

MAT4400: Notes on Linear analysis

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3 σ -Algebras

Definition 3.1 (σ -Algebra). A family \mathcal{A} of subsets of X with:

- (i) $X \in \mathcal{A}$,
- (ii) $A \in \mathcal{A} \Rightarrow A^c \in \mathcal{A}$,
- (iii) $(A_n)_{n \in \mathbb{N}} \in \mathcal{A} \Rightarrow \bigcup_{n \in \mathbb{N}} A_n \in \mathcal{A}$

Theorem 3.2 (and Definition).

(i) The intersection of arbitrarily many σ -algebras in X is again a σ -algebra in X .

(ii) For every system of sets $p \subset \mathcal{P}(X)$ there exists a smallest σ -algebra containing p . This is the σ -algebra generated by p , denoted $\sigma(p)$, and p is called its generator.

Definition 3.3 (Borel). The σ -algebra $\sigma(\mathcal{O})$ generated by the open sets $\mathcal{O} = \mathcal{O}_{\mathbb{R}^n}$ of \mathbb{R}^n is called **Borel σ -algebra**, and its members are called **Borel sets** or **Borel measurable sets**.

5 Uniqueness of Measures

Lemma 5.1. *A Dynkin system D is a σ -algebra iff it is stable under finite intersections, i.e. $A, B \in D \Rightarrow A \cap B \in D$.*

Theorem 5.2 (Dynkin). *Assume X is a set, S is a collection of subsets of X closed under finite intersections, that is, if $A, B \in S \Rightarrow A \cap B \in S$. Then $D(S) = \sigma(S)$.*

Theorem 5.3 (uniqueness of measures). *Let (X, B) be a measurable space, and $S \subset P(X)$ be the generator of B , i.e. $B = \sigma(S)$. If S satisfies the following conditions:*

1. *S is stable under finite intersections (\cap -stable), i.e. $A, C \in S \Rightarrow A \cap C \in S$.*
2. *There exists an exhausting sequence $(G_n)_{n \in \mathbb{N}} \subset S$ with $G_n \uparrow X$. Assume also that there are two measures μ, ν satisfying:*
3. *$\mu(A) = \nu(A), \forall A \in S$.*
4. *$\mu(G_n) = \nu(G_n) < \infty$.*

Then $\mu = \nu$.

6 Existence of Measures

Theorem 6.1 (Carathéodory). *Let $S \subset P(X)$ be a semi-ring and $\mu : S \rightarrow [0, \infty)$ a pre-measure. Then μ has an extension to a measure μ^* on $\sigma(S)$, i.e. that $\mu(s) = \mu^*(s)$, $\forall s \in \sigma(S)$.*

Also, if S contains an exhausting sequence, $S_n \uparrow X$, s.t. $\mu(S_n) < \infty$, then the extension is unique.

7 Measurable Mappings

We consider maps $T : X \rightarrow X'$ between two measurable spaces (X, \mathcal{A}) and (X', \mathcal{A}') which respects the measurable structures, the σ -algebras on X and X' . These maps are useful as we can transport a measure μ , defined on (X, \mathcal{A}) , to (X', \mathcal{A}') .

Definition 7.1. Let (X, \mathcal{A}) , (X', \mathcal{A}') be measurable spaces. A map $T : X \rightarrow X'$ is called \mathcal{A}/\mathcal{A}' -measurable if the pre-image of every measurable set is a measurable set:

$$T^{-1}(A') \in \mathcal{A}, \quad \forall A' \in \mathcal{A}'. \quad (1)$$

- A $\mathcal{B}(\mathbb{R}^n)/\mathcal{B}(\mathbb{R}^m)$ measurable map is often called a Borel map.
- The notation $T : (X, \mathcal{A}) \rightarrow (X', \mathcal{A}')$ is often used to indicate measurability of the map T .

