

Real Analysis Qualifying Exam Notes

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1 Spring 2020

1.1 1

Prove that if $f : [0, 1] \rightarrow \mathbb{R}$ is continuous then

$$\lim_{k \rightarrow \infty} \int_0^1 kx^{k-1} f(x) dx = f(1).$$

1.2 2

Let m_* denote the Lebesgue outer measure on \mathbb{R} .

- a. Prove that for every $E \subseteq \mathbb{R}$ there exists a Borel set B containing E such that

$$m_*(B) = m_*(E).$$

- b. Prove that if $E \subseteq \mathbb{R}$ has the property that

$$m_*(A) = m_*(A \cap E) + m_*(A \cap E^c)$$

for every set $A \subseteq \mathbb{R}$, then there exists a Borel set $B \subseteq \mathbb{R}$ such that $E = B \setminus N$ with $m_*(N) = 0$.

Be sure to address the case when $m_*(E) = \infty$.

1.3 3

- a. Prove that if $g \in L^1(\mathbb{R})$ then

$$\lim_{N \rightarrow \infty} \int_{|x| \geq N} |f(x)| dx = 0,$$

and demonstrate that it is not necessarily the case that $f(x) \rightarrow 0$ as $|x| \rightarrow \infty$.

- b. Prove that if $f \in L^1([1, \infty))$ and is decreasing, then $\lim_{x \rightarrow \infty} f(x) = 0$ and in fact $\lim_{x \rightarrow \infty} xf(x) = 0$.
- c. If $f : [1, \infty) \rightarrow [0, \infty)$ is decreasing with $\lim_{x \rightarrow \infty} xf(x) = 0$, does this ensure that $f \in L^1([1, \infty))$?

1.4 4

Let $f, g \in L^1(\mathbb{R})$. Argue that $H(x, y) := f(y)g(x - y)$ defines a function in $L^1(\mathbb{R}^2)$ and deduce from this fact that

$$(f * g)(x) := \int_{\mathbb{R}} f(y)g(x - y) dy$$

defines a function in $L^1(\mathbb{R})$ that satisfies

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

1.5 5

Compute the following limit and justify your calculations:

$$\lim_{n \rightarrow \infty} \int_0^n \left(1 + \frac{x^2}{n}\right)^{-(n+1)} dx.$$

1.6 6

a. Show that

$$L^2([0, 1]) \subseteq L^1([0, 1]) \quad \text{and} \quad \ell^1(\mathbb{Z}) \subseteq \ell^2(\mathbb{Z}).$$

b. For $f \in L^1([0, 1])$ define

$$\hat{f}(n) := \int_0^1 f(x) e^{-2\pi i n x} dx.$$

Prove that if $f \in L^1([0, 1])$ and $\{\hat{f}(n)\} \in \ell^1(\mathbb{Z})$ then

$$S_N f(x) := \sum_{|n| \leq N} \hat{f}(n) e^{2\pi i n x}.$$

converges uniformly on $[0, 1]$ to a continuous function g such that $g = f$ almost everywhere.

Hint: One approach is to argue that if $f \in L^1([0, 1])$ with $\{\hat{f}(n)\} \in \ell^1(\mathbb{Z})$ then $f \in L^2([0, 1])$.

2 Fall 2019**2.1 1.**

Let $\{a_n\}_{n=1}^{\infty}$ be a sequence of real numbers.

a. Prove that if $\lim_{n \rightarrow \infty} a_n = 0$, then

$$\lim_{n \rightarrow \infty} \frac{a_1 + \cdots + a_n}{n} = 0$$

- b. Prove that if $\sum_{n=1}^{\infty} \frac{a_n}{n}$ converges, then

$$\lim_{n \rightarrow \infty} \frac{a_1 + \cdots + a_n}{n} = 0$$

2.2 2.

Prove that

$$\left| \frac{d^n}{dx^n} \frac{\sin x}{x} \right| \leq \frac{1}{n}$$

for all $x \neq 0$ and positive integers n .

Hint: Consider $\int_0^1 \cos(tx) dt$

2.3 3.

