality. ■

Here, we used that Lipschitz functions play nicely with the Hausdorff measure in the sense that $\mathcal{H}^s(f(E)) \leq \text{Lip} f^s \mathcal{H}^s(E)$, and is equal to the Lebesgue measure. For future reference, recall also that Hausdorff measure plays nicely with scaling in that $\mathcal{H}^s(rE) = r^s \mathcal{H}^s(E)$.

The next statement is to prove that area formula holds on arbitrary (not necessarily injective) linear functions $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$.

Proposition 4.3. *If $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ linear, then for every $E \subset \mathbb{R}^n$,*

$$\mathcal{H}^n(T(E)) = JT \cdot |E|.$$

For this, we must first recall some linear algebra. Set $\text{Lin}(n, m) := \{T : \mathbb{R}^n \rightarrow \mathbb{R}^m : T \text{ linear}\}$ and $\text{Isom}(n, m) := \{P \in \text{Lin}(n, m) : \langle Px, Py \rangle = \langle x, y \rangle\}$. We think of $\text{Isom}(n, m)$ as the set of linear isometric embeddings - clearly all must be injective.

Lemma 4.4. *For $P \in \text{Isom}(\mathbb{R}^n, \mathbb{R}^m)$, we have $P^*P = id_n$.*

Proof. Recall $P^* := (\mathbb{R}^m)^* \rightarrow (\mathbb{R}^n)^*$ is precomposition with P . The composition P^*P is understood as the following isomorphism:

$$\begin{aligned} \mathbb{R}^n &\xrightarrow{P} \mathbb{R}^m \rightarrow (\mathbb{R}^m)^* \xrightarrow{P^*} (\mathbb{R}^n)^* \rightarrow \mathbb{R}^n \\ x &\mapsto Px \mapsto \langle Px, - \rangle \mapsto \langle Px, P- \rangle \mapsto x \end{aligned}$$

where the last map is justified since the covector $y \mapsto \langle Px, Py \rangle = \langle x, y \rangle$ is metrically equivalent to the vector $y \in \mathbb{R}^n$. ■

Since $P \in \text{Isom}(n, m)$ is an isometry, both P and its adjoint P^* (orthogonal projections) have Lipschitz constant 1. Recall also the spectral theorem - every symmetric real-valued matrix diagonalizes with real eigenvalues (and orthogonal eigenspaces) and the polar decomposition - every linear map $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ can be realized as

$$T = PS$$

with $S \in \text{Lin}(n, n)$ symmetric and $P \in \text{Isom}(n, m)$ (both S, T are given explicitly in terms of the diagonalization of T). It turns out linear isometric embeddings do not change the fine structure of the geometry, and in a sense we'll make precise, all the change in the geometry happens with S .

(of 4.3.) Set $\kappa := D_{\mathcal{L}^n} \nu = \frac{\mathcal{H}^n(T(B))}{|B|}$ for $\nu(E) := \mathcal{H}^n(T(E))$ to be the density. The last equality is justified by scaling since for all $r > 0$,

$$\mathcal{H}^n(T(rB)) = r^n \mathcal{H}^n(T(B))$$

$$|rB| = r^n |B|.$$

It suffices to show the following two statements:


1. $\mathcal{H}^n(T(E)) = \kappa |E|$,
2. $JT = \kappa$.

First assume $\kappa = 0$ (T is non-injective). Then, $\mathcal{H}^n(T(B)) = 0 \implies \mathcal{H}^n(T(rB)) = 0$ for every $r > 0$ by linearity of T and so in the limit, $\mathcal{H}^n(\mathbb{R}^n) = 0$. By monotonicity of the measure, $\mathcal{H}^n(T(E)) = 0$ for every E .

Next, assume $\kappa > 0$ (T is injective). Since $E \mapsto \mathcal{H}^n(T(E))$ is Radon, by the decomposition theorem for measures, it suffices to show the equality is true on balls $B_r(x)$ for $r > 0$ and $x \in \mathbb{R}^n$. This follows by translation invariance and scaling, as

$$\begin{aligned} \mathcal{H}^n(T(B_r(x))) &= \mathcal{H}^n(T(x + rB)) \\ &= r^n \mathcal{H}^n(T(B)) \\ &= r^n \kappa |B| \\ &= \kappa |B_r(x)|, \end{aligned}$$

which shows $\mathcal{H}^n(T(-)) \ll \mathcal{L}^n$ and identifies κ as the density.

Remark 4.5. For linear functions, non-injectivity is very easy to deal with as both sides evaluates to 0. We don't need to consider multiplicity for this case. 

To show $JT = \kappa$, we first show for $T = PS$ and $S(Q) = E$ for a cube Q , we have $\frac{\mathcal{H}^n(P(E))}{|E|} = 1$, since

$$|E| = |P^*P(E)| \leq \text{Lip}(P^*)^n |P(E)| = |P(E)| = \mathcal{H}^n(P(E)) \leq \text{Lip}(P)^n |E| = |E|.$$

Therefore,

$$\kappa = \frac{\mathcal{H}^n(PS(Q))}{|Q|} = \frac{\mathcal{H}^n(P(E))}{|E|} \frac{|S(Q)|}{|Q|} = \frac{|S(Q)|}{|Q|}.$$

Note we can switch to other sets when defining density (Thm 3.22, [Fol13]). By homogeneity, we take Q to be the unit cube, so we must prove $JT = |S(Q)|$. Consider now the spectral decomposition of $Sv_i = \lambda_i v_i$. Using the fact that $\nabla T = T$ as T is linear, pullback is contravariant, and

$$\langle S^* Sv_i, v_j \rangle = \langle Sv_i, Sv_j \rangle = \begin{cases} \lambda_i^2 & i = j \\ 0 & i \neq j, \end{cases}$$

we compute

$$JT = \sqrt{\det T^* T} = \sqrt{\det(S^* P^* P S)} = \sqrt{\det(S^* S)} = \sqrt{\prod_i |\lambda_i|^2} = |\det(S)| = |S(Q)|.$$

■

The next proof shows that the area formula does not see the *singular set* $\mathcal{S} := \{Jf = 0\}$. For notation, balls without mention to the dimension will be assumed to be dimension n , and without mention to the center will be assumed to be centered at the origin.