Lemma 7.2. Let (X, \mathcal{A}) , (X', \mathcal{A}') be measurable spaces and let $\mathcal{A}' = \sigma(\mathcal{G}')$. Then $T : X \rightarrow X'$ is \mathcal{A}/\mathcal{A}' -measurable iff $T^{-1}(G') \in \mathcal{A}$, i.e. if

$$T^{-1}(G') \in \mathcal{A}, \quad \forall G' \in \mathcal{G}'. \quad (2)$$

Theorem 7.3. Let (X_i, \mathcal{A}_i) , $i = 1, 2, 3$, be measurable spaces and $T : X_1 \rightarrow X_2$, $S : X_2 \rightarrow X_3$ be $\mathcal{A}_1/\mathcal{A}_2$ and $\mathcal{A}_2/\mathcal{A}_3$ -measurable maps respectively. Then $S \circ T : X_1 \rightarrow X_3$ is $\mathcal{A}_1/\mathcal{A}_3$ -measurable.

Corollary 7.4. Every continuous map between metric spaces is a Borel map.

Definition 7.5. (and lemma) Let $(T_i)_{i \in I}$, $T_i : X \rightarrow X_i$, be arbitrarily many mappings from the same space X into measurable spaces (X_i, \mathcal{A}_i) . The smallest σ -algebra on X that makes all T_i simultaneously measurable is

$$\sigma(T_i : i \in I) := \sigma \left(\bigcup_{i \in I} T_i^{-1}(\mathcal{A}_i) \right) \quad (3)$$

Corollary 7.6. A function $f : (X, \mathcal{B}) \rightarrow \mathbb{R}$ is measurable if $f((a, +\infty)) \in \mathcal{B}$, $\forall a \in \mathbb{R}$.

Corollary 7.7. Assume (X, \mathcal{B}) is a measurable space, (Y, d) is a metric space, $(f_n : (X, \mathcal{B}) \rightarrow Y)_{n=1}^{\infty}$ is a sequence of measurable maps. Assume this sequence of images $(f_n(x))_{n=1}^{\infty}$ is convergent in $Y \forall x \in X$. Define

$$f : X \rightarrow Y, \quad \text{by } f(x) = \lim_{n \rightarrow \infty} f_n(x). \quad (4)$$

Then f is measurable.

Theorem 7.8. Let (X, \mathcal{A}) , (X', \mathcal{A}') be measurable spaces and $T : X \rightarrow X'$ be an \mathcal{A}/\mathcal{A}' -measurable map. For every measurable μ on (X, \mathcal{A}) ,

$$\mu'(A') := \mu(T^{-1}(A')), \quad A' \in \mathcal{A}', \quad (5)$$

defines a measure on (X', \mathcal{A}') .

Definition 7.9. The measure $\mu'(\cdot)$ in the above theorem is called the push forward or image measure of μ under T and it is denoted as $T(\mu)(\cdot)$, $T_{*\mu}(\cdot)$ or $\mu \circ T^{-1}(\cdot)$.

Theorem 7.10. *If $T \in \mathbb{R}^{n \times n}$ is an orthogonal matrix, then $\lambda^n = T(\lambda^n)$.*

Theorem 7.11. *Let $S \in \mathbb{R}^{n \times n}$ be an invertible matrix. Then*

$$S(\lambda^n) = |\det S| \lambda^n = |\det S|^{-1} \lambda^n. \quad (6)$$

Corollary 7.12. *Lebesgue measure is invariant under motions: $\lambda^n = M(\lambda^n)$ for all motions M in \mathbb{R}^n . In particular, congruent sets have the same measure. Two sets of points are called congruent if, and only if, one can be transformed into the other by an isometry*

8 Measurable Functions

A *measurable function* is a measurable map $u : X \rightarrow \mathbb{R}$ from some measurable space (X, \mathcal{A}) to $(\mathbb{R}, \mathcal{B}(\mathbb{R}^1))$. They play central roles in the theory of integration.

We recall that $u : X \rightarrow \mathbb{R}$ is $\mathcal{A}/\mathcal{B}(\mathbb{R}^1)$ -measurable if

$$u^{-1}(B) \in \mathcal{A}, \quad \forall B \in \mathcal{B}(\mathbb{R}^1). \quad (7)$$

Moreover from a lemma from chapter 7, we actually only need to show that

$$u^{-1}(G) \in \mathcal{A}, \quad \forall G \in \mathcal{G} \text{ where } \mathcal{G} \text{ generates } \mathcal{B}(\mathbb{R}^1). \quad (8)$$

Proposition 8.1.

