Course Notes

Real Functions and Measures

Alex Rutar

BSM Fall 2018

Contents

Chapter 1

Basics of Abstract Measure Theory

Prof contact: simonp@caesar.elte.hu Grading: HW each week for 25% Midterm 30% Final 45%

1.1 Review of Topology

1.1.1 Basic Definitions

Def'n. 1.1.1 *Let $X \neq \emptyset$ and $\tau \subseteq \mathcal{P}(X)$. We say that (X, τ) is a **topological space** if τ satisfies the following conditions:*

1. $\emptyset \in \tau$ $X \in \tau$
2. $V_1, V_2 \in \tau \Rightarrow V_1 \cap V_2 \in \tau$
3. $V_\alpha \in \tau$ *for all* $\alpha \in I \Rightarrow \bigcap_{\alpha \in I} V_\alpha \in \tau$

*We call the elements of τ **open sets**.*

Def'n. 1.1.2 *$U \subseteq X$ is a **neighbourhood** of $x \in X$ if there is some $G \in \tau$ such that $x \in G \subset U$.*

Def'n. 1.1.3 *$F \subseteq X$ is **closed** if F^c is open.*

Def'n. 1.1.4 *The **closure** of a set $E \subset X$ is the smallest closed set containing E (denoted $\overline{E}$).*

Def'n. 1.1.5 *x is an **accumulation point** of H if all neighbourhoods of x contains infinitely points of H. Equivalently, x is a limit point of $H \setminus \{x\}$.*

Def'n. 1.1.6 *If $H \subseteq X$, we have a natural subspace topology $\tau|_H = \{G \cap H : G \in \tau\}$.*

1.1.2 Examples of Topological Spaces

Topological spaces are a very general construction, so here are some of the standard examples:

1. $\mathbb{R}$ along with the open sets (denoted τ_e, the Euclidean topology).
2. The discrete topology, $\tau = \mathcal{P}(X)$ for any $X \neq \emptyset$. This is the "finest" topology.

3. The antidiscrete topology, $\tau = \{\emptyset, X\}$ for any $X \neq \emptyset$ This is the "coarsest" topology.
4. One can define the extended real line, $X = \mathbb{R} \cup \{-\infty, +\infty\}$. Then

$$G \in \tau \Leftrightarrow \begin{cases} \forall x \in G \cap \mathbb{R} & \exists r > 0 \text{ s.t. } (x - r, x + r) \subset G \\ -\infty \in G & \exists b \in \mathbb{R} \text{ s.t. } (-\infty, b) \subset G \\ +\infty \in G & \exists a \in \mathbb{R} \text{ s.t. } (a, \infty) \subset G \end{cases}$$

The same can be done with a single symbol as well. In either case, the extended real line is a compact set.

5. Any metric spaces induces a topology. Consider a set $X \neq 0$ arbitrary, and let $d : X \times X \to \mathbb{R}$ such that
   (a) $0 \leq d(x, y)$ for all $x, y \in X$ and $d(x, y) = 0 \Leftrightarrow x = y$.
   (b) $d(x, y) = d(y, x)$ for all $x, y \in X$
   (c) $d(x, y) \leq d(x, z) + d(z, y)$ for any $x, y, z \in X$

   Then $G \in \tau$ if and only if for any $x \in G$, there exists r so that $B_r(x) \subset G$. There are many examples of metric spaces:
   (a) $X = \mathbb{R}$, $d(x, y) = |x - y|$
   (b) $X = \mathbb{R}$, $d(x, y) = |\tan^{-1}(x) - \tan^{-1}(y)|$
   (c) $X = \mathbb{R}^2$, $d(x, y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2}$
   (d) $X = \mathbb{R}^2$, $d(x, y) = (|x_1 - y_1|^p + |x_2 - y_2|^p)^{1/p}$ for $p \geq 1$.
   (e) and similarly for $X = \mathbb{R}^n$
   (f) $X = C[0, 1]$, $d(f, g) = \max_{x \in [0,1]} |f(x) - g(x)|$.
   (g) normed space: X is a vector space over $\mathbb{R}$, $\|\cdot\| : X \to \mathbb{R}$ such that
      i. $\|x\| = 0$ if and only if $X = 0$
      ii. $\|cx\| = |c| \|x\|$
      iii. $\left\|x + y\right\| \leq \|x\| + \left\|y\right\|$

      If $\|\cdot\|$ is a norm, then $d(x, y) = \left\|x - y\right\|$ is a metric.
6. The cofinite topology: $\tau = \{U \in \mathcal{P}(X) : U^c \text{ is finite}\}$.

1.1.3 Other Definitions

Def'n. 1.1.7 *$K \subset X$ is **compact** if every open cover of K contains a finite subcover.*

Def'n. 1.1.8 *A topological space is called **locally compact** if every point has a compact neighbourhood.*

Prop. 1.1.9 *$C[0, 1]$ with the sup norm is not locally compact.*

Proof I'll do this later. □

Def'n. 1.1.10 *A topological space is called* ***Hausdorff*** *if for any $x \neq y$, there exists neighbourhoods $U \ni x$, $V \ni y$ so that $U \cap V = \emptyset$.*

The anti-discrete topology is not Hausdorff.

1. On the discrete topology, K is compact if and only if K is finite.
2. On the anti-discrete topology, everything is compact (the only possible open cover consists of X).
3. On $(\mathbb{R}, \tau_e)$, K is compact if and only if K is closed and bounded.
4. On (X, d) metric space, K is compact if and only if K is complete and totally bounded.

Prop. 1.1.11
1. *Let $K \subset X$ be compact, let $F \subset K$ closed. Then F is also compact.*
2. *Compact sets in a Hausdorff space are closed.*

Proof
1. Let $F \subset \bigcup V_\alpha$. Then $K \subset F^c \cup (\bigcup V_\alpha)$ is an open cover for K, so it has a finite subcover $F^c \cup V_{\alpha_1} \cup \cdots V_{\alpha_n}$. But then since $F \cap F^c = \emptyset$, $F \subset V_{\alpha_1} \cup \cdots V_{\alpha_n}$ is a finite subcover.
2. Let $K \subset X$ be compact, and prove that K^c is open. Thus let $x \in K^c$. For any $y \in K$, there exist U_y, V_y disjoint neighbourhoods of x and y respectively. Now consider the open cover $K \subset \bigcup_{y \in K} V_y$, and get our finite subcover $K \subset V_{y_1} \cup \cdots \cup V_{y_n}$. But then $U_{y_1} \cap \cdots \cap U_{y_n} \cap K = \emptyset$ and is open since it is a finite intersection. □

Def'n. 1.1.12 *$\Gamma \subseteq \tau$ is a* ***base*** *for τ if every $U \in \tau$ can be written as a countable union of the elements of Γ. Γ is a* ***countable base*** *if Γ is countable.*

Prop. 1.1.13 *$\mathbb{R}$ has a countable base of intervals.*

Proof Consider the collection $\{B_r(q) : (r, q) \in \mathbb{Q} \times \mathbb{Q}\}$. To see this, for any open set U, one can write

$$S := \bigcup_{r \in U \cap \mathbb{Q}} \left(\bigcup_{\{r : B_r(q) \subseteq U\}} B_r(q) \right)$$

$U \supseteq S$ is obvious, so let $x \in U$ be arbitrary, and let s be maximal so that $B_s(x) \subseteq U$. Then choose $q \in \mathbb{Q}$ so that $|x - q| < s/3$ and $r \in \mathbb{Q}$ so that $0 < r < s/2$. Then by construction $B_r(q) \ni x$ and by the triangle inequality $B_{r/2}(q) \subseteq U$, so $x \in S$. Thus $U = S$ as desired. □

Note that the exact same argument (with some work) can be generalized to show that $\mathbb{R}^n$ has a countable base of open hyperrectangles.

Prop. 1.1.14 *Every metric space which is a countable union of compact sets has a countable base.*

Proof See my PMATH 351 notes. □

1.1.4 Functions and Continuity

Many of the standard notions of limits and continuity extend naturally to topological spaces.

Def'n. 1.1.15 *Let $(x_n) \subset X$ be a sequence and let $x \in X$. Then x is the* ***limit*** *of (x_n) if for any neighbourhood U of X, there exists $N \in \mathbb{N}$ such that $n > N \Rightarrow x_n \in U$.*

Prop. 1.1.16 *If $F \subset X$ is closed, then for all convergent sequences in F, the limit is also in F.*

Proof See Homework. □

Def'n. 1.1.17 *Let $f : X \to Y$ be a function, and $x \in X$ an accumulation point of $D(f)$. The limit of f at x is $y \in Y$ if for any neighbourhood V of y there exists a neighbourhood U of x such that $f(U \cap D(f) \setminus \{x\}) \subseteq V$.*

Def'n. 1.1.18 *Let $f : X \to Y$ be a function, and let $x \in D(f)$. Then f is **continuous at** x if for any neighbourhood V of $f(x)$, then $f^{-1}(V)$ is a neighbourhood of x.*

Def'n. 1.1.19 *$f : X \to Y$ is called **continuous** if it is continuous at every point.*

Prop. 1.1.20 *$f : X \to Y$ is continuous if and only if $f^{-1}(G)$ is open for all G open.*

Proof Exercise. □

Thm. 1.1.21 *Let $f : X \to Y$ be continuous and $K \subset X$ be compact. Then $f(K)$ is compact.*

Proof Recall that continuous functions pull back open sets. Let $f(K) \subset \bigcup U_\alpha$ be an open cover. Then $\bigcup f^{-1}(U_\alpha)$ is an open cover for K, and has a finite subcover $U_{\alpha_1} \cup \cdots U_{\alpha_n}$. But then $f(f^{-1}(U_{\alpha_1})) \cup \cdots \cup f(f^{-1}(U_{\alpha_n}))$ is a subcover of $f(K)$. □

1.2 Measure Theory

1.2.1 σ−algebras

Def'n. 1.2.1 *Let $X \neq \emptyset$ be a set. $\mathcal{M} \subset \mathcal{P}(X)$ is called a σ−**algebra** if*

1. *$X \in \mathcal{M}$*
2. *$A \in \mathcal{M} \Rightarrow A^c \in \mathcal{M}$*
3. *If $A_n \in \mathcal{M}$ for all $n \in \mathbb{N}$, then $\bigcup\limits_{n \in \mathbb{N}} A_n \in \mathcal{M}$*

*The pair $(X, \mathcal{M})$ is called a **measurable space**. The elements of $\mathcal{M}$ are called **measurable sets**.*

Def'n. 1.2.2 *Let $(X, \mathcal{M})$ be a measurable space, (Y, τ) be a topological space. Then $f : X \to Y$ is called **measurable** if $f^{-1}(V) \in \mathcal{M}$ for all $V \in \tau$.*

Here are some simple examples of σ−algebras.

Ex. 1.2.3

1. $\mathcal{M} = \{\emptyset, X\}$ is a σ−algebra.
2. $\mathcal{P}(X) = \mathcal{M}$ is a σ−algebra.
3. $\mathcal{M} = \{A \subset X : A \text{ or } A^c \text{ is countable.}\}$. To see this, given $A_n \in \mathcal{M}$, if everything is countable, then $\bigcup A_n$ is countable. If some A_i is countable, then $(\bigcup A_n)^c = \bigcap A_n^c$ is countable, so $\bigcup A_n \in \mathcal{M}$.

We will later see some proper exaples, like the σ−algebra of Lebesgue measurable sets.

