# PMATH450 — Lebesgue Integration and Fourier Analysis

Classnotes for Spring 2019

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### List of Procedures



The pre-requisite to this course is Real Analysis. We will use a lot of the concepts introduced in Real Analysis, at times without explicitly stating it. Refer to notes on PMATH351.

This course is spiritually broken into 2 pieces:

- Lebesgue Integration; and
- Fourier Analysis,

which is as the name of the course.

In this set of notes, we use a special topic environment called **culture** to discuss interesting contents related to the course, but will not be throughly studied and not tested on exams.

### Lecture 1 May 07th 2019

Since many of our results work for both  $\mathbb C$  and  $\mathbb R$ , we shall use  $\mathbb K$  throughout this course to represent either  $\mathbb C$  or  $\mathbb R$ .

#### 1.1 Riemannian Integration

#### **■** Definition 1 (Norm and Semi-Norm)

Let V be a vector space over  $\mathbb{K}$ . We define a **semi-norm** on V as a function

$$\nu:V\to\mathbb{R}$$

that satisfies

- 1. (Positive Semi-Definite)  $v(x) \ge 0$  for all  $x \in V$ ;
- 2.  $\nu(\kappa x) = |\kappa| \nu(x)$  for any  $\kappa \in \mathbb{K}$  and  $x \in V$ ; and
- 3. (Triangle Inequality)  $v(x+y) \le v(x) + v(y)$  for all  $x, y \in V$ .

If  $v(x) = 0 \implies x = 0$ , then we say that v is a **norm**. In this case, we usually write  $\|\cdot\|$  to denote the norm, instead of v.

#### 66 Note 1.1.1

• We sometimes call a semi-norm a pseudo-length.

#### Remark 1.1.1

Notice that we wrote  $v(x) = 0 \implies x = 0$  instead of  $v(x) = 0 \iff x = 0$ . This is because if  $z = 0 \in V$ , then

$$v(z) = v(0z) = 0.$$

#### Exercise 1.1.1

Show that if v is a semi-norm on a vector space V, then  $\forall x, y \in V$ ,

$$|\nu(x) - \nu(y)| \le \nu(x - y).$$

#### Proof

Notice that by condition (2) and (3), we have

$$\nu(x-y) \le \nu(x) + \nu(-y) = \nu(x) - \nu(y),$$

and

$$\nu(x - y) = -\nu(y - x) \ge -(\nu(y) - \nu(x)) = \nu(x) - \nu(y).$$

It follows that indeed

$$|\nu(x) - \nu(y)| \le \nu(x - y).$$

#### Example 1.1.1

The absolute value  $|\cdot|$  is a **norm** on  $\mathbb{K}$ .

#### \*

#### Example 1.1.2 (p-norms)

Consider  $N \ge 1$  an integer. We define a family of norms on

$$\mathbb{K}^N = \underbrace{K \times K \times \ldots \times K}_{N \text{ times}}.$$

1-norm

$$\|(x_n)_{n=1}^N\|_1 := \sum_{n=1}^N |x_n|.$$

#### Infinity-norm, ∞-norm

$$\left\| (x_n)_{n=1}^N \right\|_{\infty} \coloneqq \max_{1 \le n \le N} |x_n|.$$

#### Euclidean-norm, 2-norm

$$\left\| (x_n)_{n=1}^N \right\|_2 := \left( \sum_{n=1}^N |x_n|^2 \right)^{\frac{1}{2}}$$

It is relatively easy to check that the above norms are indeed norms, except for the 2-form. In particular, the triangle inequality is not as easy to show 1.

<sup>1</sup> See Minkowski's Inequality.

Less obviously so, but true nonetheless, we can define the following *p*-norms on  $\mathbb{K}^N$ :

$$\|(x_n)_{n=1}^N\|_p := \left(\sum_{n=1}^N |x_n|^p\right)^{\frac{1}{p}},$$

for  $1 \le p < \infty$ .



#### Culture

Consider  $V = \mathbb{M}_n(\mathbb{C})$ , where  $n \in \mathbb{N}$  is fixed. For  $T \in \mathbb{M}_n(\mathbb{C})$ , we define the singular numbers of T to be

<sup>2</sup> Note that 
$$\mathbb{M}_n(\mathbb{C})$$
 is the set of  $n \times n$  matrices over  $\mathbb{C}$ .

$$s_1(T) \geq s_2(T) \geq \ldots \geq s_n(T) \geq 0$$
,

where  $\sigma(T^*T) = \{s_1(T)^2, s_2(T)^2, \dots, s_n(T)^2\}$ , including multiplicity. Then we can define

$$||T||_p := \left(\sum_{i=1}^n s_i(T)^p\right)^{\frac{1}{p}}$$

for  $1 \leq p < \infty$ , which is called the p-norm of T on  $\mathbb{M}_n(\mathbb{C})$ .

#### Example 1.1.3

Let

$$V = \mathcal{C}([0,1],\mathbb{K}) = \{f : [0,1] \to \mathbb{K} \mid f \text{ is continuous } \}.$$

Then

$$||f||_{\sup} := \sup\{|f(x)| \mid x \in [0,1]\}$$

<sup>3</sup> defines a norm on  $\mathcal{C}([0,1],\mathbb{K})$ .

A sequence  $(f_n)_{n=1)^{\infty}}$  in V converges in this norm to some  $f \in V$ , i.e.

$$\lim_{n\to\infty}\|f_n-f\|_{\sup}=0,$$

which means that  $(f_n)_{n=1}^{\infty}$  converges uniformly to f on [0,1].

 $^3$  Some authors use  $\|f\|_{\infty}$ , but we will have the notation  $\|[f]\|_{\infty}$  later on, and so we shall use  $\|f\|_{\sup}$  for clarity.

#### **■** Definition 2 (Normed Linear Space)

A normed linear space (NLS) is a pair  $(V, \|\cdot\|)$  where V is a vector space over  $\mathbb{K}$  and  $\|\cdot\|$  is a norm on V.

#### **■** Definition 3 (Metric)

Given an NLS  $(V, \|\cdot\|)$ , we can define a metric d on V (called the metric induced by the norm) as follows:

$$d: V \times V \to \mathbb{R}$$
  $d(x,y) = ||x - y||$ ,

such that

- $d(x,y) \ge 0$  for all  $x,y \in V$  and  $d(x,y) = 0 \iff x = y$ ;
- d(x, y) = d(y, x); and
- $d(x,y) \leq d(x,z) + d(y,z)$ .

#### **66** Note 1.1.2

Norms are all metrics, and so any space that has a norm will induce a metric on the space.

#### **■** Definition 4 (Banach Space)

We say that an NLS  $(V, \|\cdot\|)$  is complete or is a **Banach Space** if the corresponding (V,d), where d is the metric induced by the norm, is complete 4.

<sup>4</sup> Completeness of a metric space is such that any of its Cauchy sequences converges in the space.

#### Example 1.1.4

$$(\mathcal{C}([0,1],\mathbb{K}),\left\|\cdot\right\|_{sup})$$
 is a Banach space.

#### Example 1.1.5

We can define a 1-norm  $\|\cdot\|_1$  on  $\mathcal{C}([0,1],\mathbb{K})$  via

$$||f||_1 \coloneqq \int_0^1 |f|.$$

Then 
$$(\mathcal{C}([0,1],\mathbb{K}),\|\cdot\|_1)$$
 is an NLS.

#### Exercise 1.1.2

Show that  $(C([0,1],\mathbb{K}),\|\cdot\|_1)$  is not complete, which will then give us an example of a normed linear space that is not Banach.

#### Proof

Consider the sequence  $(f_n)_{n=1}^{\infty}$  of continuous functions given by

$$f_n(x) = \begin{cases} 0 & 0 \le x < \frac{1}{2} \\ n\left(x + \frac{1}{2}\right) & \frac{1}{2} \le x \le \frac{1}{2} + \frac{1}{n} \\ 1 & \text{otherwise} \end{cases}$$

Note that the sequence  $(f_n)_{n=1}^{\infty}$  is indeed Cauchy: let  $\varepsilon > 0$  and  $|n-m|<rac{\varepsilon}{|x-rac{1}{2}|}$ , and then we have

$$|f_n(x) - f_m(x)| = \left| n\left(x - \frac{1}{2}\right) - m\left(x - \frac{1}{2}\right) \right|$$
$$= \left| (n - m)\left(x - \frac{1}{2}\right) \right| = |n - m|\left| x - \frac{1}{2} \right| < \varepsilon.$$

However, it is clear that the sequence  $(f_n)_{n=1}^{\infty}$  converges to the

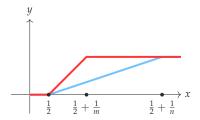


Figure 1.1: Sequence of functions  $(f_n)_{n=1}^{\infty}$ . We show for two indices n < m.

piecewise function (in particular, a non-continuous function)

$$f(x) = \begin{cases} 0 & 0 \le x < \frac{1}{2} \\ 1 & x \ge \frac{1}{2} \end{cases}.$$

#### Example 1.1.6

If  $(\mathfrak{X}, \|\cdot\|_{\mathfrak{X}})$  and  $(\mathfrak{Y}, \|\cdot\|_{\mathfrak{Y}})$  are NLS's, and if  $T: \mathfrak{X} \to \mathfrak{Y}$  is a linear map, we define the **operator norm** of T to be

$$||T|| := \sup\{||T(x)||_{\mathfrak{Y}} \mid ||x||_{\mathfrak{X}} \le 1\}.$$

We set

$$B(\mathfrak{X},\mathfrak{Y}) := \{T : \mathfrak{X} \to \mathfrak{Y} \mid T \text{ is linear }, ||T|| < \infty\}.$$

Note that for any such linear map T,  $||T|| < \infty \iff T$  is continuous. Thus  $B(\mathfrak{X}, \mathfrak{Y})$  is the set of all continuous functions from  $\mathfrak{X}$  into  $\mathfrak{Y}$ .

Then 
$$(B(\mathfrak{X},\mathfrak{Y}),\|\cdot\|)$$
 is an NLS.

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It is likely that we have seen this in Real Analysis.

#### Exercise 1.1.3

Show that  $(B(\mathfrak{X},\mathfrak{Y}),\|\cdot\|)$  is complete iff  $(\mathfrak{Y},\|\cdot\|_{\mathfrak{Y}})$  is complete.

#### 66 Note 1.1.3

One example of the last example is when  $(\mathfrak{Y}, \|\cdot\|_{\mathfrak{Y}}) = (\mathbb{K}, |\cdot|)$ . In this case,  $B(\mathfrak{X}, \mathbb{K})$  is known as the dual space of  $\mathfrak{X}$ , or simple the dual of  $\mathfrak{X}$ .

We are interested in integrating over Banach spaces.

#### **■** Definition 5 (Partition of a Set)

Let  $(\mathfrak{X}, \|\cdot\|_{\mathfrak{X}})$  be a Banach space and  $f: [a,b] \to \mathfrak{X}$  a function, where  $a < b \in \mathbb{R}$ . A partition P of [a,b] is a finite set

$$P = \{a = p_0 < p_1 < \dots < p_N = b\}$$

for some  $N \ge 1$ . The set of all partitions of [a,b] is denoted by  $\mathcal{P}[a,b]$ .

#### **■** Definition 6 (Test Values)

Let  $(\mathfrak{X}, \|\cdot\|_{\mathfrak{X}})$  be a Banach space and  $f: [a,b] \to \mathfrak{X}$  a function, where  $a < b \in \mathbb{R}$ . Let  $P \in \mathcal{P}[a,b]$ . A set

$$P^* := \{p_k^*\}_{k=1}^N$$

satisfying

$$p_{k-1} \le p_k^* \le p_k$$
, for  $1 \le k \le n$ 

is called a set of test values for P.

