

Title

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1 Basics

1.1 Useful Techniques

- General advice: try swapping the orders of limits, sums, integrals, etc.
- Limits:
 - Take the \limsup or \liminf , which always exist, and aim for an inequality like

$$c \leq \liminf a_n \leq \limsup a_n \leq c.$$

- $\lim f_n = \limsup f_n = \liminf f_n$ iff the limit exists, so to show some g is a limit, show

$$\limsup f_n \leq g \leq \liminf f_n \quad (\implies g = \lim f).$$

- A limit does *not* exist if $\liminf a_n > \limsup a_n$.

- Sequences and Series

- If f_n has a global maximum (computed using f'_n and the first derivative test) $M_n \rightarrow 0$, then $f_n \rightarrow 0$ uniformly.
- For a fixed x , if $f = \sum f_n$ converges *uniformly* on some $B_r(x)$ and each f_n is continuous at x , then f is also continuous at x .

- Equalities

- Split into upper and lower bounds:

$$a = b \iff a \leq b \text{ and } a \geq b.$$

- Use an epsilon of room:

$$a < b + \epsilon \forall \epsilon \implies a \leq b.$$

- Showing something is zero:

$$|a| \leq \epsilon \forall \epsilon \implies a = 0.$$

- Simplifications:

- To show something for a measurable set, show it for bounded/compact/elementary sets/
- To show something for a function, show it for continuous, bounded, compactly supported, simple, indicator functions, L^1 , etc
- Replace a continuous sequence ($\epsilon \rightarrow 0$) with an arbitrary countable sequence ($x_n \rightarrow 0$)
- Intersect with a ball $B_r(\mathbf{0}) \subset \mathbb{R}^n$.

- Integrals

- Break up $\mathbb{R}^n = \{|x| \leq 1\} \coprod \{|x| > 1\}$.

1.2 Definitions

Definition 1.0.1 (Uniform Continuity).

f is uniformly continuous iff

$$\begin{aligned} \forall \epsilon \quad \exists \delta(\epsilon) \quad & \left| \quad \forall x, y, \quad |x - y| < \delta \implies |f(x) - f(y)| < \epsilon \right. \\ \iff \forall \epsilon \quad \exists \delta(\epsilon) \quad & \left| \quad \forall x, y, \quad |y| < \delta \implies |f(x - y) - f(y)| < \epsilon. \right. \end{aligned}$$

Definition (Nowhere Dense Sets) A set S is **nowhere dense** iff the closure of S has empty interior
iff every interval contains a subinterval that does not intersect S .

Definition (Meager Sets) A set is **meager** if it is a *countable* union of nowhere dense sets.

Definition 1.0.2 (F_σ and G_δ Sets).

An F_σ set is a union of closed sets, and a G_δ set is an intersection of opens.

Mnemonic: “F” stands for *ferme*, which is “closed” in French, and σ corresponds to a “sum”, i.e. a union.

Theorem (Heine-Cantor) Every continuous function on a compact space is uniformly continuous.

Definition 1.0.3 (Limsup/Liminf).

$$\begin{aligned}\limsup_n a_n &= \lim_{n \rightarrow \infty} \sup_{j \geq n} a_j = \inf_{n \geq 0} \sup_{j \geq n} a_j \\ \liminf_n a_n &= \lim_{n \rightarrow \infty} \inf_{j \geq n} a_j = \sup_{n \geq 0} \inf_{j \geq n} a_j.\end{aligned}$$

1.3 Theorems

1.3.1 Topology / Sets

Lemma Metric spaces are compact iff they are sequentially compact, (i.e. every sequence has a convergent subsequence).

Proposition The unit ball in $C([0, 1])$ with the sup norm is not compact.

Proof Take $f_k(x) = x^n$, which converges to a dirac delta at 1. The limit is not continuous, so no subsequence can converge.

Proposition A *finite* union of nowhere dense is again nowhere dense.

Lemma (Convergent Sums Have Small Tails)

$$\sum a_n < \infty \implies a_n \rightarrow 0 \quad \text{and} \quad \sum_{k=N}^{\infty} a_n \xrightarrow{N \rightarrow \infty} 0$$

Theorem (Heine-Borel) $X \subseteq \mathbb{R}^n$ is compact $\iff X$ is closed and bounded.

Lemma (Geometric Series)

$$\sum_{k=0}^{\infty} x^k = \frac{1}{1-x} \iff |x| < 1.$$

Corollary: $\sum_{k=0}^{\infty} \frac{1}{2^k} = 1.$

Lemma The Cantor set is closed with empty interior.

Proof Its complement is a union of open intervals, and can't contain an interval since intervals have positive measure and $m(C_n)$ tends to zero.

Corollary The Cantor set is nowhere dense.

Lemma Singleton sets in \mathbb{R} are closed, and thus \mathbb{Q} is an F_σ set.

Theorem (Baire) \mathbb{R} is a **Baire space** (countable intersections of open, dense sets are still dense). Thus \mathbb{R} can not be written as a countable union of nowhere dense sets.

Lemma Any nonempty set which is bounded from above (resp. below) has a well-defined supremum (resp. infimum).

1.3.2 Functions

Proposition (Existence of Smooth Compactly Supported Functions) There exist smooth compactly supported functions, e.g. take

$$f(x) = e^{-\frac{1}{x^2}} \chi_{(0,\infty)}(x).$$

Lemma There is a function discontinuous precisely on \mathbb{Q} .

Proof $f(x) = \frac{1}{n}$ if $x = r_n \in \mathbb{Q}$ is an enumeration of the rationals, and zero otherwise. The limit at every point is 0.

Lemma There *do not* exist functions that are discontinuous precisely on $\mathbb{R} \setminus \mathbb{Q}$.

Proof D_f is always an F_σ set, which follows by considering the oscillation ω_f . $\omega_f(x) = 0 \iff f$ is continuous at x , and $D_f = \bigcup_n A_{\frac{1}{n}}$ where $A_\varepsilon = \{\omega_f \geq \varepsilon\}$ is closed.

Proposition A function $f : (a, b) \rightarrow \mathbb{R}$ is Lipschitz $\iff f$ is differentiable and f' is bounded. In this case, $|f'(x)| \leq C$, the Lipschitz constant.

1.4 Uniform Convergence

Theorem (Weierstrass Approximation) If $[a, b] \subset \mathbb{R}$ is a closed interval and f is continuous, then for every $\varepsilon > 0$ there exists a polynomial p_ε such that $\|f - p_\varepsilon\|_{L^\infty([a,b])} \xrightarrow{\varepsilon \rightarrow 0} 0$.

Theorem (Egorov) Let $E \subseteq \mathbb{R}^n$ be measurable with $m(E) > 0$ and $\{f_k : E \rightarrow \mathbb{R}\}$ be measurable functions such that

$$f(x) := \lim_{k \rightarrow \infty} f_k(x) < \infty$$

exists almost everywhere.

Then $f_k \rightarrow f$ *almost uniformly*, i.e.

$$\forall \varepsilon > 0, \exists F \subseteq E \text{ closed such that } m(E \setminus F) < \varepsilon \text{ and } f_k \xrightarrow{u} f \text{ on } F.$$

Proposition The space $X = C([0, 1])$, continuous functions $f : [0, 1] \rightarrow \mathbb{R}$, equipped with the norm $\|f\| = \sup_{x \in [0,1]} |f(x)|$, is a **complete** metric space.

Proof

1. Let $\{f_k\}$ be Cauchy in X .
2. Define a candidate limit using pointwise convergence:

Fix an x ; since

$$|f_k(x) - f_j(x)| \leq \|f_k - f_j\| \rightarrow 0$$

the sequence $\{f_k(x)\}$ is Cauchy in \mathbb{R} . So define $f(x) := \lim_k f_k(x)$.

3. Show that $\|f_k - f\| \rightarrow 0$:

$$|f_k(x) - f_j(x)| < \varepsilon \quad \forall x \implies \lim_j |f_k(x) - f_j(x)| < \varepsilon \quad \forall x$$

Alternatively, $\|f_k - f\| \leq \|f_k - f_N\| + \|f_N - f_j\|$, where N, j can be chosen large enough to bound each term by $\varepsilon/2$.

4. Show that $f \in X$:

The uniform limit of continuous functions is continuous.

Note: in other cases, you may need to show the limit is bounded, or has bounded derivative, or whatever other conditions define X .

Theorem (Uniform Limits of Continuous Functions are Continuous) A uniform limit of continuous functions is continuous.

Lemma (Testing Uniform Convergence) $f_n \rightarrow f$ uniformly iff there exists an M_n such that $\|f_n - f\|_\infty \leq M_n \rightarrow 0$.

Negating: find an x which depends on n for which the norm is bounded below.

Lemma (Uniform Limits Commute with Integrals) If $f_n \rightarrow f$ uniformly, then $\int f_n = \int f$.

Lemma (Uniform Convergence and Derivatives) If $f'_n \rightarrow g$ uniformly for some g and $f_n \rightarrow f$ pointwise (or at least at one point), then $g = f'$.

1.4.1 Series

Lemma (Pointwise Convergence for a Series of Functions) If $f_n(x) \leq M_n$ for a fixed x where $\sum M_n < \infty$, then the series $f(x) = \sum f_n(x)$ converges pointwise.

Lemma (Small Tails for Series of Functions) If $\sum f_n$ converges then $f_n \rightarrow 0$ uniformly.