- 1 If $f, g : (X, \mathcal{B}) \rightarrow \mathbb{C}$ are measurable, then the function $f+g, f \cdot g, cf, (c \in \mathbb{C})$ are measurable.
- 2 If $b : \mathbb{C} \rightarrow \mathbb{C}$ is Borel and $b : (\mathbb{C}, \mathcal{B}) \rightarrow \mathbb{C}$ is measurable, then $b \circ f$ is measurable.
- 3 If $f(x) = \lim_{n \rightarrow \infty} f_n(x)$, $x \in X$ and f_n are measurable, then f is measurable.
- 4 If $X = \bigcup_{n=1}^{\infty} A_n$, $(A_n \in \mathcal{B})$, $f|_{A_n} : (A_n, \mathcal{B}_{A_n}) \rightarrow \mathbb{C}$ is measurable $\forall n$, then f is measurable.

Definition 8.2. Given a measurable space (X, \mathcal{B}) , a measurable function $f : (X, \mathcal{B}) \rightarrow \mathbb{C}$ is called simple if

$$f(x) = \sum_{k=1}^N c_k \mathbb{1}_{A_k}(x), \quad (9)$$

for some $c_k \in \mathbb{C}$, $A_k \in \mathcal{B}$, where $\mathbb{1}$ is the characteristic function,

$$\mathbb{1}_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A. \end{cases} \quad (10)$$

The representation of simple function is **not** unique. We denote the standard representation of f by

$$f(x) = \sum_{n=0}^N z_n \mathbb{1}_{B_n}(x), \quad N \in \mathbb{N}, \quad z_n \in \mathbb{R}, \quad B_n \in \mathcal{A}, \quad X = \bigcup_{n=1}^N B_n, \quad \text{for } B_n \cap B_m = \emptyset, \quad n \neq m. \quad (11)$$

The set of simple functions is denoted $\mathcal{E}(\mathcal{A})$ of \mathcal{E} .

Definition 8.3. Assume μ is a measure on (X, \mathcal{B}) . Given a *positive* simple function

$$f = \sum_{k=1}^N c_k \mathbb{1}_{A_k}, \quad (c_k \geq 0). \quad (12)$$

We define

$$\int_X f d\mu = \sum_{k=1}^n c_k \mu(A_k) \in [0, +\infty]. \quad (13)$$

We also denote this by $I_\mu(f)$.

Lemma 8.4. *This is well defined, that is, $\int_X f d\mu$ does not depend on the presentation of the simple function f .*

Properties 8.5. *For every positive simple function*

$$1 \quad \int_X c f d\mu = c \int_X f d\mu, \quad \text{for only } c \geq 0$$

$$2 \quad \int_X (f + g) d\mu = \int_X f d\mu + \int_X g d\mu.$$

Corollary 8.6. *If $f \geq g \geq 0$ are simple functions, then*

$$\int_X f d\mu \geq \int_X g d\mu. \quad (14)$$

Definition 8.7. If $f : X \rightarrow [0, +\infty)$ is measurable, then we define

$$\int_X f d\mu = \sup \left\{ \int_X g d\mu : f \geq g \geq 0, \text{ } g \text{ is simple} \right\} \quad (15)$$

Remark. *This means that any measurable function can be approximated by simple functions.*

Properties 8.8. *Measurable functions like this have the following properties*

$$1 \quad \int_X c f d\mu = c \int_X f d\mu, \quad \forall c \geq 0.$$

$$2 \quad \text{If } f \geq g \geq 0, \text{ then } \int_X f d\mu \geq \int_X g d\mu \text{ for any measurable } g, f.$$

$$3 \quad \text{If } f \geq 0 \text{ is simple, then } \int_X f d\mu \text{ is the same value as obtained before.}$$

To advance in measure theory we consider measurable functions

$$f : X \rightarrow [0, +\infty].$$

Measurability is understood w.r.t the σ -algebra $\mathcal{B}([0, +\infty])$ generated by $\mathcal{B}([0, +\infty))$ and $\{+\infty\}$. In other words, $A \subset [0, +\infty] \in \mathcal{B}([0, +\infty])$ iff $A \cap [0, +\infty) \in \mathcal{B}([0, +\infty))$.

