Measure Theory Problem Set

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Question 1.3

We check the conditions for a set to be algebra or a σ- algebra. Algebra and σ- algebra must include the $\emptyset$, contain their complements and should be closed under finite and countable unions respectively.

- If $A \in \mathcal{G}_1 \implies A$ is open in $\mathbb{R} \implies A^c$ is either closed on $\mathbb{R}$ or semi-closed on $\mathbb{R}$. So $A^c \notin \mathcal{G}_1$ as it is not an open interval. Hence $\mathcal{G}_1$ is not a σ- algebra or an algebra.

- If $A_n \in \mathcal{G}_2, n \in \mathbb{N}$. Then $\bigcup_{n=1}^{\infty} A_n \notin \mathcal{G}_2$ since $\mathcal{G}_2$ contains only sets which are finite unions of intervals of the form $(a,b], (-\infty,b], (a,\infty)$. Thus $\mathcal{G}_2$ is not a σ- algebra. Now we check whether $\mathcal{G}_2$ is an algebra. It is clear that $\phi \in \mathcal{G}_2$. Now consider any interval of the form $(a,b]$. Then it's complement is of the form $(-\infty,a] \cup (b,\infty)$ which $\in \mathcal{G}_2$. Similarly for any interval of the form $(-\infty,b]$, its complement is of the form (b,∞) which $\in \mathcal{G}_2$. Thus, for all $A \in \mathcal{G}_2$, $A^c \in \mathcal{G}_2$. Consider $A_n \in \mathcal{G}_2$ for $n \in \mathbb{N}$. Then $\bigcup_{n=1}^{N} A_n$ is also a finite union of disjoint intervals of the form $(-\infty,b], (a,b]$ and (a,∞). Hence $\mathcal{G}_2$ is an algebra (but not a σ-algebra).

- If $A_n \in \mathcal{G}_3, n \in \mathbb{N}$. The first two properties for a family of sets to be an algebra hold in this case as they have already been proved above. Consider $\bigcup_{n=1}^{\infty} A_n$ where $A_n \in \mathcal{G}_3$ for $n \in \mathbb{N}$. The countable union $\bigcup_{n=1}^{\infty} A_n \in \mathcal{G}_3$ as it contains countable unions of intervals of the form $(a,b], (-\infty,b]$ and (a,∞). Thus $\mathcal{G}_3$ is a σ- algebra.

Question 1.7

Let $\mathcal{A}$ be a σ-algebra. By definition of σ-algebra, $\emptyset \in \mathcal{A}$. Similarly, $X = \emptyset^c \in \mathcal{A}$ Thus $\{\emptyset, X\} \subset \mathcal{A}$. Consider any $A \in \mathcal{A}$. Since $\mathcal{A}$ is a σ-algebra on X, $A \subset X \Rightarrow A \in \mathcal{P}(X)$. Thus $\mathcal{A} \subset \mathcal{P}(X)$. Thus $\{\emptyset, X\} \subset A \subset \mathcal{P}(X)$

Question 1.10

Since $\{S_\alpha\}$ is a family of σ- algebras, then $\emptyset \in S_\alpha \forall \alpha \Rightarrow \emptyset \in \bigcap_\alpha S_\alpha$.

Consider any $A \in \bigcap_\alpha S_\alpha$. This means that $A \in S_\alpha$ for each α ,since each S_α is a σ - algebra $\Rightarrow A^c \in S_\alpha \forall \alpha \Rightarrow A^c \in \bigcap_\alpha S_\alpha$.

Now consider $\{A_n\} \in \bigcap_\alpha (S_\alpha) \forall n \in \mathbb{N}$. Then $A_n \in S_\alpha \forall \alpha, n \in \mathbb{N}$ since each S_α is a σ-algebra, it means that $\bigcup_{n=1}^{\infty} A_n \in S_\alpha \forall \alpha$.

This in turn implies that $\bigcup_{n=1}^{\infty} A_n \in \bigcap_\alpha S_\alpha$. Hence $\bigcap_\alpha S_\alpha$ is a σ- algebra.

Question 1.17

First, we prove that if $\mu : \mathcal{S} \to [0, \infty]$ is a measure, then $\mu(\bigcup_{i=1}^{n=N} A_i) = \sum_{i=1}^{i=N} \mu(A_i)$ if $A_i \bigcap A_j = \phi, i \neq j$.

To prove this, let all A_i for $i > N = \phi$.Since $\mu(\phi) = 0$, we then get $\mu(\bigcup_{i=1}^{n=N} A_i) = \mu(\bigcup_{i=1}^{n=\infty} A_i) = \sum_{i=1}^{i=\infty} \mu(A_i) = \sum_{i=1}^{i=N} \mu(A_i)$.

