

# Real Analysis Qualifying Exam Review

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Exercises from Folland:

- Chapter 1: Exercises 3, 7, 10, 12, 14 (with the sets in 3(a) being non-empty) Exercises 15, 17, 18, 19, 22(a), 24, 28 Exercises 26, 30 (also check out 31)
- Chapter 2: Exercises 2, 3, 7, 9 (in 9(c) you can use Exercise 1.29 without proof Exercises 10, 12, 13, 14, 16, 19 Exercises 24, 25, 28(a,b), 33, 34, 35, 38, 41 (note that 24 shows that upper sums are not needed in the definition of integrals, and the extra hypotheses also show that they are not desired either) Exercises 40, 44, 47, 49, 50, 51, 52, 54, 56, 58, 59
- Chapter 3: Exercises 3(b,c), 5, 6, 9, 12, 13, 14, 16, 20, 21, 22

# 1 | Basics

Notation	Definition
$\ f\ _\infty := \sup_{x \in \text{dom}(f)}  f(x) $	The Sup norm
$\ f\ _{L^\infty} := \inf \left\{ M \geq 0 \mid  f(x)  \leq M \text{ for a.e. } x \right\}$	The $L^\infty$ norm
$f_n \xrightarrow{n \rightarrow \infty} f$	Convergence of a sequence
$f(x) \xrightarrow{ x  \rightarrow \infty} 0$	Vanishing at infinity
$\int_{ x  \geq N} f \xrightarrow{N \rightarrow \infty} 0$	Having small tails

Notation	Definition
$H, \mathcal{H}$	A Hilbert space
$X$	A topological space

## 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:
 
$$(\forall \epsilon, a < b + \epsilon) \implies a \leq b.$$

- Showing something is zero:

$$(\forall \epsilon, \|a\| < \epsilon) \implies a = 0.$$

- Continuity / differentiability: show it holds on  $[-M, M]$  for all  $M$  to get it to hold on  $\mathbb{R}$ .
- 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
  - Calculus techniques: Taylor series, IVT, MVT, etc.
  - Break up  $\mathbb{R}^n = \{|x| \leq 1\} \coprod \{|x| > 1\}$ .
    - ◊ Or break integration region into disjoint annuli.
  - Break up into  $\{f > g\} \coprod \{f = g\} \coprod \{f < g\}$ .
  - Tail estimates!
  - Most of what works for integrals will work for sums.
- Measure theory:
  - Always consider bounded sets, and if  $E$  is unbounded write  $E = \cup_n B_n(0) \cap E$  and use countable subadditivity or continuity of measure.
  - $F_\sigma$  sets are Borel, so establish something for Borel sets and use this to extend it to Lebesgue.
  - $s = \inf \{x \in X\} \implies$  for every  $\epsilon$  there is an  $x \in X$  such that  $x \leq s + \epsilon$ .
- Approximate by dense subsets of functions
- Useful facts about compactly supported ( $C_c(\mathbb{R})$ ) continuous functions:
  - Uniformly continuous
  - Bounded almost everywhere

## 1.2 Definitions

**Definition 1.2.1** (Uniform Continuity)

$f$  is uniformly continuous iff

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

**Definition 1.2.2** (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 1.2.3** (Meager Sets)

A set is **meager** if it is a *countable* union of nowhere dense sets.

**Definition 1.2.4** ( $F_\sigma$  and  $G_\delta$  Sets)

An  $F_\sigma$  set is a union of closed sets, and a  $G_\delta$  set is an intersection of opens. <sup>a</sup>

<sup>a</sup>Mnemonic: “F” stands for *ferme*, which is “closed” in French, and  $\sigma$  corresponds to a “sum”, i.e. a union.

**Definition 1.2.5** (Limsup/Liminf)

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

**Definition 1.2.6** (Topological Notions)

Let  $X$  be a metric space and  $A$  a subset. Let  $A'$  denote the limit points of  $A$ , and  $\bar{A} := A \cup A'$  to be its closure.

- A **neighborhood** of  $p$  is an open set  $U_p$  containing  $p$ .
- An  $\varepsilon$ -**neighborhood** of  $p$  is an open ball  $B_r(p) := \{q \mid d(p, q) < r\}$  for some  $r > 0$ .
- A point  $p \in X$  is an **accumulation point** of  $A$  iff every neighborhood  $U_p$  of  $p$  contains a point  $q \in A$ .
- A point  $p \in X$  is a **limit point** of  $A$  iff every *punctured* neighborhood  $U_p \setminus \{p\}$  contains a point  $q \in A$ .
- If  $p \in A$  and  $p$  is not a limit point of  $A$ , then  $p$  is an **isolated point** of  $A$ .
- $A$  is **closed** iff  $A' \subset A$ , so  $A$  contains all of its limit points.
- A point  $p \in A$  is **interior** iff there is a neighborhood  $U_p \subset A$  that is strictly contained in  $A$ .

