Math 240C Homework Problem List for S2018

0.1 Homework C1. Due Friday, April 6, 2018

- **Hand in**: 1.3, 1.4, 1.5, 1.25, 1.26
- **Look at**: 1.23

0.2 Homework C2. Due Friday, April 13, 2018 (L^p inequalities)

- **Hand in**: 1.1, 1.2, 1.6, 1.7, 1.19, 1.20
- **Look at**: 1.21, 1.22

0.3 Homework C3. Due Friday, April 20, 2018 (Fourier Series problems)

- **Hand in**: 1.8, 1.10, 1.11, 1.12, 1.13, 1.14, 1.16
- **Look at**: 1.24 (done in class), 1.9, 1.15

Problems to Solve

Exercise 1.1. If (X,ρ) is a metric space and μ is a **finite** measure on $(X,\mathcal{B}_X)$, then for all $A\in\mathcal{B}_X$ and $\varepsilon>0$ there exists a closed set F and open set V such that $F\subset A\subset V$ and $\mu(V\setminus F)=\mu(F\bigtriangleup V)<\varepsilon$.

You may find information in the supplement helpful for this problem. Here are some more suggestions.

1. Let $\mathcal{B}_0$ denote those $A\subset X$ such that for all $\varepsilon>0$ there exists a closed set F and open set V such that $F\subset A\subset V$ and $d_\mu(F,V)=\mu(V\setminus F)<\varepsilon$.
2. Show $\mathcal{B}_0$ contains all closed (or open if you like).
3. Show $\mathcal{B}_0$ is a σ-algebra.
4. Explain why this proves the result.

Exercise 1.2. Let (X,ρ) be a metric space and μ be a measure on $(X,\mathcal{B}_X)$. If there exists open sets, $\{V_n\}_{n=1}^\infty$, of X such that $V_n\uparrow X$ and $\mu(V_n)<\infty$ for all n, then for all $A\in\mathcal{B}_X$ and $\varepsilon>0$ there exists a closed set F and open set V such that $F\subset A\subset V$ and $d_\mu(F,V)=\mu(V\setminus F)<\varepsilon$. **Hints:**

1. Show it suffices to prove; for all $\varepsilon>0$ and $A\in\mathcal{B}_X$, there exists an open set $V\subset X$ such that $A\subset V$ and $\mu(V\setminus A)<\varepsilon$.
2. Now you must verify the assertion above holds. For this, you may find it useful to apply Exercise 1.1 to the measures, $\mu_n:\mathcal{B}_X\to[0,\mu(V_n)]$, defined by $\mu_n(A):=\mu(A\cap V_n)$ for all $A\in\mathcal{B}_X$. The ε in Exercise 1.1 should be replaced by judiciously chosen small quantities depending on n.

Exercise 1.3 (Folland Problem 2.62 on p. 80.). Rotation invariance of surface measure on S^{n-1}.

Exercise 1.4 (Folland Problem 2.64 on p. 80.). On the integrability of $|x|^a\left|\log|x|\right|^b$ for x near 0 and x near ∞ in $\mathbb{R}^n$.

Exercise 1.5. Show, using Problem 1.3 that

$$\int_{S^{d-1}}\omega_i\omega_j d\sigma(\omega)=\frac{1}{d}\delta_{ij}\sigma\left(S^{d-1}\right).$$

Hint: show $\int_{S^{d-1}}\omega_i^2 d\sigma(\omega)$ is independent of i and therefore

$$\int_{S^{d-1}}\omega_i^2 d\sigma(\omega)=\frac{1}{d}\sum_{j=1}^d\int_{S^{d-1}}\omega_j^2 d\sigma(\omega).$$

Exercise 1.6 (Folland 6.38 on p. 199.). Suppose $(X,\mathcal{M},\mu)$ is a measure space, $f:X\to\mathbb{C}$ is a measurable function, $0<p<\infty$, $\lambda_f(\alpha):=\mu(|f|>\alpha)$ for all $\alpha\in(0,\infty)$, and

$$M_p(f):=\sum_{k=-\infty}^{\infty}2^{kp}\lambda_f\left(2^k\right).$$

Show

$$\left(1-2^{-p}\right)M_p(f)\le\int_X|f|^p\,d\mu\le 2^pM_p(f)\tag{1.1}$$

which then implies $f\in L^p(\mu)$ iff $M_p(f)<\infty$.

