

Honours Analysis 3

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1 Borel Sets

We will work for some time on \mathbb{R} exclusively. Before beginning Measure Theory: a quick recap of Topology.

Definition 1.1 (Open Set). *A subset $U \subset \mathbb{R}$ is called open if either $U = \emptyset$ or else*

$$\forall x \in U, \exists r > 0 \text{ such that } (x - r, x + r) \subset U$$

Some examples of open sets: $\emptyset, \mathbb{R}, (a, b), (a, \infty), (-\infty, a)$. There are many more because any union of an open set is still open and any finite intersection of open sets is open.

Definition 1.2 (Closed Set). *$F \subset \mathbb{R}$ is called closed if $\mathbb{R} \setminus F := F^c$ is open.*

F is closed $\iff F$ contains all points $x \in \mathbb{R}$ which have the property that $\forall r > 0, (x - r, x + r) \cap F \neq \emptyset$.

If $F \subset \mathbb{R}$ is any set, the closure of F , denoted by \overline{F} , is the smallest closed set that contains F .

Definition 1.3 (Compact). *A subset $G \subset \mathbb{R}$ is compact if given any collection $\{U_i\}_{i \in I}$ of open sets $U_i \subset \mathbb{R}$ with $G \subset \cup_{i \in I} U_i$, there exists $J \subset I$, J finite, such that $G \subset \cup_{j \in J} U_j$*

*Notes from the lectures of Valentino Tosatti

Theorem 1.1 (Heine-Borel). $G \subset \mathbb{R}$ is compact $\iff G$ is closed and bounded. To be bounded means $G \subset (a, b)$ for some $a, b \in \mathbb{R}$.

Corollary 1.1.1 (Nested Set Theorem). Let $\{F_n\}_{n=1}^\infty$ be a countable collection of non-empty, bounded, closed sets $F_n \subset \mathbb{R}$ with $F_{n+1} \subset F_n \forall n$, then

$$\bigcap_{n=1}^\infty F_n \neq \emptyset$$

Proof. Suppose $\bigcap_{n=1}^\infty F_n = \emptyset$ so let $U_n = F_n^c$ be open sets, such that $\bigcup_{n=1}^\infty U_n = \mathbb{R}$. We also have that $U_n \subset U_{n+1}$, since the F_n were nested. Now F_1 is compact by Heine-Borel and $F_1 \subset \bigcup_{n=1}^\infty U_n \Rightarrow$ by compactness I can find a finite subcover of F_1 , say $F \subset \bigcup_{n=1}^N U_n = U_N = F_N^c$

On the other hand $F_N \subset F_1$ by the nested property which implies $F_N = \emptyset$ which is a contradiction. \square

2 Measure Theory

We want to measure the size of a set. We will deal with a subset of \mathbb{R} .

It turns out that one needs to select a class of subsets of \mathbb{R} that one wants to measure. This class of subsets will have certain properties which are as follows.

Definition 2.1 (σ -algebra). A collection \mathcal{A} of subsets of \mathbb{R} is called a σ -algebra if it satisfies

1. $\emptyset \in \mathcal{A}$
2. If $A \in \mathcal{A}$ then $A^c \in \mathcal{A}$
3. If $\{A_n\}_{n=1}^\infty \subset \mathcal{A}$ then $\bigcup_{n=1}^\infty A_n \in \mathcal{A}$

Observe the following:

- $\mathbb{R} \in \mathcal{A}$ always

- If $\{A_n\}_{n=1}^N \subset \mathcal{A}$ then $\cup_{n=1}^N A_n \in \mathcal{A}$ (just define $A_n = \emptyset$ for $n > N$)
- If $\{A_n\}_{n=1}^\infty \subset \mathcal{A}$ then $\cap_{n=1}^\infty A_n \in \mathcal{A}$ (since $(\cap_{n=1}^\infty A_n)^c = \cup_{n=1}^\infty A_n^c$)
- If $A, B \in \mathcal{A}$ then $A \setminus B \in \mathcal{A}$ too since $A \setminus B = A \cap B^c$

Examples:

1. $\mathcal{A} = \{\emptyset, \mathbb{R}\}$ “Minimal σ -algebra”
2. $\mathcal{A} = \mathcal{P}(\mathbb{R})$ = Collection of all subsets of \mathbb{R} . “Maximum σ -algebra”

