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HW 9

1 If $f \in L_1(0,\infty)$, define

$$g(s) = \int_0^\infty e^{-st} f(t)\,dt, \quad 0 < s < \infty.$$

Prove that $g(s)$ is differentiable on $(0,\infty)$ and that

$$g'(s) = -\int_0^\infty te^{-st} f(t)\,dx, \quad 0 < s < \infty.$$

Proof. Let $s \in (0,\infty)$ and $0 \le |h| \le s/2$. We have $|e^{-st}f(t)| \le |f(t)|$, so $e^{-st}f(t) \in L_1$. Hence

$$\frac{g(s+h)-g(s)}{h} = \int_0^\infty \frac{e^{-(s+h)t} - e^{-st}}{h} f(t)\,dt.$$

By the Mean Value theorem, we have

$$\begin{aligned}\left|\frac{e^{-(s+h)t} - e^{-st}}{h} f(t)\right| &\le \sup_{h \in (-s/2, s/2)} |-te^{-(s+h)t}|\,|f(t)| \\ &= te^{-(s/2)t}|f(t)| \\ &\le C_s|f(t)|\end{aligned}$$

Hence, by the DCT,

$$\lim_{h\to 0} \frac{g(s+h)-g(s)}{h} = \int_0^\infty \frac{d}{ds} e^{-st} f(t) = -\int_0^\infty te^{-st} f(t)\,dx.$$

□

2 Let (Ω, μ, Σ) be a finite measure space and (f_n) be a sequence of measurable functions on Ω. Suppose that for each $\omega \in \Omega$ there is an $M_\omega \in \mathbb{R}$ so that for all $k \in \mathbb{N}$, $|f_k(\omega)| \le M_\omega$. Let $\epsilon > 0$. Show that there is a measurable $A \subset \Omega$ and an $M \in \mathbb{R}$ so that $\mu(\Omega \setminus A) < \epsilon$ and $f_k(\omega) < M$ for all $k \in \mathbb{N}$ and all $\omega \in A$.

Proof. Let $\epsilon > 0$ and $E_j := \bigcap_n \{f_n < j\}$. Then (E_j) is increasing and $\bigcup_j E_j = \Omega$. Hence $\lim_j \mu(E_j) = \mu(\Omega)$. Since $\mu(\Omega) < \infty$, we can pick M such that $\mu(\Omega \setminus E_M) = \mu(\Omega) - \mu(E_M) < \epsilon$. Moreover, if $\omega \in E_M$, then $f_k(\omega) < M$ for all k. □

3 57/page 77. Show that $\int_0^\infty e^{-sx}x^{-1}\sin x\,dx = \arctan(s^{-1})$ for $s > 0$ by integrating $e^{-sxy}\sin x$ with respect to x and y. (Hints: $\tan(\frac{\pi}{2} - \theta) = \cot\theta$ and Exercise 31d.)

Proof. For fixed $x > 0$, we have $|e^{-sxy} \sin x| \in L_1(1, \infty)$. Moreover, since $\left|\frac{\sin x}{x}\right| \leq 1$ for all $x > 0$, we have $(x \mapsto e^{-sx} x^{-1} \sin x) \in L_1(0, \infty)$. Thus, by Tonelli's theorem, $(x \mapsto e^{-sxy} \sin x) \in L_1((0, \infty) \times (1, \infty))$. Thus, we have

$$\begin{aligned}
\int_0^\infty e^{-sx} x^{-1} \sin x \, dx &= s \int_0^\infty \int_1^\infty e^{-sxy} \sin x \, dy dx \\
&= s \int_1^\infty \int_0^\infty e^{-sxy} \sin x \, dx dy \\
&= s \int_1^\infty \int_0^\infty e^{-sxy} \sin x \, dx dy \\
&= \frac{s}{2i} \int_1^\infty \int_0^\infty e^{(i-sy)x} - e^{(-i-sy)x} \, dx dy \\
&= \frac{s}{2i} \int_1^\infty \left[\frac{1}{i - sy} e^{(i-sy)x} + \frac{1}{i + sy} e^{(-i-sy)x} \right]_{x=0}^\infty dy \\
&= -\frac{s}{2i} \int_1^\infty \frac{1}{i - sy} + \frac{i + sy}{} dy \\
&= \int_1^\infty \frac{s}{1 + s^2 y^2} \, dy \\
&= \int_s^\infty \frac{1}{1 + u^2} \, du \\
&= \frac{\pi}{2} - \arctan(s) \\
&= \arctan \cot \arctan(s) \\
&= \arctan(s^{-1})
\end{aligned}$$

$\square$

4 60/page 77. $\Gamma(x)\Gamma(y)/\Gamma(x + y) = \int_0^1 t^{x-1}(1 - t)^{y-1} \, dt$ for $x, y > 0$. (Recall that Γ was defined in Section 2.3. Write $\Gamma(x)\Gamma(y)$ as a double integral and use the argument of the exponential as a new variable of integration.)