Let (X, \mathcal{B}, μ) be a measure space with $\mu(X) = 1$ and $\{B_n\}_{n=1}^{\infty}$ be a sequence of \mathcal{B} -measurable subsets of X , and

$$B := \left\{ x \in X \mid x \in B_n \text{ for infinitely many } n \right\}.$$

- Argue that B is also a \mathcal{B} -measurable subset of X .
- Prove that if $\sum_{n=1}^{\infty} \mu(B_n) < \infty$ then $\mu(B) = 0$.
- Prove that if $\sum_{n=1}^{\infty} \mu(B_n) = \infty$ **and** the sequence of set complements $\{B_n^c\}_{n=1}^{\infty}$ satisfies

$$\mu \left(\bigcap_{n=k}^K B_n^c \right) = \prod_{n=k}^K (1 - \mu(B_n))$$

for all positive integers k and K with $k < K$, then $\mu(B) = 1$.

Hint: Use the fact that $1 - x \leq e^{-x}$ for all x .

2.4 4.

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

- Prove that for every $x \in \mathcal{H}$ one has

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

- b. Prove that for any sequence $\{a_n\}_{n=1}^\infty \in \ell^2(\mathbb{N})$ there exists an element $x \in \mathcal{H}$ such that

$$a_n = \langle x, u_n \rangle \text{ for all } n \in \mathbb{N}$$

and

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

2.5 5.

- a. Show that if f is continuous with compact support on \mathbb{R} , then

$$\lim_{y \rightarrow 0} \int_{\mathbb{R}} |f(x-y) - f(x)| dx = 0$$

- b. Let $f \in L^1(\mathbb{R})$ and for each $h > 0$ let

$$\mathcal{A}_h f(x) := \frac{1}{2h} \int_{|y| \leq h} f(x-y) dy$$

- c. Prove that $\|\mathcal{A}_h f\|_1 \leq \|f\|_1$ for all $h > 0$.
 ii. Prove that $\mathcal{A}_h f \rightarrow f$ in $L^1(\mathbb{R})$ as $h \rightarrow 0^+$.

3 Spring 2019

3.1 1

Let $C([0, 1])$ denote the space of all continuous real-valued functions on $[0, 1]$.

- a. Prove that $C([0, 1])$ is complete under the uniform norm $\|f\|_u := \sup_{x \in [0, 1]} |f(x)|$.
 b. Prove that $C([0, 1])$ is not complete under the L^1 -norm $\|f\|_1 = \int_0^1 |f(x)| dx$.

3.2 2

Let \mathcal{B} denote the set of all Borel subsets of \mathbb{R} and $\mu : \mathcal{B} \rightarrow [0, \infty)$ denote a finite Borel measure on \mathbb{R} .

- a. Prove that if $\{F_k\}$ is a sequence of Borel sets for which $F_k \supseteq F_{k+1}$ for all k , then

$$\lim_{k \rightarrow \infty} \mu(F_k) = \mu\left(\bigcap_{k=1}^{\infty} F_k\right)$$

- b. Suppose μ has the property that $\mu(E) = 0$ for every $E \in \mathcal{B}$ with Lebesgue measure $m(E) = 0$. Prove that for every $\varepsilon > 0$ there exists $\delta > 0$ so that if $E \in \mathcal{B}$ with $m(E) < \delta$, then $\mu(E) < \varepsilon$.

3.3 3

Let $\{f_k\}$ be any sequence of functions in $L^2([0, 1])$ satisfying $\|f_k\|_2 \leq M$ for all $k \in \mathbb{N}$.

Prove that if $f_k \rightarrow f$ almost everywhere, then $f \in L^2([0, 1])$ with $\|f\|_2 \leq M$ and

$$\lim_{k \rightarrow \infty} \int_0^1 f_k(x) dx = \int_0^1 f(x) dx$$

Hint: Try using Fatou's Lemma to show that $\|f\|_2 \leq M$ and then try applying Egorov's Theorem.

3.4 4

Let f be a non-negative function on \mathbb{R}^n and $\mathcal{A} = \{(x, t) \in \mathbb{R}^n \times \mathbb{R} : 0 \leq t \leq f(x)\}$.

Prove the validity of the following two statements:

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

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

3.5 5

- a. Show that $L^2([0, 1]) \subseteq L^1([0, 1])$ and argue that $L^2([0, 1])$ in fact forms a dense subset of $L^1([0, 1])$.
- b. Let Λ be a continuous linear functional on $L^1([0, 1])$.

