

Modern Analysis

Lectures by Shimon Brooks (brookss@math.biu.ac.il)
Summary by Ari Feiglin (ari.feiglin@gmail.com)

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1 Introduction

The Riemann Integral and its Faults

Recall the definition of the Riemann integral: given a function $f(x)$ on an interval $[a, b]$ we take a partition of this interval and representatives from each partition, x_i . Then the Riemann sum of this function over this partition is $\sum f(x_i)\Delta x_i$. Then if this sum converges to a value as $\sup \Delta x_i$ converges to 0, this function is *Riemann integrable* and has an integral represented by $\int_a^b f(x) dx$. Previously we have shown that a function is Riemann integrable if and only if it is almost always continuous, in particular all continuous functions are continuous.

But take for example \mathbb{Q} 's indicator function

$$\chi_{\mathbb{Q}}(x) := \begin{cases} 1 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q} \end{cases}.$$

This function is nowhere continuous and thus is not Riemann integrable. But we argue that it *should* be integrable.

Any theory if an integral should have the following two basic properties:

(1) *monotonicity*: if $f(x) \leq g(x)$ for every x in the domain then $\int f(x) dx \leq \int g(x) dx$.

(2) *linearity*: $\int (\alpha f(x) + \beta g(x)) dx = \alpha \int f(x) dx + \beta \int g(x) dx$.

Let $\{q_n\}_{n=1}^{\infty}$ be an enumeration of the rationals and $\varepsilon > 0$. Let us define $E_n := (q_n - \frac{\varepsilon}{2^{n+1}}, q_n + \frac{\varepsilon}{2^{n+1}})$, then we should think that

$$(1) \quad \int \sum_{n=1}^{\infty} \chi_{E_n}(x) dx = \sum_{n=1}^{\infty} \int \chi_{E_n}(x) dx = \sum_{n=1}^{\infty} \frac{\varepsilon}{2^n} = \varepsilon$$

Now $\chi_{\mathbb{Q}}(x) \leq \sum_{n=1}^{\infty} \chi_{E_n}(x)$ for all x and so $\int \chi_{\mathbb{Q}}(x) dx \leq \varepsilon$ for every $\varepsilon > 0$ and so we should think that $\int \chi_{\mathbb{Q}}(x) dx = 0$.

Now obviously $\chi_{\mathbb{Q}}$ is not Riemann-integrable, and so there is an issue with the above argument. In fact there are two: firstly in (1) we assumed that $\int \sum_{n=1}^{\infty} \chi_{E_n} = \sum_{n=1}^{\infty} \int \chi_{E_n}$, which only holds if the sum converges uniformly. Secondly, $\sum_{n=1}^{\infty} \chi_{E_n}(x)$ takes on infinite values (for every rational number, the sum is infinite) and so it is not even Riemann integrable.

So we want a theory of integration which allows for two things: 1) the ability to deal with convergence of an integral without necessarily needing uniform convergence, 2) the ability to deal with functions which are not Riemann-integrable. Lebesgue's theory of integration is based on the following observation: partitioning the domain of the function will necessarily require some form of continuity, so instead try partitioning the *range* of the function. So given the partition $y_0 < \dots < y_n$ we can imagine some Lebesgue sum of this partition to be

$$\sum_{i=0}^n y_i \cdot |E_i|, \quad E_i = \{x \in [a, b] \mid y_i \leq f(x) \leq y_{i+1}\}$$

where $|S|$ is some notion of the “width” of the set S , *which we have not yet defined* (it is not the cardinality of the set). For an interval this should be the length of the interval, but for arbitrary sets it becomes harder to understand how we should approach defining it. And in order to define the integral of $\chi_{\mathbb{Q}}$, it is necessary to define this width for arbitrary sets, or at least for a larger family of sets than just intervals, since computing the Lebesgue sums of $\chi_{\mathbb{Q}}$ will involve terms containing $|\mathbb{Q}|$.

