MTH5105 Differential and Integral Analysis 2008-2009

Exercises 9

Exercise 1: Is the function $f : \mathbb{R} \to \mathbb{R}$ given by

$$f(x) = \sum_{k=1}^{\infty} \sin^2(x/k)$$

differentiable?

[10 marks]

Solution: If $\sum f_k$ converges pointwise and $\sum f_k'$ converges uniformly, then $f = \sum f_k$ is differentiable and $f' = \sum f_k'$.

[1 mark]

Let $f_k(x) = \sin^2(x/k)$. Then $f_k'(x) = 2\sin(x/k)\cos(x/k)/k$.

[1 mark]

As $|\sin t| \leq |t|$ for all $t \in \mathbb{R}$, we have

$$\sum_{k=1}^{\infty} |\sin^2(x/k)| \leq x^2 \sum_{k=1}^{\infty} \frac{1}{k^2} .$$

$\sum \frac{1}{k^2}$ converges, so that the sum converges absolutely (for fixed x).

[2 marks]

[We could have proven uniform convergence on bounded intervals, but we don't need to. In fact, it would have sufficed to prove convergence at a single point, say at $x = 0$, where it is immediately obvious.]

As also $|\cos t| \leq 1$ for all $t \in \mathbb{R}$, we have

$$\left| \sum_{k=1}^{\infty} 2\sin(x/k)\cos(x/k)/k \right| \leq |x| \sum_{k=1}^{\infty} \frac{1}{k^2} .$$

[2 marks]

If we restrict x to $[-A, A]$ for some $A > 0$, then the sum converges uniformly on $[-A, A]$ by the Weierstraß criterion, as the upper bound $A \sum \frac{1}{k^2}$ is independent of x.

[2 marks]

Thus we can conclude that $f = \sum f_k$ is differentiable with $f' = \sum f_k'$ on any interval $[-A, A]$, and hence on $\mathbb{R}$.

[2 marks]

Exercise 2: Let $f_n : [0,\infty) \mapsto \mathbb{R}$ be a sequence of continuous functions that converge uniformly to $f(x) = 0$. Show that if

$$0 \le f_n(x) \le e^{-x}$$

for all $x \ge 0$ and for all $n \in \mathbb{N}$, then

$$\lim_{n\to\infty} \int_0^\infty f_n(x)\, dx = 0 \ .$$

[Recall from Calculus I the definition of the improper integral $\int_0^\infty f(x)\, dx = \lim_{A\to\infty} \int_0^A f(x)\, dx$*.]*

[10 marks]

Solution: As f_n converges uniformly to zero, we have that

$$\lim_{n\to\infty} \int_0^M f_n(x)\, dx = 0$$

for any fixed $M > 0$. [2 marks]

To deal with the improper integral, we split the integral $\int_0^\infty f_n(x)\, dx$ into two pieces by writing

$$\int_0^\infty f_n(x)\, dx = \int_0^M f_n(x)\, dx + \int_M^\infty f_n(x)\, dx \ .$$

As we are dealing with improper integrals, we need to be precise with the limits involved, so we write for $A > M$

$$\int_0^A f_n(x)\, dx = \int_0^M f_n(x)\, dx + \int_M^A f_n(x)\, dx \ ,$$

and take the appropriate limit of $A \to \infty$. [1 mark]

We have therefore

$$\begin{aligned}
\lim_{n\to\infty} \int_0^\infty f_n(x)\, dx &= \lim_{n\to\infty} \lim_{A\to\infty} \left(\int_0^M f_n(x)\, dx + \int_M^A f_n(x)\, dx \right) \\
&= \lim_{n\to\infty} \int_0^M f_n(x)\, dx + \lim_{n\to\infty} \lim_{A\to\infty} \int_M^A f_n(x)\, dx \\
&= \lim_{n\to\infty} \lim_{A\to\infty} \int_M^A f_n(x)\, dx \ .
\end{aligned}$$

[2 marks]

Now by assumption $0 \le f_n(x) \le e^{-x}$, and therefore

$$0 \le \int_M^A f_n(x)\, dx \le \int_M^A e^{-x}\, dx < e^{-M} \ .$$

[2 marks]

Thus

$$0 \le \lim_{n\to\infty} \lim_{A\to\infty} \int_M^A f_n(x)\, dx \le e^{-M} \ .$$

[2 marks]

This holds for any chosen $M > 0$, whence the upper bound is $\inf_{M>0}(e^{-M}) = 0$.

[1 mark]

Exercise 3: Let $f_n : [0,1] \mapsto \mathbb{R}$ be a sequence of differentiable functions, and let $f : [0,1] \mapsto \mathbb{R}$. Consider the statements

(a) $f_n \to f$ pointwise,

(b) $f_n \to f$ uniformly,

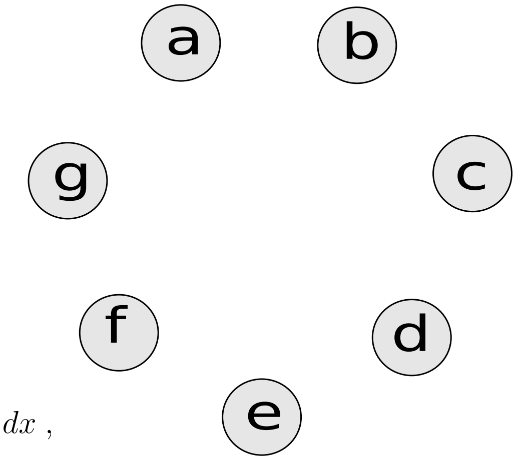
(c) f_n' converges pointwise,

(d) $f_n' \to f'$ pointwise,

(e) f continuous,

(f) f differentiable,

(g) $\lim_{n\to\infty} \int_0^1 f_n(x)\, dx = \int_0^1 f(x)\, dx$,



and cleary indicate in the enclosed figure all implications by the appropriate arrows ("$\Longrightarrow$").

[10 marks]

Solution: The only valid implications are:

(b) implies (a),(e),(g)

(d) implies (c)

(f) implies (e)

[+2 marks each for correct implications, -1 mark for incorrect implications]

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