Lemma (M-test for Series) If $|f_n(x)| \leq M_n$ which does not depend on x , then $\sum f_n$ converges uniformly.

Lemma (p-tests) Let n be a fixed dimension and set $B = \{x \in \mathbb{R}^n \mid \|x\| \leq 1\}$.

$$\begin{aligned}\sum \frac{1}{n^p} < \infty &\iff p > 1 \\ \int_\varepsilon^\infty \frac{1}{x^p} < \infty &\iff p > 1 \\ \int_0^1 \frac{1}{x^p} < \infty &\iff p < 1 \\ \int_B \frac{1}{|x|^p} < \infty &\iff p < n \\ \int_{B^c} \frac{1}{|x|^p} < \infty &\iff p > n\end{aligned}$$

2 Measure Theory

2.1 Useful Techniques

- $s = \inf \{x \in X\} \implies$ for every ε there is an $x \in X$ such that $x \leq s + \varepsilon$.
- Always consider bounded sets, and if E is unbounded write $E = \bigcup_n B_n(0) \cap E$ and use countable subadditivity or continuity of measure.

2.2 Definitions

Definition (Outer Measure) The outer measure of a set is given by

$$m_*(E) := \inf_{\substack{\{Q_i\} \supset E \\ \text{closed cubes}}} \sum |Q_i|.$$

Definition (Limsup and Liminf of Sets)

$$\begin{aligned} \limsup_n A_n &:= \bigcap_n \bigcup_{j \geq n} A_j = \left\{ x \mid x \in A_n \text{ for inf. many } n \right\} \\ \liminf_n A_n &:= \bigcup_n \bigcap_{j \geq n} A_j = \left\{ x \mid x \in A_n \text{ for all except fin. many } n \right\} \end{aligned}$$

Definition (Lebesgue Measurable Set) A subset $E \subseteq \mathbb{R}^n$ is *Lebesgue measurable* iff for every $\varepsilon > 0$ there exists an open set $O \supseteq E$ such that $m_*(O \setminus E) < \varepsilon$. In this case, we define $m(E) := m_*(E)$.

2.3 Theorems

Lemma Every open subset of \mathbb{R} (resp \mathbb{R}^n) can be written as a unique countable union of disjoint (resp. almost disjoint) intervals (resp. cubes).

Lemma (Properties of Outer Measure)

- Monotonicity: $E \subseteq F \implies m_*(E) \leq m_*(F)$.
- Countable Subadditivity: $m_*(\bigcup E_i) \leq \sum m_*(E_i)$.
- Approximation: For all E there exists a $G \supseteq E$ such that $m_*(G) \leq m_*(E) + \varepsilon$.
- Disjoint¹ Additivity: $m_*(A \amalg B) = m_*(A) + m_*(B)$.

Lemma (Subtraction of Measure)

$$m(A) = m(B) + m(C) \quad \text{and} \quad m(C) < \infty \implies m(A) - m(C) = m(B).$$

Lemma (Continuity of Measure)

$$\begin{aligned} E_i \nearrow E &\implies m(E_i) \longrightarrow m(E) \\ m(E_1) < \infty \text{ and } E_i \searrow E &\implies m(E_i) \longrightarrow m(E). \end{aligned}$$

Proof 1. Break into disjoint annuli $A_2 = E_2 \setminus E_1$, etc then apply countable disjoint additivity to $E = \amalg A_i$.

2. Use $E_1 = (\amalg E_j \setminus E_{j+1}) \amalg (\bigcap E_j)$, taking measures yields a telescoping sum, and use countable disjoint additivity.

¹This holds for outer measure **iff** $\text{dist}(A, B) > 0$.

Theorem Suppose E is measurable; then for every $\varepsilon > 0$,

1. There exists an open $O \supset E$ with $m(O \setminus E) < \varepsilon$
2. There exists a closed $F \subset E$ with $m(E \setminus F) < \varepsilon$
3. There exists a compact $K \subset E$ with $m(E \setminus K) < \varepsilon$.

Proof

- (1): Take $\{Q_i\} \rightrightarrows E$ and set $O = \bigcup Q_i$.
- (2): Since E^c is measurable, produce $O \supset E^c$ with $m(O \setminus E^c) < \varepsilon$.
 - Set $F = O^c$, so F is closed.
 - Then $F \subset E$ by taking complements of $O \supset E^c$
 - $E \setminus F = O \setminus E^c$ and taking measures yields $m(E \setminus F) < \varepsilon$
- (3): Pick $F \subset E$ with $m(E \setminus F) < \varepsilon/2$.
 - Set $K_n = F \cap \mathbb{D}_n$, a ball of radius n about 0.
 - Then $E \setminus K_n \searrow E \setminus F$
 - Since $m(E) < \infty$, there is an N such that $n \geq N \implies m(E \setminus K_n) < \varepsilon$.

Lemma Lebesgue measure is translation and dilation invariant.

Proof Obvious for cubes; if $Q_i \rightrightarrows E$ then $Q_i + k \rightrightarrows E + k$, etc.

Flesh out this proof.

Theorem (Non-Measurable Sets) There is a non-measurable set.

Proof

- Use AOC to choose one representative from every coset of \mathbb{R}/\mathbb{Q} on $[0, 1)$, which is countable, and assemble them into a set N
- Enumerate the rationals in $[0, 1]$ as q_j , and define $N_j = N + q_j$. These intersect trivially.
- Define $M := \bigsqcup N_j$, then $[0, 1) \subseteq M \subseteq [-1, 2)$, so the measure must be between 1 and 3. By translation invariance, $m(N_j) = m(N)$, and disjoint additivity forces $m(M) = 0$, a contradiction.

Proposition (Borel Characterization of Measurable Sets) If E is Lebesgue measurable, then $E = H \bigsqcup N$ where $H \in F_\sigma$ and N is null.

Useful technique: F_σ sets are Borel, so establish something for Borel sets and use this to extend it to Lebesgue.

Proof For every $\frac{1}{n}$ there exists a closed set $K_n \subset E$ such that $m(E \setminus K_n) \leq \frac{1}{n}$. Take $K = \bigcup K_n$, wlog $K_n \nearrow K$ so $m(K) = \lim m(K_n) = m(E)$. Take $N := E \setminus K$, then $m(N) = 0$.

Lemma If A_n are all measurable, $\limsup A_n$ and $\liminf A_n$ are measurable.

Proof Measurable sets form a sigma algebra, and these are expressed as countable unions/intersections of measurable sets.

Theorem (Borel-Cantelli) Let $\{E_k\}$ be a countable collection of measurable sets. Then

$$\sum_k m(E_k) < \infty \implies \text{almost every } x \in \mathbb{R} \text{ is in at most finitely many } E_k.$$

Proof

-
- If $E = \limsup_j E_j$ with $\sum m(E_j) < \infty$ then $m(E) = 0$.
 - If E_j are measurable, then $\limsup_j E_j$ is measurable.
 - If $\sum_j m(E_j) < \infty$, then $\sum_{j=N}^{\infty} m(E_j) \xrightarrow{N \rightarrow \infty} 0$ as the tail of a convergent sequence.
 - $E = \limsup_j E_j = \bigcap_{k=1}^{\infty} \bigcup_{j=k}^{\infty} E_j \implies E \subseteq \bigcup_{j=k}^{\infty} E_j$ for all k
 - $E \subseteq \bigcup_{j=k}^{\infty} E_j \implies m(E) \leq \sum_{j=k}^{\infty} m(E_j) \xrightarrow{k \rightarrow \infty} 0$.

Lemma

- Characteristic functions are measurable
- If f_n are measurable, so are $|f_n|$, $\limsup f_n$, $\liminf f_n$, $\lim f_n$,
- Sums and differences of measurable functions are measurable,
- Cones $F(x, y) = f(x)$ are measurable,
- Compositions $f \circ T$ for T a linear transformation are measurable,
- “Convolution-ish” transformations $(x, y) \mapsto f(x - y)$ are measurable

Proof (Convolution) Take the cone on f to get $F(x, y) = f(x)$, then compose F with the linear transformation $T = [1, -1; 1, 0]$.

3 Integration

Notation:

- “ f vanishes at infinity” means $f(x) \xrightarrow{|x| \rightarrow \infty} 0$.
- “ f has small tails” means $\int_{|x| \geq N} f \xrightarrow{N \rightarrow \infty} 0$.

3.1 Useful Techniques

- Break integration domain up into disjoint annuli.
- Break integrals or sums into $x < 1$ and $x \geq 1$.
- Calculus techniques: Taylor series, IVT, ...
- Approximate by dense subsets of functions
- Useful facts about compactly supported continuous functions:
 - Uniformly continuous
 - Bounded

3.2 Definitions

Definition (\$L^+\$) $f \in L^+$ iff f is measurable and non-negative.

Definition (Integrable) A measurable function is integrable iff $\|f\|_1 < \infty$.

Definition (The Infinity Norm)

$$\|f\|_\infty := \inf_{\alpha \geq 0} \left\{ \alpha \mid m\{|f| \geq \alpha\} = 0 \right\}.$$

Definition (Essentially Bounded Functions) A function $f : X \rightarrow \mathbb{C}$ is *essentially bounded* iff there exists a real number c such that $\mu(\{|f| > c\}) = 0$, i.e. $\|f\|_\infty < \infty$.

If $f \in L^\infty(X)$, then f is equal to some bounded function g almost everywhere.