This “Lebesgue sum” will not be precisely how we define Lebesgue integration, but it does give us a starting point: how do we define the “width” of a set $E \subseteq \mathbb{R}$.

2 Lebesgue Integration

2.1 The Lebesgue Measure

We would like a function m which measures the width of arbitrary sets $E \subseteq \mathbb{R}$. Such a function would ideally satisfy the following properties:

- (m1) m is a function $m: \mathcal{P}(\mathbb{R}) \rightarrow [0, \infty]$,
- (m2) for every interval I , $m(I)$ is the length of I ,
- (m3) the measure of a set is preserved under movement, ie. $m(E + \alpha) = m(E)$ for every $\alpha \in \mathbb{R}$ where $E + \alpha = \{x + \alpha \mid x \in E\}$,
- (m4) if $\{E_n\}_{n=1}^\infty$ is a sequence of disjoint sets then $m(\bigcup_{n=1}^\infty E_n) = \sum_{n=1}^\infty m(E_n)$. This is called σ -additivity.

2.1.1 Definition (The Outer Measure)

Let $E \subseteq \mathbb{R}$, then we define E 's **outer measure** to be

$$m^*(E) := \inf \left\{ \sum_{n=1}^\infty |I_n| \mid E \subseteq \bigcup_{n=1}^\infty I_n \text{ where } I_n \text{ are all open intervals} \right\}$$

This set is nonempty since \mathbb{R} can be covered by open intervals (eg. $\{(n, n+2)\}_{n \in \mathbb{Q}}$) and therefore so can every subset. Obviously we have that $m^*(\emptyset) = 0$ since we can take arbitrarily small arbitrary intervals. Notice that for every $\varepsilon > 0$, we showed in the previous section there exists open intervals $\{E_n\}_{n=1}^\infty$ such that $\mathbb{Q} \subseteq \bigcup_{n=1}^\infty E_n$ and $\sum_{n=1}^\infty |E_n| = \varepsilon$. Thus we have that $m^*(\mathbb{Q}) \leq \varepsilon$ for every $\varepsilon > 0$ and so $m^*(\mathbb{Q}) = 0$ as well.

Notice that we can also take a finite set of I_n s, as we can add infinitely many I_n s of arbitrarily small width (eg. add I_n s of length $\frac{\varepsilon}{2^n}$) and this will add ε to the sum, and so the infimum remains the same. Thus we have that

$$m^*(E) = \inf \left\{ \sum_{n=1}^\infty |I_n| \mid E \subseteq \bigcup_{j \in J} I_j \text{ where } I_n \text{ are all open intervals and } J \text{ is countable} \right\}$$

Now, does the outer measure satisfy the conditions m1 through m4?

- (1) m^* is indeed a function from $\mathcal{P}(\mathbb{R})$ to $[0, \infty]$,
- (2) $m^*(I) = |I|$ for all intervals I (proven below).
- (3) $m^*(E + \alpha) = m^*(E)$ as there is a width-preserving bijection between collections of intervals covering E and $E + \alpha$ (in particular $I \mapsto I + \alpha$).

But m^* is not σ -additive, and we can only ensure σ -subadditivity:

2.1.2 Theorem

Let $\{E_n\}_{n=1}^\infty$ be a sequence of (not necessarily disjoint) subsets of \mathbb{R} , then

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

Proof: for every E_n , let us take a cover for E_n of open intervals $\{I_k^{(n)}\}_{k=1}^\infty$ such that $m^*(E_n) \geq \sum_{k=1}^\infty |I_k^{(n)}| + \frac{\varepsilon}{2^n}$. Then we have that

$$\sum_{n=1}^\infty m^*(E_n) \geq \sum_{n=1}^\infty \left(\sum_{k=1}^\infty |I_k^{(n)}| + \frac{\varepsilon}{2^n} \right) = \sum_{n,k=1}^\infty |I_k^{(n)}| + \varepsilon$$

Since $\left\{I_k^{(n)}\right\}_{n,k=1}^{\infty}$ is a cover of $\bigcup_{n=1}^{\infty} E_n$, we have that

$$\sum_{n=1}^{\infty} m^*(E_n) \geq \sum_{n,k=1}^{\infty} \left|I_k^{(n)}\right| + \varepsilon \geq m^*\left(\bigcup_{n=1}^{\infty} E_n\right) + \varepsilon$$

Since $\varepsilon > 0$ is arbitrary, we get the desired inequality (by taking $\varepsilon \rightarrow 0$, the above inequality is preserved). ■

Of course this does not prove that m^* is not σ -additive, we have simply proven a weaker condition.