Hint: first note that

$$\int_X|f|^p\,d\mu=\sum_{k\in\mathbb{Z}}\int_{\{2^k<|f|\le 2^{k+1}\}}|f|^p\,d\mu.\tag{1.2}$$

Exercise 1.7 (Folland 6.39 on p. 199.). Suppose $(X,\mathcal{M},\mu)$ is a measure space, $f:X\to\mathbb{C}$ is a measurable function, $0<p<\infty$, and $f\in L^p(\mu)$. Show

$$\lim_{\alpha\to 0}\alpha^p\lambda_f(\alpha)=0=\lim_{\alpha\to\infty}\alpha^p\lambda_f(\alpha).$$

Hint: for the limit, $\lim_{\alpha\to 0}\alpha^p\lambda_f(\alpha)=0$, start with the special case where f is a simple function.

Exercise 1.8. Show $\sum_{k=1}^\infty k^{-2}=\pi^2/6$, by taking $f(x)=x$ on $[-\pi,\pi]$ and computing $\|f\|_2^2$ directly and then in terms of the Fourier Coefficients $\tilde f$ of f.

Exercise 1.9 (Riemann Lebesgue Lemma for Fourier Series). Show for $f\in L^1\left([-\pi,\pi]^d\right)$ that $\tilde f\in c_0(\mathbb{Z}^d)$, i.e. $\tilde f:\mathbb{Z}^d\to\mathbb{C}$ and $\lim_{k\to\infty}\tilde f(k)=0$. **Hint:** If $f\in L^2\left([-\pi,\pi]^d\right)$, this follows from Bessel's inequality. Now use a density argument.

Exercise 1.10. Suppose $f\in L^1([-\pi,\pi]^d)$ is a function such that $\tilde f\in\ell^1(\mathbb{Z}^d)$ and set

$$g(x):=\sum_{k\in\mathbb{Z}^d}\tilde f(k)e^{ik\cdot x}\text{ (pointwise).}$$

1. Show $g \in C_{per}\left(\mathbb{R}^d\right)$.
2. Show $g(x) = f(x)$ for m – a.e. x in $[-\pi,\pi]^d$. **Hint**: Show $\tilde{g}(k) = \tilde{f}(k)$ and apply Exercise **??** or results proved in class.
3. Conclude that $f \in L^1([-\pi,\pi]^d) \cap L^\infty([-\pi,\pi]^d)$ and in particular $f \in L^p([-\pi,\pi]^d)$ for all $p \in [1,\infty]$.

Exercise 1.11 (Smoothness implies decay). We use the following notation below.

Notation: Given a multi-index $\alpha \in \mathbb{Z}_+^d$, let $|\alpha| = \alpha_1 + \cdots + \alpha_d$,

$$x^\alpha := \prod_{j=1}^d x_j^{\alpha_j}, \text{ and } \partial_x^\alpha = \left(\frac{\partial}{\partial x}\right)^\alpha := \prod_{j=1}^d \left(\frac{\partial}{\partial x_j}\right)^{\alpha_j}.$$

Further for $k \in \mathbb{N}_0$, let $f \in C^k_{per}\left(\mathbb{R}^d\right)$ iff $f \in C^k\left(\mathbb{R}^d\right) \cap C_{per}\left(\mathbb{R}^d\right)$, $\partial_x^\alpha f(x)$ exists and is continuous for $|\alpha| \le k$.

Suppose $m \in \mathbb{N}_0$, α is a multi-index such that $|\alpha| \le 2m$ and $f \in C^{2m}_{per}\left(\mathbb{R}^d\right)$[1].