#### **■** Definition 7 (Riemann Sum)

Let  $(\mathfrak{X}, \|\cdot\|_{\mathfrak{X}})$  be a Banach space and  $f: [a,b] \to \mathfrak{X}$  a function, where  $a < b \in \mathbb{R}$ . Let  $P \in \mathcal{P}[a,b]$  and  $P^*$  its corresponding set of test values. We define the Riemann sum as

$$S(f, P, P^*) = \sum_{k=1}^{N} f(p_k^*)(p_k - p_{k-1}).$$

#### Remark 1.1.2

- 1. Note that because  $\square$  Definition 5,  $p_k p_{k-1} > 0$ .
- 2. When  $(\mathfrak{X},\|\cdot\|)\,=\,(\mathbb{R},|\cdot|),$  then this is the usual Riemann sum from first-year calculus.
- 3. In general, note that

$$\frac{1}{b-a}S(f, P, P^*) = \sum_{k=1}^{N} \lambda_k f(p_k^*),$$

where  $0 < \lambda_k = \frac{p_k - p_{k-1}}{b-a} < 1$  and 5

 $\sum_{k=1}^{N} \lambda_k = 1.$ 

 $^{5}$  via the fact that the  $\lambda_{k}$ 's form a telescoping sum

So  $\frac{1}{b-a}S(f,P,P^*)$  is an averaging of f over [a,b]. We call  $\frac{1}{b-a}S(f,P,P^*)$  the convex combination of the  $f(p_k^*)$ 's.

#### Example 1.1.7 (Silly example)

Let 
$$(\mathfrak{X} = \mathcal{C}([-\pi, \pi], \mathbb{K}), \|\cdot\|_{\sup})$$
. Let

$$f: [0,1] \to \mathfrak{X}$$
 such that  $x \mapsto e^{2\pi x} \sin 7\theta + \cos x \cos(12\theta)$ ,

where  $\theta \in [-\pi, \pi]$ . Now if we consider the partition

$$P = \left\{-\pi, \frac{1}{10}, \frac{1}{2}, \pi\right\}$$

and its corresponding test value

$$P^* = \left\{0, \frac{1}{3}, 2\right\},\,$$

then

$$S(f, P, P^*) = f(0) \left(\frac{1}{10} + \pi\right) + f\left(\frac{1}{3}\right) \left(\frac{1}{2} - \frac{1}{10}\right) + f(2) \left(\pi - \frac{1}{2}\right)$$

$$= (\sin 7\theta + \cos 12\theta) \left(\pi + \frac{1}{10}\right)$$

$$+ \left(e^{\frac{2\pi}{3}} \sin 7\theta + \cos \frac{1}{3} \cos 12\theta\right) \left(\frac{2}{5}\right)$$

$$+ (e^{4\pi} \sin 7\theta + \cos 2 \cos 12\theta) \left(\pi - \frac{1}{2}\right)$$

#### **■** Definition 8 (Refinement of a Partition)

Let  $a < b \in \mathbb{R}$ , and  $P \in \mathcal{P}[a,b]$ . We say Q is a **refinement** of P is  $Q \in \mathcal{P}[a,b]$  and  $P \subseteq Q$ .

#### **66** Note 1.1.4

*In simpler words, Q is a "finer" partition that is based on P.* 

#### E Definition 9 (Riemann Integrable)

Let  $a < b \in \mathbb{R}$ ,  $(\mathfrak{X}, \|\cdot\|_{\mathfrak{X}})$  be a Banach space and  $f : [a, b] \to \mathfrak{X}$  be a function. We say that f is Riemann integrable over [a, b] if  $\exists x_0 \in \mathfrak{X}$ such that

$$\forall \varepsilon > 0 \quad \exists P \in \mathcal{P}[a,b],$$

such that if Q is any refinement of P, and  $Q^*$  is any set of test values of Q, then

$$\|x_0 - S(f, Q, Q^*)\|_{\mathfrak{X}} < \varepsilon.$$

In this case, we write

$$\int_a^b f = x_0.$$

#### ♦ Proposition 1 (Uniqueness of the Riemann Integral)

*If* f *is Riemann integrable over* [a,b]*, then the value of*  $\int_a^b f$  *is unique.* 

#### Proof

Suppose not, i.e.

$$\int_a^b f = x_0 \text{ and } \int_a^b f = y_0$$

for some  $x_0 \neq y_0$ . Then, let

$$\varepsilon = \frac{\|x_0 - y_0\|}{2},$$

which is > 0 since  $||x_0 - y_0|| > 0$ . Let  $P_{x_0}, P_{y_0} \in \mathcal{P}[a, b]$  be partitions corresponding to  $x_0$  and  $y_0$  as in the definition of Riemann integrability.

Then, let  $R = P_{x_0} \cup P_{y_0}$ , so that R is a common refinement of  $P_{x_0}$  and  $P_{y_0}$ . If Q is any refinement of R, then Q is also a common refinement of  $P_{x_0}$  and  $P_{y_0}$ . Then for any test values  $Q^*$  of Q, we have

$$2\varepsilon = \|x_0 - y_0\|$$

$$\leq \|x_0 - S(f, Q, Q^*)\| + \|S(f, Q, Q^*) - y_0\| < \varepsilon + \varepsilon = 2\varepsilon,$$

which is a contradiction.

Thus  $x_0 = y_0$  as required.

#### ■Theorem 2 (Cauchy Criterion of Riemann Integrability)

Let  $(\mathfrak{X}, \|\cdot\|_{\mathfrak{X}})$  be a Banach space,  $a < b \in \mathbb{R}$  and  $f : [a, b] \to \mathfrak{X}$  be a function. TFAE:

- 1. f is Riemann integrable over [a, b];
- 2.  $\forall \varepsilon > 0$ ,  $R \in \mathcal{P}[a,b]$ , if P,Q is any refinement of R, and  $P^*$  (respectively  $Q^*$ ) is any test values of P (respectively Q), then

$$||S(f, P, P^*) - S(f, Q, Q^*)||_{\mathfrak{X}} < \varepsilon.$$

#### Proof

This is a rather straightforward proof. Suppose  $P, Q \in \mathcal{P}[a,b]$  is some refinement of the given partition  $R \in \mathcal{P}[a,b]$ , and  $P^*, Q^*$  any test values for P, Q, respectively. Then by assumption and  $P^*$  Proposition 1,  $\exists x_0 \in \mathfrak{X}$  such that

$$||x_0 - S(f, P, P^*)||_{\mathfrak{X}} < \frac{\varepsilon}{2} \text{ and } ||x_0 - S(f, Q, Q^*)||_{\mathfrak{X}} < \frac{\varepsilon}{2}.$$

It follows that

$$||S(f, P, P^*) - S(f, Q, Q^*)||_{\mathfrak{X}}$$

$$\leq ||x_0 - S(f, P, P^*)||_{\mathfrak{X}} + ||x_0 - S(f, Q, Q^*)||_{\mathfrak{X}}$$

$$< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon.$$

By hypothesis, wma  $\varepsilon = \frac{1}{n}$  for some  $n \ge 1$ , such that if P, Q are any refinements of the partition  $R_n \in \mathcal{P}[a,b]$ , and  $P^*, Q^*$  are the respective arbitrary test values, then

$$||S(f, P, P^*) - S(f, Q, Q^*)||_{\mathfrak{X}} < \frac{1}{n}$$

Now for each  $n \ge 1$ , define

$$W_n := \bigcup_{k=1}^n R_k \in \mathcal{P}[a,b],$$

so that  $W_n$  is a common refinement for  $R_1, R_2, \ldots, R_n$ . For each  $n \ge n$ 1, let  $W_n^*$  be an arbitrary set of test values for  $W_n$ . For simplicity, let us write

$$x_n = S(f, W_n, W_n^*)$$
, for each  $n \ge 1$ .

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Claim:  $(x_n)_{n=1}^{\infty}$  is a Cauchy sequence If  $n_1 \ge n_2 > N \in \mathbb{N}$ , then

$$\|x_{n_1} - x_{n_2}\|_{\mathfrak{X}} = \|S(f, W_{n_1}, W_{n_1}^*) - S(f, W_{n_2}, W_{n_2}^*)\| < \frac{1}{N}$$

by our assumption, since  $W_{n_1}$ ,  $W_{n_2}$  are refinements of  $R_N$ . Then by picking  $N = \frac{1}{\varepsilon}$  for any  $\varepsilon > 0$ , we have that  $(x_n)_{n=1}^{\infty}$  is indeed a Cauchy sequence in  $\mathfrak{X}$ .

Since  $\mathfrak{X}$  is a Banach space, it is complete, and so  $\exists x_0 := \lim_{n \to \infty} x_n \in$  $\mathfrak{X}$ . It remains to show that, indeed,

$$x_0 = \int_a^b f.$$

Let  $\varepsilon > 0$ , and choose  $N \ge 1$  such that

- $\frac{1}{N} < \frac{\varepsilon}{2}$ ; and
- $k \ge N$  implies that  $||x_k x_0|| < \frac{\varepsilon}{2}$ .

Then suppose that V is any refinement of  $W_N$ , and  $V^*$  is an arbitrary set of test values of V. Then we have

$$||x_{0} - S(f, V, V^{*})||_{\mathfrak{X}} \leq ||x_{0} - x_{N}||_{\mathfrak{X}} + ||x_{N} - S(f, V, V^{*})||_{\mathfrak{X}}$$

$$< \frac{\varepsilon}{2} + ||S(f, W_{N}, W_{N}^{*}) - S(f, V, V^{*})||_{\mathfrak{X}}$$

$$< \frac{\varepsilon}{2} + \frac{1}{N} \leq \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon.$$

It follows that

$$\int_a^b f = x_0,$$

as desired.

<sup>6</sup> Note that it would be nice if for the finer and finer partitions that we have constructed, i.e. the  $W_n$ 's, give us a convergent sequence of Riemann sums, since it makes sense that this convergence will give us the final value that we want.

In first-year calculus, all continuous functions over  $\mathbb{R}$  are integrable. A similar result holds in Banach spaces as well. In the next lecture, we shall prove the following theorem.

#### **■** Theorem (Continuous Functions are Riemann Integrable)

Let  $(\mathfrak{X}, \|\cdot\|)$  be a Banach space and  $a < b \in \mathbb{R}$ . If  $f : [a, b] \to \mathfrak{X}$  is continuous, then f is Riemann integrable over [a, b].

### Lecture 2 May 9th 2019

#### 2.1 Riemannian Integration (Continued)

We shall now prove the last theorem stated in class.

#### Theorem 3 (Continuous Functions are Riemann Integrable)

Let  $(\mathfrak{X}, \|\cdot\|)$  be a Banach space and  $a < b \in \mathbb{R}$ . If  $f : [a, b] \to \mathfrak{X}$  is continuous, then f is Riemann integrable over [a, b].

#### **✓** Strategy

This is rather routine should one have gone through a few courses on analysis, and especially on introductory courses that involves Riemannian integration.

We shall show that if  $P_N \in \mathcal{P}[a,b]$  is a partition of [a,b] into  $2^N$  subintervals of equal length  $\frac{b-a}{2^N}$ , and if we use  $P_N^* = P_n \setminus \{a\}$  as the set of test values for  $P_N$ , which consists of the right-endpoints of each the subintervals in  $P_N$ , then the sequence  $(S(f,P_N,P_N^*))_{N=1}^{\infty}$  converges in  $\mathfrak{X}$  to  $\int_a^b f$ .

Note that this choice of partition is a valid move, since any of these  $P_N$ 's, for different N's, is a refinement of some other partition of [a,b], and if we choose a different set of test values, then we may as well consider an even finer partition.