Definition (L infty)

$$L^\infty(X) := \left\{ f : X \rightarrow \mathbb{C} \mid f \text{ is essentially bounded} \right\} := \left\{ f : X \rightarrow \mathbb{C} \mid \|f\|_\infty < \infty \right\},$$

Example:

- $f(x) = x\chi_{\mathbb{Q}}(x)$ is essentially bounded but not bounded.

3.3 Theorems

Useful facts about C_c functions:

- Bounded almost everywhere
- Uniformly continuous

Theorem (p-Test for Integrals in \mathbb{R})

$$\begin{aligned} \int_0^1 \frac{1}{x^p} < \infty &\iff p < 1 \\ \int_1^\infty \frac{1}{x^p} < \infty &\iff p > 1. \end{aligned}$$

Slogan: big powers of x help us in neighborhoods of infinity and hurt around zero

Some integrable functions:

- $\int \frac{1}{1+x^2} = \arctan(x) \xrightarrow{x \rightarrow \infty} \pi/2 < \infty$
- Any bounded function (or continuous on a compact set, by EVT)
- $\int_0^1 \frac{1}{\sqrt{x}} < \infty$
- $\int_0^1 \frac{1}{x^{1-\varepsilon}} < \infty$
- $\int_1^\infty \frac{1}{x^{1+\varepsilon}} < \infty$

Some non-integrable functions:

- $\int_0^1 \frac{1}{x} = \infty$.

- $\int_1^\infty \frac{1}{x} = \infty.$
- $\int_1^\infty \frac{1}{\sqrt{x}} = \infty$
- $\int_1^\infty \frac{1}{x^{1-\varepsilon}} = \infty$
- $\int_0^1 \frac{1}{x^{1+\varepsilon}} = \infty$

3.3.1 Convergence Theorems

Theorem (Monotone Convergence) If $f_n \in L^+$ and $f_n \nearrow f$ a.e., then

$$\lim \int f_n = \int \lim f_n = \int f \quad \text{i.e.} \quad \int f_n \longrightarrow \int f.$$

Needs to be positive and increasing.

Theorem (Dominated Convergence) If $f_n \in L^1$ and $f_n \longrightarrow f$ a.e. with $|f_n| \leq g$ for some $g \in L^1$, then $f \in L^1$ and

$$\lim \int f_n = \int \lim f_n = \int f \quad \text{i.e.} \quad \int f_n \longrightarrow \int f < \infty,$$

and more generally,

$$\int |f_n - f| \longrightarrow 0.$$

Positivity *not* needed.

Theorem (Generalized DCT) If

- $f_n \in L^1$ with $f_n \longrightarrow f$ a.e.,
- There exist $g_n \in L^1$ with $|f_n| \leq g_n$, $g_n \geq 0$.
- $g_n \longrightarrow g$ a.e. with $g \in L^1$, and
- $\lim \int g_n = \int g$,

then $f \in L^1$ and $\lim \int f_n = \int f < \infty$.

Note that this is the DCT with $|f_n| < |g|$ relaxed to $|f_n| < g_n \longrightarrow g \in L^1$.

Proof (Generalized DCT) Proceed by showing $\limsup \int f_n \leq \int f \leq \liminf \int f_n$:

- $\int f \geq \limsup \int f_n$:

$$\begin{aligned}
\int g - \int f &= \int (g - f) \\
&\leq \liminf \int (g_n - f_n) \quad \text{Fatou} \\
&= \lim \int g_n + \liminf \int (-f_n) \\
&= \lim \int g_n - \limsup \int f_n \\
&= \int g - \limsup \int f_n
\end{aligned}$$

$$\implies \int f \geq \limsup \int f_n.$$

- Here we use $g_n - f_n \xrightarrow{n \rightarrow \infty} g - f$ with $0 \leq |f_n| - f_n \leq g_n - f_n$, so $g_n - f_n$ are nonnegative (and measurable) and Fatou's lemma applies.

- $\int f \leq \liminf \int f_n$:

$$\begin{aligned}
\int g + \int f &= \int (g + f) \\
&\leq \liminf \int (g_n + f_n) \\
&= \lim \int g_n + \liminf \int f_n \\
&= \int g + \liminf \int f_n
\end{aligned}$$

$$\int f \leq \liminf \int f_n.$$

- Here we use that $g_n + f_n \rightarrow g + f$ with $0 \leq |f_n| + f_n \leq g_n + f_n$ so Fatou's lemma again applies.

Lemma (Converges in L^1 implies convergence of L^1 norms) If $f \in L^1$, then

$$\int |f_n - f| \rightarrow 0 \iff \int |f_n| \rightarrow \int |f|.$$

Proof Let $g_n = |f_n| - |f_n - f|$, then $g_n \rightarrow |f|$ and

$$|g_n| = ||f_n| - |f_n - f|| \leq |f_n - (f_n - f)| = |f| \in L^1,$$

so the DCT applies to g_n and

$$\begin{aligned}
\|f_n - f\|_1 &= \int |f_n - f| + |f_n| - |f_n| = \int |f_n| - g_n \\
&\xrightarrow{DCT} \lim \int |f_n| - \int |f|.
\end{aligned}$$

Theorem (Fatou's Lemma) If f_n is a sequence of nonnegative measurable functions, then

$$\begin{aligned} \int \liminf_n f_n &\leq \liminf_n \int f_n \\ \limsup_n \int f_n &\leq \int \limsup_n f_n. \end{aligned}$$

Theorem (Tonelli) For $f(x, y)$ **non-negative and measurable**, for almost every $x \in \mathbb{R}^n$,

- $f_x(y)$ is a **measurable** function
- $F(x) = \int f(x, y) dy$ is a **measurable** function,
- For E measurable, the slices $E_x := \{y \mid (x, y) \in E\}$ are measurable.
- $\int f = \int \int F$, i.e. any iterated integral is equal to the original.

Theorem (Fubini) For $f(x, y)$ **integrable**, for almost every $x \in \mathbb{R}^n$,

- $f_x(y)$ is an **integrable** function
- $F(x) := \int f(x, y) dy$ is an **integrable** function,
- For E measurable, the slices $E_x := \{y \mid (x, y) \in E\}$ are measurable.
- $\int f = \int \int f(x, y)$, i.e. any iterated integral is equal to the original

Theorem (Fubini/Tonelli) If any iterated integral is **absolutely integrable**, i.e. $\int \int |f(x, y)| < \infty$, then f is integrable and $\int f$ equals any iterated integral.

Corollary (Measurable Slices) Let E be a measurable subset of \mathbb{R}^n . Then

- For almost every $x \in \mathbb{R}^{n_1}$, the slice $E_x := \{y \in \mathbb{R}^{n_2} \mid (x, y) \in E\}$ is measurable in \mathbb{R}^{n_2} .
- The function

$$\begin{aligned} F : \mathbb{R}^{n_1} &\longrightarrow \mathbb{R} \\ x &\mapsto m(E_x) = \int_{\mathbb{R}^{n_2}} \chi_{E_x} dy \end{aligned}$$

is measurable and

$$m(E) = \int_{\mathbb{R}^{n_1}} m(E_x) dx = \int_{\mathbb{R}^{n_1}} \int_{\mathbb{R}^{n_2}} \chi_{E_x} dy dx$$

Proof (Measurable Slices)

$\implies :$

- Let f be measurable on \mathbb{R}^n .
- Then the cylinders $F(x, y) = f(x)$ and $G(x, y) = f(y)$ are both measurable on \mathbb{R}^{n+1} .
- Write $\mathcal{A} = \{G \leq F\} \cap \{G \geq 0\}$; both are measurable.

$\impliedby :$

- Let A be measurable in \mathbb{R}^{n+1} .
- Define $A_x = \{y \in \mathbb{R} \mid (x, y) \in A\}$, then $m(A_x) = f(x)$.
- By the corollary, A_x is measurable set, $x \mapsto A_x$ is a measurable function, and $m(A) = \int f(x) dx$.
- Then explicitly, $f(x) = \chi_A$, which makes f a measurable function.

Proposition (Differentiating Under an Integral) If $\left| \frac{\partial}{\partial t} f(x, t) \right| \leq g(x) \in L^1$, then letting $F(t) = \int f(x, t) dt$,

$$\begin{aligned} \frac{\partial}{\partial t} F(t) &:= \lim_{h \rightarrow 0} \int \frac{f(x, t+h) - f(x, t)}{h} dx \\ &\stackrel{DCT}{=} \int \frac{\partial}{\partial t} f(x, t) dx. \end{aligned}$$

To justify passing the limit, let $h_k \rightarrow 0$ be any sequence and define

$$f_k(x, t) = \frac{f(x, t + h_k) - f(x, t)}{h_k},$$

$$\text{so } f_k \xrightarrow{\text{pointwise}} \frac{\partial}{\partial t} f.$$

Apply the MVT to f_k to get $f_k(x, t) = f_k(\xi, t)$ for some $\xi \in [0, h_k]$, and show that $f_k(\xi, t) \in L^1$.

Proposition (Swapping Sum and Integral) If f_n are non-negative and $\sum \int |f|_n < \infty$, then $\sum \int f_n = \int \sum f_n$.

Proof MCT. Let $F_N = \sum_{n=1}^N f_n$ be a finite partial sum; then there are simple functions $\varphi_n \nearrow f_n$ and so $\sum_{n=1}^N \varphi_n \nearrow F_N$, so apply MCT.

Lemma If $f_k \in L^1$ and $\sum \|f_k\|_1 < \infty$ then $\sum f_k$ converges almost everywhere and in L^1 .