- $A$  is **open** iff every point of  $A$  is interior.
- $A$  is **perfect** iff  $A$  is closed and  $A \subset A'$ , so every point of  $A$  is a limit point of  $A$ .
- $A$  is **bounded** iff there is a real number  $M$  and a point  $q \in X$  such that  $d(p, q) < M$  for all  $p \in A$ .
- $A$  is **dense** in  $X$  iff every point  $x \in X$  is either a point of  $A$ , so  $x \in A$ , or a limit point of  $A$ , so  $x \in A'$ . I.e.,  $X \subset A \cup A'$ .
  - Alternatively,  $\bar{A} = X$ , so the closure of  $A$  is  $X$ .

### Definition 1.2.7 (Uniform Convergence)

$$(\forall \varepsilon > 0) (\exists n_0 = n_0(\varepsilon)) (\forall x \in S) (\forall n > n_0) (|f_n(x) - f(x)| < \varepsilon).$$

Negated:<sup>a</sup>

$$(\exists \varepsilon > 0) (\forall n_0 = n_0(\varepsilon)) (\exists x = x(n_0) \in S) (\exists n > n_0) (|f_n(x) - f(x)| \geq \varepsilon).$$

<sup>a</sup>Slogan: to negate, find a bad  $x$  depending on  $n_0$  that are larger than some  $\varepsilon$ .

### Definition 1.2.8 (Pointwise Convergence)

A sequence of functions  $\{f_j\}$  is said to **converge pointwise** to  $f$  if and only if

$$(\forall \varepsilon > 0) (\forall x \in S) (\exists n_0 = n_0(x, \varepsilon)) (\forall n > n_0) (|f_n(x) - f(x)| < \varepsilon).$$

### Definition 1.2.9 (Outer Measure)

The **outer measure** of a set is given by

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

### Definition 1.2.10 (Limsup and Liminf of Sets)

$$\limsup_n A_n := \cap_n \cup_{j \geq n} A_j = \left\{ x \mid x \in A_n \text{ for inf. many } n \right\}$$

$$\liminf_n A_n := \cup_n \cap_{j \geq n} A_j = \left\{ x \mid x \in A_n \text{ for all except fin. many } n \right\}$$

### Definition 1.2.11 (Lebesgue Measurable Sets)

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  $m(E) := m_*(E)$ .

### Definition 1.2.12 ( $L^+$ : Measurable non-negative functions.)

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



**Definition 1.2.13** (Integrability)

A measurable function is **integrable** iff  $\|f\|_1 < \infty$ .

**Definition 1.2.14** (The Infinity Norm)

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

**Definition 1.2.15** (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.  $\|f\|_\infty < \infty$ .

**Definition 1.2.16** ( $L^\infty$ )

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

**Definition 1.2.17** (Dual Norm)

For  $X$  a normed vector space and  $\Lambda \in X^\vee$ ,

$$\|\Lambda\|_{X^\vee} := \sup_{\left\{ x \in X \mid \|x\|_X \leq 1 \right\}} |\Lambda(x)|.$$

**Definition 1.2.18** (Convolution)

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

**Definition 1.2.19** (Fourier Transform)

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

**Definition 1.2.20** (Dilation)

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

**Definition 1.2.21** (Approximations to the identity)

For  $\varphi \in L^1$ , the dilations satisfy  $\int \varphi_t = \int \varphi$ , and if  $\int \varphi = 1$  then  $\varphi$  is an **approximate identity**.

**Definition 1.2.22** (Baire Space)

A space  $X$  is a **Baire space** if and only if every countable intersections of open, dense sets is

still dense.

### 1.2.1 Functional Analysis

**Definition 1.2.23** (Orthonormal sequence )

A countable collection of elements  $\{u_i\}$  is **orthonormal** if and only if

1.  $\langle u_i, u_j \rangle = 0$  for all  $j \neq k$  and
2.  $\|u_j\|^2 := \langle u_j, u_j \rangle = 1$  for all  $j$ .

**Definition 1.2.24** (Basis of a Hilbert space)

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

**Definition 1.2.25** (Completeness of a Hilbert space)

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 1.2.26** (Dual of a Hilbert space)

The **dual** of a Hilbert space  $H$  is defined as

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

**Definition 1.2.27** (Linear functionals)

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

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

**Definition 1.2.28** (Operator norm)

The **operator norm** of an operator  $L$  is defined as

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

**Definition 1.2.29** (Banach Space)

A space is a **Banach space** if and only if it is a complete normed vector space.

**Definition 1.2.30** (Hilbert Space)

A **Hilbert space** is an inner product space which is a Banach space under the induced norm.

## 1.3 Theorems

### 1.3.1 Topology / Sets

**Theorem 1.3.1 (Heine-Cantor).**

Every continuous function on a compact space is uniformly continuous.

**Proposition 1.3.2 (Compact if and only if sequentially compact for metric spaces).**

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

**Proposition 1.3.3 (A unit ball that is not compact).**

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

*Proof (?)*.

