Fractal Geometry

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Contents

I. Topics in Fractal Geometry

1 Dimension Theory

1.1 Constructing Measures in Metric Spaces

[***TODO: fill in proofs and transfer to measure section***] Let X be a metric space.

Definition. Given $A, B \subseteq X$, say $d(A,B) = \inf\{d(a,b) : a \in A, b \in B\}$. Say A, B have **positive separation** if $d(A,B) > 0$.

If A, B are compact and disjoint, then they have positive separation. We say that an outer measure μ^* is a **metric outer measure** if $\mu^*(A \cup B) = \mu^*(A) + \mu^*(B)$ when A, B have positive separation.

Example. The Lebesgue outer measure is a metric outer measure. [***TODO: prove***]

1.1 Theorem. *μ^* is a metric outer measure if and only if every Borel set is μ^*−measurable (in the sense of Caratheodory).*

Proof [***TODO: prove this (homework), and find a proof of the converse? (may not be true)***] ∎

Suppose $\mathcal{A} \subseteq \mathcal{B}$ are both covers of X containing $\emptyset$ and $\mathcal{C} : \mathcal{B} \to [0,\infty]$ with $\mathcal{C}(\emptyset)$. Let $\mu^*_{\mathcal{A}}$ and $\mu^*_{\mathcal{B}}$ be the corresponding extensions of $\mathcal{C}$ and $\mathcal{C}|_{\mathcal{A}}$. Then by definition, $\mu^*_{\mathcal{B}}(E) \le \mu^*_{\mathcal{A}}(E)$ for all $E \in \mathcal{P}(X)$.

Let X be a metric space, $\mathcal{A}$ cover X containing $\emptyset$. Suppose for each $x \in X$ and $\delta > 0$, there exists $A \in \mathcal{A}$ such that $x \in A$ and $\operatorname{diam} A \le \delta$. Let $\mathcal{C} : \mathcal{A} \to [0,\infty]$ with $\mathcal{C}(\emptyset) = 0$. Set $\mathcal{A}_\epsilon = \{A \in \mathcal{A} : \operatorname{diam}(A) \le \epsilon\}$, and define μ^*_ϵ by extending $\mathcal{C}|_{\mathcal{A}_\epsilon}$. In particular, as ϵ decreases, μ^*_ϵ increases, and define

$$\mu^*(E) = \sup_\epsilon \mu^*_\epsilon(E) = \lim_{\epsilon \to 0} \mu^*_\epsilon(E)$$

1.2 Theorem. *As defined above, μ^* is a metric outer measure.*

Proof [***TODO: prove this, homework***] ∎

Example. The Lebesgue measure arises this way; in fact, the μ^*_ϵ are all the same outer measure.

Definition. We say that a collection of subsets $\mathcal{C}$ is a **semi-algebra** if it contains $\emptyset$, is closed under finite intersections, and complements are finite disoint unions of sets in $\mathcal{C}$. We then say that μ is a **measure on a semi-algebra** if $\mu : \mathcal{C} \to [0,\infty]$ has

(i) $\mu(\emptyset) = 0$

(ii) If $E_1, \dots, E_n \in \mathcal{C}$ are disjoint and $\bigcup_{i=1}^n E_i \in \mathcal{C}$, then $\mu\left(\bigcup_{i=1}^n E_i\right) = \sum_{i=1} n\mu(E_i)$.

(iii) If $\{E_i\}_{i=1}^\infty \in \mathcal{C}$ are pairwise disjoint and $\bigcup_{i=1}^\infty E_i \in \mathcal{C}$, then $\mu(\bigcup_{i=1}^\infty E_i) \le \sum_{i=1}^\infty \mu(E_i)$

An **algebra** is a semi-algebra which is closed under finite unions and complements. Then a **measure on an algebra** is a map μ satisfying the same above constraints.

1.3 Theorem. *A measure μ on a semi-algebra $\mathcal{C}$ has a unique extension to a measure on $\mathcal{A} = \langle \mathcal{C} \rangle$, the algebra generated by $\mathcal{C}$.*

Proof It is easy to verify that $\mathcal{A}$ is the set of all finite unions of elements in $\mathcal{C}$. Thus we extend μ to $\mathcal{A}$ where if $A = \dot{\bigcup}_{i=1}^{n} C_i$, set $\mu(A) = \sum_{i=1}^{n} \mu(C_i)$.

Check: well-defined and a measure ■

We then appeal to Caratheodory extension theorem to get a measure μ (on a σ-algebra) that extends μ from $\mathcal{A}$.

Let $\Sigma = \{1, \ldots, k\}$ be our alphabet and let Σ^* denote the set of all words on Σ. We then associate to Σ^* a heirarchy of subsets of $\mathbb{R}^n$ where to each $\sigma \in \Sigma$, get some subset X_σ; set $\mathcal{E} = \{X_\sigma : \sigma \in \Sigma^*\}$. We also assume that

$$X_\sigma \supseteq \dot{\bigcup_{i=1}^{k}} X_{\sigma i}$$

disjointly. Suppose $\tilde{\mu} : \mathcal{E} \to [0, \infty]$ has $\mu(X_\sigma) = \sum_{i=1}^{k} \mu(X_{\sigma i})$. We assume that for every infinite sequence $(i_1, i_2, \ldots)$, with $\sigma_j = (i_1, \ldots, i_j)$, $\lim_{j\to\infty} |X_{\sigma_j}| = 0$ and $\lim_{j\to\infty} \mu(X_{\sigma_j}) = 0$ uniformly with respect to length.

We set $E_k = \bigcup_{\omega \in \Sigma^n} X_\omega$ and $E = \bigcap_{i=k}^{\infty} E_k$. Let $\mathcal{C} = \{\emptyset, X_\omega \cap E : \omega \in \Sigma^*\}$. Define $\mu : \mathcal{C} \to [0, \infty]$ by $\mu(X_\omega \cap E) = \tilde{\mu}(X_\omega)$ and $\mu(\emptyset) = 0$.