Proof Define $F_N = \sum_{k=1}^N f_k$ and $F = \lim_N F_N$, then $\|F_N\|_1 \leq \sum_{k=1}^N \|f_k\|_1 < \infty$ so $F \in L^1$ and $\|F_N - F\|_1 \rightarrow 0$ so the sum converges in L^1 . Almost everywhere convergence: ?

3.4 L^1 Facts

Lemma (Translation Invariance) The Lebesgue integral is translation invariant, i.e. $\int f(x) dx = \int f(x+h) dx$ for any h .

Proof

- For characteristic functions, $\int_E f(x+h) = \int_{E+h} f(x) = m(E+h) = m(E) = \int_E f$ by translation invariance of measure.
- So this also holds for simple functions by linearity

- For $f \in L^+$, choose $\varphi_n \nearrow f$ so $\int \varphi_n \rightarrow \int f$.
- Similarly, $\tau_h \varphi_n \nearrow \tau_h f$ so $\int \tau_h f \rightarrow \int f$
- Finally $\left\{ \int \tau_h \varphi \right\} = \left\{ \int \varphi \right\}$ by step 1, and the suprema are equal by uniqueness of limits.

Lemma (Integrals Distribute Over Disjoint Sets) If $X \subseteq A \cup B$, then $\int_X f \leq \int_A f + \int_{A^c} f$ with equality iff $X = A \sqcup B$.

Lemma (Unif. Cts. L^1 Functions Vanish at Infinity) If $f \in L^1$ and f is uniformly continuous, then $f(x) \xrightarrow{|x| \rightarrow \infty} 0$.

Doesn't hold for general L^1 functions, take any train of triangles with height 1 and summable areas.

Lemma (L^1 Functions Have Small Tails) If $f \in L^1$, then for every ε there exists a radius R such that if $A = B_R(0)^c$, then $\int_A |f| < \varepsilon$.

Proof Approximate with compactly supported functions. Take $g \xrightarrow{L^1} f$ with $g \in C_c$, then choose N large enough so that $g = 0$ on $E := B_N(0)^c$, then $\int_E |f| \leq \int_E |f - g| + \int_E |g|$.

Lemma (L^1 Functions Have Absolutely Continuity) $m(E) \rightarrow 0 \implies \int_E f \rightarrow 0$.

Proof Approximate with compactly supported functions. Take $g \xrightarrow{L^1} f$, then $g \leq M$ so $\int_E f \leq \int_E f - g + \int_E g \rightarrow 0 + M \cdot m(E) \rightarrow 0$.

Lemma (L^1 Functions Are Finite Almost Everywhere) If $f \in L^1$, then $m(\{f(x) = \infty\}) = 0$.

Proof Idea: Split up domain Let $A = \{f(x) = \infty\}$, then $\infty > \int f = \int_A f + \int_{A^c} f = \infty \cdot m(A) + \int_{A^c} f \implies m(X) = 0$.

Proposition (Continuity in L^1)

$$\|\tau_h f - f\|_1 \xrightarrow{h \rightarrow 0} 0$$

Proof Approximate with compactly supported functions. Take $g \xrightarrow{L^1} f$ with $g \in C_c$.

$$\begin{aligned} \int f(x+h) - f(x) &\leq \int f(x+h) - g(x+h) + \int g(x+h) - g(x) + \int g(x) - f(x) \\ &\xrightarrow{??} 2\varepsilon + \int g(x+h) - g(x) \\ &= \int_K g(x+h) - g(x) + \int_{K^c} g(x+h) - g(x) \\ &\xrightarrow{??} 0, \end{aligned}$$

which follows because we can enlarge the support of g to K where the integrand is zero on K^c , then apply uniform continuity on K .

Proposition (Integration by Parts, Special Case)

$$F(x) := \int_0^x f(y)dy \quad \text{and} \quad G(x) := \int_0^x g(y)dy$$

$$\implies \int_0^1 F(x)g(x)dx = F(1)G(1) - \int_0^1 f(x)G(x)dx.$$

Proof Fubini-Tonelli, and sketch region to change integration bounds.**Theorem (Lebesgue Density)**

$$A_h(f)(x) := \frac{1}{2h} \int_{x-h}^{x+h} f(y)dy \implies \|A_h(f) - f\| \xrightarrow{h \rightarrow 0} 0.$$

Proof Fubini-Tonelli, and sketch region to change integration bounds, and continuity in L^1 .**3.5 L^p Spaces****Lemma** The following are dense subspaces of $L^2([0, 1])$:

- Simple functions
- Step functions
- $C_0([0, 1])$
- Smoothly differentiable functions $C_0^\infty([0, 1])$
- Smooth compactly supported functions C_c^∞ Theorem :

$$m(X) < \infty \implies \lim_{p \rightarrow \infty} \|f\|_p = \|f\|_\infty.$$

Proof

- Let $M = \|f\|_\infty$.
- For any $L < M$, let $S = \{|f| \geq L\}$.
- Then $m(S) > 0$ and

$$\begin{aligned} \|f\|_p &= \left(\int_X |f|^p \right)^{\frac{1}{p}} \\ &\geq \left(\int_S |f|^p \right)^{\frac{1}{p}} \\ &\geq L m(S)^{\frac{1}{p}} \xrightarrow{p \rightarrow \infty} L \\ &\implies \liminf_p \|f\|_p \geq M. \end{aligned}$$

We also have

$$\begin{aligned} \|f\|_p &= \left(\int_X |f|^p \right)^{\frac{1}{p}} \\ &\leq \left(\int_X M^p \right)^{\frac{1}{p}} \\ &= M m(X)^{\frac{1}{p}} \xrightarrow{p \rightarrow \infty} M \\ &\implies \limsup_p \|f\|_p \leq M \blacksquare. \end{aligned}$$

Theorem (Dual Lp Spaces) For $p \neq \infty$, $(L^p)^\vee \cong L^q$.

Proof (p=1) ?

Proof (p=2) Use Riesz Representation for Hilbert spaces.

Proof .

$L^1 \subset (L^\infty)^\vee$, since the isometric mapping is always injective, but *never* surjective. ■

4 Fourier Transform and Convolution

4.1 The Fourier Transform

Definition (Convolution)

$$f * g(x) = \int f(x-y)g(y)dy.$$

Definition (The Fourier Transform)

$$\hat{f}(\xi) = \int f(x) e^{2\pi i x \cdot \xi} dx.$$

Lemma If $\hat{f} = \hat{g}$ then $f = g$ almost everywhere.

Lemma (Riemann-Lebesgue: Fourier transforms have small tails)

$$f \in L^1 \implies \hat{f}(\xi) \rightarrow 0 \text{ as } |\xi| \rightarrow \infty,$$

if $f \in L^1$, then \hat{f} is continuous and bounded.

Proof

- Boundedness:

$$|\hat{f}(\xi)| \leq \int |f| \cdot |e^{2\pi i x \cdot \xi}| = \|f\|_1.$$

- Continuity:

$$\begin{aligned} & - |\hat{f}(\xi_n) - \hat{f}(\xi)| \\ & - \text{Apply DCT to show } a \xrightarrow{n \rightarrow \infty} 0. \end{aligned}$$

Theorem (Fourier Inversion)

$$f(x) = \int_{\mathbb{R}^n} \hat{f}(\xi) e^{2\pi i x \cdot \xi} d\xi.$$

Proof Idea: Fubini-Tonelli doesn't work directly, so introduce a convergence factor, take limits, and use uniqueness of limits.

- Take the modified integral:

$$\begin{aligned}
 I_t(x) &= \int \widehat{f}(\xi) e^{2\pi i x \cdot \xi} e^{-\pi t^2 |\xi|^2} \\
 &= \int \widehat{f}(\xi) \varphi(\xi) \\
 &= \int f(\xi) \widehat{\varphi}(\xi) \\
 &= \int f(\xi) \widehat{g}_t(\xi - x) \\
 &= \int f(\xi) g_t(x - \xi) d\xi \\
 &= \int f(y - x) g_t(y) dy \quad (\xi = y - x) \\
 &= (f * g_t) \\
 &\longrightarrow f \text{ in } L^1 \text{ as } t \longrightarrow 0.
 \end{aligned}$$

- We also have

$$\begin{aligned}
 \lim_{t \rightarrow 0} I_t(x) &= \lim_{t \rightarrow 0} \int \widehat{f}(\xi) e^{2\pi i x \cdot \xi} e^{-\pi t^2 |\xi|^2} \\
 &= \lim_{t \rightarrow 0} \int \widehat{f}(\xi) \varphi(\xi) \\
 &=_{DCT} \int \widehat{f}(\xi) \lim_{t \rightarrow 0} \varphi(\xi) \\
 &= \int \widehat{f}(\xi) e^{2\pi i x \cdot \xi}
 \end{aligned}$$

- So

$$I_t(x) \longrightarrow \int \widehat{f}(\xi) e^{2\pi i x \cdot \xi} \text{ pointwise and } \|I_t(x) - f(x)\|_1 \longrightarrow 0.$$

- So there is a subsequence I_{t_n} such that $I_{t_n}(x) \longrightarrow f(x)$ almost everywhere
- Thus $f(x) = \int \widehat{f}(\xi) e^{2\pi i x \cdot \xi}$ almost everywhere by uniqueness of limits.