This helps us show that $m^*(I) = |I|$ for all intervals I . For open intervals this is trivial, and we have that $m^*(E \cup \{a\}) \leq m^*(E) + m^*(\{a\}) = m^*(E)$ (the measure of a singleton is obviously zero) and $m^*(E \cup \{a\}) \geq m^*(E)$ by monotonicity. All intervals are obtained by adding a finite number of points to an open interval, so for example $m^*([a, b]) = m^*((a, b) \cup \{a, b\}) = m^*((a, b)) = b - a$ as required.

2.1.3 Proposition (The Vitali Set)

There exists no function which satisfies properties m1 through m4.

Proof: let us define an equivalence relation on \mathbb{R} as follows: $x \sim y \iff x - y \in \mathbb{Q}$. Notice that the equivalence classes of this relation are of the form $x + \mathbb{Q}$ for some $x \in \mathbb{R}$ and thus they are all countable and dense. For every equivalence class choose a single representative in $[0, 1]$ to form the set $E \subseteq [0, 1]$. Notice then that

$$\mathbb{R} = \bigcup_{q \in \mathbb{Q}} (E + q) = E + \mathbb{Q} = \{x + q \mid x \in E, q \in \mathbb{Q}\}$$

this union is disjoint since if $x \in E + q \cap E + p$ then $x = x_1 + q$ and $x = x_2 + p$ so $x \sim x_1 \sim x_2$ but we put only a single representative of each equivalence class into E . For every $y \in [0, 1]$, there exists an $x \in E$ such that $x \sim y$ so $x - y \in \mathbb{Q} \cap [-1, 1]$, and so if $y \in E + q$ for some $q \in [-1, 1]$. Thus

$$[0, 1] \subseteq \bigcup_{q \in \mathbb{Q} \cap [-1, 1]} E + q = E + \mathbb{Q} \cap [-1, 1] \subseteq [-1, 2]$$

If m is a function which satisfies the four properties above, it is also monotonic (which can be derived from σ -additivity: if $A \subseteq B$ then $m(B) = m(A) + m(B \setminus A) \geq m(A)$), and so

$$m([0, 1]) = 1 \leq \sum_{q \in \mathbb{Q} \cap [-1, 1]} m(E) \leq 3$$

Since $\mathbb{Q} \cap [-1, 1]$ is infinite, we must have that $m(E) = 0$ as otherwise the sum is infinite. But then the sum is 0 and not greater than 1, which is a contradiction. So the *Vitali set* $\bigcup_{q \in \mathbb{Q} \cap [-1, 1]} E + q$ cannot be measurable. ■

So we must weaken one of the conditions. m^* is already an example of a function which satisfies m1 through m3 so they are not contradictory (also notice that this means m^* cannot be σ -additive). But σ -additivity is extremely important to Lebesgue's theory of integration, so we will instead weaken m1 to be

$$(\mathbf{m1}) \quad m \text{ is a function } \mathcal{L}(\mathbb{R}) \longrightarrow [0, \infty]$$

where $\mathcal{L}(\mathbb{R})$ is the set of all Lebesgue-measurable sets of \mathbb{R} :

2.1.4 Definition (Carathéodory)

A set $E \subseteq \mathbb{R}$ is called **Lebesgue measurable** (or just *measurable*) if for every $A \subseteq \mathbb{R}$,

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

Notice that by subadditivity $m^*(A) \leq m^*(A \cap E) + m^*(A \cap E^c)$, to show that E is Lebesgue measurable it is sufficient to show the other direction (\geq). This implies that all sets E with zero outer measure are Lebesgue measurable: $m^*(A \cap E) + m^*(A \cap E^c) = m^*(A \cap E^c) \leq m^*(A)$ as required ($m^*(A \cap E) \leq m^*(E) = 0$). Further notice that E is measurable if and only if E^c is by symmetry of the definition.

