231 Tutorial Sheet 12: due Monday 18 Febuary 2008[1,2]

11 Febuary 2008

Useful facts:

- Parceval's formula:

$$\frac{1}{l}\int_{-l/2}^{l/2} dx|f(x)|^2 = \frac{1}{4}a_0^2 + \frac{1}{2}\sum_{n=1}^{\infty}\left(a_n^2 + b_n^2\right) = \sum_{n=-\infty}^{\infty} |c_n|^2$$

- The Fourier integral or Fourier transform:

$$f(x) = \int_{-\infty}^{\infty} dk\, \widetilde{f(k)} e^{ikx}$$
$$\widetilde{f(k)} = \frac{1}{2\pi}\int_{-\infty}^{\infty} dx\, f(x) e^{-ikx}$$

- The Dirac delta function:

$$\int_{-\infty}^{\infty} dx\, f(x)\delta(x) = f(0)$$

- If $h(x)$ is a continuous function

$$\int_{-\infty}^{\infty} dx\, f(x)\delta[h(x)] = \sum_{x_i : f(x_i)=0} \frac{f(x_i)}{|h'(x_i)|}$$

Questions

1. The Riemann zeta function is defined as follows

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s} \qquad (s > 1).$$

(a) By applying Parseval's theorem for Fourier series to the sawtooth $f(x) = x$ for $-\pi < x < \pi$ compute

$$\zeta(2) = \sum_{n=1}^{\infty} \frac{1}{n^2}.$$

(b) Consider the Fourier expansion of $f(x) = x^2$, $\quad -\pi < x < \pi$, and use the result to show that

$$\zeta(4) = \sum_{n=1}^{\infty} \frac{1}{n^4} = \frac{\pi^4}{90}.$$

Remark:

It is straightforward to compute $\zeta(n)$ if n is an even integer. On the other hand, no simple formulae are available for the odd integers, i.e. $\zeta(3)$, $\zeta(5)$, etc. Though, of course, they can be computed numerically.

The definition of $\zeta(s)$ straightforwardly extends to complex values of s. The sum defining $\zeta(s)$ clearly converges for any complex s where Re $s > 1$. In fact, the function can be 'analytically continued' to *any* complex s (apart from $s = 1$). Such a continuation boils down to finding an alternative expression for $\zeta(s)$ that agrees with the given definition when Re$s > 1$ but makes sense for any $s \neq 1$. It is rather easy to continue to s values such that Re $s > 0$. One recasts the zeta function as an alternating series

$$\zeta(s) = \frac{1}{1-2^{1-s}} \sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{n^s}.$$

A long standing problem in mathematics is to find the zeros of $\zeta(s)$. It is known that $\zeta(s)$ has zeros at the points $s = -2n$ where n is a natural number and that all other zeros lie in the strip $0 \leq$ Re $s \leq 1$.

Riemann's hypothesis: All zeros of $\zeta(s)$ in the strip $0 \leq$ Re $s \leq 1$ lie on the line Re $s = \frac{1}{2}$.

2. Determine the Fourier transform of the Gaussian function

$$f(x) = e^{-\alpha x^2},$$

where α is a positive constant.

Suggestions: Compute the integral

$$\int_{-\infty}^{\infty} dx\; e^{-\alpha x^2 + \beta x},$$

where β is real. To do this, first consider the case $\beta = 0$. Infer the result for $\beta \neq 0$ by a simple change of variable in the integral. Then formally allow β to be imaginary (you may wish to postpone the justification of this procedure to a later date!).

3. Compute $\int_{-\infty}^{\infty} dx\, x^2\, \delta(x-3)$, $\int_{-\infty}^{\infty} dx\, \delta(x^2+x)$, $\int_0^2 dx\, e^x\, \delta'(x-1)$, $\int_0^{\infty} dx\, e^{-ax}\delta(\cos x)$, $\int_0^{\infty} dx\, \delta(e^{ax}\cos x)$ and $\frac{d}{dx}e^{a\theta(x)}$. where a is a constant.

[1] Conor Houghton, `houghton@maths.tcd.ie`, see also `http://www.maths.tcd.ie/~houghton/231`

[2] Including material from Chris Ford, to whom many thanks.