Remark. Hence $f : X \rightarrow [0, +\infty]$ is measurable iff $f^{-1}(A)$ is measurable $\forall A \in \mathcal{B}([0, +\infty))$.

Definition 8.9. For measurable functions $f_X \rightarrow [0, +\infty]$, we define

$$\int_X f d\mu = \sup \left\{ \int_X g d\mu : f \geq g \geq 0 : g \text{ is simple} \right\} \in [0, +\infty]. \quad (16)$$

Theorem 8.10. Monotone convergence theorem Assume (X, \mathcal{B}, μ) is a measure space, $(f)_{n=1}^\infty$ is an increasing sequence of measurable positive functions $f_n : X \rightarrow [0, +\infty]$. Define $f(x) = \lim_{n \rightarrow \infty} f_n(x)$. Then f is measurable and

$$\int_X f d\mu = \lim_{n \rightarrow \infty} \int_X f_n d\mu. \quad (17)$$

Theorem 8.11. Assume (X, \mathcal{B}) is a measurable space and $f : X \rightarrow [0, +\infty]$ is measurable. Then there are simple functions g_n , s.t.

$$0 \leq g_1 \leq g_2 \leq \dots, \quad g_n(x) \rightarrow f(x), \quad \forall x \in X.$$

Moreover, if f is bounded, we can choose g_n s.t. the convergence is uniform, that is,

$$\lim_{n \rightarrow \infty} \sup_{x \in X} |g_n(x) - f(x)| = 0. \quad (18)$$

9 Integration of measurable functions

Through this chapter (X, \mathcal{A}, μ) will be some measure space. Recall that $\mathcal{M}^+(\mathcal{A})$ $[\mathcal{M}_{\mathbb{R}}^+(\mathcal{A})]$ are the \mathcal{A} -measurable positive functions and $\mathcal{E}(\mathcal{A})$ $[\mathcal{E}_{\mathbb{R}}^+(\mathcal{A})]$ are the positive and simple functions.

The fundamental idea of *Integration* is to measure the area between the graph of the function and the abscissa. For positive simple functions $f \in \mathcal{E}^+(\mathcal{A})$ in standard representation, this is done easily

$$\text{if } f = \sum_{i=0}^M y_i \mathbb{1}_{A_i} \in \mathcal{E}^+(\mathcal{A}) \quad \text{then} \quad \sum_{i=0}^M y_i \mu(A_i) \quad (19)$$

would be the μ -area enclosed by the graph and the abscissa. We note that the representation of f should not impact the integral of f .

Lemma 9.1. *Let $\sum_{i=0}^M y_i \mathbb{1}_{A_i} = \sum_{k=0}^N z_k \mathbb{1}_{B_k}$ be two standard representations of the same function $f \in \mathcal{E}^+(\mathcal{A})$. Then*

$$\sum_{i=0}^M y_i \mu(A_i) = \sum_{k=0}^N z_k \mu(B_k). \quad (20)$$

Definition 9.2. Let $f = \sum_{i=0}^M y_i \mathbb{1}_{A_i} \in \mathcal{E}^+(\mathcal{A})$ be a simple function in standard representation. Then the number

$$I_\mu(f) = \sum_{i=0}^M y_i \mu(A_i) \in [0, \infty] \quad (21)$$

(which is independent of the representation of f) is called the μ -integral of f .

Proposition 9.3. *Let $f, g \in \mathcal{E}^+(\mathcal{A})$. Then*

- (i) $I_\mu(\mathbb{1}_A) = \mu(A) \quad \forall A \in \mathcal{A}.$
- (ii) $I_\mu(\lambda f) = \lambda I_\mu(f) \quad \forall \lambda \geq 0.$
- (iii) $I_\mu(f + g) = I_\mu(f) + I_\mu(g).$
- (iv) $f \leq g \Rightarrow I_\mu(f) \leq I_\mu(g).$

In theorem 8.8 we saw that we could for every $u \in \mathcal{M}^+(\mathcal{A})$ write it as an increasing limit of simple functions. By corollary 8.10, the suprema of simple functions are again measurable, so that

$$u \in \mathcal{M}^+(\mathcal{A}) \Leftrightarrow u = \sup_{n \in \mathbb{N}} f_n, \quad f \in \mathcal{E}^+(\mathcal{A}), \quad f_n \leq f_{n+1} \leq \dots$$

We will use this to "inscribe" simple functions (which we know how to integrate) below the graph of a positive measurable function u and exhaust the μ -area below u .