Proposition 4.6. *If $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is Lipschitz, then on the singular set \mathcal{S} ,*

$$\mathcal{H}^n(f(\mathcal{S})) = 0.$$

Proof. We will deduce $\mathcal{H}_\infty^n(f(\mathcal{S} \cap B_R)) = 0$ for arbitrary $R > 0$ (recall $\mathcal{H}^n \ll \mathcal{H}_\infty^n$). For $x \in \mathcal{S}$ and $1 > \epsilon > 0$,³ by definition $\nabla f(x)$ is the linear map which satisfies the inequality

$$|f(x+v) - f(x) - \nabla f(x)v| < \epsilon|v|,$$

for $|v| < r(\epsilon, x)$. We can reinterpret the above (think of $f(x) = 0$.) in terms of small balls⁴: for $r = |v| < r(x, \epsilon)$, we have

$$f(B_r(x)) \subset f(x) + B_{\epsilon r}(\nabla f(x)(B_r)).$$

It would serve us well, therefore, to find a bound on the (translation-invariant) size of $B_{\epsilon r}(\nabla f(x)(B_r))$

Lemma 4.7. *For $0 < \epsilon < 1$ and $C = C(n, \text{Lip} f)$,*

$$\mathcal{H}_\infty^n(B_{\epsilon r}(\nabla f(x)(B_r))) \leq C r^n \epsilon.$$

The proof will use that \mathcal{S} is singular by using a dimension drop argument, which produces the ϵ . Assuming this lemma, we get for $x \in \mathcal{S}$,

$$\mathcal{H}_\infty^n(f(B_r(x))) \leq C r^n \epsilon. \tag{2}$$

³As far as I can tell, the restriction to $1 > \epsilon$ is for polish.

⁴Compare this to the definition of continuity in terms of balls. f is continuous at x if for $r < r(\epsilon, x)$,

$$f(B_r(x)) \subset f(x) + B_\epsilon.$$

So if you can take a derivative, the information you gain is having a modulus of control over the error tolerance ϵr in terms on your parameter r .

We take the family \mathcal{F} of balls with centers in $\mathcal{S} \cap B_R$,

$$\mathcal{F} := \{B_r(x) \subset \mathbb{R}^n : x \in \mathcal{S} \cap B_R, 0 < r < r(\epsilon, x)\}.$$

We cutoff \mathcal{S} by B_R to have bounded centers; we may therefore apply Besicovitch covering theorem to extract subfamilies $\mathcal{F}_1, \dots, \mathcal{F}_{\xi(n)}$ such that each \mathcal{F}_i is countable, pairwise disjoint and $\mathcal{S} \cap B_R \subset \cup_{\xi(n)} \mathcal{F}_i$. By inequality 2,

$$\begin{aligned} \mathcal{H}_\infty^n(f(\mathcal{S} \cap B_R)) &\leq \sum_{i=1}^{\xi(n)} \sum_{B_r(x) \in \mathcal{F}_i} \mathcal{H}_\infty^n(f(B_r(x))) \\ &\leq C\omega_n \epsilon \sum_{i=1}^{\xi(n)} \sum_{B_r(x) \in \mathcal{F}_i} r^n \\ &\leq \frac{C\epsilon}{\omega_n} \sum_{i=1}^{\xi(n)} \sum_{B_r(x) \in \mathcal{F}_i} |B_r(x)| \\ &= \frac{C\epsilon}{\omega_n} \sum_{i=1}^{\xi(n)} \left| \bigcup_{B_r(x) \in \mathcal{F}_i} B_r(x) \right| \\ &\leq \frac{C\epsilon \xi(n)}{\omega_n} |B_1(\mathcal{S} \cap B_R)|. \end{aligned}$$

Therefore, it suffices to prove the lemma.

(of Lemma 4.7). We first identify that $\nabla f(x)(B_r) \subset B_{r\text{Lip}f}^m \cap \nabla f(x)(\mathbb{R}^n)$, where the right hand side is a disk $D_{r\text{Lip}f}$ of dimension $k < n$ since $x \in \mathcal{S}$. This follows from homogeneity and $\|\nabla f\| \leq \text{Lip}f$, since we may characterize $\text{Lip}f$ as

$$\text{Lip}f = \sup_{x \neq y} \frac{|f(x) - f(y)|}{|x - y|}.$$

Therefore, we must obtain a bound of the form

$$\mathcal{H}_\infty^n(B_\epsilon(D_s)) \leq C(n, s)\epsilon, \quad (3)$$

since taking a neighborhood of a disk is [linear](#),

$$\begin{aligned} \mathcal{H}_\infty^n(B_{\epsilon r}(\nabla f(x)(B_r))) &\leq \mathcal{H}_\infty^n(B_{\epsilon r}(B_{r\text{Lip}f}^m \cap \nabla f(x)(\mathbb{R}^n))) \\ &\leq r^n \mathcal{H}_\infty^n(B_\epsilon(B_{\text{Lip}f}^m \cap \nabla f(x)(\mathbb{R}^n))) \\ &\leq r^n C(n, \text{Lip}f)\epsilon. \end{aligned}$$

To obtain inequality 3, we produce a covering of $B_\epsilon(D_s) \subset \mathbb{R}^k \times \mathbb{R}^{m-k}$ by translates of

$$B_{\epsilon s}^k \times B_\epsilon^{m-k} \subset \mathbb{R}^k \times \mathbb{R}^{m-k}.$$

Note that we need $C\epsilon^{-k}$ number of translates to cover $B_\epsilon(D_s) \approx B_s^k \times B_\epsilon^{m-k}$ for small ϵ , since area of B_s^k grows like s^k .⁵ By Pythagorean theorem,

$$\text{diam}(B_{\epsilon s}^k \times B_\epsilon^{m-k})^2 = \text{diam}(B_{\epsilon s}^k)^2 + \text{diam}(B_\epsilon^{m-k})^2 = 4\epsilon^2(1 + s^2).$$

⁵e.g. For 2-dimensional disks, need (up to a dimensional constant) one-hundred small disks $D_{1/10}$ to cover one big disk D_1 .

Since $k < n$, we have

$$\begin{aligned}
\mathcal{H}_\infty^n(B_\epsilon(D_s)) &\leq \omega_n \sum_{\# \text{ translates}} \left(\frac{\text{diam}(B_{\epsilon s}^k \times B_\epsilon^{m-k})}{2} \right)^n \\
&= \omega_n C \epsilon^{-k} (2\epsilon^2(1+s^2))^{\frac{n}{2}} \\
&= C(n, s) \epsilon^{n-k} \\
&\leq C\epsilon.
\end{aligned}$$

■

By the lemma, $\mathcal{H}^n(\mathcal{S}) = 0$.

■

5 Approximate Tangent Spaces (9.20.23)

We primarily follow [Mag12] Chapters 10.1-10.2, but mix it with Chapter 3 of [Sim14].

