PMATH451 — Measure and Integration

Class notes for Fall 2019

by

Johnson Ng

BMath (Hons), Pure Mathematics major, Actuarial Science Minor University of Waterloo

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Assignment problems is introduced in class as we go, so we have the special environment homework for these in this note.

E Lecture 1 Sep 04th, 2019

1.1 Motivation for the Study of Measures

Recall Riemann integration.

■ Definition (Riemann Integration)

Let $f:[a,b] \to \mathbb{R}$ be a bounded function. We call

$$P = \{a = x_0 < x_1 < \ldots < x_n = b\} \subseteq [a, b]$$

a partition of [a,b], and

$$\Delta x_i = x_i - x_{i-1}$$

as the length of the i^{th} interval for i = 1, ..., n.

Let

$$M_i = \sup\{f(x) : x \in [x_{i-1}, x_i]\}$$

be the supremum of f on the ith interval, and

$$m_i = \inf\{f(x) : x \in [x_{i-1}, x_i]\}$$

be the infimum of f on the ith interval. We define the Riemann upper sum as

$$U(f,P) = \sum_{i} M_i \Delta x_i,$$

and the Riemann lower sum as

$$L(f,P) = \sum_{i} m_i \Delta x_i.$$

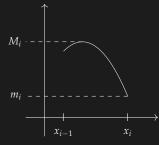


Figure 1.1: Idea of Riemann integration

We define the Riemann upper integral as

$$\int_{a}^{b} f \, dx = \inf_{P} U(f, P)$$

and the Riemann lower integral as

$$\int_{a}^{b} f \, dx = \sup L(f, P).$$

We say that f is Riemann integrable if

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

and we write the integral of f as

$$\int_a^b f \, dx = \overline{\int_a^b} f \, dx = \int_a^b f \, dx.$$

As hyped up as one does earlier in university about Riemann integration, there are functions that are not Riemann integrable!

Example 1.1.1

Consider a function $f : [0,1] \to \mathbb{R}$ given by

$$f(x) = \begin{cases} 1 & x \in \mathbf{Q} \\ 0 & x \notin \mathbf{Q} \end{cases}.$$

Then

$$\overline{\int_a^b} f dx = 1$$
 and $\int_a^b f dx = 0$.

Thus f is not Riemann integrable.

66 Note 1.1.1 (Shortcomings of the Riemann integral)

1. We cannot characterize functions that are Riemann integrable, i.e. we do not have a list of characteristics that we can check against to see if a function is Riemann integrable.

This remained an open problem in the earlier 1920s.

- 2. The Riemann integral behaves badly when it comes to pointwise limits of functions. The next example shall illustrate this.
- 3. The Riemann integral is awkward when f is unbounded. In particular, we used to hack our way around by looking at whether the Riemann integral converges to some value the function approaches the unbounded point, and then "conclude" that the integral is the limit of that convergence.
- 4. Recall that the Fundamental Theorem of Calculus states that

$$\frac{d}{dx}\int_{a}^{x}f(t)\,dt=f(x).$$

We know that this works for Riemann integrals. By the first shortcoming, the problem here is that we do not fully know what are the functions that the Fundamental Theorem is true for.

- 5. In PMATH450, we saw that Fourier developed the Fourier series, which is an extremely useful tool in solving Differential Equations using sines and cosines. However, the convergence of the Fourier series remains largely unexplained by Fourier, and we have but developed some roundabout ways of showing some convergence.
- 6. Consider the set R if Riemann integrable functions on the interval [a, b]. The set R has a natural metric:

$$d(f,g) = \int_a^b |f - g| \, dx.$$

However, the metric space (R, d) is not complete. This means many of our favorite results in PMATH351 are not usable!

7. There are many functions that seem like they should have an integral, but turned out that they did not under Riemann integration.

Example 1.1.2 (Pointwise Limits of Riemann Integrable Functions is not necessarily Riemann Integrable)

Let $\mathbb{Q} = \{x_n\}_{n \in \mathbb{N}}$. Then consider a sequence of functions

$$f_n(x) = \begin{cases} 1 & x \in \{x_1, \dots, x_n\} \\ 0 & x \notin \{x_1, \dots, x_n\} \end{cases}.$$

It is rather clear that

$$\int_{a}^{b} f \, dx = \int_{a}^{b} f \, dx = 0.$$

However, the pointwise limit of the f_n 's, and that is

$$\lim_{n\to\infty} f_n(x) = f(x) = \begin{cases} 1 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q} \end{cases}$$

is, as mentioned in the last example, not Riemann integrable.