Prove the Riesz Representation Theorem for $L^1([0, 1])$ by following the steps below:

- i. Establish the existence of a function $g \in L^2([0, 1])$ which represents Λ in the sense that

$$\Lambda(f) = \int_0^1 f(x)g(x)dx \text{ for all } f \in L^2([0, 1]).$$

Hint: You may use, without proof, the Riesz Representation Theorem for $L^2([0, 1])$.

- ii. Argue that the g obtained above must in fact belong to $L^\infty([0, 1])$ and represent Λ in the sense that

$$\Lambda(f) = \int_0^1 f(x)\overline{g(x)}dx \quad \text{for all } f \in L^1([0, 1])$$

with

$$\|g\|_{L^\infty([0,1])} = \|\Lambda\|_{L^1([0,1])^\vee}$$

4 Fall 2018**4.1 1**

Let $f(x) = \frac{1}{x}$. Show that f is uniformly continuous on $(1, \infty)$ but not on $(0, \infty)$.

4.2 2

Let $E \subset \mathbb{R}$ be a Lebesgue measurable set. Show that there is a Borel set $B \subset E$ such that $m(E \setminus B) = 0$.

4.3 3

Suppose $f(x)$ and $xf(x)$ are integrable on \mathbb{R} . Define F by

$$F(t) := \int_{-\infty}^{\infty} f(x) \cos(xt) dx$$

Show that

$$F'(t) = - \int_{-\infty}^{\infty} xf(x) \sin(xt) dx.$$

4.4 4

Let $f \in L^1([0, 1])$. Prove that

$$\lim_{n \rightarrow \infty} \int_0^1 f(x) |\sin nx| dx = \frac{2}{\pi} \int_0^1 f(x) dx$$

Hint: Begin with the case that f is the characteristic function of an interval.

4.5 5

Let $f \geq 0$ be a measurable function on \mathbb{R} . Show that

$$\int_{\mathbb{R}} f = \int_0^{\infty} m(\{x : f(x) > t\}) dt$$

4.6 6

Compute the following limit and justify your calculations:

$$\lim_{n \rightarrow \infty} \int_1^n \frac{dx}{\left(1 + \frac{x}{n}\right)^n \sqrt[n]{x}}$$

5 Spring 2018**5.1 1**

Define

$$E := \left\{ x \in \mathbb{R} : \left| x - \frac{p}{q} \right| < q^{-3} \text{ for infinitely many } p, q \in \mathbb{N} \right\}.$$

Prove that $m(E) = 0$.

5.2 2

Let

$$f_n(x) := \frac{x}{1+x^n}, \quad x \geq 0.$$

- Show that this sequence converges pointwise and find its limit. Is the convergence uniform on $[0, \infty)$?
- Compute

$$\lim_{n \rightarrow \infty} \int_0^\infty f_n(x) dx$$

5.3 3

Let f be a non-negative measurable function on $[0, 1]$.

Show that

$$\lim_{p \rightarrow \infty} \left(\int_{[0,1]} f(x)^p dx \right)^{\frac{1}{p}} = \|f\|_\infty.$$

5.4 4

Let $f \in L^2([0, 1])$ and suppose

$$\int_{[0,1]} f(x) x^n dx = 0 \text{ for all integers } n \geq 0.$$

Show that $f = 0$ almost everywhere.

5.5 5

Suppose that

- $f_n, f \in L^1$,
- $f_n \rightarrow f$ almost everywhere, and
- $\int |f_n| \rightarrow \int |f|$.

Show that $\int f_n \rightarrow \int f$

6 Fall 2017**6.1 1**

Let

$$f(x) = s \sum_{n=0}^{\infty} \frac{x^n}{n!}.$$

Describe the intervals on which f does and does not converge uniformly.

6.2 2

Let $f(x) = x^2$ and $E \subset [0, \infty) := \mathbb{R}^+$.

1. Show that

$$m^*(E) = 0 \iff m^*(f(E)) = 0.$$

2. Deduce that the map

$$\begin{aligned} \varphi : \mathcal{L}(\mathbb{R}^+) &\longrightarrow \mathcal{L}(\mathbb{R}^+) \\ E &\mapsto f(E) \end{aligned}$$

is a bijection from the class of Lebesgue measurable sets of $[0, \infty)$ to itself.