Set $k \leq n$. We say a set $M \subset \mathbb{R}^n$ is **k -rectifiable** if there are countably many Lipschitz maps $f_i : \mathbb{R}^k \rightarrow \mathbb{R}^n$ such that

$$\mathcal{H}^k(M \setminus \bigcup_{i=1}^\infty f_i(\mathbb{R}^k)) = 0.$$

The point is that a k -rectifiable set is a measure-theoretic version of a k -dimensional manifold. We say M is **locally k -rectifiable** if in addition, for every compact K , $\mathcal{H}^k(K \cap M) < \infty$. The point here is that $\mathcal{H}^k \llcorner M$ is Radon (not just Borel) iff M is locally k -rectifiable. By Kirezbraun theorem and regularity properties of Hausdorff measure, M is k -rectifiable iff there exists Borel M_0 which is \mathcal{H}^k -null such that

$$M = M_0 \cup \bigcup_{i=1}^\infty f_i(E_i),$$

where $E_i \subset \mathbb{R}^k$ are bounded, Borel sets, and f_i is Lipschitz. This decomposition is highly non-unique, and we will exploit this in the following lemma by asking for a decomposition with nice regularity properties. Namely, for each $i \in \mathbb{N}$, the pair (f_i, E_i) will form a regular Lipschitz image. We say (f, E) form a **regular Lipschitz image** if

1. f is injective and differentiable on E , and $Jf > 0$ (i.e. $Jf \neq 0$ anywhere) on E .⁶
2. All points in E form a point of density 1 for E .
3. All point in E are Lebesgue points of ∇f (\implies all points are Lebesgue points of Jf).
4. There exists a lower bound for $\text{Lip}(f)$ on E .

Morally speaking, this is saying (f, E) is a Lipschitz injective immersion with good C^1 control. Such a decomposition of a rectifiable set M always exists (Theorem 10.1) by a number of previous theorems. Here are the quoted ones from [Mag12].

⁶So f is an injective immersion on E , but ∇f is not necessarily continuous.

1. **Theorem 2.10:** Borel sets admit inner/outer approximations, if the measure is a locally finite Borel measure.
2. **Theorem 8.7:** Singular values of a Lipschitz function are \mathcal{H}^k -null.
3. **Theorem 8.8:** The regular points of a Lipschitz function admit a countable, almost flat partition, on the function is injective on each leaf.
4. **Rademacher's:** Lipschitz functions are differentiable almost everywhere.
5. **Theorem 5.16:** Almost every point of a $L^1_{\text{loc}}(\mu)$ function satisfies MVP, if μ is Radon.

The point of the above four axioms is that they are sufficient conditions to make the following lemma true. This lemma classifies the approximate tangent space for the image of a regular Lipschitz function. Observe that if f is an C^1 injective immersion, the conclusion is clear. So the key point here is to drop in regularity.

Lemma 5.1. *Suppose $M^k = f(E)$ with (f, E) a regular Lipschitz image. Then, then for any $x \in M$, the approximate tangent space is given by*

$$T_x M = (\nabla f|_z)(\mathbb{R}^k),$$

where $x = f(z)$.

Proof. Recall that the approximate tangent plane to M at x is the k -plane $T_x M \subset \mathbb{R}^n$ such that

$$\lim_{r \downarrow 0} \frac{1}{r^k} \int_M \phi \left(\frac{y - x}{r} \right) d\mathcal{H}^k(y) = \int_{T_x M} \phi(y) d\mathcal{H}^k(y),$$

for all $\phi \in C_c(\mathbb{R}^n)$. This is the measure-theoretic version of a tangent space. By pulling back along f , and using change of variables,

$$\begin{aligned} \frac{1}{r^k} \int_M \phi \left(\frac{y - x}{r} \right) d\mathcal{H}^k(y) &= \frac{1}{r^k} \int_E \phi \left(\frac{f(\tilde{w}) - f(z)}{r} \right) Jf(\tilde{w}) d\tilde{w} \\ &= \int_{\mathbb{R}^k} \underbrace{\mathbb{1}_E(z + rw) \cdot \phi \left(\frac{f(z + rw) - f(z)}{r} \right) Jf(z + rw)}_{:= u_r(w)} dw \end{aligned}$$

Since $z \in E$ is a point of density 1 for E ,

$$\lim_{r \downarrow 0} \int_{\mathbb{R}^k} \mathbb{1}_E(z + rw) dw = \mathbb{1}_E(z) = 1.$$

Since $z \in E$ is Lebesgue point for Jf ,

$$\lim_{r \downarrow 0} \int_{\mathbb{R}^k} Jf(z + rw) dw = J(z).$$

Take the limit as $r \downarrow 0$ on both sides. For the moment, take on faith that DCT can be justified, and switch $\lim_{r \downarrow 0}$ with \int . Since ϕ is continuous and f is differentiable at $z \in E$,

$$\phi \left(\frac{f(z + rw) - f(z)}{r} \right) \xrightarrow{r \downarrow 0} \phi(\nabla f|_z w).^7$$

⁷ *Type check:* note that $\nabla f|_z$ is a linear map from $\mathbb{R}^k \rightarrow \mathbb{R}^n$ (the Jacobian), and w is a vector in \mathbb{R}^k .

Altogether,⁸

$$\begin{aligned}
\lim_{r \downarrow 0} \int_{\mathbb{R}^k} u_r(w) dw &= \int_{\mathbb{R}^k} \phi(\nabla f|_z w) Jf(z) dw \\
&= \int_{\mathbb{R}^k} \phi(\nabla f|_z w) J(\nabla f|_z)(w) dw \\
&= \int_{\nabla f|_z(\mathbb{R}^k)} \phi d\mathcal{H}^k,
\end{aligned}$$

where the last step follows from area formula of injective, Lipschitz maps. Now to justify DCT. Observe the L^∞ (not pointwise, as values of Jf can take ∞ on a null set) upper bound

$$\|u_r\|_\infty \leq \left(\sup_{\mathbb{R}^n} \phi \right) \cdot \text{Lip}(f)^k,$$

and notice the RHS is a constant function. It suffices then to show that for all $r > 0$, $\text{spt} u_r \subset B_R$, for some R which is independent of r . Since $\text{spt} u_r := \overline{\{u_r > 0\}}$, and a set is bounded iff its closure is, it suffices to show $\{u_r > 0\} \subset B_R$. Take $w \in \{u_r > 0\}$, so that

$$0 < \mathbb{1}_E(z + rw) \cdot \phi \left(\frac{f(z + rw) - f(z)}{r} \right) Jf(z + rw);$$

in particular, $z + rw \in E$. Thus, last condition of a regular Lipschitz image immediately gives for some $\lambda = \lambda(E) > 0$,

$$|f(z + rw) - f(z)| \geq \lambda r |w|. \quad (4)$$

On the other hand, since

$$0 < \mathbb{1}_E(z + rw) \cdot \phi \left(\frac{f(z + rw) - f(z)}{r} \right) Jf(z + rw),$$

it follows that

$$\frac{f(z + rw) - f(z)}{r} \in \text{spt} \phi.$$

Since $\text{spt} \phi \subset B_\Lambda$ for some $\Lambda = \Lambda(\phi)$,

$$\left| \frac{f(z + rw) - f(z)}{r} \right| \leq \Lambda. \quad (5)$$

Together, inequalities 4 and 5 together give the conclusion upon setting $R := \frac{\Lambda}{\lambda}$, as

$$\lambda r |w| \leq r \Lambda \implies w \in B_{\frac{\Lambda}{\lambda}}.$$

■

⁸The gradient of the linear map $\nabla f|_z$ is $\nabla f|_z$. Thus

$$J(\nabla f|_z)(w) = \sqrt{\det((\nabla(\nabla f|_z)|_w)^* \cdot (\nabla(\nabla f|_z)|_w))} = \sqrt{\det(\nabla f|_z^* \cdot \nabla f|_z)} = Jf(z).$$

In the next theorem, we ask that M be decomposed as

$$M = M_0 \sqcup \bigcup_{i=1}^{\infty} f_i(E_i),$$

where $\mathcal{H}^k(M_0) = 0$, and each (f_i, E_i) is a regular Lipschitz image.

