Methods

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1 Fourier Series

1.1 Motivation

In 1807 J. Fourier was studying head conduction along a metal rod. This lead him to study 2π-periodic functions i.e. functions $f : \mathbb{R} \to \mathbb{R}$ was such that $f(\theta + 2\pi) = f(\theta)$ for all $\theta \in \mathbb{R}$ then he found that if

$$f(\theta) = \sum_{n\in\mathbb{Z}} \hat{f}_n e^{in\theta}$$

then you can write down the coefficients $\{\hat{f}_n\}$ via the formula

$$\hat{f}_n = \frac{1}{2\pi}\int_0^{2\pi} f(\theta)e^{-in\theta}\mathrm{d}\theta, \quad n \in \mathbb{Z}.$$

And Fourier believed that this worked for any 2π-periodic function f. So computing each $\{\hat{f}_n\}$ and construcuted the sum as above, then it would return the original function. He was wrong.

1.2 Modern Treatment

Introduce a vector space V of L-periodic functions. Hence

$$V = \{f : \mathbb{R} \to \mathbb{C} : \text{ with } f \text{ a "nice" function, } f(\theta + L) = f(\theta), \forall\theta \in \mathbb{R}\}.$$

Note for $f \in V$ need only to consider values of f taken in an interval of length L, i.e. $[0, L)$ or $(-\frac{L}{2}, \frac{L}{2}]$ since periodicity covers elsewhere.

We can introduce an inner product on V with

$$\langle f, g\rangle = \int_0^1 f(\theta)\overline{g(\theta)}\mathrm{d}\theta.$$

This gives the associated norm,

$$||f|| = \sqrt{\langle f, f\rangle}.$$

For $n \in \mathbb{Z}$ consider $e_n \in V$ defined by $e_n(\theta) = e^{2\pi in\theta/L}$.

$$\langle e_n, e_m\rangle = \int_0^L e^{2\pi i(n-m)\theta/L}\,\mathrm{d}\theta = L\,\delta_{nm}.$$

So $\{e_n\}$ are orthogonal and $||e_n||^2 = L$ for each $n \in \mathbb{Z}$. This looks like IA Vectors and Matrices.

Recall that if v_N is N-dim vector space equipped with usual inner product and $\{e_n\}_{n=1}^N$ are orthogonal with $|e_n| = L$, then for each $x \in V$ we can write $x = \sum_{n=1}^N \hat{x}_n e_n$ for some $\{\hat{x}_n\}$. To find $\{\hat{x}_n\}$ take the inner product of both sides with e_m. So

$$(x, e_m) = \sum_{n=1}^N \hat{x}_n(e_n \cdot e_m) = L\hat{x}_m$$

i.e

$$\hat{x}_n = \frac{1}{L}(x \cdot e_n).$$

Now could this work on V? V is not finite dimensional so it's not obvious. Every subset of $\{e_n\}$ is linearly indepedent. Ignoring this for now we assume that for all $f \in V$ we can write f in our basis $\{e_n\}$. Then

$$f(\theta) = \sum_n \hat{f}_n e_n(\theta),$$

So taking the inner product as before

$$\langle f, e_m \rangle = \sum_n \hat{f}_n \langle e_n, e_m \rangle$$

so using the delta as before

$$= L\hat{f}_m$$

i.e.

$$\hat{f}_n = \frac{1}{L}\langle f, e_n \rangle = \frac{1}{L}\int_0^1 f(\theta) e^{-2\pi i n\theta/L} \mathrm{d}\theta$$

Definition. (Complex Fourier series) For an L-periodic $f : \mathbb{R} \to \mathbb{C}$ define its *complex Fourier series* by

$$\sum_n \hat{f}_n e^{2\pi i n\theta/L}$$

where

$$\hat{f}_n = \frac{1}{L}\int_0^1 f(\theta) e^{-2\pi i n\theta/L} \mathrm{d}\theta$$

are called the complex Fourier coefficients. We will write for $f \in V$

$$f(\theta) \sim \sum_n \hat{f}_n e^{2\pi i n\theta/L}$$

to mean the series on the right corresponds to complex Fourier series for the function on the left.