Definition 9.4. Let (X, \mathcal{A}, μ) be a measure space. The (μ) -integral of a positive function $u \in \mathcal{M}_{\mathbb{R}}^+(\mathcal{A})$ is given by

$$\int u d\mu = \sup \{ I_\mu(g) : g \leq u, g \in \mathcal{E}^+(\mathcal{A}) \} \in [0, +\infty]. \quad (22)$$

If we need to emphasize the *integration variable*, we write $\int u(x) \mu(dx)$. The key observation is that the integral $\int \dots d\mu$ extends I_μ .

Lemma 9.5. For all $f \in \mathcal{E}^+(\mathcal{A})$ we have $\int f d\mu = I_\mu(f)$.

The next theorem is one of many convergence theorems. It shows that we could have defined 22 using any increasing sequence $f_n \uparrow u$ of simple functions $f_n \in \mathcal{E}^+(\mathcal{A})$.

Theorem 9.6. (*Beppo Levi*) Let (X, \mathcal{A}, μ) be a measure space. For an increasing sequence of functions $(u_n)_{n \in \mathbb{N}} \subset \mathcal{M}_{\mathbb{R}}^+(\mathcal{A})$, $0 \leq u_n \leq u_{n+1} \leq \dots$, we have for the supremum $u = \sup_{n \in \mathbb{N}} u_n \in \mathcal{M}_{\mathbb{R}}^+(\mathcal{A})$ and

$$\int \sup_{n \in \mathbb{N}} u_n d\mu = \sup_{n \in \mathbb{N}} \int u_n d\mu. \quad (23)$$

Note we can write $\lim_{n \rightarrow \infty}$ instead of $\sup_{n \in \mathbb{N}}$ as the supremum of an increasing sequence is its limit. Moreover, this theorem holds in $[0, +\infty]$, so the case $+\infty = +\infty$ is possible.

Corollary 9.7. Let $u \in \mathcal{M}_{\mathbb{R}}^+(\mathcal{A})$. Then

$$\int u d\mu = \lim_{n \rightarrow \infty} \int f_n d\mu$$

holds for every sequence $(f_n)_{n \in \mathbb{N}} \subset \mathcal{E}^+(\mathcal{A})$ with $\lim_{n \rightarrow \infty} f_n = u$.

Proposition 9.8. (of integral) Let $u, v \in \mathcal{M}_{\mathbb{R}}^+(\mathcal{A})$. Then

$$(i) \int \mathbf{1}_A d\mu = \mu(A) \quad \forall A \in \mathcal{A}.$$

$$(ii) \int \alpha u d\mu = \alpha \int u d\mu \quad \forall \alpha \geq 0.$$

$$(iii) \int u + v d\mu = \int u d\mu + \int v d\mu.$$

$$(iv) u \leq v \Rightarrow \int u d\mu \leq \int v d\mu.$$

Corollary 9.9. Let $(u_n)_{n \in \mathbb{N}} \subset \mathcal{M}_{\mathbb{R}}^+(\mathcal{A})$. Then $\sum_{n=1}^{\infty} u_n$ is measurable and we have

$$\int \sum_{n=1}^{\infty} u_n d\mu = \sum_{n=1}^{\infty} \int u_n d\mu$$

(including the possibility $+\infty = +\infty$.)