2.1.5 Theorem

Every open interval of the form (a, ∞) is measurable.

Proof: let A be a subset of \mathbb{R} . Let us define

$$A^+ := A \cap (a, \infty), \quad A^- := A \cap (a, \infty)^c = A \cap (-\infty, a]$$

We must show that $m^*(A^+) + m^*(A^-) \leq m^*(A)$. Let $\varepsilon > 0$ and let $\{I_n\}_{n=1}^\infty$ be a cover of A consisting of open intervals where $\sum_{n=1}^\infty |I_n| \leq m^*(A) + \varepsilon$. Then for every n , define $I_n^+ = I_n \cap (a, \infty)$ and $I_n^- = I_n \cap (a, \infty)^c$, so $\{I_n^+\}$ is a cover for A^+ and $\{I_n^-\}$ is a cover for A^- . And since these are intervals we have $|I_n| = |I_n^+| + |I_n^-|$. So we have

$$m^*(A) \geq \sum_{n=1}^\infty |I_n| - \varepsilon = \sum_{n=1}^\infty |I_n^+| + \sum_{n=1}^\infty |I_n^-| + \varepsilon \geq m^*(A^+) + m^*(A^-) + \varepsilon$$

And since $\varepsilon > 0$ is arbitrary, we get $m^*(A) \geq m^*(A^+) + m^*(A^-)$ as required. \blacksquare

2.1.6 Proposition

The set of all measurable sets is invariant under movement, meaning if E is measurable so too is $E + \alpha$.

Proof: let $A \subseteq \mathbb{R}$ then notice that $x - \alpha \in A \cap (E + \alpha) - \alpha \iff x \in A \cap (E + \alpha) \iff x \in A, E + \alpha \iff x - \alpha \in A - \alpha, E$. So $A \cap (E + \alpha) - \alpha = (A - \alpha) \cap E$, and so we get

$$\begin{aligned} m^*(A \cap (E + \alpha)) + m^*(A \cap (E + \alpha)^c) &= m^*(A \cap (E + \alpha) - \alpha) + m^*(A \cap (E + \alpha)^c - \alpha) \\ &= m^*((A - \alpha) \cap E) + m^*((A - \alpha) \cap E^c) = m^*(A - \alpha) = m^*(A) \end{aligned}$$

as required. \blacksquare

2.1.7 Lemma

The finite union of measurable sets is measurable. And if $\{E_k\}_{k=1}^n$ are disjoint and measurable, then

$$m^*\left(\bigcup_{k=1}^n E_k\right) = \sum_{k=1}^n m^*(E_k)$$

Proof: it is sufficient to prove this for two measurable sets and then to proceed inductively for arbitrary n . So suppose E, F are measurable, we must show that $E \cup F$ is. Let $A \subseteq \mathbb{R}$, then

$$\begin{aligned} m^*(A \cap (E \cup F)) + m^*(A \cap (E \cup F)^c) &= m^*((A \cap E) \cup (A \cap F)) + m^*(A \cap E^c \cap F^c) \\ &= m^*((A \cap E) \cup (A \cap F \cap E^c)) + m^*(A \cap E^c \cap F^c) \leq m^*(A \cap E) + m^*(A \cap E^c \cap F) + m^*(A \cap E^c \cap F^c) \\ &= m^*(A \cap E) + m^*(A \cap E^c) = m^*(A) \end{aligned}$$

The final equality is due to F being measurable, and so it satisfies Carathéodory's definition for $A \cap E^c$.