Take  $f_k(x) = x^n$ , which converges to  $\chi(x = 1)$ . The limit is not continuous, so no subsequence can converge. ■

**Proposition 1.3.4 (?).**

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

**Proposition 1.3.5 (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 1.3.6 (Heine-Borel).**

$X \subseteq \mathbb{R}^n$  is compact  $\iff X$  is closed and bounded.

**Proposition 1.3.7 (Geometric Series).**

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

**Corollary 1.3.8 (?).**

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

**Proposition 1.3.9(?)**.

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 1.3.10(?)**.

The Cantor set is nowhere dense.

**Proposition 1.3.11(?)**.

Singleton sets in  $\mathbb{R}$  are closed, and thus  $\mathbb{Q}$  is an  $F_\sigma$  set.

**Theorem 1.3.12(Baire)**.

$\mathbb{R}$  is a **Baire space** Thus  $\mathbb{R}$  can not be written as a countable union of nowhere dense sets.

**Lemma 1.3.13(?)**.

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

**1.3.2 Functions****Proposition 1.3.14(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 1.3.15(Function discontinuous on the rationals)**.

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. ■

**Proposition 1.3.16(No functions discontinuous on the irrationals)**.

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

*Proof (?)*.

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

**Proposition 1.3.17** (*Lipschitz  $\iff$  differentiable with bounded derivative.*).

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

**Proposition 1.4.1** (*Testing Uniform Convergence: The Sup Norm Test*).

$f_n \rightarrow f$  uniformly iff there exists an  $M_n$  such that  $\|f_n - f\|_\infty \leq M_n \rightarrow 0$ .

**Remark 1.4.2** (*Negating the Sup Norm test*): **Negating:** find an  $x$  which depends on  $n$  for which  $\|f_n\|_\infty > \varepsilon$  (negating small tails) or  $\|f_n - f_m\| > \varepsilon$  (negating the Cauchy criterion).

### 1.4.1 Example: Completeness of a Normed Function Space

:::{proposition title="  $C(I)$  is complete"} The space  $X = C([0, 1])$ , continuous functions  $f : [0, 1] \rightarrow \mathbb{R}$ , equipped with the norm

$$\|f\|_\infty := \sup_{x \in [0, 1]} |f(x)|$$

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.

**Remark 1.4.3:** In other cases, you may need to show the limit is bounded, or has bounded derivative, or whatever other conditions define  $X$ .

**Theorem 1.4.4 (Uniform Limit Theorem).**

If  $f_n \rightarrow f$  pointwise and uniformly with each  $f_n$  continuous, then  $f$  is continuous. <sup>a</sup>

<sup>a</sup>Slogan: a uniform limit of continuous functions is continuous.

*Proof.*

- Follows from an  $\varepsilon/3$  argument:

$$|F(x) - F(y)| \leq |F(x) - F_N(x)| + |F_N(x) - F_N(y)| + |F_N(y) - F(y)| \leq \varepsilon \rightarrow 0.$$

- The first and last  $\varepsilon/3$  come from uniform convergence of  $F_N \rightarrow F$ .
- The middle  $\varepsilon/3$  comes from continuity of each  $F_N$ .
- So just need to choose  $N$  large enough and  $\delta$  small enough to make all 3  $\varepsilon$  bounds hold.

■

**Proposition 1.4.5 (Uniform Limits Commute with Integrals).**

If  $f_n \rightarrow f$  uniformly, then  $\int f_n = \int f$ .

## 1.4.2 Series

**Proposition 1.4.6 ( $p$ -tests).**

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

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

**Proposition 1.4.7 (Comparison Test).**

If  $0 \leq a_n \leq b_n$ , then

- $\sum b_n < \infty \implies \sum a_n < \infty$ , and

$$\bullet \sum a_n = \infty \implies \sum b_n = \infty.$$

**Proposition 1.4.8** (*Small Tails for Series of Functions*).

If  $\sum f_n$  converges then  $f_n \rightarrow 0$  uniformly.

**Corollary 1.4.9** (*Term by Term Continuity Theorem*).

If  $f_n$  are continuous and  $\sum f_n \rightarrow f$  converges uniformly, then  $f$  is continuous.

**Proposition 1.4.10** (*Weak M-Test*).

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.<sup>a</sup>

<sup>a</sup>Note that this is only pointwise convergence of  $f$ , whereas the full  $M$ -test gives uniform convergence.

**Proposition 1.4.11** (*The Weierstrass M-Test*).

If  $\sup_{x \in A} |f_n(x)| \leq M_n$  for each  $n$  where  $\sum M_n < \infty$ , then  $\sum_{n=1}^{\infty} f_n(x)$  converges uniformly and absolutely on  $A$ .<sup>a</sup> Conversely, if  $\sum f_n$  converges uniformly on  $A$  then  $\sup_{x \in A} |f_n(x)| \rightarrow 0$ .

<sup>a</sup>It suffices to show  $|f_n(x)| \leq M_n$  for some  $M_n$  not depending on  $x$ .

