Master's Project

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Preface

I plan to write and detail everything(almost) I study and learn for my Master's project into these latex files. I assume it will be much easier to track whatever I have learned and to have a good overview of the topic with this note taking. Also since I am doing it on LaTeX I am sure it will save me from the last minute rush to type everything out and make the report of the project. I will start with Fourier series and will introduce new concepts when they are required as we go along. So, let us start

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Chapter 1

Fourier Series

1.1   Definition and basic properties

We'll begin by reviewing the definition of L^p space since we'll be mostly working on functions from these space.

Definition 1.1.1 (L^p function)**.** A real valued function f defined on a lebesgue measure space S is called an L^p function on S or a p-integrable function on S if

$$\left(\int_S |f(x)|^p \right)^{1/p} < \infty$$

For such a function the integral above is called the p-norm of the function f and often denoted by $\|f\|_{L^p(S)}$ or $\|f\|_p$ if the space is known.

Although we've defined general L^p spaces, we'll mostly be concerned about L^1 and L^2 functions in $\mathbb{R}$ and $\mathbb{T} = [0, 1)$.

Now let's define what a periodic function is.

Definition 1.1.2 (Periodic function)**.** A function $f : \mathbb{R} \to \mathbb{R}$ is called periodic with period p(or p-periodic) if $f(x + p) = f(x)$ for all $x \in \mathbb{R}$

Although we're defining real valued periodic functions the definition holds well for any function f from the reals to a space where equality is defined. Also note that if we know the value of a p periodic function f in a closed-open (or open-close or closed) interval of length p say $[x, x + p)$, then using the definition of periodic function we can get the function value at the whole of $\mathbb{R}$(we leave it for the reader to verify). That is, we can identify any p periodic function f on

$\mathbb{R}$ with the restriction of f onto an interval of length p. We can also identify f with the values in a unit circle in $\mathbb{C}$. Specifically we'll be working with 1-periodic functions identified by their restrictions in $\mathbb{T}$.

Definition 1.1.3 (Continuous functions in $\mathbb{T}$). Continuous functions on $\mathbb{T}$, are precisely those functions which are continuous in $\mathbb{R}$ with period 1. We'll denote the collection of continuous functions in $\mathbb{T}$ with $C(\mathbb{T})$.

Now let's prove an important result of periodic functions.

Lemma 1.1.1. *If* $f : \mathbb{R} \to \mathbb{R}$ *is of period 1 and* $\int_0^1 f(x)dx$ *exists, then for any real number* a,

$$\int_a^{a+1} f(x)dx = \int_0^1 f(x)dx$$

Proof. Let $a = n + b$, where $0 \leq b < 1$ and n is an integer. Then since f has period 1,

$$\int_a^{a+1} f(x)dx = \int_{n+b}^{n+b+1} f(x)dx = \int_b^{b+1} f(x+n)dx = \int_b^{b+1} f(x)dx$$

and,

$$\int_b^{b+1} f(x)dx = \int_b^1 f(x)dx + \int_1^{b+1} f(x)dx$$
$$= \int_b^1 f(x)dx + \int_0^b f(x+1)dx$$
$$= \int_b^1 f(x)dx + \int_0^b f(x)dx$$
$$= \int_0^1 f(x)dx$$

Hence the result.

$\square$

Now we'll define fourier coefficients of a periodic function $f \in L^1(\mathbb{T})$

Definition 1.1.4 (Fourier coefficient). Let $f \in L^1(\mathbb{T})$, i.e $\int_{\mathbb{T}} f < \infty$. Then for each integer n we define the nth fourier coefficient, $\widehat{f}(n)$ as

$$\widehat{f}(n) = \int_0^1 f(x)e^{-2\pi i n x}dx$$

$\widehat{f}(n)$ is finite and well defined for each n since $f \in L^1(\mathbb{T})$, since

$$|\widehat{f}(n)| \leq \int_0^1 |f(x)e^{-2\pi inx}|dx \leq \int_0^1 |f(x)||e^{-2\pi inx}|dx = \int_0^1 |f(x)|dx < \infty$$

Once we have the fourier coefficients of a function at hand we can combine them together to make a series called the fourier series. We'll be investigating the conditions at which this series converges to our initial function f.

Also note that the map which takes f to $\widehat{f}$ is linear since if $f, g \in L^1(\mathbb{T})$, then

$$\widehat{f+g}(n) = \int_0^1 (f+g)(x)e^{-2\pi inx} \, dx = \int_0^1 f(x)e^{-2\pi inx} \, dx + \int_0^1 g(x)e^{-2\pi inx} \, dx = \widehat{f}(n) + \widehat{g}(n)$$

and for some $\lambda \in \mathbb{R}$,

$$\widehat{\lambda f}(n) \, dx = \int_0^1 \lambda f(x)e^{-2\pi inx} \, dx = \lambda \int_0^1 f(x)e^{-2\pi inx} \, dx = \lambda \widehat{f}(n)$$

Definition 1.1.5 (Fourier series). Given a function $f \in L^1(\mathbb{T})$, the fourier series of the function f is defined as

$$\sum_{n \in \mathbb{Z}} \widehat{f}(n)e^{2\pi inx}$$

where $\widehat{f}(n)$ is the nth fourier coefficient as Definition 1.1.4

Proposition 1.1.1 (Properties of Fourier coefficients). *Suppose that $f \in L^1(\mathbb{T})$.*

(a) *If a is a real number and $g(x) = f(x+a)$ for all x, then $\widehat{g}(n) = \widehat{f}(n)e^{2\pi ina}$ for all $n \in \mathbb{Z}$.*

(b) *if b is an integer and $h(x) = f(x)e^{2\pi ibx}$ for all x, then $\widehat{h}(n) = \widehat{f}(n-b)$ for all $n \in \mathbb{Z}$.*

(c) *if $j(x) = f(-x)$ for all x, then $\widehat{j}(n) = \widehat{f}(-n)$*

Proof. Given $f(x) \in L^1(\mathbb{T})$ and n^{th} Fourier coefficient of f,

$$\widehat{f}(n) = \int_0^1 f(x)e^{-2\pi inx}.$$

(a) Then, the nth Fourier coefficient of $g(x) = f(x + a)$ is

$$\widehat{g}(n) = \int_0^1 g(x)e^{-2\pi inx}dx$$

$$= \int_0^1 f(x+a)e^{-2\pi inx}dx$$

$$= \int_0^1 f(x)e^{-2\pi in(x-a)}dx$$

$$= e^{2\pi ina}\int_0^1 f(x)e^{-2\pi inx}dx$$

$$= e^{2\pi ina}\widehat{f}(n)$$

(b) If $h(x) = f(x)e^{2\pi ibx}$, then

$$\widehat{h}(n) = \int_0^1 f(x)e^{-2\pi i(n-b)x}dx = \widehat{f}(n-b)$$

(c) $j(x) = f(-x)$, then

$$\widehat{j}(n) = \int_0^1 f(-x)e^{-2\pi inx}dx$$

$$= -\int_0^{-1} f(y)e^{2\pi iny}dy \qquad\qquad \text{by } y = -x$$

$$= \int_{-1}^0 f(y)e^{2\pi iny}dy$$

$$= \int_0^1 f(y)e^{2\pi iny}dy \qquad\qquad \text{by Lemma 1.1.1}$$

$$= \widehat{f}(-n)$$

$\square$

1.2   Convolution

Now we'll define another important operation with function called the convolution of two functions.

Definition 1.2.1. Let $f, g \in L^1(\mathbb{T})$, then the convolution of f and g is defined as

$$f * g(x) = \int_0^1 f(x-y)g(y)dy$$
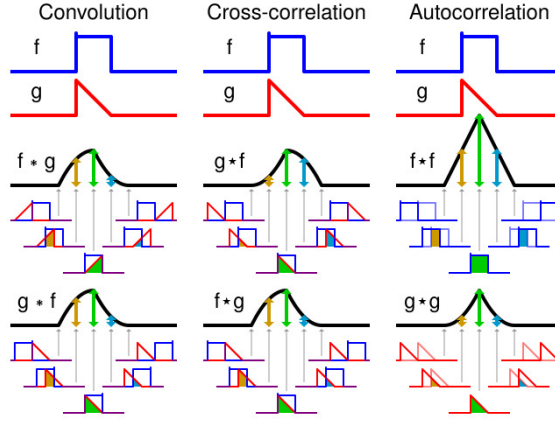
Figure 1.1: convolution

Convolution can be thought of as taking the moving average of a function with another function. Refer Figure 1.1.

Proposition 1.2.1 (Properties of convolution). *Let $f, g \in L^1(\mathbb{T})$, then*

(a) $f * g = g * f$

(b) $f * (g + h) = f * g + f * h$

(c) $(cf) * g = c(f * g)$

(d) $f * (g * h) = (f * g) * h$

Proof. We'll just prove the commutativity and will leave the rest for the reader to verify. (Hint: Use properties of integration)

Put $v = x - y$, we get $dv = -dy$ and

$$
\begin{aligned}
f * g(x) &= \int_0^1 f(x - y)g(y) \ dy \\
&= -\int_x^{x-1} f(v)g(x - v) \ dv \\
&= \int_{x-1}^x g(x - v)f(v) \ dv \\
&= \int_0^1 g(x - v)f(v) \ dv \qquad \text{by Lemma 1.1.1} \\
&= g * f(x)
\end{aligned}
$$

□

We'll prove another important result that the convolution of two $L^1(\mathbb{T})$ functions is again in $L^1(\mathbb{T})$.

Proposition 1.2.2. *Let $f, g \in L^1(\mathbb{T})$. Then $h = f * g \in L^1(\mathbb{T})$, and $\widehat{h}(n) = \widehat{f}(n)\widehat{g}(n)$.*

Proof.

$$
\begin{aligned}
\int_0^1 |h(x)|dx &= \int_0^1 \left| \int_0^1 f(y)g(x-y) \ dy \right| dx \\
&\leq \int_0^1 \int_0^1 |f(y)g(x-y)| \ dy \ dx \\
&= \int_0^1 \int_0^1 |f(y)g(x-y)| \ dx \ dy \qquad \text{by Tonelli's theorem} \\
&= \int_0^1 \left(\int_0^1 |g(x-y)|dx \right) |f(y)|dy \\
&= \|f\|_1 \|g\|_1
\end{aligned}
$$

Note that we're using Tonelli's theorem here to interchange the limits of integration since the space is a finite measure space. This proves that $h = f * g \in L^1(\mathbb{T})$.

To prove the next part,

$$
\begin{aligned}
\widehat{h}(n) &= \int_0^1 \left(\int_0^1 f(y)g(x-y)dy \right) e^{-2\pi inx} dx \\
&= \int_0^1 f(y) \left(\int_0^1 g(x-y)e^{-2\pi inx} dx \right) dy \qquad \text{by Tonelli's theorem} \\
&= \int_0^1 f(y)\widehat{g}(n)e^{-2\pi inx} dy \qquad\qquad \text{by Proposition 1.1.1(a)} \\
&= \widehat{f}(n)\widehat{g}(n)
\end{aligned}
$$

□

1.3 Partial sums of Fourier series

Given a function f in the $\mathbb{T}$, we are interested in the convergence of fourier series of f. We'll discuss about the convergence of the symmetric partial sum of the Fourier series.

Definition 1.3.1 (Symmetric partial sum of a Fourier series)**.** Given a function $f \in L^1(\mathbb{T})$ with its fourier series, $\sum_{-\infty}^{\infty} \widehat{f}(n)e^{2\pi inx}$, we define the nth symmetric parial sum of the fourier series as

$$S_N(x) = \sum_{n=-N}^{N} \widehat{f}(n)e^{2\pi inx}$$

But it may happen that the summetric partial sum of the Fourier seies may not converge. To deal with this we'll define another partial sum called the Cesáro partial sum.

Definition 1.3.2 (Cesáro partial sum of Fourier series)**.** Given a function $f \in L^1(\mathbb{T})$ with its Fourier series, $\sum_{-\infty}^{\infty} \widehat{f}(n)e^{2\pi inx}$, we define the nth Cesáro parial sum of its Fourier series as

$$\sigma_N(x) = \frac{1}{N} \sum_{n=0}^{N-1} S_n(x)$$

where $S_n(x)$ is the symmetric partial sum of the Fourier series in Definition 1.3.1

For an example, $\{-1^n\}$ is a sequence whose symmetric partial sums do not converge but the Cesáro partial sums converge to $\frac{1}{2}$. Also if the symmetric partial sums of a series converge, then the Cesáro partial sums will also converge to the same limit. (Prove it!)

Now we'll show that the Cesáro partial sum can be rewritten to another form which will help our proofs down the road.

Lemma 1.3.1. *If $\sigma_N(x)$ is the Nth Cesáro partial sum of the Fourier series of a function $f \in L^1(\mathbb{T})$, then*

$$\sigma_N(x) = \sum_{n=-N}^{N} \left(1 - \frac{|n|}{N}\right) \widehat{f}(n)e^{2\pi inx}$$

Proof. We'll prove the result for a general series so that it'll help us also in Fourier series.

Let $S_N = \sum_{n=-N}^{N} a_n$ be the Nth partial sum of the series $\sum_{-\infty}^{\infty} a_n$. Then by

the definition of Cesáro partial sum,

$$\sigma_N = \frac{1}{N} \sum_{n=0}^{N-1} S_n$$

$$= \frac{1}{N} \sum_{n=0}^{N-1} \sum_{k=-n}^{n} a_k$$

$$= \frac{1}{N} \sum_{k=-N+1}^{N-1} a_k \sum_{n=|k|}^{N-1} 1$$

$$= \frac{1}{N} \sum_{k=-N+1}^{N-1} (N - |k|) \, a_k$$

$$= \sum_{k=-N+1}^{N-1} \left(1 - \frac{|k|}{N}\right) a_k$$

$$= \sum_{k=-N}^{N} \left(1 - \frac{|k|}{N}\right) a_k$$

Now speficially if we take $a_k = \widehat{f}(k)e^{2\pi i k x}$, we get the required result. $\square$

1.4   Summability Kernels

Now we'll define a family of functions called the sumambility kernels, which we will use heavily in our proofs and simplify it.

Definition 1.4.1 (Summability kernel)**.** A collection of functions $K_N \in L^1(\mathbb{T})$ is called a summability kernel or an approximation identity if

(a) $\int_0^1 K_N(x)dx = 1$

(b) $\int_0^1 |K_N(x)|dx \leq C$ for some constant $C > 0$

(c) $\lim_{N\to\infty} \int_\delta^{1-\delta} |K_N(x)|dx = 0$

Now we'll define one of the important summability kernels.