To prove monotonicity, consider two sets $A, B \in \mathcal{S}, A \subset B$. Define $C = A^c \cap B$. Since $\mathcal{S}$ is a σ- algebra $A^c \cap B \in \mathcal{S}$. Furthermore, $A \cap C = \phi$. Since μ is a measure, $\mu(A \cup C) = \mu(A) + \mu(B) \Rightarrow \mu(B) = \mu(A) + \mu(C)$. Since the range of μ is non-negative, $\mu(C) \geq 0$. Thus $\mu(B) \geq \mu(A)$.

We now proceed to prove countable sub-additivity. Consider 2 sets A_1, A_2. We can write, $A_1 \cup A_2 = ({A_1}^c \cap A_2) \cup ({A_2}^c \cap A_1) \cup (A_1 \cap A_2)$ i.e as a union of disjoint sets. Using the result proved above, we get $\mu(A_1 \cup A_2) = \mu({A_1}^c \cap A_2) + \mu({A_2}^c \cap A_1) + \mu(A_1 \cap A_2) \leq \mu({A_1}^c \cap A_2) + \mu(A_1 \cap A_2) + \mu({A_2}^c \cap A_1) + \mu(A_1 \cap A_2) = \mu(A_1) + \mu(A_2)$. Thus we have $\mu(A_1 \cup A_2) \leq \mu(A_1) + \mu(A_2)$

The same argument can be carried out inductively for all $n \in \mathbb{N}$. For example in the case of three sets, A_1, A_2 and A_3, we can assume $A_1 \cup A_2 = A$ and proceed as before. Therefore $\mu(\bigcup_{i=1}^{i=\infty} A_i) \leq \sum_{i=1}^{i=\infty} \mu(A_i)$.

Question 1.18

$\lambda(\phi) = \mu(\emptyset \cap B) = \mu(\emptyset) = 0$. Let $\{A_i\}_{i=1}^{i=\infty}$ be a collection of disjoint sets. We have, $\lambda(\bigcup_{i=1}^{i=\infty} A_i) = \mu(B \cap \bigcup_{i=1}^{i=\infty} A_i) = \mu(\bigcup_{i=1}^{i=\infty} (B \cap A_i))$ where we have used De-Morgan's laws in the last step. Since all A_i's are disjoint, so are $(B \cap A_i)$'s. Now since μ is a measure, we have, $\mu(\bigcup_{i=1}^{i=\infty} (B \cap A_i)) = \sum_{i=1}^{i=\infty} \mu(B \cap A_i) = \sum_{i=1}^{i=\infty} \lambda(A_i)$. Thus $\lambda(\bigcup_{i=1}^{i=\infty} A_i) = \sum_{i=1}^{i=\infty} \lambda(A_i)$. Hence λ is a measure.

Question 1.20

Let $A_1 \supset A_2 \supset ... \supset A_n$. This is equivalent to saying $(A_1 - A_1 = \emptyset) \subset (A_1 - A_2) \subset (A_1 - A_3)... \subset (A_1 - A_n)$ From the previous result, we have $\lim_{n\to\infty} \mu(A_1 - A_n) = \mu(\bigcup_{n=1}^{n=\infty}(A_1 - A_n)) = \mu(A_1 - \bigcap_{n=1}^{n=\infty} A_n)$ where we have used De Morgan's Law in the last step. We have already proved previously, the property of finite additivity of a measure. Therefore we have $\mu(A_1) - \lim_{n\to\infty} \mu(A_n) = \mu(A_1) - \mu(\bigcap_{n=1}^{n=\infty} A_n)$. Since $\mu(A_1) < \infty$, we can cancel it out from both sides to get the result.

Question 2.10

To prove this result, note that countable subadditivity of an outer-measure $\Rightarrow$ finite subadditivity.

This can be seen by taking $A_i = \emptyset$ for $i > N$. Since $\mu^*(\emptyset) = 0$, we have $\mu^*(\bigcup_{i=1}^{i=N} A_i) \leq \sum_{i=1}^{i=N} \mu^*(A_i)$ which follows from the definition of the outer-measure.

We can write $B = (B \cap E) \cup (B \cap E^c)$. Therefore, using finite sub-additivity, we have $\mu^*(B) \leq \mu^*(B \cap E) + \mu^*(B \cap E^c)$. Since the inequality in the other direction is already given, we can replace the inequality with an equality.