To address the shortcomings of the Riemann integral, Henri Lebesgue developed the **Lebesgue integral**, of which we have seen in PMATH₄₅₀.

Instead of dividing the *x*-axis, Lebesgue decided to divide the *y*-axis first.

If the range of a function f is [c,d], where c,d can be infinite, then we partition the interval such that

$$P = \{c = y_0 < y_1 < \ldots < y_n = d\},$$

and we define

$$E_i = \{x : f(x) \in [y_{i-1}, y_i]\}.$$

Then if A_i is the area of the "rectangle" for the ith interval of [c,d], we have

$$y_{i-1} \cdot \ell(E_i) \leq A_i \leq y_i \cdot \ell(E_i),$$

where $\ell(E_i)$ is the **Lebesgue measure** of the set E_i . Then if we let $\int_a^b f$ denote the Lebesgue integral of f, we would expect

$$\sum_{i=1}^{n} y_{i-1} \cdot \ell(E_i) \le \int_a^b f \le \sum_{i=1}^{n} y_i \cdot \ell(E_i).$$

However, to truly understand what this means, we need to under-

stand what the Lebesgue measure is.

Furthermore, recall that in PMATH450, we saw that not all sets, in R for example, are measurable, and for 'good' reasons, there always exists non-measurable sets.

1.2 Algebras and σ -Algebra of Sets

■ Definition 1 (Algebra of Sets)

Given X, a non-empty collection of subsets of X, i.e. $\emptyset \neq A \subseteq \mathcal{P}(X)$, is called an algebra of sets of X provided that:

1.
$$A_1, \ldots, A_n \in \mathcal{A} \implies \bigcup_{i=1}^n A_i \in \mathcal{A}$$
; and

2.
$$A \in \mathcal{A} => A^{C} \in \mathcal{A}$$
.

♦ Proposition 1 (Properties of Algebra of Sets)

If A is an algebra of sets of X, then

3. \emptyset , $X \in \mathcal{A}$;

4.
$$A, B \in \mathcal{A} \implies A \setminus B = \{x \in X \mid x \in A \land x \notin B\} \in \mathcal{A} ; and$$

5.
$$A_1, \ldots, A_n \in \mathcal{A} \implies \bigcap_{i=1}^n A_i \in \mathcal{A}$$
.

Proof

3.
$$A \neq \emptyset \implies \exists A \in A \implies A^{C} \in A \implies A \cup A^{C} = X \in A \implies \emptyset = X^{C} \in A$$
.

4.
$$A, B \in \mathcal{A} \implies A^C \in \mathcal{A} \implies A^C \cup B \in \mathcal{A} \implies A \setminus B = (A^C \cup B)^C \in \mathcal{A}$$
.

5. (De Morgan's Law) Notice that $(A_1 \cap A_2 \cap ... \cap A_n)^C = A_1^C \cup$ $A_2^C \cup \dots A_n^C \in \mathcal{A}$ since $A_i^C \in \mathcal{A}$. Thus the complement

$$A_1 \cap A_2 \cap \ldots \cap A_n \in \mathcal{A}$$
.

For this course, we shall use the convention that

- the 'ambient' space *X* is always non-empty;
- $\mathcal{P}(X)$, the power set of X, has nontrivial elements; and
- we denote $A^C = \{x \in X : x \notin A\}$ for $A \subseteq X$.

\blacksquare Definition 2 (σ -Algebra of Sets)

Given X and $\emptyset \neq A \subseteq \mathcal{P}(X)$, we say that A is a σ -algebra of sets of X if it is an algebra of sets and

$$\forall A_n \in \mathcal{A}, n \in \mathbb{N}, \quad \bigcup_{n \in \mathbb{N}} A_n \in \mathcal{A}.$$

Example 1.2.1

- 1. $\mathcal{P}(X)$ is a σ -algebra.
- 2. Consider X as an infinite set. We say that a set A is **cofinite** if A^C is finite. Let

$$A := \{ A \in \mathcal{P}(X) \mid A \text{ is finite or cofinite } \}.$$

Then A is an algebra of sets:

- finite union of finite sets remains finite;
- finite union of finite and cofinite sets remains cofinite; and
- complement of finite sets are the cofinite sets and vice versa.