1.4 Proposition. *$\mathcal{C}$ is a semialgebra and μ is a measure on a semialgebra.*

Proof We have closure under finite intersections due to the disjoint / nested property. Moreover,

$$(X_\omega \cap E)^c = \bigcup_{\substack{\sigma \in \Sigma^{|\omega|} \\ \sigma \neq \omega}} X_\sigma \cap E$$

is closed under complementation.

It is left as an exercise to verify that μ is a measure. ■

Thus μ extends to a measure μ on the σ-algebra generated by $\mathcal{C}$. Moreover, since $\operatorname{diam} X_\omega \to 0$ as $|\omega| \to \infty$, μ extends to a metric outer measure and hence the σ-algebra contains the Borel sets.

1.2 Hausdorff Measure and Dimension

For the remainder of this chapter, if X is a metric space and $U \subseteq X$, we denote $|U| = \operatorname{diam}(U)$.

Definition. A **δ–cover** of a set $F \subseteq X$ is any countable collection $\{U_n\}_{n=1}^{\infty}$ such that $\bigcup_{n=1}^{\infty} U_n \supseteq F$ and $|U_n| \leq \delta$.

Let $\mathcal{A} = \mathcal{P}(X)$, and $\mathcal{A}_\delta = \{A \subseteq X : |A| \leq \delta\}$. For $\delta \geq 0$, put $\mathcal{C}_s(A) = |A|^s$. Then for $s \geq 0$, $\delta > 0$, and $E \subseteq$, we define

$$\begin{aligned} H^s_\delta(E) &= \inf\left\{\sum_{n=1}^\infty |U_n|^s : \{U_n\} \text{ is a } \delta\text{–cover of } E\right\} \\ &= \inf\left\{\sum_{n=1}^\infty \mathcal{C}_s(U_n) : \bigcup_{n=1}^\infty U_n \supseteq E, U_n \in \mathcal{A}_\delta\right\} \end{aligned}$$

This is the outer measure as constructed in **??** with covering family A_δ and function $\mathcal{C}_s$. In particular, as $\delta \to 0$, H^s_δ increases; in particular, by Theorem 1.2, $H^s(E) = \sup_\delta H^s_\delta(E)$ is a metric outer measure. Then apply Caratheodory (**??**) to get the s–dimensional Hausdorff measure, which is a complete Borel measure.

Example. (i) H^0 is the counting measure on any metric space.

(ii) Take $X = \mathbb{R}$ and $s = 1$. Then H^1 is the Lebesgue measure (on Borel sets). To see this, we have

$$\begin{aligned} \lambda(E) &= \inf\left\{\sum_{n=1}^\infty |I_n| : \bigcup_{n=1}^\infty I_n \supseteq E, |I_n| \leq \delta\right\} \\ &\geq H^1_\delta(E) \end{aligned}$$

for any $\delta > 0$; and conversely, take any δ–cover of E, say $\{U_n\}_{n=1}^\infty$ and set $I_n = \overline{\operatorname{conv} U_n}$ so $|I_n| = |U_n| \leq \delta$. Thus $\sum_{n=1}^\infty |U_n| = \sum_{n=1}^\infty |I_n| \geq \lambda(E)$ for any such cover, so $\lambda(E) = H^1_\delta(E)$ for any $\delta > 0$. Thus $\lambda(E) = H^1(E)$ for any Borel set E.

(iii) More generally, if $X = \mathbb{R}^n$ and $s = n$, then $\lambda = \pi_n \cdot H^n$ where π_n is the n–dimensional volume of the ball of diameter 1.

We will verify that $H^n \leq m$ where m is n–dimensional Lebesgue measure on $\mathbb{R}^n$; the general result is harder and left as an exercise. To see this, we have

$$\begin{aligned} m(E) &= \inf\left\{\sum_{i=1}^\infty \operatorname{vol}(C_i) : C_i \text{ cube}, \bigcup_{i=1}^\infty C_i \supseteq E, \text{sides } \leq \frac{1}{\sqrt{n}}\delta\right\} \\ &= \inf\left\{\sum_{i=1}^\infty \left(\frac{1}{\sqrt{n}}\right)^n |C_i|^n : \{C_i\} - \delta\text{-cover of cubes of } E\right\} \\ &\geq c_n \inf\left\{\sum_{i=1}^\infty |c_i|^n : \text{all } \delta\text{–covers of } E = c_n H^n_\delta(E)\right\} \end{aligned}$$

where $c_n = (1/\sqrt{n})^n \leq 1$.

(iv) If $s < t$, then $H^s(E) \geq H^t(E)$.

Suppose $s < t$. Clearly $H^s(E) \geq H^t(E)$, but we can in fact make stronger statements. Suppose we have some U_i where $|U_i| \leq \delta$, and

$$\sum_{i=1}^\infty |U_i|^t = \sum_{i=1}^\infty |U_i|^s |U_i|^{t-s} \leq \delta^{t-s} \sum_{i=1}^\infty |U_i|^s$$

so that

$$H^t_\delta(E) \leq \delta^{t-s} \inf\left\{\sum_{i=1}^\infty |U_i|^s : \{U_i\}_{i=1}^\infty \ \delta\text{–cover of } E\right\} = \delta^{t-s} H^s_\delta(E).$$

In particular, as $\delta \to 0$, $H^t_\delta(E) \to H^t(E)$ and $H^s_\delta(E) \to H^s(E)$ and $\delta^{t-s} \to 0$ since $s < t$. Thus if $H^s(E) \neq \infty$, then $H^t(E) = 0$ for all $t > s$. Similarly, if $H^t(E) > 0$, then $H^s(E) = \infty$ for all $s < t$. As a result, there exists some unique number $S_0 := \dim_H(E) \geq 0$ such that for all $s < S_0$, $H^s(E) = \infty$, and for all $t > S_0$, $H^t(E) = 0$. We call this value the **Hausdorff dimension** of E. Note that $H^{S_0}(E) \in [0, \infty]$ and all choices are possible.