6.3 3

Let

$$S = \text{span}_{\mathbb{C}} \left\{ \chi_{(a,b)} \mid a, b \in \mathbb{R} \right\},$$

the complex linear span of characteristic functions of intervals of the form (a, b) .

Show that for every $f \in L^1(\mathbb{R})$, there exists a sequence of functions $\{f_n\} \subset S$ such that

$$\lim_{n \rightarrow \infty} \|f_n - f\|_1 = 0$$

6.4 4

Let

$$f_n(x) = nx(1-x)^n, \quad n \in \mathbb{N}.$$

1. Show that $f_n \rightarrow 0$ pointwise but not uniformly on $[0, 1]$.

Hint: Consider the maximum of f_n .

- 2.

$$\lim_{n \rightarrow \infty} \int_0^1 n(1-x)^n \sin x dx = 0$$

6.5 5

Let φ be a compactly supported smooth function that vanishes outside of an interval $[-N, N]$ such that $\int_{\mathbb{R}} \varphi(x) dx = 1$.

For $f \in L^1(\mathbb{R})$, define

$$K_j(x) := j\varphi(jx), \quad f * K_j(x) := \int_{\mathbb{R}} f(x-y)K_j(y) dy$$

and prove the following:

1. Each $f * K_j$ is smooth and compactly supported.
- 2.

$$\lim_{j \rightarrow \infty} \|f * K_j - f\|_1 = 0$$

Hint:

$$\lim_{y \rightarrow 0} \int_{\mathbb{R}} |f(x-y) - f(x)| dy = 0$$

6.6 6

Let X be a complete metric space and define a norm

$$\|f\| := \max\{|f(x)| : x \in X\}.$$

Show that $(C^0(\mathbb{R}), \|\cdot\|)$ (the space of continuous functions $f : X \rightarrow \mathbb{R}$) is complete.

7 Spring 2017

7.1 1

Let K be the set of numbers in $[0, 1]$ whose decimal expansions do not use the digit 4.

We use the convention that when a decimal number ends with 4 but all other digits are different from 4, we replace the digit 4 with $399\ldots$. For example, $0.8754 = 0.8753999\ldots$.

Show that K is a compact, nowhere dense set without isolated points, and find the Lebesgue measure $m(K)$.

7.2 2

- a. Let μ be a measure on a measurable space (X, \mathcal{M}) and f a positive measurable function.

Define a measure λ by

$$\lambda(E) := \int_E f \, d\mu, \quad E \in \mathcal{M}$$

Show that for g any positive measurable function,

$$\int_X g \, d\lambda = \int_X fg \, d\mu$$

- b. Let $E \subset \mathbb{R}$ be a measurable set such that

$$\int_E x^2 \, dm = 0.$$

Show that $m(E) = 0$.

7.3 3

Let

$$f_n(x) = ae^{-nax} - be^{-nbx} \quad \text{where } 0 < a < b.$$

Show that

a. $\sum_{n=1}^{\infty} |f_n|$ is not in $L^1([0, \infty), m)$

Hint: $f_n(x)$ has a root x_n .

b.

$$\sum_{n=1}^{\infty} f_n \text{ is in } L^1([0, \infty), m) \quad \text{and} \quad \int_0^{\infty} \sum_{n=1}^{\infty} f_n(x) \, dm = \ln \frac{b}{a}$$

7.4 4

Let $f(x, y)$ on $[-1, 1]^2$ be defined by

$$f(x, y) = \begin{cases} \frac{xy}{(x^2 + y^2)^2} & (x, y) \neq (0, 0) \\ 0 & (x, y) = (0, 0) \end{cases}$$

Determine if f is integrable.

7.5 5

Let $f, g \in L^2(\mathbb{R})$. Prove that the formula

$$h(x) := \int_{-\infty}^{\infty} f(t)g(x-t)dt$$

defines a uniformly continuous function h on \mathbb{R} .