We'd like to replace the $\sim$ symbol with equality, but we require a bit more than that.

If we split the complex Fourier series into the parts $\{n = 0\} \cup \{n > 0\} \cup \{n < 0\}$ we get

$$\sum_n \hat{f}_n e^{2\pi i n\theta/L} = \hat{f}_0 + \sum_{n=1}^{\infty} \hat{f}_n \left[\cos\left(\frac{2\pi n\theta}{L}\right) + i\sin\left(\frac{2\pi n\theta}{L}\right)\right] + \sum_{n=1}^{\infty} \hat{f}_{-n} \left[\cos\left(\frac{2\pi n\theta}{L}\right) - i\sin\left(\frac{2\pi n\theta}{L}\right)\right].$$

Definition. (Fourier series) For $f : \mathbb{R} \to \mathbb{C}$ an L-periodic function define its *Fourier series* by

$$\frac{1}{L}a_0 + \sum_{n=1}^{\infty} \left[a_n \cos\left(\frac{2\pi n\theta}{L}\right) + b_n \sin\left(\frac{2\pi n\theta}{L}\right)\right]$$

where

$$a_n = \frac{2}{L}\int_0^L f(\theta)\cos\left(\frac{2\pi n\theta}{L}\right) \mathrm{d}\theta$$

and

$$b_n = \frac{2}{L}\int_0^L f(\theta)\sin\left(\frac{2\pi n\theta}{L}\right) \mathrm{d}\theta$$

are called the Fourier cofficients for f.

If we set

$$\begin{aligned} c_n(\theta) &= \cos\left(\frac{2\pi n\theta}{L}\right), \\ s_n(\theta) &= \sin\left(\frac{2\pi n\theta}{L}\right), \end{aligned}$$

then we can show, for $m, n \geq 1$ that $\langle c_n, c_m\rangle = \langle s_n, s_m\rangle = \frac{L}{2}\delta_{mn}$ and

$$\langle c_n, 1\rangle = \langle s_m, 1\rangle = \langle c_n, s_m\rangle = 0.$$

So we have that $\{1, c_n, c_n\}$ is orthogonal set in V.

For an example take $f : \mathbb{R} \to \mathbb{R}$, 1-periodic, such that $f(\theta) = \theta(1-\theta)$ on $[0, 1)$. For $n \neq 0$ we have

$$\hat{f}_n = \int_0^1 \theta(1-\theta)e^{-2\pi i n\theta} \mathrm{d}\theta.$$

Integrating by parts (or using a standard Fourier integral computation) yields

$$\hat{f}_n = -\frac{1}{2(\pi n)^2}, \qquad n \neq 0,$$

and

$$\hat{f}_0 = \int_0^1 (\theta - \theta^2) \mathrm{d}\theta = \frac{1}{6}.$$

Hence

$$f(\theta) \sim \frac{1}{6} - \sum_{n\neq 0} \frac{e^{2\pi i n\theta}}{2(\pi n)^2}.$$

so the sine terms cancel in the sum giving just cosine terms as we expect since our f function is even.

1.3 Convergence of Fourier series

This subject is extremely subtle.

Definition. For $f : \mathbb{R} \to \mathbb{C}$ an L-periodic function we defined the *partial Fourier series* as

$$\begin{aligned} (S_N f)(\theta) &= \sum_{|n|<N} \hat{f}_n e^{2\pi i n\theta/L} \\ &= \frac{1}{2}a_0 + \sum_{n=1}^{N}\left[a_n \cos\left(\frac{2\pi n\theta}{L}\right) + b_n \sin\left(\frac{2\pi n\theta}{L}\right)\right] \end{aligned}$$

Natural to ask if $(S_N f) \to f$. For this we need to specify what type of functional convergence we're looking at. Pointwise? Uniform? Maybe they converge in the idea of our new norm?

$$||S_N f - f|| = \sqrt{\int_0^L |(S_N f)(\theta) - f(\theta)|^2 \mathrm{d}\theta} \to 0$$

. For simplicity, we will only consider pointwise convergence.

Proposition. Let $f : \mathbb{R} \to \mathbb{C}$ be an L-periodic function for which on $[0, L)$ we have the following,

(i) f has finitely many discontinuities.