Theorem 5.2. *Suppose $M \subset \mathbb{R}^n$ is a locally k -rectifiable set. Then for \mathcal{H}^k -a.e. point $x \in M$, there exists a unique k -dimensional plane $T_x M$ such that:*

1. *The blow-up (defined below) of the measure $\mathcal{H}^k \llcorner M$ weak-star converges to $\mathcal{H}^k \llcorner T_x M$. That is, as $r \downarrow 0$,*

$$\mathcal{H}^k \llcorner \left(\frac{M - x}{r} \right) \xrightarrow{*} \mathcal{H}^k \llcorner T_x M.$$

2. *For \mathcal{H}^k -a.e. $x \in M$,*

$$\lim_{r \downarrow 0} \frac{\mathcal{H}^k(M \cap B_r(x))}{\omega_k r^k} = 1.$$

More precisely, this happens whenever x admits an approximate tangent space.

Proof. In the proof, we will need the notion of a blow-up. For fixed $x \in M$ and $r > 0$, we set

$$\eta_{x,r}(y) = \eta(y) := \frac{y - x}{r},$$

which centers a chosen point $x \in M$ at the origin, then rescales (in fact, magnifies when $0 < r < 1$) a point of distance r to unit distance.

1. This would immediately follow from Lemma 5.1 upon setting $T_x M = \nabla f|_z(\mathbb{R}^k)$, if not for the \mathcal{H}^k -null set M_0 . This will be taken care of by the *upper density theorem* which tells us for each i , as M_i is locally k -rectifiable, for a.e. $x \notin M_i$,

$$\lim_{r \downarrow 0} \frac{\mathcal{H}^k(M_i \cap B_r(x))}{\omega_k r^k} = 0.$$

Note that since the RHS is 0, in fact the numerator and denominator need not decay at the same rate. So more generally, for any $R > 0$,

$$\lim_{r \downarrow 0} \frac{\mathcal{H}^k(RM_i \cap B_{rR}(x))}{\omega_k r^k} = 0.$$

We use this as follows. Let $\phi \in C_c(\mathbb{R}^n)$ such that $\text{spt} \phi \subset B_R(0)$. For $x \in M_i$, using

elementary interactions of Hausdorff measure with symmetries,

$$\begin{aligned}
\left| \frac{1}{r^k} \int_{M \setminus M_i} \phi \circ \eta_{x,r} d\mathcal{H}^k \right| &= \left| \int_{\eta_{x,r}(M \setminus M_i)} \phi d\mathcal{H}^k \right| \\
&\leq \mathcal{H}^k(B_R(0) \cap \eta_{x,r}(M \setminus M_i)) \cdot \sup_{\mathbb{R}^n} \phi \\
&= \omega_k \sup_{\mathbb{R}^n} \phi \cdot \frac{\mathcal{H}^k(B_{rR}(0) \cap (M \setminus M_i) - x)}{\omega_k r^k} \\
&= \omega_k \sup_{\mathbb{R}^n} \phi \cdot \frac{\mathcal{H}^k(B_{rR}(x) \cap (M \setminus M_i))}{\omega_k r^k} \\
&\xrightarrow{r \downarrow 0} 0.
\end{aligned}$$

2. This again follows from algebraic set-theoretic interactions of the blow-up with Hausdorff measure. Choose a sequence $\{\phi_i\} \subset C_c(\mathbb{R}^n)$ such that $\phi_i \xrightarrow{i \rightarrow \infty} \mathbb{1}_{B_1^n(0)}$. On one hand,

$$\lim_{r \downarrow 0} \frac{1}{r^k} \int_M \phi_i \circ \eta(y) d\mathcal{H}^k(y) = \lim_{r \downarrow 0} \int_{\eta M} \phi_i(y) d\mathcal{H}^k(y) \xrightarrow{i \rightarrow \infty} \lim_{r \downarrow 0} \mathcal{H}^k(\eta M \cap B_1^n(0)).$$

On the other hand,

$$\int_{T_x M} \phi_i(y) d\mathcal{H}^k(y) \xrightarrow{i \rightarrow \infty} \mathcal{H}^k(T_x M \cap B_1(0)) = \mathcal{H}^k(B_1^k(0)) = \omega_k.$$

As the two expressions are equal, we calculate

$$\begin{aligned}
1 &= \lim_{r \downarrow 0} \frac{\mathcal{H}^k(\eta M \cap B_1^n(0))}{\omega_k} \\
&= \lim_{r \downarrow 0} \frac{r^k \mathcal{H}^k(\eta M \cap B_1^n(0))}{\omega_k r^k} \\
&= \lim_{r \downarrow 0} \frac{\mathcal{H}^k((M - x) \cap B_r^n(0))}{\omega_k r^k} \\
&= \lim_{r \downarrow 0} \frac{\mathcal{H}^k(M \cap B_r^n(x))}{\omega_k r^k}.
\end{aligned}$$

■

Remark 5.3. This completes the forwards (easy) direction of the heuristic “measure-theoretic manifold iff admits measure-theoretic tangent planes”.

As an application of Lemma 5.1, we can classify approximate tangent spaces of graphs of Lipschitz functions.

Corollary 5.4. *If $u : \mathbb{R}^n \rightarrow \mathbb{R}$ is a Lipschitz function and $f : \mathbb{R}^n \rightarrow \mathbb{R}^{n+1}$ is given by $f(z) = (z, u(z))$, then the graph of u , $\Gamma := f(\mathbb{R}^n)$, is locally \mathcal{H}^n -rectifiable. Furthermore, for a.e. $z \in \mathbb{R}^n$,*

$$T_{f(z)}\Gamma = \nu^\perp|_z,$$

where $\nu|_z = (-\nabla u|_z, 1)$.

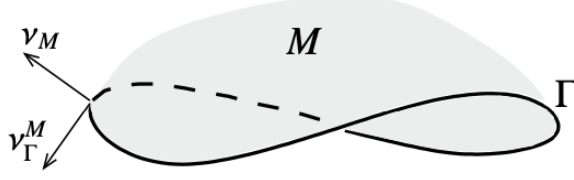


Figure 2: $\nu_{\partial M}^M$ as in Theorem 6.1.