And we similarly prove additivity by induction on n . For two disjoint measurable sets E, F , we have by Carathéodory on E :

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

Since the complement of a set is measurable, and the empty set is measurable, this proposition tells us that $\mathcal{L}(\mathbb{R})$, the set of all Lebesgue measurable sets, is an algebra of sets (non-empty, closed under complements and unions/intersections). Intersections are of course measurable since $\bigcap_{k=1}^n E_k = (\bigcup_{k=1}^n E_k^c)^c$, and so are differences since $E \setminus F = E \cap F^c$. Notice that since $m^*(E) = m^*(E \cap F) + m^*(E \cap F^c)$, we have

$$m^*(E \setminus F) = m^*(E \cap F^c) = m^*(E) - m^*(E \cap F)$$

But stronger than this, $\mathcal{L}(\mathbb{R})$ is in fact a σ -algebra (to be defined later).

2.1.8 Lemma

Suppose E_1, \dots, E_n are measurable and disjoint, then for every $A \subseteq \mathbb{R}$,

$$m^* \left(A \cap \bigcup_{k=1}^n E_k \right) = \sum_{k=1}^n m^*(A \cap E_k)$$

Proof: We prove this by induction on n ; for $n = 1$ this is trivial. If this holds for n , then using the inductive assumption for $E_1, \dots, E_{n-1}, E_n \cup E_{n+1}$

$$m^* \left(A \cap \bigcup_{k=1}^{n+1} E_k \right) = \sum_{k=1}^{n-1} m^*(A \cap E_k) + m^*(A \cap (E_n \cup E_{n+1}))$$

Now,

$$\begin{aligned} m^*(A \cap (E_n \cup E_{n+1})) &= m^*(A \cap (E_n \cup E_{n+1}) \cap E_n) = m^*(A \cap (E_n \cup E_{n+1}) \cap E_n^c) \\ &= m^*(A \cap E_n) + m^*(A \cap E_{n+1}) \end{aligned}$$

and so we get that indeed

$$m^* \left(A \cap \bigcup_{k=1}^{n+1} E_k \right) = \sum_{k=1}^{n+1} m^*(A \cap E_k) \quad \blacksquare$$

2.1.9 Theorem

Let $\{E_n\}_{n=1}^\infty$ be Lebesgue measurable, then $\bigcup_{n=1}^\infty E_n$ is also Lebesgue measurable (equivalently $\mathcal{L}(\mathbb{R})$ is a σ -algebra). Furthermore if the sets are disjoint, then we have σ -additivity:

$$m^* \left(\bigcup_{n=1}^\infty E_n \right) = \sum_{n=1}^\infty m^*(E_n)$$

Proof: we can assume from the outset that $\{E_n\}$ are disjoint as we can define $F_n := E_n \setminus \bigcup_{k=1}^{n-1} E_k$. This is measurable by the previous lemmas, and $\bigcup_{n=1}^\infty E_n = \bigcup_{n=1}^\infty F_n$. Now define

$$E := \bigcup_{n=1}^\infty E_n, \quad G_n := \bigcup_{k=1}^n E_k$$

Let $A \subseteq \mathbb{R}$, and by G_n 's measurability we have that

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

By the above lemma this means $m^*(A) \geq \sum_{k=1}^n m^*(A \cap E_k) + m^*(A \cap E^c)$, and this inequality is preserved by taking the limit $n \rightarrow \infty$ so

$$(1) \quad m^*(A) \geq \sum_{k=1}^\infty m^*(A \cap E_k) + m^*(A \cap E^c)$$

By subadditivity, we have that $m^*(A \cap E) = m^*(\bigcup_{k=1}^\infty (A \cap E_k)) \leq \sum_{k=1}^\infty m^*(A \cap E_k)$, so

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

so E is indeed measurable, as required. If we let $A = E = \bigcup_{n=1}^\infty E_n$, then we get that $A \cap E_k = E_k$ and so by (1) we get that

$$m^*(E) \geq \sum_{k=1}^\infty m^*(E_k)$$

and \leq is given by subadditivity so we have equality. \blacksquare

Notice that the Lebesgue outer measure defines a pseudometric on $\mathcal{P}(\mathbb{R})$ by $d(A, B) := m^*(A \Delta B)$.