Question 2.14

Let $\mathcal{A} = \{A : A$ is a countable union of intervals of the form $(a, b], (-\infty, b]$ and $(a, \infty)\}$. We first show that $\sigma(\mathcal{A}) \subset \sigma(\mathcal{O})$.

To see this, let $A \in \sigma(\mathcal{A})$. We can write $(a, b] = \bigcap_{n=1}^{n=\infty}(a, b - 1/n), (-\infty, b] = \bigcap_{n=1}^{n=\infty}(-\infty, b - 1/n)$. Thus A can be written as a countable union of intervals of the form $\bigcap_{n=1}^{n=\infty}(a, b - 1/n), \bigcap_{n=1}^{n=\infty}(-\infty, b - 1/n), (a, \infty)$.

By the property of a σ- algebras, each of these terms, being countable intersections of open intervals, belong to $\sigma(\mathcal{O})$. Thus the countable union of these terms also belongs to $\sigma(\mathcal{O})$. Thus $\sigma(\mathcal{A}) \subset \sigma(\mathcal{O})$.

Now we show that $\sigma(\mathcal{O}) \subset \sigma(\mathcal{A})$. To see this, let $A \in \sigma(\mathcal{O})$. Thus A is an open interval. Let $A = (a, b)$. We can write $A = (a, b) = \bigcup_{n=1}^{n=\infty}(a, b - 1/n]$. Similarly, any interval of the form $(-\infty, b)$ can be written as $\bigcup_{n=1}^{n=\infty}(-\infty, b-1/n]$ and any interval of the form (a, ∞) can be written as $\bigcup_{n=1}^{n=\infty}[a - 1/n, \infty)$.

Note that each of the terms is a countable union of sets that $\in \mathcal{A}$ which $\Rightarrow$ that they $\in \sigma(\mathcal{A})$. Thus any countable union of open sets also $\in \sigma(\mathcal{A})$. Thus $\sigma(\mathcal{O}) \subset \sigma(\mathcal{A})$.

We thus have $\sigma(\mathcal{A}) = \sigma(\mathcal{O})$. By Caratheodory's Theorem, $\mathcal{B}(\mathbb{R}) \subset \mathcal{M}$.

Question 3.1

Let $X \subset \mathbb{R}$ be a countable set. Let $x_1, x_2, x_3...$ be the elements of X. For every $\epsilon > 0$, define, $A_n = (x_n - \frac{\epsilon}{2^{n+2}}, x_n + \frac{\epsilon}{2^{n+2}}) \forall n \in \mathbb{N}$.

Let μ denote the Lebesgue Measure. Therefore $\mu(\bigcup_{n=1}^{n=\infty} A_n) = \sum_{n=1}^{n=\infty} \frac{\epsilon}{2^{n+1}}$. Summing the terms of the Geometric Progression on the RHS, we get $\mu(\bigcup_{n=1}^{n=\infty})A_n = \epsilon/2$. Since ϵ is arbitrary, we get $\mu(\bigcup_{n=1}^{n=\infty})A_n = 0$. Now each $x_n \in X$ also implies $x_n \in A_n$ as A_n has been defined in a manner that includes x_n.

Thus $X \subset \bigcup_{n=1}^{n=\infty} A_n$. By the monotonicity property, $\mu(X) \leq \mu(\bigcup_{n=1}^{n=\infty} A_n) = 0$. Thus $\mu(X) = 0$ since the range of μ is non-negative.

Question 3.4

We show that the following conditions are equivalent:

1. $\{x \in X : f(x) < a\} \in \mathcal{M}$
2. $\{x \in X : f(x) \geq a\} \in \mathcal{M}$
3. $\{x \in X : f(x) > a\} \in \mathcal{M}$
4. $\{x \in X : f(x) \leq a\} \in \mathcal{M}$

(1) $\implies$ (2):
Suppose $\{x \in X : f(x) < a\} \in \mathcal{M}$. We can write $f^{-1}([a, \infty)) = (f^{-1}(-\infty, a))^c$. $\mathcal{M}$ is closed under complements, therefore $f^{-1}([a, \infty)) \in \mathcal{M}$.

(2) $\implies$ (3):
Suppose $\{x \in X : f(x) \geq a\} \in \mathcal{M}$. We can write $f^{-1}((a, \infty)) = \cap_{n=1}^{\infty} f^{-1}([a - \frac{1}{n}, \infty))$. By assumption, each of the sets in this intersection is in $\mathcal{M}$. $\mathcal{M}$ is closed under countable intersections. Therefore, $f^{-1}(a, \infty) \in \mathcal{M}$.

