Mathematical Methods I | Natural Sciences Tripos, Part IB
Professor Nigel Peake | Michaelmas Term 2019

Example Sheet 2

1. Define $\delta_\epsilon(x)$ for $\epsilon > 0$ by

$$\delta_\epsilon(x) = \begin{cases} (x+\epsilon)/\epsilon^2 & -\epsilon < x < 0 \\ (\epsilon - x)/\epsilon^2 & 0 \leqslant x < \epsilon \\ 0 & \text{otherwise}\,. \end{cases}$$

   (a) Evaluate

$$\int_{-\infty}^{\infty} \delta_\epsilon(x)\,\mathrm{d}x$$

   (b) Argue that for a 'good' function f and a constant ξ

$$\lim_{\epsilon \to 0+} \int_{-\infty}^{\infty} \delta_\epsilon(x-\xi) f(x)\,\mathrm{d}x = f(\xi\,).$$

   Hint: Consider the substitution $x - \xi = \epsilon t$.

   (c) Sketch $\delta_\epsilon(x)$ and comment.

2. (a) Starting from the definition that $\delta(x)$ is the generalized function such that for all 'good' functions $f(x)$

$$\int_{-\infty}^{\infty} \delta(x-\xi) f(x)\,\mathrm{d}x = f(\xi)\,,$$

   show that, for constant $a \neq 0$,

$$\delta(ax) = \frac{1}{|a|}\delta(x)\,.$$

   (b) Evaluate

$$\int_{-\infty}^{\infty} |x|\delta(x^2 - a^2)\,\mathrm{d}x\,,$$

   where a is a non-zero constant. *Hint: the answer is not* $2a$. *Consider a substitution such as* $t = x^2$ *or one similar.*

3. Show that the equation

$$y'' + py' + qy = f(x)\,,$$

where p and q are constants, can be written in the form

$$z' - az = f\,, \qquad y' - by = z\,,$$

for suitable choices of the constants a and b. Solve these first-order equations using integrating factors, subject to the initial conditions $y(0) = y'(0) = 0$, to obtain the solution

$$y(x) = \mathrm{e}^{bx} \int_0^x \int_0^\eta f(\xi)\, \mathrm{e}^{-a\xi}\, \mathrm{e}^{(a-b)\eta}\, \mathrm{d}\xi\, \mathrm{d}\eta\,.$$

By changing the order of integration and carrying out the integration with respect to η, show that

$$y(x) = \frac{1}{a-b} \int_0^x f(\xi) \left[\mathrm{e}^{a(x-\xi)} - \mathrm{e}^{b(x-\xi)}\right] \mathrm{d}\xi$$

and interpret this result.

4. The differential equation

$$y'' + y = H(x) - H(x - \epsilon)\,,$$

where H is the Heaviside step function and ϵ is a positive parameter, represents a simple harmonic oscillator subject to a constant force for a finite time. By solving the equation in the three intervals of x separately and applying appropriate matching conditions, show that the solution that vanishes for $x < 0$ is

$$y = \begin{cases} 0\,, & x < 0\,, \\ 1 - \cos x\,, & 0 < x < \epsilon\,, \\ \cos(x - \epsilon) - \cos x\,, & x > \epsilon\,. \end{cases}$$

Hence show that the solution of

$$y'' + y = \frac{H(x) - H(x - \epsilon)}{\epsilon}$$

that vanishes for $x < 0$ agrees, in the limit $\epsilon \to 0$, with the appropriate solution of $y'' + y = \delta(x)$, namely $y = H(x)\sin x$.

5. The function $G(x, \xi)$ is defined by

$$G(x, \xi) = \begin{cases} x(\xi - 1)\,, & 0 \leqslant x \leqslant \xi\,, \\ \xi(x - 1)\,, & \xi \leqslant x \leqslant 1\,. \end{cases}$$

If $f(x)$ is continuous for $0 \leqslant x \leqslant 1$, and

$$y(x) = \int_0^1 f(\xi) G(x, \xi)\, \mathrm{d}\xi\,,$$

show by direct calculation that $y''(x) = f(x)$ and find $y(0)$ and $y(1)$.

Hint: use the definition of $G(x, \xi)$ to write $y(x)$ as the sum of two integrals, one with $\xi \leqslant x$ and the other with $x \leqslant \xi$.

6. Use the method of Green's function to solve

(a)

$$y'' - y = x^2 \qquad \text{with} \quad y(0) = y(1) = 0\,,$$

(b)

$$y'' + \omega^2 y = x \qquad \text{with} \quad y'(0) = y(\pi/\omega) = 0\,,$$

(c)

$$y'' + \alpha y' = e^{-\beta x} \qquad \text{with} \quad x \geqslant 0 \text{ and } y(0) = y'(0) = 0$$

(d)

$$y'''' = f(x) \qquad \text{with} \quad y(0) = y'(0) = y''(0) = y'''(0) = 0\,.$$

7. Let α and β be positive constants, and let $H(x)$ denote the Heaviside step function. Find the Fourier transforms of

(a) the odd function $f_o(x)$, where f_o is defined for $x > 0$ by

$$f_o(x) = \begin{cases} 1\,, & 0 < x \leqslant 1\,, \\ 0\,, & x > 1\,. \end{cases}$$

(b) the even function $f_e(x) = \mathrm{e}^{-|x|}$.

(c) the even function $g(x)$, where

$$g(x) = \begin{cases} 1\,, & |x| < \alpha\,, \\ 0\,, & |x| \geqslant \alpha\,. \end{cases}$$

(d) the function

$$h(x) = H(x)\sinh(\alpha x)\,\mathrm{e}^{-\beta x}\,, \quad \text{where} \quad \alpha < \beta\,.$$

8. (a) Use Parseval's theorem and the result of question 7a to show that

$$\int_{-\infty}^{\infty} \left(\frac{1 - \cos x}{x} \right)^2 \mathrm{d}x = \pi\,.$$

(b) Use Parseval's theorem and the result of question 7b to evaluate the integral

$$\int_0^{\infty} \frac{\mathrm{d}k}{(1 + k^2)^2}\,.$$

9. For $g(x)$ as given in question 7c define

$$G(x) = \int_{-\infty}^{\infty} g(x-\xi)\, g(\xi)\, \mathrm{d}\xi\,.$$

Find an expression for $G(x)$. Explicitly demonstrate that the Fourier transforms of $G(x)$ and $g(x)$ satisfy the convolution theorem.

10. Show that, if a function f and its Fourier transform $\tilde{f}$ are both real, then f is even. Show also that, if a function f is real and its Fourier transform $\tilde{f}$ is purely imaginary, then f is odd.

11. By taking the Fourier transform of the equation

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} - m^2\phi \;=\; f(x)$$

show that its solution $\phi(x)$ can be written as

$$\phi(x) \;=\; -\frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{e^{\mathrm{i}kx}\tilde{f}(k)}{k^2+m^2}\,\mathrm{d}k$$

where $\tilde{f}(k)$ is the Fourier transform of $f(x)$.

This example sheet is available on the Cambridge University Moodle site.
Hints and answers will also be posted on the Moodle site.

Supervisors may request these early. Comments/corrections to `n.peake@damtp.cam.ac.uk`