2.1.10 Theorem

$E \subseteq \mathbb{R}$ is Lebesgue measurable if and only if for all $\varepsilon > 0$ there exists a countable union of open intervals $\bigcup_{n=1}^{\infty} I_n$ such that $d(\bigcup_{n=1}^{\infty} I_n, E) < \varepsilon$.

Proof: suppose E is measurable, then for every $\varepsilon > 0$ there exists a cover $E \subseteq \bigcup I_n$ of open intervals such that $m^*(E) + \varepsilon > m^*(\bigcup I_n)$. Now

$$d\left(\bigcup I_n, E\right) = m^*\left(\bigcup I_n \setminus E\right) = m^*\left(\bigcup I_n\right) - m^*(E) < \varepsilon$$

since all the sets in play are measurable, as required. Now suppose that the condition holds, we must prove that E is measurable. We can assume without loss of generality that $E \subseteq \bigcup I_n$ (as we can cover the symmetric difference with open intervals). Now let us take a sequence of such covers U_k such that $m^*(U_k \setminus E) < \frac{1}{k}$, and define $U = \bigcap U_k$. And $m^*(U \setminus E) \leq m^*(U_k \setminus E) < \frac{1}{k}$ so $m^*(U \setminus E) = 0$, and this means that $U \setminus E$ is measurable. Since U_k are all measurable, so is U and since $E = U \setminus (U \setminus E)$, E is measurable. ■

In fact what we have shown is that every measurable set E is of the form $G \setminus N$, where G is a countable intersection of open sets (a G_δ set), and N is a set of zero measure. This theorem implies that every open interval is Lebesgue measurable, as just define $I_n = I$. Recall that \mathbb{R} is a second-countable topological space, meaning it has a countable basis, namely the basis $\{(p, q) \mid p < q \in \mathbb{Q}\}$. This means that every open set in \mathbb{R} is the countable union of open intervals, and therefore every open set is contained in $\mathcal{L}(\mathbb{R})$. And so closed sets, which are complements of open sets, are also measurable. And so too are G_δ sets as the countable intersection of measurable sets, and so sets of the form $G \setminus N$ where G is G_δ and $m^*(N) = 0$ are measurable. So we have proven

2.1.11 Proposition

E is measurable if and only if there exists a G_δ set G and a zero-measure set N such that $E = G \setminus N$.

2.1.12 Definition

Let X be a set, then a non-empty collection $\Sigma \subseteq \mathcal{P}(X)$ is called a **σ -algebra** if it satisfies

- (1) $S \in \Sigma \iff S^c \in \Sigma$
- (2) if $\{S_n\}_{n=1}^{\infty} \subseteq \Sigma$ then $\bigcup_{n=1}^{\infty} S_n \in \Sigma$

By (1) and (2) we get that σ -algebras are also closed under intersections, and so $\emptyset = S \cap S^c \in \Sigma$ and $X = \emptyset^c \in \Sigma$.

If X is a set and Σ a σ -algebra over X , then (X, Σ) is called a **measurable space**. And a **measure space** is a triplet (X, Σ, μ) where μ is a σ -algebra over X , and μ is a **measure** over Σ :

- (1) $\mu: \Sigma \longrightarrow [0, \infty]$,
- (2) μ is σ -additive: if $\{S_n\}_{n=1}^{\infty} \subseteq \Sigma$ are disjoint $\mu(\bigcup_{n=1}^{\infty} S_n) = \sum_{n=1}^{\infty} \mu(S_n)$
- (3) $\mu(\emptyset) = 0$.

2.1.13 Example

Let m be the **Lebesgue measure** over \mathbb{R} , the restriction of m^* to the collection of Lebesgue measurable sets: $m := m^*|_{\mathcal{L}(\mathbb{R})}$. Then $(\mathbb{R}, \mathcal{L}(\mathbb{R}), m)$ is a measure space.