We have the following properties of σ−algebras.

Prop. 1.2.4 *1. $\emptyset \in \mathcal{M}$*
2. *$A_1, A_2, \dots, A_n \in \mathcal{M} \Rightarrow A_1 \cup A_2 \cup \cdots \cup A_n \in \mathcal{M}$*
3. *$A_n \in \mathcal{M}$ for all $n \in \mathbb{N}$ then $\bigcap_{n=1}^{\infty} A_n \in \mathcal{M}$*
4. *$A, B \in \mathcal{M} \Rightarrow A \setminus B \in \mathcal{M}$*
5. *f is measurable, $H \subset Y$ is closed, then $f^{-1}(H) \in \mathcal{M}$.*

Proof 1. $X \in \mathcal{M} \Rightarrow X^c \in \mathcal{M}$.
2. We can extend this to a countable union by introduction $A_{n+i} = \emptyset$ for $i \in \mathbb{N}$.
3. By DeMorgan's identities, $(\bigcap A_n)^c = \bigcup A_n^c \in \mathcal{M}$.
4. $A \setminus B = A \cap B^c \in \mathcal{M}$.
5. H^c is open implies $f^{-1}(H^c) \in \mathcal{M}$. Then $f^{-1}(H) = (f^{-1}(H^c))^c \in \mathcal{M}$. □

Prop. 1.2.5 *Let $f : X \to Y$ be measurable, let $g : Y \to Z$ be continuous, then $g \circ f : X \to Z$ is measurable.*

Proof Let $V \subset Z$ be open, so $g^{-1}(V) \subset Y$ is open, so $f^{-1}(g^{-1}(V)) \in \mathcal{M}$ which is $(g \circ f)^{-1}(V)$.□

Prop. 1.2.6 *Let $(X, \mathcal{M})$ be a measurable space, Y be a topological space. Let $\phi : \mathbb{R}^2 \to Y$ be continuous. If $u, v : X \to \mathbb{R}$ are measurable, then $h(x) = \phi(u(x), v(x))$ is measurable.*

Proof Define $f : X \to \mathbb{R}^2$ by $f(x) = (u(x), v(x))$ We will see that f is measurable, so that $h = \phi \circ f$ is measurable since ϕ is continuous. Let $I_1, I_2 \subset \mathbb{R}$ be open intervals, so $R = I_1 \times I_2$ is an open rectangle. Then $f^{-1}(R) = u^{-1}(I_1) \cap v^{-1}(I_2) \in \mathcal{M}$. Let $G \subset \mathbb{R}^2$ be an open set, so there exist R_n open rectangles so that

$$G = \bigcup_{n=1}^{\infty} R_n \Rightarrow f^{-1}(G) = \bigcup_{n=1}^{\infty} f^{-1}(R_n) \in \mathcal{M}$$

so that f is measurable. □

Cor. 1.2.7 *1. If $u, v : X \to \mathbb{R}$ are measurable, then $u + v$ and $u \cdot v$ are measurable.*
2. *$u + iv : X \to \mathbb{C}$ is measurable.*
3. *$f : X \to \mathbb{C}$ is measurable, $f = u + iv \Rightarrow u, v, |f|$ are measurable.*

Prop. 1.2.8 *Define*

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

Then χ_E is measurable if and only if $E \in \mathcal{M}$.

Proof Naturally, $\chi_E^{-1}(1) = E$ and $\chi_E^{-1}(0) = E^c$, so χ_E is measurable if and only if $E, E^c \in \mathcal{M}$. □

Thm. 1.2.9 *Let $\mathcal{F} \subset \mathcal{P}(X)$, then there exists a smallest $\sigma-$algebra containing $\mathcal{F}$. This is denoted by $S(\mathcal{F})$, the $\sigma-$**algebra generated by** $\mathcal{F}$.*

Proof Let $\Omega = \{\mathcal{M} : \mathcal{M} \text{ is a } \sigma\text{-algebra}, \mathcal{F} \subset M\}$. Certainly $\Omega \neq \emptyset$ since $\mathcal{P}(X) \in \Omega$. Let $S(\mathcal{F}) = \bigcap_{\mathcal{M} \in \Omega} \mathcal{M}$. We will see that $S(\mathcal{F})$ is a $\sigma-$algebra.
(i) Since $X \in \mathcal{M}$, it follows that $X \in \cap \mathcal{M}$.

(ii) If $A \in S(\mathcal{F})$, then $A \in \mathcal{M}$ for all $\mathcal{M}$. Thus $A^c \in \mathcal{M}$ for all $\mathcal{M}$ and $A^c \in \cap \mathcal{M}$.

(iii) In the same way, of $A_n \in S(\mathcal{F}$ for all n, then $A_n \in \mathcal{M}$ for all $n, \mathcal{M}$. Thus $\bigcup A_n \in \mathcal{M}$ for all $\mathcal{M}$ so $\bigcup A_n \in \mathcal{M} \in \bigcap \mathcal{M} = S(\mathcal{F})$.

By definition, $\mathcal{F} \subset \bigcap \mathcal{M}$. Finally, $S(\mathcal{F})$ is minimal, since if $\mathcal{F} \subset \mathcal{N}$ is a σ−algebra, then $\mathcal{N} \in \Omega \Rightarrow S(\mathcal{F}) \subset \mathcal{N}$, so we are done. □

Def'n. 1.2.10 *Let (X, τ) be a topological space. Then $\mathcal{B} = S(\tau)$ is called the **Borel σ−algebra**. Borel sets are the elements of $S(\tau)$. A function $f : X \to Y$ is Borel measurable if $f^{-1}(G) \in \mathcal{B}$ for all $G \subset Y$ open.*

Prop. 1.2.11 *1. If $F \subset X$ is closed, then $F \in \mathcal{B}$.*
2. $G_n \subset X$ are open, then $\bigcap_{n=1}^{\infty} G_n \in B$. These are called G_δ−sets.
3. $F_n \subset X$ are closed, then $\bigcup_{n=1}^{\infty} F_n \in B$. These are called F_σ−sets.

Proof These follow directly from the definition of a σ−algebra. □

Ex. 1.2.12 $X = \mathbb{R}, \tau_e$, then $\mathcal{B} = S(\tau_e)$. Let $\Gamma_0 = \{(a,b) : a < b\}$ be a family of open intervals. We see that $S(\Gamma_0) = \mathcal{B}$. Since $\Gamma_0 \subset \tau$, $S(\Gamma_0) \subset S(\tau) = \mathcal{B}$. Conversely, let $G \in \tau$, then we have open intervals $G = \bigcup_{n=1}^{\infty} I_n$ so that $G \in S(\Gamma_0)$. Thus $S(\tau) \subset S(\Gamma_0)$ and $S(\Gamma_0) = \beta$.

Ex. 1.2.13 Let $\Gamma_\infty = \{(a,\infty) : a \in \mathbb{R}\}$. I claim that $S(\Gamma_\infty) = \mathcal{B}$. Certainly $S(\Gamma_\infty) \subset S(\tau) = \mathcal{B}$. Then $(-\infty, a] = (a_1, \infty)^c \in S(\Gamma_\infty)$.Similarly, $(-\infty, a) = \bigcup_{n=1}^{\infty}(-\infty, a - 1/n] \in S(\Gamma_\infty)$.Thus $(a,\infty) \cap (-\infty, b) = (a,b) \in S(\gamma_0)$, and using the previous example, $\mathcal{B} = S(\Gamma_\infty)$.

Prop. 1.2.14 *Let $(X, \mathcal{M})$ be a measurable space, and let $f : X \to \overline{\mathbb{R}} = \mathbb{R} \cup \{-\infty, \infty\}$ with the eucildean topology. If $f^{-1}((\alpha, \infty]) \in \mathcal{M}$ for any $\alpha \in \mathbb{R}$, then f is measurable.*

Proof Recall that f is measurable if its inverse image takes open sets to measurable sets.

We have $f^{-1}([-\infty, \alpha]) = (f^{-1}((\alpha, \infty])^c \in \mathcal{M}$. Similarly,

$$f^{-1}([-\infty, \alpha)) = f^{-1}\left(\bigcap_{n=1}^{\infty}[-\infty, \alpha - 1/n]\right) = \bigcup_{n=1}^{\infty} f^{-1}([-\infty, \alpha - 1/n]) \in \mathcal{M}$$

We then have

$$f^{-1}((\alpha, \beta) = f^{-1}([-\infty, \beta) \cap (\alpha, \infty]) = f^{-1}([-\infty, \beta)) \cap f^{-1}((\alpha, \infty]) \in \mathcal{M}$$

Recall that the open intervals are a base for τ_e. Thus if $G \subset \overline{\mathbb{R}}$ is open, then there exists open intervals so that $G = \bigcup_{n=1}^{\infty} I_n$ and

$$f^{-1}(G) = f^{-1}\left(\bigcup_{n=1}^{\infty} I_n\right) = \bigcup_{n=1}^{\infty} f^{-1}(I_n) \in \mathcal{M}$$

as desired. □

1.2.2 Sequences of Measurable Functions

Our goal is to prove that the pointwise limit of measurable functions is measurable. This does not hold for Riemann integrability! For example, a function with a finite number of discontinuities is Riemann integrable, but the dirichlet function is not Riemann integrable and is discontinuous only at a countable number of points.

Def'n. 1.2.15 *Let $(a_n)_{n\in\mathbb{N}} \subset \overline{R}$ be a sequence, and $b_k = \sup\{a_k, a_{k+1}, \dots\}$. Then $\beta = \inf_{k\in\mathbb{N}} b_k$ is called the* $\limsup$ *of (a_n). We can similarly define $c_k = \inf\{a_k, a_{k+1}, \dots\}$ and $\liminf = \sup_{k\in\mathbb{N}} c_k$.*

Def'n. 1.2.16 *Let $f_n : X \to \overline{\mathbb{R}}$ be a sequence of functions. Then $(\sup f_n) : X \to \overline{\mathbb{R}}$, $(\sup f_n)(x) = \sup f_n(x)$ for all $x \in X$. Similarly, $(\inf f_n) : X \to \overline{\mathbb{R}}$, $(\inf f_n)(x) = \inf f_n(x)$ for all $x \in X$. Then $(\liminf f_n)(x) = \liminf f_n(x)$. If $\lim f_n(x)$ exists for all x, then we say $(\lim f_n)(x) = \lim f_n(x)$.*

Thm. 1.2.17 *Let $f_n : X \to \overline{R}$ be measurable. Then $\sup f_n$, $\inf f_n$, $\limsup f_n$, $\liminf f_n$ are measurable.*

Proof Let $g = \sup f_n$. It is enough to prove that $g^{-1}((\alpha, +\infty]) \in \mathcal{M}$ for all α. Let $H = g^{-1}((\alpha, +\infty]) = \{x \in X : \sup f_n(x) > \alpha\}$. Let $H_n = f_n^{-1}((\alpha, +\infty]) = \{x \in X : f_n(x) > \alpha\} \in \mathcal{M}$. We show that $H = \bigcup_{n=1}^{\infty} H_n$.

First let $x \in H$, so $\sup f_n(x) > \alpha$. Thus get N so that $f_N(x) > \alpha$, so $x \in H_N$ and x is in the union. The converse is obvious.