First, note that since [a, b] is closed and bounded in  $\mathbb{R}$ , it is compact. Also, we have that X is a metric space (via the metric induced by the norm). This means that **any continuous function** f **on** [a, b] **is uniformly continuous on** [a, b]. In other words,

$$\forall \varepsilon > 0 \ \exists \delta > 0 \ \forall x, y \in [a, b]$$
$$|x - y| < \delta \implies ||f(x) - f(y)|| < \frac{\varepsilon}{2(b - a)}.$$

Claim:  $(S(f, P_N, P_N^*))_{N=1}^\infty$  is Cauchy Now by picking  $P_N \in \mathcal{P}[a, b]$  and set of test values  $P_N^*$  as described in the strategy above, we proceed by picking M > 0 such that  $\frac{b-a}{2^M} < \delta$ . Then for any  $K \ge L \ge M$ , since each of the subintervals have length  $\frac{b-a}{2^L}$  and  $\frac{b-a}{2^K}$  for  $P_L$  and  $P_K$  respectively, if we write

$$P_L = \{a = p_0 < p_1 < \ldots < p_{2^L} = b\}$$

and

$$P_K = \{a = q_0 \le q_1 < \ldots < q_{2^K} = b\},\$$

then  $p_j=q_j2^{K-L}$  1 for all  $0\leq j\leq 2^L$ . By uniform continuity, for  $1\leq j\leq 2^L$ , wma

$$||f(p_j^*) - f(q_s^*)|| < \frac{\varepsilon}{2(b-a)}, \text{ where } (j-1)2^{K-L} < s \le j2^{K-L}.$$

We can see that

$$||S(f, P_L, P_L^*) - S(f, P_K, P_K^*)||$$

$$= \left\| \sum_{j=1}^{2^L} \sum_{s=(j-1)2^{K-L}+1}^{j2^{K-L}} (f(p_j) - f(q_s))(q_s - q_{s-1}) \right\|$$

$$\leq \sum_{j=1}^{2^L} \sum_{s=(j-1)2^{K-L}+1}^{j2^{K-L}} ||f(p_j) - f(q_s)|| (q_s - q_{s-1})$$

$$\leq \sum_{j=1}^{2^L} \sum_{s=(j-1)2^{K-L}+1}^{j2^{K-L}} \frac{\varepsilon}{b-a} (q_s - q_{s-1})$$

$$= \frac{\varepsilon}{b-a} \sum_{s=1}^{2^K} (q_s - q_{s-1})$$

$$= \frac{\varepsilon}{2(b-a)} (b-a) = \frac{\varepsilon}{2}.$$

<sup>1</sup> This is not immediately clear on first read. Think of *a* as 0.

This proves our claim.

Since  $\mathfrak{X}$  is a Banach space, and hence complete, we have that the sequence  $(S(f, P_N, P_N^*))_{N=1}^{\infty}$  has a limit  $x_0 \in \mathfrak{X}$ .

It remains to show that  $\int_a^b f = x_0$ . <sup>2</sup>

Let  $\varepsilon > 0$ , and choose  $T \ge 1$  such that  $\frac{b-a}{2^T} < \delta^3$ , so that we have

$$||x_0-S(f,P_T,P_T^*)||<\frac{\varepsilon}{2}.$$

Now let  $R = \{a = r_0 < r_1 < ... < r_I = b\} \in \mathcal{P}[a, b]$  such that  $P_T \subseteq R$ . Then there exists a sequence

$$0 = j_0 < j_1 < \dots < j_{2^T} = J$$

such that

$$r_{j_k} = p_k$$
, where  $0 \le k \le 2^T$ .

Let  $R^*$  be any set of test values of R. Note that for  $j_{k-1} \le s \le j_k$ , it is clear that

$$|p_k^* - r_s^*| \le |p_k - p_{k-1}| = \frac{b-a}{2^T} < \delta.$$

Thus

$$||S(f, P_T, P_T^*) - S(f, R, R^*)||$$

$$\leq \sum_{k=1}^{2^T} \sum_{s_{j_{k-1}+1}}^{j_k} ||f(p_k^*) - f(r_s^*)|| (r_s - r_{s-1})$$

$$< \frac{\varepsilon}{2(b-a)} \sum_{k=1}^{2^T} \sum_{s_{j_{k-1}+1}}^{j_k} (r_s - r_{s-1})$$

$$= \frac{\varepsilon}{2(b-a)} (b-a) = \frac{\varepsilon}{2}.$$

Putting everything together, we have

$$||x_{0} - S(f, R, R^{*})||$$

$$\leq ||x_{0} - S(f, P_{T}, P_{T}^{*})|| + ||S(f, P_{T}, P_{T}^{*}) - S(f, R, R^{*})||$$

$$< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon.$$

<sup>2</sup> The rest of this proof is similar to the above proof.

 $^3$  Note that this is still the same  $\delta$  as in the first  $\delta$  in this entire proof.

We can also find another refinement of  $P_T$ , say Q, that works similarly as in the case of R. It follows from  $\square$  Theorem 2 that

$$x_0 = \int_a^b f,$$

i.e. that f is indeed Riemann integrable over [a, b].

The following is a corollary whose proof shall be left as an exercise.

#### Corollary 4 (Piecewise Functions are Riemann Integrable)

A piecewise continuous function is also Riemann integrable: if f:  $[a,b] \to \mathfrak{X}$  is piecewise continuous, then f is Riemann integrable.

#### Exercise 2.1.1

Prove Corollary 4.

Let us exhibit a function that is not Riemann integrable.

#### **■** Definition 10 (Characteristic Function)

Given a subset E of a set  $\mathbb{R}$ , we define the characteristic function of E as a function  $\chi_E : \mathbb{R} \to \mathbb{R}$  given by

$$\chi_E(x) = \begin{cases} 1 & x \in E \\ 0 & x \notin E \end{cases}.$$

#### Example 2.1.1

Consider the set  $E = \mathbb{Q} \cap [0,1] \subseteq \mathbb{R}$ . Let  $P \in \mathcal{P}[0,1]$  such that

$$P = \{0 = p_0 < p_1 < \ldots < p_N = 1\},\,$$

and let

$$P^* = \{p_k^*\}_{k=1}^N$$
 and  $P^{**} = \{p_k^{**}\}_{k=1}^N$ 

be 2 sets of test values for *P*, such that we have

$$p_k^* \in \mathbb{Q}$$
 and  $p_k^{**} \in \mathbb{R} \setminus \mathbb{Q}$ .

Then we have

$$S(\chi_E, P, P^*) = \sum_{k=1}^{N} \chi_E(p_k^*)(p_k - p_{k-1})$$
$$= \sum_{k=1}^{N} 1 \cdot (p_k - p_{k-1})$$
$$= p_N - p_0 = 1 - 0 = 1,$$

and

$$S(\chi_E, P, P^{**}) = \sum_{k=1}^{N} \chi_E(p_k^{**})(p_k - p_{k-1})$$
$$= \sum_{k=1}^{N} 0 \cdot (p_k - p_{k-1})$$
$$= 0.$$

It is clear that the Cauchy criterion fails for  $\chi_E$ . This shows that  $\chi_E$  is not Riemann integrable.

#### Remark 2.1.1

Let us once again consider  $E = \mathbb{Q} \cap [0,1]$ . Note that E is denumerable <sup>4</sup>. We may thus write

<sup>4</sup> This means that *E* is countably infinite.

$$E = \{q_n\}_{n=1}^{\infty}.$$

*Now, for*  $k \ge 1$ *, define* 

$$f_k(x) = \sum_{n=1}^k \chi_{\{q_n\}}(x).$$

In other words,  $f_k = \chi_{\{q_1,...,q_k\}}$ . Furthermore, we have that

$$f_1 \leq f_2 \leq f_3 \ldots \leq \chi_E$$
.

*Moreover, we have that*  $\forall x \in [0,1]$ *,* 

$$\chi_E(x) = \lim_{k \to \infty} f_k(x),$$

and

$$\int_0^1 f_k = 0 \text{ for all } k \ge 1.$$

And yet, we have that  $\int_0^1 \chi_E$  does not exist!

WE WANT TO develop a different integral that will 'cover' for this 'pathological' behavior of where the Riemann integral fails.

The rough idea is as follows.

In Riemann integration, when integrating over an interval [a, b], we partitioned [a, b] into subintervals. This happens on the x-axis.

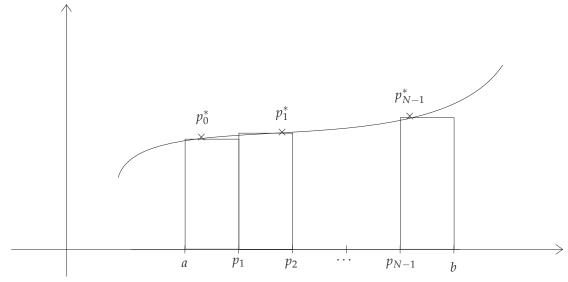


Figure 2.1: Rough illustration of how Riemann's integration works

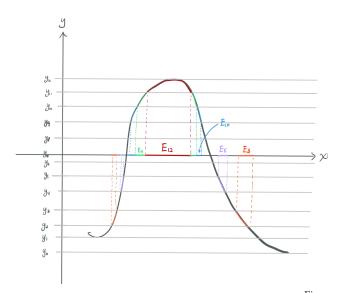
In each of the subintervals of the partition, we pick out a **test value**  $p_i^*$ , and basically draw a rectangle with base at  $[p_i, p_{i+1}]$  and height from 0 to  $p_i^*$ .

What we shall do now is that we **partition the range of** *f* **on the y-axis**, instead of the *x*-axis as we do in Riemannian integration.

In particular, given a function  $f : [a, b] \to \mathbb{R}$ , we first partition the

range of f into subintervals  $[y_{k-1}, y_k]$ , where  $1 \le k \le N$ . Then, we set

$$E_k = \{x \in [a, b] : f(x) \in [y_{k-1}, y_k]\} \text{ for } 1 \le k \le N.$$



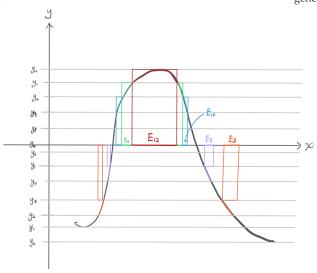
This will then allow us to estimate the integral of f over [a, b] by the expression

$$\sum_{k=1}^{N} y_k m E_k,$$

where each of the  $y_k m E_k$  are called **simple functions**. In the expression,  $mE_k$  denotes a "measure" <sup>5</sup> of  $E_k$ .

Figure 2.2: A sketch of what's happening with the construction of the

<sup>&</sup>lt;sup>5</sup> Note that a measure is simply a generalization of the notion of 'length'.



We observe that  $E_k$  need not be a particularly well-behaved set.

Figure 2.3: Drawing out the rectangles of  $y_k m E_k$  from Figure 2.2.

However, note that we may rearrange the possibly scattered pieces of each  $E_k$  together, so as to form a 'continuous' base for the rectangle. We need our definition of a measure to be able to capture this.

The following is an analogy from Lebesgue himself on comparing Lebesgue integration and Riemann integration <sup>6</sup>:

I have to pay a certain sum, which I have collected in my pocket. I take the bills and coins out of my pocket and give them to the creditor in the order I find them until I have reached the total sum. This is the Riemann integral.

But I can proceed differently. After I have taken all the money out of my pocket I order the bills and coins according to identical values and then I pay the several heaps one after the other to the creditor. This is my integral.

The insight here is that one can freely arrange the values of te functions, all the while preserving the value of the integral.