**Proposition 1.4.12** (*Cauchy criterion for sums*).

$f_n$  are uniformly Cauchy (so  $\|f_n - f_m\|_{\infty} < \varepsilon$ ) iff  $f_n$  is uniformly convergent.

## Derivatives

**Theorem 1.4.13** (*Term by Term Differentiability Theorem*).

If  $f_n$  are differentiable,  $\sum f'_n \rightarrow g$  uniformly, and there exists one point<sup>a</sup>  $x_0$  such that  $\sum f_n(x)$  converges, then there exist an  $f$  such that  $\sum f_n \rightarrow f$  uniformly and  $f' = g$ .<sup>b</sup>

<sup>a</sup>So this implicitly holds if  $f$  is the pointwise limit of  $f_n$ .

<sup>b</sup>See Abbott theorem 6.4.3, pp 168.

## 1.5 Commuting Limiting Operations

**Proposition 1.5.1** (*Limits of bounded functions need not be bounded*).

$$\lim_{n \rightarrow \infty} \sup_{x \in X} |f_n(x)| \neq \sup_{x \in X} \left| \lim_{n \rightarrow \infty} f_n(x) \right|.$$

**Proposition 1.5.2** (*Limits of continuous functions need not be continuous*).

$$\lim_{k \rightarrow \infty} \lim_{n \rightarrow \infty} f_n(x_k) \neq \lim_{n \rightarrow \infty} \lim_{k \rightarrow \infty} f_n(x_k).$$

**Proposition 1.5.3** (*Limits of differentiable functions need not be differentiable*).

$$\lim_{n \rightarrow \infty} \frac{\partial}{\partial x} f_n \neq \frac{\partial}{\partial n} \left( \lim_{n \rightarrow \infty} f_n \right).$$

**Proposition 1.5.4** (?).

$$\lim_{n \rightarrow \infty} \int_a^b f_n(x) dx \neq \int_a^b \lim_{n \rightarrow \infty} (f_n(x)) dx.$$

## 1.6 Slightly Advanced Stuff

**Theorem 1.6.1 (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

$p_\varepsilon$  such that  $\|f - p_\varepsilon\|_{L^\infty([a, b])} \xrightarrow{\varepsilon \rightarrow 0} 0$ .

Equivalently, polynomials are dense in the Banach space  $C([0, 1], \|\cdot\|_\infty)$ .

**Theorem 1.6.2 (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.

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

## 1.7 Examples

**Example 1.7.1** (?): A series of continuous functions that does *not* converge uniformly but is still continuous:

$$g(x) := \sum \frac{1}{1 + n^2 x}.$$

Take  $x = 1/n^2$ .



# 2 | Measure Theory

## 2.1 Theorems

### Proposition 2.1.1 (*Opens are unions of almost disjoint intervals.*).

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).

### Proposition 2.1.2 (*Properties of Outer Measure*).

1. Monotonicity:  $E \subseteq F \implies m_*(E) \leq m_*(F)$ .
2. Countable Subadditivity:  $m_*(\cup E_i) \leq \sum m_*(E_i)$ .
3. Approximation: For all  $E$  there exists a  $G \supseteq E$  such that  $m_*(G) \leq m_*(E) + \varepsilon$ .
4. Disjoint<sup>a</sup> Additivity:  $m_*(A \sqcup B) = m_*(A) + m_*(B)$ .

<sup>a</sup>This holds for outer measure iff  $\text{dist}(A, B) > 0$ .

### Proposition 2.1.3 (*Subtraction of Measures*).

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

### Proposition 2.1.4 (*Continuity of Measure*).

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

*Proof (of continuity of measure).*

1. Break into disjoint annuli  $A_2 = E_2 \setminus E_1$ , etc then apply countable disjoint additivity to  $E = \bigsqcup A_i$ .
2. Use  $E_1 = (\bigsqcup E_j \setminus E_{j+1}) \sqcup (\cap E_j)$ , taking measures yields a telescoping sum, and use countable disjoint additivity.

■

### Theorem 2.1.5 (*Measurable sets can be approximated by open/closed/compact sets.*).

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 (that measurable sets can be approximated).*

- (1): Take  $\{Q_i\} \rightrightarrows E$  and set  $O = \cup Q_i$ .
- (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  $n \geq N \implies m(E \setminus K_n) < \varepsilon$ .

■

**Proposition 2.1.6 (Translation and Dilation Invariance).**

Lebesgue measure is translation and dilation invariant.

*Proof ((Todo) of translation/dilation invariance).*

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

■

**Theorem 2.1.7 (Non-measurable sets exist).**

There is a non-measurable set.

*Proof (Constructing a non-measurable set).*

- 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 2.1.8 (Borel Characterization of Measurable Sets).**

If  $E$  is Lebesgue measurable, then  $E = H \bigsqcup N$  where  $H \in F_\sigma$  and  $N$  is null.