Theorem 9.10. (*Fatou*) Let $(u_n)_{n \in \mathbb{N}} \subset \mathcal{M}_{\mathbb{R}}^+(\mathcal{A})$ be a sequence of positive measurable functions. Then $u = \liminf_{n \rightarrow \infty} u_n$ is measurable and

$$\int \liminf_{n \rightarrow \infty} u_n d\mu = \liminf_{n \rightarrow \infty} \int u_n d\mu \quad (24)$$

10 Integrals of Measurable Functions

We have defined our integral for positive measurable functions, i.e. functions in $\mathcal{M}^+(\mathcal{A})$. To extend our integral to not only functions in $\mathcal{M}^+(\mathcal{A})$ we first notice that

$$u \in \mathcal{M}_{\mathbb{R}}(\mathcal{A}) \Leftrightarrow u = u^+ - u^-, \quad u^+, u^- \in \mathcal{M}_{\mathbb{R}}^+, \quad (25)$$

i.e. that every measurable function can be written as a sum of **positive** measurable functions.

Definition 10.1 (μ -integrable). A function $u : X \rightarrow \overline{\mathbb{R}}$ on (X, \mathcal{A}, μ) is μ -integrable, if it is $\mathcal{A}/\mathcal{B}(\mathbb{R})$ -measurable and if $\int u^+ d\mu, \int u^- d\mu < \infty$ (recall the definition for the integral of positive measurable functions). Then

$$\int u d\mu := \int u^+ d\mu - \int u^- d\mu \in (-\infty, \infty) \quad (26)$$

is the (μ -)integral of u . We write $\mathcal{L}^1(\mu)$ for the set of all real-valued μ -integrable functions¹.

Theorem 10.2. Let $u \in \mathcal{M}_{\mathbb{R}}(\mathcal{A})$, then the following conditions are equivalent:

- (i) $u \in \mathcal{L}_{\mathbb{R}}^1(\mu)$.
- (ii) $u^+, u^- \in \mathcal{L}_{\mathbb{R}}^1(\mu)$.
- (iii) $|u| \in \mathcal{L}_{\mathbb{R}}^1(\mu)$.
- (iv) $\exists w \in \mathcal{L}_{\mathbb{R}}^1(\mu)$ with $w \geq 0$ s.t. $|u| \leq w$.

Theorem 10.3 (Properties the μ -integral). The μ -integral has the following properties: **homogeneous, additive**, and:

- (i) $\min\{u, v\}, \max\{u, v\} \in \mathcal{L}_{\mathbb{R}}^1(\mu)$ (lattice property)
- (ii) $u \leq v \Rightarrow \int u d\mu \leq \int v d\mu$ (monotone)
- (iii) $\left| \int u d\mu \right| \leq \int |u| d\mu$ (triangle inequality)

Remark. If $u(x) \pm v(x)$ is defined in $\overline{\mathbb{R}}$ for all $x \in X$ then we can exclude $\infty - \infty$ and the theorem above just says that the integral is linear:

$$\int (au + bv) d\mu = a \int u d\mu + b \int v d\mu. \quad (27)$$

¹In words, we extend our integral to ~~positive~~ measurable functions by noticing that we can write every measurable function as a sum of positive measurable functions, something that we do know how to integrate. We don't want to run into the problem of $\infty - \infty$, thus we require the integral of the positive and negative parts to both (separately) be less than infinity.

This is always true for real-valued $u, v \in \mathcal{L}^1(\mu) = \mathcal{L}_{\mathbb{R}}^1(\mu)$, making $\mathcal{L}^1(\mu)$ a vector space with addition and scalar multiplication defined by

$$(u + v)(x) := u(x) + v(x), \quad (a \cdot u)(x) := a \cdot u(x), \quad (28)$$

and

$$\int \dots d\mu : \mathcal{L}^1(\mu) \rightarrow \mathbb{R}, \quad u \mapsto \int u d\mu, \quad (29)$$

*is a **positive linear functional**.*

11 Null sets and the "Almost Everywhere"

Definition 11.1. A (μ) -null set $N \in \mathcal{N}_\mu$ is a measurable set $N \in \mathcal{A}$ satisfying

$$N \in \mu \Leftrightarrow N \in \mathcal{A} \text{ and } \mu(N) = 0. \quad (30)$$

This can be used generally about a 'statement' or 'property', but we will be interested in questions like 'when is $u(x)$ equal to $v(x)$ ', and we answer this by saying

$$u = v \text{ a.e.} \Leftrightarrow \{x : u(x) \neq v(x)\} \text{ is (contained in) a } \mu\text{-null set.}, \quad (31)$$

i.e.

$$u = v \text{ } \mu\text{-a.e.} \Leftrightarrow \mu(\{x : u(x) \neq v(x)\}) = 0. \quad (32)$$

The last phrasing should of course include that the set $\{x : u(x) \neq v(x)\}$ is in \mathcal{A} , but this can be trivially seen.