- This requires us to have a better understanding of what a measure is.
- This process of rearrangement converts certain functions which are extremely difficult to deal with, or outright impossible, with the Riemann integral, into easily digestible pieces using Lebesgue integral.

#### 2.2 Lebesgue Outer Measure

Goals of the section

- 1. Define a "measure of length" on as many subsets of  $\mathbb R$  as possible.
- The definition should agree with our intuition of what a 'length' is.

### Definition 11 (Length)

For  $a \leq b \in \mathbb{R}$ , we define the *length* of the interval (a,b) to be b-a, and

<sup>6</sup> Siegmund-Schultze, R. (2008). Henri Lesbesgue, in Timothy Gowers, June Barrow-Green, Imre Leader (eds.), Princeton Companion to Mathematics. Princeton University Press we write

$$\ell((a,b)) := b - a.$$

We also define

- $\ell(\emptyset) = 0$ ; and
- $\ell((a,\infty)) = \ell((-\infty,b)) = \ell((-\infty,\infty)) = \infty$ .

#### **■** Definition 12 (Cover by Open Intervals)

Let  $E \subseteq \mathbb{R}$ . A countable collection  $\{I_n\}_{n=1}^{\infty}$  of open intervals is said to be a cover of E by open intervals if  $E \subseteq \bigcup_{n=1}^{\infty} I_n$ .

#### 66 Note 2.2.1

In this course, the only covers that we shall use are open intervals, and so we shall henceforth refer to the above simply as covers of E.

Before giving what immediately follows from the above, I shall present the following notion of an outer measure.

#### **■** Definition 13 (Outer Measure)

Let  $\emptyset \neq X$  be a set. An **outer measure**  $\mu$  on X is a function

$$\mu: \mathcal{P}(X) \to [0, \infty] := [0, \infty) \cup \{\infty\}$$

which satisfies

- 1.  $\mu \emptyset = 0$ ;
- 2. (monotone increment or monotonicity)  $E \subseteq F \subseteq X \implies \mu E \le$ μF; and
- 3. (countable subadditivity or  $\sigma$ -subadditivity)  $\{E_n\}_{n=1}^{\infty} \subseteq \mathcal{P}(X)$

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

#### **66** Note 2.2.2

Note that by the monotonicity, the  $\sigma$ -subadditivity condition is equivalent to: given  $\{E_n\}_{n=1}^{\infty} \subseteq \mathcal{P}(X)$  and  $F \subseteq \bigcup_{n=1}^{\infty} E_n$ , we have that

$$\mu(F) \leq \sum_{n=1}^{\infty} \mu(E_n).$$

#### **■** Definition 14 (Lebesgue Outer Measure)

We define the Lebesgue outer measure as a function  $m^*: \mathcal{P}(X) \to \mathbb{R}$  such that

$$m^*E := \inf \left\{ \sum_{n=1}^{\infty} \ell(I_n) : E \subseteq \bigcup_{n=1}^{\infty} I_n \right\}.$$

We cheated a little bit by calling the above an outer measure, so let us now justify our cheating.

#### **♦** Proposition 5 (Validity of the Lebesgue Outer Measure)

*m*\* *is indeed an outer measure.* 

#### Proof

 $\mu\emptyset = 0$  We consider a sequence of sets  $\{I_n\}_{n=1}^{\infty}$  such that  $I_n = \emptyset$  for each  $n = 1, ..., \infty$ . It is clear that  $\emptyset \subseteq \bigcup_{n=1}^{\infty} I_n$ . Also, we have that  $\ell(I_n) = 0$  for all  $n = 1, ..., \infty$ . It follows that

$$0 \le m^*(\emptyset) \le \sum_{n=1}^{\infty} m^*(I_n) = \sum_{n=1}^{\infty} 0 = 0,$$

where the inequality is simply by the definition of  $m^*$  being an infimum, **not to be confused with**  $\sigma$ **-subadditivity**. We thus have that

$$m^*(\emptyset) = 0.$$

Monotonicity Suppose  $E \subseteq F \subseteq \mathbb{R}$ , and  $\{I_n\}_{n=1}^{\infty}$  a cover of F. Then

$$E \subseteq F \subseteq \bigcup_{n=1}^{\infty} I_n$$
.

In particular, all covers of *F* are also covers of *E*, i.e.

$$\left\{ \{J_m\}_{m=1}^{\infty} : E \subseteq \bigcup_{m=1}^{\infty} J_m \right\} \subseteq \left\{ \{I_n\}_{n=1}^{\infty} : F \subseteq \bigcup_{n=1}^{\infty} I_n \right\}.$$

It follows that

$$m^*E < m^*F$$
.

 $\sigma$ -subaddivitity Consider  $\{E_n\}_{n=1}^{\infty} \subseteq \mathcal{P}(X)$  such that  $E \subseteq \bigcup_{n=1}^{\infty} E_n$ . **WTS** 

$$m^*E \leq \sum_{n=1}^{\infty} m^*E_n.$$

Now if the sum of the RHS is infinite, i.e. if any of the  $m^*E_n$  is infinite, then the inequality comes for free. Thus WMA  $\sum_{n=1}^{\infty} E_n <$  $\infty$ , and in particular that  $m^*E_n < \infty$  for all  $n = 1, ..., \infty$ .

To do this, let  $\varepsilon > 0$ . Since  $m^*E_n < \infty$  for all n, we can find covers  $\left\{I_k^{(n)}\right\}_{k=1}^{\infty}$  for each of the  $E_n$ 's such that

$$\sum_{k=1}^{\infty} \ell\left(I_k^{(n)}\right) < m^* E_n + \frac{\varepsilon}{2^n}.$$

Then, we have that

$$E \subseteq \bigcup_{n=1}^{\infty} E_n \subseteq \bigcup_{n=1}^{\infty} \bigcup_{k=1}^{\infty} I_k^{(n)}.$$

Then by  $m^*E$  being the infimum of the sum of lengths of the covering intervals, we have that

$$m^*E \le \sum_{n=1}^{\infty} \sum_{k=1}^{\infty} \ell\left(I_k^{(n)}\right)$$
$$\le \sum_{n=1}^{\infty} \left(m^*E_n + \frac{\varepsilon}{2^n}\right)$$
$$= \sum_{n=1}^{\infty} m^*E_n + \sum_{n=1}^{\infty} \frac{\varepsilon}{2^n}$$
$$= \sum_{n=1}^{\infty} m^*E_n + \varepsilon.$$

Since  $\varepsilon$  was arbitrary, we have that

$$m^*E_n\leq \sum_{n=1}^\infty m^*E_n,$$

as desired.

### Corollary 6 (Lebesgue Outer Measure of Countable Sets is Zero)

*If*  $E \subseteq \mathbb{R}$  *is countable, then*  $m^*E = 0$ .

#### Proof

We shall prove for when E is denumerable, for the finite case follows a similar proof. Let us write  $E = \{x_n\}_{n=1}^{\infty}$ . Let  $\varepsilon > 0$  and

$$I_n = \left(x_n - \frac{\varepsilon}{2^{n+1}}, x_n + \frac{\varepsilon}{2^{n+1}}\right).$$

Then it is clear that  $\{I_n\}_{n=1}^{\infty}$  is a cover of E.

It follows that

$$0 \le m^* E \le \sum_{n=1}^{\infty} \ell(I_n) = \sum_{n=1}^{\infty} \frac{\varepsilon}{2^n} = \varepsilon.$$

Thus as  $\varepsilon \to 0$ , we have that

$$m^*E = 0$$
,

as expected.

#### Corollary 7 (Lebesgue Outer Measure of Q is Zero)

We have that  $m^*\mathbb{Q} = 0$ .

IN THE PROOFS above that we have looked into, and based on the

intuitive notion of the length of an open interval, it is compelling to simply conclude that

$$m^*(a,b) = \ell(a,b) = b - a.$$

However, looking back at <a> Definition 14</a>, we know that that is not how  $m^*(a, b)$  is defined.

This leaves us with an interesting question:

how does our notion of measure  $m^*(a,b)$  of an interval compare with the notion of the length of an interval?

By taking  $I_1 = (a, b)$  and  $I_n = \emptyset$  for  $n \ge 2$ , it is rather clear that  ${I_n}_{n=1}^{\infty}$  is a cover of (a,b), and so we have

$$m^*(a,b) \le \ell(a,b) = b - a.$$
 (2.1)

However, the other side of the game is not as easy to confirm: we would have to consider all possible covers of (a, b), which is a lot.

Another question that we can ask ourselves seeing Equation (2.1) is why can't  $m^*(a, b)$  be something that is strictly less than the length to give us an even more 'precise' measurement?

To answer these questions, it is useful to first consider the outer measure of a closed and bounded interval, e.g. [a, b], since these intervals are compact under the Heine-Borel Theorem. This will give us a finite subcover for every infinite cover of the compact interval, which is easy to deal with.

We shall see that with the realization of the outer measure of a compact interval, we will also be able to find the outer measure of intervals that are neither open nor closed.

We shall prove the following proposition in the next lecture. Note that for the sake of presentation, I shall abbreviate the Lebesgue Outer Measure as LOM.

Suppose  $a < b \in \mathbb{R}$ . Then

1. 
$$m^*([a,b]) = b - a$$
; and therefore

2. 
$$m^*((a,b]) = m^*([a,b)) = m^*((a,b)) = b - a$$
.

#### 3.1 Lebesgue Outer Measure Continued

#### **♦** Proposition 8 (LOM of Arbitrary Intervals)

Suppose  $a < b \in \mathbb{R}$ . Then

- 1.  $m^*([a,b]) = b a$ ; and therefore
- 2.  $m^*((a,b)) = m^*([a,b)) = m^*((a,b)) = b a$ .

#### Proof

1. Consider  $a < b \in \mathbb{R}$ . Let  $\varepsilon > 0$ , and let

$$I_1 = \left(a - \frac{\varepsilon}{2}, b + \frac{\varepsilon}{2}\right)$$

and  $I_n = \emptyset$  for  $n \ge 2$ . Then  $\{I_n\}_{n=1}^{\infty}$  is a cover of [a,b]. This means that

$$m^*([a,b]) \le \sum_{n=1}^{\infty} \ell(I_n) = b - a + \varepsilon.$$

So for all  $\varepsilon \to 0$ , we have that

$$m^*([a,b]) \le b-a.$$

¹ Conversely, if [a,b] is covered by open intervals  $\{I_n\}_{n=1}^{\infty}$ , then by compactness of [a,b] (via the Heine-Borel Theorem), we know that we can cover [a,b] by finitely many of these intervals, and let us denote these as  $\{I_n\}_{n=1}^N$ , for some  $1 \le N < \infty$ .

¹ For the converse, we know that  $m^*([a,b]) = \inf \bigstar$ , where  $\bigstar$  is just a placeholder for you-know-what. So  $m^*([a,b])$  is one of the sums. So if we can show that for an arbitrary sum,  $\geq$  holds, our work is done.

WTS

$$\sum_{n=1}^{N} \ell(I_n) \ge b - a.$$

If LHS =  $\infty$ , then our work is done. Thus wlog, WMA each  $I_n = (a_n, b_n)$  is a finite interval. Note that we have

$$[a,b]\subseteq\bigcup_{n=1}^N(a_n,b_n).$$

In particular,  $a \in \bigcup_{n=1}^{N} I_n$ . Thus,  $\exists 1 \leq n_2 \leq N$  such that  $a \in I_{n_1}$ . Now if  $b_{n_1} > b$ , we shall stop this process for our work is done, since then  $[a,b] \subseteq I_{n_1}$ . Otherwise, if  $b_{n_1} \leq b$ , then  $b_{n_1} \in [a,b] \subseteq \bigcup_{n=1}^{N} I_n$ , which means that  $\exists 1 \leq n_2 \leq N$  such that  $b_{n_1} \in I_{n_2}$ . Notice that  $n_1 \neq n_2$ , since  $b_{n_1} \notin I_{n_1}$  but  $b_{n_1} \in I_{n_2}$ .