However, A is **not** a σ -algebra: consider $A_n = \{2^n\} \subseteq X = \mathbb{N}$, which we then realize that

$$\bigcup_{n\in\mathbb{N}}A_n= ext{ set of all even numbers },$$

but the set of all even numbers is clearly not finite, and its complement, which is the set of all odd numbers, is not finite.

3. Consider X as an uncountable set. We say that a set A is co-countable if A^C is countable. ¹ The set

$$A := \{ A \subseteq X \mid A \text{ is countable or co-countable } \}$$

is a σ -algebra:

• countable union of countable sets is countable;

¹ Recall that a set *A* is said to be countable if there is a one-to-one correspondence between elements of *A* and the natural numbers.

- countable union of countable and co-countable sets is cocountable; and
- complement of countable sets are co-countable and vice versa.



E Lecture 2 Sep 06th 2019

2.1 Algebra and σ -algebra of Sets (Continued)

We've seen some examples of σ -algebras. Let's now look at some other important properties of σ -algebras.

\phi Proposition 2 (Closure of σ -algebras under Countable Intersection)

Let X be a set, A a σ -algebra on X. If $A_n \in A$ for each $n \in \mathbb{N}$, then $\bigcap_n A_n \in A$.

This follows rather similarly to • Proposition 1 where we used De Morgan's Law.

Proof

We observe that

$$A_n \in \mathcal{A} \implies A_n^C \in \mathcal{A}$$

$$\implies \bigcup_n A_n^C \in \mathcal{A}$$

$$\implies \bigcap_n A_n = \left(\bigcup_n A_n^C\right)^C \in \mathcal{A}.$$

Let $A_{\alpha} \subseteq \mathcal{P}(X)$, where α is from some index set. We denote

$$\bigcap_{\alpha} \mathcal{A}_{\alpha} = \{ A \subseteq X : A \in \mathcal{A}_{\alpha}, \ \forall \alpha \}.$$

lack Proposition 3 (Existence of the 'Smallest' σ -algebra on a Set)

Let X be a set and $\{A_{\alpha}\}_{\alpha}$ as a collection of σ -algebras on X. Then $\bigcap_{\alpha} A_{\alpha}$ is a σ -algebra.

Proof

$$A \in \bigcap_{\alpha} \mathcal{A}_{\alpha} \implies \forall \alpha, A \in \mathcal{A}_{\alpha}$$

$$\implies \forall \alpha, A^{C} \in \mathcal{A}_{\alpha}$$

$$\implies A^{C} \in \bigcap_{\alpha} \mathcal{A}_{\alpha}$$

and

$$\forall n \in \mathbb{N}, A_n \in \bigcap_{\alpha} \mathcal{A}_{\alpha} \implies \forall n \in \mathbb{N}, \forall \alpha, A_n \in \mathcal{A}_{\alpha}$$

$$\implies \forall \alpha, \bigcup_n A_n \in \mathcal{A}_{\alpha}$$

$$\implies \bigcup_n A_n \in \bigcap_{\alpha} \mathcal{A}_{\alpha}.$$

Due to the above proposition, the following definition is well-defined.

\blacksquare Definition 3 (Generator of a σ -algebra)

Let X be a set, and $\xi \subseteq \mathcal{P}(X)$ has some non-trivial set(s). Consider all σ -algebras \mathcal{A}_{α} with the property that $\xi \subseteq \mathcal{A}_{\alpha}$. Then we say that $\bigcap_{\alpha} \mathcal{A}_{\alpha}$ is

the σ -algebra generated by ξ , and we denote this generated σ -algebra as

$$\mathfrak{M}(\xi) = \bigcap_{\alpha} \mathcal{A}_{\alpha}.$$

Remark 2.1.1

- 1. It is clear from the definition that if A is a σ -algebra on X and $\xi \subseteq A$, then $\mathfrak{M}(\xi) \subseteq \mathcal{A}$.
- 2. We often say that $\mathfrak{M}(\xi)$ is the "smallest σ -algebra containing ξ ".