*Proof (of Borel characterization).*

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  $K = \cup K_n$ , wlog  $K_n \nearrow K$  so  $m(K) = \lim m(K_n) = m(E)$ . Take  $N := E \setminus K$ , then  $m(N) = 0$ .

■

**Proposition 2.1.9 (Limsups/infs of measurable sets are measurable.).**

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

*Proof (That limsups/infs are measurable).*

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

**Theorem 2.1.10 (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 (of Borel-Cantelli).*

- 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.
- $E = \limsup_j E_j = \cap_{k=1}^{\infty} \cup_{j=k}^{\infty} E_j \implies E \subseteq \cup_{j=k}^{\infty} E_j$  for all  $k$
- $E \subseteq \cup_{j=k}^{\infty} E_j \implies m(E) \leq \sum_{j=k}^{\infty} m(E_j) \xrightarrow{k \rightarrow \infty} 0$ .

■

**Proposition 2.1.11 (Extending the class of measurable functions.).**

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

## 3.1 Theorems

**Remark 3.1.1:** If  $f \in L^\infty(X)$ , then  $f$  is equal to some bounded function  $g$  almost everywhere. 

**Example 3.1.2(?)**:  $f(x) = x\chi_{\mathbb{Q}}(x)$  is essentially bounded but not bounded. 

**Theorem 3.1.3 (*p-Test for Integrals*).**

$$\int_0^1 \frac{1}{x^p} < \infty \iff p < 1$$

$$\int_1^\infty \frac{1}{x^p} < \infty \iff p > 1.$$

**Slogan 3.1.4**

Large powers of  $x$  help us in neighborhoods of infinity and hurt around zero

### 3.1.1 Convergence Theorems

**Theorem 3.1.5 (*Monotone Convergence*).**

If  $f_n \in L^+$  and  $f_n \nearrow f$  almost everywhere, then

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

*Needs to be positive and increasing.*

**Theorem 3.1.6 (*Dominated Convergence*).**

If  $f_n \in L^1$  and  $f_n \rightarrow f$  almost everywhere with  $|f_n| \leq g$  for some  $g \in L^1$ , then  $f \in L^1$  and

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

and more generally,

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

*Positivity not needed.*

**Theorem 3.1.7 (Generalized DCT).**

If

- $f_n \in L^1$  with  $f_n \rightarrow f$  almost everywhere,
- There exist  $g_n \in L^1$  with  $|f_n| \leq g_n$ ,  $g_n \geq 0$ .
- $g_n \rightarrow g$  almost everywhere 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  $|f_n| < g_n \rightarrow g \in L^1$ .*

*Proof.*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.

■

**Proposition 3.1.8 (Convergence in  $L^1$  implies convergence of  $L^1$  norm).**

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

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

■

**Theorem 3.1.9 (Fatou).**

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 3.1.10 (Tonelli (Non-Negative, Measurable)).**

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 3.1.11 (Fubini (Integrable)).**

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 3.1.12 (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.

**Proposition 3.1.13 (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

$$F : \mathbb{R}^{n_1} \rightarrow \mathbb{R}$$

$$x \mapsto m(E_x) = \int_{\mathbb{R}^{n_2}} \chi_{E_x} dy$$

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.*

$\implies :$

- 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 3.1.14 (Differentiating Under an Integral).**

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

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

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

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

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 3.1.15 (Commuting Sums with Integrals (non-negative)).**

If  $f_n$  are non-negative and  $\sum \int |f_n| < \infty$ , then  $\sum \int f_n = \int \sum f_n$ .

*Proof.* • Idea: MCT.

- Let  $F_N = \sum_{n=1}^N f_n$  be a finite partial sum;
- Then there are simple functions  $\varphi_n \nearrow f_n$
- So  $\sum \varphi_n \nearrow F_N$  and MCT applies

■

**Theorem 3.1.16 (Commuting Sums with Integrals (integrable)).**

If  $\{f_n\}$  integrable with either  $\sum \int |f_n| < \infty$  or  $\int \sum |f_n| < \infty$ , then

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

*Proof.* • By Tonelli, if  $f_n(x) \geq 0$  for all  $n$ , taking the counting measure allows interchanging the order of “integration”.

- By Fubini on  $|f_n|$ , if either “iterated integral” is finite then the result follows.

■

**Proposition 3.1.17 (?).**

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: ?