Figure 3.1: Our continual picking of  $I_{n_1}, I_{n_2}, \ldots, I_{n_k}$ 

Now once again, if  $b_{n_2} > b$ , then we shall stop this process since our work is done. Otherwise, we have  $a < b_{n_2} \le b$ , and so  $\exists 1 \le n_3 \le N, n_3 \ne n_1, n_2$ , such that  $b_{n_2} \in I_3$ ...

We continue with the above process for as long as  $b_{n_k} \leq b$ . We can thus find, for each k,  $I_{n_{k+1}}$ , where  $n_{k+1} \in \{1, ..., N\} \setminus \{n_1, n_2, ..., n_k\}$ , such that  $b_{n_k} \in I_{n_{k+1}}$ .

However, since each of the  $I_{n_k}$ 's are different, and since we only have N such intervals, there must exists a  $K \leq N$  such that

$$b_{n_{K-1}} \leq b$$
 and  $b_{n_K} > b$ .

It now suffices for us to show that

$$\sum_{j=1}^K \ell(I_{n_j}) \ge b - a.$$

Observe that

$$\sum_{j=1}^{K} \ell(I_{n_j}) = (b_{n_K} - a_{n_K}) + (b_{n_{K-1}} - a_{n_{K-1}}) + \dots$$

$$+ (b_{n_2} - a_{n_2}) + (b_{n_1} - a_{n_1})$$

$$= b_{n_K} + (b_{n_{K-1}} - a_{n_K}) + (b_{n_{K-2}} - a_{n_{K-1}}) + \dots$$

$$\geq 0$$

$$+ (b_{n_1} - a_{n_2}) - a_{n_1}$$

$$\geq b_{n_K} - a_{n_1} \geq b - a.$$

Thus

$$\sum_{n=1}^{\infty} \ell(I_n) \geq \sum_{n=1}^{N} \ell(I_n) \geq \sum_{j=1}^{K} \ell(I_{n_j}) \geq b - a,$$

whence

$$m^*([a,b]) \ge b - a.$$

It follows that, indeed,

$$m^*([a,b]) = b - a.$$

2. First, note that

$$m^*((a,b)) \le m^*([a,b]) \le b-a.$$

On the other hand, notice that  $\forall 0 < \varepsilon < \frac{b-a}{2}$ , we have that

$$[a+\varepsilon,b-\varepsilon]\subseteq (a,b),$$

and so by monotonicity,

$$(b-a)-2\varepsilon=m^*([a+\varepsilon,b-\varepsilon])\leq m^*((a,b)).$$

As  $\varepsilon \to 0$ , we have that

$$b - a \le m^*((a, b)) \le b - a.$$

So

$$m^*((a,b)) = b - a$$

as desired.

Finally, we have that

$$b-a=m^*((a,b)) \le m^*((a,b]) \le m^*([a,b]) = b-a,$$

and similarly

$$b-a=m^*((a,b)) \le m^*([a,b)) \le m^*([a,b]) = b-a.$$

Thus

$$m^*((a,b)) = m^*((a,b]) = m^*([a,b)) = b - a$$

as required.

# **♦** Proposition 9 (LOM of Infinite Intervals)

We have that  $\forall a, b \in \mathbb{R}$ ,

$$m^*((a,\infty)) = m^*([a,\infty))$$
$$= m^*((-\infty,b)) = m^*((-\infty,b])$$
$$= m^*\mathbb{R} = \infty.$$

## Proof

Observe that

$$(a, a + n) \subseteq (a, \infty)$$

for all  $n \ge 1$ . Thus

$$n = m^*((a, a + n)) \le m^*((a, \infty))$$

for all  $n \ge 1$ . Hence

$$m^*((a,\infty))=\infty$$

by definition.

All other cases follow similarly.

## Corollary 10 (Uncountability of R)

 $\mathbb{R}$  is uncountable.

#### Proof

We have that

$$m^*\mathbb{R}=\infty\neq 0$$
,

and so it follows from ightharpoonup Corollary 6, we must have that  $\mathbb{R}$  is uncountable.

# **■** Definition 15 (Translation Invariant)

Let  $\mu$  be an outer measure on  $\mathbb{R}$ . We say that  $\mu$  is translation invariant if  $\forall E \subseteq \mathbb{R}$ ,

$$\mu(E) = \mu(E + \kappa)$$

for all  $\kappa \in \mathbb{R}$ , where

$$E + \kappa := \{x + \kappa : x \in E\}.$$

# ♦ Proposition 11 (Translation Invariance of the LOM)

The Lebesgue outer measure is translation invariant.

## Proof

Let  $E \subseteq \mathbb{R}$  and  $\kappa \in \mathbb{R}$ . Note that *E* is covered by open intervals  ${I_n}_{n=1}^{\infty}$  iff  $E + \kappa$  is covered by  ${I_n + \kappa}_{n=1}^{\infty}$ .

Claim:  $\forall n \geq 1$ ,  $\ell(I_n + \kappa) = \ell(I_n)$  Write

$$I_n = (a_n, b_n).$$

Then

$$I_n + \kappa = (a_n + \kappa, b_n + \kappa).$$

Observe that

$$\ell(I_n + \kappa) = b_n + \kappa - (a_n - \kappa) = b_n - a_n = \ell(I_n),$$

as claimed. ⊢

By the claim, it follows that

$$m^{*}(E) = \inf \left\{ \sum_{n=1}^{\infty} \ell(I_{n}) : E \subseteq \bigcup_{n=1}^{\infty} \right\}$$
$$= \inf \left\{ \sum_{n=1}^{\infty} \ell(I_{n} + \kappa) : E + \kappa \subseteq \bigcup_{n=1}^{\infty} (I_{n} + \kappa) \right\}$$
$$= m^{*}(E + \kappa).$$

#### Remark 3.1.1

Suppose  $E \subseteq \mathbb{R}$  and  $E = \bigcup_{n=1}^{\infty} E_n$ , where

$$E_i \cap E_j = \emptyset$$
 if  $i \neq j$ .

Now by  $\sigma$ -subadditivity of  $m^*$ , we have that

$$m^*E \leq \sum_{n=1}^{\infty} m^*E_n.$$

However, equality is not guaranteed. Consider the following case: if E = [0,1], we may have  $E_n = [0,1]$  for all n >= 1, in which case  $E = \bigcup_{n=1}^{\infty} E_n = [0,1]$ , but

$$m^*E = m^*[0,1] = 1 < \infty = \sum_{n=1}^{\infty} m^*E_n.$$

It would be desirable to have

$$m^*E=\sum_{n=1}^{\infty}m^*E_n,$$

when the  $E_i$ 's are pairwise disjoint, i.e.  $E = \bigcup_{n=1}^{\infty} E_n$ . In fact, this would agree with our intuition, that if the outer measure is going to be our 'length'. Consider the example  $A = [0,2] \cup [5,7]$ . Then we would expect  $m^*A = 2+2=4$ .

However, this is actually impossible for an arbitrary number of collections.

# Theorem 12 (Non-existence of a sensible Translation Invariant Outer Measure that is also $\sigma$ -additive)

There does not exist a translation-invariant outer measure  $\mu$  on  $\mathbb R$  that satisfies

- 1.  $\mu(\mathbb{R}) > 0$ ;
- 2.  $\mu[0,1] < \infty$ ; and
- 3.  $\mu$  is  $\sigma$ -additive; i.e. if  $\{E_n\}_{n=1}^{\infty}$  is a countable collection of disjoint subsets of  $\mathbb{R}$  that covers  $E \subseteq \mathbb{R}$ , then

$$\mu E = \sum_{n=1}^{\infty} \mu E_n.$$

Consequently, the Lebesgue outer measure  $m^*$  is **not**  $\sigma$ -additive.

#### Proof

Suppose to the contrary that such a  $\mu$  exists.

Step 1 Consider the relation  $\sim$  on  $\mathbb{R}$  such that  $x \sim y$  if  $x - y \in \mathbb{Q}$ .

Claim:  $\sim$  is an equivalence relation

- (reflexivity) We know that  $0 \in \mathbb{Q}$  and x x = 0. Thus  $x \sim x$ .
- (symmetry) Since Q is a field, it is closed under multiplication, and  $-1 \in \mathbb{Q}$ . Thus if  $x \sim y$ , then  $x - y \in \mathbb{Q}$ , and so (-1)(x  $y) = y - x \in \mathbb{Q}$ , which means  $y \sim x$ .
- (transitivity) Again, since Q is a field, it is closed under (this time) addition. Thus

$$x \sim y \land y \sim z \implies (x - y), (y - z) \in \mathbb{Q}$$
  
 $\implies (x - y) + (y - z) = x - z \in \mathbb{Q}.$ 

Thus  $x \sim z$ .

This proves the claim.  $\dashv$ 

Let

$$[x] := x + \mathbb{Q} := \{x + q : q \in \mathbb{Q}\}\$$

denote the equivalence class of x wrt  $\sim$ . Note that the set of equivalence classes, which we shall represent as

$$\mathcal{F} := \{ [x] : x \in \mathbb{R} \},$$

partitions  $\mathbb{R}$ , i.e.

- $[x] = [y] \iff x y \in \mathbb{Q}$ ; and
- $[x] \cap [y] = \emptyset$  otherwise.

Note that since  $\mathbb{Q}$  is **dense** in  $\mathbb{R}$ , we have that  $[x] = x + \mathbb{Q}$  is also dense in  $\mathbb{R}$ , for all  $x \in \mathbb{R}$ . Then for each  $^2F \in \mathcal{F}$ ,  $\exists x_F \in F$  such that

<sup>2</sup> Notice that here, we have invoked the Axiom of Choice .

$$0 \le x_F \le 1$$
.

Now consider the set

$$\mathbb{V} := \{x_F : F \in \mathcal{F}\} \subseteq [0,1],$$

which is called Vitali's Set.

Step 2 Since  $\mathcal{F}$  partitions  $\mathbb{R}$ , we have that

$$\mathbb{R} = \bigcup_{F \in \mathcal{F}} F = \bigcup_{F \in \mathcal{F}} [x_F]$$

$$= \bigcup_{F \in \mathcal{F}} x_F + \mathbb{Q}$$

$$= \mathbb{V} + \mathbb{Q} := \{x + q : q \in \mathbb{Q}, x \in \mathbb{V}\}.$$

Step 3 Claim:  $p \neq q \in \mathbb{Q} \implies (\mathbb{V} + p) \cap (\mathbb{V} + q) = \emptyset$  Suppose not, and suppose  $\exists y \in (\mathbb{V} + p) \cap (\mathbb{V} + q)$ . Then  $\exists F_1, F_2 \in \mathcal{F}$  such that

$$y = x_{F_1} + p = x_{F_2} + q. (3.1)$$

Then we may rearrange the above equation to get

$$x_{F_1}-x_{F_2}=q-p\in\mathbb{Q}.$$

This implies that

$$[x_{F_1}] = [x_{F_2}] \implies F_1 = F_2$$

since V consists of one unique representative from each of the equivalence classes. However, this would mean that

$$x_{F_1} = x_{F_2}$$
.