(ii) f has finitely many local maxima and minima.

Then for each $\theta \in [0, 1)$ we have

$$\begin{aligned}\frac{\theta_+ + \theta_-}{2} &= \lim_{n\to\infty} (S_N f)(\theta) \\ &= \sum_n \hat{f}_n e^{2\pi i n\theta/L}\end{aligned}$$

where $f(\theta_\pm) = \lim_{\varepsilon \to 0^+} f(\theta \pm \varepsilon)$. So at the points of continuity the Fourier series gives back the original function, and at points of discontunity the Fourier series gives back the average of the function at the disconunity neighbourhood.

We call functions which properties (i) and (ii) Dirichlet functions. For now on assume all functions are Dirichlet functions so that $\sim$ means that the series on the RHS coincides with the function on the LHS at points of continuity and to the average at points of discontinuity.

Proof. We'll prove the proposition only for functions in $C^\infty(\mathbb{R})$ (actually $C^1(\mathbb{R})$ will do. Assume *wlog* that $L = 2\pi$. Examine $\lim S_N f(\theta_0)$ for some $\theta_0 \in [0, 2\pi)$. By replacing $f(\theta)$ with $f(\theta + \theta_0)$ can assume that $\theta_0 = 0$ *wlog*.

$$\begin{aligned}(S_N f)(\theta) &= \sum_{|n|\le N} \hat{f}_n e^{in\cdot\theta} \\ &= \sum_{|n|\le N} \left(\frac{1}{2\pi}\int_{-\pi}^{\pi} f(\theta)e^{-in\theta}\mathrm{d}\theta\right) \\ &= \frac{1}{2\pi}\int_{-\pi}^{\pi} f(\theta)\left[\sum_{|n|\le N} e^{-in\theta}\right]\mathrm{d}\theta\end{aligned}$$

We can sum the series as a geometric series, so

$$e^{-iN\theta}\sum_{n=0}^{2N} e^{-in\theta} = \frac{\sin[(N+\frac{1}{2})\theta]}{\sin\left(\frac{\theta}{2}\right)}$$

when $\theta \in \mathbb{R} \setminus 2\pi\mathbb{Z}$ and the sum is $2N + 1$ when $\theta \in 2\pi\mathbb{Z}$.
Define the *Dirichlet Kernal* as

$$D_N(\theta) = \begin{cases} \frac{\sin[(N+\frac{1}{2})\theta]}{\sin\left(\frac{\theta}{2}\right)} & \theta \in \mathbb{R} \setminus 2\pi\mathbb{Z} \\ 2N+1 & \text{otherwise} \end{cases}$$

For each $N \geq 0$,

(i) D_N is continiuous, even 2π perioidic

(ii) $\int_{-\pi}^{\pi} D_N(\theta)\mathrm{d}\theta = 2\pi$

Property (ii) follows by intergrating $\sum$ termwise, only 1 is non-zero. This means that

$$f(0) = \frac{1}{2\pi}\int_{-\pi}^{\pi} D_N(\theta)f(\theta)\mathrm{d}\theta$$

So

$$S_N(f)(0) = f(0) = \frac{1}{2\pi}\int_{-\pi}^{\pi} D_N(\theta)[f(\theta) - f(0)]\mathrm{d}\theta$$

now set $F(\theta) = \frac{\theta}{\sin\left(\frac{\theta}{2}\right)}\left[\frac{f(\theta)-f(0)}{\theta}\right]$ so we get

$$(S_N f)(0) = \frac{1}{2\pi}\int_{-\pi}^{\pi} \sin[(N + \frac{1}{2})\theta]F(\theta)\mathrm{d}\theta$$

Note that $\theta \to F(\theta)$ is smooth since

$$\frac{f(\theta) - f(0)}{\theta} = \frac{1}{\theta}\int_0^{\theta} f'(t)\mathrm{d}t = \frac{1}{\theta}\int_0^1 f'(\tau\theta)\theta\mathrm{d}\tau$$