■



## 3.2 Examples of (Non)Integrable Functions

**Example 3.2.1** (*Examples of 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)
- $\int_0^1 \frac{1}{\sqrt{x}} < \infty$
- $\int_0^1 \frac{1}{x^{1-\varepsilon}} < \infty$
- $\int_1^\infty \frac{1}{x^{1+\varepsilon}} < \infty$

**Example 3.2.2** (*Examples of 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 $L^1$ Facts

**Proposition 3.3.1** (*Zero in  $L^1$  iff zero almost everywhere*).

For  $f \in L^+$ ,

$$\int f = 0 \iff f \equiv 0 \text{ almost everywhere.}$$

*Proof.*

- Obvious for simple functions:
  - If  $f(x) = \sum_{j=1}^n c_j \chi_{E_j}$ , then  $\int f = 0$  iff for each  $j$ , either  $c_j = 0$  or  $m(E_j) = 0$ .
  - Since nonzero  $c_j$  correspond to sets where  $f \neq 0$ , this says  $m(\{f \neq 0\}) = 0$ .
- $\Leftarrow$  :

- If  $f = 0$  almost everywhere and  $\varphi \nearrow f$ , then  $\varphi = 0$  almost everywhere since  $\varphi(x) \leq f(x)$  -Then

$$\int f = \sup_{\varphi \leq f} \int \varphi = \sup_{\varphi \leq f} 0 = 0.$$

•  $\implies$  :

- Instead show negating “ $f = 0$  almost everywhere” implies  $\int f \neq 0$ .
- Write  $\{f \neq 0\} = \cup_{n \in \mathbb{N}} S_n$  where  $S_n := \left\{x \mid f(x) \geq \frac{1}{n}\right\}$ .
- Since “not  $f = 0$  almost everywhere”, there exists an  $n$  such that  $m(S_n) > 0$ .
- Then

$$0 < \frac{1}{n} \chi_{E_n} \leq f \implies 0 < \int \frac{1}{n} \chi_{E_n} \leq \int f.$$

■

**Proposition 3.3.2 (Translation Invariance).**

The Lebesgue integral is translation invariant, i.e.

$$\int f(x) \, dx = \int f(x+h) \, dx \quad \text{for any } h.$$

*Proof .*

- Let  $E \subseteq X$ ; for characteristic functions,

$$\int_X \chi_E(x+h) = \int_X \chi_{E+h}(x) = m(E+h) = m(E) = \int_X \chi_E(x)$$

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.

■

**Proposition 3.3.3 (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  $X = A \sqcup B$ .

**Proposition 3.3.4 (Uniformly continuous  $L^1$  functions vanish at infinity.).**

If  $f \in L^1$  and  $f$  is uniformly continuous, then  $f(x) \xrightarrow{|x| \rightarrow \infty} 0$ .

**⚠ Warning 3.3.5**

This doesn't hold for general  $L^1$  functions, take any train of triangles with height 1 and summable

areas.

**Theorem 3.3.6 (Small Tails in  $L^1$ ).**

If  $f \in L^1$ , then for every  $\varepsilon$  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  $E := B_N(0)$
- Then

$$\int_E |f| \leq \int_E |f - g| + \int_E |g|.$$

■

**Proposition 3.3.7 ( $L^1$  functions are absolutely continuous.).**

$m(E) \rightarrow 0 \implies \int_E f \rightarrow 0$ .

*Proof (?)*.

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

■

**Proposition 3.3.8 ( $L^1$  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  $\infty > \int f = \int_A f + \int_{A^c} f = \infty \cdot m(A) + \int_{A^c} f \implies m(X) = 0$ .

■

**Theorem 3.3.9 (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  $g \in C_c$ .

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

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 3.3.10** (*Integration by parts, special case*).

$$\begin{aligned} F(x) &:= \int_0^x f(y)dy \quad \text{and} \quad G(x) := \int_0^x g(y)dy \\ \implies \int_0^1 F(x)g(x)dx &= F(1)G(1) - \int_0^1 f(x)G(x)dx. \end{aligned}$$

*Proof* (?).

Fubini-Tonelli, and sketch region to change integration bounds. ■

**Theorem 3.3.11** (*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  $L^1$ . ■

## 3.4 $L_p$ Facts

**Proposition 3.4.1** (*Dense subspaces of  $L^2(I)$* ).

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  $C_c^\infty$

**Theorem 3.4.2(?)**.

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

*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 3.4.3 (Duals for  $L^p$  spaces).**

For  $1 \leq p < \infty$ ,  $(L^p)^\vee \cong L^q$ .

*Proof ( $p = 1$  case).*

?

■

todo

*Proof ( $p = 2$  case).*

Use Riesz Representation for Hilbert spaces.

■

**Proposition 3.4.4** ( $L^1$  is not quite the dual of  $L^\infty$ ).  
 $L^1 \subset (L^\infty)^\vee$ , since the isometric mapping is always injective, but *never* surjective.

## 4 | Fourier Transform and Convolution

### 4.1 The Fourier Transform

**Proposition 4.1.1** (?).  
 If  $\widehat{f} = \widehat{g}$  then  $f = g$  almost everywhere.

**Proposition 4.1.2** (Riemann-Lebesgue: *Fourier transforms have small tails.*).

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

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

*Proof* (?).

- Boundedness:

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

- Continuity:

- $|\widehat{f}(\xi_n) - \widehat{f}(\xi)|$

- Apply DCT to show  $a \xrightarrow{n \rightarrow \infty} 0$ .

■

**Theorem 4.1.3** (*Fourier Inversion*).

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

#### **Warning 4.1.4**

Fubini-Tonelli does not work here!

*Proof* (?).