Proof. We have $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} \, dt$ for $\Re z > 0$. Thus

$$\begin{aligned}
\Gamma(x)\Gamma(y) &= \left(\int_0^\infty s^{x-1} e^{-s} \, ds \right) \left(\int_0^\infty t^{y-1} e^{-t} \, dt \right) \\
&= \int_0^\infty \int_0^\infty s^{x-1} t^{y-1} e^{-s-t} \, ds dt \\
&= \int_0^\infty \int_0^\infty s^{x-1} (u - s)^{y-1} e^{-u} \, du ds
\end{aligned}$$

$\square$

5 Given a bounded function $f : [a, b] \to \mathbb{R}$, define

$$H(x) = \lim_{\delta \to 0} \sup_{|x-y| \leq \delta} f(y), \text{ and } h(x) = \lim_{\delta \to 0} \inf_{|x-y| \leq \delta} f(y)$$

a) For $x \in [a,b]$, f continuous at $x \iff H(x) = h(x)$.

b) Assume now that (P_k) is an increasing sequence of partitions of $[a,b]$ for which the mesh converges to zero. Write $P_k = (t_0^{(k)}, t_1^{(k)}, \ldots, t_{n_k}^{(k)})$. Define for $x \in [a,b]$,

$$G(x) = \lim_{k\to\infty} G_{P_k}(x) \text{ and } g(x) = \lim_{k\to\infty} g_{P_k}(x),$$

where for a partition $P = (t_0, t_1, \ldots, t_n)$

$$G_P = \sum_{i=1}^{n} \chi_{(t_{i-1},t_i]} \sup_{t\in(t_{i-1},t_i]} f(t) \text{ and } g_P = \sum_{i=1}^{n} \chi_{(t_{i-1},t_i]} \inf_{t\in(t_{i-1},t_i]} f(t).$$

Prove that $H = G$ and $h = g$ m-a.e.

c) Show that f is Riemann integrable $\iff$ the set of discontinuities of f has Lebesgue measure zero.

Proof. Let $H_\delta(x) = \sup_{|x-y|\le\delta} f(y)$ and $h_\delta(x) = \inf_{|x-y|\le\delta} f(y)$. For fixed x, note that $H_\delta(x)$ is an increasing function of δ, and $h_\delta(x)$ is a decreasing function of δ.

For (a), suppose f is continuous at x. Let $\epsilon > 0$. Pick $\delta > 0$ such that $|f(x) - f(y)| < \epsilon$ for all $|x-y| < \delta$. Then $f(x) \le H_\delta \le f(x) + \epsilon$ and $f(x) - \epsilon \le h_\delta \le f(x)$. By the monotinicity of H_δ and h_δ in δ, it follows that for $0 < \gamma \le \delta$ we have $f(x) \le H_\gamma \le f(x) + \epsilon$ and $f(x) - \epsilon \le h_\gamma \le f(x)$. Thus $\lim_{\delta\to 0} H_\delta = f(x) = \lim_{\delta\to 0} h_\delta$.

For the converse, we assume that $H(x) = h(x)$. Suppose $f(x) \ne H(x)$. Note that $h(x) \le f(x) \le H(x)$. Hence $h(x) < H(x)$, a contradiction. Hence $f(x) = H(x) = h(x)$. Let $\epsilon > 0$. Pick $\delta > 0$ such that $H_\delta - f(x) < \epsilon$ and $f(x) - h_\delta < \epsilon$. Then if $|x - y| < \delta$, we have $f(y) - f(x) \le H_\delta(x) - h(y) < \epsilon$ and $f(y) - f(x) \ge h_\delta(x) - f(x) > -\epsilon$.

For (b), I first claim that H is upper semicontinuous. Let $x_n \to x$. Let $\epsilon > 0$. Pick $\delta > 0$ such that $H_\delta(x) - H(x) < \epsilon$. Then if $|x - y| < \delta/2$ we have $H(y) \le H_{\delta/2}(y) \le H_\delta(x) < H(x) + \epsilon$. Therefore, $\limsup H(x_n) \le H(x) + \epsilon$ for every $\epsilon > 0$, so H is upper semicontinuous. A similar argument (or taking negatives) shows that h is lower semicontinuous.

For any partition P we have $G_P > H$, so $G > H$. Suppose $m(\{G > H\}) > 0$. Then by continuity from below, there exists $n > 0$ such that $m(\{G - H > 1/n\}) > 0$.

For (c), note that if $x_n \to x$ we have $\limsup f(x_n) = \limsup H(x_n) \le H(x)$ and $\liminf f(x_n) \le \liminf h(x_n) \le h(x)$. Hence, if $H(x) = h(x)$, then $f(x)$ is continuous at x. The converse is also true. Thus, for (c), it suffices to show that f is Riemann integrable $\iff$ $H = h$ a.e.