1. Using integration by parts, show (using Notation above) that

$$(ik)^\alpha \tilde{f}(k) = \langle \partial^\alpha f | \varphi_k \rangle \text{ for all } k \in \mathbb{Z}^d.$$

   Note: This equality implies

$$\left|\tilde{f}(k)\right| \le \frac{1}{k^\alpha} \|\partial^\alpha f\|_H \le \frac{1}{k^\alpha} \|\partial^\alpha f\|_\infty .$$

2. Now let $\Delta f = \sum_{i=1}^d \partial^2 f/\partial x_i^2$, Working as in part 1) show

$$\langle (1-\Delta)^m f | \varphi_k \rangle = (1 + \|k\|^2)^m \tilde{f}(k). \tag{1.3}$$

   where $\|k\|^2 = \sum_{j=1}^d k_j^2$.

Exercise 1.12 (A Sobolev Imbedding Theorem). Suppose $s \in \mathbb{R}$ and $\left\{c_k \in \mathbb{C} : k \in \mathbb{Z}^d\right\}$ are coefficients such that

$$\sum_{k \in \mathbb{Z}^d} |c_k|^2 (1 + |k|^2)^s < \infty.$$

Show if $s > \frac{d}{2} + m$, the function f defined by

$$f(x) = \sum_{k \in \mathbb{Z}^d} c_k e^{ik\cdot x}$$

is in $C^m_{per}\left(\mathbb{R}^d\right)$. **Hint**: Work as in the above remark to show

$$\sum_{k \in \mathbb{Z}^d} |c_k| \, |k^\alpha| < \infty \text{ for all } |\alpha| \le m.$$

Exercise 1.13 (Poisson Summation Formula). Let $F \in L^1\left(\mathbb{R}^d\right)$,

$$E := \left\{ x \in \mathbb{R}^d : \sum_{k \in \mathbb{Z}^d} |F(x + 2\pi k)| = \infty \right\}$$

and set (see Section **??** below for an introduction to the Fourier transform)

$$\hat{F}(k) := (2\pi)^{-d/2} \int_{\mathbb{R}^d} F(x) e^{-ik\cdot x} dx \text{ for } k \in \mathbb{Z}^d.$$

Further **assume** $\hat{F} \in \ell^1(\mathbb{Z}^d)$. [This can be achieved by assuming F is sufficiently differentiable with the derivatives being integrable like in Exercise 1.11.]

1. Show $m(E) = 0$ and $E + 2\pi k = E$ for all $k \in \mathbb{Z}^d$. **Hint**: Compute $\int_{[-\pi,\pi]^d} \sum_{k \in \mathbb{Z}^d} |F(x + 2\pi k)| \, dx$.
2. Let

$$f(x) := \begin{cases} \sum_{k \in \mathbb{Z}^d} F(x + 2\pi k) & \text{for } x \notin E \\ 0 & \text{if } x \in E. \end{cases}$$

   Show $f \in L^1([-\pi,\pi]^d)$ and $\tilde{f}(k) = (2\pi)^{-d/2} \hat{F}(k)$.
3. Using item 2) and the assumptions on F, show

$$f(x) = \sum_{k \in \mathbb{Z}^d} \tilde{f}(k) e^{ik\cdot x} = \sum_{k \in \mathbb{Z}^d} (2\pi)^{-d/2} \hat{F}(k) e^{ik\cdot x} \text{ for } m - \text{a.e. } x,$$

   i.e.

$$\sum_{k \in \mathbb{Z}^d} F(x + 2\pi k) = (2\pi)^{-d/2} \sum_{k \in \mathbb{Z}^d} \hat{F}(k) e^{ik\cdot x} \text{ for } m - \text{a.e. } x \tag{1.4}$$

   and form this conclude that $f \in L^1([-\pi,\pi]^d) \cap L^\infty([-\pi,\pi]^d)$.
   Hint: see the hint for item 2. of Exercise 1.10.
4. Suppose we now assume that $F \in C\left(\mathbb{R}^d\right)$ and F satisfies $|F(x)| \le C(1 + |x|)^{-s}$ for some $s > d$ and $C < \infty$. Under these added assumptions on F, show Eq. (1.4) holds for **all** $x \in \mathbb{R}^d$ and in particular

$$\sum_{k \in \mathbb{Z}^d} F(2\pi k) = (2\pi)^{-d/2} \sum_{k \in \mathbb{Z}^d} \hat{F}(k).$$

[1] We view $C_{per}(\mathbb{R}^d)$ as a subspace of $H = L^2\left([-\pi,\pi]^d\right)$ by identifying $f \in C_{per}(\mathbb{R}^d)$ with $f|_{[-\pi,\pi]^d} \in H$.