Proposition (Eigenfunction of the Fourier Transform)

$$g(x) := e^{-\pi |t|^2} \implies \widehat{g}(\xi) = g(\xi) \quad \text{and} \quad \widehat{g}_t(x) = g(tx) = e^{-\pi t^2 |x|^2}.$$

Proposition (Properties of the Fourier Transform)

?????.

4.2 Approximate Identities

Definition (Dilation)

$$\varphi_t(x) = t^{-n} \varphi(t^{-1}x).$$

Definition (Approximation to the Identity) For $\varphi \in L^1$, the dilations satisfy $\int \varphi_t = \int \varphi$, and if $\int \varphi = 1$ then φ is an *approximate identity*.

Example: $\varphi(x) = e^{-\pi x^2}$

Theorem (Convolution Against Approximate Identities Converge in L^1)

$$\|f * \varphi_t - f\|_1 \xrightarrow{t \rightarrow 0} 0.$$

Proof

$$\begin{aligned} \|f - f * \varphi_t\|_1 &= \int |f(x) - \int f(x-y)\varphi_t(y) dy| dx \\ &= \int |f(x)| \int \varphi_t(y) dy - \int |f(x-y)\varphi_t(y)| dy dx \\ &= \int \int \varphi_t(y) |f(x) - f(x-y)| dy dx \\ &=_{FT} \int \int \varphi_t(y) |f(x) - f(x-y)| dx dy \\ &= \int \varphi_t(y) \int |f(x) - f(x-y)| dx dy \\ &= \int \varphi_t(y) \|f - \tau_y f\|_1 dy \\ &= \int_{y < \delta} \varphi_t(y) \|f - \tau_y f\|_1 dy + \int_{y \geq \delta} \varphi_t(y) \|f - \tau_y f\|_1 dy \\ &\leq \int_{y < \delta} \varphi_t(y) \varepsilon + \int_{y \geq \delta} \varphi_t(y) (\|f\|_1 + \|\tau_y f\|_1) dy \quad \text{by continuity in } L^1 \\ &\leq \varepsilon + 2\|f\|_1 \int_{y \geq \delta} \varphi_t(y) dy \\ &\leq \varepsilon + 2\|f\|_1 \cdot \varepsilon \quad \text{since } \varphi_t \text{ has small tails} \\ &\xrightarrow{\varepsilon \rightarrow 0} 0. \end{aligned}$$

Theorem (Convolutions Vanish at Infinity)

$$f, g \in L^1 \text{ and bounded} \implies \lim_{|x| \rightarrow \infty} (f * g)(x) = 0.$$

Proof

- Choose $M \geq f, g$.
- By small tails, choose N such that $\int_{B_N^c} |f|, \int_{B_N^c} |g| < \varepsilon$

- Note

$$|f * g| \leq \int |f(x-y)| |g(y)| dy := I.$$

- Use $|x| \leq |x-y| + |y|$, take $|x| \geq 2N$ so either

$$|x-y| \geq N \implies I \leq \int_{\{x-y \geq N\}} |f(x-y)| M dy \leq \varepsilon M \longrightarrow 0$$

then

$$|y| \geq N \implies I \leq \int_{\{y \geq N\}} M |g(y)| dy \leq M\varepsilon \longrightarrow 0.$$

Proposition (Young's Inequality?) :

$$\frac{1}{r} := \frac{1}{p} + \frac{1}{q} - 1 \implies \|f * g\|_r \leq \|f\|_p \|g\|_q.$$

Corollary Take $q = 1$ to obtain

$$\|f * g\|_p \leq \|f\|_p \|g\|_1.$$

Corollary If $f, g \in L^1$ then $f * g \in L^1$.

5 Functional Analysis

5.1 Definitions

Notation: H denotes a Hilbert space.

Definition (Orthonormal Sequence) ?

Definition (Basis) A set $\{u_n\}$ is a *basis* for a Hilbert space \mathcal{H} iff it is dense in \mathcal{H} .

Definition (Complete) A collection of vectors $\{u_n\} \subset H$ is *complete* iff $\langle x, u_n \rangle = 0$ for all $n \iff x = 0$ in H .

Definition (Dual Space)

$$X^\vee := \left\{ L : X \longrightarrow \mathbb{C} \mid L \text{ is continuous} \right\}.$$

Definition A map $L : X \longrightarrow \mathbb{C}$ is a linear functional iff

$$L(\alpha \mathbf{x} + \mathbf{y}) = \alpha L(\mathbf{x}) + L(\mathbf{y}).$$

Definition (Operator Norm)

$$\|L\|_{X^\vee} := \sup_{\substack{x \in X \\ \|x\|=1}} |L(x)|.$$

Definition (Banach Space) A complete normed vector space.

Definition (Hilbert Space) An inner product space which is a Banach space under the induced norm.

5.2 Theorems

Theorem (Bessel's Inequality) For any orthonormal set $\{u_n\} \subseteq \mathcal{H}$ a Hilbert space (not necessarily a basis),

$$\left\| x - \sum_{n=1}^N \langle x, u_n \rangle u_n \right\|^2 = \|x\|^2 - \sum_{n=1}^N |\langle x, u_n \rangle|^2$$

and thus

$$\sum_{n=1}^{\infty} |\langle x, u_n \rangle|^2 \leq \|x\|^2.$$

Proof

- Let $S_N = \sum_{n=1}^N \langle x, u_n \rangle u_n$

$$\begin{aligned} \|x - S_N\|^2 &= \langle x - S_N, x - S_N \rangle \\ &= \|x\|^2 + \|S_N\|^2 - 2\Re \langle x, S_N \rangle \\ &= \|x\|^2 + \|S_N\|^2 - 2\Re \left\langle x, \sum_{n=1}^N \langle x, u_n \rangle u_n \right\rangle \\ &= \|x\|^2 + \|S_N\|^2 - 2\Re \sum_{n=1}^N \langle x, \langle x, u_n \rangle u_n \rangle \\ &= \|x\|^2 + \|S_N\|^2 - 2\Re \sum_{n=1}^N \overline{\langle x, u_n \rangle} \langle x, u_n \rangle \\ &= \|x\|^2 + \left\| \sum_{n=1}^N \langle x, u_n \rangle u_n \right\|^2 - 2 \sum_{n=1}^N |\langle x, u_n \rangle|^2 \\ &= \|x\|^2 + \sum_{n=1}^N |\langle x, u_n \rangle|^2 - 2 \sum_{n=1}^N |\langle x, u_n \rangle|^2 \\ &= \|x\|^2 - \sum_{n=1}^N |\langle x, u_n \rangle|^2. \end{aligned}$$

- By continuity of the norm and inner product, we have

$$\begin{aligned} \lim_{N \rightarrow \infty} \|x - S_N\|^2 &= \lim_{N \rightarrow \infty} \|x\|^2 - \sum_{n=1}^N |\langle x, u_n \rangle|^2 \\ \implies \left\| x - \lim_{N \rightarrow \infty} S_N \right\|^2 &= \|x\|^2 - \lim_{N \rightarrow \infty} \sum_{n=1}^N |\langle x, u_n \rangle|^2 \\ \implies \left\| x - \sum_{n=1}^{\infty} \langle x, u_n \rangle u_n \right\|^2 &= \|x\|^2 - \sum_{n=1}^{\infty} |\langle x, u_n \rangle|^2. \end{aligned}$$

- Then noting that $0 \leq \|x - S_N\|^2$,

$$0 \leq \|x\|^2 - \sum_{n=1}^{\infty} |\langle x, u_n \rangle|^2$$

$$\implies \sum_{n=1}^{\infty} |\langle x, u_n \rangle|^2 \leq \|x\|^2 \blacksquare.$$

Theorem (Riesz Representation for Hilbert Spaces) If Λ is a continuous linear functional on a Hilbert space H , then there exists a unique $y \in H$ such that

$$\forall x \in H, \quad \Lambda(x) = \langle x, y \rangle.$$

Proof

- Define $M := \ker \Lambda$.
- Then M is a closed subspace and so $H = M \oplus M^\perp$.
- There is some $z \in M^\perp$ such that $\|z\| = 1$.
- Set $u := \Lambda(x)z - \Lambda(z)x$.
- Check

$$\Lambda(u) = \Lambda(\Lambda(x)z - \Lambda(z)x) = \Lambda(x)\Lambda(z) - \Lambda(z)\Lambda(x) = 0 \implies u \in M$$

- Compute

$$\begin{aligned} 0 &= \langle u, z \rangle \\ &= \langle \Lambda(x)z - \Lambda(z)x, z \rangle \\ &= \langle \Lambda(x)z, z \rangle - \langle \Lambda(z)x, z \rangle \\ &= \Lambda(x)\langle z, z \rangle - \Lambda(z)\langle x, z \rangle \\ &= \Lambda(x)\|z\|^2 - \Lambda(z)\langle x, z \rangle \\ &= \Lambda(x) - \Lambda(z)\langle x, z \rangle \\ &= \Lambda(x) - \langle x, \overline{\Lambda(z)}z \rangle, \end{aligned}$$

- Choose $y := \overline{\Lambda(z)}z$.
- Check uniqueness:

$$\begin{aligned} \langle x, y \rangle &= \langle x, y' \rangle \quad \forall x \\ \implies \langle x, y - y' \rangle &= 0 \quad \forall x \\ \implies \langle y - y', y - y' \rangle &= 0 \\ \implies \|y - y'\| &= 0 \\ \implies y - y' &= \mathbf{0} \implies y = y'. \end{aligned}$$

Theorem (Continuous iff Bounded) Let $L : X \longrightarrow \mathbb{C}$ be a linear functional, then the following are equivalent:

1. L is continuous
2. L is continuous at zero
3. L is bounded, i.e. $\exists c \geq 0 \mid |L(x)| \leq c\|x\|$ for all $x \in H$

Proof

2 \implies 3: Choose $\delta < 1$ such that

$$\|x\| \leq \delta \implies |L(x)| < 1.$$

Then

$$\begin{aligned} |L(x)| &= \left| L\left(\frac{\|x\|}{\delta} \frac{\delta}{\|x\|} x\right) \right| \\ &= \frac{\|x\|}{\delta} \left| L\left(\delta \frac{x}{\|x\|}\right) \right| \\ &\leq \frac{\|x\|}{\delta} 1, \end{aligned}$$

so we can take $c = \frac{1}{\delta}$. ■

3 \implies 1:

We have $|L(x - y)| \leq c\|x - y\|$, so given $\varepsilon \geq 0$ simply choose $\delta = \frac{\varepsilon}{c}$.