The following is an example of such a σ -algebra.

\blacksquare Definition 4 (Borel σ -algebra)

Let X be a metric space (or topological space). The σ -algebra generated by the open subsets of X is called the Borel σ -algebra, of which we denote by $\mathfrak{B}(X)$.

Remark 2.1.2 (Some sets in $\mathfrak{B}(X)$)

Given an arbitrary metric space (or topological space) X. It is often hard to firmly grasp what kind of sets are in the Borel σ -algebra $\mathfrak{B}(X)$. The following are some examples that are in $\mathfrak{B}(X)$.

- 1. Let $\{\mathcal{O}_n\}_{n\in\mathbb{N}}$ denote a countable collection of open sets. By \bullet Proposition 2, $\bigcap_n \mathcal{O}_n \in \mathfrak{B}(X)$. We call these countable union of open sets as G_δ sets.
- 2. Let $\{\mathcal{F}_n\}_{n\in\mathbb{N}}$ denote a countable collection of closed sets. By \bullet Proposition 2, $\bigcup_n \mathcal{F}_n \in \mathfrak{B}(X)$. We call these countable intersection of closed sets as F_{σ} sets.
- 3. Let $\{H_n\}$ be a countable collection of G_δ sets. Then $\bigcup_n H_n \in \mathfrak{B}(X)$. *These are called the* $G_{\delta\sigma}$ *sets.*
- 4. Let $\{K_n\}$ be a countable collection of F_{σ} sets. Then $\bigcap_n K_n \in \mathfrak{B}(X)$. *These are called the* $F_{\sigma\delta}$ *sets.*

We can continue constructing the $G_{\delta\sigma...}$ and $F_{\sigma\delta...}$ similarly, and all these sets belong to the Borel σ -algebra $\mathfrak{B}(X)$.

lack Proposition 4 (Other Formulations of the Borel σ -algebra (aka Proposition 1.2))

The following collection of sets are all equal:

- 1. $\mathfrak{B}_1 = \mathfrak{B}(\mathbb{R})$;
- 2. $\mathfrak{B}_2 = \sigma$ -algebra generated by open intervals (e.g. (a,b));
- 3. $\mathfrak{B}_3 = \sigma$ -algebra generated by closed intervals (e.g. [a,b]);
- 4. $\mathfrak{B}_4 = \sigma$ -algebra generated by half-open intervals (e.g. (a,b]);
- 5. $\mathfrak{B}_5 = \sigma$ -algebra generated by $(-\infty, a)$ and (b, ∞) ; and
- 6. $\mathfrak{B}_6 = \sigma$ -algebra generated by $(-\infty, a]$ and $[b, \infty)$.

As commented before, it is often hard knowing that is in a Borel σ -algebra, and what is not, despite knowing what its generator is. However, when talking about containments, this is a fairly straightforward discussion thanks to its closure under countable unions and \bullet Proposition 2. We simply need to talk about the generators.

Proof

 $\mathfrak{B}_2 \subseteq \mathfrak{B}_1$ Given an arbitrary generator (a,b) in \mathfrak{B}_2 , we know that (a,b) is an open set, and clearly $(a,b) \subseteq \mathbb{R}$. Thus $(a,b) \in \mathfrak{B}_1$, so $\mathfrak{B}_2 \subseteq \mathfrak{B}_1$.

 $\mathfrak{B}_3 \subseteq \mathfrak{B}_2$ Given an arbitrary generator [a,b] of \mathfrak{B}_2 , we have

$$[a,b] = \bigcap_{n} \left(a - \frac{1}{n}, b + \frac{1}{n}\right) \in \mathfrak{B}_2.$$

Thus $\mathfrak{B}_3 \subseteq \mathfrak{B}_2$.

 $\mathfrak{B}_4 \subseteq \mathfrak{B}_3$ Given an arbitrary generator (a, b] of \mathfrak{B}_4 ,

$$(a,b] = \bigcup_{n} \left[a + \frac{1}{n}, b \right] \in \mathfrak{B}_3.$$

Thus $\mathfrak{B}_4 \subseteq \mathfrak{B}_3$.