Thus g is measureable. In the exact same way, $\inf f_n$ is measurable. As well,

$$\limsup f_n = \inf_i \sup_{k\geq i} f_k$$

is measurable. □

Cor. 1.2.18 *If $\lim f_n$ exists, then it is measurable.*

Proof If $\lim f_n$ exists, then $\lim f_n = \limsup f_n$. □

Cor. 1.2.19 *If f, g are measurable, then $\max\{f, g\}$, $\min\{f, g\}$ are measurable.*

Cor. 1.2.20 *Let f be a function. Then $f_+ = \max\{f, 0)\}$ and $f_- = -\min\{f, 0\}$ (the positive and negative parts of f) are measurable. Similarly, $|f| = f_+ + f_i$ is measurable.*

1.2.3 Measures

Def'n. 1.2.21 *Let $(X, \mathcal{M})$ be a measurable space. A function $\mu : \mathcal{M} \to [0, +\infty]$ is called a **(positive) measure** if it is countably additive and not constant $+\infty$. In other words,*

1. $\mu\left(\bigcup_{n=1}^{\infty} A_n\right) = \sum_{n=1}^{\infty} \mu(A_n)$ *if* $A_i \cap A_j = \emptyset$
2. $\exists A \in \mathcal{M}$ *so that* $\mu(A) < \infty$

*$(X, \mathcal{M}, \mu)$ is called a **measure space**.*

Prop. 1.2.22 *1.* $\mu(\emptyset)=0$

2. *If* $A_i\cap A_j=\emptyset$ *then* $\mu\left(\sum_{i=1}^{n}A_i\right)=\sum_{i=1}^{n}\mu(A_i)$
3. $A\subset B$ *implies* $\mu(A)\le\mu(B)$
4. $A_1\subset A_2\subset A_3\cdots$ *then* $\lim_{n\to\infty}\mu A_n=\mu\left(\bigcup_{n=1}^{\infty}A_n\right)$
5. $A_1\supset A_2\supset A_3\cdots$ *and* $\mu(A_i)<\infty$ *then* $|lim_{n\to\infty}\mu(A_n)=\mu\left(\bigcap_{n=1}^{\infty}A_n\right)$

Proof
1. Let $A\in\mathcal{M}$ so that $\mu(A)<\infty$, and fix $A_1=A$, $A_2=A_3=\cdots=\emptyset$. Then $\bigcup A_n=A$ so $\mu(A)=\mu(A)+\sum_{i=2}^{\infty}\mu(\emptyset)$ so $\mu(\emptyset)=0$.
2. Obvious
3. Note that $B=A\cup(B\setminus A)$ is a disjoint union.
4. Define $B_1:=A_1$ and $B_i=A_i\setminus A_{i-1}$ for $i\ge 2$. Then $B_i\cap B_j=\emptyset$ and $\mu(A_n)=\mu\left(\bigcup_{i=1}^{n}B_i\right)=\sum_{i=1}^{\infty}\mu(B_i)$. Similary, $\mu\left(\bigcup_{n=1}^{\infty}A_n\right)=\mu\left(\bigcup_{n=1}^{\infty}B_n\right)=\sum_{n=1}^{\infty}\mu(B_n)$ Therefore, $\lim_{n\to\infty}\sum_{i=1}^{n}\mu(B_i)=\sum_{n=1}^{\infty}\mu(B_n)$.
5. Let $C_n=A_1\setminus A_n$, $C_1=\emptyset$. Then $C_1\subset C_2\subset\cdots$ and $\mu(C_n)+\mu(A_n)=\mu(A_1)$. Let $A=\bigcap_{n=1}^{\infty}A_n$ so $A_1\setminus A=\bigcup_{n=1}^{\infty}C_n$ and $(\bigcup C_n)\cup A=A_1$ is a disjoint union. But then $\mu(\bigcup A_n)+\mu(A)=\mu(A_1)$ so that
$$\mu(A_1)-\mu(A)=\mu(\bigcup C_n)=\lim_{n\to\infty}\mu(C_n)=\mu(A_n)-\lim\mu(A_n)$$
Since $\mu(A_1)$ is finite, we have $\mu(A)=\lim\mu(A_n)$. □

Ex. 1.2.23 Here are a few examples of measures that exist on arbitrary sets.

1. X arbitrary, $\mathcal{M}=\mathcal{P}(X)$, and
$$\mu(E)=\begin{cases}|E| & \text{if } E \text{ is finite}\\ +\infty & \text{if } E \text{ is not finite}\end{cases}$$
It is easy to verify it is countably additive.
2. X arbitrary, $\mathcal{M}=\mathcal{P}(X)$. Fix $x_0\in X$. Then
$$\mu(E)=\begin{cases}1 & \text{if } x_0\in E\\ 0 & \text{if } x_0\notin E\end{cases}$$

1.3 Towards Integration

1.3.1 Simple Functions

Def'n. 1.3.1 $s : X \to \mathbb{R}$ *or* $\mathbb{C}$ *is called a simple function if its range is finite.*

Prop. 1.3.2 *Let s be a simple function, so that* $R(s) = \{\alpha_1, \alpha_2, \ldots, \alpha_n\}$*. Then* $s = \sum_{i=1}^{n} \alpha_i \chi_{A_i}$ *where* $A_i = s^{-1}(\{\alpha_i\})$ *and s is measurable if and only if* $A_i \in \mathcal{M}$*.*

Proof Obvious. □

The following theorem is used later to define the intergral. It is clear that we should define the integral of a simple function as the sum of the integrals of its characteristic functions, and this allows us to extend the integral by limits to the function f.

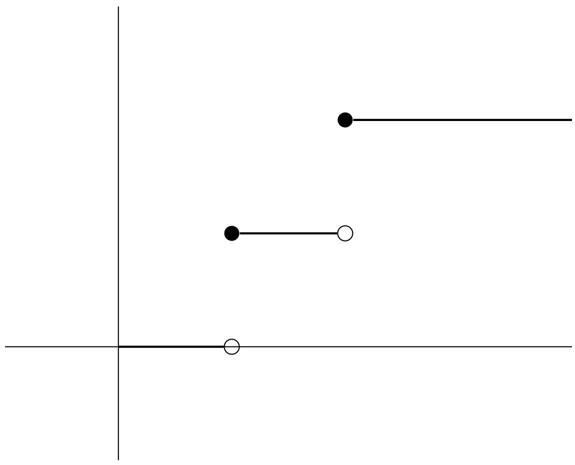
Thm. 1.3.3 *Let* $f : X \to [0, +\infty]$ *be nonnegative measurable functions. Then there exists a sequence* $s_n : X \to [0, +\infty]$ *of simple measurable functions with*

1. (s_n) *is increasing and bounded above by* f
2. $\lim s_n = f$ *pointwise.*

Proof Let $n \in \mathbb{N}$, $t \geq 0$, and $k_n(t) = [2^n \cdot t]$ (i.e. $k_n(t) \leq 2^n \cdot t < k_n(t) + 1$). Then define

$$\phi_n(t) = \begin{cases} k_n(t) \cdot 2^{-n} & \text{if } t \leq n \\ n & \text{if } t > n \end{cases}$$

I've drawn ϕ_1 below:



Then $t - 2^{-n} \leq \phi_n(t) \leq t$, $\lim \phi_n(t) = t$, and $\phi_n \leq \phi_{n+1}$. Define $s_n = \phi_n \circ f$, so for any $x \in X$, $\lim s_n(x) = \lim \phi_n \circ f(x) = f(x)$. Note that s_n is simple since it has finite range (from ϕ_n), and $s_n \leq s_{n+1}$ because $\phi_n \leq \phi_{n+1}$, and $s_n \leq f$ since $\phi_n(t) \leq t$. Furthermore, ϕ_n is measurable since its level sets are intervals, so $\phi_n \circ f$ is measurable. □

1.3.2 Integration of Positive Functions

Let $(X, \mathcal{M}, \mu)$ be a measure space.

Def'n. 1.3.4 *Let $S : X \to [0, +\infty)$ be a measurable simple function $s = \sum_{n=1}^{n} \alpha_i X_{A_i}$.Let $E \in \mathcal{M}$. Then define the **integral of** s over E be with respect to μ as*

$$\int_E s \, \mathrm{d}\mu = \sum_{n=1}^{n} \alpha_i \mu(A_i \cap E)$$

where we define $0 \cdot \infty = 0$.

Def'n. 1.3.5 *Let $f : X \to [0, +\infty]$ be a measurable function. Let $E \in \mathcal{M}$. Then the **(Lebesgue) integral** of f over E with respect to μ is*

$$\int_E f \, \mathrm{d}\mu = \sup \left\{ \int_E s \, \mathrm{d}\mu : 0 \le s \le f;\ s \text{ is simple measurable} \right\}$$

Unlike the Riemann integral, we take the supremum over lower sums only.

Prop. 1.3.6 *Let $f, g : X \to [0, +\infty]$ be measurable functions. Let $E, A, B \in \mathcal{M}$.*

1. *If $f \le g$ then $\int_E f \, \mathrm{d}\mu$ and $\int_E g \, \mathrm{d}\mu$*
2. *If $A \subset B$, then $\int_A f \, \mathrm{d}\mu \le \int_B f \, \mathrm{d}\mu$*
3. *$\int_E c \cdot f \, \mathrm{d}\mu = c \cdot \int_E f \, \mathrm{d}\mu$ for all $c \ge 0$*
4. *If $f(x) = 0$ for all $x \in E$, then $\int_E f \, \mathrm{d}\mu = 0$*
5. *If $\mu(E) = 0$, then $\int_E f \, \mathrm{d}\mu = 0$*
6. *$\int_E f \, \mathrm{d}\mu = \int_X f \cdot \chi_E \, \mathrm{d}\mu$.*

Proof 1. Note that

$$\left\{ \int_E s \, \mathrm{d}\mu : 0 \le s \le f \right\} \subset \left\{ \int_E s \, \mathrm{d}\mu : 0 \le s \le g \} Let \right.$$

$0 \le s \le f$ be simple measurable. Then

$$\int_A s \, \mathrm{d}\mu = \sum \alpha_i \mu(A \cap A_i) \le \sum \alpha_i \mu(B \cap A_i) = \int_B s \, \mathrm{d}mu$$

Take the supremum for all $0 \le s \le f$, then the result follows.