Proof. We first show Γ is locally \mathcal{H}^n -rectifiable. Since u is Lipschitz, so is f ; therefore, Γ is manifestly rectifiable. We argue Γ is locally n -rectifiable, that is, for all compact $K \subset \mathbb{R}^{n+1}$,

$$\mathcal{H}^n(K \cap \Gamma) < \infty.$$

Since Γ is closed since it's a graph, so $K \cap \Gamma$ is compact. Since \mathcal{H}^n is Radon, $\mathcal{H}^n(K \cap \Gamma) < \infty$. Next, we characterize the approximate tangent space of Γ . By Lemma 5.1, we have (weakly)

$$T_{f(z)}\Gamma = \nabla f|_z(\mathbb{R}^n).$$

But $\nabla f|_z = \nabla(\tilde{z}, u(\tilde{z}))|_{\tilde{z}=z} = (1, \nabla u|_z)$. Note that for any $w \in \mathbb{R}^n$, we have

$$\nabla f|_z w \cdot \nu|_z w = (1, \nabla u|_z w) \cdot (-\nabla u|_z w, 1) = -\nabla u|_z w + \nabla u|_z w = 0.$$

The conclusion follows. ■

6 Gauss-Green on Hypersurfaces (10.17.23)

Following [Mag12] 11.3, but we shift indexing of dimensions by 1. ☞ ————— 🌀🌀🌀🌀🌀

Theorem 6.1 (Gauss-Green). *$M^n \subset \mathbb{R}^{n+1}$ is a C^2 -hypersurface with boundary ∂M , then there exists a normal vector field $H_M \in C^0(M, \mathbb{R}^{n+1})$ and unit normal vector field $\nu_{\partial M}^M \in C^1(\partial M, \mathbb{S}^n)$ such that*

$$\int_M \nabla^M \phi \, d\mathcal{H}^n = \int_M \phi H_M \, d\mathcal{H}^n + \int_{\partial M} \phi \nu_{\partial M}^M \, d\mathcal{H}^{n-1},$$

where $\phi \in C_c^1(\mathbb{R}^{n+1})$. Here, $\nu_{\partial M}^M \perp T$ for every vector field $T \in \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$ such that $T \perp M$.

Remark 6.2. Gauss-Green is an equality of vector fields in \mathbb{R}^{n+1} . This is also equivalent to a certain version of divergence theorem as

$$\int_M \operatorname{div}^M T \, d\mathcal{H}^n = \int_M T \cdot H_M \, d\mathcal{H}^n + \int_{\partial M} T \cdot \nu_{\partial M}^M \, d\mathcal{H}^{n-1},$$

where $\operatorname{div}^M T := \operatorname{div} T - (\nabla T \nu_M) \cdot \nu_M$.

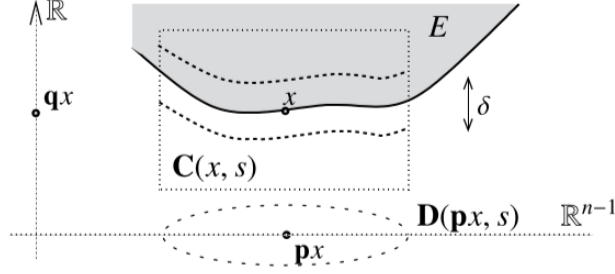


Figure 3: Hypersurface as graph of function.

Remark 6.3. There's no need for M to be orientable. The mean curvature vector field does not see orientation, but the scalar mean curvature H_M defined as

$$\mathbf{H}_M = H_M \nu_M$$

manifestly depends on choice of unit normal.

Remark 6.4. The last condition is since ∂M has codimension 2, so there are two normal directions, as in Figure 2. The condition specifies which normal direction $\nu_{\partial M}^M$ lies in, namely the one tangent to M . Since ν_M is assumed to be continuous, we (can and do) extend it to the boundary, so that the equation

$$\nu_{\partial M}^M \cdot \nu_M = 0$$

is well-defined on ∂M .

The basic idea, as with Aidan's talk last week, is to write M locally as a graph of a function, then pullback to a top-dimensional set to use divergence theorem/Gauss-Green.

To begin, we recall Corollary 11.7 which relates integration on graph and on its domain in low-regularity. As with a lemma in my previous talk, this is standard for high enough regularity.

Proposition 6.5. *Consider S is locally \mathcal{H}^{n-1} -rectifiable in \mathbb{R}^n , $u : \mathbb{R}^n \rightarrow \mathbb{R}$ is a Lipschitz function and $\Gamma := (z, u(z))$ is its graph. Then for any $g \geq 0$ or $g \in L^1(\mathbb{R}^n, \mathcal{H}^{n-1} \llcorner \Gamma)$,*

$$\int_{\Gamma} g \, d\mathcal{H}^{n-1} = \int_S \bar{g} \sqrt{1 + |\nabla^S u|^2} \, d\mathcal{H}^n,$$

where $\bar{g} = g(z, u(z))$.

This bar notation will be frequently used in the proof of Theorem 6.1. Think of this notation as “pulling back” an object on graph Γ to S along u .

Proof of 6.1. By partitions of unity and an action by the Euclidean group and homotheties, we normalize to take $\phi \in C_c^1(C)$, where $C := D^n \times [0, 1]$ is the cylinder over the unit hyperdisk. We assume that M is given locally as the graph of a C^2 function u over $\mathbb{D} \cap U$ for some open set $U \subset \mathbb{R}^n$. Namely,

$$\begin{aligned} C \cap M &= \{(z, u(z)) : z \in \mathbb{D} \cap U\} \\ C \cap \partial M &= \{(z, u(z)) : z \in \mathbb{D} \cap \partial U\} \end{aligned}$$

where $U \subset \mathbb{R}^n$ is a set with (possibly empty) C^2 boundary as in Figure 3.

By modifying Corollary 5.4, we define the unit normal $\nu_M \in C^1(C \cap M, \mathbb{S}^n)$ as

$$\bar{\nu}_M = \frac{(-\nabla u, 1)}{\sqrt{1 + |\nabla u|^2}} \text{ on } \mathbb{D} \cap U.$$

Define the (scalar) mean curvature by setting

$$\overline{H}_M = -\operatorname{div} \left(\frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} \right) \text{ on } \mathbb{D} \cap U.$$

■

Compute for $\phi \in C_c^1(\mathbb{R}^{n+1})$,

$$\begin{aligned} \nabla \phi \cdot \nu_M &= (\nabla \phi, \partial_n u) \cdot \frac{(-\nabla u, 1)}{\sqrt{1 + |\nabla u|^2}} \\ &= \frac{-\nabla \phi \cdot \nabla u + \partial_{n+1} \phi}{\sqrt{1 + |\nabla u|^2}} \end{aligned}$$

Pulling back to $\mathbb{D} \cap U$, we have for $\bar{\phi} \in C_c^1(\mathbb{D})$,

$$\overline{\nabla \phi \cdot \nu_M} = -\frac{\overline{\nabla \phi} \cdot \nabla u - \overline{\partial_{n+1} \phi}}{\sqrt{1 + |\nabla u|^2}}.$$