Hence integrating by parts gives that

$$\begin{aligned}(S_N f)(0) - f(0) &= \frac{1}{N + \frac{1}{2}}\frac{1}{2\pi}\int_{-\pi}^{\pi} \cos[(N + \frac{1}{2})\theta]F'(\theta)\mathrm{d}\theta \\ &\to 0 \text{ as } N \to \infty\end{aligned}$$

For an example consider the function

$$f(\theta) = \begin{cases} +1 & 0 \leq \theta < \pi \\ -1 & -\pi \leq \theta < 0 \end{cases}$$

Since f is odd, $a_n = 0$ for each n and

$$\begin{aligned}b_n &= \frac{2}{2\pi}\int_{-\pi}^{\pi} f(\theta)\sin(n\theta)\mathrm{d}\theta \\ &= \frac{2}{\pi}\int_0^{\pi} \sin(n\theta)\mathrm{d}\theta \\ &= \frac{2}{n\pi}[1 - (-1)^n]\end{aligned}$$

Thus

$$f(\theta) \sim \frac{4}{\pi}\sum_{n \text{ odd}} \frac{\sin(n\theta)}{n}$$

1.4 Peridoic extensions: Cosine and sine series

Given a function $f : [0, L) \to \mathbb{C}$ we can define $2L$-periodic even/odd extensions called f_{even}, f_{odd}. Define,

$$f_{even}(\theta) = \begin{cases} f(\theta) & \theta \in [0, L) \\ f(-\theta) & \theta \in [-L, 0) \end{cases}$$

and

$$f_{odd}(\theta) = \begin{cases} f(\theta) & \theta \in [0, L) \\ -f(-\theta) & \theta \in [-L, 0) \end{cases}$$

. Note that $f(\theta) = f_{even}(\theta) = f_{odd}(\theta)$ if $\theta \in [0, L)$.

$$\begin{aligned} f_{even}(\theta) &\sim \frac{1}{2}A_0 + \sum_{n=1}^{\infty} A_n \cos\left(\frac{2\pi n\theta}{2L}\right) \\ A_n &= \frac{2}{2L}\int_{-L}^{L} f_{even}(\theta) cos\left(\frac{2\pi n\theta}{2L}\right) \mathrm{d}\theta \\ &= \frac{2}{L}\int_{0}^{L} f(\theta) cos\left(\frac{2\pi\theta}{L}\right) \mathrm{d}\theta \end{aligned}$$

simiarly we have that

$$\begin{aligned} f_{odd}(\theta) &\sim \sum_{n=1}^{\infty} B_n \sin\left(\frac{2\pi n\theta}{2L}\right) \\ B_n &= \frac{2}{L}\int_{0}^{L} f(\theta) \sin\left(\frac{n\pi\theta}{L}\right) \mathrm{d}\theta \end{aligned}$$

Definition. For $f : [0, L) \to \mathbb{C}$ define its *cosine* and *sine* series by

$$\frac{1}{2}A_0 + \sum_{n=1}^{\infty} A_n \cos\left(\frac{n\pi\theta}{L}\right), \quad \sum_{n=1}^{\infty} B_n \sin\left(\frac{n\pi\theta}{L}\right)$$

where A_n and B_n defined as before.

For an example consider $f(\theta) = 1$ on $[0, \pi)$. For the sine series,

$$B_n = \frac{2}{\pi}\int_{0}^{\pi} \sin(n\theta)\mathrm{d}\theta = \frac{2}{n\pi}(1 - (-1)^n)$$

On the interval $(0, \pi)$ we get that $1 = f(\theta) = f_{odd}(\theta) = 4\sum_{n\in\mathbb{N}} \frac{\sin(n\theta)}{n\pi}$. Whereas for the cosine series we get that

$$A_0 = 2, \quad A_n = 0 \quad n \geq 1$$

So for $\theta \in [0, \pi)$ we get that $f_{even} = \frac{1}{2} \cdot 2 = 1 = f(\theta)$.