Example. (i) Since $1 = m([0,1]) = H^1([0,1])$, $\dim_H[0,1] = 1$
(ii) $\dim_H \mathbb{R} = 1$ but $m(\mathbb{R}) = H^1(\mathbb{R}) = \infty$.
(iii) It is possible to have $S_0 = 1$ but $m(E) = 0$.
(iv) There is a Cantor-like set with Hausdorff-dimension 0.
(v) If E is countable and $s > 0$, $H^s_\delta(E) \leq \sum_{x \in E} |\{x\}|^s = 0$. In particular, there exist compact countable sets, and in this case, $\dim_H C = 0$ while $H^0(C) = \infty$.

Here are some basic properties of Hausdorff dimension.

1.5 Proposition. (Properties of Hausdorff Dimension) *(i) If $A \subseteq B$, then $\dim_H A \leq \dim_H B$.*
(ii) If $F \subseteq \mathbb{R}^n$, then $\dim_H F \leq n$.
(iii) If $U \subset \mathbb{R}^n$ is open, then $\dim_H U = n$.
(iv) If $F = \bigcup_{i=1}^\infty F_i$, then $\dim_H(F) = \sup_{i \in \mathbb{N}} \dim_H F_i$.

Proof (i) If $H^s(B) = 0$, then $H^s(A) = 0$ by monotonicity of measures so $\dim_H A \leq \dim_H B$.
(ii) First consider the unit cube $I^n \subset \mathbb{R}^n$. Then

$$H^s_{\sqrt{n}\delta}(I^n) \leq \left(\frac{2}{\delta}\right)^n (\sqrt{n}\delta)^s = 2^n \sqrt{n}^n \delta^{s-n}$$

so if $s > n$, then $\delta^{s-n} \to 0$ as $\delta \to 0$. Thus for all $s > n$, $H^s(I^n) = \lim_{\delta \to 0} H^s_{\sqrt{n}\delta}(I^n) = 0$ so that $\dim_H(I^n) \leq n$. Moreover, $\mathbb{R}^n$ is the countable union of unit cubes, so that $H^s(\mathbb{R}^n) = 0$ and $\dim_H(\mathbb{R}^n) \leq n$. Then appeal to (i).
(iii) Cubes have positive Hausdorff n–measure.
(iv) If $s > \sup\{\dim_H F_i\}$, then $H^s(F_i) = 0$ for all i and by subadditivity $H^s(F) = 0$. Thus $s \geq \dim_H F$. By monotonicity, $\dim_H F \geq \dim_H F_j$ for all j. ■

Suppose $X = \mathbb{R}^n$, $E \subseteq \mathbb{R}^n$, $\lambda > 0$. Set $\lambda E = \{\lambda e : e \in E\}$: then $H^s(\lambda E) = \lambda^s H^s(E)$ since there is a bijection between δ–covers and $\lambda\delta$–covers.

Definition. Let X, Y be metric spaces. A function $f : X \to Y$ is called **Lipschitz** if there exists C such that $d(f(x), f(y)) \leq C d(x, y)$.

Certainly if f is Lipschitz, then f is uniformly continuous. Functions $f : \mathbb{R} \to \mathbb{R}$ with bounded derivative are Lipschitz by the mean value theorem.

Definition. A function $f : X \to Y$ is **Hölder continuous** with exponent α if there exists c such that $d(f(x), f(y)) \leq c d(x, y)^\alpha$.

Example. (i) If $\alpha = 1$, then f is Lipschitz, and if $\alpha = 0$, then f is bounded.
(ii) If $f : \mathbb{R}^n \to \mathbb{R}^n$ and $\alpha > 0$, then f is constant (by considering derivatives). Thus the most interesting cases occur for $0 < \alpha \leq 1$.

1.6 Proposition. *If $f : X \to Y$ is Hölder continuous with exponent α. Then $H^{s/\alpha}(f(E)) \leq c H^s(E)$ for some constant c.*

Proof If $\{U_i\}$ are a δ-cover of E, then $\{f(U_i)\}$ cover $f(E)$. Then $\operatorname{diam} f(U_i) = \sup\{d(f(x), f(y)) : x, y \in U_i\} \leq c \sup\{d(x,y)^\alpha : x, y \in U_i\} = C \cdot (\operatorname{diam} U_i)^\alpha$. Thus if $\{U_i\}$ is a δ–cover of E, then $\{f(U_i)\}$ is a $c\delta^\alpha$–cover of $f(E)$. Passing through the definition, we get $H^{s/\alpha} \leq c^{s/\alpha} H^s(E)$. ■

We then have the easy corollaries

1.7 Corollary. $\dim_H f(X) \leq \frac{1}{\alpha} \dim_H X$.

1.8 Corollary. *If f is an isometry, then $H^s(f(X)) = H^s(X)$.*

1.9 Corollary. *If $f : X \to Y$ are bi-Lipschitz, then $\dim_H X = \dim_H Y$.*

Example. Let C denote the Cantor set. Let's show that $\frac{1}{2} \leq H^s(C) \leq 1$ for $s = \frac{\log 2}{\log 3}$. In particular, this implies that $\dim_H C = \frac{\log 2}{\log 3}$.

Let $\delta = 3^{-n}$ and cover C with a δ–covering with generation n Cantor intervals. Then $H^s_\delta(C) \leq \sum_{I \in C_n} |I|^s = 2^n 3^{-ns} = 1$ by choice of s. Thus $\lim_{\delta \to 0} H^s_\delta(C) = \lim_{n\to\infty} H^s_{3^{-n}}(C) \leq 1$.

For the lower bound, take any δ–cover $\{U_i\}$ of C. Without loss of generality, we may assume that the U_i are open intervals. Since C is compact, get some finite subcover $U_1, \dots, U_N$. For each i, get $k_i \in \mathbb{N}$ so that $3^{-(k_i+1)} \leq |U_i| < 3^{-k_i}$; set $k = \max\{k_1, \dots, k_N\}$. Since U_i intersects at most 1 interval in C_{k_i}, U_i intersects at most 2^{k-k_i} intervals of C_k. Thus $2^k \leq \sum_{i=1}^N 2^{k-k_i}$ where $2^{k-k_i} = 2^k 3^{-sk_i} = 2^k 3^{-s(k_i+1)} \leq 2^k |U_i|^s 3^s$. Thus

$$2^k \leq \sum_{i=1}^N 2^k |U_i|^s 3^s$$

so $\frac{1}{2} = 3^{-s} \leq \sum_{i=1}^N |U_i|^s \leq \sum_{i=1}^\infty |U_i|^s$ so $H^s_\delta(C) \geq \frac{1}{2}$ so $H^s(C) \geq \frac{1}{2}$.