Since  $p \neq q$ , we have that

$$x_{F_1} + p \neq x_{F_2} + q,$$

which contradicts Equation (3.1). Thus

$$(\mathbb{V}+p)\cap(\mathbb{V}+q)=\emptyset,$$

as claimed.  $\dashv$ 

This in turn means that the  $\mathbb{V} + q$ , for each  $q \in \mathbb{Q}$ , also partitions  $\mathbb{R}$ . In other words, if we write  $\mathbb{Q} = \{p_n\}_{n=1}^{\infty}$ , then

$$\mathbb{R} = \mathbb{V} + \mathbb{Q} = \bigcup_{n=1}^{\infty} \mathbb{V} + p_n.$$

Now, note that

$$0 \neq \mu \mathbb{R} \stackrel{(1)}{=} \sum_{n=1}^{\infty} \mu(\mathbb{V} + p_n) \stackrel{(2)}{=} \sum_{n=1}^{\infty} \mu(\mathbb{V}),$$

where (1) is by  $\mu$  being  $\sigma$ -additive and (2) is by  $\mu$  being translation invariant, both directly from our assumptions. This means that

$$\mu V > 0$$
.

Step 4 Now consider  $S = \mathbb{Q} \cap [0,1]$  such that S is denumerable. Write

$$S = \{s_n\}_{n=1}^{\infty}.$$

Note that for all  $n \ge 1$ ,

$$\mathbb{V} \subseteq [0,1] \implies \mathbb{V} + s_n \subseteq [0,2],$$

and as proven above

$$i \neq j \implies (\mathbb{V} + s_i) \cap (\mathbb{V} + s_i) = \emptyset.$$

Thus it follows that

$$\mu\left(\bigcup_{n=1}^{\infty} \mathbb{V} + s_n\right) = \sum_{n=1}^{\infty} \mu(\mathbb{V} + s_n) = \sum_{n=1}^{\infty} \mu(\mathbb{V}) = \infty.$$

Also,

$$\mu\left(\bigcup_{n=1}^{\infty} \mathbb{V} + s_n\right) = \sum_{n=1}^{\infty} \mu(\mathbb{V} + s_n)$$

$$\leq \mu([0,2]) = \mu([0,1] \cup ([0,1]+1))$$

$$\leq \mu[0,1] + \mu([0,1]+1)$$

$$= 2\mu([0,1]) = 2 < \infty,$$

contradicting what we have right above.

Therefore, no such  $\mu$  exists.

With the realization of Theorem 12, we find ourselves facing a losing dilemma: we may either

- 1. be happy with the Lebesgue outer measure  $m^*$  for all subsets  $E \subseteq \mathbb{R}$ , which would agree with our intuitive notion of length, at the price of  $\sigma$ -additivity; or
- 2. restrict the **domain** of our function  $m^*$  to some family of subsets of  $\mathbb{R}$ , where  $m^*$  would have  $\sigma$ -additivity.

We shall adopt the second approach. We shall call the collection of sets where  $m^*$  has  $\sigma$ -additivity as the collection of Lebesgue measurable sets.

## 3.2 *Lebesgue Measure*

We shall first introduce Carathéodory's definition of a Lebesgue measurable set.

# **■** Definition 16 (Lebesgue Measureable Set)

*A set*  $E \subseteq \mathbb{R}$  *is said to be Lebesgue measurable if,*  $\forall X \subseteq \mathbb{R}$ *,* 

$$m^*X = m^*(X \cap E) + m^*(X \setminus E).$$

We denote the collection of all Lebesgue measurable sets as  $\mathfrak{M}(\mathbb{R})$ .

#### Remark 3.2.1

Since we shall almost exclusively focus on the Lebesgue measure, we shall hereafter refer to "Lebesgue measurable sets" as simply "measurable sets".

## **66** Note 3.2.1

*I shall quote and paraphrase this remark from our course notes* <sup>3</sup>:

*Informally, we see that a set E*  $\mathbb{R}$  is measurable provided that it is a "universal slicer", that it "slices" every other set X into two disjoint sets, into where the Lebesgue outer measure is

Also, note that we get the following inequality for free, simply from  $\sigma$ -subadditivity of  $m^*$ :

$$m^*X \le m^*(X \cap E) + m^*(X \setminus E).$$

Thus, it suffices for us to check if the reverse inequality holds for all sets  $X \subseteq \mathbb{R}$ .

Before ploughing forward to getting out hands dirty with examples, let us first study a result on a structure of  $\mathfrak{M}(\mathbb{R})$  that is rather

<sup>3</sup> Marcoux, L. W. (2018). PMath 450 Introduction to Lebesgue Measure and Fourier Analysis. (n.p.)

interesting. 4

**■** Definition 17 (Algebra of Sets)

A collection  $\Omega \subseteq \mathcal{P}(\mathbb{R})$  is said to be an algebra of sets if

- 1.  $\mathbb{R} \in \Omega$ ;
- 2. (closed under complementation)  $E \in \Omega \implies E^C \in \Omega$ ; and
- 3. (closed under finite union) given  $N \ge 1$  and  $\{E_n\}_{n=1}^N \subseteq \Omega$ , then

$$\bigcup_{n=1}^N E_n \in \Omega.$$

We say that  $\Omega$  is a  $\sigma$ -algebra of sets if

- 1.  $\Omega$  is an algebra of sets; and
- 2. (closed under countable union) if  $\{E_n\}_{n=1}^{\infty} \subseteq \Omega$ , then

$$\bigcup_{n=1}^{\infty} E_n \in \Omega.$$

66 Note 3.2.2

We often call a  $\sigma$ -algebra of sets as simply a  $\sigma$ -algebra.

**P**Theorem 13 ( $\mathfrak{M}(\mathbb{R})$  is a  $\sigma$ -algebra)

*The collection*  $\mathfrak{M}(\mathbb{R})$  *of Lebesgue measurable sets in*  $\mathbb{R}$  *is a*  $\sigma$ *-algebra.* 

Due to time constraints, we shall prove the first 2 requirements in this lecture and prove the last requirement next time (which is also really long).

Proof

<sup>4</sup> For those who has dirtied themselves in the world of probability and statistics, especially probability theory, get ready to get excited!  $\mathbb{R} \in \mathfrak{M}(\mathbb{R})$  Observe that  $\forall X \subseteq \mathbb{R}$ ,

$$m^*X = m^*X + 0 = m^*X + m^*\emptyset = m^*(X \cap \mathbb{R}) + m^*(X \setminus \mathbb{R})$$

 $E \in \mathfrak{M}(\mathbb{R}) \implies E^C \in \mathfrak{M}(\mathbb{R})$  Observe that  $\forall X \subseteq \mathbb{R}$ , since  $E \in \mathbb{R}$  $\mathfrak{M}(\mathbb{R})$ , we have

$$m^*X = m^*(X \cap E) + m^*(X \setminus E)$$

$$= m^*(X \cap (E^C)^C) + m^*(X \cap E^C)$$

$$= m^*(X \setminus E^C) + m^*(X \cap E^C)$$

$$= m^*(X \cap E^C) + m^*(X \setminus E^C)$$

$$= m^*(X \cap E^C) + m^*(X \setminus E^C)$$
rearrangement

Thus  $E^C \in \mathfrak{M}(\mathbb{R})$ .

## 4.1 Lebesgue Measure (Continued)

Recalling the last theorem we were in the middle of proving, it remains for us to prove that  $\mathfrak{M}(\mathbb{R})$  is closed under arbitrary unions of its elements.

But before we dive in, let's first have a little pep talk.

# **✓** Strategy

Since  $m^*$  is  $\sigma$ -subadditive, given  $\{E_n\}_{n=1}^{\infty}$ , we need only prove that  $\forall X \subseteq \mathbb{R}$ ,

$$m^*X \ge m^* \left(X \cap \bigcup_{n=1}^{\infty} E_n\right) + m^* \left(X \setminus \bigcup_{n=1}^{\infty} E_n\right).$$

Recall our discussion near the end of Section 3.1. We want  $\sigma$ -additivity, especially when we are given a set of disjoint intervals. However, our  $E_n$ 's are arbitrary, and so they are not necessarily disjoint.

It helps if one has seen how we can slice  $\mathbb{R}$  up into disjoint unions, and consequently we can do so for any of its subsets. We shall not take that for granted and immediately use it, but we shall work through this proof in the spirit of that. We shall see how we can slice  $\mathbb{R}$  up in A1.

Once we can, in some way, express  $\bigcup_{n=1}^{\infty} E_n$  as a disjoint union of intervals, we will then show that, indeed, we have  $\sigma$ -additivity instead of  $\sigma$ -subadditivity on this disjoint union.

 $\mathfrak{M}(\mathbb{R})$  is closed under arbitrary unions Suppose  $\{E_n\}_{n=1}^{\infty}\subseteq \mathfrak{M}(\mathbb{R})$ . To show that  $\bigcup_{n=1}^{\infty} E_n \in \mathfrak{M}(\mathbb{R})$ , WTS

$$m^*X = m^* \left(X \cap \bigcup_{n=1}^{\infty} E_n\right) + m^* \left(X \setminus \bigcup_{n=1}^{\infty} E_n\right).$$

Since  $m^*$  is  $\sigma$ -subadditive, it suffices for us to show that

$$m^*X \ge m^* \left(X \cap \bigcup_{n=1}^{\infty} E_n\right) + m^* \left(X \setminus \bigcup_{n=1}^{\infty} E_n\right).$$
 (4.1)

Step 1 Consider

$$H_n = \bigcup_{i=1}^n E_i, \quad \forall n \geq 1.$$

Claim:  $H_n \in \mathfrak{M}(\mathbb{R}), \forall n \geq 1$  We shall prove this by induction on n.

When n=1, we have  $H_1=E_1\in\mathfrak{M}(\mathbb{R})$  by assumption, and so we are done. Suppose that  $H_k\in\mathfrak{M}(\mathbb{R})$  for some  $k\in\mathbb{N}$ . Consider n=k+1.

Since we will need the piece  $X \cap H_{k+1}$ , first, notice that

$$X \cap H_{k+1} = X \cap (H_k \cup E_{k+1}) = (X \cap H_k) \cup ((X \setminus H_k) \cap E_{k+1}),$$

and in particular that

$$X \cap H_{k+1} = X \cap (H_k \cup E_{k+1}) \subseteq (X \cap H_k) \cup ((X \setminus H_k) \cap E_{k+1}).$$
 (4.2)

This may be (will be) useful later on, and we can guess that we will be using  $\sigma$ -subadditivity on this.

By the IH, since  $H_k \in \mathfrak{M}(\mathbb{R})$ , we have

$$m^*X = m^*(X \cap H_k) + m^*(X \setminus H_k).$$

Notice the similarity between the above equation and Equation (4.2), where we are just off by that  $\cap E_{k+1}$ .

Since  $E_{k+1} \in \mathfrak{M}(\mathbb{R})$ , we have

$$m^*(X \setminus H_k) = m^*(X \setminus H_k \cap E_{k+1}) + m^*(X \setminus H_k \setminus E_{k+1}).$$

To clean the above equation up a little bit, notice that by De Morgan's Law,

$$X \setminus H_k \setminus E_{k+1} = X \cap \bigcup_{i=1}^k E_i^C \cap E_{k+1}^C = X \setminus H_{k+1}.$$

So

$$m^*(X \setminus H_k) = m^*(X \setminus H_k \cap E_{k+1}) + m^*(X \setminus H_{k+1}).$$

Thus

$$m^*X = m^*(X \cap H_k) + m^*(X \setminus H_k \cap E_{k+1}) + m^*(X \setminus H_{k+1}).$$

Using Equation (4.2) and  $\sigma$ -subadditivity, we have that

$$m^*X \ge m^*(X \cap H_{k+1}) + m^*(X \setminus H_{k+1}),$$

which is what we need. Thus  $\forall k \geq 1$ ,  $H_k \in \mathfrak{M}(\mathbb{R})$ .  $\dashv$ 

Step 2 Consider  $F_1 = H_1 = E_1 \in \mathfrak{M}(\mathbb{R})$ , and for  $k \geq 2$ ,

$$F_k = H_k \setminus H_{k-1} = H_k \cap H_{k-1}^C.$$

<sup>1</sup> Claim:  $\forall k \geq 2$ ,  $F_k \in \mathfrak{M}(\mathbb{R})$  First, notice that

$$F_k^C = (H_k \cap H_{k+1}^C)^C = H_k^C \cup H_{k+1}.$$

By **step 1** <sup>2</sup>, we have that  $F_k^C \in \mathfrak{M}(\mathbb{R})$ , and thus by closure under complementation,  $F_k \in \mathfrak{M}(\mathbb{R})$ .

