12d. Poisson summation

Paul Garrett  garrett@math.umn.edu  http://www.math.umn.edu/~garrett/

The simplest Poisson summation formula is

\[ \sum_{n \in \mathbb{Z}} f(n) = \sum_{n \in \mathbb{Z}} \hat{f}(n) \quad \text{(suitable } f, \text{ Fourier transform } \hat{f}) \]

with Fourier transform \( f \rightarrow \hat{f} \) normalized as

\[ \text{Fourier transform of } f = \hat{f}(\xi) = \int_{\mathbb{R}} f(x) e^{-2\pi i x \xi} \, dx \]

The simplest heuristic for the truth of Poisson summation is in terms of representability of functions by Fourier series, as follows. Given \( f \) a function on \( \mathbb{R} \), periodicize \( f \)

\[ F(x) = \sum_{n \in \mathbb{Z}} f(x + n) \]

The periodic function \( F \) should be represented by its Fourier series, so

\[ F(x) = \sum_{\ell \in \mathbb{Z}} e^{2\pi i \ell x} \int_{0}^{1} F(x) e^{-2\pi i \ell x} \, dx \]

The Fourier coefficients of \( F \) expand to be seen as the Fourier transform of \( f \):

\[ \int_{0}^{1} F(x) e^{-2\pi i \ell x} \, dx = \int_{0}^{1} \sum_{n \in \mathbb{Z}} f(x + n) e^{-2\pi i \ell x} \, dx = \sum_{n \in \mathbb{Z}} \int_{0}^{1} f(x) e^{-2\pi i \ell x} \, dx = \int_{\mathbb{R}} f(x) e^{-2\pi i \ell x} \, dx = \hat{f}(\ell) \]

Evaluating at 0 should give

\[ \sum_{n \in \mathbb{Z}} f(n) = F(0) = \sum_{\ell \in \mathbb{Z}} \hat{f}(\ell) \]

Under what hypotheses is this legitimate? Certainly \( f \) must be of sufficient decay so that the integral for its Fourier transform is (absolutely?) convergent, and so that summing its translates by \( \mathbb{Z} \) is nicely convergent. We’d want \( f \) to be continuous, probably at least once-differentiable, so that we can talk about pointwise values of \( F \), and so that the Fourier series of \( F \) converges pointwise to \( F \).

For \( f \) and several derivatives rapidly decreasing, the Fourier transform \( \hat{f} \) will be of sufficient decay so that its sum over \( \mathbb{Z} \) does converge. In this vein, a simple sufficient hypothesis for convergence is that \( f \) be in the Schwartz space of infinitely-differentiable functions all of whose derivatives are of rapid decay, that is,

\[ \text{Schwartz space } = \{ \text{smooth } f : \sup_{x} (1 + x^2)^{i} |f^{(i)}(x)| < \infty \text{ for all } i, \ell \} \]

This assumption is too restrictive for some applications, and, indeed, is needlessly restrictive, but is simple and robust, and allows straightforward proofs.

The least obvious ingredient is pointwise convergence of Fourier series. Recall a simple elementary version:
[0.1] Claim: For periodic $f$ piecewise-$C^\infty$ functions left-continuous and right-continuous at its discontinuities, for points $x_o$ at which $f$ is $C^0$ and left-differentiable and right-differentiable, the Fourier series of $f$ evaluated at $x_o$ converges to $f(x_o)$:

$$f(x_o) = \sum_{n \in \mathbb{Z}} \hat{f}(n) e^{2\pi inx_o}$$

That is, for such functions, at such points, the Fourier series represents the function pointwise. ///

We want to be sure not only that the periodicization $F$ of a Schwartz function $f$ is $C^1(S^1)$, but that the sum expressing it converges to it in a $C^1$-topology, to be able to differentiate termwise. The finite partial sums $\sum_{|n| \leq N} f(x + n)$ are not periodic, so cannot converge to $F$ in $C^1(S^1)$, since they’re not in that space. Nevertheless, we can show that the partial sums converge in the Fréchet space $C^1(\mathbb{R})$, whose topology is given by semi-norms

$$\nu_T(f) = \sup_{|x| \leq T} |f(x)| + \sup_{|x| \leq N} |f'(x)| \quad (\text{for } T = 1, 2, \ldots)$$

The topology cannot be given by a single norm, so is not Banach, but it is complete-metrizable, with many different metrics, no canonical one, all approximately of the form

$$d(f, g) = \sum_{N \geq 1} 2^{-N} \frac{\nu_N(f - g)}{1 + \nu_N(f - g)}$$

The periodicity of the full sum is separate from the issue of convergence in $C^1(\mathbb{R})$.

The rapid decay certainly implies, for example, that there are constants $A, B$ such that

$$|f(x)| \leq A(1 + |x|)^{-2} \quad \text{and} \quad |f'(x)| \leq B(1 + |x|)^{-2}$$

Thus, the tails are estimated by

$$\sup_{|x| \leq T} \left| \sum_{M < |n| \leq N} |f(x + n)| + |f'(x + n)| \right| \leq (A + B) \sup_{|x| \leq T} \sum_{M < |n| \leq N} (1 + |x| + |n|)^{-2} \leq (A + B) \int_M^\infty \frac{dt}{t^2} \leq (A + B) \frac{1}{M}$$

This can be made arbitrarily small by taking $M$ large, giving convergence with respect to the $T^{th}$ seminorm, hence, with in the metrizable topology on $C^1(\mathbb{R})$. ///

A similar argument shows that the periodicization is smooth.