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*

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

Proof. Suppose $\cap_{n=1}^{\infty} F_n = \emptyset$ so let $U_n = F_n^c$ be open sets, such that $\cup_{n=1}^{\infty} U_n = \mathbb{R}$. 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 $F_1 \subset \cup_{n=1}^{\infty} U_n \Rightarrow$ by compactness I can find a finite subcover of F_1, say $F \subset \cup_{n=1}^{N} U_n = U_N = F_N^c$

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

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 $\cup_{n=1}^{\infty} A_n \in \mathcal{A}$*

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 $m = \{\mathcal{A} \mid \mathcal{A}$ is a σ-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 $\mathcal{A} \cap \mathcal{B} = \{A \subset \mathbb{R} \mid A \in \mathcal{A}$ 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 $\hat{F}_i = \cap_{\mathcal{A} \in m} \mathcal{A}$ 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

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

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 $m(I) = b - a =$ 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
$$m\left(\cup_{j=1}^{n} E_j\right) = \sum_{j=1}^{n} m(E_j)$$
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 $m : \mathcal{P}(\mathbb{R}) \to [0, \infty]$ but now we will just be happy with $m : \mathcal{A} \to [0, \infty]$ where $\mathcal{A}$ is a σ-algebra which has enough elements. For example $\mathcal{A} > \mathcal{B}$.

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

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

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

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 $E_j \subset \mathbb{R}$

$$m^\star(\cup_{j=1}^{\infty} E_j) \leq \sum_{j=1}^{\infty} m(E_j)$$

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

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

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

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

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

Definition 3.1 (Outer Measure)**.**

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

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

Simple Properties:

- *Monotonicity*: If $A \subseteq B$ then $m^\star(A) \leq m^\star(B)$. 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*: $m^\star(\emptyset) = 0$. 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 $m^\star(\emptyset) \leq \frac{2\epsilon}{1-\epsilon}\ \forall 0 < \epsilon < 1$

- If $A \in \mathbb{R}$ is finite or countable infinite then $m^\star(A) = 0$. 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 $I_j = \left(-\epsilon^j + a_j, a_j + \epsilon^j\right)$ 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, $m^\star(A) = 0$. For example $m^\star(\mathbb{Q}) = 0$

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

Proof of Property 1: i.e $m^\star(I) = \ell(I)$ 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 $m^\star(I) = b - a$. One direction of inequality is easy to prove, the other is quite tedious and will be left out.

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

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

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

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

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

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

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

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

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

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

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

Proof.

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

□

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

Proof. If not, then

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

4 The σ-Algebra Of Lebesgue Measurable Sets

$m^\star$ 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 $m^\star(A \cup B) < m^\star(A) + m^\star(B)$ 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)**.** *$E \subseteq R$ is called (Lebesgue) measurable if* $\forall A \subset \mathbb{R}$

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

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

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

But we will discuss this later.

Suppose that A is measurable and $B \subset \mathbb{R}$ is any set such that $A \cap B = \emptyset$ then

$$m^\star(A \cup B) = m^\star\left(\underbrace{(A \cup B) \cap A}_{=A}\right) + m^\star\left(\underbrace{(A \cup B) \cap A^c}_{=B}\right)$$

Going back to our counter example for $m^\star$ and measurability requirement 3, A or B would have to be unmeasurable.

Here's another observation: For $E, A \subset \mathbb{R}$ arbitrary sets we have

$$A = (A \cap E) \cup (A \cap E^c)$$

So by 3w $m^\star(A) \leq m^\star(A \cap E) + m^\star(A \cap E^c)$, so E is measurable $\iff$ $\forall A \subset \mathbb{R}$

$$\boxed{m^\star(A) \geq m^\star(A \cap E) + m^\star(A \cap E^c)}$$

This holds trivially for $m^\star(A) = \infty$

Example 1: $\emptyset$ is measurable. $\forall A \subset \mathbb{R}$

$$m^\star(A) = \cancel{m^\star(A \cap \emptyset)} + m^\star(A \cap \mathbb{R})$$

Example 2: $\mathbb{R}$ is measurable. $\forall A \subset \mathbb{R}$

$$m^\star(A) = m^\star(A \cap \mathbb{R}) + m^\star(A \cap E^c)$$

Proposition. *$E \subset \mathbb{R}$ with $m^\star(E) = 0$, then E is measurable.*

Corollary. *Every countable set is measurable. $\mathbb{Q}$ measurable $\to \mathbb{R} \setminus \mathbb{Q}$ are measurable*

Proof. Let $A \subset \mathbb{R}$ be any set

$$A \cap E \subset E \Rightarrow m^\star(A \cap E) \leq m^\star(E) = 0$$
$$A \cap E^c \subset A \Rightarrow m^\star(A \cap E^c) \leq m^\star(A)$$
$$\text{So } m^\star(A) \geq m^\star(A \cap E^c) + \cancel{m^\star(A \cap E)}$$

□

Our goal is to show that Lebesgue measurable sets $\mathcal{L} = \{E \subset \mathbb{R} \mid E \text{ is measurable}\}$ is a σ-algebra on $\mathbb{R}$. We just need to show that if $\{E_j\}_{j=1}^{\infty}$ with $E_j \in \mathcal{L}$, $\forall j$, then $\cup_{j=1}^{\infty} E_j \in \mathcal{L}$

Proposition. *If* $\{E_j\}_{j=1}^{n} \subset \mathcal{L}$ *then* $\cup_{j=1}^{n} E_i \in \mathcal{L}$

Proof. We use mathematical induction. $n = 1$ is trivial so we set the base case as $n = 2$. E_1, E_2 are measurable, Let $A \subset \mathbb{R}$ be any set

$$\begin{aligned} m^{\star}(A) &= m^{\star}(E_1 \cap A) + m^{\star}(A \cap E_1^c) \\ &= m^{\star}(A \cap E_1) + m^{\star}((A \cap E_1^c) \cap E_2) + m^{\star}((A \cap E_1^c) \cap E_2^c) \\ &= m^{\star}(A \cap E_1) + m^{\star}((A \cap E_1^c) \cap E_2) + m^{\star}(A \cap (E_1^c \cap E_2^c)) \\ &= m^{\star}(A \cap E_1) + m^{\star}((A \cap E_1^c) \cap E_2) + m^{\star}(A \cap (E_1 \cup E_2)^c) \\ &\geq m^{\star}(A \cap (E_1 \cup E_2)) + m^{\star}(A \cap (E_1 \cup E_2)^c) \end{aligned} \tag{3w}$$

So $E_1 \cup E_2 \in \mathcal{L}$.

Induction step $n \geq 2$

$$\bigcup_{j=1}^{\infty} E_j = \left(\bigcup_{j=1}^{n-1} E_j \right) \cup E_n \in \mathcal{L} \text{ by the } n = 2 \text{ case}$$

$\square$

To prove that this also applies to countable sets, we use

Proposition (Analog of measurability requirement 3 for $m^{\star} \mid \mathcal{L}$)**.** *Suppose* $A \subset \mathbb{R}$ *is any set* $\{E_j\}_{j=1}^{n}$ *finite disjoint collection of sets* $E_j \in \mathcal{L}$*, then* $m^{\star}\left(A \cap \cup_{j=1}^{n} E_j\right) = \sum_{j=1}^{n} m^{\star}(A \cap E_j)$*. Take* $A = \mathbb{R}$*, get* $m^{\star}\left(\cup_{j=1}^{n} E_j\right) = \sum m^{\star}(E_j)$