

# Problem Set 8

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## 1 Problem 1

### 1.1 Part a

It follows from the definition that  $\|f\|_\infty = 0 \iff f = 0$  almost everywhere, and if  $\|f\|_\infty$  is the best upper bound for  $f$  almost everywhere, then  $\|cf\|_\infty$  is the best upper bound for  $cf$  almost everywhere.

So it remains to show the triangle inequality. Suppose that  $|f(x)| \leq \|f\|_\infty$  a.e. and  $|g(x)| \leq \|g\|_\infty$  a.e., then by the triangle inequality for the  $|\cdot|_{\mathbb{R}}$  we have

$$\begin{aligned} |(f+g)(x)| &\leq |f(x)| + |g(x)| \quad a.e. \\ &\leq \|f\|_\infty + \|g\|_\infty \quad a.e., \end{aligned}$$

which means that  $\|f+g\|_\infty \leq \|f\|_\infty + \|g\|_\infty$  as desired.

## 1.2 Part b

$\Rightarrow$  : Suppose  $\|f_n - f\|_\infty \rightarrow 0$ , then for every  $\varepsilon$ ,  $N_\varepsilon$  can be chosen large enough such that  $|f_n(x) - f(x)| < \varepsilon$  a.e., which precisely means that there exist sets  $E_\varepsilon$  such that  $x \in E_\varepsilon \Rightarrow |f_n(x) - f(x)| < \varepsilon$  and  $m(E_\varepsilon^c) = 0$ .

But then taking the sequence  $\varepsilon_n := \frac{1}{n} \rightarrow 0$ , we have  $f_n \Rightarrow f$  uniformly on  $E := \bigcap_n E_n$  by definition, and  $E^c = \bigcup_n E_n^c$  is still a null set.

$\Leftarrow$  : Suppose  $f_n \Rightarrow f$  uniformly on some set  $E$  and  $m(E^c) = 0$ . Then for any  $\varepsilon$ , we can choose  $N$  large enough such that  $|f_n(x) - f(x)| < \varepsilon$  on  $E$ ; but then  $\varepsilon$  is an upper bound for  $f_n - f$  almost everywhere, so  $\|f_n - f\|_\infty < \varepsilon \rightarrow 0$ .

## 1.3 Part c

To see that simple functions are dense in  $L^\infty(X)$ , we can use the fact that  $f \in L^\infty(X) \iff$  there exists a  $g$  such that  $f = g$  a.e. and  $g$  is bounded.

Then there is a sequence  $s_n$  of simple functions such that  $\|s_n - g\|_\infty \rightarrow 0$ , which follows from a proof in Folland:

*Proof.* (a) For  $n = 0, 1, 2, \dots$  and  $0 \leq k \leq 2^{2^n} - 1$ , let

$$E_n^k = f^{-1}((k2^{-n}, (k+1)2^{-n}]) \quad \text{and} \quad F_n = f^{-1}((2^n, \infty]),$$

and define

$$\phi_n = \sum_{k=0}^{2^{2^n}-1} k2^{-n} \chi_{E_n^k} + 2^n \chi_{F_n}.$$

(This formula is messy in print but easily understood graphically; see Figure 2.1.) It is easily checked that  $\phi_n \leq \phi_{n+1}$  for all  $n$ , and  $0 \leq f - \phi_n \leq 2^{-n}$  on the set where  $f \leq 2^n$ . The result therefore follows.



However,  $C_c^0(X)$  is dense  $L^\infty(X) \iff$  every  $f \in L^\infty(X)$  can be approximated by a sequence  $\{g_k\} \subset C_c^0(X)$  in the sense that  $\|f - g_n\|_\infty \rightarrow 0$ . To see why this can *not* be the case, let  $f(x) = 1$ , so  $\|f\|_\infty = 1$  and let  $g_n \rightarrow f$  be an arbitrary sequence of  $C_c^0$  functions converging to  $f$  pointwise.

Since every  $g_n$  has compact support, say  $\text{supp}(g_n) := E_n$ , then  $g_n|_{E_n^c} \equiv 0$  and  $m(E_n^c) > 0$ . In particular, this means that  $\|f - g_n\|_\infty = 1$  for every  $n$ , so  $g_n$  can not converge to  $f$  in the infinity norm.