Definition 1.4.2 (Fejér kernel)**.** Fejér kernel is defined as a collection of functions Δ_N where for each $N \in \mathbb{N}$, $\Delta_N : \mathbb{R} \to \mathbb{R}$ is defined as

$$\Delta_N(x) = \sum_{n=-N}^{N} \left(1 - \frac{|n|}{N}\right) e^{2\pi i n x}$$

Notice that each Δ_N is a $1-$periodic function.

We'll prove that Fejér kernel as in Definition 1.4.2 satify the properties in Definition 1.4.1. But before that we'll explore some properties of Fejér kernel so that it'll aid us in our proof.

Proposition 1.4.1 (Properties of Fejér kernel). *If $\Delta_N(x)$ is as in Definition 1.4.2, then the following hold true*

(a)
$$\Delta_N(x) = 1 + 2\sum_{n=1}^{N}(1 - \frac{n}{N})\cos 2\pi nx$$

(b)
$$\int_0^1 \Delta_N(x)dx = 1$$

(c)
$$\Delta_N(x) = \Delta_N(1 - x)$$

(d) *For $0 \leq \delta \leq \frac{1}{2}$,*
$$\int_\delta^{\frac{1}{2}} \Delta_N(x)dx = \int_{\frac{1}{2}}^{1-\delta} \Delta_N(x)dx$$

and therefore,
$$\int_0^{\frac{1}{2}} \Delta_N(x)dx = \int_{\frac{1}{2}}^1 \Delta_N(x)dx = \frac{1}{2}$$

(e)
$$\Delta_N(x) = \begin{cases} \frac{1}{N}\left(\frac{\sin(\pi Nx)}{\sin(\pi x)}\right)^2, & \text{if } x \notin \mathbb{Z} \\ N, & \text{if } x \in \mathbb{Z} \end{cases}$$

(f) *If $0 \leq x \leq \frac{1}{2}$, then*
$$\Delta_N(x) \leq \min\left(N, \frac{1}{4Nx^2}\right)$$

(g) *If $0 < \delta \leq \frac{1}{2}$, then*
$$\int_\delta^{\frac{1}{2}} \Delta_N(x) < \frac{1}{4N\delta}$$

(h)
$$(\Delta_N * f)(x) = \sigma_N(x)$$

where $\sigma_n(x)$ is the nth Cesáro partial sum of the Fourier series of f as defined in Definition 1.3.2.

Proof.   (a) This follows straight from De Moivre's formula that $e^{ix} = \cos(x) + i\sin(x)$ and $e^{ix} + e^{-ix} = 2\cos(x)$.

(b) By previous result,

$$\Delta_N(x) = 1 + 2\sum_{n=1}^{N}\left(1 - \frac{|n|}{N}\right)\cos(2\pi nx)$$

Therefore,

$$\int_0^1 \Delta_N(x)\,dx = \int_0^1 1\,dx + 2\sum_{n=1}^{N}\left(1 - \frac{|n|}{N}\right)\int_0^1 \cos(2\pi nx)\,dx$$

$$= 1 + 0$$

(c) This follows from the fact that $\cos(2\pi n(1-x)) = \cos(2\pi n - 2\pi nx) = \cos(2\pi nx)$ in the last result.

(d) From Proposition 1.4.1, we know that $\Delta_N(x) = \Delta_N(1-x)$. Therefore by change of variables,

$$\int_\delta^{\frac{1}{2}}\Delta_N(x)dx = \int_\delta^{\frac{1}{2}}\Delta_N(1-x)dx = -\int_{1-\delta}^{\frac{1}{2}}\Delta_N(y)dy = \int_{\frac{1}{2}}^{1-\delta}\Delta_N(y)dy$$

Also from previous result, we know

$$\int_0^{\frac{1}{2}}\Delta_N(x)dx + \int_{\frac{1}{2}}^1\Delta_N(x)dx = \int_0^1\Delta_N(x)dx = 1$$

Hence

$$\int_0^{\frac{1}{2}}\Delta_N(x)dx = \int_{\frac{1}{2}}^1\Delta_N(x)dx = \frac{1}{2}$$

(e) If $x \in \mathbb{N}$ then $e^{2\pi inx} = 1$ for all n and then,

$$\sum_{n=0}^{N-1}e^{2\pi inx} = \sum_{n=0}^{N-1}1 = N$$

Hence the last case is solved. But if $x \notin \mathbb{N}$ then from the finite sum of geometric series,

$$\sum_{n=0}^{N-1} e^{2\pi i n x} = \frac{e^{2\pi i N x} - 1}{e^{2\pi i x} - 1}$$

$$= \frac{e^{\pi i N x}}{e^{\pi i x}} \times \frac{e^{\pi i N x} - e^{-\pi i N x}}{e^{\pi i x} - e^{-\pi i x}}$$

$$= e^{\pi i (N-1)x} \frac{\sin(\pi N x)}{\sin(\pi x)}$$

Since $|e^{ix}| = 1$ for all $x \in \mathbb{R}$, we'll get

$$\left| \sum_{n=0}^{N-1} e^{2\pi i n x} \right|^2 = \frac{\sin^2(\pi N x)}{\sin^2(\pi x)}$$

But we also know that,

$$\left| \sum_{n=0}^{N-1} e^{2\pi i n x} \right|^2 = \left(\sum_{n=0}^{N-1} e^{2\pi i n x} \right) \left(\sum_{n=0}^{N-1} \overline{e^{2\pi i n x}} \right)$$

$$= \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} e^{2\pi i (m-n)x}$$

$$= \sum_{k=-(N-1)}^{N-1} e^{2\pi i k x} \sum_{\substack{0 \le m \le N-1 \\ 0 \le n \le N-1 \\ m-n=k}} 1$$

$$= \sum_{k=-(N-1)}^{N-1} e^{2\pi i k x} (N - |k|)$$

$$= N \Delta_N(x)$$

Which implies that

$$\Delta_N(x) = \frac{1}{N} \frac{\sin^2(\pi N x)}{\sin^2 \pi x}$$

Hence the proposition.

(f) We'll first see that $\sin(\pi x) \ge 2x$ whenever $0 \le x \le \frac{1}{2}$. But this is because the $h(x) := \sin(\pi x) - 2x = 0$ only for $x = 0$ and $x = 2$ and the derivative of h, $h'(x) := \pi \cos(\pi x) - 2 = 0$, only for a unique real number $r \in [0, \frac{1}{2}]$. Now

since f is smooth, f cannot have more roots in $[0, \frac{1}{2}]$. Hence $\sin(\pi x) \geq 2x$ for all $x \in [0, \frac{1}{2}]$

Now we'll get to the main proof. Assume $0 < \delta \leq \frac{1}{2}$. Then by previous result, when $0 < x \leq \frac{1}{2}$,

$$
\begin{aligned}
\Delta_N(x) &= \frac{1}{N} \left(\frac{\sin(\pi N x)}{\sin(\pi x)} \right)^2 \\
&\leq \frac{1}{N \sin^2(\pi x)} \\
&\leq \frac{1}{4 N x^2} \qquad\qquad \text{since } \sin(\pi x) \geq 2x
\end{aligned}
$$

We also know that

$$
\Delta_N(x) = 1 + 2 \sum_{n=1}^{N} \left(1 - \frac{n}{N} \right) \cos(2\pi n x)
$$

But this shows that $\Delta_N(x)$ is maximum when $\cos(2\pi n x)$ is maximum, i.e at $x = 0, 1$. At both cases $\cos(2\pi n x) = 1$. Also

$$
1 + 2 \sum_{n=1}^{N} \left(1 - \frac{n}{N} \right) = 1 + 2N - \frac{2}{N} \sum_{n=1}^{N} n = 1 + 2N - \frac{2}{N} \frac{N(N+1)}{2} = N
$$

Therefore, $\Delta_N(x) \leq N$ for all $0 \leq x \leq 1$ Hence combining this with the result above, we get that while $0 \leq x \leq \frac{1}{2}$

$$
\Delta_N(x) \leq \min \left(N, \frac{1}{4 N x^2} \right)
$$

(g) From last result we know that when $0 < \delta \leq \frac{1}{2}$,

$$
\Delta_N(x) \leq \frac{1}{4 N x^2}
$$

Then,

$$
\int_{\delta}^{\frac{1}{2}} \Delta_N(x) dx \leq \int_{\delta}^{\frac{1}{2}} \frac{1}{4 N x^2} dx \leq \int_{\delta}^{\infty} \frac{1}{4 N x^2} dx = \frac{1}{4 N \delta}
$$

(h)

$$
\begin{aligned}
(\Delta_N * f)(x) &= \int_0^1 \Delta_N(y) f(x-y) \; dy \\
&= \int_0^1 \sum_{n=-N}^N \left(1 - \frac{|n|}{N}\right) e^{2\pi i n y} f(x-y) \; dy \\
&= \sum_{n=-N}^N \left(1 - \frac{|n|}{N}\right) \int_0^1 f(x-y) e^{2\pi i n y} \; dy \\
&= \sum_{n=-N}^N \left(1 - \frac{|n|}{N}\right) e^{2\pi i n x} \int_0^1 f(x-y) e^{-2\pi i n(x-y)} \; dy \\
&= \sum_{n=-N}^N \left(1 - \frac{|n|}{N}\right) e^{2\pi i n x} \int_x^{x-1} -f(v) e^{-2\pi i n v} \; dv \\
&= \sum_{n=-N}^N \left(1 - \frac{|n|}{N}\right) e^{2\pi i n x} \int_{x-1}^x f(v) e^{-2\pi i n v} \; dv \\
&= \sum_{n=-N}^N \left(1 - \frac{|n|}{N}\right) e^{2\pi i n x} \int_0^1 f(v) e^{-2\pi i n v} \; dv \qquad \text{by Lemma 1.1.1} \\
&= \sum_{n=-N}^N \left(1 - \frac{|n|}{N}\right) e^{2\pi i n x} \widehat{f}(n) \\
&= \sigma_N(x)
\end{aligned}
$$

$\square$

Proposition 1.4.2. *Fejér kernel as defined in Definition 1.4.2 is a summability kernel as in Definition 1.4.1*

Proof. To prove that Fejér kernel is a summability kernel, we'll verify the three properties given in Definition 1.4.1.

1. We proved that $\int_0^1 \Delta_N(x) = 1$ at Proposition 1.4.1

2. From Proposition 1.4.1, we know that

$$
\Delta_N(x) = \begin{cases} \frac{1}{N} \left(\frac{\sin(\pi N x)}{\sin(\pi x)}\right)^2, & \text{if } x \notin \mathbb{Z} \\ N, & \text{if } x \in \mathbb{Z} \end{cases}
$$

Since $N \in \mathbb{N}$, this implies $\Delta_N(x) \geq 0$. Therefore,

$$\int_0^1 |\Delta_N(x)| \, dx = \int_0^1 \Delta(x) dx = 1$$

This proves the 2nd condition for the summability kernel.

3. To prove that

$$\lim_{N \to \infty} \int_\delta^{1-\delta} |\Delta_N(x)| \, dx = 0$$

we note that from Proposition 1.4.1 if $0 < \delta \leq \frac{1}{2}$,

$$\int_\delta^{\frac{1}{2}} \Delta_N(x) dx \leq \frac{1}{4N\delta}$$

and

$$\int_{\frac{1}{2}}^{1-\delta} \Delta_N(x) = \int_\delta^{\frac{1}{2}} \Delta_N(x)$$

Hence,

$$\int_\delta^{1-\delta} \Delta_N(x) = \int_\delta^{\frac{1}{2}} \Delta_N(x) + \int_{\frac{1}{2}}^{1-\delta} \Delta_N(x) = 2 \int_\delta^{\frac{1}{2}} \Delta_N(x) \leq \frac{1}{2N\delta}$$

Therefore, for $0 < \delta \leq \frac{1}{2}$, we have

$$\lim_{N \to \infty} \int_\delta^{1-\delta} |\Delta_N(x)| = \lim_{N \to \infty} \int_\delta^{1-\delta} \Delta_N(x) = 0$$

If $\frac{1}{2} < \delta < 1$ then by change of variable $y = 1 - x$

$$\lim_{N \to \infty} \int_\delta^{1-\delta} \Delta_N(x) = \lim_{N \to \infty} - \int_{1-\delta}^\delta \Delta_n(y) = 0$$

And therefore for all $0 < \delta < 1$

$$\lim_{N \to \infty} \int_\delta^{1-\delta} |\Delta_N(x)| = 0$$

Which completes the proof that Fejér kernel is a summability kernel.

$\square$

1.5   Convergence of Fourier Series

Now with the help of summability kernels and convolution we'll prove an important theorem which will serve as a backbone for the discussion of convergence forward.

Theorem 1.5.1 (Convergence to convolution of summability kernels). *If $f \in L^1(\mathbb{T})$ and K_N is a summability kernel then $f * K_N$ converges to f in L^1 norm. That is*

$$\lim_{N \to \infty} \int_0^1 |f(x) - (f * K_N)(x))| = 0$$

Proof.

$$f * K_N(x) = \int_0^1 f(x - y)K_N(y)dy$$

Since $\int_0^1 K_N(y)dy = 1$, by the 2nd property of summability kernel,

$$f(x) - f * K_N(x) = \int_0^1 (f(x) - f(x - y)) K_N(y)dx$$

Now then,

$$\int_0^1 |f(x) - K_N(x)|dx = \int_0^1 \left| \int_0^1 (f(x) - f(x - y))K_N(y)dy \right| dx$$

$$\leq \int_0^1 \int_0^1 |f(x) - f(x - y)K_N(y)| \, dy \, dx$$

$$= \int_0^1 |K_N(y)| \int_0^1 |f(x) - f(x - y)|dx \, dy$$

$$= \int_{-\delta}^{1-\delta} \qquad\qquad \text{by lemma 1.1.1}$$

$$= \int_{-\delta}^{\delta} + \int_{\delta}^{1-\delta} = I_1 + I_2$$

Note that the change of order of integration above is justified by Tonelli's theorem, since the space if of finite measure. We'll show that for a given ϵ we can find an N such that for all $n > N$, $I_1 + I_2 < \epsilon$

Since $f \in L^1(\mathbb{T})$ we can find $\delta > 0$ such that $\int_0^1 |f(x + \delta) - f(x)|dx = \epsilon/2C$, where C is the constant in the second condition of summability kernel. The proof can be found in any measure theory textbook.