1.10 Proposition. *Let (X, d) be a metric space. If $\dim_H X < 1$, then X is totally disconnected.*

Proof Let $x \in X$ and define $f : X \to [0, \infty)$ by $f(z) = d(z, x)$. Then f is Lipschitz with constant 1 so $\dim_H f(X) \leq \dim_H X < 1$ so $m(f(X)) = 0$. Then if $y \neq x$, $d(y, x) = f(y) > 0$ while $f(x) = 0$. In particular, $(0, f(y)) \not\subset f(X)$ so there exists $0 < r < f(y)$ such that $r \notin f(X)$. Then $U_1 = \{z \in X : f(z) < r\}$ and $U_2 = \{z \in X : f(z) > r\}$ are disconnecting sets for X separating x and y.

1.3 Box Dimensions

Definition. Let $E \subseteq \mathbb{R}^n$ be a bounded Borel set, and for each $\delta > 0$, let $N_\delta(E)$ be the least number of closed balls of diameter δ. We then define the **upper box dimension** of E

$$\overline{\dim}_B E = \limsup_{\delta \to 0} \frac{\log N_\delta(E)}{|\log \delta|}$$

and similarly $\underline{\dim}_B E$ (the **lower box dimension**) with a liminf in place of limsup. If $\underline{\dim}_B E = \overline{\dim}_B E$, then we define the **box dimension** to be this shared quantity.

If I is any interval, it is easy to see that $\dim_B I = 1$. Note that if $N_\delta(E) \sim \delta^{-s}$, then $\dim_B E = S$.

Example. Let's show that the box dimension of $C_{1/3}$ exists, and compute it. Given some $\delta > 0$, let n be so that $3^{-n} \le \delta < 3^{-(n-1)}$. Certainly we can cover $C_{1/3}$ by Cantor intervals of level n, so that $N_\delta(C_{1/3}) \le 2^n$. Moreover, the endpoints of Cantor inverals of level $n-1$ are distance at least $3^{-(n-1)} > \delta$ apart. Thus $N_\delta(C_{1/3})$ is at least the number of endpoints of level $n-1$, i.e. $N_\delta(C_{1/3}) \ge 2^n$. Thus $N_\delta(C_{1/3}) = 2^n$, so that

$$\frac{\log 2}{\log 3} = \frac{\log 2^n}{\log 3^n} \le \frac{\log N_\delta(C_{1/3})}{|\log \delta|} \le \frac{\log 2^n}{\log 3^{n-1}} = \frac{n}{n-1} \cdot \frac{\log 2}{\log 3}$$

and, as $\delta \to 0$, $n \to \infty$ so that the $\dim_B C_{1/3} = \frac{\log 2}{\log 3}$.

More generally, using the same technique, we may compute $\dim_B C_r = \frac{\log 2}{\log 1/r}$. However, the box dimension has poor properties: for example, we may verify $\dim_B\{0, 1, 1/2, 1/3, \dots\} = \frac{1}{2}$. In particular, the box dimension does not have countable stability (the box dimension of any singleton is 0). But this is very concerning from a measure theoretic perspective, since this is a countable set with larger "dimension" than some uncountable sets (e.g. C_r for small r).

1.11 Theorem. *The value of the various box dimensions are equal for all following definitions of $N_\delta(E)$:*

1. *least number of open balls of radius δ that cover E*
2. *least number of cubes of side length δ*
3. *the number of δ–mesh cubes that intersect E: $[m_1\delta, (m_1+1)\delta] \times \cdots \times [m_n\delta, (m_n+1)\delta]$ for $(m_1, \dots, m_n) \in \mathbb{Z}^n$.*
4. *the largest number of disjoint closed balls of radius δ with centers in E.*

Proof Throughout, from the logarithms in the definition, it suffices to bound $N_\delta^{(i)}(E)$ with respect to $N_\delta(E)$ up to some constant factor either with respect to δ or with respect to N_δ.

1. Exercise.
2. Exercise.
3. In general, the diameter of a δ–cube in $\mathbb{R}^n$ is $\sqrt{n}\delta$. Let $N_\delta^{(3)}(E)$ denote the number of δ–mesh cubes intersecting E. Then the cubes which intersect E cover E and these have diameter $\sqrt{n}\delta$, so $N_{\sqrt{n}\delta}(E) \le N_\delta^{(3)}(E)$.
   Conversely, any set with diameter at most δ is contained in at most 3^n δ–mesh cubes. Thus $N_\delta^{(3)}(E) \le 3^n N_\delta(E)$.
4. Let $N_\delta^{(4)}$ denote the largest number of disjoint balls of radius δ centred in E. Say $B_1, \dots, B_{N_\delta^{(4)}(F)}$ are such balls. If $x \in F$, then $d(x, B_i) \le \delta$ for some i, else $B(x, \delta)$ would be disjoint from all B_i, contradicting maximality. Thus the balls $B_1^1, \dots, B^1_{N_\delta^{(4)}(E)}$ cover E and have diameter 4δ, so $N_{4\delta}(E) \le N_\delta^{(4)}(E)$.
   Conversely, let $U_1, \dots, U_{N_\delta(E)}$ be any collection of sets of diameter at most δ that cover E. Let $B_1, \dots, B_m$ be any disjoint balls with radius δ and centres $x_i \in E$. Since the U_j cover E, each $x_i \in U_{j(i)}$ for some $j(i)$ so $U_{j(i)} \subseteq B_i$ and $U_{j(i)} \cap B_k = \emptyset$ for $k \ne i$. Thus $N_\delta(E) \ge N_\delta^{(4)}(E)$. ■

Note that, in the box dimension computation, it suffices to verify along a sequence of $(\delta_k)_{k=1}^\infty \to 0$ such that $\delta_{k+1} \ge c \cdot \delta_k$ for some $c > 0$ (i.e. not faster than exponentially).