Exercise 1.14 (Heat Equation 1.). Let $[0,\infty)\times\mathbb{R}\ni(t,x)\to u(t,x)$ be a continuous function such that $u(t,\cdot)\in C_{per}(\mathbb{R})$ for all $t\geq 0$, $\dot{u}:=u_t$, u_x, and u_{xx} exists and are continuous when $t>0$. Further assume that u satisfies the heat equation $\dot{u}=\frac{1}{2}u_{xx}$. Let $\tilde{u}(t,k):=\langle u(t,\cdot)|\varphi_k\rangle$ for $k\in\mathbb{Z}$. Show for $t>0$ and $k\in\mathbb{Z}$ that $\tilde{u}(t,k)$ is differentiable in t and $\frac{d}{dt}\tilde{u}(t,k)=-k^2\tilde{u}(t,k)/2$. Use this result to show

$$u(t,x)=\sum_{k\in\mathbb{Z}}e^{-\frac{t}{2}k^2}\tilde{f}(k)e^{ikx} \tag{1.5}$$

where $f(x):=u(0,x)$ and as above

$$\tilde{f}(k)=\langle f|\varphi_k\rangle=\int_{-\pi}^{\pi}f(y)\,e^{-iky}dy=\frac{1}{2\pi}\int_{-\pi}^{\pi}f(y)\,e^{-iky}dm(y).$$

Notice from Eq. (1.5) that $(t,x)\to u(t,x)$ is C^∞ for $t>0$.

Exercise 1.15 (Heat Equation 2.). Let $q_t(x):=\frac{1}{2\pi}\sum_{k\in\mathbb{Z}}e^{-\frac{t}{2}k^2}e^{ikx}$. Show;

1. Eq. (1.5) may be rewritten as
$$u(t,x)=\int_{-\pi}^{\pi}q_t(x-y)f(y)\,dy$$
and
2. $q_t(x)$ may be expresses
$$q_t(x)=\sum_{k\in\mathbb{Z}}p_t(x+k2\pi)$$
where $p_t(x):=\frac{1}{\sqrt{2\pi t}}e^{-\frac{1}{2t}x^2}$.
3. Also show $u(t,x)$ may be written as
$$u(t,x)=(p_t*f)(x):=\int_{\mathbb{R}^d}p_t(x-y)f(y)\,dy.$$

Hint: To show $q_t(x)=\sum_{k\in\mathbb{Z}}p_t(x+k2\pi)$, use the Poisson summation formula (Exercise 1.13) and the Gaussian integration identity,

$$\hat{p}_t(\omega)=\frac{1}{\sqrt{2\pi}}\int_{\mathbb{R}}p_t(x)\,e^{i\omega x}dx=\frac{1}{\sqrt{2\pi}}e^{-\frac{t}{2}\omega^2}. \tag{1.6}$$

Exercise 1.16 (Wave Equation). Let $u\in C^2(\mathbb{R}\times\mathbb{R})$ be such that $u(t,\cdot)\in C_{per}(\mathbb{R})$ for all $t\in\mathbb{R}$. Further assume that u solves the wave equation, $u_{tt}=u_{xx}$. Let $f(x):=u(0,x)$ and $g(x)=\dot{u}(0,x)$. Show $\tilde{u}(t,k):=\langle u(t,\cdot),\varphi_k\rangle$ for $k\in\mathbb{Z}$ is twice continuously differentiable in t and $\frac{d^2}{dt^2}\tilde{u}(t,k)=-k^2\tilde{u}(t,k)$. Use this result to show

$$u(t,x)=\sum_{k\in\mathbb{Z}}\left(\tilde{f}(k)\cos(kt)+\tilde{g}(k)\frac{\sin kt}{k}\right)e^{ikx} \tag{1.7}$$

with the sum converging absolutely. Also show that $u(t,x)$ may be written as

$$u(t,x)=\frac{1}{2}\left[f(x+t)+f(x-t)\right]+\frac{1}{2}\int_{-t}^{t}g(x+\tau)d\tau. \tag{1.8}$$