7.6 5

Show that the space $C^1([a, b])$ is a Banach space when equipped with the norm

$$\|f\| := \sup_{x \in [a, b]} |f(x)| + \sup_{x \in [a, b]} |f'(x)|.$$

8 Fall 2016 (Neil-ish)**8.1 1**

Define

$$f(x) = \sum_{n=1}^{\infty} \frac{1}{n^x}.$$

Show that f converges to a differentiable function on $(1, \infty)$ and that

$$f'(x) = \sum_{n=1}^{\infty} \left(\frac{1}{n^x} \right)'.$$

Hint:

$$\left(\frac{1}{n^x} \right)' = -\frac{1}{n^x} \ln n$$

8.2 2

Let $f, g : [a, b] \rightarrow \mathbb{R}$ be measurable with

$$\int_a^b f(x) \, dx = \int_a^b g(x) \, dx.$$

Show that either

1. $f(x) = g(x)$ almost everywhere, or
2. There exists a measurable set $E \subset [a, b]$ such that

$$\int_E f(x) \, dx > \int_E g(x) \, dx$$

8.3 3

Let $f \in L^1(\mathbb{R})$. Show that

$$\lim_{x \rightarrow 0} \int_{\mathbb{R}} |f(y-x) - f(y)| \, dy = 0$$

8.4 4

Let (X, \mathcal{M}, μ) be a measure space and suppose $\{E_n\} \subset \mathcal{M}$ satisfies

$$\lim_{n \rightarrow \infty} \mu(X \setminus E_n) = 0.$$

Define

$$G := \left\{ x \in X \mid x \in E_n \text{ for only finitely many } n \right\}.$$

Show that $G \in \mathcal{M}$ and $\mu(G) = 0$.

8.5 5

Let $\varphi \in L^\infty(\mathbb{R})$. Show that the following limit exists and satisfies the equality

$$\lim_{n \rightarrow \infty} \left(\int_{\mathbb{R}} \frac{|\varphi(x)|^n}{1+x^2} \, dx \right)^{\frac{1}{n}} = \|\varphi\|_\infty.$$

8.6 6

Let $f, g \in L^2(\mathbb{R})$. Show that

$$\lim_{n \rightarrow \infty} \int_{\mathbb{R}} f(x)g(x+n)dx = 0$$

9 Spring 2016 (Neil-ish)**9.1 1**

For $n \in \mathbb{N}$, define

$$e_n = \left(1 + \frac{1}{n}\right)^n \quad \text{and} \quad E_n = \left(1 + \frac{1}{n}\right)^{n+1}$$

Show that $e_n < E_n$, and prove Bernoulli's inequality:

$$(1+x)^n \geq 1+nx \text{ for } -1 < x < \infty \text{ and } n \in \mathbb{N}$$

Use this to show the following:

1. The sequence e_n is increasing.
2. The sequence E_n is decreasing.
3. $2 < e_n < E_n < 4$.
4. $\lim_{n \rightarrow \infty} e_n = \lim_{n \rightarrow \infty} E_n$.

9.2 2

Let $0 < \lambda < 1$ and construct a Cantor set C_λ by successively removing middle intervals of length λ .

Prove that $m(C_\lambda) = 0$.

9.3 3

Let f be Lebesgue measurable on \mathbb{R} and $E \subset \mathbb{R}$ be measurable such that

$$0 < A = \int_E f(x)dx < \infty.$$

Show that for every $0 < t < 1$, there exists a measurable set $E_t \subset E$ such that

$$\int_{E_t} f(x)dx = tA.$$

9.4 4

Let $E \subset \mathbb{R}$ be measurable with $m(E) < \infty$. Define

$$f(x) = m(E \cap (E+x)).$$

Show that

1. $f \in L^1(\mathbb{R})$.
2. f is uniformly continuous.
3. $\lim_{|x| \rightarrow \infty} f(x) = 0$

Hint:

$$\chi_{E \cap (E+x)}(y) = \chi_E(y) \chi_E(y-x)$$

9.5 5

Let (X, \mathcal{M}, μ) be a measure space. For $f \in L^1(\mu)$ and $\lambda > 0$, define

$$\varphi(\lambda) = \mu(\{x \in X | f(x) > \lambda\}) \quad \text{and} \quad \psi(\lambda) = \mu(\{x \in X | f(x) < -\lambda\})$$