1.12 Proposition. $\dim_H(E) \le \underline{\dim}_B(E)$.

Proof Suppose we cover E by $N_\delta(E)$ sets of diameter at most δ. Then $\inf\{\sum |U_i|^s : \{U_i\}\delta\text{-cover of } E\} \le \delta^s N_\delta(E)$ so that $H^s_\delta(E) \le \delta^s N_\delta(E)$. Suppose $s < \dim_H E$, so $H^s(E) > \lambda$ for some $\lambda > 0$. Then $\delta^s N_\delta(E) \ge \lambda$ so that $\frac{\log N_\delta(E)}{-\log\delta} \ge s + \frac{\log\lambda}{-\log\delta}$. Then as $\delta \to 0$, $\liminf \frac{\log N_\delta(E)}{-\log\delta} \ge s$. Thus $\underline{\dim}_B E \ge \dim_H E$. ■

1.13 Proposition. (Properties of Box Dimension) *(i)* $\underline{\dim}_B E = \underline{\dim}_B \overline{E}$ *and* $\overline{\dim}_B E = \overline{\dim}_B \overline{E}$

(ii) $\overline{\dim}_B E = n$ *if E is dense in an open set in* $\mathbb{R}^n$.

(iii) $\overline{\dim}_B(E \cup F) = \max(\overline{\dim}_B E, \overline{\dim}_B F)$. *However,* $\underline{\dim}_B E \cup \underline{\dim}_B F \ge \max\{\underline{\dim}_B E, \underline{\dim}_B F\}$ *and the inequality can hold strictly.*

(iv) Box dimension is Lipschitz invariant.

1.14 Theorem. (Mass Distribution Principle) *Let μ be a finite Borel measure on F with $\mu(F) > 0$. Suppose there exists $c > 0$ and $\delta_0 > 0$ such that whenever $|U| \le \delta_0$, $\mu(U) \le c|U|^s$. Then $H^s(F) \ge \frac{\mu(F)}{c} > 0$.*

Proof Let $\{U_i\}$ be a δ-cover of F with $\delta \le \delta_0$. Then $\mu(F) \le \mu(\bigcup_{i=1}^\infty U_i) \le \sum_{i=1}^\infty \mu(U_i) \le c\sum_{i=1}^\infty |U_i|^s$. Thus $\inf\{\sum_{i=1}^\infty |U_i|^s : \{U_i\}\delta\text{-cover of } F\} \ge \frac{\mu(F)}{c}$ and let $\delta \to 0$. ■

Example. Let $C(r)$ denote the Cantor set with contraction ratio r. Define $\mu(I_\omega \cap C) = r^{|\omega|}$, and extend to the uniform r-Cantor measure. We now apply the mass distribution principle. Let U be arbitrary with $r^{k+1} \le |U| < r^k$. Then U cannot intersect 3 level k intervals (or U would have diameter greater than r^k). Thus $\mu(U) = \mu(U \cap C) \le c\mu(I_\omega) = 3^s$... So $\dim_G(C_r) = \frac{\log 2}{|\log r|}$.

1.15 Proposition. *Suppose μ is a finite Borel measure on $\mathbb{R}^n$ and $F \subseteq \mathbb{R}^n$ is Borel. Let $0 < c < \infty$.*

(i) If $\limsup_{r\to 0} \frac{\mu(B(x,r))}{r^s} \le c$ for all $x \in F$, then $H^s(F) \ge \frac{\mu(F)}{c}$

(ii) If $\limsup_{r\to 0} \frac{\mu(B(x,r))}{r^s} \ge c$ for all $x \in F$, then $H^s(F) \le \frac{10^s}{c}\mu(\mathbb{R}^n) < \infty$.

Proof (i) Fix $\epsilon > 0$. For each $\delta > 0$, let $F_\delta = \{x \in X : \mu(B(x,r)) \le (c+\epsilon)r^s\}$. By hypothesis, $F \subseteq \bigcup_{\delta>0} F_\delta$; moreover, for $\delta_1 < \delta_2$, $F_{\delta_1} \supseteq F_{\delta_2}$.

Fix some δ and take a δ-cover $\{U_i\}_{i=1}^\infty$ of F. This is also a δ-cover for F_δ. If $x \in F_\delta$, $\mu(B(x,|U_i|)) \le (c+\epsilon)|U_i|^s$ as $|U_i| \le \delta$. Since $U_i \subseteq B(x_i,|U_i|)$ for any $x_i \in U_i$, if $U_i \cap F_\delta \ne \emptyset$, then $x_i \in U_i \cap F_\delta$, so that $\mu(U_i) \le \mu(B(x_i,|U_i|)) \le (c+\epsilon)|U_i|^s$. Thus

$$\begin{aligned} F_\delta &= \bigcup_{U_i \cap F_\delta \ne \emptyset} (U_i \cap F_\delta) \\ &\le \sum_{i=1}^\infty (c+\epsilon)|U_i|^s \end{aligned}$$

so that $\mu(F_\delta) \le (c+\epsilon)H^s_\delta(F)$. But $F_\delta \to F$ and $H^s_\delta(F) \to H^s(F)$, so that $\mu(F) \le (c+\epsilon)H^s(F)$, where $\epsilon > 0$ is arbitrary.

(ii) Fix $\epsilon > 0$ and $\delta > 0$. Let $\mathcal{B} = \{B(x,r) : x \in F, 0 < r \leq \delta, \mu(B(x,r)) \geq (x-\epsilon)r^s\}$. By assumption, $F \subseteq \bigcup_{B \in \mathcal{B}} B$. Use the Vitali covering lemma, so there exists disjoint balls $B_1, B_2, \ldots \in \mathcal{B}$ such that B_i' is the ball with the same centre and 5 times the radius, then $\bigcup_{i=1}^\infty B_i' \supseteq F$. Since $\operatorname{diam} B(x,r) = 2r$, $|B_i'| \leq 10r \leq 10\delta$ so the $\{B_i'\}_{i=1}^\infty$ are a 10δ-cover of F. Thus

$$\begin{aligned} H^s_{10\delta}(F) &\leq \sum_{i=1}^\infty |B_i'|^s = \sum_{i=1}^\infty |B_i|^s 5^s \\ &= \sum_{i=1}^\infty (2r_i)^s 5^s \\ &\leq 10^s \sum_{i=1}^\infty \frac{\mu(B_i)}{c-\epsilon} \\ &= \frac{10^s}{c-\epsilon}\mu\left(\bigcup_{i=1}^\infty B_i\right) \leq \frac{10^s}{c-\epsilon}\mu(\mathbb{R}^n) \end{aligned}$$

and taking $\delta \to 0$ and noting that $\epsilon > 0$ is arbitrary, we have $H^s(F) \geq \frac{10^s \mu(\mathbb{R}^n)}{c}$. ∎