Then,

$$|I_1| \leq \frac{\epsilon}{2C} \int_{-\delta}^{\delta} |K_N(y)| dy \leq \frac{\epsilon}{2C} \int_0^1 |K_N(y)| dy \leq \frac{\epsilon}{2}$$

For I_2, we see that

$$\int_0^1 |f(x) - f(x-y)| dx \leq \int_0^1 |f(x)| dx + \int_0^1 |f(x-y)| dx = 2\|f\|_1$$

Then,

$$|I_2| \leq 2\|f\|_1 \int_{\delta}^{1-\delta} |K_N(y)| dy$$

But by the 3rd property of the summability kernel, we know that the integral in the above converges to zero. Therefore there exists an N such that for an $n > N, |I_2| < \epsilon/2$, which completes our proof. $\qquad\square$

Corollary 1.5.1.1. *Convergence of Cesáro sum of functions in $L^1(\mathbb{T})$ If $f \in L^1(\mathbb{T})$ then $\sigma_N(x)$, the Cesáro sum of the Fourier series of f converge to $f(x)$ in L^1 norm. That is,*

$$\lim_{N\to\infty} \int_0^1 |f(x) - \sigma_N(x)| = 0$$

Proof. Since we know that Fejér kernel, $\Delta_N(x)$ is a summability kernel by proposition 1.4.2 and that $(\Delta_N * f)(x) = \sigma_N(x)$ by prop 1.4.1, the result follows from theorem 1.5.1. $\qquad\square$

Theorem 1.5.2 (Fejér's Theorem). *Let $f \in L^1(\mathbb{T})$ and $f(a^-) = \lim_{x\to a^-} f(x)$ and $f(a^+) = \lim_{x\to a^+} f(x)$ exist and are finite, then*

$$\lim_{N\to\infty} \sigma_N(x) = \frac{f(x^-) + f(x^+)}{2}$$

Proof. Let ϵ be given. Since we assumed $f(x^+)$ and $f(x^-)$ exist and are finite, we can take $\delta < \frac{1}{2}$ small enough such that $|f(x-u) - f(x^-)| < \epsilon$ for $0 \leq u \leq \delta$ and $|f(x-u) - f(x^+)| < \epsilon$ for $1 - \delta \leq u \leq 1$. Notice that while the bounds for u seems obvious for $f(x^-)$, for $f(x^+)$ we are using the fact that f is periodic with period 1, and hence f has the same value in $[1-\delta, 1]$, and $[-\delta, 0]$.

$$\sigma_N(x) = \int_0^1 f(x-u)\Delta_N(u)du = \int_0^{\delta} + \int_{\delta}^{1-\delta} + \int_{1-\delta}^1 = I_1 + I_2 + I_3$$

Then,

$$I_1 = \int_0^{\delta} (f(x-u) - f(x^-))\Delta_N(u)du + \int_0^{\delta} f(x^-)\Delta_N(u)du = T_1 + T_1^{'}$$

where by the property of summability kernels as in 1.4.1, and by our choice of δ, we have

$$|T_1| \leq \int_0^\delta |f(x-u) - f(x^-)|\Delta_N(u)du < \epsilon \int_0^\delta \Delta_N(x) \leq \epsilon$$

Therefore T_1 converge to 0 as $N \to \infty$.

Again, from the proposition 1.4.1, we get

$$\frac{1}{2} \geq \int_0^\delta \Delta_N(x)dx = \int_0^{\frac{1}{2}} \Delta_N(x)dx - \int_\delta^{\frac{1}{2}} \Delta_N(x)dx \geq \frac{1}{2} - \frac{1}{4N\delta}$$

which then implies that,

$$\frac{f(x^-)}{2} \geq T_1' = f(x^-)\int_0^\delta \Delta_N(x)dx \geq \frac{f(x^-)}{2} - \frac{f(x^-)}{4N\delta}$$

Therefore,

$$0 \geq T_1' - \frac{f(x^-)}{2} \geq -\frac{f(x^-)}{4N\delta}$$

and hence,

$$\left| T_1' - \frac{f(x^-)}{2} \right| \leq \left| \frac{f(x^-)}{4N\delta} \right|$$

which implies that $I_1 = T_1 + T_1'$ converge to $\frac{f(x^-)}{2}$ as $N \to \infty$.

Now by proposition 1.4.1 we know that if $0 < x \leq \frac{1}{2}$, then

$$\Delta_N(x) \leq \frac{1}{4Nx^2}$$

which implies that

$$|I_2| \leq \frac{1}{4N\delta^2} \int_\delta^{1-\delta} f(x-u)du \leq \frac{1}{4N\delta^2} \int_0^1 |f(u)|du = \frac{\|f\|_1}{4N\delta^2}$$

Therefore I_2 converge to 0 as $N \to \infty$

Now we'll prove that I_3 converge to $\frac{f(x^+)}{2}$. For this we'll split I_3 into T_3 and T_3' like we did with I_1.

$$I_3 = \int_{1-\delta}^1 (f(x-u) - f(x^+))\Delta_N(u)du + f(x^+)\int_{1-\delta}^1 \Delta_N(u)du = T_3 + T_3'$$

Then by our choice of δ,

$$|T_3| \leq \int_{1-\delta}^1 |((f(x-u) - f(x^+))|\Delta_N(u)du < \epsilon \int_{1-\delta}^1 \Delta_N(x)dx \leq \epsilon$$

Therefore T_3 converge to 0 as $N \to \infty$. Also

$$\int_{1-\delta}^{1} \Delta_N(x)dx = -\int_{\delta}^{0} \Delta_N(x)dx = \int_{0}^{\delta} \Delta_N(x)dx$$

Therefore by the same inequality we used for T_1' from proposition 1.4.1, we'll get

$$\left| T_3' - \frac{f(x^+)}{2} \right| \leq \left| \frac{f(x^+)}{4N\delta} \right|$$

which implies that $I_3 = T_3 + T_3'$ converge to $\frac{f(x^+)}{2}$ as $N \to \infty$

Therefore since $\sigma_N(x) = I_1 + I_2 + I_3$, by the algebra of limits,

$$\lim_{N \to \infty} \sigma_N(x) = \frac{f(x^-) + f(x^+)}{2}$$

$\square$

Theorem 1.5.3 (Hardy Tauberian Theorem)**.** *Let $\sum_{n=1}^{\infty} a_n$ is Cesáro summable to a, then if there exist a constant C such that*

$$|a_n| \leq \frac{C}{n}$$

for all n, then the series $\sum_{n=1}^{\infty} a_n$ converge to a

Chapter 2

Fourier Series in $L^p(\mathbb{T})$

Before we go into the general L^p, we'll first recall some importatnt results from functional analysis which are essential for the discussion of further topics.

Recall that in Definition 1.1.1, we've discussed what is an L^p function for a general space S. Here the space is $\mathbb{T}$ and $L^p(\mathbb{T})$ are precisely the set of all L^p functions in $\mathbb{T}$.

Theorem 2.0.1 (Holder's Inequality). *Let $1 \leq p \leq \infty$ and q such that $1/p + 1/q = 1$ (for convention we will assume that the tuples $(1, \infty)$, and $(\infty, 1)$, satify the above relation) then for lebesgue measure space S and functions $f \in L^p(S)$, and $g \in L^q(S)$*

$$\left| \int_S f(x)g(x)dx \right| \leq \|f\|_p \|g\|_q$$

where

$$\|f\|_p = \left(\int_s |f(x)|^p \right)^{\frac{1}{p}}$$

as in Definition 1.1.1.

Theorem 2.0.2 (Minkowski's Inequality). *Let $1 \leq p \leq \infty$ then for a lebesgue measure space S and a fucntion $f \in L^p(S)$, then*

$$\|f + g\|_p \leq \|f\|_p + \|g\|_p$$

The proofs of the above two theorems can be found in any measure theory textbook and since it is a common proof, we'll ommit it from detailing it here.

2.1   Fourier Series in $L^2(\mathbb{T})$

Before we proceed with the fourier coefficients and fourier series for $L^2(\mathbb{T})$ functions we first prove some important results.

Proposition 2.1.1. *If $f \in L^2(\mathbb{T})$, then*

$$\lim_{\delta \to 0} \int_0^1 |f(x+\delta) - f(x)|^2 dx = 0$$

Proof. From measure theory we know that continuous functions are dense in $L^2(\mathbb{T})$. Then given any ϵ there exists a function $g \in C(\mathbb{T})$ such that $\|f - g\|_2 < \epsilon$. Then,

$$f(x+\delta) - f(x) = (f(x+\delta) - g(x+\delta)) - (f(x) - g(x)) + (g(x+\delta) - g(x))$$

Now by triangle inequality, (i.e minkowski's inequality for $p = 2$),

$$\|f(x+\delta) - f(x)\|_2 = \|f(x+\delta) - g(x+\delta)\|_2 - \|f(x) - g(x)\|_2 + \|g(x+\delta) - g(x)\|_2$$

Now since g is continuous on $\mathbb{T}$ it is uniformly continuous (since it is continuous on $\mathbb{R}$, it'll be continuous on $[0, 1]$, a compact set) and therefore δ can be taken such that $\|g(x+\delta) - g(x)\|_2 < \epsilon$. Hence the theorem. □

Proposition 2.1.2. *If $f, g \in L^2(\mathbb{T})$, then their convolution, $f * g$ is continuous and moreover $\|f * g\|_\infty \le \|f\|_2 \|g\|_2$*

Proof.

$$(f * g)(x+\delta) - (f * g)(x) = \int_0^1 f(u)(g(x+\delta-u) - g(x-u))du$$

Therefore by Cauchy Shwarz inequality,

$$|f * g(x+\delta) - f * g(x)| = \left| \int_0^1 f(u)(g(x+\delta-u) - g(x-u))du \right|$$

$$\le \|f\|_2 \left(\int_0^1 |g(x+\delta-u) - g(x-u)|^2 du \right)^{1/2}$$

which converge to zero as $\delta \to 0$ by Proposition 2.1.1. Therefore $f*g$ is continuous in $\mathbb{T}$. Also,

$$|f*g(x)| = \left| \int_0^1 f(u)g(x-u)du \right|$$
$$\leq \left(\int_0^1 |f(u)|^2 du \right)^{1/2} \left(\int_0^1 |g(u)|^2 du \right)^{1/2}$$
$$= \|f\|_2 \|g\|_2$$

Hence the theorem. $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\square$

Now that we've proved some important results, we'll define the fourier coeffients $\hat{f}(n)$ the same way we defined them for $L^1(\mathbb{T})$ in Definition 1.1.4 as

$$\hat{f}(n) = \int_0^1 f(x)e^{-2\pi inx}dx$$

Note that $\hat{f}(n)$ is a finite quantity since $|e^{ix}| = 1$ and,

$$|\hat{f}(n)| = \left| \int_0^1 f(x)e^{-2\pi inx}dx \right| \leq \|f\|_2 \left(\int_0^1 |e^{-2\pi inx}|^2 dx \right)^{1/2} = \|f\|_2$$

Hence we define the fourier series the same way as in Definition 1.1.5. Then we'll investigate if the Fourier series of $L^2(\mathbb{T})$ functions are Cesáro summable to f. In fact this is true.

Theorem 2.1.1 (Fourier series of $L^2(\mathbb{T})$ functions are Cesáro summable)**.** *If* $f \in L^2(\mathbb{T})$, *and* $\sigma_N(x)$ *is the* N^{th} *Cesáro partial sum of the Fourier series of* f, *then*

$$\lim_{N\to\infty} \int_0^1 |f(x) - \sigma_N(x)|^2 \ dx = 0$$

Proof. From Proposition 1.4.1 we know that

$$\sigma_N(x) = \int_0^1 \Delta_N(u)f(x-u) \ du$$

Hence,

$$f(x) - \sigma_N(x) = \int_0^1 (f(x) - f(x-u))\Delta_N(u) \ du$$

By Holder's inequality in Theorem 2.0.1 applied to $(f(x) - f(x - u))\sqrt{\Delta_N(u)}$ and $\sqrt{\Delta_N(u)}$

$$
|f(x) - \sigma_N(x)| = \left| \int_0^1 (f(x) - f(x - u))\Delta_N(u) \right| \, du
$$

$$
\leq \left(\int_0^1 |f(x) - f(x - u)|^2 \Delta_N(u) \, du \right)^{1/2} \left(\int_0^1 \Delta_N(u) \, du \right)^{1/2}
$$

Since by Proposition 1.4.1, $\int_0^1 \Delta_N(x)dx = 1$ and by Tonelli's theorem,

$$
\int_0^1 |f(x) - \sigma_N(x)|^2 dx = \int_0^1 \int_0^1 |f(x) - f(x - u)|^2 \Delta_N(u) \, du \, dx
$$

$$
= \int_0^1 \Delta_N(u) \int_0^1 |f(x) - f(x - u)|^2 \, dx \, du
$$

$$
= \int_{-\delta}^{\delta} + \int_{\delta}^{1-\delta}
$$

$$
= I_1 + I_2
$$

Also from Proposition 2.1.1, given ϵ, we can find δ such that

$$
\int_0^1 |f(x) - f(x - \delta)|^2 \, dx < \epsilon
$$

Then for that choice of δ,

$$
|I_1| \leq \epsilon \int_{-\delta}^{\delta} \Delta_N(u)du \leq \epsilon \int_0^1 \Delta_N(u)du = \epsilon
$$

To prove I_2 is also bounded, we'll use a small trick aided by Minkowski's inequality. We know that $\|f - g\|_p \leq \|f\|_p + \|g\|_p$. Therefore $\|f - g\|_p \leq 2\max\{\|f\|_p, \|g\|_p\}$ and $\|f - g\|_p^p \leq 2\max\{\|f\|_p^p, \|g\|_p^p\}$, and finally, $\|f - g\|_p^p \leq 2(\|f\|_p^p + \|g\|_p^p)$.Then for $p = 2$,

$$
\int_0^1 |f(x) - f(x - u)|^2 dx \leq 2(\|f\|_2^2 + \|f\|_2^2) = 4\|f\|_2^2
$$

Therefore by Proposition 1.4.1, we get

$$
|I_2| = \int_{\delta}^{1-\delta} \Delta_N(u) \int_0^1 |f(x) - f(x - u)|^2 \, dx \, du \leq 4\|f\|_2^2 \int_{\delta}^{1-\delta} \Delta_N(u)du
$$

But by Proposition 1.4.1

$$\int_{\delta}^{1-\delta} \Delta_N(u)du = 2\int_{\delta}^{1/2} \Delta_N(x) \leq \frac{1}{2N\delta}$$