In fact, if \mathcal{A} is any σ -algebra, then $\{\emptyset, \mathbb{R}\} \subseteq \mathcal{A} \subseteq \mathcal{P}(\mathbb{R})$

For better examples, let F be any collection of subsets of \mathbb{R} . I want to make F into a σ -algebra. Define $m = \{\mathcal{A} \mid \mathcal{A} \text{ is a } \sigma\text{-algebra that satisfies } F \subset \mathcal{A}\}$. $m \neq \emptyset$ since it contains $\mathcal{P}(\mathbb{R})$

If $\mathcal{A}, \mathcal{B} \in m$, I can define $\mathcal{A} \cap \mathcal{B} = \{A \subset \mathbb{R} \mid A \in \mathcal{A} \text{ and } A \in \mathcal{B}\}$ and I can do the same for $\cap_{i \in I} \mathcal{A}$ arbitrary intersection of σ -algebra is still a σ -algebra

Define $\hat{F} = \cap_{\mathcal{A} \in m} \mathcal{A}$ as a σ -algebra and $F \subset \hat{F}$ and it is the minimal σ -algebra with these properties. If G is a σ -algebra with $F \subset G$, then $\hat{F} \subset G$. \hat{F} is the σ -algebra generated by F . Concretely, \hat{F} consists of all subsets of \mathbb{R} that can be constructed by applying countable unions, intersections, and complements to elements of F .

Definition 2.2 (Borel Sets). *The σ -algebra \mathcal{B} of Borel Sets is the σ -algebra \hat{F} generated by*

$$F = \{U \subset \mathbb{R} \mid U \text{ open} \}$$

Remark. \mathcal{B} is also the σ -algebra generated by the family of all closed subsets of \mathbb{R}

Singletons $\{x\} \subset \mathbb{R}$ are closed so if $A \subset \mathbb{R}$ is at most countable then A is Borel. (e.g $\mathbb{Q} \subset \mathbb{R}$) (e.g $\mathbb{R} \setminus \mathbb{Q}$)

Not all Subsets of \mathbb{R} are Borel. One can actually show that the cardinality of \mathcal{B} is the same as the cardinality of \mathbb{R} . On the other hand $\mathcal{P}(\mathbb{R})$ has strictly larger cardinality.

3 Lebesgue Outer Measure

We are hoping to measure the size of subsets of \mathbb{R} . Ideally we would like to find or construct a function

$$m : \mathcal{P}(\mathbb{R}) \rightarrow \mathbb{R}_{\geq 0} \cup \{+\infty\} = [0, \infty]$$

Which satisfies the following measure requirements:

1. If $I = [a, b]$ or (a, b) or $[a, b)$, or $(a, b]$, $a, b \in \mathbb{R}, a \leq b$ then $m(I) = b - a = \text{measure of interval}$
2. m is translation invariant. i.e if $E \subset \mathbb{R}$ and $x \in \mathbb{R}$, let $E + x = \{y + x \mid y \in E\}$ then $m(E + x) = m(E)$
3. If $\{E_j\}_{j=1}^n$ is a finite collection of pairwise disjoint $E_j \subset \mathbb{R}$ then

$$m\left(\bigcup_{j=1}^n E_j\right) = \sum_{j=1}^n m(E_j)$$

4. The same as (3) except for $n = \infty$

Theorem 3.1. *There is no such m satisfying all 4 requirements*

The proof for this will come later. The solution for this is that we do not try to measure all subsets of \mathbb{R} . So we have $m : \mathcal{P}(\mathbb{R}) \rightarrow [0, \infty]$ but now we will just be happy with $m : \mathcal{A} \rightarrow [0, \infty]$ where \mathcal{A} is a σ -algebra which has enough elements. For example $\mathcal{A} \supset \mathcal{B}$.

We will follow H. Lebesgue as we proceed in two steps.

Step 1: construct Lebesgue outer measure $m^* : \mathcal{P}(\mathbb{R}) \rightarrow [0, \infty]$ satisfying requirements 1, 2, and 3.