1.16 Proposition. *Suppose F is Borel and $0 < H^s(F) < \infty$. Then there exists c and a compact $E \subseteq F$ such that $H^s(E) > 0$ and $H^s(B(x,r) \cap E) \leq cr^s$ for all $x \in E$ and $r > 0$.*

Proof Let

$$F_1 = \left\{x : \limsup_{r \to 0} \frac{H^s(F \cap B(x,r))}{r^s} > 10^{s+1}\right\}$$

and apply (b) above with $\mu = H^s|_F$ so that

$$H^s(F_1) \leq \frac{10^s}{10^{s+1}}\mu(\mathbb{R}^n) = \frac{1}{10}H^s(F).$$

In particular, $H^s(F \setminus F_1) \geq \frac{9}{10}H^s(F) > 0$. For all $x \in F \setminus F_1$, there exists $r_0(x)$ such that for all $r \leq r_0$, then

$$\frac{H^s(F \cap B(x,r))}{r^s} \leq 10 \cdot 10^{s+1} = 10^{s+2}.$$

Let

$$E_n = \left\{x \in F \setminus F_1 : \frac{H^s(F \cap B(x,r))}{r^s} \leq 10^{s+2} \text{ for all } r \leq \frac{1}{n}\right\}$$

so that $\bigcup_{n=1}^\infty E_n = F \setminus F_1$. By continuity of measure, $H^s(E_n) \to H^s(F \setminus F_1) > 0$ so there exists N such that $H^s(E_N) > 0$. Since H^s is inner regular (TODO prove), get $E \subseteq E_N$ compact such that $H^s(E) > 0$. Then if $x \in E$, $x \in E_N$ so $H^s(E \cap B(x,r)) \leq H^s(F \cap B(x,r)) \leq 10^{s+2}r^s$ if $r \leq 1/N$. For any r, $H^s(E \cap B(x,r)) \leq H^s(F) = C_0$. If $r > 1/N$, then $C_0 \leq C_0 N^s r^s$. Take $c = \max\{10^{s+2}, C_0 N^s\}$. ∎

Remark. The assumption $H^s(F) < \infty$ can be removed when F is closed.

1.4 Potential-Theoretic Methods

Definition. For $s \geq 0$, the **s-potential at x due to μ** is

$$\phi_s(x) = \int_{\mathbb{R}^n} \frac{d\mu(y)}{\left\|x-y\right\|^s}$$

and the **s-energy of μ**

$$I_s(\mu) = \int_{\mathbb{R}^n} \phi_s d\mu = \int_{\mathbb{R}^n \times \mathbb{R}^n} \frac{d\mu(x)d\mu(y)}{\left\|x-y\right\|^s}$$

Example. (i) If $s=0$, then $\phi_0(x) = \mu(\mathbb{R}^n)$ and $I_0(\mu) = \mu(\mathbb{R}^n)^s < \infty$.

(ii) If $s > 0$ and $\mu = \delta_0$, then $I_s(\delta_0) = \phi_s(0) = \infty$

(iii) If $n = 1$ and $\mu = m|_{[0,1]}$, $s < 1$. Then $I_s(\mu) = \int_0^1 \int_0^1 \frac{dxdy}{|x-y|^s} < \infty$.

1.17 Theorem. *Let F be a closed set, $s > 0$.*

(i) If there exists a finite, non-zero measure μ supported on F such that $I_s(\mu) < \infty$, then $H^s(F) = \infty$ implies that $\dim_H F \geq s$.

(ii) If $H^s(F) > 0$, then there exists a finite non-zero measure μ on F such that $I_t(\mu) < \infty$ for all $t < s$.

Proof (i) Suppose $I_s(\mu) < \infty$ for μ a finite measure on F. We will show that $\limsup_{r\to 0} \frac{\mu(B(x,r))}{r^s} = 0$ for μ a.e. $x \in F$. Assuming this, then $H^s(F) \geq \frac{\mu(F\setminus N)}{\epsilon}$ for some μ-null N, but this holds for any $\epsilon > 0$, so $H^s(F) = \infty$.

Let $F_1 = \{x \in F : \limsup_{r\to 0} \frac{\mu(B(x,r))}{r^s} > 0\}$. We want to show that $\mu(F_1) = 0$. We first show that $\phi_s(\mu) = \infty$ on F_1. If $x \in F_1$, then there exists $\epsilon > 0$ and $\{r_i\}_{i=1}^{\infty}$ converging to 0 such that $(B(x,r_i)) \geq \epsilon r_i^s$. Since $I_s(\mu) < \infty$ for some $s > 0$, μ is not atomic so by downward continuity of meaure, $\mu(B(x,q)) \to \mu(\{x\}) = 0$ as $q \to 0$. Thus get q_i such that $\mu(B(x,q_i)) < \frac{\epsilon}{2} r_i^s$. Let $A_i = B(x,r_i) \setminus B(x,q_i)$, so that $\mu(A_i) \geq \frac{\epsilon}{2} r_i^s$. Relabelling the r_i if necessary, we may assume that $r_{i+1} < q_i$ so that the annuli are disjoint and nested. In particular,

$$\begin{aligned}
\phi_s(x) &= \int_{\mathbb{R}^n} \frac{d\mu(y)}{\left\|x-y\right\|^s} \\
&\geq \sum_{i=1}^{\infty} \int_{A_i} \frac{d\mu(y)}{\left\|x-y\right\|^s} \\
&\geq \sum_{i=1}^{\infty} \frac{1}{\max_{y\in A_i} \left\|x-y\right\|^s} \mu(A_i) \\
&\geq \sum_{i=1}^{\infty} \frac{1}{r_i^s} \mu(A_i) \geq \sum_{i=1}^{\infty} \frac{1}{r_i^s} \cdot \frac{\epsilon}{2} r_i^s = \infty
\end{aligned}$$

But now,

$$\infty > I_s(\mu) = \int_{\mathbb{R}^n} \phi_s d\mu \geq \int_{F_1} \phi_s d\mu$$

so if $\phi_s = +\infty$ on F_1, then $\mu(F_1) = 0$.