1.5 Regularity and decay of Fourier coefficients

A true but non-examinable fact is that if $g : [a, b] \to \mathbb{C}$ is integrable on $[a, b]$ and $\lambda \in \mathbb{R}$ then

$$\int_{a}^{b} e^{-i\lambda\theta} g(\theta)\mathrm{d}\theta \to 0 \text{ as } |\lambda| \to \infty.$$

IF $f:\mathbb{R}\to\mathbb{C}$ is a L-periodic function and integrable on $[0,L)$ then

$$\hat{f} = \frac{1}{L}\int_0^L e^{-2\pi i n\theta/L} f(\theta)\mathrm{d}\theta$$

so taking $\lambda = \frac{2\pi n}{L}$ gives that $\hat{f}_n \to 0$ as $n\to\infty$ by the Riemann-Lebesgue lemma. Also

$$a_n = \hat{f}_n + \hat{f}_{-n} \quad b_n = i(\hat{f}_n - \hat{f}_{-n}),$$

both go to zero as $n\to\infty$.

Suppose that f is L-periodic and $f\in C^k(\mathbb{R})$.

$$\begin{aligned}
\hat{f}_n &= \frac{1}{L}\int_0^L e^{-2\pi i n\theta/L} f(\theta)\mathrm{d}\theta \\
&= -\frac{1}{L}\left(\frac{L}{2\pi i n}\right) f(\theta) e^{-2\pi i n\theta/L}\Big|_{\theta=0}^{L} + \left(\frac{L}{2\pi i n}\right)\frac{1}{L}\int_0^L e^{-2\pi i n\theta/L} f'(\theta)\mathrm{d}\theta \\
&= -\frac{L}{2\pi i n}\left[\frac{f(L^-)-f(0^+)}{L}\right] + \frac{L}{2\pi i n}\frac{1}{L}\int_0^L e^{-2\pi i n\theta} f'(\theta)\mathrm{d}\theta
\end{aligned}$$

Since f is periodic and continuously differentiable we have that

$$f(0^+) = f(L^+) = f(L^-)$$

hence the boundary term cancels so repeating we get that

$$\hat{f}_n = \left(\frac{L}{2\pi i n}\right)^k \frac{1}{L}\int_0^L e^{-2\pi i n\theta/L} f^{(k)}(\theta)\mathrm{d}\theta$$

and the integral is $o(1)$ by the Rieman-Lebesgue lemma.

So we get that if f is $C^k(\mathbb{R})$ then $\hat{f}_n = o\left(\frac{1}{n^k}\right)$ as $|n|\to\infty$.

1.6 Termwise differentiation

Suppose f is L-periodic continuously differentiable on $[0,L)$ with $f'=g$ thne g is continuous on $[0,L)$ so

$$\begin{aligned}
\hat{g}_n &= \frac{1}{L}\int_0^L e^{-2\pi i n\theta/L} f'(\theta)\mathrm{d}\theta \\
&= \frac{f(L^-)-f(0^+)}{L} + \left(\frac{2\pi i n}{L}\right)\frac{1}{L}\int_0^L e^{-2\pi i n\theta/L} f(\theta)\mathrm{d}\theta
\end{aligned}$$

If f is continuous on $\mathbb{R}$ then by periodicity we have that

$$f(0^+) = f(L^+) = f(L^-)$$

so that

$$\hat{g}_n = \left(\frac{2\pi i n}{L}\right)\hat{f}_n$$

i.e.

$$f'(\theta) = g(\theta) \sim \sum_n \left(\frac{2\pi i n}{L}\right)\hat{f}_n e^{2\pi i n\theta/L}$$

1.7 Parseval's theorem

If we have that

$$f(\theta) \sim \sum_n \hat{f}_n e_n(\theta)$$

and

$$g(\theta) \sim \sum_n \hat{g}_n e_n(\theta)$$

then taking the inner product of both function we get that

$$\begin{aligned}\langle f, g\rangle &= \sum_{n,m} \hat{f}_n \overline{\hat{g}_n} \langle e_n, e_m\rangle \\ &= L \sum_n \hat{f}_n \overline{\hat{g}_n}\end{aligned}$$

finally that

$$\frac{1}{L}\int_0^L f(\theta)\overline{g(\theta)}\mathrm{d}\theta = \sum_n \hat{f}_n \overline{\hat{g}_n}$$

and when f and g are the same we get that

$$\frac{1}{L}\int_0^L |f(\theta)|^2 \mathrm{d}\theta = \sum_n |\hat{f}_n|^2$$