Recall that f is Riemann integrable $\iff$ for every (P_k) with mesh converging to zero we have $\int G_{P_k} - g_{P_k} \to 0$. Since $G_{P_k} - g_{P_k}$ is decreasing in k, by the DCT we have $\lim_k \int G_{P_k} - g_{P_k} = \int \lim_k G_{P_k} - g_{P_k} = \int H - h$. Thus f is Riemann integrable $\iff$ $H = h$ a.e. $\square$

6 Problem 30/page 60. Hint: AM-GM. Show that $\lim_{k\to\infty}\int_0^k x^n(1-k^{-1}x)^k\,dx = n!$.

Proof. Using Exercise (4), we have

$$\begin{aligned}\int_0^k x^n(1-k^{-1}x)^k\,dx &= k^{n+1}\int_0^1 (u)^n(1-u)^k\,du\\ &= k^{n+1}\frac{\Gamma(n+1)\Gamma(k+1)}{\Gamma(n+k+2)}\\ &= n\left(\frac{k}{k+1}\right)\left(\frac{k}{k+2}\right)\cdots\left(\frac{k}{k+n+1}\right)\\ &\to n\end{aligned}$$

as $k\to\infty$, $k\in\mathbb{N}$. $\square$

7 Problem 1/88. Let ν be a signed measure on $(X,\mathcal{M})$. If (E_j) is an increasing sequence in $\mathcal{M}$, the $\nu(\bigcup_1^\infty E_j) = \lim_{j\to\infty}\nu(E_j)$. If (E_j) is a decreasing sequence in $\mathcal{M}$ and $\nu(E_1)$ is finite, then $\nu(\bigcap_1^\infty E_j) = \lim_{j\to\infty}\nu(E_j)$.

Proof. For the first part, we have

$$\begin{aligned}\nu(\bigcup_1^\infty E_j) &= \nu(E_1\cup\bigcup_1^\infty E_{j+1}\setminus E_j)\\ &= \nu(E_1)+\sum_1^\infty \nu(E_{j+1}\setminus E_j)\\ &= \lim_{J\to\infty}\nu(E_1)+\sum_1^J \nu(E_{j+1}\setminus E_j)\\ &= \lim_{J\to\infty}\nu(E_1+\bigcup_1^J \nu(E_{j+1}\setminus E_j)\\ &= \lim_{J\to\infty}\nu(E_{J+1}).\end{aligned}$$

For the second part, first note that if $A\subset E_1$ with $A\in\mathcal{M}$ then $\nu(A)+\nu(E_1\setminus A)=\nu(E_1)$. Since $\nu(E_1)$ is finite, $\nu(A)$ must be finite. Hence $\nu(E_1\setminus A)=\nu(E_1)-\nu(A)$. Using this fact and the previous part, we have

$$\begin{aligned}\nu(\bigcap_1^\infty E_j) &= \nu(E_1\setminus\bigcup_1^\infty (E_1\setminus E_j))\\ &= \nu(E_1)-\lim_{j\to\infty}\nu(E_1\setminus E_j)\\ &= \nu(E_1)-\lim_{j\to\infty}\nu(E_1)-\nu(E_j)\\ &= \lim_{j\to\infty}\nu(E_j)\end{aligned}$$

$\square$

8 Problem 4/88. If ν is a signed measure and λ, μ are positive measures such that $\nu = \lambda - \mu$, then $\lambda \geq \nu^+$ and $\mu \geq \nu^-$.

Proof. Suppose not. WLOG there exists a measurable set A such that $\lambda(A) < \nu^+(A)$. From the Haar decomposition, there exists a partition $P \cup N = X$ where P contains the support of ν^+ and N contains the support ν^-. Then $\lambda(A \cap P) \leq \lambda(A) < \nu^+(A) = \nu(A \cap P) = \lambda(A \cap P) - \mu(A \cap P) < \lambda(A \cap P)$, a contradiction. $\square$

9 Problem 7/88. Suppose that ν is a signed measure on $(X, \mathcal{M})$ and $E \in \mathcal{M}$.

a. $\nu^+(E) = \sup\{\nu(F) : F \in \mathcal{M}, F \subset E\}$ and $\nu^-(E) = -\inf\{\nu(F) : F \in \mathcal{M}, F \subset E\}$.

b. $|\nu|(E) = \sup\{\sum_1^n |\nu(E_j)| : n \in \mathbb{N}, E_1, \ldots, E_n$ are disjoint, and $\bigcup_1^n E_j = E\}$.

Proof. For (a), we have the partition $X = P \cup N$ where P and N contain the support of ν^+ and ν^- respectively. Hence $\nu^+(E) = \nu(E \cap P) \leq \sup\{\nu(F) : F \in \mathcal{M}, F \subset E\}$. On the other hand, if $F \in \mathcal{M}, F \subset E$ then $\nu(F) = \nu^+(F) - \nu^-(F) \leq \nu^+(F) \leq \nu^+(E)$. The ν^- part follows from applying the first part to $-\nu$.

For (b), let $K = \sup\{\sum_1^n |\nu(E_j)| : n \in \mathbb{N}, E_1, \ldots, E_n$ are disjoint, and $\bigcup_1^n E_j = E\}$. We have $|\nu|(E) = \nu^+(E) + \nu^-(E) = |\nu(E \cap P)| + |\nu(E \cap N)| \leq K$. On the other hand, if $(E_j)_1^n$ is a partition of E then $\sum_1^n |\nu(E_j)| = \sum_1^n |\nu^+(E_j) - \nu^-(E_j)| \leq= \sum_1^n |\nu|(E_j) \leq |\nu|(E)$. $\square$