(ii) Suppose $H^s(F) > 0$. By the previous proposition, there exists sompact $E \subseteq F$ with $0 < H^s(E) < \infty$ and $H^s(E \cap B(x,r)) \le cr^s$ for all $x \in E$ and $r > 0$. Put $\mu = H^s|_E$. Then $\mu(B(x,r)) \le cr^s$ for all $x \in E$. For $x \in E$,

$$\phi_i(x) = \int_{\|x-y\|\le 1} \frac{d\mu(y)}{\|x-y^t\|} + \int_{\|x-y\|>1} \frac{d\mu(y)}{\|x-y\|^t}.$$

Certainly the second integral is finite independent of x. The first integral is finite since

$$\begin{aligned}\int_{\|x-y\|\le 1} \frac{d\mu(y)}{\|x-y^t\|} &= \sum_{k=0}^{\infty} \int_{B(x,2^{-k})\setminus B(x,2^{-(k+1)})} \frac{d\mu(y)}{\|x-y\|^t} \\ &\le \sum_{k=0}^{\infty} \frac{1}{2^{-(k+1)t}} \mu(B(x,2^{-k})) \\ &\le \sum_{k=0}^{\infty} \frac{c}{2^{-(k+1)t}} \cdot 2^{-ks} < \infty\end{aligned}$$

since $s > t$. Again, this bound does not depend on x. Thus ϕ_t is a bounded function on E, so that $I_t(\mu) < \infty$. ■

"can't have both the measure and it's fourier transform small"

Suppose f is integrable on $\mathbb{R}^n$ or $\mu \in M(\mathbb{R}^n)$ is a complex measure. We then define the **fourier transform**

$$\hat{f}(z) = \int_{\mathbb{R}^n} f(x) e^{-ix\cdot z} \, \mathrm{d}m(x)$$

$$\hat{\mu}(z) = \int_{\mathbb{R}^n} e^{-ix\cdot z} \, \mathrm{d}\mu(x)$$

If $f, g \in L^1$, then $f * g \in L^1$ by

$$f * g(x) = \int_{\mathbb{R}^n} f(x-y) g(y) \, \mathrm{d}y$$
$$f * \mu(x) = \int_{\mathbb{R}^n} f(x-y) \, \mathrm{d}\mu(y)$$

By Fubini, $\|f * g\|_1 \le \|f\|_1 \|g\|_1$ and $\|f * \mu\| \le \|f\|_1 \|\mu\|_{M(\mathbb{R}^n)}$. One reason for doing this is that L^1 is not closed under pointwise multiplication. Importantly, we have

$$(f * g)\hat{}(z) = \hat{f}(z)\hat{g}(z)$$
$$(f * \mu)\hat{}(z) = \hat{f}(z)\hat{\mu}(z)$$

in other words that the fourier transform converts convolution to multiplication.

Now consider $g_s(t) = \|t\|^{-s}$. Then

$$\phi_s(x) = \int_{\mathbb{R}^n} \frac{\mathrm{d}\mu(y)}{\|x-y\|^s} = \int_{\mathbb{R}^n} g_s(x-y) \, \mathrm{d}\mu(y) = g_s * \mu(x)$$

It is known that $\hat{g}_s(z) = c(n,s)\|z\|^{s-n}$ for $0 < s < n$. In particular, $\hat{\phi}_s(z) = \hat{g}_s(z)\hat{\mu}(z) = c(n,s)\|z\|^{s-n}\hat{\mu}(z)$.

1.18 Theorem. (Parseval) *We have*

$$\int f \cdot \overline{g}\,\mathrm{d}x = (2\pi)^n \int \hat{f} \cdot \overline{\hat{g}}\,\mathrm{d}z$$

for $f, g \in L^2$ *and thus* $\int |f|^2 = (2\pi)^n \int |\hat{f}|^2$. *When* g *is "nice",*

$$\int g(x)\,\mathrm{d}\mu(x) = (2\pi)^n \int \hat{g}(z)\overline{\hat{\mu}(z)}\,\mathrm{d}z$$

In particular (with some technicalities ...)

$$\begin{aligned} I_s(\mu) &= \int \phi_s(x)\,\mathrm{d}\mu(x) = c_n \int \hat{\phi}_s(z)\overline{\hat{\mu}(z)}\,\mathrm{d}z \\ &= c_n' \int \|z\|^{s-n}\,|\hat{\mu}(z)|^2\,\mathrm{d}z \end{aligned}$$

Example. If $|\hat{\mu}(z)| \le C\,\|z\|^{-t/z}$, then $\dim_H \operatorname{supp} \mu \ge t$.

Proof We have since $\hat{\mu}(z)$ is bounded that

$$\begin{aligned} I_s(\mu) &= c \int \|z\|^{s-n}\,|\hat{\mu}(z)|^2\,\mathrm{d}z \\ &= c\left(\int_{\|z\|\le 1} \|z\|^{s-n}\,|\hat{\mu}(z)|^2\,\mathrm{d}z + \int_{\|z\|>1} \|z\|^{s-n}\,|\hat{\mu}(z)|^2\,\mathrm{d}z\right) \\ &\le c\left(\int_{\|z\|\le 1} C_0\,\|z\|^{s-n}\,\mathrm{d}z + \int_{\|z\|\ge 1} \|z\|^{s-n}\,\|z\|^{-t}\,\mathrm{d}z\right) \\ &= c\left(c_1 \int_0^1 r^{s-n} r^{n-1}\,\mathrm{d}r + \int_1^\infty t^{s-t-1}\,\mathrm{d}r\right) < \infty \end{aligned}$$

as $s < t$. Thus $I_s(\mu) < \infty$ for any $0 < s < t$, and apply the energy theorem. ■

1.5 Projections of Fractals

Let $F \subset \mathbb{R}^2$ be a region and consider the (orthogonal) projection onto some line through the origin. Write $\operatorname{proj}_\theta(f)$ to denote the projection onto the line L_θ. Note that $d(\operatorname{proj}_\theta(x), \operatorname{proj}_\theta(y)) \le d_{\mathbb{R}^2}(x,y)$ so $\operatorname{proj}_\theta$ is Lipschitz and $\dim_H \operatorname{proj}_\theta F \le \min\{1, \dim_H F\}$.