Theorem 11.2. Let $u \in \mathcal{M}_{\mathbb{R}}(\mathcal{A})$, then:

$$(i) \quad \int |u| d\mu = 0 \Leftrightarrow |u| = 0 \text{ a.e.} \Leftrightarrow \mu\{u \neq 0\} = 0,$$

$$(ii) \quad \mathbb{1}_N u \in \mathcal{L}_{\mathbb{R}}^1(\mu) \quad \forall N \in \mathcal{N}_\mu,$$

$$(iii) \quad \int_N u d\mu = 0.$$

Corollary 11.3. Let $u = v \text{ } \mu\text{-a.e.}$ Then

$$(i) \quad u, v \geq 0 \Rightarrow \int u d\mu = \int v d\mu,$$

$$(ii) \quad u \in \mathcal{L}_{\mathbb{R}}^1(\mu) \Rightarrow v \in \mathcal{L}_{\mathbb{R}}^1(\mu) \text{ and } \int u d\mu = \int v d\mu.$$

Corollary 11.4. If $u \in \mathcal{M}_{\mathbb{R}}(\mathcal{A})$, $v \in \mathcal{L}_{\mathbb{R}}^1(\mu)$ and $v \geq 0$ then

$$|u| \leq v \text{ a.e.} \Rightarrow u \in \mathcal{L}_{\mathbb{R}}^1(\mu). \quad (33)$$

Proposition 11.5 (Markow inequality). For all $u \in \mathcal{L}_{\mathbb{R}}^1(\mu)$, $A \in \mathcal{A}$ and $c > 0$

$$\mu(\{|u| \geq c\} \cap A) \leq \frac{1}{c} \int_A |u| d\mu, \quad (34)$$

if $A = X$, then (obviously)

$$\mu\{|u| \geq c\} \leq \frac{1}{c} \int |u| d\mu. \quad (35)$$

Corollary 11.6. If $u \in \mathcal{L}_{\mathbb{R}}^1(\mu)$, then μ is a.e. \mathbb{R} -valued. In particular, we can find a version $\tilde{u} \in \mathcal{L}^1(\mu)$ s.t. $\tilde{u} = u$ a.e. and $\int \tilde{u} d\mu = \int u d\mu$

13 The Function Spaces \mathcal{L}^p

Assume V is a vector space over $\mathbb{K} \in \{\mathbb{C}, \mathbb{R}\}$.

Definition 13.1. A seminorm on V is a map $p : V \rightarrow [0, +\infty)$ s.t.

- (1) $p(cx) = |c|p(x) \quad \forall x \in V, \forall c \in \mathbb{K}$.
- (2) $p(x + y) \leq p(x) + p(y) \quad \forall x, y \in V$. **triangle inequality**.

A seminorm is called a norm if we also have

$$p(x) = 0 \iff x = 0.$$

A norm is commonly denoted $\|x\|$, and a vectorspace equipped with a norm is called a **normed space**.

Definition 13.2. Assume (X, d) is a measure space. Fix $1 \leq p \leq \infty$. For every measurable function $f : X \rightarrow \mathbb{C}$ we define the following

$$\|f\|_p = \left(\int_X |f|^p d\mu \right)^{1/p} \in [0, +\infty]. \quad (36)$$

We can see that $\|cf\|_p = |c|\|f\|_p \quad \forall c \in \mathbb{C}$.

Lemma 13.3.

$$\|f + g\|_p \leq \|f\|_p + \|g\|_p. \quad (37)$$

Definition 13.4. We define

$$\mathcal{L}^p(X, d\mu) = \{f : X \rightarrow \mathbb{C} \mid f \text{ is measurable and } \|f\|_p < \infty\}. \quad (38)$$

This is a vectorspace with seminorm $f \mapsto \|f\|_p$. And in general this is not a normed space, since $\|f\|_p = 0 \iff f = 0$ a.e.