 $\mathfrak{B}_5 \subseteq \mathfrak{B}_4$ Given an arbitrary generator $(-\infty, a)$ for \mathfrak{B}_5 ,

$$(-\infty,a)=\bigcup_{n}\left(-\infty,a-\frac{1}{n}\right)\in\mathfrak{B}_{4}.$$

On the other hand, for (b, ∞) in \mathfrak{B}_5 ,

$$(b,\infty)=\bigcup_n(b,n)\in\mathfrak{B}_4.$$

 $\mathfrak{B}_6 \subseteq \mathfrak{B}_5$ We have that

$$(-\infty,a]=\bigcap_{n}\left(-\infty,a+\frac{1}{n}\right)\in\mathfrak{B}_{5}$$

and

$$[b,\infty)=\bigcap_n\left(b-\frac{1}{n},\infty\right)\in\mathfrak{B}_5.$$

 $\mathfrak{B}_1 \subseteq \mathfrak{B}_6$ Let $c < d \in \mathbb{R}$. Notice that

$$(-\infty,d]\cap[c,\infty)=[c,d]\in\mathfrak{B}_6.$$

Furthermore,

$$(c,d) = \bigcup_{n} \left[c + \frac{1}{n}, d - \frac{1}{n} \right] \in \mathfrak{B}_6.$$

Recall that given an open set $\mathcal{O} \subseteq \mathbb{R}$, we have

$$\mathcal{O}=\bigcup\{(c,d)\subseteq\mathcal{O}:c,d\in\mathbb{Q}\},$$

which shows that \mathcal{O} is a countable union of open sets (with rational endpoints). It follows that $\mathcal{O} \in \mathfrak{B}_6$ and so $\mathfrak{B}_1 \subseteq \mathfrak{B}_6$.

Exercise 2.1.1

Show that $\mathfrak{B}(\mathbb{R}^2)$ is generated by open rectangles $(a,b) \times (c,d)$.

■ Definition 5 (Infinitely Often)

Given $E_n \subseteq X$ for $n \in \mathbb{N}$, we say that $x \in E_n$ infinitely often (i.o.) if

$${n:x\in E_n}$$

is an infinite set. We typically let

$$A := \{x \in X : x \in E_n \text{ i.o. } \}$$

be the set of x's that are in the E_n 's infinitely often.

■ Definition 6 (Almost always)

Given $E_n \subseteq X$ for $n \in \mathbb{N}$, we say that $x \in E_n$ almost always (a.a.) if

$${n:x \notin E_n}$$

is a finite set. We typically let

$$B := \{x \in X : x \in E_n \ a.a. \}$$

be the set of x's that are in the E_n 's almost always.

♦ Homework (Homework 1)

Let X be a set, A a σ -algebra on X, and $E_n \in A$ for $n \in \mathbb{N}$. Prove that

$$A := \{x \in X : x \in E_n \text{ i.o. } \}$$

and

$$B := \{x \in X : x \in E_n \ a.a. \}$$

are both in A.

■ Definition 7 (Characteristic Function)

Let $E \subseteq X$ *. We call the function*

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

the characteristic function of E.

🗫 Homework (Homework 2 – A review on limsup and liminf)

Let $E_n \subseteq X$ for $n \in \mathbb{N}$, and

$$A := \{x \in X : x \in E_n \text{ i.o. }\}$$
$$B := \{x \in X : x \in E_n \text{ a.a. }\}.$$

Show that

$$\chi_A(x) = \limsup_n \chi_{E_n}(x)$$
 $\chi_B(x) = \liminf_n \chi_{E_n}(x).$

Remark 2.1.3

Due to the above result, some people write

$$A = \limsup E_n$$
$$B = \liminf E_n.$$

2.2 Measures

E Definition 8 (Measure)

Let X be a set and A a σ -algebra of subsets of X. A function $\mu: \mathcal{A} \to$ $[0,\infty]$ is called a measure on A provided that:

- 1. $\mu(\emptyset) = 0$; and
- 2. if $E_n \in A$ for each $n \in \mathbb{N}$, and $\{E_n\}$ is disjoint, we have

$$\mu\left(\bigcup_n E_n\right) = \sum_n \mu(E_n).$$





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