Show that φ, ψ are Borel measurable and

$$\int_X |f| \, d\mu = \int_0^\infty [\varphi(\lambda) + \psi(\lambda)] \, d\lambda$$

9.6 6

Without using the Riesz Representation Theorem, compute

$$\sup \left\{ \left| \int_0^1 f(x) e^x dx \right| \mid f \in L^2([0, 1], m), \|f\|_2 \leq 1 \right\}$$

10 Fall 2015

10.1 1

Define

$$f(x) = c_0 + c_1 x^1 + c_2 x^2 + \dots + c_n x^n \text{ with } n \text{ even and } c_n > 0.$$

Show that there is a number x_m such that $f(x_m) \leq f(x)$ for all $x \in \mathbb{R}$.

10.2 2

Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be Lebesgue measurable.

1. Show that there is a sequence of simple functions $s_n(x)$ such that $s_n(x) \rightarrow f(x)$ for all $x \in \mathbb{R}$.
2. Show that there is a Borel measurable function g such that $g = f$ almost everywhere.

10.3 3

Compute the following limit:

$$\lim_{n \rightarrow \infty} \int_1^n \frac{n e^{-x}}{1 + n x^2} \sin\left(\frac{x}{n}\right) dx$$

10.4 4

Let $f : [1, \infty) \rightarrow \mathbb{R}$ such that $f(1) = 1$ and

$$f'(x) = \frac{1}{x^2 + f(x)^2}$$

Show that the following limit exists and satisfies the equality

$$\lim_{x \rightarrow \infty} f(x) \leq 1 + \frac{\pi}{4}$$

10.5 5

Let $f, g \in L^1(\mathbb{R})$ be Borel measurable.

1. Show that
 - The function

$$F(x, y) := f(x - y)g(y)$$

is Borel measurable on \mathbb{R}^2 , and

- For almost every $y \in \mathbb{R}$,

$$F_y(x) := f(x - y)g(y)$$

is integrable with respect to y .

2. Show that $f * g \in L^1(\mathbb{R})$ and

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

10.6 6

Let $f : [0, 1] \rightarrow \mathbb{R}$ be continuous. Show that

$$\sup \left\{ \|fg\|_1 \mid g \in L^1[0, 1], \|g\|_1 \leq 1 \right\} = \|f\|_\infty$$

11 Spring 2015**11.1 1**

Let (X, d) and (Y, ρ) be metric spaces, $f : X \rightarrow Y$, and $x_0 \in X$.

Prove that the following statements are equivalent:

1. For every $\varepsilon > 0$ $\exists \delta > 0$ such that $\rho(f(x), f(x_0)) < \varepsilon$ whenever $d(x, x_0) < \delta$.
2. The sequence $\{f(x_n)\}_{n=1}^\infty \rightarrow f(x_0)$ for every sequence $\{x_n\} \rightarrow x_0$ in X .

11.2 2

Let $f : \mathbb{R} \rightarrow \mathbb{C}$ be continuous with period 1. Prove that

$$\lim_{N \rightarrow \infty} \frac{1}{N} \sum_{n=1}^N f(n\alpha) = \int_0^1 f(t) dt \quad \forall \alpha \in \mathbb{R} \setminus \mathbb{Q}.$$

Hint: show this first for the functions $f(t) = e^{2\pi i k t}$ for $k \in \mathbb{Z}$.

11.3 3

Let μ be a finite Borel measure on \mathbb{R} and $E \subset \mathbb{R}$ Borel. Prove that the following statements are equivalent:

1. $\forall \varepsilon > 0$ there exists G open and F closed such that

$$F \subseteq E \subseteq G \quad \text{and} \quad \mu(G \setminus F) < \varepsilon.$$

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

$$H \subseteq E \subseteq V \quad \text{and} \quad \mu(V \setminus H) = 0$$

11.4 4

Define

$$f(x, y) := \begin{cases} \frac{x^{1/3}}{(1+xy)^{3/2}} & \text{if } 0 \leq x \leq y \\ 0 & \text{otherwise} \end{cases}$$

Carefully show that $f \in L^1(\mathbb{R}^2)$.

11.5 5

Let \mathcal{H} be a Hilbert space.