Idea: Fubini-Tonelli doesn't work directly, so introduce a convergence factor, take limits, and

use uniqueness of limits.

- Take the modified integral:

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

- 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

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

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

■

**Proposition 4.1.5 (Eigenfunction of the Fourier transform).**

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

## 4.2 Approximate Identities

**Example 4.2.1** (of an approximation to the identity.):

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

**Theorem 4.2.2** (Convolving against an approximate identity converges 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 4.2.3** (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

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

then

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

■

**Proposition 4.2.4 (Corollary of Young's inequality).**

Take  $q = 1$  in Young's inequality to obtain

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

**Proposition 4.2.5 ( $L^1$  is closed under convolution.).**

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

## 5 | Functional Analysis

### 5.1 Theorems

**Theorem 5.1.1 (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 (of Bessel's inequality).*

- 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  $0 \leq \|x - S_N\|^2$ ,

$$\begin{aligned}
0 &\leq \|x\|^2 - \sum_{n=1}^{\infty} |\langle x, u_n \rangle|^2 \\
\implies \sum_{n=1}^{\infty} |\langle x, u_n \rangle|^2 &\leq \|x\|^2 \blacksquare.
\end{aligned}$$

■

**Theorem 5.1.2 (Riesz Representation for Hilbert Spaces).**

If  $\Lambda$  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 5.1.3 (Functionals are continuous if and only if bounded).**

Let  $L : X \rightarrow \mathbb{C}$  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 5.1.4** (*The 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 5.1.5** (*The operator norm on  $X^\vee$  yields a Banach space*).

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  $\|L_n - L\| \rightarrow 0$ .
- 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  $n \rightarrow \infty$  to obtain

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

- 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 5.1.6 (Riesz-Fischer).**

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

1. There is an isometric surjection

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

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  $S_N \rightarrow \mathbf{x}$  for some  $\mathbf{x} \in \mathcal{H}$ .
- $\langle x, \mathbf{u}_n \rangle = \langle x - S_N, \mathbf{u}_n \rangle + \langle S_N, \mathbf{u}_n \rangle \rightarrow a_n$
- By construction,  $\|x - S_N\|^2 = \|x\|^2 - \sum_{n=1}^N |a_n|^2 \rightarrow 0$ , 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.  $E = H \cup Z$  here  $H$  is  $F_\sigma$  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  $m(E) = \sup \{m(K) \mid K \subset E \text{ compact}\}$  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  $t$ .
- \*: Prove that the Lebesgue integral is translation invariant, i.e. if  $\tau_h(x) = x + h$  then  $\int \tau_h f = \int f$ .
- \*: Prove that the Lebesgue integral is dilation invariant, i.e. if  $f_\delta(x) = \frac{f(\frac{x}{\delta})}{\delta^n}$  then  $\int f_\delta = \int f$ .
- \*: Prove continuity in  $L^1$ , i.e.

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

- \*: Show that

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

- \*: Show that if  $X \subseteq \mathbb{R}$  with  $\mu(X) < \infty$  then

$$\|f\|_p \xrightarrow{p \rightarrow \infty} \|f\|_\infty.$$

## 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  $\widehat{f}$  is bounded and uniformly continuous.
- Is it the case that  $f \in L^1$  implies  $\widehat{f} \in L^1$ ?
- Show that if  $f, \widehat{f} \in L^1$  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  $\widehat{f} = 0$  almost everywhere then  $f = 0$  almost everywhere.
  - Prove that  $\widehat{f} = \widehat{g}$  implies that  $f = g$  a.e.
- Show that if  $f, g \in L^1$  then

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



- 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  $\varphi$  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  $\varphi_t$  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 | Midterm Exam 2 (December 2014)

### 7.1 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  $\Lambda(f) = \int_X g \bar{f}$ .

## 7.2 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  $f : \mathbb{R}^n \rightarrow \mathbb{C}$ ,

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

## 7.3 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:

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

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

## 7.4 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  $\|f - P\|_\infty < \varepsilon$ .

## 8 | Midterm Exam 1 (October 2018)

## 8.1 Problem 1

Let  $E \subseteq \mathbb{R}^n$  be bounded. Prove the following are equivalent:

1. For any  $\epsilon > 0$  there exists an open set  $G$  and a closed set  $F$  such that

$$F \subseteq E \subseteq G \qquad m(G \setminus F) < \epsilon.$$

2. There exists a  $G_\delta$  set  $V$  and an  $F_\sigma$  set  $H$  such that

$$m(V \setminus H) = 0.$$

## 8.2 Problem 2

Let  $\{f_k\}_{k=1}^\infty$  be a sequence of extended real-valued Lebesgue measurable functions.

- a. Prove that  $\sup_k f_k$  is a Lebesgue measurable function.
- b. Prove that if  $\lim_{k \rightarrow \infty} f_k(x)$  exists for every  $x \in \mathbb{R}^n$  then  $\lim_{k \rightarrow \infty} f_k$  is also a measurable function.