Generally, if p is a seminorm on a vectorspace V , then

$$V_0 = \{x \in V \mid p(x) = 0\} \quad (39)$$

which is a subspace of V . Then we consider the quotient/factor space V/V_0 .

Definition 13.5. For $x, y \in V$, define

$$x \sim y \iff x - y \in V_0. \quad (40)$$

This is an equivalence relation on V . The representation class of V is defined by $[x]$ or $x + V_0$.

Then V/V_0 is equals the set of equivalence classes. We can show that it is a normed space.

$$[x] + [y] = [x + y] \quad , \quad c[x] = [cx] \quad , \quad ||[x]|| = p(x).$$

Applying this to $\mathcal{L}^p(X, d\mu)$ we get the normed space

$$L^p(X, d\mu) = \mathcal{L}^p(X, d\mu)/\mathcal{N}. \quad (41)$$

Where \mathcal{N} is the space of measurable functions f s.t. $f = 0$ a.e. We will further continue to denote the norm by $|| \cdot ||_p$, and we will normally **not** distinguish between $f \in \mathcal{L}^p(X, d\mu)$ and the vector in $L^p(X, d\mu)$ that f defines.

Definition 13.6. A normed space $(X, || \cdot ||)$ is called a Banach space if V is complete w.r.t the metric $d(x, y) = ||x - y||$.

Theorem 13.7. If (X, \mathcal{B}, μ) is a measure space, $1 \leq p \leq \infty$, then $L^p(X, d\mu)$ is a Banach space.

Definition 13.8. A measurable function $f : X \rightarrow \mathbb{C}$ is called **essentially bounded** if there is $c \geq 0$ s.t.

$$\mu(\{x : |f(x)| > c\}) = 0. \quad (42)$$

That is $|f| \leq c$ a.e. The smallest such c is called the essential supremum of f and is denoted by $||f||_\infty$.

Definition 13.9.

$$\mathcal{L}^\infty(X, d\mu) = \{f : X \rightarrow \mathbb{C} \mid f \text{ is measurable and } ||f||_\infty < \infty\}.$$

$$L^\infty(X, d\mu) = \mathcal{L}^\infty(X, d\mu)/\mathcal{N}.$$

Where by the previous definiton these spaces become the spaces of all essentially bounded functions.

Theorem 13.10. If (X, \mathcal{B}, μ) is a σ -finite measure space, then $L^\infty(X, d\mu)$ is a Banach space.

Appendix

H Regularity of measures

We let (X, d) be a metric space and denote by \mathcal{O} the open, by \mathcal{C} the closed and $\mathcal{B}(X) = \sigma(\mathcal{O})$ the Borel set of X .

Definition H.1. A measure μ on $(X, d, \mathcal{B}(X))$ is called outer regular, if

$$\mu(B) = \inf \{ \mu(U) \mid B \subset U, U \text{ open} \} \quad (43)$$

and inner regular, if $\mu(K) < \infty$ for all compact sets $K \subset X$ and

$$\mu(U) = \sup \{ \mu(K) \mid K \subset U, K \text{ compact} \}. \quad (44)$$

A measure which is both inner and outer regular is called **regular**. We write $\mathfrak{m}_r^+(X)$ for the family of regular measures on $(X, \mathcal{B}(X))$.

Remark. The space X is called σ -compact if there is a sequence of compact sets $K_n \uparrow X$. A typical example of such a space is a locally compact, separable metric space.

Theorem H.2. Let (X, d) be a metric space. Every finite measure μ on $(X, \mathcal{B}(X))$ is outer regular. If X is σ -compact, then μ is also inner regular, hence regular.

Theorem H.3. Let (X, d) be a metric space and μ be a measure on $(X, \mathcal{B}(X))$ such that $\mu(K) < \infty$ for all compact sets $K \subset X$.

- 1 If X is σ -compact, then μ is inner regular.
- 2 If there exists a sequence $G_n \in \mathcal{O}$, $G_n \uparrow X$ such that $\mu(G_n) < \infty$, then μ is outer regular.