If L is a line segment, then for all values of θ (except for 2), then the projection has maximal dimension.

1.19 Theorem. *Let* $F \subseteq \mathbb{R}^2$ *be closed.*

(i) If $\dim_H F \le 1$, *then* $\dim_H \operatorname{proj}_\theta F = \dim_H F$ *for a.e.* θ.

(ii) If $\dim_H F > 1$, *then* $m(\operatorname{proj}_\theta F) > 0$ *for a.e.* θ.

Proof (i) Choose $0 < s < \dim_H F$, so $H^s(F) > 0$. Thus there exists some μ on F such that $I_s(\mu) < \infty$. Write $x.\theta$ to denote the projection of x onto the line L_θ. Then define μ_θ on $\operatorname{proj}_\theta F$ by

$$\int_{-\infty}^{\infty} f(t)\,\mathrm{d}\mu_\theta(t) = \int f(x.\theta)\,\mathrm{d}\mu(x)$$

for all $f \in C_c(\mathbb{R})$ (Radon-Markov). Note that $\mu_\theta(S) = \mu(\mathrm{proj}_\theta^{-1}(S))$. We will show that $\int_0^\pi I_s(\mu_\theta)\,\mathrm{d}\theta < \infty$, so that $I_s(\mu_\theta) < \infty$ for a.e. θ and we will be done.
We have since $|x.\theta - y.\theta| = \left\|x-y\right\| \cos(\theta - (x-y))$.

$$\begin{aligned}
\int_0^\pi I_s(\mu_\theta)\,\mathrm{d}\theta &= \int_0^\pi \int_F \int_F \frac{\mathrm{d}\mu(x)\,\mathrm{d}\mu(y)}{|x.\theta - y.\theta|^s} \\
&= \int_0^\pi \int_F \int_F \frac{\mathrm{d}\mu(x)\,\mathrm{d}\mu(y)}{\left\|x-y\right\|^s |\cos(\theta-(x-y))|^s} \\
&= \int_F \int_F \left(\int_0^\pi \frac{\mathrm{d}\theta}{|\cos(\theta-(x-y))|^s} \right) \frac{\mathrm{d}\mu(x)\,\mathrm{d}\mu(y)}{\left\|x-y\right\|^s} \\
&= \int_{F\times F} \left(\int_0^\pi \frac{\mathrm{d}\theta}{|\cos\theta|^s} \right) \frac{\mathrm{d}\mu(x)\,\mathrm{d}\mu(y)}{\left\|x-y\right\|^s}
\end{aligned}$$

Note that $\int_0^\pi \frac{\mathrm{d}\theta}{|\cos\theta|^s} < \infty$, but the remaining term is just the s−energy of μ, which is finite.

(ii) Assume $\dim_H F > 1$, so there exists some $t > 1$ such that $H^t(F) > 0$. Get μ on F such that $I_1(\mu) < \infty$. Define μ_θ as above. We will show that μ_θ is absolutely continuous with density in L^2 for almost every θ. Then $f_\theta \neq 0$ in L^2 since $\mu_\theta \neq 0$ so that $m\{x : f_\theta(x) \neq 0\} > 0$ where $\{x : f_\theta(x) \neq 0\} \subseteq \operatorname{supp}\mu_\theta$.
Recall that $f \in L^2$ if and only if $\hat{f} \in L^2$. We have

$$\begin{aligned}
|\hat{\mu_\theta}(z)|^2 &= \int e^{-ivz}\,\mathrm{d}\mu_\theta(v) \overline{\int e^{-izw}\,\mathrm{d}\mu_\theta(w)} \\
&= \int_{\mathbb{R}\times\mathbb{R}} e^{-iz(v-w)}\,\mathrm{d}\mu_\theta(v)\,\mathrm{d}\mu_\theta(w) \\
&= \int_{F\times F} e^{-iz(x-y).\theta}\,\mathrm{d}\mu(x)\,\mathrm{d}\mu(y)
\end{aligned}$$

so that

$$\begin{aligned}
|\hat{\mu_\theta}(z)|^2 + |\hat{\mu_{\theta+\pi}}(z)|^2 &= \int_{F\times F} \left(e^{-iz(x-y).\theta} + e^{-iz(x-y).(-\theta)} \right) \mathrm{d}\mu(x)\,\mathrm{d}\mu(y) \\
&= 2 \int_{F\times F} \cos(z(x-y).\theta)\,\mathrm{d}\mu(x)\,\mathrm{d}\mu(y)
\end{aligned}$$

First note that

$$\begin{aligned}
\int_0^{2\pi} |\hat{\mu_\theta}(z)|^2\,\mathrm{d}\theta &= \int_0^\pi |\hat{\mu_\theta}(z)|^2 + |\hat{\mu_{\theta+\pi}}(z)|^2\,\mathrm{d}\theta \\
&= 2\int_0^\pi \int_f \int_F \cos(z(x-y).\theta)\,\mathrm{d}\mu(x)\,\mathrm{d}\mu(y)\,\mathrm{d}\theta \\
&= 2\int_0^\pi \int_f \int_F \cos\Big(z\left\|x-y\right\|\cos(\theta-(x-y))\Big)\,\mathrm{d}\mu(x)\,\mathrm{d}\mu(y)\,\mathrm{d}\theta \qquad \blacksquare
\end{aligned}$$

Bessel function: $J_0(\mu) = \frac{1}{2\pi}\int_0^{2\pi} \cos(u\cos\theta)\,\mathrm{d}\theta$.