For e_i the constant vector fields on \mathbb{R}^{n+1} , we calculate

$$e_i \cdot \nu_M := \begin{cases} \frac{1}{\sqrt{1 + |\nabla u|^2}} & i = n + 1 \\ -\frac{\partial_i u}{\sqrt{1 + |\nabla u|^2}} & 1 \leq i \leq n \end{cases}$$

which suggests that we should separate out our analysis into two pieces, the vertical bit $i = n + 1$ and the horizontal bits $1 \leq i \leq n$. Since we have $\nabla^M \phi = \nabla \phi - (\nabla \phi \cdot \nu_M) \nu_M$, we calculate for $1 \leq i \leq n$,

$$e_{n+1} \cdot \int_M \nabla^M \phi \, d\mathcal{H}^n = \int_{\mathbb{D} \cap U} \left(\overline{\partial_{n+1} \phi} + \frac{\overline{\nabla \phi} \cdot \nabla u - \overline{\partial_{n+1} \phi}}{1 + |\nabla u|^2} \right) \sqrt{1 + |\nabla u|^2} \, d\mathcal{H}^n, \quad (6)$$

$$e_i \cdot \int_M \nabla^M \phi \, d\mathcal{H}^n = \int_{\mathbb{D} \cap U} \left(\overline{\partial_i \phi} - \frac{\overline{\nabla \phi} \cdot \nabla u - \overline{\partial_{n+1} \phi}}{1 + |\nabla u|^2} \partial_i u \right) \sqrt{1 + |\nabla u|^2} \, d\mathcal{H}^n. \quad (7)$$

where the factors of $\sqrt{1 + |\nabla u|^2}$ come from Proposition 6.5. We have the equality

$$\nabla \bar{\phi} = \overline{\nabla \phi} + \overline{\partial_{n+1} \phi} \nabla u, \quad (8)$$

which is immediate from chain rule for $1 \leq i \leq n$,

$$\begin{aligned}
\nabla \bar{\phi}|_x &= \nabla \phi(x, u(x)) \\
&= \sum_i \frac{\partial \phi(x, u(x))}{\partial x^k} \frac{\partial x^k}{\partial x^i} + \frac{\partial \phi(x, u(x))}{\partial x^{n+1}} \frac{\partial u}{\partial x^i} \\
&= \sum_i \partial_i \phi(x, u(x)) + \partial_{n+1} \phi(x, u(x)) \sum_i \partial_i u(x) \\
&= \overline{\nabla \phi}|_x + \overline{\partial_{n+1} \phi}|_x \nabla u|_x.
\end{aligned}$$

Similarly, we record that

$$\partial_i \bar{\phi} = \overline{\partial_i \phi} + \overline{\partial_{n+1} \phi} \partial_i u.$$

We work on the vertical bit. Via equation 8, we rewrite the integrand of 6 as

$$\begin{aligned}
\left(\overline{\partial_{n+1} \phi} + \frac{\overline{\nabla \phi} \cdot \nabla u - \overline{\partial_{n+1} \phi}}{1 + |\nabla u|^2} \right) \sqrt{1 + |\nabla u|^2} &= \frac{\nabla u \cdot \overline{\nabla \phi}}{\sqrt{1 + |\nabla u|^2}} + \overline{\partial_{n+1} \phi} \sqrt{1 + |\nabla u|^2} - \frac{\overline{\partial_{n+1} \phi}}{\sqrt{1 + |\nabla u|^2}} \\
&= \frac{\nabla u \cdot \overline{\nabla \phi}}{\sqrt{1 + |\nabla u|^2}} + \frac{\overline{\partial_{n+1} \phi} (1 + |\nabla u|^2) - \overline{\partial_{n+1} \phi}}{\sqrt{1 + |\nabla u|^2}} \\
&= \frac{\nabla u \cdot \overline{\nabla \phi}}{\sqrt{1 + |\nabla u|^2}} + \frac{\overline{\partial_{n+1} \phi} |\nabla u|^2}{\sqrt{1 + |\nabla u|^2}} \\
&= \frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} \cdot \overline{\nabla \phi} + \overline{\partial_{n+1} \phi} \nabla u \\
&= \frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} \cdot \nabla \bar{\phi}
\end{aligned}$$

By $\phi \equiv 0$ on $\partial \mathbb{D}$, and product rule for divergences,

$$\begin{aligned}
(6) &= \int_{\mathbb{D} \cap U} \frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} \cdot \nabla \bar{\phi} d\mathcal{H}^n \\
&= \int_{\mathbb{D} \cap U} \operatorname{div} \left(\frac{\bar{\phi} \nabla u}{\sqrt{1 + |\nabla u|^2}} \right) - \bar{\phi} \operatorname{div} \left(\frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} \right) d\mathcal{H}^n \\
&= \int_{\mathbb{D} \cap \partial U} \frac{\bar{\phi}}{\sqrt{1 + |\nabla u|^2}} \nabla u \cdot \nu_U d\mathcal{H}^{n-1} - \int_{\mathbb{D} \cap U} \bar{\phi} \operatorname{div} \left(\frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} \right) d\mathcal{H}^n \\
&= e_{n+1} \cdot \int_{\partial M} \phi \nu_{\partial M}^M d\mathcal{H}^{n-1} + \int_{\mathbb{D} \cap E} \bar{\phi} \bar{H}_M d\mathcal{H}^n \\
&= e_{n+1} \cdot \int_{\partial M} \phi \nu_{\partial M}^M d\mathcal{H}^{n-1} + e_{n+1} \cdot \int_M \phi \mathbf{H}_M d\mathcal{H}^n,
\end{aligned}$$

where the second term in the last equality follows from a previous calculation of $e_{n+1} \cdot \nu_M$, while the first term follows from defining on $C \cap \partial M$

$$e_{n+1} \cdot \overline{\nu_{\partial M}^M} := \frac{\nabla u \cdot \nu_U}{\sqrt{1 + |\nabla u|^2} \sqrt{1 + |\nabla^S u|^2}},$$

where $S := \mathbb{D} \cap \partial U$.

Next, we work on the horizontal bit. For $1 \leq i \leq n$, we calculate by equation 7 divergence theorem, and $\bar{\phi} \equiv 0$ on $\partial \mathbb{D}$,

$$\begin{aligned}
e_i \cdot \int_M \phi \mathbf{H}_M d\mathcal{H}^n &= e_i \cdot \int_M \phi H_M \nu_M d\mathcal{H}^n \\
&= \int_{\mathbb{D} \cap U} \bar{\phi} \partial_i u \operatorname{div} \left(\frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} \right) d\mathcal{H}^n \\
&= \int_{\mathbb{D} \cap U} \operatorname{div} \left(\bar{\phi} \partial_i u \frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} \right) - \nabla(\bar{\phi} \partial_i u) \cdot \frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} d\mathcal{H}^n \\
&= \int_{\mathbb{D} \cap \partial U} \frac{\bar{\phi} \partial_i u}{\sqrt{1 + |\nabla u|^2}} \nabla u \cdot \nu_U d\mathcal{H}^{n-1} - \underbrace{\int_{\mathbb{D} \cap U} \frac{\bar{\phi}}{\sqrt{1 + |\nabla u|^2}} \nabla(\partial_i u) \cdot \nabla u d\mathcal{H}^n}_{(*)} \\
&\quad - \int_{\mathbb{D} \cap U} \partial_i u \nabla \bar{\phi} \cdot \frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} + \frac{\partial_i u \overline{\partial_{n+1} u} |\nabla u|^2}{\sqrt{1 + |\nabla u|^2}} d\mathcal{H}^n
\end{aligned}$$