3. Let S be simple and measurable, so $s = \sum \alpha_i \chi_{A_i}$. Then

$$\int_E c \cdot s \, \mathrm{d}\mu = \sum_{i=1}^{n} \alpha_I \cdot c \cdot \mu(E \cap A_i) = c \cdot \sum \alpha_i \mu(E \cap A_i) = c \int_E s \, \mathrm{d}\mu$$

Thus

$$\begin{aligned}
\int_E c\cdot f\,\mathrm{d}\mu &= \sup\left\{\int_E s\,\mathrm{d}\mu : 0\le s\le cf\right\}\\
&= \sup\left\{\int_E c\cdot t\,\mathrm{d}\mu : 0\le t\le f\right\}\\
&= c\cdot\sup\left\{\int_E t\,\mathrm{d}\mu : 0\le t\le f\right\}\\
&= c\cdot\int_E f\,\mathrm{d}\mu
\end{aligned}$$

4. If $0\le s\le f$, then $s=\sum \alpha_i\chi_{A_i}$. If $x\in A_i\cap E$, then $s(x)=\alpha_i$ and $\alpha_i=0$. Then $\alpha_i\mu(A_i\cap E)=0$ for all i: either $A_i\cap E=\emptyset$, or $A_i\cap E$ is not empty, and $\alpha_i=0$. This is true for any $0\le s\le f$, and taking supremums yields the result.
5. If $\mu(E)=0$ then $\mu(A_i\cap E)=0$, and $\int_E s\,\mathrm{d}\mu=\sum\alpha_i\mu(A_i\cap E)=0$ and taking supremums, the result holds.
6. Exercise. First prove if $0\le s\le f\cdot\chi_E$, then $\int_X s\,\mathrm{d}\{\mu\}=\int_E s\,\mathrm{d}\mu$. Then prove $\left\{\int_E s\,\mathrm{d}\mu : 0\le s\le f\cdot\chi_E\right\}=\left\{|\int_E s\,\mathrm{d}\mu : 0\le s\le f\right\}$. □

Prop. 1.3.7 *Let s be a simple and measurable. Then $\phi(E)=\int_e s\,\mathrm{d}\mu$ is a measure.*

Proof $\phi(\emptyset)=0$, so ϕ is not constant $+\infty$. Let $E=\bigcup_{n=1}^\infty E_n$ be a disjoint union. Then

$$\begin{aligned}
\phi(E) &= \sum_{i=1}^m \alpha_i\mu(A_i\cap E)\\
&= \sum_{i=1}^m \alpha_i\mu\left(A_i\cap\left(\bigcup_{n=1}^\infty E_n\right)\right) = \sum_{i=1}^m\alpha_i\mu\left(\bigcup_{n=1}^\infty (A_i\cap E_n)\right)\\
&= \sum_{i=1}^m\alpha_i\sum_{n=1}^\infty \mu(A_i\cap E_n) = \sum_{n=1}^\infty\sum_{i=1}^m \alpha_i\mu(A_i\cap E_n)\\
&= \sum_{n=1}^\infty\int_{E_n} s\,\mathrm{d}\mu = \sum_{n=1}^\infty \phi(E_n)
\end{aligned}$$

□

Prop. 1.3.8 *Let s,t be nonnegative, measurable simple functions. Then*

$$\int_X (s+t)\,\mathrm{d}\mu = \int_X s\,\mathrm{d}\mu + \int_X t\,\mathrm{d}\mu$$

Proof Write

$$s=\sum_{i=1}^m \alpha_i X_{A_i},\quad t=\sum_{j=1}^n \beta_j X_{\beta_j}$$

and let $E_{ij} = A_i \cap B_j$, so $X = \bigcup_{i,j} E_{ij}$ is a disjoint union. We now have

$$\int_{E_{ij}} (s+t)\,\mathrm{d}\mu = (\alpha_i + \beta_j)\mu(E_{ij}) = \alpha_i\mu(E_{ij}) + \beta_j\mu(E_{ij}) = \int_{E_{ij}} s\,\mathrm{d}\mu + \int_{E_{ij}} t\,\mathrm{d}\mu$$

Let $\mu(E) = \int_E (s+t)\,\mathrm{d}\mu$, which is a measure as above. Thus

$$\begin{aligned}\int_X (s+t)\,\mathrm{d}\mu = \phi(X) &= \phi\left(\bigcup_{i,j} E_{ij}\right)\\ &= \sum_{i,j}\phi(E_{ij}) = \sum_{i,j}\int_{E_{ij}}(s+t)\,\mathrm{d}\mu\\ &= \sum_{i,j}\left(\int_{E_{ij}} s\,\mathrm{d}\mu + \int_{E_{ij}} t\,\mathrm{d}\mu\right)\\ &= \sum_{i,j}\varphi(E_{ij}) + \sum_{i,j}\theta(E_{ij})\\ &= \int_X s\,\mathrm{d}\mu + \int_X t\,\mathrm{d}\mu\end{aligned}$$

where $\varphi(E) = \int_E s\,\mathrm{d}\mu$, $\theta(X) = \int_E t\,\mathrm{d}\mu$. □

1.3.3 Lebesgue's Monotone Convergence Theorem

Thm. 1.3.9 (Lebesgue's Monotone Convergence) *Let $f_n : X \to [0,+\infty]$ be measurable, such that*
(i) $0 \le f_1 \le f_2 \le \cdots$
(ii) $f(x) := \lim_{n\to\infty} f_n(x)$ *for all* $x \in X$
Then f is measurable, and $\int_X f\,\mathrm{d}\mu = \lim \int_x f_n\,\mathrm{d}\mu$.

Proof It was already proven that f is measurable. We have $\int_X f_n\,\mathrm{d}\mu \le \int_x f_{n+1}\,\mathrm{d}\mu$ for all n, so $\alpha := \lim_{n\to\infty}\int_X f_n\,\mathrm{d}\mu$ exists. We also have $f_n \le f$, so $\int f_n \le \int f$ and $\alpha \le \int_X f_n\,\mathrm{d}\mu$. Thus we wish to show $\alpha \ge \int_x f\,\mathrm{d}\mu$. It suffices to prove that $\alpha \ge \int_x s\,\mathrm{d}\mu$ for any simple $s \le f$. Let $c \in (0,1)$; it suffices to show that $\alpha \ge \int_x c\cdot s\,\mathrm{d}\mu$. Define $E_n = \{x \in X : f_n(x) \ge c\cdot s(x)\}$. We have $E_1 \subset E_2 \subset \cdots$ so that $\bigcup E_n = X$. Then

$$\int_X f_n\,\mathrm{d}\mu \ge \int_{E_n} f_n\,\mathrm{d}\mu \ge \int_{E_n} c\cdot s\,\mathrm{d}\mu$$

Let $\phi(E) = \int_E s\,\mathrm{d}\mu$, so $\int_{E_n} s\,\mathrm{d}\mu = \phi(E_n) \to \phi(\cup E_n) = \phi(X) = \int_X s\,\mathrm{d}\mu$. Thus

$$\alpha \ge c\cdot\lim_{n\to\infty}\phi(E_n) = c\cdot\int_X s\,\mathrm{d}\mu = \int_X cs\,\mathrm{d}\mu$$

as desired. □

Ex. 1.3.10 Consider the function consisting of a triangle with base $2/n$ and height n. Then $\int_0^1 f_n = 1$ as a Riemannian integral. However, $\lim f_n(x) = 0$ for any x, so $\int_0^1 f = 0 \ne 1 = \lim\int_0^1 f_n$.

Thm. 1.3.11 *Let $f, g : X \to [0, +\infty]$ measurable, then $\int_X (f+g)\,\mathrm{d}\mu = \int_X f\,\mathrm{d}\mu + \int_X g\,\mathrm{d}\mu$.*

Proof We proved that there exists increasing sequences of simple functions s_n, t_n such that $\lim s_n(x) = f(x)$, $\lim t_n(x) = g(x)$. Then $s_n(x) + t_n(x) \to f(x) + g(x)$ monotonically. But then

$$\begin{aligned}
\int_X (f+g)\,\mathrm{d}\mu &= \int_X \lim_{n\to\infty} (s_n + t_n)\,\mathrm{d}\mu \\
&= \lim_{n\to\infty} \int_X (s_n + t_n)\,\mathrm{d}\mu \\
&= \lim_{n\to\infty} \left(\int_X s_n\,\mathrm{d}\mu + \int_X t_n\,\mathrm{d}\mu \right) \\
&= \int_X \lim_{n\to\infty} s_n\,\mathrm{d}\mu + \int_X \lim_{n\to\infty} t_n\,\mathrm{d}\mu \\
&= \int_X f\,\mathrm{d}\mu + \int_X g(\mathrm{d}\mu)
\end{aligned}$$

□

Cor. 1.3.12 *If $f_n : X \to [0, +\infty]$ is a sequence of measurable functions, then*

$$\sum_{n=1}^{\infty} \int_X f_n\,\mathrm{d}\mu = \int_x \sum_{n=1}^{\infty} f_n\,\mathrm{d}\mu$$

Ex. 1.3.13 Let $X = \mathbb{N}$, $\mathcal{M} = \mathcal{P}(X)$, $\mu(E)$ is the counting measure. Let $a : X \to [0, \infty)$ be a function. This is a sequence. Every function is measurable. Let $s_n(i) = a(i)$ for $i \leq n$ and 0 otherwise, which is a simple function, and $s_n \leq s_{n+1}$. Then $\lim_{n\to\infty} s_n(i) = a(i)$ so $s_n \to a$ pointwise, so by LMC $\int_X s_n\,\mathrm{d}\mu = \int_X a\,\mathrm{d}\mu$. Also,

$$\int_X s_n\,\mathrm{d}\mu = \sum_{i=1}^{n} a(i)\mu(\{i\}) = \sum_{i=1}^{n} a(i)$$

so $\int_X a\,\mathrm{d}\mu = \sum\limits_{n=1}^{\infty} a(n)$.

Lemma 1.3.14 (Fatou) *Let $f_n : X \to [0, \infty)$ be a sequence of measurable functions. Then*

$$\int_X \liminf f_n\,\mathrm{d}\mu \leq \liminf \int_X f_n\,\mathrm{d}\mu$$

Proof Let $g_k = \inf\{f_k, f_{k+1}, \dots\}$ so $\liminf f_n = \lim_{n\to\infty}$ and g_n is increasing. Note that $g_k \leq f_k$ for any k, so $\int_x g_k\,\mathrm{d}\mu \leq \int_X f_k\,\mathrm{d}\mu$. Thus

$$\begin{aligned}
\int_X \liminf f_n\,\mathrm{d}\mu &= \int_X \lim g_n\,\mathrm{d}\mu \\
&= \lim \int_X g_n\,\mathrm{d}\mu \\
&= \liminf \int_X g_n\,\mathrm{d}\mu \\
&\leq \liminf \int_X f_n\,\mathrm{d}\mu
\end{aligned}$$

□

Ex. 1.3.15 It is possible for the inequality to be strict. Define $f_{2n} = \chi_{[0,1]}$ and $f_{2n+1} = \chi_{[1,2]}$. Thus $\liminf f_n(x) = 0$ so $\int_{[0,2]} \liminf f_n \, \mathrm{d}\mu = 0$ but $\inf_[0,2] \int_{[0,2]} f_n \, \mathrm{d}\mu = 1$

Thm. 1.3.16 *Let $f : X \to [0,\infty]$ be measurable. Let $\phi(E) = \int_E f \, \mathrm{d}\mu$, $E \in \mathcal{M}$. Then ϕ is a measure and $\int_X g \, \mathrm{d}\phi = \int_X g \cdot f \, \mathrm{d}\mu$.*

Proof Certainly $\phi(\emptyset) = 0$, so $\phi \neq +\infty$. Thus let $E = \bigcup_{i=1}^{\infty} E_i$ be a disjoint union. Then $\chi_E f = \sum_{i=1}^{\infty} \chi_{E_i} f$. Thus we have

$$\begin{aligned}
\phi(E) &= \int_E f \, \mathrm{d}\mu \\
&= \int_X \chi_E f \, \mathrm{d}\mu \\
&= \int_X \sum_{i=1}^{\infty} \chi_{E_i} f \, \mathrm{d}\mu \\
&= \sum_{i=1}^{\infty} \int_X \chi_{E_i} f \, \mathrm{d}\mu \\
&= \sum_{i=1}^{\infty} \int_{E_i} \mathrm{d}\mu \\
&= \sum_{i=1}^{\infty} \phi(E_i)
\end{aligned}$$

Now, we prove that $\int_X g \, \mathrm{d}\mu = \int_X gf \, \mathrm{d}\mu$.

First, we do this for $g = \chi_E$. Then $\int_X \chi_E \, \mathrm{d}\mu = \phi(E)$ on the left, and $\int_X \chi_E f \, \mathrm{d}\mu = \int_E f \, \mathrm{d}\mu = \phi(E)$ and equality holds.