Theorem (Operator Norm is a Norm) If H is a Hilbert space, then $(H^\vee, \|\cdot\|_{\text{op}})$ is a normed space.

Proof The only nontrivial property is the triangle inequality, but

$$\|L_1 + L_2\|_{\text{op}} = \sup |L_1(x) + L_2(x)| \leq \sup |L_1(x)| + \sup |L_2(x)| = \|L_1\|_{\text{op}} + \|L_2\|_{\text{op}}.$$

Theorem (Completeness in Operator Norm) If X is a normed vector space, then $(X^\vee, \|\cdot\|_{\text{op}})$ is a Banach space.

Proof

- Let $\{L_n\}$ be Cauchy in X^\vee .
- Then for all $x \in C$, $\{L_n(x)\} \subset \mathbb{C}$ is Cauchy and converges to something denoted $L(x)$.
- Need to show L is continuous and $\|L_n - L\| \longrightarrow 0$.
- Since $\{L_n\}$ is Cauchy in X^\vee , choose N large enough so that

$$n, m \geq N \implies \|L_n - L_m\| < \varepsilon \implies |L_m(x) - L_n(x)| < \varepsilon \quad \forall x \mid \|x\| = 1.$$

- Take $n \longrightarrow \infty$ to obtain

$$\begin{aligned} m \geq N \implies |L_m(x) - L(x)| &< \varepsilon \quad \forall x \mid \|x\| = 1 \\ \implies \|L_m - L\| &< \varepsilon \longrightarrow 0. \end{aligned}$$

- Continuity:

$$\begin{aligned}
|L(x)| &= |L(x) - L_n(x) + L_n(x)| \\
&\leq |L(x) - L_n(x)| + |L_n(x)| \\
&\leq \varepsilon \|x\| + c \|x\| \\
&= (\varepsilon + c) \|x\| \blacksquare.
\end{aligned}$$

Theorem (Riesz-Fischer) Let $U = \{u_n\}_{n=1}^\infty$ be an orthonormal set (not necessarily a basis), then

1. There is an isometric surjection

$$\begin{aligned}
\mathcal{H} &\longrightarrow \ell^2(\mathbb{N}) \\
\mathbf{x} &\mapsto \{\langle \mathbf{x}, \mathbf{u}_n \rangle\}_{n=1}^\infty
\end{aligned}$$

i.e. if $\{a_n\} \in \ell^2(\mathbb{N})$, so $\sum |a_n|^2 < \infty$, then there exists a $\mathbf{x} \in \mathcal{H}$ such that

$$a_n = \langle \mathbf{x}, \mathbf{u}_n \rangle \quad \forall n.$$

2. \mathbf{x} can be chosen such that

$$\|\mathbf{x}\|^2 = \sum |a_n|^2$$

Note: the choice of \mathbf{x} is unique $\iff \{u_n\}$ is **complete**, i.e. $\langle \mathbf{x}, \mathbf{u}_n \rangle = 0$ for all n implies $\mathbf{x} = \mathbf{0}$.

Proof

- Given $\{a_n\}$, define $S_N = \sum_{n=1}^N a_n \mathbf{u}_n$.
- S_N is Cauchy in \mathcal{H} and so $S_N \longrightarrow \mathbf{x}$ for some $\mathbf{x} \in \mathcal{H}$.
- $\langle x, \mathbf{u}_n \rangle = \langle x - S_N, \mathbf{u}_n \rangle + \langle S_N, \mathbf{u}_n \rangle \longrightarrow a_n$
- By construction, $\|x - S_N\|^2 = \|x\|^2 - \sum_{n=1}^N |a_n|^2 \longrightarrow 0$, so $\|x\|^2 = \sum_{n=1}^\infty |a_n|^2$.

6 Extra Problems

6.1 Greatest Hits

- ★: Show that for $E \subseteq \mathbb{R}^n$, TFAE:
 1. E is measurable
 2. $E = H \bigcup Z$ here H is F_σ and Z is null
 3. $E = V \setminus Z'$ where $V \in G_\delta$ and Z' is null.
- ★: Show that if $E \subseteq \mathbb{R}^n$ is measurable then $m(E) = \sup \left\{ m(K) \mid K \subset E \text{ compact} \right\}$ iff for all $\varepsilon > 0$ there exists a compact $K \subseteq E$ such that $m(K) \geq m(E) - \varepsilon$.
- ★: Show that cylinder functions are measurable, i.e. if f is measurable on \mathbb{R}^s , then $F(x, y) := f(x)$ is measurable on $\mathbb{R}^s \times \mathbb{R}^t$ for any t .

- \star : Prove that the Lebesgue integral is translation invariant, i.e. if $\tau_h(x) = x + h$ then $\int \tau_h f = \int f$.
- \star : Prove that the Lebesgue integral is dilation invariant, i.e. if $f_\delta(x) = \frac{f(\frac{x}{\delta})}{\delta^n}$ then $\int f_\delta = \int f$.
- \star : Prove continuity in L^1 , i.e.

$$f \in L^1 \implies \lim_{h \rightarrow 0} \int |f(x+h) - f(x)| = 0.$$

- \star : Show that

$$f, g \in L^1 \implies f * g \in L^1 \quad \text{and} \quad \|f * g\|_1 \leq \|f\|_1 \|g\|_1.$$

6.2 By Topic

6.2.1 Topology

- Show that every compact set is closed and bounded.
- Show that if a subset of a metric space is complete and totally bounded, then it is compact.
- Show that if K is compact and F is closed with K, F disjoint then $\text{dist}(K, F) > 0$.

6.2.2 Continuity

- Show that a continuous function on a compact set is uniformly continuous.

6.2.3 Differentiation

- Show that if $f \in C^1(\mathbb{R})$ and both $\lim_{x \rightarrow \infty} f(x)$ and $\lim_{x \rightarrow \infty} f'(x)$ exist, then $\lim_{x \rightarrow \infty} f'(x)$ must be zero.

6.2.4 Advanced Limitology

- If f is continuous, is it necessarily the case that f' is continuous?
- If $f_n \rightarrow f$, is it necessarily the case that f'_n converges to f' (or at all)?
- Is it true that the sum of differentiable functions is differentiable?
- Is it true that the limit of integrals equals the integral of the limit?
- Is it true that a limit of continuous functions is continuous?
- Show that a subset of a metric space is closed iff it is complete.
- Show that if $m(E) < \infty$ and $f_n \rightarrow f$ uniformly, then $\lim \int_E f_n = \int_E f$.

Uniform Convergence

- Show that a uniform limit of bounded functions is bounded.
- Show that a uniform limit of continuous function is continuous.
 - I.e. if $f_n \rightarrow f$ uniformly with each f_n continuous then f is continuous.
- Show that if $f_n \rightarrow f$ pointwise, $f'_n \rightarrow g$ uniformly for some f, g , then f is differentiable and $g = f'$.
- Prove that uniform convergence implies pointwise convergence implies a.e. convergence, but none of the implications may be reversed.

- Show that $\sum \frac{x^n}{n!}$ converges uniformly on any compact subset of \mathbb{R} .

Measure Theory

- Show that continuity of measure from above/below holds for outer measures.
- Show that a countable union of null sets is null.

Measurability

- Show that $f = 0$ a.e. iff $\int_E f = 0$ for every measurable set E .

Integrability

- Show that if f is a measurable function, then $f = 0$ a.e. iff $\int f = 0$.
- Show that a bounded function is Lebesgue integrable iff it is measurable.
- Show that simple functions are dense in L^1 .
- Show that step functions are dense in L^1 .
- Show that smooth compactly supported functions are dense in L^1 .