1. Let $x \in \mathcal{H}$ and $\{u_n\}_{n=1}^N$ be an orthonormal set. Prove that the best approximation to x in \mathcal{H} by an element in $\text{span}_{\mathbb{C}} \{u_n\}$ is given by

$$\hat{x} := \sum_{n=1}^N \langle x, u_n \rangle u_n.$$

2. Conclude that finite dimensional subspaces of \mathcal{H} are always closed.

11.6 6

Let $f \in L^1(\mathbb{R})$ and g be a bounded measurable function on \mathbb{R} .

1. Show that the convolution $f * g$ is well-defined, bounded, and uniformly continuous on \mathbb{R} .
2. Prove that one further assumes that $g \in C^1(\mathbb{R})$ with bounded derivative, then $f * g \in C^1(\mathbb{R})$ and

$$\frac{d}{dx}(f * g) = f * \left(\frac{d}{dx} g \right)$$

12 Fall 2014

12.1 1

Let $\{f_n\}$ be a sequence of continuous functions such that $\sum f_n$ converges uniformly.

Prove that $\sum f_n$ is also continuous.

12.2 2

Let I be an index set and $\alpha : I \rightarrow (0, \infty)$.

1. Show that

$$\sum_{i \in I} a(i) := \sup_{\substack{J \subset I \\ J \text{ finite}}} \sum_{i \in J} a(i) < \infty \implies I \text{ is countable.}$$

2. Suppose $I = \mathbb{Q}$ and $\sum_{q \in \mathbb{Q}} a(q) < \infty$. Define

$$f(x) := \sum_{\substack{q \in \mathbb{Q} \\ q \leq x}} a(q).$$

Show that f is continuous at $x \iff x \notin \mathbb{Q}$.

12.3 3

Let $f \in L^1(\mathbb{R})$. Show that

$$\forall \varepsilon > 0 \exists \delta > 0 \text{ such that } m(E) < \delta \implies \int_E |f(x)| dx < \varepsilon$$

12.4 4

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

$$\int_{[0,1]} f(x)g(x)dx = 0 \quad \text{for all continuous } f : [0, 1] \rightarrow \mathbb{R} \implies g(x) = 0 \text{ almost everywhere.}$$

12.5 5

1. Let $f \in C_c^0(\mathbb{R}^n)$, and show

$$\lim_{t \rightarrow 0} \int_{\mathbb{R}^n} |f(x+t) - f(x)| dx = 0.$$

2. Extend the above result to $f \in L^1(\mathbb{R}^n)$ and show that

$$f \in L^1(\mathbb{R}^n), g \in L^\infty(\mathbb{R}^n) \implies f * g \text{ is bounded and uniformly continuous.}$$

12.6 6

Let $1 \leq p, q \leq \infty$ be conjugate exponents, and show that

$$f \in L^p(\mathbb{R}^n) \implies \|f\|_p = \sup_{\|g\|_q=1} \left| \int f(x)g(x)dx \right|$$

13 Spring 2014**13.1 1**

1. Give an example of a continuous $f \in L^1(\mathbb{R})$ such that $f(x) \not\rightarrow 0$ as $|x| \rightarrow \infty$.
2. Show that if f is *uniformly* continuous, then

$$\lim_{|x| \rightarrow \infty} f(x) = 0.$$

13.2 2

Let $\{a_n\}$ be a sequence of real numbers such that

$$\{b_n\} \in \ell^2(\mathbb{N}) \implies \sum a_n b_n < \infty.$$

Show that $\sum a_n^2 < \infty$.

Note: Assume a_n, b_n are all non-negative.

13.3 3

Let $f : \mathbb{R} \rightarrow \mathbb{R}$ and suppose

$$\forall x \in \mathbb{R}, \quad f(x) \geq \limsup_{y \rightarrow x} f(y)$$

Prove that f is Borel measurable.

13.4 4

Let (X, \mathcal{M}, μ) be a measure space and suppose f is a measurable function on X . Show that

$$\lim_{n \rightarrow \infty} \int_X f^n d\mu = \begin{cases} \infty \\ \mu(f^{-1}(1)) \end{cases} \quad \text{or}$$

and characterize the collection of functions of each type.

13.5 5

Let $f, g \in L^1([0, 1])$ and for all $x \in [0, 1]$ define

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

Prove that

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