Now, let $g = \sum_{i=1}^{n} \alpha_i \chi_{A_i}$ be a simple function. Then $\int_X \sum \alpha_i \chi_{A_i} \, \mathrm{d}\phi = \sum \alpha_i \int_X \chi_{A_i} \, \mathrm{d}\phi$ on the left and $\int_X \sum \alpha_i \chi_{A_i} f \, \mathrm{d}\mu = \sum \alpha_i \int_X \chi_{A_i} f \, \mathrm{d}\mu$.

Finally, let g be an arbitrary measurable function, and let $(s_n) \to g$ be an increasing sequence of simple functions. Note that $s_n f \to gf$. Thus

$$\begin{aligned}
\int_X g \, \mathrm{d}\phi = \int_X \lim s_n \, \mathrm{d}\phi = \lim \int_X s_n \, \mathrm{d}\phi \\
= \lim \int_X s_n f \, \mathrm{d}\mu = \int_X \lim(s_n f) \, \mathrm{d}\mu \\
= \int_X g \cdot f \, \mathrm{d}\mu
\end{aligned}$$

as desired. □

1.4 Integration of Complex Valued Functions

Def'n. 1.4.1 *A function $f : X \to \mathbb{C}$ is called **Lebesgue integrable** if $\int_X |f| \, \mathrm{d}\mu < \infty$. The collection of such functions is $L^1(\mu)$.*

1.4.1 Basic Properties

Def'n. 1.4.2 *Let $f \in L^1(\mu)$. Then $f = u + iv$ and denote $u = \operatorname{Re} f$, $v = \operatorname{Im} f$. Let $E \in \mathcal{M}$; then the integral of f over E with respect to μ is*

$$\int_E f \, \mathrm{d}\mu = \int_E u^+ \, \mathrm{d}\mu - \int_E u^- \, \mathrm{d}\mu i \left(\int_E v^+ \, \mathrm{d}\mu - \int_E v^- \, \mathrm{d}\mu \right)$$

Thm. 1.4.3 *Let $f, g \in L^1(\mu)$, $\alpha, \beta \in \mathbb{C}$, so $\alpha f + = L^1(\mu)$ and*

$$\int_X (\alpha f + \beta g) \, \mathrm{d}\mu = \alpha \int_X f \, \mathrm{d}\mu + \beta \int_X g \, \mathrm{d}\mu$$

Proof Note that $\alpha f + \beta g$ is measurable, so $\int_X |\alpha f + \beta g| \, \mathrm{d}\mu \leq |\alpha| \int_X |f| \, \mathrm{d}\mu + |\beta| \int_X |g| \, \mathrm{d}\mu < \infty$. For real measurable functions, $\int_X (f + g) \, \mathrm{d}\mu = \int_X f \, \mathrm{d}\mu + \int_X g \, \mathrm{d}\mu$ directly by expanding the definition and using additivity over positive functions. We thus show $\int_X \alpha f \, \mathrm{d}\mu = \alpha \int_X f \, \mathrm{d}\mu$. If $\alpha \geq 0$, then

$$\begin{aligned}
\int_X \alpha f \, \mathrm{d}\mu = \int_X \alpha(u + iv) &= \int_X (\alpha u^+ - \alpha u^- + i\alpha v^+ - i\alpha v^-) \, \mathrm{d}\mu \\
&= \int_X ((\alpha u)^+ - (\alpha u)^- + (i\alpha v)^+ - (i\alpha v)^-) \, \mathrm{d}\mu \\
&= \int_X (\alpha u)^+ \, \mathrm{d}\mu - \int_X (\alpha u)^- \, \mathrm{d}\mu + \int_X i(\alpha v)^+ \, \mathrm{d}\mu - \int_X i(\alpha v)^- \, \mathrm{d}\mu \\
&= \alpha \int_X u^+ \, \mathrm{d}\mu - \alpha \int_X u^- \, \mathrm{d}\mu + \alpha \int_X iv^+ \, \mathrm{d}\mu - \alpha \int_X iv^- \, \mathrm{d}\mu \\
&= \alpha \int_X f \, \mathrm{d}\mu
\end{aligned}$$

and similarly for $\alpha = -1$, $\alpha = i$. □

Thm. 1.4.4 *Let $f \in L^1(\mu)$. Then $\left| \int_X f \, \mathrm{d}\mu \right| \leq \int_X |f| \, \mathrm{d}\mu$.*

Proof Let $z = \int_X f \, \mathrm{d}\mu$. Let $\alpha = \frac{|z|}{z}$ if $z \neq 0$, and $\alpha = 1$ otherwise. Then $\alpha \int_X f \, \mathrm{d}\mu = |z|$. Let $u = \operatorname{Re}(\alpha \cdot f) \leq |\alpha \cdot f| \leq |f|$ since $|\alpha| = 1$. Thus

$$\begin{aligned}
\left| \int_X f \, \mathrm{d}\mu \right| &= \alpha \cdot \int_X f \, \mathrm{d}\mu \\
&= \int_X \alpha f \, \mathrm{d}\mu \\
&= \int_X \operatorname{Re}(\alpha f) \, \mathrm{d}\mu \\
&\leq \int_X |f| \, \mathrm{d}\mu
\end{aligned}$$

□

1.4.2 More Dominated Convergence

Naturally, we want similar results as we have before. Indeed, we have the following theorem:

Thm. 1.4.5 (Lebesgue's Dominated Convergence) *Let $f_n : X \to \mathbb{C}$ be measurable functions such that $f = \lim f_n$. Assume that there is some $g \in L^1(\mu)$ such that $|f_n| \leq g$ for all n. Then $f \in L^1(\mu)$ and $\int_X f \,\mathrm{d}\mu = \lim_{n\to\infty} \int_X f_n \,\mathrm{d}\mu$.*

Proof We certainly know that f is measurable, and $|f| \leq g$, so $f \in L^1(\mu)$. As well, the triangle inequality show that $|f - f_n| \leq 2g$ for any n. We will see that $0 \leq \liminf \int_X |f - f_n| \,\mathrm{d}\mu \leq \limsup \int_X |f - f_n| \,\mathrm{d}\mu \leq 0$. Assuming that this holds, then $\lim \int_X |f - f_n| \,\mathrm{d}\mu = 0$ and

$$0 \leq \lim \left| \int_X f \,\mathrm{d}\mu - \int_X f_n \,\mathrm{d}\mu \right| \leq \int_X |f - f_n| \,\mathrm{d}\mu = 0$$

The first two inequalities are obvious: we must show that $\limsup \int_X |f_{f\,n}| \,\mathrm{d}\mu \leq 0$. Firstly, we have

$$\begin{aligned}
\int_X 2g \,\mathrm{d}\mu &= \int_X \left(2g - \lim_{n\to\infty} |f - f_n|\right) \mathrm{d}\mu \\
&= \int_X \liminf(2g - |f - f_n|) \,\mathrm{d}\mu \\
&\leq \lim \int \int_X (2g - |f - f_n|) \,\mathrm{d}\mu && \text{By Fatou's Lemma} \\
&= \int_X 2g + \liminf \left(- \int_X |f - f_n| \,\mathrm{d}\mu \right) \\
&= \int_X 2g - \limsup \int_X |f - f_n| \,\mathrm{d}\mu
\end{aligned}$$

and since $\int_X 2g \,\mathrm{d}\mu$ is finite, we subtract and $\limsup \int_X |f - f_n| \,\mathrm{d}\mu \leq 0$. □

Ex. 1.4.6 Consider $\lim_{n\to\infty} \int_0^n e^{-nx} \,\mathrm{d}x$. Define

$$f_n(x) = \begin{cases} e^{-nx} & \text{if } x \leq n \\ 0 & \text{if } x > n \end{cases}$$

Note that $f_n(x) \leq g(x) = e^{-x}$ and $\int_0^\infty e^{-x} \,\mathrm{d}x < \infty$. Thus

$$\begin{aligned}
\lim_{n\to\infty} \int_0^n e^{-nx} \,\mathrm{d}x &= \int_{[0,\infty)} \lim_{n\to\infty} f_n(x) \,\mathrm{d}x \\
&= \int_{[0,\infty)]} \chi_{\{0\}} \,\mathrm{d}x \\
&= 0
\end{aligned}$$

Rmk. 1.4.7 For the Riemann integral, we have $\int \lim f_n = \lim \int f_n$ as long as the convergence of f_n is uniform.

Chapter 2

The Lebesgue measure

2.1 The Vector Space $L^1(\mu)$

2.1.1 Almost Everywhere

Let $(X, \mathcal{M}, \mu)$ be a measure space.

Def'n. 2.1.1 *Let $E \in \mathcal{M}$. We say that property P holds almost everywhere in E if there exists $N \in \mathcal{M}$ such that $\mu(N) = 0$, $N \subset E$, and P holds in $E \setminus N$.*

Ex. 2.1.2 Two functions $f, g : X \to \mathbb{C}$ are equal almost everywhere if $\exists N \subset X$ such that $\mu(N)$ and $f(x) = g(x)$ on $X \setminus N$.

Prop. 2.1.3 *Let $E \subset X$ be such that $A_1, A_2, B_1, B_2 \in \mathcal{M}$ for which $\int_X f \,\mathrm{d}\mu = \int_X g \,\mathrm{d}\mu$. Then $A_1 \subset E \subset B_1$, $A_2 \subset E \subset B_2$, and $\mu(B_1 \setminus A_1) = 0$ and $\mu(B_2 \setminus A_2) = 0$. Then $\mu(A_1) = \mu(A_2)$.*

Proof Note that $A_1 \setminus A_2 \subset E \setminus A_2 \subset B_2 \setminus A_2$. As well, $\mu(A_1 \setminus A_2) \leq \mu(B_2 \setminus A_2) = 0$. Then

$$\mu(A_1) = \mu(A_1 \cap A_2^c) + \mu(A_1 \cap A_2) = \mu(A_1 \setminus A_2) + \mu(A_1 \cap A_2) = \mu(A_1 \cap A_2)$$
$$\mu(A_2) = \mu(A_2 \cap A_1^c) + \mu(A_2 \cap A_1) = \mu(A_2 \setminus A_1) + \mu(A_2 \cap A_1) = \mu(A_1 \cap A_2) \qquad \square$$

Prop. 2.1.4 *Let $(X, \mathcal{M}, \mu)$ be a measure space. Let*

$$\mathcal{M}^* = \{E \subset X : \exists A, B \in \mathcal{M}, A \subset E \subset B, \mu(B \setminus A) = 0\}$$

Then $\mathcal{M}^*$ is a $\sigma-$algebra, and $\mu^* : \mathcal{M}^* \to [0, +\infty]$ defined by $\mu^*(E) = \mu(A)$.

Proof We show that $\mathcal{M}^*$ is a $\sigma-$algebra, and μ is countably additive.