Convergence

- Prove Fatou's lemma using the Monotone Convergence Theorem.
- Show that if $\{f_n\}$ is in L^1 and $\sum \int |f_n| < \infty$ then $\sum f_n$ converges to an L^1 function and

$$\int \sum f_n = \sum \int f_n.$$

Convolution

- Show that if $f \in L^1$ and g is bounded, then $f * g$ is bounded and uniformly continuous.
- If f, g are compactly supported, is it necessarily the case that $f * g$ is compactly supported?
- Show that under any of the following assumptions, $f * g$ vanishes at infinity:
 - $f, g \in L^1$ are both bounded.
 - $f, g \in L^1$ with just g bounded.
 - f, g smooth and compactly supported (and in fact $f * g$ is smooth)
 - $f \in L^1$ and g smooth and compactly supported (and in fact $f * g$ is smooth)
- Show that if $f \in L^1$ and g' exists with $\frac{\partial g}{\partial x_i}$ all bounded, then

$$\frac{\partial}{\partial x_i} (f * g) = f * \frac{\partial g}{\partial x_i}$$

Fourier Analysis

- Show that if $f \in L^1$ then \hat{f} is bounded and uniformly continuous.
- Is it the case that $f \in L^1$ implies $\hat{f} \in L^1$?
- Show that if $f, \hat{f} \in L^1$ then f is bounded, uniformly continuous, and vanishes at infinity.
 - Show that this is not true for arbitrary L^1 functions.
- Show that if $f \in L^1$ and $\hat{f} = 0$ almost everywhere then $f = 0$ almost everywhere.
 - Prove that $\hat{f} = \hat{g}$ implies that $f = g$ a.e.
- Show that if $f, g \in L^1$ then

$$\int \hat{f}g = \int f\hat{g}.$$

-
- Give an example showing that this fails if g is not bounded.
 - Show that if $f \in C^1$ then f is equal to its Fourier series.

Approximate Identities

- Show that if φ is an approximate identity, then

$$\|f * \varphi_t - f\|_1 \xrightarrow{t \rightarrow 0} 0.$$

- Show that if additionally $|\varphi(x)| \leq c(1 + |x|)^{-n-\varepsilon}$ for some $c, \varepsilon > 0$, then this converges almost everywhere.
- Show that if f is bounded and uniformly continuous and φ_t is an approximation to the identity, then $f * \varphi_t$ uniformly converges to f .

L^p Spaces

- Show that if $E \subseteq \mathbb{R}^n$ is measurable with $\mu(E) < \infty$ and $f \in L^p(X)$ then

$$\|f\|_{L^p(X)} \xrightarrow{p \rightarrow \infty} \|f\|_\infty.$$

- Is it true that the converse to the DCT holds? I.e. if $\int f_n \rightarrow \int f$, is there a $g \in L^p$ such that $f_n < g$ a.e. for every n ?
- Prove continuity in L^p : If f is uniformly continuous then for all p ,

$$\|\tau_h f - f\|_p \xrightarrow{h \rightarrow 0} 0.$$

- Prove the following inclusions of L^p spaces for $m(X) < \infty$:

$$L^\infty(X) \subset L^2(X) \subset L^1(X) \\ \ell^2(\mathbb{Z}) \subset \ell^1(\mathbb{Z}) \subset \ell^\infty(\mathbb{Z}).$$

7 Practice Exam (November 2014)

7.1 1: Fubini-Tonelli

7.1.1 a

Carefully state Tonelli's theorem for a nonnegative function $F(x, t)$ on $\mathbb{R}^n \times \mathbb{R}$.

7.1.2 b

Let $f : \mathbb{R}^n \rightarrow [0, \infty]$ and define

$$\mathcal{A} := \left\{ (x, t) \in \mathbb{R}^n \times \mathbb{R} \mid 0 \leq t \leq f(x) \right\}.$$

Prove the validity of the following two statements:

1. f is Lebesgue measurable on $\mathbb{R}^n \iff \mathcal{A}$ is a Lebesgue measurable subset of \mathbb{R}^{n+1} .
2. If f is Lebesgue measurable on \mathbb{R}^n then

$$m(\mathcal{A}) = \int_{\mathbb{R}^n} f(x) dx = \int_0^\infty m\left(\left\{x \in \mathbb{R}^n \mid f(x) \geq t\right\}\right) dt.$$

7.2 2: Convolutions and the Fourier Transform**7.2.1 a**

Let $f, g \in L^1(\mathbb{R}^n)$ and give a definition of $f * g$.

7.2.2 b

Prove that if f, g are integrable and bounded, then

$$(f * g)(x) \xrightarrow{|x| \rightarrow \infty} 0.$$

7.2.3 c

1. Define the *Fourier transform* of an integrable function f on \mathbb{R}^n .
2. Give an outline of the proof of the Fourier inversion formula.
3. Give an example of a function $f \in L^1(\mathbb{R}^n)$ such that \hat{f} is not in $L^1(\mathbb{R}^n)$.

7.3 3: Hilbert Spaces

Let $\{u_n\}_{n=1}^\infty$ be an orthonormal sequence in a Hilbert space H .

7.3.1 a

Let $x \in H$ and verify that

$$\left\| x - \sum_{n=1}^N \langle x, u_n \rangle u_n \right\|_H^2 = \|x\|_H^2 - \sum_{n=1}^N |\langle x, u_n \rangle|^2.$$

for any $N \in \mathbb{N}$ and deduce that

$$\sum_{n=1}^{\infty} |\langle x, u_n \rangle|^2 \leq \|x\|_H^2.$$

7.3.2 b

Let $\{a_n\}_{n \in \mathbb{N}} \in \ell^2(\mathbb{N})$ and prove that there exists an $x \in H$ such that $a_n = \langle x, u_n \rangle$ for all $n \in \mathbb{N}$, and moreover x may be chosen such that

$$\|x\|_H = \left(\sum_{n \in \mathbb{N}} |a_n|^2 \right)^{\frac{1}{2}}.$$

Proof

- Take $\{a_n\} \in \ell^2$, then note that $\sum |a_n|^2 < \infty \implies$ the tails vanish.
- Define $x := \lim_{N \rightarrow \infty} S_N$ where $S_N = \sum_{k=1}^N a_k u_k$

- $\{S_N\}$ is Cauchy and H is complete, so $x \in H$.
- By construction,

$$\langle x, u_n \rangle = \left\langle \sum_k a_k u_k, u_n \right\rangle = \sum_k a_k \langle u_k, u_n \rangle = a_n$$

since the u_k are all orthogonal.

- By Pythagoras since the u_k are normal,

$$\|x\|^2 = \left\| \sum_k a_k u_k \right\|^2 = \sum_k \|a_k u_k\|^2 = \sum_k |a_k|^2.$$

7.3.3 c

Prove that if $\{u_n\}$ is *complete*, Bessel's inequality becomes an equality.

Proof Let x and u_n be arbitrary.

$$\begin{aligned} \left\langle x - \sum_{k=1}^{\infty} \langle x, u_k \rangle u_k, u_n \right\rangle &= \langle x, u_n \rangle - \left\langle \sum_{k=1}^{\infty} \langle x, u_k \rangle u_k, u_n \right\rangle \\ &= \langle x, u_n \rangle - \sum_{k=1}^{\infty} \langle \langle x, u_k \rangle u_k, u_n \rangle \\ &= \langle x, u_n \rangle - \sum_{k=1}^{\infty} \langle x, u_k \rangle \langle u_k, u_n \rangle \\ &= \langle x, u_n \rangle - \langle x, u_n \rangle = 0 \\ \implies x - \sum_{k=1}^{\infty} \langle x, u_k \rangle u_k &= 0 \quad \text{by completeness.} \end{aligned}$$

So

$$x = \sum_{k=1}^{\infty} \langle x, u_k \rangle u_k \implies \|x\|^2 = \sum_{k=1}^{\infty} |\langle x, u_k \rangle|^2. \blacksquare$$

7.4 4: L^p Spaces

7.4.1 a

Prove Holder's inequality: let $f \in L^p, g \in L^q$ with p, q conjugate, and show that

$$\|fg\|_p \leq \|f\|_p \cdot \|g\|_q.$$

7.4.2 b

Prove Minkowski's Inequality:

$$1 \leq p < \infty \implies \|f + g\|_p \leq \|f\|_p + \|g\|_p.$$

Conclude that if $f, g \in L^p(\mathbb{R}^n)$ then so is $f + g$.

7.4.3 c

Let $X = [0, 1] \subset \mathbb{R}$.

1. Give a definition of the Banach space $L^\infty(X)$ of essentially bounded functions of X .
2. Let f be non-negative and measurable on X , prove that

$$\int_X f(x)^p dx \xrightarrow{p \rightarrow \infty} \begin{cases} \infty & \text{or} \\ m(\{f^{-1}(1)\}) \end{cases},$$

and characterize the functions of each type

Proof

$$\begin{aligned} \int f^p &= \int_{x<1} f^p + \int_{x=1} f^p + \int_{x>1} f^p \\ &= \int_{x<1} f^p + \int_{x=1} 1 + \int_{x>1} f^p \\ &= \int_{x<1} f^p + m(\{f=1\}) + \int_{x>1} f^p \\ &\xrightarrow{p \rightarrow \infty} 0 + m(\{f=1\}) + \begin{cases} 0 & m(\{x \geq 1\}) = 0 \\ \infty & m(\{x \geq 1\}) > 0. \end{cases} \end{aligned}$$

Justify passing
limit into integrals.

7.5 5: Dual Spaces

Let X be a normed vector space.

7.5.1 a

Give the definition of what it means for a map $L : X \rightarrow \mathbb{C}$ to be a *linear functional*.

7.5.2 b

Define what it means for L to be *bounded* and show L is bounded $\iff L$ is continuous.

7.5.3 c

Prove that $(X^\vee, \|\cdot\|_{\text{op}})$ is a Banach space.

8 Midterm Exam 2 (November 2018)

8.1 1 (Integration by Parts)

Let $f, g \in L^1([0, 1])$, define $F(x) = \int_0^x f$ and $G(x) = \int_0^x g$, and show

$$\int_0^1 F(x)g(x) dx = F(1)G(1) - \int_0^1 f(x)G(x) dx.$$

8.2 2

Let $\varphi \in L^1(\mathbb{R}^n)$ such that $\int \varphi = 1$ and define $\varphi_t(x) = t^{-n}\varphi(t^{-1}x)$.