(3) $\implies$ (4):
Suppose $\{x \in X : f(x) > a\} \in \mathcal{M}$. We can write $f^{-1}((-\infty, a]) = (f^{-1}(a, \infty))^c$. $\mathcal{M}$ is closed under complements, therefore $f^{-1}((-\infty, a]) \in \mathcal{M}$.

(4) $\implies$ (1):
Suppose $\{x \in X : f(x) \leq a\} \in \mathcal{M}$. We can write $f^{-1}((-\infty, a)) = \cap_{n=1}^{\infty} f^{-1}((-\infty, a + \frac{1}{n}))$. By assumption, each of the sets in this intersection is in $\mathcal{M}$. $\mathcal{M}$ is closed under countable intersections. Therefore, $f^{-1}((a, \infty)) \in \mathcal{M}$.

Question 3.7

Suppose f and g are measurable functions on $(X, \mathcal{M})$. Then the following are measurable:

1. $f + g$
2. $f \cdot g$
3. $\max(f, g)$
4. $\min(f, g)$
5. $|f|$

We can prove (3), (4), and (5) directly from the definition of measurable functions and use results from Question 3.4 to rewrite the condition for measurability in equivalent forms.

1. Consider $F(f(x)+g(x)) = f(x)+g(x)$. Then F is continuous and by part 4 of Theorem 3.6, measurable. Therefore, $f + g$ is measurable.

2. Consider $F(f(x) + g(x)) = f(x)g(x)$. Then F is continuous and by part 4 of Theorem 3.6, measurable. Therefore, $f \cdot g$ is measurable.

3. Because f and g are measurable functions on $(X, \mathcal{M})$, we have that for all $a \in \mathbb{R}$, $\{x \in X : f(x) < a\} \in \mathcal{M}$ and $\{x \in X : g(x) < a\} \in \mathcal{M}$. Therefore, it follows that $\{x \in X : \max(f(x), g(x)) < a\} = \{x \in X : f(x) < a\} \cap \{x \in X : g(x) < a\}$. $\mathcal{M}$ is closed under countable intersections, therefore, $\{x \in X : \max(f(x), g(x)) < a\} \in \mathcal{M}$, so that $\max(f(x), g(x))$ is measurable.

4. The proof that $\min(f, g)$ is measurable is analogous to the proof of (3). The key observation here is that $\{x \in X : \min(f(x), g(x)) > a\} = \{x \in X : f(x) > a\} \cap \{x \in X : g(x) > a\}$. $\mathcal{M}$ is closed under countable intersections, therefore, $\{x \in X : \min(f(x), g(x)) > a\} \in \mathcal{M}$, so that $\min(f(x), g(x))$ is measurable.

5. Observe that $\{x \in X : |f(x)| > a\} = \{x \in X : f(x) < -a\} \cup \{x \in X : f(x) > a\}$. Both of these sets are in $\mathcal{M}$. $\mathcal{M}$ is closed under countable unions, therefore, $\{x \in X : |f(x)| > a\} \in \mathcal{M}$, so that $|f(x)|$ is measurable.

Question 3.14

Let f be bounded, and fix $\epsilon > 0$. Then, there exists an $M \in \mathbb{R}$ such that $|f(x)| \leq M$ for all $x \in X$. Therefore, $x \in E_i^M$ for some i and all $x \in X$. Observe that there is an $N \in \mathbb{R}$ and $N \geq M$ such that $\frac{1}{2^N} < \epsilon$. Therefore, for all $x \in X$ and $n \geq N$, $||s_n(x) - f(x)|| < \epsilon$ .Hence, the convergence in part (1) of Theorem 3.13 is uniform.

Question 4.13

To show that $f \in \mathscr{L}^1(\mu, E)$, we must show that both $\int_E f^+ d\mu$ and $\int_E f^- d\mu$ are finite.

Recall that $||f|| = f^+ + f^-$. Also note that $0 \leq f^+$ and $0 \leq f^-$ by definition. Because $||f|| < M$ on E, then $0 \leq f^+ < M$ and $0 \leq f^- < M$ on E.

Then, by Proposition 4.5, because $\mu(E) < \infty$, we have that,

$$\int_E f^+ d\mu < M\mu(E) < \infty$$

and

$$\int_E f^- d\mu < M\mu(E) < \infty$$

Therefore, both $\int_E f^+ d\mu$ and $\int_E f^- d\mu$ are finite. Then by definition, $f \in \mathscr{L}^1(\mu, E)$.