1. $X \in \mathcal{M}$ so $X \in \mathcal{M}^*$.
2. If $E \in \mathcal{M}^*$, get $A \subset E \subset B$ so $B^c \subset E^c \subset A^c$, $A^c, B^c \in \mathcal{M}$. As well, $\mu(A^c \setminus B^c) = \mu(A^c \cap B) = \mu(B \setminus A) = 0$, so $E^c \in \mathcal{M}^*$.
3. If $E_i \in \mathcal{M}^*$ is a countable collection, then get $A_i \subset E_i \subset B_i$. Fix $A = \bigcup A_i$ and $B = \bigcup B_i$. Then $B \setminus A = \bigcup (B_i \setminus A) \subset U(B_i \subset A_i)$ so $\mu(B \setminus A) = 0$ and $A \subset \bigcup E_i \subset B$ so $\bigcup E_i \in \mathcal{M}^*$.
4. Let E_i be disjoint, $E = \bigcup E_i$, and $E_i \in \mathcal{M}^*$. Get $A_i \subset E_i \subset B_i$. Then $\mu^*(\bigcup E_i) = \mu(\bigcup A_i) = \sum \mu(A_i) = \sum \mu(E_i)$. $\square$

Def'n. 2.1.5 *We call the space $(X, \mathcal{M}^*, \mu^*)$ the **completion** of $(X, \mathcal{M}, \mu)$.*

In particular, every subset of a set with measure 0 is measurable.

2.1.2 $L^1(\mu)$ as a normed space

Prop. 2.1.6 *1. Let $f : X \to [0, +\infty)$ be measurable, $E \in \mathcal{M}$. If $\int_E f \, \mathrm{d}\mu = 0$, then $f = 0$ almost everywhere in E.*

2. Let $f \in L^1(\mu)$. If $\int_E f \, \mathrm{d}\mu = 0$ for all $E \in \mathcal{M}$, then $f = 0$ almost everywhere in X.

Proof 1. Let $A_n = \{x \in E : f(x) > 1/n\}$, so that

$$\frac{1}{n}\mu(A_n) \leq \int_{A_n} \mathrm{d}\mu \leq \int_E f \, \mathrm{d}\mu = 0 \Longrightarrow \mu(A_n) = 0$$

for all n. But then

$$N = \{x \in E : f(x) > 0\} = \bigcup_{n=1}^{\infty} A_n \to \mu(N) \leq \sum \mu(A_n) = 0$$

2. Write $f = u + iv$ so that

$$\int_E f \, \mathrm{d}\mu = \int_E u^+ \, \mathrm{d}\mu - \int_E u^- \, \mathrm{d}\mu + i \int_E v^+ \, \mathrm{d}\mu - i \int_E v^- \, \mathrm{d}\mu$$

We show that $u^+ = 0$ almost everywhere (the other terms are identical). Let $E = \{x \in X : u(x) \geq 0\}$, so $\int_E f \, \mathrm{d}\mu = 0$, so its real part is zero and $\int_E u^+ \, \mathrm{d}\mu = 0$. Thus $u^+ = 0$ almost everywhere in E. The result follows. □

Def'n. 2.1.7 *A **normed space** over $\mathbb{R}$ is a vector space V over $\mathbb{R}$ with a map $\|\cdot\| : V \to \mathbb{R}$ such that*

(i) $x \in V \Rightarrow \|x\| \geq 0$ and $\|x\| = 0$ if and only if $x = 0$.

(ii) $\|\lambda x\| \leq |\lambda| \|x\|$ for all $\lambda \in \mathbb{R}$ and $x \in V$

(iii) $\|x + y\| \leq \|x\| + \|y\|$ for all $x, y \in V$.

Now $L^1(\mu) = \{f : X \to \mathbb{C}$ measurable and $\int_X |f| \mathrm{d}\mu < \infty\}$. We certainly have that $L^1(\mu)$ is a vector space. We wish to define $\|f\| = \int_X |f| \mathrm{d}\mu$. The only problem is that

$$\int_X |f| \mathrm{d}\mu = 0 \Longrightarrow f = 0 \text{ almost everywhere}$$

To deal with this problem, we quotient our space by the equivalence relation $f \sim g$ if and only if $f = g$ almost everywhere. With this in mind, define $V = L^1(\mu)/\sim$ denote the set of equivalence classes. We need to define $+, \cdot, \|\cdot\|$ on V. Let $[f]$ denote the class of f. Then

$$[f] + [g] = [f + g]$$
$$c[f] = [cf]$$
$$\|[f]\| = \int_X |f| \mathrm{d}\mu$$

Let's verify that this is well defined: if $f_1 \sim f_2$ and $g_1 \sim g_2$, then $f_1 + g_1 \sim f_2 + g_2$. Indeed, this is true since the sums are equal except perhaps on a union of measure zero sets, so equality holds almost everywhere. The second definition is obviously well defined. Finally, by a homework assignment, $\|[f]\|$ is also well defined. Now, let's verify the properties of the norm.

(i) Certainly $\|[f]\| \geq 0$, and $\|[f]\| = 0$ implies $f = 0$ almost everywhere, so $[f] = [0] = 0$.

(ii) We have $\|\lambda \cdot [f]\| = \int_X |\lambda f| \,\mathrm{d}\mu = |\lambda| \int_X |f| \,\mathrm{d}\mu = |\lambda| \|[f]\|$

(iii) We have $\|[f] + [g]\| = \int_X |f + g| \,\mathrm{d}\mu \leq \int_X |f| + \int_X |g| = \|[f]\| + \|[g]\|$

In $L^1(\mu)$, two functions are the same if they are equal almost everywhere. However, this can be a challenge: if $f \in L^1(\mu)$ and $x_0 \in X$, then $f(x_0)$ is not well defined. For example, it is challenging to give meaning to boundary conditions of functions.

2.1.3 Construction of the Lebesgue measure

We begin from the Riemann integral $\int_a^b f(x)\,\mathrm{d}x$ for a continuous function f. Define $\operatorname{supp} f = \overline{\{x \in \mathbb{R} : f(x) \neq 0\}}$. For continuous functions with compact (bounded) support, define $\Lambda f = \int_{\mathbb{R} f(x)\,\mathrm{d}x}$ is the Riemann integral, which is a functional. In particular,

$$\text{measure}((a,b)) = \text{length}((a,b)) = \sup\{\Lambda f : f \text{ is continuous, compact support, } 0 \leq f \leq 1, \operatorname{supp} f \subset (a,b)\}$$

We will extend this to a σ−algebra containing the Borel sets. In order to define these, for open sets, $\mu(G) = \sup\{\Lambda f : 0 \leq f \leq 1, \operatorname{supp} f \subset G\}$, where Λ is the Riemann integral. For an arbitrary set, $\mu(E) = \inf\{\mu(G) : E \subset G \in \tau\}$. However, this "measure" is not countably additive: the σ−algebra $\mathcal{P}(X)$ is too large (Vitali's construction). Instead, we will define $\mathcal{M} = \{E \subset X : E \text{ is locally regular}\}$, which means that $E \cap K$ is regular for any K compact, and regular means that the outer measure and inner measure are equal. The outer measure is $\sup\{\mu(K) : K \subset E \text{ compact}\} = \mu(E)$.

2.2 The Riesz Representation Theorem

In this section, we assume that (X, τ) be a locally compact, Hausdorff topological space.

Def'n. 2.2.1 *We denote the space of continuous functions with compact support by* $C_c(X) = \{f : X \to \mathbb{C} \mid f \in C(X), \operatorname{supp} f \textit{ is compact}\}$.

Def'n. 2.2.2 *Let* $\Lambda : C_c(X) \to \mathbb{C}$ *be a* ***linear functional****, i.e.* $\Lambda(cf + g) = c\Lambda f + \Lambda g$. Λ *is called a* ***positive*** *linear functional if* $f \geq 0 \Rightarrow \Lambda f \geq 0$.

Def'n. 2.2.3 *We say that* $K \prec f$ *if* K *is compact and* $f \in C_c(X)$, $0 \leq f \leq 1$ *implies that* $x \in K \Rightarrow f(x) = 1$. *We say that* $f \prec G$ *if* G *is open,* $f \in C_c(X)$, $0 \leq f \leq 1$, *and* $\operatorname{supp} f \subset G$.

Lemma 2.2.4 (Urysohn) *Let* $G \in \tau$, $K \subset G$ *compact. Then there exists* $f \in C_c(X)$ *such that* $K \prec f \prec G$.

Proof Will do later. It's pretty fun - it's a construction using the Dyadic rationals. □

Lemma 2.2.5 (Partition of Unity) *Let* $G_1, G_2, \ldots, G_n \in \tau$, *an let* $K \subset G_1 \cup \cdots \cup G_n$ *be compact. Then there are functions* $h_i \in C_c(X)$ *such that* $h_i \prec G_i$ *and* $K \prec \sum h_i$.

Proof Also will do later. □

How can we create a positive linear functional on $C_c(X)$? If μ is a measure, and functions on $C_c(X)$ are measurable, then $\Lambda f = \int_X f \, d\mu$ is a positive linear functional. The representation theorem says that there are no other examples.

Thm. 2.2.6 (Riesz Representation) *Let (X,τ) be as above. If $\Lambda : C_c(X) \to \mathbb{C}$ is a positive linear functional, then there exists a unique measure space $(X,\mathcal{M},\mu)$ such that $\Lambda f = \int_X f \, d\mu$ for any $f \in C_c(X)$, $\mathcal{M} \supset \tau$, and*

(i) $\mu(E) = \inf\{\mu(G) : E \subset G$ *open*$\}$ *for all* $E \in \mathcal{M}$.
(ii) $\mu(E) = \sup\{\mu(K) : K \subset E$ *compact*$\}$ *for all* $E \in \mathcal{M}$ *with* $\mu(E) < \infty$.
(iii) $\mu(K) < \infty$ *for any* K *compact.*
(iv) $\mathcal{M}$ *is complete.*

First, let's get some definitions out of the way. Fix the notation as above.

Def'n. 2.2.7 *Fix a Borel measure μ. The **Lebesgue outer measure** is defined $\mu(E) = \inf\{\mu(G) : E \subset G$ open$\}$.*

Def'n. 2.2.8 *We say that $E \subset X$ is **regular** if $\mu(E) = \sup\{\mu(K) : K \subset E$ compact$\}$. Similarly, $E \subset X$ is **locally regular** if there exists a compact K so that $K \cap E$ is regular.*

Proof For an open set $G \in \tau$, let $\mu(G) = \sup\{\Lambda f : f \prec G\}$. Then $\mu(\emptyset) = 0$ and $G_1 \subset G_2$ implies that $\mu(G_1) \le \mu(G_2)$. Then extend μ to arbitrary $E \subset X$ as an outer measure.

Now let $\mathcal{M} = \{E \subset X : E$ is locally regular$\}$. Let's first see that $\mathcal{M}$ satisfies the desired properties. We first see that $\mathcal{M}$ is complete. Let $E \in \mathcal{M}$, $\mu(E) = 0$ and $A \subset E$. We want to show that $A \in \mathcal{M}$. Let K be compact, and consider $K \cap A$ so that $\mu(K \cap A) = 0$. Then if $F \subset K \cap A$ is compact, $\mu(F) = 0$ implies $\sup\{\mu(F) : F \subset K \cap A$ compact$\} = 0$.

Claim 1: μ is σ−subadditive.

Proof If $\mu(E_j) = \infty$ for some j, then we are done. Thus assume $\mu(E_j) < \infty$ for all j. Let $\epsilon > 0$, $\gamma < \mu\left(\bigcup_{j=1}^{\infty} E_j\right)$ be arbitrary. Let $G_j \supset E_j$ be open, such that $\mu(G_j) \le \mu(E_j) + \frac{\epsilon}{2^j}$. Then

$$j < \mu\left(\bigcup_{j=1}^{\infty} E_j\right) \le \mu\left(\bigcup_{j=1}^{\infty} G_j\right)$$

so there exists some $f \prec \bigcup_{j=1}^{\infty} G_j$ so $j < \Lambda f$. Let $K = \operatorname{supp} f$ and $K \subset \bigcup_{j=1}^{\infty} G_j$ and by compactness there exists some n so $K \subset \bigcup_{j=1}^{n} G_j$. Apply our partition of unity and get some $h_j \prec G_j$ for each $j = 1, \dots, n$ such that if $x \in K$, then $\sum_{j=1}^{n} h_j(x) = 1$. Then $f \cdot h_j \prec G_j$ so $f = f \cdot \sum_{j=1}^{n} h_j$.