## 8.3 Problem 3

### 8.3.1 a

Prove that if  $E \subseteq \mathbb{R}^n$  is a Lebesgue measurable set, then for any  $h \in \mathbb{R}$  the set

$$E + h := \{x + h \mid x \in E\}$$

is also Lebesgue measurable and satisfies  $m(E + h) = m(E)$ .

### 8.3.2 b

Prove that if  $f$  is a non-negative measurable function on  $\mathbb{R}^n$  and  $h \in \mathbb{R}^n$  then the function

$$\tau_h d(x) := f(x - h)$$

is a non-negative measurable function and

$$\int f(x) dx = \int f(x - h) dx.$$

## 8.4 Problem 4

Let  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  be a Lebesgue measurable function.

- a. Prove that for all  $\alpha > 0$ ,

$$A_\alpha := \left\{ x \in \mathbb{R}^n \mid |f(x)| > \alpha \right\} \implies m(A_\alpha) \leq \frac{1}{\alpha} \int |f(x)| dx.$$

- b. Prove that

$$\int |f(x)| dx = 0 \iff f = 0 \text{ almost everywhere.}$$

## 8.5 Problem 5

Let  $\{f_k\}_{k=1}^\infty \subseteq L^2([0, 1])$  be a sequence which *converges in  $L^1$*  to a function  $f$ .

- a. Prove that  $f \in L^1([0, 1])$ .
- b. Give an example illustrating that  $f_k$  may not converge to  $f$  almost everywhere.
- c. Prove that  $\{f_k\}$  must contain a subsequence that converges to  $f$  almost everywhere.

# 9 | Midterm Exam 2 (November 2018)

## 9.1 Problem 1

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

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

## 9.2 Problem 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.

### 9.3 Problem 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

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

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

### 9.4 Problem 4

See [section 10.3](#)

## 10 | Practice Exam (November 2014)

### 10.1 1: Fubini-Tonelli

#### 10.1.1 a

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

#### 10.1.2 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

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

## 10.2 2: Convolutions and the Fourier Transform

### 10.2.1 a

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

### 10.2.2 b

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

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

### 10.2.3 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  $\widehat{f}$  is not in  $L^1(\mathbb{R}^n)$ .

## 10.3 3: Hilbert Spaces

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

### 10.3.1 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

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

## 10.3.2 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,

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

## 10.3.3 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

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

## 10.4 4: $L^p$ Spaces

### 10.4.1 a

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

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

### 10.4.2 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  $f + g$ .

### 10.4.3 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

**Solution:**



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

## 10.5 5: Dual Spaces

Let  $X$  be a normed vector space.

### 10.5.1 a

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

### 10.5.2 b

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

### 10.5.3 c

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

# 11 | Common Inequalities

**Proposition 11.0.1 (Reverse Triangle Inequality).**

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

**Proposition 11.0.2 (Chebyshev's Inequality).**

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

**Proposition 11.0.3 (Holder's Inequality).**

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

*Proof (of 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

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

■

**Example 11.0.4 (Application of Holder's inequality: containment of  $L^p$  spaces):** 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 (of containment of  $L^p$  spaces).*

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  $\ell_p$  spaces, but just note that  $\sum |x_n| < \infty \implies x_n < 1$  for large enough  $n$ , and thus  $p < q \implies |x_n|^q \leq |x_n|^p$ .*

■


**Proposition 11.0.5 (Cauchy-Schwarz Inequality).**

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

**Remark 11.0.6:** In general, Cauchy-Schwarz relates inner product to norm, and only happens to relate norms in  $L^1$ .

**Proposition 11.0.7 (Minkowski's Inequality).**

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

**Remark 11.0.8:** This 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

$$\begin{aligned} \frac{1}{q} &= 1 - \frac{1}{p} = \frac{p-1}{p} \\ q &= \frac{p}{p-1}. \end{aligned}$$

- Then taking integrals yields

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

- 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 11.0.9 (Young's Inequality).**

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

**Remark 11.0.10 (some useful special 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 11.0.11 (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 that this does not need to be a basis.*

**Proposition 11.0.12 (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  $H$ .

## 12 | Less Explicitly Used Inequalities

**Proposition 12.0.1 (AM-GM Inequality).**

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

**Proposition 12.0.2 (Jensen's Inequality).**

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

**Proposition 12.0.3 (Young's Product Inequality).**

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

**Proposition 12.0.4(?)**.

$$(a + b)^p \leq 2^{p-1}(a^p + b^p).$$

**Proposition 12.0.5 (Bernoulli's Inequality)**.

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

**Proposition 12.0.6 (Exponential Inequality)**.

$$\forall t \in \mathbb{R}, \quad 1 + t \leq e^t.$$

*Proof .*

- It's an equality when  $t = 0$ .
- $\frac{\partial}{\partial t} 1 + t < \frac{\partial}{\partial t} e^t \iff t < 0$

■

**Proposition 12.0.7 (Young's Convolution Inequality)**.

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