Hint: To show Eq. (1.7) implies (1.8) use

$$\cos kt=\frac{e^{ikt}+e^{-ikt}}{2},$$
$$\sin kt=\frac{e^{ikt}-e^{-ikt}}{2i},\text{ and}$$
$$\frac{e^{ik(x+t)}-e^{ik(x-t)}}{ik}=\int_{-t}^{t}e^{ik(x+\tau)}d\tau.$$

Exercise 1.17. Let $f\in L^1((-\pi,\pi])$ which we extend to a $2\pi-$periodic function on $\mathbb{R}$ and continue to denote by f. If there exists $q\in\mathbb{N}$ such that $f\left(x+\frac{2\pi}{q}\right)=f(x)$ for $m-$a.e. x, then $\tilde{f}(k)=0$ unless q divides k.

Exercise 1.18. In this problem we assume the notation from subsection **??** with $d=1$. For simplicity of notation we identify $L^2((-\pi,\pi],d\theta)$ with $2\pi-$periodic functions on $\mathbb{R}$ via,

$$L^2((-\pi,\pi],d\theta)\ni f\longleftrightarrow\sum_{n\in\mathbb{Z}}f(x+n2\pi)\,1_{(-\pi,\pi]}(x+n2\pi)\in L^2_{per}(\mathbb{R}).$$

Given $\alpha\in\mathbb{R}$ let $(U_\alpha f)(\theta)=f(\theta+\alpha 2\pi)$ wherein we have used the above identification. If $\alpha\notin\mathbb{Q}$ show

$$M_\alpha=\mathrm{Nul}(U_\alpha-I)=\mathbb{C}\cdot 1.$$

If $\alpha\in\mathbb{Q}$ write $\alpha=\frac{p}{q}$ where $\gcd(q,p)=1$, i.e. p and q are relatively prime. In this case show $M_\alpha=\mathrm{Nul}(U_\alpha-I)$ consists of those $f\in L^2_{per}(\mathbb{R})$ such that $f\left(x+\frac{2\pi}{q}\right)=f(x)$ for $m-$a.e. x. [Consequently, combining this exercise with Mean Ergodic Theorem **??** shows,

$$\frac{1}{n}\sum_{k=0}^{n-1}U_\alpha^k\xrightarrow{s}P_{M_\alpha}$$

where M_α depends on α as described above.]

Exercise 1.19 (Folland 6.27 on p. 196. Hilbert's Inequality). Hint: See Theorem **??** which is Theorem 6.20 in Folland .

Exercise 1.20 (Folland 6.22). Exercise, Folland 6.22 on p. 192.

Exercise 1.21 (Global Integration by Parts Formula). Suppose that $f, g : \mathbb{R} \to \mathbb{C}$ are locally absolutely continuous functions[2] such that $f'g$, fg', and fg are all Lebesgue integrable functions on $\mathbb{R}$. Prove the following integration by parts formula;

$$\int_{\mathbb{R}} f'(x) \cdot g(x)\, dx = -\int_{\mathbb{R}} f(x) \cdot g'(x)\, dx. \tag{1.9}$$

Similarly show that; if $f, g : [0, \infty) \to [0, \infty)$ are locally absolutely continuous functions such that $f'g$, fg', and fg are all Lebesgue integrable functions on $[0, \infty)$, then

$$\int_0^\infty f'(x) \cdot g(x)\, dx = -f(0)\, g(0) - \int_0^\infty f(x) \cdot g'(x)\, dx. \tag{1.10}$$

Outline: 1. First use the theory developed to see that Eq. (1.9) holds if $f(x) = 0$ for $|x| \geq N$ for some $N < \infty$.

2. Let $\psi : \mathbb{R} \to [0, 1]$ be a continuously differentiable function such that $\psi(x) = 1$ if $|x| \leq 1$ and $\psi(x) = 0$ if $|x| \geq 2$.[3] For any $\varepsilon > 0$ let $\psi_\varepsilon(x) = \psi(\varepsilon x)$ Write out the identity in Eq. (1.9) with $f(x)$ being replaced by $f(x)\, \psi_\varepsilon(x)$.