Thus

$$\begin{aligned}\gamma < \Lambda f = \Lambda\left(\sum_{j=1}^{n} f h_j\right) = \sum_{j=1}^{n} \Lambda(f h_j)\\ \leq \sum_{j=1}^{n} \mu(G_j) \leq \sum_{j=1}^{n}\left(\mu(E_j) + \frac{\epsilon}{2^j}\right)\\ \leq \sum_{j=1}^{\infty}\left(\mu(E_j)\right) + \epsilon\end{aligned}$$

which holds for all $\epsilon > 0$ if and only if

$$\gamma \leq \sum_{j=1}^{\infty} \mu(E_j)$$

for all $\gamma \leq \mu\left(\bigcup_{j=1}^{\infty} E_j\right)$ and the result follows. □

Claim 2: If $K \prec f \prec G$, then $\mu(K) \leq \Lambda f \leq \mu(G)$. Thus if K is compact, $\mu(K) = \inf\{\Lambda f : K \prec f\}$, so $\mu(K) < \infty$.

Proof It is obvoius that $\Lambda f \leq \mu(G)$. Thus let $\gamma < \mu(K)$ and $\alpha \in (0,1)$. Let $V_\alpha := \{x \in X : f(x) > \alpha\}$ and $K \subset V_\alpha$. Now $\gamma < \mu(K) \leq \mu(V_\alpha)$, so we have some $h \prec V_\alpha$ such that $\gamma < \Lambda h$. Then $\alpha \cdot h \leq f$ since in V_α, $\alpha \cdot h \leq \alpha < f$ and in V_α^c, $\alpha \cdot h = 0 \leq f$. Now $\alpha \cdot \Lambda h = \Lambda(\alpha h) \leq \Lambda f$ so $\gamma < \Lambda f/\alpha$. This is true for all $\alpha \in (0,1)$ and $\gamma \leq \Lambda f$. Since this holds for all $\gamma < \mu(K)$, we have $\mu(K) \leq \Lambda f$ as required.

Now, let K be compact. Since $\mu(K) \leq \Lambda f$ for all $K \prec f$. Let $\epsilon > 0$, so we have $G \in \tau$, $G \supset K$ such that $\mu(G) \leq \mu(K) + \epsilon$. Then by Urysohn's lemma, get some f so that $\mu(K) \leq \Lambda f \leq \mu(G)$, so $\Lambda f \leq \mu(K) + \epsilon$ and the result holds. □

Claim 3: If $0 \leq f \leq 1$, then $\Lambda f \leq \mu(\operatorname{supp} f)$.

Proof Let $G \supset \operatorname{supp} f$ be open, so $f \prec G$ and $\mu(G) \geq \Lambda f$. Then $\mu(\operatorname{supp} f) = \inf\{\mu(G) : E \subset G \in \tau\} \geq \Lambda f$. □

Claim 4: If $G \in \tau$, then G is regular.

Proof We must show $\mu(G) = \sup\{\mu(K) : K \subset E \text{ compact}\}$. Take $\gamma < \mu(G)$. We know that $\sup\{\mu(K) : K \subset G \text{ compact}\} \leq \mu(G)$, so we prove the $\geq$ case. We need K compact so that $\mu(K) > \gamma$. Let $f \prec G$ be such that $\Lambda f > \gamma$. Then $\mu(\operatorname{supp} f) > \gamma$ is compact, as desired. □

Claim 5: If E_i are disjoint regular, then $\mu\left(\bigcup_{i=1}^{\infty} E_i\right) = \sum_{i=1}^{\infty} \mu(E_i)$.

Proof We first prove this for two compact sets. Thus let K_1, K_2 be disjoint compact sets. Then K_2^c is open and $K_2^c \supset K_1$. By Urysohn's lemma, get $f \in C_c(X)$ so that $K_1 \prec f \prec K_2^c$ and $x \in K_1$ implies $f(x) = 1$, and $x \in K_2$ implies $f(x) = 0$. Since $K_1 \cup K_2$ is compact, for all $\epsilon > 0$, get $g \prec K_1 \cup K_2$ such that $\mu(K_1 \cup K_2) + \epsilon > \Lambda g$. Note that $K_1 \prec f \cdot g$ and $K_2 \prec (1-f)\cdot g$. Thus $\mu(K_1) + \mu(K_2) \leq \Lambda(f \cdot g) + \Lambda((1-f)\cdot g = \Lambda g < \mu(K_1 \cup K_2) + \epsilon$ which is true for any $\epsilon > 0$. Thus $\mu(K_1) + \mu(K_2) \leq \mu(K_1 \cup K_2) \leq \mu(K_1) + \mu(K_2)$ as required.

We now prove that $\mu(\cup E_i) \geq \sum \mu(E_i)$. If $\mu(\cup E_i) = +\infty$, we are done, so assume $\mu(\cup E_i) < +\infty$. If the E_i are regular, then there is a compact set $H_i \subset E_i$ so that

$$\mu(H_i) > \mu(E_i) - \frac{\epsilon}{2^i}$$

Let $K_n = \bigcup_{i=1}^{n} H_i$. Now

$$\begin{aligned}\mu\left(\bigcup_{i=1}^{\infty} E_i\right) &\geq \mu(K_n) \\ &= \sum_{i=1}^{n} \mu(H_i) \\ &> \sum_{i=1}^{n} \mu(E_i) - \epsilon\end{aligned}$$

As well, this holds for any $\epsilon > 0$ and $n \in \mathbb{N}$, so we are done. □

Claim 6: If the E_i are regular, then $\bigcup_{i=1}^{\infty} E_i$ is regular when $\mu(\cup E_i) < \infty$.

Proof We have

$$\begin{aligned}\mu\left(\bigcup_{i=1}^{\infty} E_i\right) &\leq \sum_{i=1}^{N} \mu(E_i) + \epsilon \\ &\leq \mu(K_N) + 2\epsilon\end{aligned}$$

Thus for any $\epsilon > 0$, get N so that

$$\mu\left(\bigcup_{i=1}^{\infty} E_i\right) - 2\epsilon \leq \mu(K_n)$$

so $\cup E_i$ is regular. □

Claim 6(?): E is regular and $\mu(E) < \infty$ if and only if for any $\epsilon > 0$, there exists K compact, G open so that $K \subset E \subset G$ and $\mu(G \setminus K) < \epsilon$.

Proof There exists by regularity (and the definition of the outer measure) K, G so that

$$\mu(E) - \frac{\epsilon}{2} \leq \mu(K) \leq \mu(G) \leq \mu(E) + \epsilon/2$$

As well, $\mu(G) = \mu(K \cup (G \setminus K)) = \mu(K) + \mu(G \setminus K)$ and $\mu(G \setminus K) = \mu(G) - \mu(K) < \epsilon$.

Conversely, let $K \subset E \subset G$ and $\mu(G \setminus K) < \epsilon$. Then

$$\mu(E) \leq \mu(G) = \mu(K) + \mu(G \setminus K) < \mu(K) + \epsilon$$

so $\mu(E) < \infty$ and $\mu(E) = \sup\{\mu(K) : K \subset E \text{ compact}\}$, and E is regular. □

Claim 7:

1. **Let A, B be regular with $\mu(A), \mu(B) < \infty$. Then $A \setminus B$, $A \cup B$, $A \cap B$ are regular and have finite measure.**
2. **If E is regular and $\mu(E) < \infty$, then E is locally regular.**
3. **If E_i are regular, then $\bigcup_{i=1}^{\infty} E_i$ is regular.**

Proof Recall that for any $\epsilon > 0$, there exists $K_1 \subset A \subset G_1$ and $K_2 \subset B \subset G_2$ such that $\mu(G_1 \setminus K_1) < \epsilon$ and $\mu(G_2 \setminus K_2) < \epsilon$.

1. Note that $A \setminus B \subset G_1 \setminus K_2 \subset (G_1 \setminus K_1) \cup (K_1 \setminus G_2) \cup (G_2 \setminus K_2)$, where $K_1 \setminus G_2$ is compact. Thus $\mu(A \setminus B) \leq \epsilon + \mu(K_1 \setminus G_1) + \epsilon < \infty$ and $\mu(A \setminus B) - 2\epsilon \leq \mu(K_1 \setminus G_2)$ so $A \setminus B$ is regular. Finally since $A \cup B = (A \setminus B) \cup B$, $A \cup B$ is regular and $\mu(A \cup B) < \infty$. Thus $A \cap B = (A \cup B) \setminus ((A \setminus B) \cup (B \setminus A))$ is regular and has measure less than infinity.
2. Let E be regular, $\mu(E) < \infty$, and K be a compact set. Then $\mu(K) < \infty$, K is regular, $E \cap K$ is regular and E is locally regular.
3. Set $F_1 = E_1$, $F_n = E_n \setminus \left(\bigcup_{i=1}^{n-1} E_i \right)$ so $\bigcup_{i=1}^{\infty} F_i = \bigcup_{i=1}^{\infty} E_i$ and the F_i as disjoint. By Claim 5, $\cup F_i$ is regular and F_i are regular. □

Claim 8: If E is locally regular and $\mu(E) < \infty$, then E is regular.

Proof Let $\epsilon > 0$ and $G \supset E$ be open so that $\mu(G) < \mu(E) + 1 < \infty$. As well, G is regular, so there exists K with $\mu(G) < \mu(K) + \epsilon/2$. Now,

$$\begin{aligned} \mu(E) = \mu((E \setminus K) \cup (E \cap K)) &\leq \mu(E \setminus K) + \mu(E \cap K) \\ &\leq \mu(G \setminus K) + \mu(E \cap K) \\ &< \frac{\epsilon}{2} + \mu(E \cap K) \end{aligned}$$

so $\mu(E \cap K) > \mu(E) - \epsilon/2$. Then since E is locally regular, $E \cap K$ is regular and get a compact set $L \subset E \cap K$ such that $\mu(L) > \mu(E \cap K) - \epsilon/2 > \mu(E) - \epsilon$. Thus E is regular. □

Claim 9: $\mathcal{M}$ is a $\sigma-$algebra, $M \subset \tau$, and μ is countably additive on $\mathcal{M}$.

Proof Let $A \in \mathcal{M}$: we see that $A^c \in \mathcal{M}$. For any K compact, $A \cap K$ is regular. Let K be compact and take $A^c \cap K = K \setminus (A \cap K)$ is regular by Claim 7.

Now let $A_n \in \mathcal{M}$: we see that $A := \bigcup_{n=1}^{\infty} A_n \in \mathcal{M}$. Let K be an arbitrary compact set, so

$$A \cap K = \bigcup_{n=1}^{\infty} (A_n \cap K)$$

is regular by Claim 7.

We now show $\mathcal{M} \supset \tau$. It suffices by closure under complement that al the closed sets are in $\mathcal{M}$. If A is closed, then $A \cap K$ is compact and thus regular, so $A \in \mathcal{M}$.