Which implies,

$$|I_2| \leq \frac{2\|f\|_2^2}{N\delta}$$

Therefore I_2 converge to 0 as $N \to \infty$. Hence the theorem. $\qquad\square$

2.2 Fourier Series in $L^p(\mathbb{T})$

Proposition 2.2.1. *If $f \in L^p(\mathbb{T})$, then*

$$\lim_{\delta \to 0} \int_0^1 |f(x+\delta) - f(x)|^p dx = 0$$

Proof. From measure theory we know that continuous functions are dense in $L^p(\mathbb{T})$. Then given any ϵ there exists a function $g \in C(\mathbb{T})$ such that $\|f - g\|_p < \epsilon$. Then,

$$f(x+\delta) - f(x) = (f(x+\delta) - g(x+\delta)) - (f(x) - g(x)) + (g(x+\delta) - g(x))$$

Now by triangle inequality, (i.e minkowski's inequality for $p = 2$),

$$\|f(x+\delta) - f(x)\|_p = \|f(x+\delta) - g(x+\delta)\|_p - \|f(x) - g(x)\|_p + \|g(x+\delta) - g(x)\|_p$$

Now since g is continuous on $\mathbb{T}$ it is uniformly continuous (since it is continuous on $\mathbb{R}$, it'll be continuous on $[0,1]$, a compact set) and therefore δ can be taken such that $\|g(x+\delta) - g(x)\|_p < \epsilon$. Hence the theorem. $\qquad\square$

Proposition 2.2.2. *If $f \in L^p(\mathbb{T})$ and $g \in L^q(\mathbb{T})$, then their convolution, $f * g$ is continuous and moreover $\|f * g\|_\infty \leq \|f\|_p \|g\|_q$*

Proof.

$$(f * g)(x+\delta) - (f * g)(x) = \int_0^1 f(u)(g(x+\delta - u) - g(x-u))du$$

Therefore by Minkowski's inequality from Theorem 2.0.2,

$$|f * g(x+\delta) - f * g(x)| = \left|\int_0^1 f(u)(g(x+\delta - u) - g(x-u))du\right|$$

$$\leq \|f\|_p \left(\int_0^1 |g(x+\delta - u) - g(x-u)|^q du\right)^{1/q}$$

which converge to zero as $\delta \to 0$ by Proposition 2.2.1. Therefore $f * g$ is continuous in $\mathbb{T}$. Also,

$$
\begin{aligned}
|f * g(x)| &= \left| \int_0^1 f(u)g(x - u)du \right| \\
&\leq \left(\int_0^1 |f(u)|^p du \right)^{1/p} \left(\int_0^1 |g(u)|^q du \right)^{1/q} \\
&= \|f\|_p \|g\|_q
\end{aligned}
$$

Hence the theorem. $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $\square$

Now that we've proved some important results, we'll define the fourier coeffients $\widehat{f}(n)$ the same way we defined them for $L^1(\mathbb{T})$ in Definition 1.1.4 as

$$
\hat{f}(n) = \int_0^1 f(x)e^{-2\pi inx}dx
$$

Note that $\widehat{f}(n)$ is a finite quantity since $|e^{ix}| = 1$ and,

$$
|\widehat{f}(n)| = \left| \int_0^1 f(x)e^{-2\pi inx}dx \right| \leq \|f\|_p \left(\int_0^1 |e^{-2\pi inx}|^q dx \right)^{1/q} = \|f\|_p
$$

where $1/p + 1/q = 1$.

Hence we define the fourier series the same way as in Definition 1.1.5. Then we'll investigate if the Fourier series of $L^p(\mathbb{T})$ functions are Cesáro summable to f. In fact this is true.

Theorem 2.2.1 (Fourier series of $L^p(\mathbb{T})$ functions are Cesáro summable). *If $f \in L^p(\mathbb{T})$, and $\sigma_N(x)$ is the Nth Cesáro partial sum of the Fourier series of f, then*

$$
\lim_{N \to \infty} \int_0^1 |f(x) - \sigma_N(x)|^p \; dx = 0
$$

Proof. From Proposition 1.4.1 we know that

$$
\sigma_N(x) = \int_0^1 \Delta_N(u)f(x - u) \; du
$$

Hence,

$$
f(x) - \sigma_N(x) = \int_0^1 (f(x) - f(x - u))\Delta_N(u) \; du
$$

By Holder's inequality as in Theorem 2.0.1 applied to $(f(x)-f(x-u))(\Delta_N(u))^{1/p}$ and $(\Delta_N(u))^{1/q}$

$$|f(x) - \sigma_N(x)| = \left| \int_0^1 (f(x) - f(x-u))\Delta_N(u) \right| du$$

$$\leq \left(\int_0^1 |f(x) - f(x-u)|^p \Delta_N(u) \, du \right)^{1/p} \left(\int_0^1 \Delta_N(u) \, du \right)^{1/q}$$

Since by Proposition 1.4.1, $\int_0^1 \Delta_N(x)dx = 1$ and by Tonelli's theorem,

$$\int_0^1 |f(x) - \sigma_N(x)|^2 dx = \int_0^1 \int_0^1 |f(x) - f(x-u)|^p \Delta_N(u) \, du \, dx$$

$$= \int_0^1 \Delta_N(u) \int_0^1 |f(x) - f(x-u)|^p \, dx \, du$$

$$= \int_{-\delta}^{\delta} + \int_{\delta}^{1-\delta}$$

$$= I_1 + I_2$$

Also from Proposition 2.2.1, given ϵ, we can find δ such that

$$\int_0^1 |f(x) - f(x-\delta)|^p \, dx < \epsilon$$

Then for that choice of δ,

$$|I_1| \leq \epsilon \int_{-\delta}^{\delta} \Delta_N(u)du \leq \epsilon \int_0^1 \Delta_N(u)du = \epsilon$$

To prove I_2 is also bounded, we'll use a small trick aided by Minkowski's inequality. We know that $\|f - g\|_p \leq \|f\|_p + \|g\|_p$. Therefore $\|f - g\|_p \leq 2 \max\{\|f\|_p, \|g\|_p\}$ and $\|f - g\|_p^p \leq 2 \max\{\|f\|_p^p, \|g\|_p^p\}$, and finally, $\|f - g\|_p^p \leq 2(\|f\|_p^p + \|g\|_p^p)$. Then,

$$\int_0^1 |f(x) - f(x-u)|^p dx \leq 2(\|f\|_p^p + \|f\|_p^p) = 4\|f\|_p^p$$

Therefore by Proposition 1.4.1, we get

$$|I_2| = \int_{\delta}^{1-\delta} \Delta_N(u) \int_0^1 |f(x) - f(x-u)|^p \, dx \, du \leq 4\|f\|_p^p \int_{\delta}^{1-\delta} \Delta_N(u)du$$

But by Proposition 1.4.1

$$\int_{\delta}^{1-\delta} \Delta_N(u)du = 2\int_{\delta}^{1/2} \Delta_N(x) \leq \frac{1}{2N\delta}$$

Which implies,

$$|I_2| \leq \frac{2\|f\|_p^p}{N\delta}$$

Therefore I_2 converge to 0 as $N \to \infty$. Hence the theorem.   □

If looked close enough one can see that the proof of convergence of fourier series in $L^p(\mathbb{T})$ is almost the same as in $L^2(\mathbb{T})$. This is in fact true and L^2 convergence is just a special case of L^p convergence.

Chapter 3

Fourier Transform

3.1 Definiton and basic properties

While defining Fourier series we were mainly focused on periodic functions. Now we'll try to expand that into another set of functions. We'll be interested on functions in $L^1(\mathbb{R})$, that is those real or complex valued functions $f(x)$ in $\mathbb{R}$ for which

$$\int_{-\infty}^{\infty} |f(x)| \, dx < \infty$$

. For those functions in $L^1(\mathbb{R})$ the integral above will be called the L^1 norm of the function f and will be denoted by $\|f\|_{L^1(\mathbb{R})}$ or in short $\|f\|_1$. Also note that the notations $\int_{\mathbb{R}}$ and $\int_{-\infty}^{\infty}$ means the same and we might use them interchangably as we see fit.

Analogous to what we did in finding the nth fourier coefficient in Definition 1.1.4, we'll define the fourier transform of f

Definition 3.1.1 (Fourier transform of a function f)**.** Let $f \in L^1(\mathbb{R})$, then we define the Fourier transform of f, $\widehat{f} : \mathbb{R} \to \mathbb{C}$ as

$$\widehat{f}(t) = \int_{\mathbb{R}} f(x) e^{-2\pi i t x} \, dx$$

Note that while we say $\widehat{f}$ is the Fourier transform of the function f, the term "Fourier transform" is also used for the map which takes f to $\widehat{f}$.

Also note that $\widehat{f}(t)$ is a finite quantity (real or complex) for all $t \in \mathbb{T}$ since $f \in L^1(\mathbb{T})$ and $|e^{-2\pi i t x}| = 1$ implies

$$|\widehat{f}(t)| \leq \int_{-\infty}^{\infty} |f(x)| \, dx < \infty$$

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This shows that the fourier transform of a function in $L^1(\mathbb{R})$ is in $L^\infty(\mathbb{R})$. We state this as a seperate result.

Proposition 3.1.1. *If $f \in L^1(\mathbb{R})$, then $\widehat{f} \in L^\infty(\mathbb{R})$, i.e*

$$\sup_{t \in \mathbb{R}} |\widehat{f}(t)| \leq \infty$$

.

By the linearity of the integral we can also show that for functions $f, g \in L^2(\mathbb{R})$ and scalars μ, ν, $\widehat{\mu f + \nu g}(t) = \mu \widehat{f}(t) + \nu \widehat{g}(t)$.

Now we'll prove some important properties of Fourier transforms. Note that this will almost remind you of the properties of Fourier coefficinets in Proposition 1.1.1.

Proposition 3.1.2 (Properties of Fourier transform). *If $f \in L^1(\mathbb{R})$ and $\widehat{f}$ is the Fourier tranform of f as in Definition 3.1.1, then*

(a) *If $a \in \mathbb{R}$ and $g(x) = f(x + a)$ for all $x \in \mathbb{R}$, then $g \in L^1(\mathbb{R})$ and $\widehat{g}(t) = e^{2\pi i t a} \widehat{f}(t)$ for all t.*

(b) *If $b \in \mathbb{R}$ and $h(x) = e^{2\pi i b x} f(x)$, then $h \in L^1(\mathbb{R})$ and $\widehat{h}(t) = \widehat{f}(t - b)$ for all t.*

(c) *If $c \in \mathbb{R}$ is not 0, and $j(x) = f(cx)$, then $j \in L^1(\mathbb{R})$ and $\widehat{j}(t) = \frac{\widehat{f}(t/c)}{|c|}$ for all t.*

(d) *if $l(x) = \overline{f(x)}$, then $l \in L^1(\mathbb{R})$ and $\widehat{l}(t) = \overline{\widehat{f}(-t)}$*

Proof. Note that by appropriate change of variable we can see that all the above functions g, h, j, l are in $L^1(\mathbb{R})$. We'll prove the other properties.

(a) By the change of variable $y = x + a$, we get that

$$\widehat{g}(t) = \int_{\mathbb{R}} g(x)e^{-2\pi i t x} \, dx = \int_{\mathbb{R}} f(x+a)e^{-2\pi i t x} \, dx = e^{2\pi i t a} \int_{\mathbb{R}} f(y)e^{-2\pi i t y} \, dy$$

which is equal to $e^{2\pi i t a} \widehat{f}(t)$

(b)
$$\widehat{h}(t) = \int_{\mathbb{R}} h(x)e^{-2\pi i t x} \, dx = \int_{\mathbb{R}} f(x)e^{-2\pi i (t-b)x} \, dx = \widehat{f}(t - b)$$

(c) Here we'll need to be careful because c maybe negative.Assume $c > 0$, then by a change of variable $y = cx$, we get

$$\widehat{j}(t) = \int_{-\infty}^{\infty} j(x)e^{-2\pi itx} \ dx = \int_{-\infty}^{\infty} f(cx)e^{-2\pi itx} \ dx = \frac{1}{c}\int_{-\infty}^{\infty} f(y)e^{-2\pi i\frac{t}{c}y}$$

Then if $c > 0$, $\widehat{j}(t) = \frac{\widehat{f}(t/c)}{c}$. Now if $c < 0$ the limits of integration will reverse, i.e

$$\int_{-\infty}^{\infty} f(cx)e^{-2\pi itx} \ dx = \frac{1}{c}\int_{\infty}^{-\infty} f(y)e^{-2\pi i\frac{t}{c}y} \ dx = \frac{1}{-c}\int_{-\infty}^{\infty} f(y)e^{-2\pi i\frac{t}{c}y} \ dx$$

Which shows that if $c \neq 0$, $\widehat{j}(t) = \frac{\widehat{f}(t/c)}{|c|}$.

(d) Since we know that integral of the conjugate is the conjugate of the integral,

$$\widehat{l}(t) = \int_{\mathbb{R}} \overline{f(x)}e^{-2\pi itx} = \int_{\mathbb{R}} \overline{f(x)e^{-2\pi i(-t)x}} = \overline{\int_{\mathbb{R}} f(x)e^{-2\pi i(-t)x}} = \overline{\widehat{f}(-t)}$$

$\square$

Now we prove another important result from measure theory.