3. Now use the dominated convergence theorem to pass to the limit as $\varepsilon \downarrow 0$ in the identity you found in step 2.

4. A similar outline works to prove Eq. (1.10).

Exercise 1.22 (Heisenberg's Inequality). Suppose that $f : \mathbb{R} \to \mathbb{C}$ is a locally absolutely continuous function[4], show

$$\int_{\mathbb{R}} |f(x)|^2\, dx \leq 2 \left[\int_{\mathbb{R}} |x f(x)|^2\, dx\right]^{1/2} \left[\int_{\mathbb{R}} |f'(x)|^2\, dx\right]^{1/2}. \tag{1.11}$$

Hint: assuming the right hand side of the above inequality is finite show

$$\int_{\mathbb{R}} |f(x)|^2\, dx = -2 \operatorname{Re} \int_{\mathbb{R}} x \bar{f}(x)\, f'(x)\, dx. \tag{1.12}$$

[2] This means that f and g restricted to any bounded interval in $\mathbb{R}$ are absolutely continuous on that interval.

[3] You may assume the existence of such a ψ, we will deal with this later.

[4] This means that f restricted to any bounded interval in $\mathbb{R}$ are absolutely continuous on that interval.

Exercise 1.23. Let

$$f(t) = \begin{cases} e^{-1/t} & \text{if } t > 0 \\ 0 & \text{if } t \leq 0. \end{cases}$$

Show $f \in C^\infty(\mathbb{R}, [0, 1])$. **Hints:** you might start by first showing $\lim_{t \downarrow 0} f^{(n)}(t) = 0$ for all $n \in \mathbb{N}_0$.

Exercise 1.24. Show $C_c^\infty(\mathbb{R}^d)$ is dense in $L^p(\mathbb{R}^d, m)$ for any $1 \leq p < \infty$.

Exercise 1.25. If $f \in L^1_{loc}(\mathbb{R}^d, m)$ and $\varphi \in C_c^1(\mathbb{R}^d)$, then $f * \varphi \in C^1(\mathbb{R}^d)$ and $\partial_i (f * \varphi) = f * \partial_i \varphi$. Moreover if $\varphi \in C_c^\infty(\mathbb{R}^d)$ then $f * \varphi \in C^\infty(\mathbb{R}^d)$.

Exercise 1.26 (Integration by Parts). Suppose that $(x, y) \in \mathbb{R} \times \mathbb{R}^{d-1} \to f(x, y) \in \mathbb{C}$ and $(x, y) \in \mathbb{R} \times \mathbb{R}^{d-1} \to g(x, y) \in \mathbb{C}$ are measurable functions such that for each fixed $y \in \mathbb{R}^d$, $x \to f(x, y)$ and $x \to g(x, y)$ are continuously differentiable. Also assume $f \cdot g$, $\partial_x f \cdot g$ and $f \cdot \partial_x g$ are integrable relative to Lebesgue measure on $\mathbb{R} \times \mathbb{R}^{d-1}$, where $\partial_x f(x, y) := \frac{d}{dt} f(x + t, y)|_{t=0}$. Show

$$\int_{\mathbb{R} \times \mathbb{R}^{d-1}} \partial_x f(x, y) \cdot g(x, y) dx dy = -\int_{\mathbb{R} \times \mathbb{R}^{d-1}} f(x, y) \cdot \partial_x g(x, y) dx dy. \tag{1.13}$$

(Note: this result and Fubini's theorem proves Lemma **??**.)

Hints: Let $\psi \in C_c^\infty(\mathbb{R})$ be a function which is 1 in a neighborhood of $0 \in \mathbb{R}$ and set $\psi_\varepsilon(x) = \psi(\varepsilon x)$. First verify Eq. (1.13) with $f(x, y)$ replaced by $\psi_\varepsilon(x) f(x, y)$ by doing the x – integral first. Then use the dominated convergence theorem to prove Eq. (1.13) by passing to the limit, $\varepsilon \downarrow 0$.