Step 2: Use m^* to define \mathcal{A} and let $m \subset m^* \mid \mathcal{A}$

To create this Lebesgue outer measure on \mathbb{R} we satisfy a weakened version of requirement (3) that can be called (3w). For any countably infinite collection $\{E_j\}_{j=1}^\infty$ of arbitrary subsets $E_j \subset \mathbb{R}$

$$m^*\left(\bigcup_{j=1}^\infty E_j\right) \leq \sum_{j=1}^\infty m(E_j)$$

Theorem 3.2 (Lebesgue Outer Measure). *There is a map $m^* : \mathcal{P}(\mathbb{R}) \rightarrow \mathbb{R}_{\geq 0} \cup \{+\infty\}$ that satisfies the measure requirements 1, 2, and 3w.*

This m^* is called the Lebesgue outer measure on \mathbb{R} .

How do we define outer measure $m^*(A)$?

Observe that any $A \subseteq \mathbb{R}$ can be covered by some countable infinite collection $\{I_j\}_{j=1}^{\infty}$ of bounded open intervals, which are allowed to be empty, but we do not assume that I_j be pairwise disjoint.

For example: $I_j = (-j, j)$, $j = 1, 2, 3 \dots$

Let

$$\mathcal{C}_A = \{\{I_j\}_{j=1}^{\infty} \mid I_j \text{ bounded open intervals such that } A \subset \cup_{j=1}^{\infty} I_j\}$$

$\mathcal{C}_A \neq \emptyset$ by our example so for each $\{I_j\} \in \mathcal{C}_A$, I can consider

$$\sum_{j=1}^{\infty} \ell(I_j) \in \mathbb{R}_{\geq 0} \cup \{+\infty\} \quad (\ell \text{ denotes length})$$

Definition 3.1 (Outer Measure).

$$m^*(A) := \inf_{\{I_j\} \in \mathcal{C}_A} \sum_{j=1}^{\infty} \ell(I_j) \in \mathbb{R}_{\geq 0} \cup \{+\infty\}$$

This defines a map $m^* : \mathcal{P}(\mathbb{R}) \rightarrow \mathbb{R}_{\geq 0} \cup \{+\infty\}$

Simple Properties:

- *Monotonicity:* If $A \subseteq B$ then $m^*(A) \leq m^*(B)$. Indeed by definition $\mathcal{C}_B \subseteq \mathcal{C}_A$ hence the infimum over \mathcal{C}_B is \geq than the infimum over \mathcal{C}_A .
- *Empty Set:* $m^*(\emptyset) = 0$. Given any $1 > \epsilon > 0$, let $I_j = (-\epsilon^j, \epsilon^j)$, $j = 1, 2, \dots$ $\{I_j\} \in \mathcal{C}_{\emptyset}$ and $\sum_{j=1}^{\infty} \ell(I_j) = 2 \sum_{j=1}^{\infty} \epsilon^j = \frac{2\epsilon}{1-\epsilon}$ from the geometric series going to zero so $m^*(\emptyset) \leq \frac{2\epsilon}{1-\epsilon} \forall 0 < \epsilon < 1$

- If $A \in \mathbb{R}$ is finite or countable infinite then $m^*(A) = 0$. Indeed enumerate all elements of A by $\{a_j\}_{j=1}^\infty$. (If A is finite say $|A| = n$ let $a_j = a_n$ for all $j > n$). For any $0 < \epsilon < 1$, let $I_j = (-\epsilon^j + a_j, a_j + \epsilon^j)$ so $A \subseteq \cup_{j=1}^\infty I_j$ and $\sum_{j=1}^\infty \ell(I_j) = \frac{2\epsilon}{1-\epsilon}$ hence as before, $m^*(A) = 0$. For example $m^*(\mathbb{Q}) = 0$

We will now prove that the Lebesgue outer measure satisfies 1, 2, and 3w of the measure requirements.

Proof of Property 1: i.e $m^*(I) = \ell(I)$ for any interval $I \subseteq \mathbb{R}$

Assume that $I = [a, b]$, $a < b$ are finite numbers. Assume that I is a bounded closed interval. Our goal is to show that $m^*(I) = b - a$. One direction of inequality is easy to prove, the other is quite tedious and will be left out.