Also, note that the  $F_i$ 's are pairwise disjoint. Suppose not, i.e. that  $\exists x \in F_a \cap F_b$  for some  $a, b \ge 1$  and  $a \ne b$ . Wlog, wma a < b. Note that  $H_a \subseteq H_b$ , since

$$H_a = \bigcup_{i=1}^a E_i \subsetneq \bigcup_{i=1}^b E_i = H_b.$$

Since  $F_b = H_b \setminus H_{b-1}$ ,

$$x \in F_b \implies x \notin \bigcup_{i=1}^{b-1} E_i \supseteq \bigcup_{i=1}^a E_i,$$

- <sup>1</sup> Note that we cannot assume that  $\mathfrak{M}(\mathbb{R})$  is closed under finite intersections because that is part of what we want to prove.
- <sup>2</sup> I need to get this clarified.

and so  $x \notin E_i$  for  $1 \le i \le a \le b - 1$ . But we assumed that

$$x \in F_a = H_a \setminus H_{a-1}$$
,

i.e. it must be that  $x \in E_a$ , a contradiction.

Step 3 We now have

$$E = \bigcup_{i=1}^{\infty} E_i = \bigcup_{i=1}^{\infty} H_i = \bigcup_{i=1}^{\infty} F_i.$$

Equation (4.1) becomes <sup>3</sup>

$$m^*X \ge m^* \left(X \cap \left(\bigcup_{i=1}^{\infty} F_i\right)\right) + m^* \left(X \setminus E\right).$$

Since the  $F_i$ 's are disjoint, we expect

$$m^*\left(X\cap\bigcup_{i=1}^{\infty}F_i\right)=\sum_{i=1}^{\infty}m^*(X\cap F_i).$$

i.e. for every n,

$$m^*\left(X\cap\bigcup_{i=1}^n F_i\right)=\sum_{i=1}^n m^*(X\cap F_i).$$

Let's prove this inductively. It is clear that case n=1 is trivially true. Suppose that this is true up to some  $k \in \mathbb{N}$ . Consider case n=k+1. Since  $F_{k+1} \in \mathfrak{M}(\mathbb{R})$ , we have that <sup>4</sup>

<sup>4</sup> This is quite a smart trick!

$$m^* \left( X \cap \bigcup_{i=1}^{k+1} F_i \right)$$

$$= m^* \left( X \cap \bigcup_{i=1}^{k+1} F_i \cap F_{k+1} \right) + m^* \left( \left( X \setminus \bigcup_{i=1}^{k-1} F_i \right) \setminus F_{k+1} \right)$$

$$= m^* (X \cap F_{k+1}) + m^* \left( X \cap \bigcup_{i=1}^k F_i \right)$$

$$= m^* (X \cap F_{k+1}) + \sum_{i=1}^k m^* (X \cap F_i)$$

$$= \sum_{i=1}^{k+1} m^* (X \cap F_i).$$

Our claim is complete by induction.

<sup>3</sup> I refrained from changing the second term to the disjoint union. Retrospectively (i.e. once you're done with the proof), it makes sense to not consider this move, since there is no point looking at *X* take away a bunch of disjoint

intervals.

Step 4 With Step 3, Equation (4.1) has become

$$m^*X \ge \sum_{i=1}^{\infty} m^*(X \cap F_i) + m^*(X \setminus E).$$

<sup>5</sup> Since  $H_k \in \mathfrak{M}(\mathbb{R})$  for each  $k \geq 1$ , we have

$$m^*X = m^*(X \cap H_k) + m^*(X \setminus H_k). \tag{*}$$

<sup>5</sup> This is a reward for the clear-minded, cause I certainly did not find it an obvious step to take.

Since

$$H_k = \bigcup_{i=1}^k E_i = \bigcup_{i=1}^\infty E_i = E,$$

we have that

$$X \setminus H_k \supseteq X \setminus E$$
,

for each  $k \ge 1$ . Thus by monotonicity, Equation (\*) becomes

$$m^*X \ge m^*(X \cap H_k) + m^*(X \setminus E)$$

$$= m^* \left( X \cap \left( \bigcup_{i=1}^{\infty} F_i \right) \right) + m^*(X \setminus E)$$

$$= \sum_{i=1}^{k} m^*(X \cap F_i) + m^*(X \setminus E),$$

for each  $k \ge 1$ .

By letting  $k \to \infty$ , we have that

$$m^*X \ge \sum_{i=1}^{\infty} m^*(X \cap F_i) + m^*(X \setminus E).$$

Note that

$$X \cap E = X \cap \bigcup_{i=1}^{\infty} F_i = \bigcup_{i=1}^{\infty} (X \cap F_i).$$

By  $\sigma$ -subadditivity, we have that

$$m^*(X \cap E) \le \sum_{i=1}^{\infty} m^*(X \cap F_i).$$

Therefore

$$m^*X \ge m^*(X \cap E) + m^*(X \setminus E),$$

which is what we want!

## 66 Note 4.1.1 (Post-mortem for proof of PTheorem 13)

In steps 1 - 3, we try to slice  $\bigcup_{n=1}^{\infty} E_n$  into disjoint **measurable** intervals  $F_i$ 's. Along the process of constructing them, it is the showing of them being measurable that takes up most of the proof, since we require induction.

## ♦ Proposition 14 (Some Lebesgue Measurable Sets)

- 1. If  $E \subseteq \mathbb{R}$  and  $m^*E = 0$ , then E is Lebesgue measurable.
- 2.  $\forall b \in \mathbb{R}, (-\infty, b) \in \mathfrak{M}(\mathbb{R}).$
- 3. Every open and every closed set is Lebesgue measurable.

#### Proof

1. Let  $X \subseteq \mathbb{R}$ . Note that  $X \setminus E \subseteq X$ , and so  $\sigma$ -subadditivity gives

$$m^*X \ge m^*(X \setminus E). \tag{4.3}$$

On the other hand,  $X \cap E \subseteq E$ , and so

$$m^*(X \cap E) \le m^*E = 0 \implies m^*(X \cap E) = 0.$$

Thus, from Equation (4.3),

$$m^*X \ge ml * (X \setminus E) = m^*(X \cap E) + m^*(X \setminus E).$$

Hence  $E \in \mathfrak{M}(\mathbb{R})$  as required.

2. Let  $b \in \mathbb{R}$  and  $X \subseteq \mathbb{R}$  be arbitrary. WTS

$$m^*X > m^*(X \cap (-\infty, b)) + m^*(X \setminus (-\infty, b)).$$

<sup>6</sup> Let E = (-∞, b). Note that if  $m^*X = ∞$ , then there is nothing to show. Thus WMA  $m^*X < ∞$ . In this case, let ε > 0, and

<sup>&</sup>lt;sup>6</sup> We will look at  $X \cap (\infty, b)$  and  $X \setminus (-\infty, b)$  more closely, and then realize that since we can cover X, we can "extend" this cover for these disjoint pieces by taking intersections and set removals on each of the covering sets.

 $\{I_n\}_{n=1}^{\infty}$  a cover of *X* by open intervals, where we write

$$I_n = (a_n, b_n)$$

for each  $n \ge 1$ , so that <sup>7</sup>

$$\sum_{n=1}^{\infty} \ell(I_n) < m^* X + \varepsilon.$$

For each  $n \ge 1$ , consider the sets

$$I_n = I_n \cap E + I_n \cap (-\infty, b)$$

and

$$K_n = I_n \setminus E = I_n \setminus (\infty, b) = I_n \cap [b, \infty).$$

The following table captures all possible  $J_n$ 's and  $K_n$ 's:

$$\begin{array}{c|cccc} Case & 1 & 2 & 3 \\ \hline b & > b_n & \in I_n & < a_n \\ \hline J_n & I_n & (a_n,b) & \varnothing \\ K_n & \varnothing & [b,b_n) & I_n \\ \hline \end{array}$$

Notice that  $\{J_n\}_{n=1}^{\infty}$  is an open cover for  $X \cap E$ .  $\{K_n\}_{n=1}^{\infty}$  is also a cover of  $X \setminus E$  but it is not an open cover (the only covers of which we consider in this course). Thus, we consider a small extension  $L_n$  of  $K_n$  such that

- if  $K_n = \emptyset$ , then  $L_n = \emptyset$ ;
- if  $K_n = I_n$ , then  $L_n = I_n$ ; and
- if  $K_n = [b, b_n)$ , then  $L_n = (b \frac{\varepsilon}{2^n}, b_n)$ .

Then  $\{L_n\}_{n=1}^{\infty}$  is a cover of  $X \setminus E$ . By  $\sigma$ -subadditivity of  $m^*$ , we have that

$$m^*(X \cap E) \le \sum_{n=1}^{\infty} \ell(J_n)$$

and

$$m^*(X \setminus E) \leq \sum_{n=1}^{\infty} \ell(L_n).$$

Thus

$$m^*(X \cap E) + m^*(X \setminus E) \le \sum_{n=1}^{\infty} (\ell(J_n) + \ell(L_n)).$$

<sup>7</sup> Note that this is legitimate because  $m^*X$  is the infimum of such sums on the LHS, and we can definitely find such a cover as a result. Also, there is no harm in assuming that each of the  $I_n$ 's are non-empty, since we may simply remove all the empty  $I_n$ 's from the cover.

Table 4.1: Possible outcomes of  $J_n$  and  $K_n$ , for each  $n \ge 1$ 

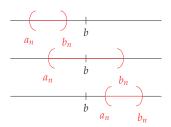


Figure 4.1: Three possible scenarios of where b stands for different  $I_n$ 's

Now, notice that in cases 1 and 3,

$$\ell(I_n) + \ell(L_n) = \ell(I_n).$$

In case 2, we have that

$$(\ell(I_n) + \ell(L_n)) - \ell(I_n) < \frac{\varepsilon}{2^n}$$

and so

$$\ell(J_n) + \ell(L_n) < \ell(I_n) + \frac{\varepsilon}{2^n}.$$

Therefore

$$m^{*}(X \cap E) + m^{*}(X \setminus E)$$

$$\leq \sum_{n=1}^{\infty} (\ell(J_{n}) + \ell(L_{n}))$$

$$\leq \sum_{n=1}^{\infty} (\ell(I_{n}) + \frac{\varepsilon}{2^{n}})$$

$$= \sum_{n=1}^{\infty} \ell(I_{n}) + \varepsilon$$

$$< (m^{*}X + \varepsilon) + \varepsilon$$

$$= m^{*}X + 2\varepsilon.$$

Since  $\varepsilon > 0$  is arbitrary, we have that

$$m^*X \ge m^*(X \cap E) + m^*(X \setminus E),$$

and since *X* is arbitrary, we have that  $E = (-\infty, b) \in \mathfrak{M}(\mathbb{R})$ .