and for $1 \leq j \leq n$, we calculate

$$\begin{aligned}
(*) &= \frac{\bar{\phi}}{\sqrt{1 + |\nabla u|^2}} \sum_j u_{ij} u_j \\
&= \frac{\bar{\phi}}{2\sqrt{1 + |\nabla u|^2}} \partial_i \left(\sum_j u_j^2 \right) \\
&= \frac{\bar{\phi}}{2\sqrt{1 + |\nabla u|^2}} \partial_i |\nabla u|^2 \\
&= \bar{\phi} \partial_i (\sqrt{1 + |\nabla u|^2})
\end{aligned}$$

where subscripts in the above calculation denote partial derivatives. It follows that

$$\begin{aligned}
& e_i \cdot \int_M (\nabla^M \phi - \phi \mathbf{H}_M) d\mathcal{H}^n \\
&= \int_{\mathbb{D} \cap U} (\bar{\partial}_i \phi + \bar{\partial}_{n+1} \phi \partial_i u) \sqrt{1 + |\nabla u|^2} + \bar{\phi} \partial_i (\sqrt{1 + |\nabla u|^2}) d\mathcal{H}^n \\
&\quad - \int_{\mathbb{D} \cap \partial U} \bar{\phi} \partial_i u \frac{\nabla u \cdot \nu_U}{\sqrt{1 + |\nabla u|^2}} d\mathcal{H}^{n-1} \\
&= \int_{\mathbb{D} \cap U} \partial_i \bar{\phi} \sqrt{1 + |\nabla u|^2} + \bar{\phi} \partial_i (\sqrt{1 + |\nabla u|^2}) d\mathcal{H}^n \\
&\quad - \int_{\mathbb{D} \cap \partial U} \bar{\phi} \partial_i u \frac{\nabla u \cdot \nu_U}{\sqrt{1 + |\nabla u|^2}} d\mathcal{H}^{n-1} \\
&= \int_{\mathbb{D} \cap U} \underbrace{\partial_i (\bar{\phi} \sqrt{1 + |\nabla u|^2})}_{\text{divergence quantity}} d\mathcal{H}^n - \int_{\mathbb{D} \cap \partial U} \bar{\phi} \partial_i u \frac{\nabla u \cdot \nu_U}{\sqrt{1 + |\nabla u|^2}} d\mathcal{H}^{n-1} \\
&= \int_{\mathbb{D} \cap \partial U} \bar{\phi} (\sqrt{1 + |\nabla u|^2} e_i - \frac{\partial_i u}{\sqrt{1 + |\nabla u|^2}} \nabla u) \cdot \nu_U d\mathcal{H}^{n-1}.
\end{aligned}$$

On $\mathbb{D} \cap \partial U$, we set

$$e_i \cdot \bar{\nu}_{\partial M}^M := (\sqrt{1 + |\nabla u|^2} e_i - \frac{\partial_i u}{\sqrt{1 + |\nabla u|^2}} \nabla u) \cdot \frac{\nu_U}{\sqrt{1 + |\nabla^S u|^2}}.$$

It suffices to check $\bar{\nu}_{\partial M}^M$ defined in this way is unit and normal to ν_M and ∂M , but we stop here.

7 Compactness (9.14.23)

Theorem 7.1. *Suppose $\{E_i\}$ is a sequence of sets of finite perimeter in \mathbb{R}^n such that*

1. $E_i \subset B_R$ for some $R > 0$,
2. $P(E_i) \leq C$ for some constant uniform in i .

Then, there E_i subsequentially converges to a set of finite perimeter $E \subset B_R$ and $\mu_{E_i} \xrightarrow{} \mu_E$.*

Proof. The compactness comes from a setup in a specific function space. The ambient is the complete metric space

$$\begin{aligned}
X &:= \{E \in \mathcal{M}(\mathcal{L}^n) : P(E) < \infty\} / \sim, \\
d(E, F) &:= |E \Delta F| = \|\mathbb{1}_E - \mathbb{1}_F\|_{L^1(\mathbb{R}^n)}
\end{aligned}$$

where \sim means up to measure 0 identification. Define subsets for $r, p > 0$,

$$Y_{r,p} := \{E \in \mathcal{M}(\mathcal{L}^n) : P(E) \leq p, E \subset B_r\},$$

and we claim these are compact (\iff totally bounded + complete) subsets of X . The sets $Y_{r,p}$ are closed by lower semi-continuity of perimeter, so they are complete. It's clear that

the conclusion follows upon showing $Y_{r,p}$ is totally bounded. That is, for every $\sigma > 0$, there is a finite collection $\{T_1, \dots, T_M\}$ such that for any $E \in Y_{r,p}$,

$$\min_j d(E, T_j) = \min_j |E \Delta T_j| \leq \sigma.$$

Therefore, the goal is to estimate $|E \Delta T_j|$ in terms of n, p and an extra parameter r to control the scale. For fixed $r > 0$, let $\{Q_i\}$ to be an enumeration of open cubes with vertices in $r\mathbb{Z}^n \subset \mathbb{R}^n$. $|E| < \infty$ by monotonicity and for only the first N cubes (up to reindexing), is E is contained in at least half the cube. That is, for $i \in \{1, \dots, N\}$,

$$|Q_i \cap E| \geq \frac{r^n}{2}.$$

It follows for $i \geq N + 1$, over half Q_i does not see E . That is for $i \in \{1, \dots, N\}$,

$$|Q_i \setminus E| \geq \frac{r^n}{2}.$$

We set $T := \cup_{i=1}^N Q_i$. From here, we derive the desired bound, assuming a corollary of the Poincare-Wirtinger inequality. For $\epsilon > 0$ and $u_\epsilon := \mathbb{1}_E * \rho_\epsilon$,

$$\sqrt{n}r \int_{\mathbb{R}^n} |\nabla u_\epsilon| = \sqrt{n}r \sum_{i \in \mathbb{N}} \int_{Q_i} |\nabla u_\epsilon| \geq \sum_{i \in \mathbb{N}} \int_{Q_i} |u_\epsilon - \bar{u}_{\epsilon,i}|,$$

where $\bar{u}_{\epsilon,i}$ denotes the average value of u_ϵ on Q_i . Taking $\epsilon \downarrow 0$, by L^1_{loc} convergence of mollification,

