Notes on Fourier Analysis

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1 Notation and Preliminaries

Let $\mathrm{i} = \sqrt{-1}$; the italicized variant i is reserved for indices. For $D \subseteq \mathbb{R}$ and $k \in \mathbb{Z}_{\geq 0}$, let $C^k(D)$ denote the set of functions from D to $\mathbb{R}$ that are k times continuously differentiable.

Definition 1.1. The length of an interval I, denoted as $\mu(I)$, is the difference between its right endpoint and its left. We shall restrict the definition of intervals to those with positive length.

Definition 1.2. Let $D \subseteq \mathbb{R}$. A function from D to $\mathbb{R}$ is said to be piecewise continuous if it is bounded and admits at most finitely many discontinuities.

Definition 1.3. A partition of $[a, b]$ is a finite subset of $[a, b]$ containing a and b. It is typically denoted as $a = x_0 < \cdots < x_n = b$.

Definition 1.4. A bounded function $f\colon [a, b] \to \mathbb{R}$ is said to be Riemann integrable if for any $\epsilon > 0$ there exists a partition $P = \{x_0, \cdots, x_n\}$ of $[a, b]$ such that

$$\mathcal{U}(P, f) - \mathcal{L}(P, f) < \epsilon,$$

where $a = x_0 < \cdots < x_n = b$. Here, we define

$$\begin{cases} \mathcal{U}(P, f) \coloneqq \sum_{i=1}^{n} \sup f([x_{i-1}, x_i]) \cdot (x_i - x_{i-1}) \\ \mathcal{L}(P, f) \coloneqq \sum_{i=1}^{n} \inf f([x_{i-1}, x_i]) \cdot (x_i - x_{i-1}). \end{cases}$$

Definition 1.5. If a bounded function $f\colon [a, b] \to \mathbb{R}$ is Riemann integrable, then $\sup U(P, f)$ and $\inf U(P, f)$ coincide, where the supremum and the infimum are both taken over partitions of $[a, b]$. This common value is defined as the Riemann integral of f over $[a, b]$, denoted as $\int_a^b f(x)\,\mathrm{d}x$.

Definition 1.6. A bounded function $f\colon [a, b] \to \mathbb{C}$ is said to be Riemann integrable if $\Re \circ f$ and $\Im \circ f$ are Riemann integrable. The Riemann integrable of f over $[a, b]$ is defined as $\int_a^b \Re f(x)\,\mathrm{d}x + \mathrm{i} \cdot \int_a^b \Im f(x)\,\mathrm{d}x$, denoted also as $\int_a^b f(x)\,\mathrm{d}x$.

Definition 1.7. The set of all Riemann integrable functions from $[a, b]$ to $\mathbb{C}$ is denoted as $\mathcal{R}([a, b])$.

Theorem 1.8 (Weierstrass' M-Test). *Let $\{f_n(x)\}_{n=1}^{\infty}$ be a sequence of functions from $A \subseteq \mathbb{R}$ to $\mathbb{C}$. Suppose there exists a sequence $\{M_n\}_{n=1}^{\infty}$ of non-negative numbers such that $\sum_{n=1}^{\infty} M_n$ converges and $|f_n(x)| \leq M_n$ for all $n \in \mathbb{Z}_{>0}$ and all $x \in A$. Then, $\sum_{n=1}^{\infty} f_n(x)$ converges absolutely and uniformly on A.*

Proof. Let $T \coloneqq \sum_{n=1}^{\infty} M_n \geq 0$ and define $S(x) \coloneqq \sum_{n=1}^{\infty} f_n(x)$ formally. The latter converges pointwise absolutely. Denote $S_n(x) \coloneqq f_1(x) + \cdots + f_n(x)$.

Let $\epsilon > 0$. Because $M_1 + \cdots + M_N$ converges to T as $N \to \infty$, the partial sums can be arbitrarily close to T. In particular, fix $N \in \mathbb{Z}_{>0}$ such that $|T - (M_1 + \cdots + M_N)| < \epsilon$. Then,

$$\left| \sum_{n=1}^{\infty} f_n(x) - \sum_{n=1}^{N} f_n(x) \right| \leq \sum_{n=N+1}^{\infty} |f_n(x)| \leq \sum_{n=N+1}^{\infty} M_n < \epsilon.$$

The proof is complete. □

2 Fourier Series

Continuous functions on a compact interval form an inner product space, and the Fourier "basis" functions form an orthonormal collection whose span can approximate continuous functions by projecting thereto. This is true in greater generality, and the various senses of convergence of the Fourier series are discussed.

2.1 Definitions

We first define the structure on Riemann integrable functions.

Proposition 2.1. Let $f\colon [a,b] \to [0,+\infty)$ be continuous. Then, $\int_a^b f(x)\,\mathrm{d}x = 0$ implies f is identically zero.