## 2 Problem 2

### 2.1 Part a

#### 2.1.1 Part i

**Lemma:**  $\|1\|_p = m(X)^{1/p}$

This follows from  $\|1\|_p^p = \int_X |1|^p = \int_X 1 = m(X)$  and taking  $p$ th roots.  $\square$

By Holder with  $p = q = 2$ , we can now write

$$\begin{aligned} \|f\|_1 &= \|1 \cdot f\|_1 \leq \|1\|_2 \|f\|_2 = m(X)^{1/2} \|f\|_2 \\ \implies \|f\|_1 &\leq m(X)^{1/2} \|f\|_2. \end{aligned}$$

Letting  $M := \|f\|_\infty$ , We also have

$$\begin{aligned} \|f\|_2^2 &= \int_X |f|^2 \leq \int_X |M|^2 = M^2 \int_X 1 = M^2 m(X) \\ \implies \|f\|_2 &\leq m(X)^{1/2} \|f\|_\infty \\ \implies m(X)^{1/2} \|f\|_2 &\leq m(X) \|f\|_\infty, \end{aligned}$$

and combining these yields

$$\|f\|_1 \leq m(X)^{1/2} \|f\|_2 \leq m(X) \|f\|_\infty,$$

from which it immediately follows

$$m(X) < \infty \implies L^\infty(X) \subseteq L^2(X) \subseteq L^1(X).$$

#### The Inclusions Are Strict:

$\exists f \in L^1(X) \setminus L^2(X)$ :

Let  $E_k = X \cap B(t_k)$  where  $B(t_k)$  is a ball centered at the origin (with radius depending on a parameter),  $A_k = E_k \setminus E_{k-1}$  to be disjoint annuli where  $t_k$  is chosen for each  $k$  such that  $m(A_k) = 1$ .

(Note: since  $m(X) < \infty$ ,  $X \subseteq \bigcup A_k$ .)

Let  $s : \mathbb{N} \rightarrow \mathbb{C}$  be arbitrary, then define  $f : X \rightarrow \mathbb{C}$  by  $f(x) = \sum_k s(k) \chi_{A_k}$  so we have

$$\begin{aligned}\|f\|_1 &= \int_X |f| = \sum_k \int_{A_k} s(k) = \sum_k s(k) \int_{A_k} 1 = \sum_k s(k) \\ \|f\|_2 &= \sum_k s(k)^2.\end{aligned}$$

Now setting  $s(k) = \left(\frac{1}{k}\right)^{1/2}$  yields  $\|f\|_1 < \infty$  but  $\|f\|_2 = \infty$ , so  $f \notin L^2(X)$ .

$\exists f \in L^2(X) \setminus L^\infty(X)$ :

Let  $X = (0, 1]$  and  $f(x) = x^{-1/4}$ . Then  $\|f\|_2 = \int_0^1 \frac{1}{x^{1/4}} < \infty$  by the  $p$ -test, but  $f$  is unbounded near 0. In particular, for any upper bound  $M$ , we have  $m(\{x \ni f(x) > M\}) > 0$ , so  $\|f\|_\infty = \infty$  and  $f \notin L^\infty(X)$ .

### 2.1.2 Part ii

$\exists f \in L^2(X) \setminus L^1(X)$  when  $m(X) = \infty$ :

Take  $X = [1, \infty)$  and let  $f(x) = x^{-1}$ . Then  $\|f\|_2 < \infty$  but  $\|f\|_1 = \infty$  by the  $p$ -test.

$\exists f \in L^\infty(X) \setminus L^2(X)$  when  $m(X) = \infty$ :

Take  $X = \mathbb{R}$  and  $f(x) = 1$ . Then  $\|f\|_\infty = 1 < \infty$  but  $\|f\|_2 = \int_{\mathbb{R}} 1 = \infty$ .

$L^2(X) \subseteq L^1(X) \implies m(X) < \infty$ :

Let  $f = \chi_X$ , by assumption we can find a constant  $M$  such that  $\|\chi_X\|_2 \leq M\|\chi_X\|_1$ .

Then pick a sequence of sets  $E_k \nearrow X$  such that  $m(E_k) < \infty$  for all  $k$ ,  $\chi_{E_k} \nearrow \chi_X$ , and thus  $\|\chi_{E_k}\|_p \leq M\|\chi_{E_k}\|_1$ . By the lemma,  $\|\chi_{E_k}\|_p = m(E_k)^{1/p}$ , so we have

$$\begin{aligned}\|\chi_{E_k}\|_2 \leq M\|\chi_{E_k}\|_1 &\implies \frac{\|\chi_{E_k}\|_2}{\|\chi_{E_k}\|_1} \leq M \\ &\implies \frac{m(E_k)^{1/2}}{m(E_k)} \leq M \\ &\implies m(E_k)^{-1/2} \leq M \\ &\implies m(E_k) \leq M^2 < \infty.\end{aligned}$$

and by continuity of measure, we have  $\lim_K m(E_k) = m(X) \leq M^2 < \infty$ .  $\square$

**2.2 Part b**

**3 Problem 3**

**4 Problem 4**

**5 Problem 5**

**6 Problem 6**