3. Wlog, suppose  $a < b \in \mathbb{R}$ . By part 2, we have that

$$(-\infty,b)\in\mathfrak{M}(\mathbb{R}),$$

and similarly, for  $n \ge 1$ ,

$$\left(\infty, a + \frac{1}{n}\right) \in \mathfrak{M}(\mathbb{R}).$$

Since  $\mathfrak{M}(\mathbb{R})$  is a  $\sigma$ -algebra, we have that

$$\left[a+\frac{1}{n},\infty\right)=\left(-\infty,a+\frac{1}{n}\right)^{C}\in\mathfrak{M}(\mathbb{R}),$$

for each  $n \ge 1$ . Consequently,

$$(a,\infty) = \bigcup_{n=1}^{\infty} \left[ a + \frac{1}{n}, \infty \right) \in \mathfrak{M}(\mathbb{R}).$$

Therefore, we have that

$$(a,b) = (-\infty,b) \cap (a,\infty) \in \mathfrak{M}(\mathbb{R}).$$

<sup>8</sup> Since every open set  $G \subseteq \mathbb{R}$  is a countable disjoint union of open intervals in  $\mathbb{R}$ , it follows that  $G \in \mathfrak{M}(\mathbb{R})$  since  $\mathfrak{M}(\mathbb{R})$  is a  $\sigma$ -algebra. If  $F \subseteq \mathbb{R}$  is closed, notice that

<sup>8</sup> We shall prove this in A<sub>1</sub>.

$$F^C = G \in \mathfrak{M}(\mathbb{R})$$

since G is open, and so by closure under complementation of  $\sigma$ -algebras,  $F \in \mathfrak{M}(\mathbb{R})$ .

## **Definition 18 (Lebesgue Measure)**

Let  $m^*$  denote the Lebesgue outer measure on  $\mathbb{R}$ . We define the Lebesgue measure m to be

$$m=m^*\upharpoonright_{\mathfrak{M}(\mathbb{R})}$$
,

*i.e.*  $\forall E \in \mathfrak{M}(\mathbb{R})$ , we have that

$$mE = m^*E = \inf \left\{ \sum_{n=1}^{\infty} \ell(I_n) \mid E \subseteq \bigcup_{n=1}^{\infty} I_n \right\}.$$

In A1, we shall prove that

# **P**Theorem 15 ( $\sigma$ -additivity of the Lebesgue Measure on Lebesgue **Measurable Sets**)

The Lebesgue measure is  $\sigma$ -additive on  $\mathfrak{M}(\mathbb{R})$ , i.e. if  $\{E_n\}_{n=1}^{\infty}\subseteq \mathfrak{M}(\mathbb{R})$ with  $E_i \cap E_j = \emptyset$  for all  $i \neq j$ , then

$$m\bigcup_{n=1}^{\infty}E_n=\sum_{n=1}^{\infty}mE_n.$$

## Corollary 16 (Existence of Non-Measurable Sets)

There exists non-measurable sets.

#### Proof

Suppose not, i.e.  $\mathfrak{M}(\mathbb{R})=\mathcal{P}(\mathbb{R})$ . Then  $m=m^*$  is a translation invariant outer measure on  $\mathbb{R}$ , with  $m^*\mathbb{R}=\infty>0$ ,  $m^*[0,1]=1<\infty$ , and  $m^*$  is  $\sigma$ -additive, which contradicts  $\blacksquare$  Theorem 12. Thus  $\mathfrak{M}(\mathbb{R})\neq\mathcal{P}(\mathbb{R})$ .

The following proposition is left as an exercise.

## ♦ Proposition 17 (Non-measurability of the Vitali Set)

The Vitali set V, defined in PTheorem 12, is not measurable.

# $\blacksquare$ Definition 19 ( $\sigma$ -algebra of Borel Sets)

The  $\sigma$ -algebra of sets generated by the collection

$$\mathfrak{G} := \{G \subseteq \mathbb{R} : G \text{ is open } \}$$

is called the  $\sigma$ -algebra of Borel sets of  $\mathbb{R}$ , and is denoted by

$$\mathfrak{Bor}(\mathbb{R}).$$

#### **66** Note 4.1.2

Since  $\mathfrak{Bor}(\mathbb{R})$  is generated by open sets in  $\mathbb{R}$  and all open subsets of  $\mathbb{R}$  are Lebesgue measurable (cf.  $\lozenge$  Proposition 14), we have that

$$\mathfrak{Bor}(\mathbb{R})\subseteq\mathfrak{M}(\mathbb{R}).$$

#### Exercise 4.1.1

*Prove* • *Proposition* 17.

#### Remark 4.1.1

Since  $\mathfrak{Bor}(\mathbb{R})$  is a  $\sigma$ -algebra, and it is, in particular, generated by open subsets of  $\mathbb{R}$ , it also contains all of the closed subsets of  $\mathbb{R}$ . Thus, we could have instead defined  $\mathfrak{Bor}(\mathbb{R})$  to be the  $\sigma$ -algebra of subsets of  $\mathbb{R}$  generated by the collection

$$\mathfrak{F} := \{ F \subseteq \mathbb{R} : F \text{ is closed } \},$$

and in turn conclude that  $\mathfrak{Bor}(\mathbb{R})$  contains  $\mathfrak{G}$ .

## Remark 4.1.2

Let  $A \subseteq \mathcal{P}(\mathbb{R})$ , with  $\emptyset$ ,  $\mathbb{R} \in A$ . Let

$$\mathcal{A}_{\sigma} := \left\{ \bigcup_{n=1}^{\infty} A_n : A_n \in \mathcal{A}, n \ge 1 \right\}$$
$$\mathcal{A}_{\delta} := \left\{ \bigcap_{n=1}^{\infty} A_n : A_n \in \mathcal{A}, n \ge 1 \right\}.$$

We call the elements of  $A_{\sigma}$  as A-sigma sets, and elements of  $A_{\delta}$  as Adelta sets.

Recalling our definitions

$$\mathfrak{G} = \{ G \subseteq \mathbb{R} \mid G \text{ is open } \}$$
$$\mathfrak{F} = \{ F \subseteq \mathbb{R} \mid F \text{ is closed } \}$$

from above, notice that

$$\mathfrak{G}_{\delta} = \left\{ \bigcap_{n=1}^{\infty} G_n \mid G_n \in \mathfrak{G}, n \geq 1 \right\},$$

which is a countable intersection of open subsets of  $\mathbb{R}$ , and

$$\mathfrak{F}_{\sigma} = \left\{ \bigcup_{n=1}^{\infty} F_n \mid F_n \in \mathfrak{F}, n \geq 1 \right\},$$

which is a **countable union of closed subsets** of  $\mathbb{R}$ , are both subsets of  $\mathfrak{Bor}(\mathbb{R}).$ 

As MENTIONED BEFORE, the definition of which we provided for

a Lebesgue measurable set is from Carathéodory, which is not the most intuitive definition. We shall now show that it is equivalent to the original definition of which Lebesgue himself has provided.

# ■ Theorem 18 (Carathéodory's and Lebesgue's Definition of Measurability)

*Let*  $E \subseteq \mathbb{R}$ *. TFAE:* 

- 1. E is Lebesgue measurable (Carathéodory).
- 2.  $\forall \varepsilon > 0$ , there exists an open  $G \supseteq E$  such that

$$m^*(G \setminus E) < \varepsilon$$
.

3. There exists a  $\mathfrak{G}_{\delta}$ -set H such that  $E \subseteq H$  and

$$m^*(H \setminus E) = 0.$$

## Proof

(1)  $\Longrightarrow$  (2) If we can find such a G that is open, then since E is Lebesgue measurable, we have

$$mG = m(G \cap E) + m(G \setminus E) = mE + m(G \setminus E),$$

and so

$$m(G \setminus E) = mG - mE. (4.4)$$

So if we can construct such a G, that is particularly small enough (within  $\varepsilon$ -bigger) to contain E, our statement is good as done.

Case 1:  $mE < \infty$  In this case, we may consider a cover  $\{I_n\}_{n=1}^{\infty}$  of E such that

$$\sum_{n=1}^{\infty} \ell(I_n) < mE + \varepsilon.$$

Then we may simply let  $G = \bigcup_{n=1}^{\infty} I_n$ . Note that since  $\mathfrak{M}(\mathbb{R})$  is a

 $\sigma$ -algebra,  $G \in \mathfrak{M}(\mathbb{R})$ . Thus by monotonicity,

$$mG = m\left(\bigcup_{n=1}^{\infty} I_n\right) \leq \sum_{n=1}^{\infty} mI_n = \sum_{n=1}^{\infty} \ell(I_n) < mE + \varepsilon.$$

With this, Equation (4.4) becomes

$$m(G \setminus E) < mE + \varepsilon - mE = \varepsilon$$
.

Case 2:  $\forall r \in \mathbb{R}, mE > r$  Consider

$$E_k = [-k, k] \cap E$$

measurable, and so for each  $k \ge 1$ ,  $E_k \in \mathfrak{M}(\mathbb{R})$ . Note that

$$E = \bigcup_{k>1} E_k.$$

<sup>10</sup> Note that  $E_k \subseteq [-k, k]$ , and so

$$mE_k \leq m[-k,k] = 2k < \infty.$$

Using a similar approach as in Case 1, we can construct an open set  $G_k$  such that  $G_k \supseteq E_k$ , and

$$m(G_k \setminus E_k) < \frac{\varepsilon}{2^k}$$

for each  $k \ge 1$ . Now let

$$G := \bigcup_{k>1} G_k \supseteq \bigcup_{k>1} E_k = E.$$

Note that if  $x \in G \setminus E$ , then  $x \notin E_k$  for all  $k \ge 1$ , and  $\exists N \ge 1$  such that  $x \in G_N$ . In particular, we have that

$$x \in G_N \setminus E_N$$
,

and so

$$G \setminus E \subseteq \bigcup_{k \ge 1} G_k \setminus E_k$$

11. Therefore

- <sup>9</sup> I should get clarification for my understanding of this approach. We picked closed intervals instead of open ones so that we deal with the possible quirkiness of E.
- 10 It would be a quick job if we take the union of the  $E_k$ 's but note that the  $E_k$ 's are not necessarily open!

<sup>11</sup> It is, however, true that equality holds, and it is not difficult to prove so.

$$m(G \setminus E) \leq \sum_{k \geq 1} m(G_k \setminus E_k) \leq \sum_{k \geq 1} \frac{\varepsilon}{2^k} = \varepsilon.$$

(2)  $\Longrightarrow$  (3) By (2), for each  $n \ge 1$ , let  $G_n \supseteq E$  such that

$$m(G_n \setminus E) < \frac{1}{n}.$$

Let  $H := \bigcap_{n \ge 1} G_n$ , which then  $H \in \mathfrak{G}_{\delta}$ . Also, since  $E \subseteq G_n$  for all  $n \ge 1$ , we have  $E \subseteq H$ . Also,  $H \subseteq G_n$  for each n. Thus

$$H \setminus E \subseteq G_n \setminus E$$
,

for each  $n \ge 1$ . By monotonicity,

$$m(H \setminus E) \le m(G_n \setminus E) < \frac{1}{n}$$

for each  $n \ge 1$ . Therefore

$$m(H \setminus E) = 0.$$

(3)  $\Longrightarrow$  (1) Notice that  $\mathfrak{G}_{\delta} \subseteq \mathfrak{Bor}(\mathbb{R}) \subseteq \mathfrak{M}(\mathbb{R})$ . Suppose  $G \in \mathfrak{G}_{\delta}$ , and  $E \subseteq H$  such that

$$m(H \setminus E) = 0.$$

By lacktriangle Proposition 14,  $H \setminus E \in \mathfrak{M}(\mathbb{R})$ . Since  $\mathfrak{M}(\mathbb{R})$  is a  $\sigma$ -algebra, notice that

$$E = H \setminus (H \setminus E) = H \cap (H \cap E^{C})^{C} = H \cap H^{C} \cup E \in \mathfrak{M}(\mathbb{R}). \quad \Box$$



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