Proposition 3.1.3. *If $f \in L^1(\mathbb{R})$, then*

$$\lim_{\delta \to 0} \int_{\mathbb{R}} |f(x+\delta) - f(x)| \ dx = 0$$

Proof. Since $f \in L^1(\mathbb{R})$, there exists an X such that

$$\int_{|x|>X-1} |f(x)| \ dx < \epsilon$$

Then by triangle inequality, for $\delta \leq 1$,

$$\int_{\mathbb{R}} |f(x+\delta) - f(x)| \ dx \leq \int_{-X}^{X} |f(x+\delta) - f(x)| \ dx + 2\epsilon$$

Now since $f \in L^1(\mathbb{R})$ and continuous functions are dense in L^1 norm in compact intervals, there exists a $g \in C([-X-1, X+1]) \cap L^1([-X, X])$ such that for any given ϵ,

$$\int_{-X-1}^{X+1} |f(x) - g(x)| \ dx < \epsilon$$

Then by triangle inequality

$$\int_{-X}^{X} |f(x+\delta) - f(x)| \ dx \le \int_{-X}^{X} |g(x+\delta) - g(x)| \ dx + 2\epsilon$$

. Morever since g is continuous on $[-X-1, X+1]$, it is uniformly continuous on the interval and hence the integral tends to 0 as $\delta \to 0$. Hence the proof.   □

Using the above result we'll prove an important theorem

Theorem 3.1.1 (Riemann Lebesgue Lemma). *Let $f \in L^1(\mathbb{R})$. Then*

$$\lim_{t \to \pm\infty} \widehat{f}(t) = 0$$

Proof. We know that

$$\widehat{f}(t) = \int_{\mathbb{R}} f(x)e^{-2\pi itx} \ dx$$

By change of variables $x = y + \frac{1}{2t}$, we see that the above equation becomes

$$\widehat{f}(t) = \int_{\mathbb{R}} f(y + \frac{1}{2t})e^{-2\pi it(y + \frac{1}{2t})} \ dy = -\int_{\mathbb{R}} f(y + \frac{1}{2t})e^{-2\pi it(y)} \ dy$$

Therefore

$$2\widehat{f}(t) = \int_{\mathbb{R}} (f(x + \frac{1}{2t}) - f(x))e^{-2\pi itx} \ dx$$

and therefore

$$\left| \widehat{f}(t) \right| \le \frac{1}{2} \int_{\mathbb{R}} |f(x + \frac{1}{2t}) - f(x)| dx$$

Now by Proposition 3.1.3 as $t \to \infty$, $\frac{1}{2t} \to 0$ and therefore $\widehat{f}(t) \to 0$. Hence proved.   □

Convolution was one important operation which helped us in the theory of Fourier series. We will define the convolution of two functions in $L^1(\mathbb{R})$ the same way we defined it for functions in $L^1(\mathbb{T})$ in Definition 1.2.1. That is if $f, g \in L^1(\mathbb{R})$, we define the convolution of f and g as

$$(f * g)(x) = \int_{\mathbb{R}} f(x - y)g(y)dy$$

But unlike $L^1(\mathbb{T})$, $L^1(\mathbb{R})$ is not finite measure space. So we'll need to make sure this definition of convolution is well defined for functions in $L^1(\mathbb{R})$.

Proposition 3.1.4. *For functions $f, g \in L^1(\mathbb{R})$, $f(x-y)g(y)$ is Lebesgue measurable in the product space $\mathbb{R}^2$. Moreover $f(x-y)g(y) \in L^1(\mathbb{R}^2)$. And therefore by Fubini's theorem $\int_{\mathbb{R}} f(x-y)g(y)dx$ exists and is well defined for all $x \in \mathbb{R}$.*

Proof. Consider $h, k : \mathbb{R}^2 \to \mathbb{R}$ defined as $h(x, y) = f(x)$ and $k(x, y) = g(x)$. Then $h^{-1}(a, \infty) = f^{-1}(a, \infty) \times \mathbb{R}$ and $k^{-1}(b, \infty) = \mathbb{R} \times g^{-1}(b, \infty)$ and therefore h, k are measurable functions. Moreover we know from the theory of measurable functions that the product of measurable functions is measurable. Therefore $F(x, y) = h(x, y)k(x, y) = f(x)g(y)$ is measurable. Also the map $T(x, y) = (x - y, y)$ is linear. Hence $H(x, y) = F \circ T(x, y) = f(x-y)g(y)$ is measurable.

Also $H \in L^1(\mathbb{R}^2)$ implies

$$\int_{\mathbb{R}^2} |H(x,y)| \, dx \, dy = \int_{\mathbb{R}} \left(\int_{\mathbb{R}} |f(x-y)| \, dx \right) |g(y)| \, dy = \int_{\mathbb{R}} \|f\|_1 |g(y)| \, dy = \|f\|_1 \|g\|_1$$

Hence $f(x-y)g(y) \in L^1(\mathbb{R}^2)$ and the result follows.

$\square$

Almost all the properties of the convolution in $L^1(\mathbb{T})$ has its analogues in $L^1(\mathbb{R})$, but we will only quote the most important one, that is the convolution is commutative, $f * g = g * f$. One can easily prove this using a change of variable like we did in Proposition 1.2.1

We'll also prove that for functions $f, g \in L^1(\mathbb{R})$, $f * g \in L^1(\mathbb{R})$.

Proposition 3.1.5. *Let $f, g \in L^1(\mathbb{R})$, then $f * g \in L^1(\mathbb{R})$ and $\widehat{f * g}(t) = \widehat{f}(t)\widehat{g}(t)$.*

Proof. By the definition of the convolution of f and g,

$$\int_{\mathbb{R}} |(f * g)(x)| dx = \int_{\mathbb{R}} \left| \int_{\mathbb{R}} f(x-y)g(y) \, dy \right| \, dx$$
$$\leq \int_{\mathbb{R}} \int_{\mathbb{R}} |f(x-y)g(y)| \, dy \, dx$$

Now by Fubini's theorem we know that last integral is equal to

$$\int_{\mathbb{R}^2} f(x-y)g(y)$$

and by previous theorem it is less than or equal to $\|f\|_1 \|g\|_1$.

For the fourier transform

$$
\begin{aligned}
\widehat{f * g}(t) &= \int_{\mathbb{R}} \widehat{f * g}(x) e^{-2\pi itx} \, dx \\
&= \int_{\mathbb{R}} \int_{\mathbb{R}} f(x - y) g(y) e^{-2\pi itx} \, dy \, dx \\
&= \int_{\mathbb{R}} g(y) e^{-2\pi ity} \int_{\mathbb{R}} f(x - y) e^{-2\pi it(x-y)} \, dx \, dy \\
&= \int_{\mathbb{R}} g(y) e^{-2\pi ity} \widehat{f}(t) dy \\
&= \widehat{f}(t) \widehat{g}(t)
\end{aligned}
$$

Note that the change of variable is justified since we know that for all $x \in \mathbb{R}$, $|e^{-2\pi itx}| = 1$ and hence the integral is absolutely convergent by the proof similar to last theorem. $\qquad\square$

Now we'll prove a result which has close relations with the Plancherel's theorem we'll prove in Theorem 3.4.1. We'll use this result to prove some propoerties of the Poisson Kernel in Proposition 3.2.2

Proposition 3.1.6. *Let $f, g \in L^1(\mathbb{R})$, then*

$$
\int_{\mathbb{R}} \widehat{f}(t) g(t) \, dt = \int_{\mathbb{R}} f(t) \widehat{g}(t) \, dt
$$

Proof. Since $f, g \in L^1(\mathbb{R})$ from Proposition 3.1.1 we get that $\widehat{f}, \widehat{g} \in L^\infty(\mathbb{R})$. Then we get that

$$
\begin{aligned}
\int_{\mathbb{R}} \widehat{f}(t) g(t) \, dt &= \int_{\mathbb{R}} g(t) \int_{\mathbb{R}} f(x) e^{-2\pi itx} \, dx \, dt \\
&= \int_{\mathbb{R}} f(x) \int_{\mathbb{R}} g(t) e^{-2\pi itx} \, dt \, dx \\
&= \int_{\mathbb{R}} f(x) \widehat{g}(x) \, dx
\end{aligned}
$$

where the change of order of integration is justified by Fubini's theorem since $\widehat{f}$ is uniformly bounded by some constand M and we know that $g \in L^1(\mathbb{R})$. $\qquad\square$

3.2 Poisson Kernel

when you pull an all nighter thinking you missed an important step in your master's thesis, but it was your misunderstanding and you really didn't need Poisson kernel. Yes, I'm crying now at 3 AM

Now we'll define Poisson kernel which will be quite useful for the fourier inversion.

Definition 3.2.1 (Poisson Kernel)**.** Let $r > 0$ define $P_r : \mathbb{R} \to \mathbb{R}$, as

$$P_r = \frac{1}{\pi} \frac{r}{x^2 + r^2}$$

Then the collection of functions P_r are called Poisson kernel.

Since we defined Poisson kernel and approximation identities we'll now show that Poisson kernel is an approximation identity.

Proposition 3.2.1. *Let P_y be the Poisson kernel as in Definition 3.2.1, then P_y satisfy the following conditions*

 (a) $\int_{\mathbb{R}} P_y(x) dx = 1$

 (b) $\int_{\mathbb{R}} |P_y(x)| dx \leq C$ *for some constant $C > 0$*

 (c) $\lim_{y \downarrow 0} \int_{|x|>\delta} |P_y(x)| dx = 0$ *for each δ*

Proof.   (a)

$$\int_{\mathbb{R}} P_y(x) \ dx = \frac{1}{\pi} \int_{\mathbb{R}} \frac{y}{x^2 + y^2} \ dx$$

$$= \frac{1}{\pi} \left[\tan^{-1} \left(\frac{x}{y} \right) \right]_{-\infty}^{\infty}$$

$$= \frac{1}{\pi} \left(\frac{\pi}{2} + \frac{\pi}{2} \right)$$

$$= 1$$

  (b) This follows straight from (a) upon observing that since $y > 0$, $P_y(x) > 0$ for all $x \in \mathbb{R}$.

  (c)

$$\int_{|x|>\delta} P_y(x) \ dx = \int_{\mathbb{R}} P_y(x) \ dx - \int_{|x|<\delta} P_y(x) \ dx$$

$$= 1 - \frac{1}{\pi} \left[\tan^{-1} \left(\frac{x}{y} \right) \right]_{-\delta}^{\delta}$$

$$= 1 - \frac{2}{\pi} \left[\tan^{-1} \left(\frac{\delta}{y} \right) \right]$$

which implies

$$\lim_{y\downarrow 0} \int_{|x|>\delta} P_y(x) \ dx = 1 - \lim_{y\downarrow\infty} \frac{2}{\pi} \left[\tan^{-1}\left(\frac{\delta}{y} \right) \right] = 0$$

$\square$

Like we used convolutions of the summability kernels in Fourier series, here the convolutions of the Poisson kernels will be an important tool in our analysis. Here we'll prove an important result.

Proposition 3.2.2. *Consider the function* $h_{y,b}(x) = e^{2\pi ibx} e^{-2\pi y|x|}$ *and* $f \in L^1(\mathbb{R})$. *Then*

$$\int_{\mathbb{R}} \widehat{f}(x) h_{y,b}(x) \ dx = \int_{\mathbb{R}} \widehat{f}(x) e^{2\pi ibx} e^{-2\pi y|x|} \ dx = (f * P_y)(x)$$

where $f * P_y$ *is the convolution of* f *and* P_y.

Proof. Before we start analyse $h_{y,b}(x)$, let's break down that into two simple functions. Let $g(x) = e^{-2\pi y|x|}$. Then,

$$\begin{aligned}
\widehat{g}(t) &= \int_{\mathbb{R}} e^{-2\pi y|x|} e^{-2\pi itx} \ dx \\
&= \int_{-\infty}^{0} e^{2\pi yx} e^{-2\pi itx} \ dx + \int_{0}^{\infty} e^{-2\pi yx} e^{-2\pi itx} \ dx \\
&= \left[\frac{e^{2\pi(y-it)x}}{2\pi(y-it)} \right]_{-\infty}^{0} + \left[-\frac{e^{-2\pi(y+it)x}}{2\pi(y+it)} \right]_{0}^{\infty} \\
&= \frac{1}{2\pi(y-it)} - \frac{1}{2\pi(y+it)} \\
&= \frac{1}{\pi} \frac{y}{t^2 + y^2}
\end{aligned}$$

Now by Proposition 3.1.2 we get that

$$\widehat{h_{y,b}}(t) = \frac{1}{\pi} \frac{y}{(t-b)^2 + y^2}$$

By Proposition 3.1.6 we get

$$\int_{\mathbb{R}} \widehat{f}(x) h_{y,b}(x) \ dx = \int_{\mathbb{R}} f(t) \widehat{h_{y,b}}(t) \ dt$$

$$= \int_{\mathbb{R}} f(t) \frac{1}{\pi} \frac{y}{(t-b)^2 + y^2} \ dt$$

$$= \int_{\mathbb{R}} f(t) P_y(b-t) \ dt$$

$$= (f * P_y)(b)$$

$\square$

We'll show another important property of Poisson kernel.

Proposition 3.2.3. *Let $f : \mathbb{R} \to \mathbb{C}$ be uniformly continuous and bounded. Then*

$$\lim_{y \downarrow 0} \|f - (f * P_y)\|_\infty = 0$$

Proof. Let M be a constant such that $|f(x)| < M$ for all $x \in \mathbb{R}$. Since it is given that f is uniformly continuous, given any $\epsilon > 0$ ther exist a $\delta > 0$ such that whenever $y \leq \delta$, $|f(x) - f(x+y)| < \epsilon$ for all $x \in \mathbb{R}$. Therefore,

$$f(x) - (f * P_y)(x) = \int_{\mathbb{R}} f(x) P_y(t) \ dt - \int_{\mathbb{R}} f(x-y) P_y(t) \ dt$$

$$= \int_{\mathbb{R}} (f(x) - f(x-y)) P_y(t) \ dt$$

$$= \int_{-\infty}^{-\delta} + \int_{-\delta}^{\delta} + \int_{\delta}^{\infty}$$

$$= I_1 + I_2 + I_3$$

From Definition 3.2.1 and Proposition 3.2.1, we get that

$$I_1 + I_3 \leq 2M \int_{|x|>\delta} P_y(t) \ dt$$

converges to 0 as $y \downarrow 0$. Also by the choice of δ

$$I_2 \leq \epsilon \int_{-\delta}^{\delta} P_y(t) \ dt = \epsilon$$

Since our choice of ϵ was arbitary it can be taken arbitrarily small and it does not depend on x. Hence the result. $\square$

We'll state another property of poisson kernel

Proposition 3.2.4. *Let* $1 \leq p < \infty$ *and* $f \in L^p(\mathbb{R})$. *Then*

$$\lim_{y \downarrow 0} \| f - (f * P_y) \|_p = 0$$

For proof refer [Axl20, Theorem 11.74 p. 388] or [Rud87, Theorem 9.10 p. 184]

3.3   Fourier Inversion Theorem

For L^1 periodic functions, we were able to represent them using their Fourier series. We wish to do the same for functions in $L^1(\mathbb{R})$, by trying to represent them using their Fourier transform. We hope that

$$f(x) = \int_{\mathbb{R}} \widehat{f}(t) e^{2\pi i t x} dt$$

But, we might encounter difficulties in convergence, like we had in Fourier series. We might need to introduce analogous techniques to Fejér kernel to define the integral. As a first step towards that we'll consider functions like

$$B(x) = \int_{-T}^{T} b(t) e^{2\pi i t x} \; dt$$

For the Fourier transform, these functions will serve as analogue for trigonometric polynomials in Fourier series.