Question 4.14

We prove the contrapositive of this statement. Suppose there exists a measurable set $\hat{E} \subset E$ such that f is infinite on $\hat{E}$. Here, we assume that f reaches positive infinity (without loss of generality, the proof for negative infinity or mixed between positive and negative infinity is analogous). It follows that,

$$\infty = \int_{\hat{E}} f d\mu \leq \int_E f d\mu \leq \int_E ||f|| d\mu \tag{1}$$

The first inequality is proved in 4.16, below. However, this implies that $f \notin \mathscr{L}^1(\mu, E)$.

Question 4.15

Let $f, g \in \mathscr{L}^1(\mu, E)$. Define the set of simple functions $B(f) = \{s : 0 \leq s \leq f, s \text{ simple, measurable}\}$. Let $f \leq g$. If follows that $f^+ \leq g^+$ and $f^- \geq g^-$. Then following a similar proof to Proposition 4.7, we have that $B(f^+) \subset B(g^+)$ and $B(g^-) \subset B(f^-)$.

These two relationships imply that $\int_E f^+ d\mu \leq \int_E g^+ d\mu$ and $\int_E f^- d\mu \geq \int_E g^- d\mu$. Then by the definition of the Lebesgue integral, we observe that,

$$\int_E f d\mu = \int_E f^+ d\mu - \int_E f^- d\mu \leq \int_E g^+ d\mu - \int_E g^- d\mu = \int_E g d\mu \tag{2}$$

Therefore, we have that,

$$\int_E f d\mu \leq \int_E g d\mu \tag{3}$$

Question 4.16

Following Definition 4.1, fix a simple function $s(x) = \sum_{i=1}^N c_i \chi_{E_i}$, where $E_i \in \mathcal{M}$. Let $A \subset E \in \mathcal{M}$. Then, by the monotoncity of measures, we have that $\mu(A \cap E_i) \leq \mu(E \cap E_i)$ for all i. Therefore, combining this result with Definition 4.1, we have that,

$$\int_A s d\mu = \sum_{i=1}^N c_i \mu(A \cap E_i) \leq \sum_{i=1}^N c_i \mu(E \cap E_i) = \int_E s d\mu \tag{4}$$

Now, by Definition 4.2, we have that,

$$\int_A f d\mu = \sup\{\int_A s d\mu : 0 \leq s \leq f, s \text{ simple, measurable}\}$$

and

$$\int_E f d\mu = \sup\{\int_E s d\mu : 0 \leq s \leq f, s \text{ simple, measurable}\}$$

Now because our choice of s was arbitrary, we have by Equation (4) that,

$$\int_A f d\mu \leq \int_E f d\mu \tag{5}$$

Because $f \in \mathscr{L}^1(\mu, E)$, by definition we have that $\int_E ||f|| d\mu < \infty$. Therefore, $\int_E f d\mu < \infty$. Finally, it follows that $\int_A f d\mu < \infty$, which in turn implies $\int_A f^+ d\mu < \infty$ and $\int_A f^- d\mu < \infty$, so that $f \in \mathscr{L}^1(\mu, A)$.

Question 4.21

Let $A, B \in \mathcal{M}$, $B \subset A$, $\mu(A - B) = 0$, and $f \in \mathscr{L}^1$. Then, by Proposition 4.6. we have that,

$$\int_{A-B} f d\mu = 0. \tag{6}$$

Recall that f^+ and f^- are non-negative $\mathcal{M}$-measurable functions because $f \in \mathscr{L}^1$. By Theorem 4.19, we have that $\mu_1(A) = \int_A f^+ d\mu$ and $\mu_2(A) = \int_A f^- d\mu$ are measures on $\mathcal{M}$. Therefore, by the definition of the Lesbesgue integral,

$$\int_A f d\mu = \int_A f^+ d\mu - \int_A f^- d\mu = \mu_1(A) - \mu_2(A) \tag{7}$$

Now, consider the disjoint union $A = (A - B) \cup B$. Because both $\mu_1(A)$ and $\mu_2(A)$ are measures, we have that $\mu_i(A) = \mu_i(A - B) + \mu_i(B)$ for $i = 1, 2$, because measures are additively separable on disjoint sets. Therefore, we have that $\mu_i(A) = \mu_i(B)$ for $i = 1, 2$ because $\mu(A - B) = 0$. Therefore,

$$\int_A f d\mu = \mu_1(B) - \mu_2(B) = \int_B f d\mu \tag{8}$$

This result clearly implies that

$$\int_A f d\mu \leq \int_B f d\mu \tag{9}$$