Finally, let $E_i \in \mathcal{M}$ be disjoint: we see that $\mu\left(\bigcup_{i=1}^{\infty} E_i\right) = \sum_{i=1}^{\infty} \mu(E_i)$. It suffices to show $\geq$. If $\mu(E_i) = +\infty$, we are done, so assume $\mu(E_i) < \infty$ for all i. But then by Claim 8, E_i are regular, and the result holds by Claim 5. □

Claim 10: $\Lambda f = \int_X f \,\mathrm{d}\mu$ for all $f \in C_c(X)$.

Proof It suffices to prove this for real valued functions. If $f = u + iv$, then $\Lambda f = \Lambda u + i\Lambda v = \int_X u \,\mathrm{d}\mu + i\int_X v \,\mathrm{d}\mu = \int_X f \,\mathrm{d}\mu$. Furthermore, it suffices to show $\Lambda f \leq \int_X f \,\mathrm{d}\mu$ since $\Lambda(-f) \leq \int_X -f \,\mathrm{d}\mu$ so that $-\Lambda f \leq -\int_X f \,\mathrm{d}\mu$ and $\Lambda f \geq \int_X f \,\mathrm{d}\mu$, implying equality.

As well, it is enough to prove that $\Lambda \leq \int f$ for $f \geq 0$. Let $K = \operatorname{supp} f$ be compact, and $a = \min f$, $b = \max f$. Let $\epsilon > 0$ be arbitrary. For every K, there exists $G \supset K$ so that $\mu(G) \leq \mu(K) + \epsilon$. Then by Urysohn's lemma, there exists $h \in C_c(X)$ so that $K \prec g \prec G$. Thus $|a| \cdot h(x) = |a|$ for all $x \in K$, so $F = f + |a|h \geq 0$ since $f \geq -|a|$. Now

$$\Lambda f \leq \int_X F \,\mathrm{d}\mu = \int_X f + |a| \int_X h$$

so $\Lambda f \leq \int_X f + |a|\left(\int_X h - \Lambda g\right)$. As well, by Claim 2,

$$\mu(K) \leq \Lambda h \leq \mu(G)$$

so that

$$\int_X \chi_K \leq \int_X h \,\mathrm{d}\mu] \leq \int_X \chi_G = \mu(G)$$

and $|\Lambda h - \int h| < \epsilon$. Thus $\Lambda f \leq \int f + |a|\epsilon$ for all $\epsilon > 0$, so $\Lambda f \leq \int f$.

It now remains to show $\Lambda f \leq \int_X f \,\mathrm{d}\mu$ for $f \geq 0$. Since $f = Mf/M$ where $M = \max f$, we can assume $0 \leq f \leq 1$. Fix $K = \operatorname{supp} f$, let $\epsilon > 0$ be arbitrary. Let $0 = c_0 < c_1 < c_2 < \cdots < c_n = 1$ with $c_k - c_{k-1} < \epsilon$ for all k and $\mu(f^{-1}(c_k)) = 0$ for all $k = 1, \ldots, n-1$. The existence of such a set follows from Assignment 6. Let $K_j = K \cap f^{-1}([c_{j-1}, c_j])$ for $j = 1, 2, \ldots, n$ and $L_j = K \cap f^{-1}([c_{j-1}, c_j))$ for $j = 1, 2, \ldots, n-1$. To K_j and ϵ, there exists $G_j \supset K_j$ such that $\mu(G_j) \leq \mu(K_j) + \frac{\epsilon}{2^j}$. By Urysohn's lemma, get h_j so that $K_h \prec h_j \prec G_j$, so $f \leq \sum_{j=1}^{n} c_j h_j$ since for $x \notin \operatorname{supp} f = K$, $f = 0$, and otherwise, there exists j so that $x \in K_j$ implies $h_j = 1$ and $f(x) \leq c_j = c_j h_j(x) \leq \sum c_i h_i$. Then

$$\begin{aligned}
\Lambda f \leq \Lambda\left(\sum c_j h_j\right) &= \sum_{i=1}^{n} c_j \Lambda h_j \\
&\leq \sum_{j=1}^{n} c_j \mu(G_j) \\
&\leq \sum_{j=1}^{n} c_j \mu(K_j) + \sum c_j \frac{\epsilon}{2^j} \\
&\leq \sum_{j=1}^{n} (c_{j-1} + c_j - c_{j-1}) \mu(L_j) + \epsilon \\
&\leq \sum_{j=1}^{n} c_{j-1} \mu(L_j) + \epsilon \cdot \mu(K) + \epsilon
\end{aligned}$$

where g is a simple function such that $g(x) = c_{j-1}$ if $x \in L_j$ and $g \leq f$. Then

$$\begin{aligned} &= \int_X g \, \mathrm{d}\mu + \epsilon(1+\mu(K)) \\ &\leq \int_X f \, \mathrm{d}\mu + \epsilon(1+\mu(K)) \end{aligned}$$

for any $\epsilon > 0$, and we are done! □

2.3 Regularity Properties of Borel Measures

We have the Riesz representation theorem in a locally compact Hausdorff space. Our aim is to intruduce the Lebesgue measure in $\mathbb{R}^k$ which respects translation as well.

Def'n. 2.3.1 *A measure defined on the family of Borel sets is called a* ***Borel measure****.*

Def'n. 2.3.2 *Let $\mu : \mathcal{B} \to [0, +\infty]$ be a Borel measure.*

1. *E is called* ***outer regular*** *if $\mu(E) = \inf\{\mu(G) : E \subset G \in \tau\}$.*
2. *E is called* ***inner regular*** *if $\mu(E) = \sup\{\mu(K) : K \subset E, K \text{ compact}\}$*
3. *μ is called* ***regular*** *if every $E \in \mathcal{B}$ is inner and outer regular.*

Def'n. 2.3.3 *A set $E \subset X$ is called $\sigma-$**compact** if $E = \bigcup_{n=1}^{\infty} E_n$, for E_n compact.*

Def'n. 2.3.4 *A G_δ set is one of the form $\bigcap_{n=1}^{\infty} A_n$ with A_n open, and a F_σ set is one of the form $\bigcup_{n=1}^{\infty} B_n$ for B_n closed.*

Thm. 2.3.5 *Let X be a locally compact, $\sigma-$compact Hausdorff space. Let $\mathcal{M} \supset \mathcal{B}$ be a $\sigma-$algebra, $\mu : \mathcal{M} \to [0, +\infty]$ be a measure such that*

(i) $\mu(E) = \inf\{\mu(G) : E \subset G \in \tau\}$

(ii) $\mu(E) = \sup\{\mu(K) : K \subset E \text{ compact}\}$, $\mu(E) < \infty$

(iii) $\mu(K) < \infty$ *for K compact.*

Then

1. *For all $E \in \mathcal{M}$ and $\epsilon > 0$, there exists F closed and G open so that $F \subset E \subset G$ and $\mu(G \setminus F) < \infty$.*
2. *μ is regular*
3. *For all $E \in \mathcal{M}$, there exists a F_σ set A and a G_δ set B so $A \subset E \subset B$ and $\mu(B \setminus A) = 0$.*

Proof Since X is $\sigma-$compact, $X = \bigcup_{n=1}^{\infty} K_n$, K_n compact.

1. By (iii), we have $\mu(K_n \cap E) < \infty$. Thus by (i), get G_n open so that $G_n \supset K_n \cap E$ with $\mu(G_n \setminus (K_n \cap E)) < \frac{\epsilon}{2^{n+1}}$. Let $G = \bigcup_{n=1}^{\infty} G_n$ be open, so that $G \setminus E \subset \bigcup (G_n \setminus (K_n \cap E))$ and $\mu(G \setminus U) < \frac{\epsilon}{2}$. Repeat this for E^c: get an open set H such that $\mu(H \setminus E^c) < \frac{\epsilon}{2}$. Then $F = H^c E$ satisfies $\mu(E \setminus F) = \mu(F^c \setminus E^c) = \mu(H \setminus E^c) < \frac{\epsilon}{2}$. Then $\mu(G \setminus F) \leq \mu(G \setminus E) + \mu(E \setminus F) < \epsilon$. Then $\mu(G \setminus F) \leq \mu(G \setminus E) + \mu(E \setminus F) < \epsilon$.

2. E is outer regular by (i). If $\mu < \infty$, then E is inner regular by (ii). If $\mu(E) = \infty$, let $F \subset E$ be given by 1. Then $\mu(F) = +\infty$, or $\mu(E)$ would be finite. Let $H_n = \bigcup_{k=1}^{n} (F \cap K_k)$ compact, $H_n \subset F$. Then $\bigcup_{n=1}^{\infty} H_n = F$, and $\mu(H_n) \to \mu(F) = \infty$. Thus $\mu(E) = \sup\{\mu(K) : K \subset E \text{ compact}\}$.

3. Apply 1 wih $\epsilon = 1/j$ for $j \in \mathbb{N}$. Then there exists $F_j \subset E \subset G_j$ so $\mu(G_j \setminus F_j) < \frac{1}{j}$. Let $A = \bigcup_{j=1}^{\infty} F_j$ and $B = \bigcap_{j=1}^{\infty} G_j$. Then $A \subset E \subset B$ and $\mu(B \setminus A) \le \mu(G_j \setminus F_j) < \frac{1}{j}$, so $\mu(B \setminus A) = 0$. □

Thm. 2.3.6 *Let X be locally compact and Hausdorff, and assume that every open set is $\sigma-$compact. Let $\lambda : \mathcal{B} \to [0, \infty]$ be a Borel measure such that $\lambda(K) < \infty$. Then λ is regular.*

Proof Let $\Lambda f = \int_X f \, \mathrm{d}\lambda$. Then $\Lambda : C_c(X) \to \mathbb{C}$ is a positive linear functional. By the Riesz representation theorem, there exists $\mu : \mathcal{M} \to [0, \infty]$ such that $\int_X f \, \mathrm{d}\mu = \Lambda f = \int_X f \, \mathrm{d}\lambda$. We see that $\lambda = \mu$ on $\mathcal{B}$. We first prove this for open sets. Let $G \in \tau$; then there exists K_n so $G = \bigcup_{n=1}^{\infty} K_n$. By Urysohn's lemma, there exists f_i such that $K_i \prec f_i \prec G$. Let $g_n = \max\{f_1, f_2, \dots, f_n\}$, so $g_n \in C_c(X)$, and $g_n \to \chi_G$ pointwise. But then

$$\begin{aligned}
\lambda(G) &= \int_X \chi_G \, \mathrm{d}\lambda \\
&= \int_X \lim_{n\to\infty} g_n \, \mathrm{d}\lambda \\
&= \lim_{n\to\infty} \int_X g_n \, \mathrm{d}\lambda \\
&= \lim_{n\to\infty} \int_X g_n \, \mathrm{d}\mu \\
&= \int_X \lim_{n\to\infty} g_n \, \mathrm{d}\mu \\
&= \int_X \chi_G \, \mathrm{d}\mu \\
&= \mu(G)
\end{aligned}$$

Now for any $E \in \mathcal{B}$, apply (i). Then $F \subset E \subset G$, $\mu(G \setminus F) < \epsilon$. Since $G \setminus F$ is open, $\lambda(G \setminus F) = \mu(G \setminus F) < \epsilon$ so $\lambda(G) \le \lambda(E) + \epsilon$. Thus $|\mu(E) - \lambda(E)| < \epsilon$ for all $\epsilon > 0$ so $\lambda(E) = \mu(E)$. □