Show that if f is bounded and uniformly continuous then $f * \varphi_t \xrightarrow{t \rightarrow 0} f$ uniformly.

8.3 3

Let $g \in L^\infty([0, 1])$.

a. Prove

$$\|g\|_{L^p([0,1])} \xrightarrow{p \rightarrow \infty} \|g\|_{L^\infty([0,1])}.$$

b. Prove that the map

$$\begin{aligned} \Lambda_g : L^1([0, 1]) &\longrightarrow \mathbb{C} \\ f &\mapsto \int_0^1 fg \end{aligned}$$

defines an element of $L^1([0, 1])^\vee$ with $\|\Lambda_g\|_{L^1([0,1])^\vee} = \|g\|_{L^\infty([0,1])}$.

Note: 4 is a repeat.

9 Midterm Exam 2 (December 2014)**9.1 1**

Note: (a) is a repeat.

- Let $\Lambda \in L^2(X)^\vee$.
 - Show that $M := \{f \in L^2(X) \mid \Lambda(f) = 0\} \subseteq L^2(X)$ is a closed subspace, and $L^2(X) = M \oplus M^\perp$.
 - Prove that there exists a unique $g \in L^2(X)$ such that $\Lambda(f) = \int_X g \bar{f}$.

9.2 2

a. In parts:

- Given a definition of $L^\infty(\mathbb{R}^n)$.
- Verify that $\|\cdot\|_\infty$ defines a norm on $L^\infty(\mathbb{R}^n)$.
- Carefully prove that $(L^\infty(\mathbb{R}^n), \|\cdot\|_\infty)$ is a Banach space.

b. Prove that for any measurable $f : \mathbb{R}^n \rightarrow \mathbb{C}$,

$$L^1(\mathbb{R}^n) \cap L^\infty(\mathbb{R}^n) \subset L^2(\mathbb{R}^n) \quad \text{and} \quad \|f\|_2 \leq \|f\|_1^{\frac{1}{2}} \cdot \|f\|_\infty^{\frac{1}{2}}.$$

9.3 3

- a. Prove that if $f, g : \mathbb{R}^n \rightarrow \mathbb{C}$ is both measurable then $F(x, y) := f(x)$ and $h(x, y) := f(x-y)g(y)$ is measurable on $\mathbb{R}^n \times \mathbb{R}^n$.
- b. Show that if $f \in L^1(\mathbb{R}^n) \cap L^\infty(\mathbb{R}^n)$ and $g \in L^1(\mathbb{R}^n)$, then $f * g \in L^1(\mathbb{R}^n) \cap L^\infty(\mathbb{R}^n)$ is well defined, and carefully show that it satisfies the following properties:

$$\|f * g\|_\infty \leq \|g\|_1 \|f\|_\infty \|f * g\|_1 \leq \|g\|_1 \|f\|_1 \|f * g\|_2 \leq \|g\|_1 \|f\|_2.$$

Hint: first show $|f * g|^2 \leq \|g\|_1 (|f|^2 * |g|)$.

9.4 4 (Weierstrass Approximation Theorem)

Note: (a) is a repeat.

Let $f : [0, 1] \rightarrow \mathbb{R}$ be continuous, and prove the Weierstrass approximation theorem: for any $\varepsilon > 0$ there exists a polynomial P such that $\|f - P\|_\infty < \varepsilon$.

10 Inequalities and Equalities

Proposition (Reverse Triangle Inequality)

$$||x| - |y|| \leq \|x - y\|.$$

Proposition (Chebyshev's Inequality)

$$\mu(\{x : |f(x)| > \alpha\}) \leq \left(\frac{\|f\|_p}{\alpha} \right)^p.$$

Proposition (Holder's Inequality When Surjective)

$$\frac{1}{p} + \frac{1}{q} = 1 \implies \|fg\|_1 \leq \|f\|_p \|g\|_q.$$

Application: For finite measure spaces,

$$1 \leq p < q \leq \infty \implies L^q \subset L^p \quad (\text{and } \ell^p \subset \ell^q).$$

Proof (Holder's Inequality) Fix p, q , let $r = \frac{q}{p}$ and $s = \frac{r}{r-1}$ so $r^{-1} + s^{-1} = 1$. Then let $h = |f|^p$:

$$\|f\|_p^p = \|h \cdot 1\|_1 \leq \|1\|_s \|h\|_r = \mu(X)^{\frac{1}{s}} \|f\|_q^{\frac{q}{r}} \implies \|f\|_p \leq \mu(X)^{\frac{1}{p} - \frac{1}{q}} \|f\|_q.$$

Note: doesn't work for ℓ_p spaces, but just note that $\sum |x_n| < \infty \implies x_n < 1$ for large enough n , and thus $p < q \implies |x_n|^q \leq |x_n|^p$.

Proof (Holder's Inequality) It suffices to show this when $\|f\|_p = \|g\|_q = 1$, since

$$\|fg\|_1 \leq \|f\|_p \|g\|_q \iff \int \frac{|f|}{\|f\|_p} \frac{|g|}{\|g\|_q} \leq 1.$$

Using $AB \leq \frac{1}{p}A^p + \frac{1}{q}B^q$, we have

$$\int |f| |g| \leq \int \frac{|f|^p}{p} \frac{|g|^q}{q} = \frac{1}{p} + \frac{1}{q} = 1.$$

Proposition (Cauchy-Schwarz Inequality)

$$|\langle f, g \rangle| = \|fg\|_1 \leq \|f\|_2 \|g\|_2 \quad \text{with equality} \iff f = \lambda g.$$

Note: Relates inner product to norm, and only happens to relate norms in L^1 .

Proof ?

Proposition (Minkowski's Inequality:)

$$1 \leq p < \infty \implies \|f + g\|_p \leq \|f\|_p + \|g\|_p.$$

Note: does not handle $p = \infty$ case. Use to prove L^p is a normed space.

Proof

- We first note

$$|f + g|^p = |f + g| |f + g|^{p-1} \leq (|f| + |g|) |f + g|^{p-1}.$$

- Note that if p, q are conjugate exponents then

$$\frac{1}{q} = 1 - \frac{1}{p} = \frac{p-1}{p}$$

$$q = \frac{p}{p-1}.$$

- Then taking integrals yields

$$\begin{aligned}
\|f + g\|_p^p &= \int |f + g|^p \\
&\leq \int (|f| + |g|) |f + g|^{p-1} \\
&= \int |f| |f + g|^{p-1} + \int |g| |f + g|^{p-1} \\
&= \|f(f + g)^{p-1}\|_1 + \|g(f + g)^{p-1}\|_1 \\
&\leq \|f\|_p \|(f + g)^{p-1}\|_q + \|g\|_p \|(f + g)^{p-1}\|_q \\
&= (\|f\|_p + \|g\|_p) \|(f + g)^{p-1}\|_q \\
&= (\|f\|_p + \|g\|_p) \left(\int |f + g|^{(p-1)q} \right)^{\frac{1}{q}} \\
&= (\|f\|_p + \|g\|_p) \left(\int |f + g|^p \right)^{1 - \frac{1}{p}} \\
&= (\|f\|_p + \|g\|_p) \frac{\int |f + g|^p}{(\int |f + g|^p)^{\frac{1}{p}}} \\
&= (\|f\|_p + \|g\|_p) \frac{\|f + g\|_p^p}{\|f + g\|_p}.
\end{aligned}$$

- Cancelling common terms yields

$$\begin{aligned}
1 &\leq (\|f\|_p + \|g\|_p) \frac{1}{\|f + g\|_p} \\
&\implies \|f + g\|_p \leq \|f\|_p + \|g\|_p.
\end{aligned}$$

Proposition (Young's Inequality*)

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{r} + 1 \implies \|f * g\|_r \leq \|f\|_p \|g\|_q$$

Application: Some useful specific cases:

$$\begin{aligned}
\|f * g\|_1 &\leq \|f\|_1 \|g\|_1 \\
\|f * g\|_p &\leq \|f\|_1 \|g\|_p, \\
\|f * g\|_\infty &\leq \|f\|_2 \|g\|_2 \\
\|f * g\|_\infty &\leq \|f\|_p \|g\|_q.
\end{aligned}$$

Proposition (Bessel's Inequality:)

For $x \in H$ a Hilbert space and $\{e_k\}$ an orthonormal sequence,

$$\sum_{k=1}^{\infty} \|\langle x, e_k \rangle\|^2 \leq \|x\|^2.$$

Note: this does not need to be a basis.

Proposition (Parseval's Identity:) Equality in Bessel's inequality, attained when $\{e_k\}$ is a *basis*, i.e. it is complete, i.e. the span of its closure is all of H .

10.1 Less Explicitly Used Inequalities**Proposition (AM-GM Inequality)**

$$\sqrt{ab} \leq \frac{a+b}{2}.$$

Proposition (Jensen's Inequality)

$$f(tx + (1-t)y) \leq tf(x) + (1-t)f(y).$$

Proposition (???) :

$$AB \leq \frac{A^p}{p} + \frac{B^q}{q}.$$

Proposition (? Inequality)

$$(a+b)^p \leq 2^p(a^p + b^p).$$

Proposition (Bernoulli's Inequality)

$$(1+x)^n \geq 1+nx \quad x \geq -1, \text{ or } n \in 2\mathbb{Z} \text{ and } \forall x.$$