We'll now prove an important property of functions $B(x)$ as defined above.

Proposition 3.3.1. *Let* $b \in L^1[-T, T]$, *and* $f \in L^1(\mathbb{R})$, *then*

$$B(x) = \int_{-T}^{T} b(t) e^{2\pi i t x} \; dt \implies (f * B)(x) = \int_{-T}^{T} b(t) \widehat{f}(t) e^{2\pi i t x} \; dx$$

Proof. Since $|e^{2\pi i t x}| = 1$, and $b \in L^1[-T, T]$, by triangle inequaltiy

$$|B(x)| \leq \int_{-T}^{T} |b(t)| \; dt < \infty$$

Thus B is a bounded function in the finite interval $[-T, T]$. Hence $|(f * B)(x)| \leq$

$\|f\|_1\|b\|_1$ for all x. Moreover,

$$(f * B)(x) = \int_{\mathbb{R}} f(x - y)B(y)\ dy$$

$$= \int_{\mathbb{R}} f(x - y) \int_{-T}^{T} b(t)e^{2\pi ity}\ dt\ dy$$

$$= \int_{-T}^{T} b(t)e^{2\pi itx} \int_{\mathbb{R}} f(x - y)e^{-2\pi it(x-y)}\ dy\ dt$$

$$= \int_{-T}^{T} b(t)\widehat{f}(t)e^{2\pi itx}\ dt$$

Note that the change of intergral is justified because we already know that the integral is finite since $|(f * B)(x)| \leq \infty$. $\qquad\qquad\qquad\qquad\qquad\qquad\square$

Now we'll prove some propositions which will help us in $L^2(\mathbb{R})$.

Proposition 3.3.2. *We have*

$$\int_{-\infty}^{\infty} \left(\frac{\sin(\pi x)}{\pi x}\right)^2\ dx = 1$$

Proof. from (b) and (e) of Proposition 1.4.1, and Lemma 1.1.1 we get that

$$\int_{-\frac{1}{2}}^{\frac{1}{2}} \frac{1}{N} \left(\frac{\sin(\pi N x)}{\sin(\pi x)}\right)^2\ dx = 1$$

We can write this integral as

$$\int_{-\frac{1}{2}}^{\frac{1}{2}} \frac{1}{N} \left(\frac{\sin(\pi N x)}{\pi x}\right)^2\ dx + \int_{-\frac{1}{2}}^{\frac{1}{2}} \frac{\sin^2 \pi N x}{N} \left(\frac{1}{\sin^2 \pi x} - \frac{1}{(\pi x)^2}\right)\ dx = I_1 + I_2 = 1$$

For I_1, we see that by the change of variable $y = Nx$, it becomes

$$I_1 = \int_{-\frac{N}{2}}^{\frac{N}{2}} \left(\frac{\sin(\pi x)^2}{\pi x}\right)^2\ dx$$

. And for I_2, we see that the difference of fractions inside paranthesis is

$$\frac{(\pi x)^2 - \sin^2(\pi x)}{(\pi x \sin(\pi x))^2} = \frac{(\pi x - \sin(\pi x))(\pi x + \sin(\pi x))}{(\pi x \sin(\pi x))^2}$$

Here $\pi x - \sin(\pi x)$ has a zero of order 3, and $\pi x + \sin(\pi x)$ has a zero of order 1 at $x = 0$. Hence the numerator has a zero of order 4 at $x = 0$. Again the

denominator also has a zero of order 0 at $x = 0$. Then the expression has a bounded value at $x = 0$. Also everywhere else in the interval $-\frac{1}{2} \leq x \leq \frac{1}{2}$, the expression is continuous being a product and quotient of continuous function. Hence the expression is bounded in the same interval. Hence $|I_2| \leq \frac{C}{N}$, for some constant C. Therefore as $N \to \infty$, I_1 tends to our desired integral and $I_2 \to 0$. Since $I_1 + I_2 = 1$ our result follows. $\qquad\square$

Let's define the $L^1(\mathbb{R})$ analogue of Fejér kernel.

Definition 3.3.1. For real numbes $T > 0$, we define

$$\Delta_T(x) = \begin{cases} \frac{1}{T}\left(\frac{\sin \pi Tx}{\pi x}\right)^2, & \text{if } x \neq 0 \\ T, & \text{if } x = 0 \end{cases}$$

Proposition 3.3.3 (Properties of Δ function)**.** *Let $T > 0$, and $\Delta(x)$ be as defined above, then the following holds*

(a)
$$\int_{\mathbb{R}} \Delta_T(x) \, dx = 1$$

(b)
$$\Delta(-x) = \Delta(x)$$

(c)
$$\int_{-T}^{T} \left(1 - \frac{|t|}{T}\right) e^{2\pi itx} \, dt = \Delta_T(x)$$

Proof. (a) From Proposition 3.3.2,

$$\int_{\mathbb{R}} \left(\frac{\sin(\pi x)}{\pi x}\right)^2 \, dx = 1$$

Put $x = Ty$, then $dx = T \, dy$ and we get the desired result

(b) This is clear from the definition, since $\sin^2(-x) = \sin^2(x)$.

(c) To prove this first we'll find the Fourier transform of the function g, where $g(x) = 1 - |x|$ for $|x| \leq 1$ and $g(x)$ is 0 everywhere else.

$$\widehat{g}(t) = \int_{-1}^{1} (1 - |x|)e^{-2\pi itx} \, dx = 2\int_{0}^{1} (1 - x)\cos(2\pi tx) \, dx$$

$$= 2\left[(1 - x)\frac{\sin(2\pi tx)}{2\pi t}\right]_0^1 + \int_{0}^{1} \frac{\sin(2\pi tx)}{\pi t} \, dx$$

$$= \left[-\frac{\cos(2\pi tx)}{2(\pi t)^2}\right]_0^1 = \frac{1 - \cos(2\pi tx)}{2(\pi t)^2} = \left(\frac{\sin(\pi t)}{\pi t}\right)^2$$

Now from the (c) of Proposition 3.1.2, we get that the fourier transform of the function $h(x) = g(Tx)$,

$$\widehat{h}(t) = \frac{1}{T}\left(\frac{\sin(\pi Tx)}{\pi x}\right)^2 = \Delta(x)$$

Note that the above holds true for values $x \neq 0$ and when $x = 0$, the integral reduces to

$$\frac{1}{T}\int_{-T}^{T}(T - |t|)\ dt = \frac{2}{T}\int_{0}^{T}(T - t)\ dt = T = \Delta(0)$$

Hence the proof.

$\square$

From the above properties we conclude the following result.

Corollary 3.3.0.1. *If $f \in L^1(\mathbb{R})$, and Δ_T is as in Definition 3.3.1, then*

$$(f * \Delta_T)(x) = \int_{-T}^{T}\left(1 - \frac{|t|}{T}\right)\widehat{f}(t)e^{2\pi itx}\ dt$$

Proof. From last proposition we get that

$$\Delta_T(x) = \int_{-T}^{T}\left(1 - \frac{|t|}{T}\right)e^{-2\pi itx}\ dx$$

Using the result of Proposition 3.3.1, on Δ_T, we get the result. $\square$

Now we prove the $L^1(\mathbb{R})$ analogue of the Fejer's theorem (Theorem 1.5.2)

Theorem 3.3.1. *Let $f \in L^1(\mathbb{R})$. If f is continuous at x, then*

$$\lim_{T\to\infty}\int_{-T}^{T}\left(1 - \frac{|t|}{T}\right)\widehat{f}(t)e^{2\pi itx}\ dt = f(x)$$

Proof. Let ϵ be given, since we know that f is continuous at x, there exist a δ, such that $|f(x - y) - f(x)| < \epsilon$, when $|y| < \delta$. Also since we know that $\int_{\mathbb{R}}\Delta_T(x)\ dx = 1$ by Proposition 3.3.3 and by Corollary 3.3.0.1,

$$\int_{-T}^{T}\left(1 - \frac{|t|}{T}\right)\widehat{f}(t)e^{2\pi itx}dt - f(x) = (f * \Delta_T)(x) - f(x)$$

$$= \int_{\mathbb{R}}f(x - y)\Delta_T(y)dy - \int_{\mathbb{R}}f(x)\Delta_T(y)\ dy$$

$$= \int_{\mathbb{R}}(f(x - y) - f(y))\Delta_T(y)dy$$

Now we'll evaluate the last integral into I_1, I_2, I_3, where I_1 is when $-\infty < y \leq -\delta$, I_2 is when $-\delta < y < \delta$ and I_3 is $\delta \leq y < \infty$. When y is in I_1 and I_3, we see from the Definition 3.3.1 that since $|y| > |\delta|$ in I_1 and I_3, $|\Delta_T(y)| \leq \frac{1}{T(\pi\delta)^2}$. Thus

$$|I_1| \leq \frac{1}{T\pi^2\delta^2} \int_{-\infty}^{-\delta} |f(x-y)| \ dy + |f(x)| \int_{-\infty}^{-\delta} \Delta_T(y) \ dy$$

$$|I_3| \leq \frac{1}{T\pi^2\delta^2} \int_{\delta}^{\infty} |f(x-y)| \ dy + |f(x)| \int_{\delta}^{\infty} \Delta_T(y) \ dy$$

where the first integral in both the inequalities is less than $\|f\|_1$ which is finite, and second integral

$$\int_{-\infty}^{-\delta} \Delta_T(y) \ dy = \int_{\delta}^{\infty} \Delta_T(y) \ dy \leq \int_{\delta}^{\infty} \frac{1}{T\pi^2\delta^2} \ dx = \frac{1}{T\pi^2\delta}$$

Therefore $I_1, I_3 \to 0$, as $T \to \infty$. Now in I_2, by the continuity of f at x,

$$|I_2| \leq \epsilon \int_{-\delta}^{\delta} \Delta_T(y) \ dy \leq \epsilon \int_{\mathbb{R}} \Delta_T(y) \ dy = \epsilon$$

Therefore I_2 can also be made arbitarily small. Hence the theorem. $\qquad\square$

Now we'll prove some results which will help us to prove the general Fourier inversion theorem. The below result is analogous to the fact that Cesáro sum of a convergent sequence converges to the same limit as the original sequence, given it exists.

Proposition 3.3.4. *Let $f \in L^1[-T, T]$ and let*

$$I(T) = \int_{-T}^{T} f(t) \ dt, \quad J(T) = \int_{-T}^{T} \left(1 - \frac{|t|}{T}\right) f(t) \ dt$$

Then

$$\lim_{T \to \infty} I(T) = \lim_{T \to \infty} J(T)$$

Proof. We'll first show that $\lim_{T\to\infty} I(T)$ exists. But since $f \in L^1(\mathbb{R})$,

$$|I(T)| \ dt \leq \int_{-T}^{T} |f(t)| \ dt \leq \|f\|_1$$

Therefore $\lim_{T\to\infty} I(T) \leq \|f\|_1$, and the limit exists. Moreover we see that by Fubini's theorem,

$$\frac{1}{T} \int_0^T I(u) \ du = \frac{1}{T} \int_0^T \int_{-u}^{u} f(t) \ dt \ du = \frac{1}{T} \int_{-T}^{T} f(t) \left(\int_{|t|}^{T} 1 \ du\right) \ dt = J(T)$$

Since we assumed that $\lim_{T \to \infty} I(T) = a$, given $\epsilon > 0$, there exists an N such that $|I(u) - a| < \epsilon$ for all $u \geq N$. Now we can write

$$J(T) - a = \frac{1}{T} \int_0^T I(u) - a \ du = \frac{1}{T} \int_0^N I(u) - a \ du + \frac{1}{T} \int_N^T I(u) - a \ du = E_1 + E_2$$

Now since $I(u)$ is bounded for all u, the integral in E_1 is finite and therefore $E_1 \to 0$ as $T \to \infty$. As for E_2,

$$|E_2| \leq \frac{1}{T} \int_N^T |I(u) - a| \ du < \frac{1}{T} \int_N^T \epsilon \ du = \frac{T - N}{T} \epsilon < \epsilon$$

Therefore E_2 converge to 0 as ϵ can be made arbitarily small. Hence the result.
$\square$

As a result of the above result combined with Theorem 3.3.1, we get

Corollary 3.3.1.1. *Let $f \in L^1(\mathbb{R})$ and f is continuous at x. If*

$$\lim_{T \to \infty} \int_{-T}^T \widehat{f}(t) e^{2\pi i t x} \ dt$$

exists, then it is equal to $f(x)$.

Since we'll be working a lot with functions f which are continuous everywhere in the real line, we explicityly state the next theorem.

Theorem 3.3.2. *If $f \in L^1(\mathbb{R})$, f is continuous in $\mathbb{R}$, and if $\widehat{f} \in L^1(\mathbb{R})$, then*

$$\int_{\mathbb{R}} \widehat{f}(t) e^{2\pi i t x} \ dt = f(x)$$

Note that the condition that $\widehat{f} \in L^1(\mathbb{R})$ in the above theorem guarantee the existence of the limit from the corollary above.