For any $\epsilon > 0$ let $I_1 = (a - \epsilon, b + \epsilon) \supset I$, let $I_j = \emptyset, j \geq 2$ so $\{I_j\} \in \mathcal{C}_I \Rightarrow m^*(I) \leq \sum_{j=1}^\infty \ell(I_j) = b - a + 2\epsilon$. Let $\epsilon \rightarrow 0$ and we obtain $m^*(I) \leq b - a$.

Proof of Property 2: i.e $\forall A \subset \mathbb{R}, \forall x \in \mathbb{R}, m^*(A + x) = m^*(A)$

\mathcal{C}_A and \mathcal{C}_{A+x} are naturally in bijection via $\{I_j\} \leftrightarrow \{I_j + x\}$. Furthermore $\ell(I_j + x) = \ell(I_j)$

$$\begin{aligned} m^*(A + x) &= \inf_{\{I_j+x\} \in \mathcal{C}_{A+x}} \sum_{j=1}^\infty \ell(I_j + x) \\ &= \inf_{\{I_j\} \in \mathcal{C}_A} \sum_{j=1}^\infty \ell(I_j) = m^*(A) \end{aligned}$$

Proof of Property 3w: i.e If $\{E_j\}_{j=1}^n$ is a finite collection of pairwise disjoint $E_j \subset \mathbb{R}$ then $m^*\left(\cup_{j=1}^n E_j\right) = \sum_{j=1}^n m^*(E_j)$

If $m^*(E_j) = +\infty$ for some j , then the property holds. We may assume that $m^*(E_j) < +\infty \forall j$. Let $\epsilon > 0$. By the definition of infimum, for each $j \geq 0$, there is

$$\{I_{j,k}\}_{k=1}^\infty \in \mathcal{C}_{E_j} \text{ such that } \sum_{k=1}^\infty \ell(I_{j,k}) < m^*(E_j) + \epsilon 2^{-j}$$

Thus $\{I_{j,k}\}_{k=1}^{\infty}$ is still countable and it covers $\cup_{j=1}^{\infty} E_j$ meaning it belongs to $\mathcal{C}_{\cup_{j=1}^{\infty} E_j}$, so by definition

$$m^* \left(\bigcup_{j=1}^{\infty} E_j \right) \leq \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} \ell(I_{j,k}) < \sum_{j=1}^{\infty} (m^*(E_j) + \epsilon 2^{-j}) = \sum_{j=1}^{\infty} m^*(E_j) + \epsilon$$

Then let $\epsilon \rightarrow 0$. Clearly, by taking all $E_j = \emptyset$ except finitely many, we have the same subadditivity 3w for finite collections.

Corollary 3.2.1. $m^*([0, 1] \cap (\mathbb{R} \setminus \mathbb{Q})) = 1 = \ell([0, 1])$

Proof.

$$\begin{aligned} m^*([0, 1] \cap (\mathbb{R} \setminus \mathbb{Q})) &\leq m^*([0, 1]) = 1 \\ &\leq m^*([0, 1] \cap (\mathbb{Q})) + m^*([0, 1] \cap (\mathbb{R} \setminus \mathbb{Q})) \\ &\leq 0 + 1 \end{aligned}$$

□

Corollary 3.2.2. $\mathbb{R} \setminus \mathbb{Q}$ is uncountable

Proof. If not, then

$$m^*(\mathbb{R} \setminus \mathbb{Q}) = 0 \geq m^*([0, 1] \cap (\mathbb{R} \setminus \mathbb{Q})) = 1$$

□

4 The σ -Algebra Of Lebesgue Measurable Sets

m^* does not satisfy the third measurability requirement without the weak 3w condition. We can construct some examples to prove this. $A, B \subset \mathbb{R}$, $A \cap B = \emptyset$, such that $m^*(A \cup B) < m^*(A) + m^*(B)$ later in the class.

The idea to avoid this problem is to look at “reasonable” subsets of \mathbb{R} for which this paradox disappears.

Definition 4.1 (Carathéodory). $E \subseteq \mathbb{R}$ is called (Lebesgue) measurable if $\forall A \subset \mathbb{R}$

$$m^*(A) = m^*(A \cap E) + m^*(A \cap E^c)$$

Remark. *This is equivalent to Lebesgue's definition: E is measurable if and only if*

$$\exists U \subset \mathbb{R} \text{ such that } E \subset U \text{ and } m^*(U \setminus E) < \epsilon$$

But we will discuss this later.