$$\begin{aligned} \sqrt{n}r P(E) &\geq \sum_{i \in \mathbb{N}} \int_{Q_i} |\mathbb{1}_E - \bar{\mathbb{1}}_i| \\ &= \sum_{i \in \mathbb{N}} \int_{Q_i} \left| \mathbb{1}_E - \frac{|Q_i \cap E|}{r^n} \right| \\ &= \sum_{i \in \mathbb{N}} \underbrace{|E \cap Q_i| \left(1 - \frac{|Q_i \cap E|}{r^n}\right)}_{\mathbb{1}_{E=1}} + \underbrace{|Q_i \setminus E| \frac{|Q_i \cap E|}{r^n}}_{\mathbb{1}_{E=0}} \\ &= \frac{|E \cap Q_i|}{r^n} \sum_{i \in \mathbb{N}} \underbrace{r^n - |Q_i \cap E|}_{|Q_i \setminus E|} + |Q_i \setminus E| \\ &= \sum_{i=1}^N \frac{2|E \cap Q_i||Q_i \setminus E|}{r^n} + \sum_{i=N+1}^\infty \frac{2|E \cap Q_i||Q_i \setminus E|}{r^n} \\ &\geq \sum_N |Q_i \setminus E| + \sum_\infty |Q_i \cap E| \\ &= \sum_N |T \setminus E| + |E \setminus T| \\ &= |E \Delta T| \end{aligned}$$

With this inequality, we simply choose r such that $\sqrt{n}pr \leq \sigma$, and we apply the above inequality. The uniformity in E comes from the fact that $E \subset B_R$, so that we can immediately

restrict to $\{Q_i\}$ (associated to scale r) to the finitely many cubes which intersect B_R . So then $M = M(r, R, n) = |\text{Pow}(S)|$ where S is the subset of cubes $\{Q_i\}$ which intersects B_R . The conclusion follows.

It remains to show the inequality on cubes $Q = x + (0, r)^n$ and $u \in C^1(\mathbb{R}^n)$,

$$\int_Q |u - \bar{u}_Q| \leq \sqrt{n}r \int_Q |\nabla u|.$$

Up to change of variable and normalizing the average to be 0, it suffices to show

$$\int_Q |u| \leq \int_Q |\nabla u|$$

where Q is the unit cube and $\bar{u}_Q = 0$. By Cauchy-Schwarz,

$$\sum_i |\partial_i u| \leq \sqrt{n} \sqrt{\sum_i (\partial_i u)^2} = \sqrt{n} |\nabla u|,$$

so it suffices to show the Poincare inequality over the unit cube

$$\int_Q |u| \leq \sum_i \int_Q |\partial_i u|.$$

The proof proceeds by induction. For $n = 1$, by MVT and FTC, there is some $x_o \in (0, 1)$ such that

$$\int_Q |u| dx = |u(x)| = |u(x) - u(x_o)| \leq \int_0^1 |u'(x)| dx.$$

For higher dimensions, consider (x^1, x) to be a decomposition of $\mathbb{R}^n = \mathbb{R} \times \mathbb{R}^{n-1}$. Set $v(x^1) := \int u(x^1, x) dx$, and note that $\int_0^1 v(x^1) dx^1 = 0$.

$$\begin{aligned} \int_Q |u| &\leq \int_0^1 \int_{(0,1)^{n-1}} |u(x) - v(x^1)| dx dx^1 + \int_0^1 |v(x^1)| dx^1 \cdot \underbrace{\int_{(0,1)^{n-1}} dx}_{=1} \\ &\leq \int_0^1 \underbrace{\sum_{i=2}^n |\partial_i u|}_{\text{ind. hyp.}} dx dx^1 + \int_0^1 \underbrace{|v'|}_{n=1} dx^1 \\ &\leq \sum_{i=1}^n \int_Q |\partial_i u|. \end{aligned} \quad \blacksquare$$

Remark 7.2. Replacing uniformly bounded perimeter with uniformly bounded diameters, this still converges subsequentially to a set of finite perimeter. The difference here is that we get convergence up to translation, that is there is a sequence $\{x_i\} \subset \mathbb{R}^n$ such that subsequentially $x_i + E_i \xrightarrow{L^1} E, \mu_{x_i + E_i} \xrightarrow{*} \mu_E$

Lastly, we localize the compactness theorem.

Corollary 7.3. *Suppose E_i are sets of locally finite perimeter in \mathbb{R}^n such that for any $R > 0$,*

$$\sup_i P(E_i; B_R) < \infty.$$

Then, there exists a set E of locally finite perimeter such that

$$E_i \rightarrow E, \mu_i \xrightarrow{*} \mu_E$$

subsequentially.

Proof. For each $j \in \mathbb{N}$, we apply the compactness theorem to the sequence $\{(E_i \cap B_j)\}_{i \in \mathbb{N}}$, which is justified by the inequality

$$P(E_i \cap B_j) \leq P(E_i; B_j) + P(B_j),$$

to be proved. By a standard diagonalization argument, we extract a for each j , a set of finite perimeter F_j . Furthermore, by construction $F_j \subset F_{j+1}$ and $E = \cup_{\infty} F_j$ will be a set of locally finite perimeter.

Let $0 \leq u_\epsilon, v_\epsilon \leq 1$ be convolutions of the indicator functions of $E, B_{R'}$ respectively, for $R' < R$. Taking $R' \uparrow R$ will give the result.

$$\begin{aligned} P(E \cap B_{R'}) &\leq \underbrace{\liminf_{\epsilon \downarrow 0} \int_{\mathbb{R}^n} |\nabla(u_\epsilon v_\epsilon)|}_{\text{lower semi-continuity}} \\ &\leq \limsup_{\epsilon \downarrow 0} \int_{\mathbb{R}^n} u_\epsilon |\nabla v_\epsilon| + v_\epsilon |\nabla u_\epsilon| \\ &\leq \limsup_{\epsilon \downarrow 0} \int_{\mathbb{R}^n} |\nabla v_\epsilon| + v_\epsilon |\nabla u_\epsilon| \\ &\leq P(B_{R'}) + \limsup_{\epsilon \downarrow 0} \int_{B_{R'}} |\nabla u_\epsilon| \\ &\leq P(B_{R'}) + P(E; B_{R'}) \end{aligned} \quad \blacksquare$$

References

- [Fol13] G.B. Folland. *Real Analysis: Modern Techniques and Their Applications*. Pure and Applied Mathematics: A Wiley Series of Texts, Monographs and Tracts. Wiley, 2013. ISBN: 9781118626399.
- [Mag12] Francesco Maggi. *Sets of Finite Perimeter and Geometric Variational Problems: An Introduction to Geometric Measure Theory*. Cambridge Studies in Advanced Mathematics. Cambridge University Press, 2012. DOI: [10.1017/CBO9781139108133](https://doi.org/10.1017/CBO9781139108133).
- [Sim14] L. Simon. *Introduction to Geometric Measure Theory*. <https://web.stanford.edu/class/math285/ts-gmt.pdf>. 2014.
- [SS05] Elias M. Stein and Rami Shakarchi. *Real Analysis: Measure Theory, Integration, and Hilbert Spaces*. Princeton University Press, 2005. ISBN: 9780691113869.

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