Now we'll prove one important theorem

Theorem 3.3.3. *If $f \in L^1(\mathbb{R})$ and $\sigma_T(x) = (f * \Delta_T)(x)$, where Δ_T is as in Definition 3.3.1, then*

$$\lim_{T \to \infty} \int_{-\infty}^{\infty} |f(x) - \sigma_T(x)| \ dx = 0$$

Proof. From Proposition 3.3.3, we know that $\int_{\mathbb{R}} \Delta_T(x) \ dx = 1$, therefore

$$f(x) - \sigma_T(x) = \int_{\mathbb{R}} (f(x) - f(x - u)) \Delta_T(u) \ du$$

which implies

$$|f(x) - \sigma_T(x)| \le \int_{\mathbb{R}} |f(x) - f(x - u)| \, \Delta_T(u) \, du$$

and therefore

$$\int_{\mathbb{R}} |f(x) - \sigma_T(x)| \, dx \le \int_{\mathbb{R}} \int_{\mathbb{R}} |f(x) - f(x - u)| \, \Delta_T(u) \, du \, dx$$

Again we see that

$$\int_{\mathbb{R}} \Delta_T(u) \int_{\mathbb{R}} |f(x) - f(x - u)| \, dx \, du \le \int_{\mathbb{R}} \Delta_T(u) \cdot 2\|f\|_1 \, du = 2\|f\|_1$$

and since $\mathbb{R}^2$ is a sigma finite measure space by Fubini-Tonelli theorem, we can change the order of integration. Then

$$\int_{\mathbb{R}} |f(x) - \sigma_T(x)| \, dx \le \int_{\mathbb{R}} \Delta_T(u) \int_{\mathbb{R}} |f(x) - f(x - u)| \, dx \, du$$

Now we'll analyse the last integral. Let us denote the inner integral by $I(u)$. Since $f \in L^1(\mathbb{R})$, by Proposition 3.1.3 given any ϵ, there exists a δ such that for all $|u| < \delta$,

$$I(u) = \int_{\mathbb{R}} |f(x) - f(x - u)| \, dx < \epsilon$$

Moreover,

$$I(u) \le \int_{\mathbb{R}} |f(x)| + |f(x - u)| \, du = 2\|f\|_1$$

We'll split the integral into three intervals and analyse there. For that let

$$\int_{\mathbb{R}} \Delta_T(u) I(u) \, du = \int_{-\infty}^{-\delta} + \int_{-\delta}^{\delta} + \int_{\delta}^{\infty} = I_1 + I_2 + I_3$$

Then by the definition of Δ_T in Definition 3.3.1,

$$I_1 \le 2\|f\|_1 \int_{-\infty}^{-\delta} \Delta_T(u) \, du \le 2\|f\|_1 \int_{-\infty}^{-\delta} \frac{1}{T\pi^2 u^2} \le \frac{2\|f\|_1}{T\pi^2\delta}$$

$$I_3 \le 2\|f\|_1 \int_{\delta}^{\infty} \Delta_T(u) \, du \le 2\|f\|_1 \int_{\delta}^{\infty} \frac{1}{T\pi^2 u^2} \le \frac{2\|f\|_1}{T\pi^2\delta}$$

And by the choice of δ and Proposition 3.3.3, I_2 can be estimated as

$$I_2 \le \epsilon \int_{-\delta}^{\delta} \Delta_T(u) \, du \le \epsilon \int_{\mathbb{R}} \Delta_T(u) \, du = \epsilon$$

Since ϵ can be chosen arbitrarily small and for the corresponding δ, we see that $I_1, I_3 \to 0$ as $T \to \infty$. Hence the result. $\square$

Now armed with the above theorem we can conclude some important results.

Corollary 3.3.3.1. *If $f \in L^1(\mathbb{R})$ and $\widehat{f}(t) = 0$ for all t, then f is 0 almost everywhere. That is*

$$\int_{\mathbb{R}} |f(x)| \ dx = 0$$

Proof. Since we know that $\widehat{f}(t) = 0$ for all $t \in \mathbb{R}$, by Corollary 3.3.0.1, $\sigma_T = (f * \Delta_T) = 0$(zero function) for all T. Then by previous theorem the result follows. $\square$

Applying the corollary above to $f - g$ where $f, g \in L^1(\mathbb{R})$, we get

Corollary 3.3.3.2. *Let $f, g \in L^1(\mathbb{R})$ and $\widehat{f} = \widehat{g}$. Then $f = g$ almost everywhere. That is*

$$\int_{\mathbb{R}} |f(x) - g(x)| \ dx = 0$$

.

Now we can explicitly state the most important theorem in this section. The Fourier inversion theorem. The theorem states that given any function $\widehat{f} \in L^1(\mathbb{R})$, it is almost everywhere equal to the Fourier transform of some function $f \in L^1(\mathbb{R})$.

Theorem 3.3.4. *Let $f, \widehat{f} \in L^1(\mathbb{R})$. If*

$$g(x) = \int_{\mathbb{R}} \widehat{f}(t) e^{2\pi i t x} \ dx$$

then $f = g$ almost everywhere.

Proof. Since it is given that $\widehat{f} \in L^1(\mathbb{R})$, g is well defined and $g(x)$ exists for all points $x \in \mathbb{R}$. Also at points of continuity of f, $g(x) = f(x)$ by Corollary 3.3.1.1. But since $f \in L^1(\mathbb{R})$, it is continuous almost everywhere. Therefore $f = g$ almost everywhere. $\square$

3.4 Fourier Transform in $L^2(\mathbb{R})$

We are intereseted in defining the Fourier transfrom for functions in $L^2(\mathbb{R})$ because a lot of important relations appear when the space is $L^2(\mathbb{R})$. But here arise a new problem. The way we defined Fourier transforms for L^1 functions were by directly using the fact that since their L^1 norm is finite, the integral in Definition 3.1.1 is well defined. But since there is no containment between the

spaces $L^1(\mathbb{R})$ and $L^2(\mathbb{R})$, we will not be able to define the Fourier transform for all $L^2(\mathbb{R})$ functions. Therefore we restrict ourself to the space $L^1(\mathbb{R}) \cap L^2(\mathbb{R})$.

Since our new space $L^1(\mathbb{R}) \cap L^2(\mathbb{R})$ is a subspace of $L^1(\mathbb{R})$, the Fourier transform of all functions $f \in L^1(\mathbb{R}) \cap L^2(\mathbb{R})$ is well defined.

Now we'll prove an important result which is the $L^2(\mathbb{R})$ analogue of the Proposition 3.1.3

Now we'll discuss about the convolution of functions in $L^2(\mathbb{R})$. We'll follow the same definition as before in $L^1(\mathbb{R})$. (For formula refer to Definition 1.2.1). It is natural to think if such a definition is well defined. In fact by the Holders inequality (Theorem 2.0.1) one can show that it is well defined. Since if $f, g \in L^2(\mathbb{R})$, then

$$
\begin{aligned}
|f * g(x)| &= \left| \int_R f(x - y) g(y) \ dy \right| \\
&\leq \int_{\mathbb{R}} |f(x - y) g(y)| \ dy \\
&\leq \left(\int_{\mathbb{R}} |f(x - y)|^2 \ dy \right)^{\frac{1}{2}} \left(\int_{\mathbb{R}} |g(y)|^2 \ dy \right)^{\frac{1}{2}} \\
&= \|f\|_2 \|g\|_2
\end{aligned}
$$

We can now discuss about the convolution of $L^2(\mathbb{R})$ functions. We'll now show that the convolution of two functions in $L^2(\mathbb{R})$ is uniformly continuous. This proposition will be a stepping stone to the celebrated Plancherel's Theorem.

Proposition 3.4.1. *If $f, g \in L^2(\mathbb{R})$, then $f * g$ is uniformly continuous.*

Proof. Let $h(x) = (f * g)(x)$. Then

$$
h(x + \delta) - h(x) = \int_{\mathbb{R}} (f(x + \delta - y) - f(x - y)) g(y) \ dy
$$

By Holder's inequality,

$$
\begin{aligned}
|h(x + \delta) - h(x)| &\leq \int_{\mathbb{R}} |(f(x + \delta - y) - f(x - y)) g(y)| \ dy \\
&\leq \left(\int_{\mathbb{R}} |f(x + \delta - y) - f(x - y)|^2 \, dy \right)^{\frac{1}{2}} \left(\int_{\mathbb{R}} |g(y)|^2 \right)^{\frac{1}{2}}
\end{aligned}
$$

where the first integral converge to zero by Proposition A.0.4 and the last integral is a constant. Since the first integral is over all of $\mathbb{R}$, it is independent of x and hence the result follows. $\qquad\square$

Now we'll prove the famous Plancherel's theorem.

Theorem 3.4.1 (Plancherel's Theorem)**.** *If $f \in L^1(\mathbb{R}) \cap L^2(\mathbb{R})$, then*

$$\int_{\mathbb{R}} |f(x)|^2 \ dx = \int_{\mathbb{R}} |\widehat{f}(t)|^2 \ dt$$

Proof. Let $g(x) = \overline{f(-x)}$. Then $g \in L^1(\mathbb{R}) \cap L^2(\mathbb{R})$. Put $h(x) = (f * g)(x)$. Since $f, g \in L^1(\mathbb{R})$, by Proposition 3.1.5, $h \in L^1(\mathbb{R})$. Since $f, g \in L^2(\mathbb{R})$, by Proposition A.0.4, h is uniformly continuous. Hence by Theorem 3.3.1

$$h(x) = \lim_{T \to \infty} \int_{-T}^{T} \left(1 - \frac{|t|}{T}\right) \widehat{h}(t) e^{2\pi i t x} \ dt$$

for all x. In particular, for $x = 0$ we get

$$h(0) = \lim_{T \to \infty} \int_{-T}^{T} \left(1 - \frac{|t|}{T}\right) \widehat{h}(t) \ dt$$

By the Proposition 3.1.5 $\widehat{h}(t) = \widehat{f}(t)\widehat{g}(t)$. By the definition of g, and combining (c), (d) from Proposition 3.1.2, we get that $\widehat{g}(t) = \overline{\widehat{f}(t)}$. Since

$$h(0) = (f * g)(0) = \int_{\mathbb{R}} f(y) g(-y) \ dy = \int_{\mathbb{R}} |f(y)|^2 \ dy$$

we get that

$$\int_{\mathbb{R}} |f(x)|^2 \ dx = \lim_{T \to \infty} \int_{-T}^{T} \left(1 - \frac{|t|}{T}\right) |\widehat{f}(t)|^2 \ dt$$

Since the integral in the right is always positive, the limit is an increasing limit. Then for any $0 < \epsilon < 1$, we have

$$(1 - \epsilon) \int_{-\epsilon T}^{\epsilon T} |\widehat{f}(t)|^2 \ dt \le \int_{-T}^{T} \left(1 - \frac{|t|}{T}\right) |\widehat{f}(t)|^2 dt \le \int_{\mathbb{R}} |\widehat{f}(t)|^2 \ dt$$

Then as $T \to \infty$,

$$(1 - \epsilon) \int_{\mathbb{R}} |\widehat{f}(t)|^2 \ dt \le \int_{\mathbb{R}} |f(t)|^2 dt \le \int_{\mathbb{R}} |\widehat{f}(t)|^2 \ dt$$

Since ϵ can be made arbitrary small, the result follows. $\square$

Also by Proposition A.0.3, $L^1(\mathbb{R}) \cap L^2(\mathbb{R})$ is dense in $L^2(\mathbb{R})$. Then by Plancherel's theorem Fourier transform in $L^1(\mathbb{R}) \cap L^2(\mathbb{R})$ can be extended into an equinorm transform $\mathcal{F} : L^2(\mathbb{R}) \to L^2(\mathbb{R})$. When working with $L^2(\mathbb{R})$, by Fourier transform we'll mean this $\mathcal{F}$. Also note that $\mathcal{F}(L^1(\mathbb{R}) \cap L^2(\mathbb{R}))$ is dense in $L^2(\mathbb{R})$. The proof can be seen at [Rud87, Theorem 9.13 p. 186] or [Pin09, Theorem 2.4.1 p. 128]

Chapter 4

Holomorphic Fourier Transforms

4.1 Motivation and Basic Results

In last chapter we explored the Fourier transforms of functions in $\mathbb{R}$. Frequently the fourier transform of functions in $\mathbb{R}$ can be extended to a holomorphic function in certain regions. For example say $f(x) = e^{-|x|}$, then $\widehat{f}(t) = \frac{1}{1+(2\pi t)^2}$. Since,

$$
\begin{aligned}
\widehat{f}(t) = \int_{\mathbb{R}} e^{-|x|}e^{-2\pi itx} \ dx &= \int_{-\infty}^{0} e^{x(1-2\pi it)} \ dx + \int_{0}^{\infty} e^{-x(1+2\pi it)} \ dx \\
&= \left[\frac{e^{x(1-2\pi it)}}{1-2\pi it}\right]_{-\infty}^{0} - \left[\frac{e^{-x(1+2\pi it)}}{1+2\pi it}\right]_{0}^{\infty} \\
&= \frac{1}{1-2\pi it} + \frac{1}{1+2\pi it} \\
&= \frac{1}{1+(2\pi t)^2}
\end{aligned}
$$

Clearly $w(z) = \frac{1}{1+(2\pi z)^2}$ is a holomorphic extension of $\widehat{f}$ into the regions of the complex plane without the points $z = \pm\frac{i}{2\pi}$.

We will study two classes of functions which can be extended in this manner. The first class of such functions is

$$
f(z) = \int_{0}^{\infty} F(t)e^{2\pi itz} \ dt
$$

where $z \in \Pi^+ = \{z \in \mathbb{C} \,|\, \Im(z) > 0\}$ and $F \in L^2(\mathbb{R})$ is a function which vanishes on $(-\infty, 0)$. The second class of functions will be

$$f(z) = \int_{-A}^{A} F(t)e^{2\pi i t z} \, dt$$

where $0 < A < \infty$ and $F \in L^2(-A, A)$. We'll now prove some important results regarding these two classes of functions

Proposition 4.1.1. *Let $F \in L^2(\mathbb{R})$ such that F vanishes at $(-\infty, 0)$. Then $f : \Pi^+ \to \mathbb{C}$ defined as,*

$$f(z) = \int_{0}^{\infty} F(t)e^{2\pi i t z} \, dt$$

is holomorphic in the upper half plane, i.e $f \in H(\Pi^+)$. Moreover f restricted to horizontal lines in Π^+ is bounded in the L^2 norm and the bound is independent of the horizontal line. That is if $z = x + iy$, then

$$\sup_{0 < y < \infty} \int_{-\infty}^{\infty} |f(x + iy)|^2 \, dx < \infty$$

Proof. Let $z \in \Pi^+$. Then there exists a δ such that $0 < \delta < \Im(z)$. Since Π^+ is open, there exists a sequence z_n in Π^+ such that $\delta < \Im(z_n)$, and $z_n \to z$. Also

$$\begin{aligned}
\left|e^{2\pi i t z_n} - e^{2\pi i t z}\right|^2 &= \left|\left(e^{2\pi i t z_n} - e^{2\pi i t z}\right)^2\right| \\
&= \left|e^{4\pi i t z_n} + e^{4\pi i t z} - 2e^{2\pi i t(z + z_n)}\right| \\
&\leq \left|e^{4\pi i t z_n}\right| + \left|e^{4\pi i t z}\right| + 2\left|e^{2\pi i t(z_n + z)}\right| \\
&= e^{-4\pi t \Im(z_n)} + e^{-4\pi t \Im(z)} + 2e^{-2\pi t \Im(z_n - z)} \\
&\leq e^{-4\pi t \delta} + e^{-4\pi t \delta} + 2e^{-4\pi t \delta} \\
&= 4e^{-4\pi t \delta}
\end{aligned}$$

Now since

$$\int_{0}^{\infty} 4e^{-4\pi t \delta} \, dt = \frac{4}{2\pi \delta}$$

the integrad is L^1 in $(0, \infty)$ and therefore by dominated convergence theorem,

$$\lim_{n \to \infty} \int_{0}^{\infty} \left|e^{2\pi i t z_n} - e^{2\pi i t z}\right|^2 \, dt = 0$$

Now therefore if $w \in \Pi^+$ and $w_n \to w$, then

$$f(w_n) - f(w) = \int_0^\infty F(t)(e^{2\pi i t w_n} - e^{2\pi i t w}) \, dt$$

$$\leq \|F\|_2 \|e^{2\pi i t w_n} - e^{2\pi i t w}\|_2$$

By assumption $\|F\|_2$ is a finite quantity and from above result $\|e^{2\pi i t w_n} - e^{2\pi i t w}\|_2 \to 0$ as $w_n \to w$. Therefore $f(w_n) \to f(w)$. Since our choice of w was arbitary, this implies that f is continuous everywhere in Π^+. Also if γ is any triangle in Π^+, then γ can be parametrized by $s \in [a, b]$ as $\gamma(s) = x(s) + iy(s)$, where $y(s) > 0$ since $\gamma \in \Pi^+$. Now let $M = \inf_{s \in [a,b]} |\gamma'(s)|$ (here we take only differentiable points in γ for infimum, since the non-differentiable points will be measure zero and adds nothing to the integral). Also since $\gamma \in \Pi^+$, there exist an $m > 0$ such that $y(s) > m$ for all s. Then we get that

$$\int_\gamma \int_0^\infty |F(t)e^{itz}| \, dt \, d|z| = \int_a^b \int_0^\infty |F(t)|e^{-ty(s)} \, dt \, |\gamma'(s)| \, ds$$

$$\leq M \int_a^b \int_0^\infty |F(t)|e^{-mt} \, dt \, ds$$

$$= M(b-a) \int_0^\infty |F(t)|e^{-mt} \, dt$$

$$\leq M(b-a)\|F\|_{L^2((0,\infty))} \cdot \left(\int_0^\infty (e^{-mt})^2 \, dt \right)^{1/2}$$

Therfore by Fubini's Theorem we can change the order of integration and we get,

$$\int_\gamma f(z) \, dz = \int_\gamma \int_0^\infty F(t)e^{2\pi i t z} \, dt \, dz$$

$$= \int_0^\infty F(t) \int_\gamma e^{2\pi i t z} \, dz \, dt$$

$$= \int_0^\infty F(t) \cdot 0 \, dt$$

$$= 0$$

Then by Morera's theorem, f is holomorphic everywhere in the upper half plane.

Now consider $z = x + iy$, then f can be written as

$$f(x + iy) = \int_0^\infty F(t)e^{2\pi i t(x+iy)} \, dt = \int_0^\infty F(t)e^{-2\pi t y}e^{2\pi i t x} \, dx$$

Now for a fixed $y \in \mathbb{R}$, consider $g_y(t) = F(t)e^{-2\pi ty}$. Then from above equation $f(x + iy) = \widehat{g_y}(x)$. By Holder's inequality we get that

$$\int_0^\infty |g_y(t)|\ dt = \int_0^\infty \left|F(t)e^{-2\pi ty}\right|\ dt$$

$$\leq \left(\int_0^\infty |F(t)|^2\ dt\right)^{\frac{1}{2}} \left(\int_0^\infty e^{-4\pi ity}\ dt\right)^{\frac{1}{2}}$$

where both of the integrals are finite. Therefore $g_y \in L^1(0, \infty)$. Again since $0 < e^{-x} \leq 1$ when $0 \leq x < \infty$, we know that

$$\int_0^\infty |g_y(t)|^2\ dt = \int_0^\infty |F(t)|^2 \left|e^{-2\pi ty}\right|^2\ dt \leq \int_0^\infty |F(t)|^2\ dt$$

which is again finite. Therefore $g \in L^2(0, \infty)$. Therefore by Plancherel's theorem (refer theorem 3.4.1) on g_y we get that,

$$\int_{-\infty}^\infty |f(x + iy)|^2\ dx = \int_{-\infty}^\infty |\widehat{g_y}(x)|^2\ dx = \int_{-\infty}^\infty |g_y(t)|^2\ dt = \int_0^\infty |g_y(t)|^2\ dt$$

Note that the change in limit in the last integral is because $g_y(t) = 0$ when $t < 0$. But from last inequality

$$\int_0^\infty |g_y(t)|^2\ dt \leq \int_0^\infty |F(t)|^2\ dt$$

which is finite since $F \in L^2(0, \infty)$, and independent of y. Therefore

$$\sup_{0 < y < \infty} \int_{-\infty}^\infty |f(x + iy)|^2\ dx \leq \int_0^\infty |F(t)|^2\ dt$$

$\square$

Proposition 4.1.2. *Let $0 < A < \infty$ and $F \in L^2(-A, A)$. Then $f : \mathbb{C} \to \mathbb{C}$ defined as*

$$f(z) = \int_{-A}^A F(z)e^{2\pi itz}\ dt$$

is an entire function which satisfy

$$|f(z)| \leq Ce^{2\pi A|z|}$$

for some constant C and f when restricted to horizontal lines is bounded in the L^2 norm. That is if $f(z)$ is written as $f(x + iy)$ then

$$\int_{-\infty}^\infty f(x + iy)\ dx < \infty$$

Proof. Like in proof of the above theorem for $z \in \mathbb{C}$ we write $z = x + iy$. Then

$$f(x + iy) = \int_{-A}^{A} F(t) e^{2\pi it(x+iy)} \, dt = \int_{-A}^{A} F(t) e^{-2\pi ty} e^{2\pi itx} \, dt$$

Therefore since $|e^{2\pi itx}| = 1$,

$$|f(x+iy)| \leq \int_{-A}^{A} |F(t)| \, e^{-2\pi ty} \, dt \leq e^{2\pi A|y|} \int_{-A}^{A} |F(t)| \, dt$$

We know that $F \in L^2(-A, A)$. But since $(-A, A)$ under Lebesgue measure is a finite measure space, $f \in L^1(-A, A)$. And therefore the last integral above is finite. Let's call it C. Also since $e^{\Im(z)} \leq e^z$, it follows that

$$|f(z)| \leq C e^{2\pi A|z|}$$

Now consider points $z \in \mathbb{C}$. Then for $\delta \in \mathbb{C}$,

$$f(z + \delta) - f(z) = \int_{-A}^{A} F(t) \left(e^{it(z+\delta)} - e^{itz} \right) \, dt$$

$$\leq \left(\int_{-A}^{A} |F(t)|^2 \, dt \right)^{\frac{1}{2}} \left(\int_{-A}^{A} \left| e^{it(z+\delta)} - e^{itz} \right|^2 \, dt \right)^{\frac{1}{2}}$$

Now the first integral is finite since $F \in L^2(-A, A)$. Again since e^{itz} is a continuous function in a finite measure space it is in $L^2(-A, A)$ and by a change of variable $r = At$, a we can use proposition 2.1.1 and conclude that the second integral converge to zero as $\delta \to 0$. Therefore f is continuous in the whole of $\mathbb{C}$.

Moreover if γ is any closed path in $\mathbb{C}$, and Ω is the interior of the space enclosed by γ, then $(-A, A) \times \Omega$ is a finite measure space. Therefore by Fubini's Theorem we change of order of integration and

$$\int_{\gamma} f(z) \, dz = \int_{\gamma} \int_{-A}^{A} F(t) e^{2\pi itz} \, dt \, dz = \int_{-A}^{A} F(t) \int_{\gamma} e^{2\pi itz} \, dz \, dt = \int_{-A}^{A} F(t) \cdot 0 \, dt = 0$$

since $e^{2\pi itz}$ is entire. Then by Morera's theorem, f is entire. $\qquad\square$

4.2 Paley Wiener Theorems

What is interesting is that the converse of the above two results is also true. These are known as the classical Paley Wiener theorems. With the help of these we can extend the definition of Fourier transforms to holomorphic functions in the upper half plane and entire functions of exponential type (functions where $|f(z)| \leq C e^{2\pi A|z|}$).

Theorem 4.2.1 (Paley Wiener Theorem). *Let $f \in H(\Pi^+)$ and*

$$\sup_{0 < y < \infty} \frac{1}{2\pi} \int_{\mathbb{R}} |f(x+iy)|^2 \ dx = C < \infty$$

Then there exists an $F \in L^2(0, \infty)$ such that for $z \in \Pi^+$,

$$f(z) = \int_0^\infty F(t) e^{2\pi i t z} \ dt$$

and

$$\int_0^\infty |F(t)|^2 \ dt = C$$

Note. Let's analyse this intuitively. Rewriting the second equation in the theorem, we see that

$$f(x+iy) = e^{-2\pi t y} \int_0^\infty F(t) e^{2\pi i t x} \ dt$$

which implies

$$\int_0^\infty F(t) e^{2\pi i t x} \ dt = e^{2\pi t y} f(x+iy)$$

From this we see that the required function F is the inverse transform of $f(x + iy) e^{2\pi t y}$ along the horizontal line $\Im(z) = y$ Therefore a good candidate is

$$F(t) = \int_{\mathbb{R}} f(x+iy) e^{2\pi t y} e^{-2\pi i t x} \ dy = \int_{\Im(z)=y} f(z) e^{-2\pi i t z} \ dz$$

Here the left hand side of the equation seems to be depending on only t, while the left hand side seems to depend on y. So we will have that the value fo $F(t)$ is independent of y, i.e $F(t)$ will depend only on the choice of the function f and not the horizontal lines in which f is evaluated.

Proof.   □

[Axl20] [Rud87], Grafakos et al. [Gra+17]

Appendix A

Results from Measure Theory

Here'll we'll discuss some important results from measure theory which are essential for our subject. We already defined what is an L^p function in a given space at Definition 1.1.1.

Proposition A.0.1. *Continuous functions in* $\mathbb{T}$, *(refer Definition 1.1.3) are dense in* $L^p(\mathbb{T})$ *for* $1 \leq p < \infty$.

Proof. This is a direct consequence of [Rud87, Theorem 3.14 on p. 69]. Since $\mathbb{T}$ is identified with $[0, 1)$, all continuous functions in $\mathbb{T}$ are compactly supported. $\square$

Proposition A.0.2. *Let* $C_c(\mathbb{R})$ *be the set of all compactly supported continuous functions in* $\mathbb{R}$, *then* $C_c(\mathbb{R})$ *is dense in* $L^p(\mathbb{R})$. *This is [Rud87, Theorem 3.14 p. 69].*

Proposition A.0.3. $L^1(\mathbb{R}) \cap L^2(\mathbb{R})$ *is dense in* $L^2(\mathbb{R})$.

Proof. Let $C_c(\mathbb{R})$ denote the set of compactly supported continuous functions in $\mathbb{R}$. Since every function is continuous and compactly supported, $C_c(\mathbb{R}) \subset L^p(\mathbb{R})$ for all $1 \leq p < \infty$. Therefore $C_c(\mathbb{R}) \subset L^1(\mathbb{R}) \cap L^2(\mathbb{R})$. Then by [Rud87, Theorem 3.14 on p. 69] $C_c(\mathbb{R})$ is dense in $L^2(\mathbb{R})$ and therefore $L^1(\mathbb{R}) \cap L^2(\mathbb{R})$ is dense in $L^2(\mathbb{R})$. $\square$

If you follow the proof of the above theorem close enough, you'll see that we can make a stronger claim. Since, $C_c(\mathbb{R}) \subset L^p(\mathbb{R})$ for all $1 \leq p < \infty$,

$$C_c(\mathbb{R}) \subset \bigcap_{1 \leq p < \infty} L^p(\mathbb{R})$$

and therefore again by [Rud87, Theorem 3.14 on p. 69], $\bigcap_{1 \leq p < \infty} L^p(\mathbb{R})$ is dense in $L^q(\mathbb{R})$ for all $1 \leq q < \infty$. We will state the generalization of this as a seperate result.

Proposition A.0.4. *If $f \in L^p(\mathbb{R})$, then*

$$\lim_{\delta \to 0} \int_{\mathbb{R}} |f(x + \delta) - f(x)|^p \ dx = 0$$

Proof. Since $f \in L^p(\mathbb{R})$, for every $\epsilon > 0$ there exist an X such that

$$\left(\int_{|x| > X-1} |f(x)|^p \ dx \right)^{\frac{1}{p}} < \epsilon$$

Therefore by Minkowski's inequality, for $\delta \leq 1$,

$$\left(\int_{\mathbb{R}} |f(x + \delta) - f(x)|^p \ dx \right)^{\frac{1}{p}} \leq \left(\int_{-X}^{X} |f(x + \delta) - f(x)|^p \ dx \right)^{\frac{1}{p}} + 2\epsilon$$

Now since $C_c(\mathbb{R}) \cap L^p(\mathbb{R})$ are dense in $L^p(\mathbb{R})$ by Proposition A.0.2, there exists a $g \in C([-X - 1, X + 1]) \cap L^p([-X - 1, X + 1])$ such that

$$\|f - g\|_{L^p([-X-1,X+1])} = \left(\int_{-X-1}^{X+1} |f(x) - g(x)|^p \ dx \right)^{\frac{1}{p}} < \epsilon$$

Then by Minkowski's inequality

$$\left(\int_{-X}^{X} |f(x + \delta) - f(x)|^p \ dx \right)^{\frac{1}{p}} \leq \left(\int_{-X}^{X} |g(x + \delta) - g(x)|^p \ dx \right)^{\frac{1}{p}} + 2\epsilon$$

Now since g is continuous in a compact space $[-X - 1, X + 1]$, it is uniformly continuous. and since ϵ does not depend on the therefore as $\delta \to 0$ the above integral tends to 0. Hence the proof. $\square$

Bibliography

[Axl20]   Sheldon Axler. *Measure, Integration & Real Analysis*. Vol. 282. Graduate Texts in Mathematics. Springer, 2020. ISBN: 978-3-030-33143-6.

[Gra+17]   Loukas Grafakos et al. "Some Problems in Harmonic Analysis". In: (Jan. 2017). DOI: 10.48550/ARXIV.1701.06637. arXiv: 1701.06637.

[Pin09]   Mark A. Pinsky. *Introduction to fourier analysis and wavelets*. American Mathematical Society, 2009. ISBN: 9780821847978.

[Rud87]   Walter Rudin. *Real and complex analysis*. McGraw-Hill, 1987, p. 483. ISBN: 978-0-07-054234-1.