Proof. Suppose for contradiction that $0 \in [a,b]$ and $f(0) > 0$ without loss of generality. Fix $\delta > 0$ such that $f(x) > f(0)/2$ for all $x \in (-\delta,\delta) \cap [a,b]$. Let $I \coloneqq [-\delta,\delta] \cap [a,b]$, which is an interval via straightforward verification when $0 = a$, $a < 0 < b$, and $0 = b$. Then,

$$\int_a^b f(x)\,\mathrm{d}x = \int_I f(x)\,\mathrm{d}x + \int_{[a,b]\setminus I} f(x)\,\mathrm{d}x \geq \int_I \frac{f(0)}{2}\,\mathrm{d}x \geq \frac{f(0)\mu(I)}{2} > 0,$$

a contradiction. □

Corollary 2.2. The set $C^0([a,b])$ of complex-valued, continuous functions on a segment $[a,b]$ is made into an infinite-dimensional inner product space with the inner product

$$\langle f,g\rangle \coloneqq \frac{1}{L}\int_a^b f(x)\cdot\overline{g(x)}\,\mathrm{d}x,$$

where $L = b - a > 0$.

Proof. We first show that the inner product is well-defined. Suppose $f,g \in C^0([a,b])$. Firstly, $\langle f,f\rangle = \frac{1}{L}\int_a^b |f(x)|^2\,\mathrm{d}x$ is clearly non-negative. When it is equal to zero, $|f(x)|^2$ is identically zero, so $f(x)$ is identically zero. (Sesqui)-linearity and conjugate symmetry are straightforward, which concludes this proof. □

Definition 2.3. Let $[a,b]$ be an interval. For $n \in \mathbb{Z}$, the n-th Fourier basis function on $[a,b]$ is defined as $e_n \coloneqq [a,b] \to \mathbb{C}$ via $e_n(x) \coloneqq \mathrm{e}^{2\pi i n x/L}$, where $L = b - a > 0$.

Lemma 2.4. $\{e_n\}_{n=-\infty}^{\infty}$ is an orthonormal set of vectors in $C^0([a,b])$.

Proof. Suppose $m,n \in \mathbb{Z}$. Then,

$$\langle e_n, e_m\rangle = \frac{1}{L}\int_a^b \mathrm{e}^{2\pi\mathrm{i}(n-m)x/L}\,\mathrm{d}x.$$

When $n = m$, the integrand is 1 and $\langle e_n, e_n\rangle = 1/L \cdot L = 1$. Otherwise, the integral is

$$\langle e_n, e_m\rangle = \frac{1}{L}\cdot\frac{1}{2\pi\mathrm{i}(n-m)/L}\cdot\cancel{\mathrm{e}^{2\pi\mathrm{i}(n-m)x/L}\Big|_{x=a}^{b}} = 0.$$

The proof is finished. □

Definition 2.5. Let $f \in \mathcal{R}([a,b])$. The n-th Fourier coefficient of f, where $n \in \mathbb{Z}$, is defined as $\hat{f}(n) \coloneqq \langle f, e_n\rangle$, where $L \coloneqq b - a$.

Definition 2.6. Let $f \in \mathcal{R}([a,b])$. The Fourier series of f is the formal series

$$\sum_{n=-\infty}^{\infty} \hat{f}(n)\cdot e_n(x)$$

with an indeterminate $x \in \mathbb{R}$.

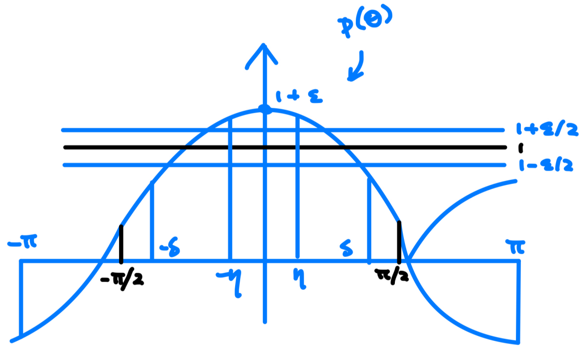

Figure 1: The plot of $p(\theta)$ in the proof of Theorem 2.10

One typically writes

$$f(x) \sim \sum_{n=-\infty}^{\infty} \hat{f}(n) \cdot e_n(x)$$

to denote that $f(x)$ has the Fourier series on the right-hand side of the $\sim$ relation.

Definition 2.7. A function $f\colon \mathbb{R} \to \mathbb{C}$ is said to be a trigonometric series if it admits the form

$$f(x) = \sum_{n=-\infty}^{\infty} c_n \cdot e_n(x) \qquad \text{for all } x \in \mathbb{R}$$

for some complex-valued sequence $\{c_n\}_{n=-\infty}^{\infty}$.

Definition 2.8. A trigonometric polynomial p is a trigonometric series whose associated sequence $\{c_n\}_{n=-\infty}^{\infty}$ has all but finitely many zero terms. The degree of the trigonometric polynomial, denoted as $\deg p$, is defined as $\max_{n\in\mathbb{Z}} |n|$ subject to $c_n \neq 0$.

Corollary 2.9. Trigonometric polynomials are closed under addition, negation, and multiplication.

Proof. That trigonometric polynomials are closed under addition and negation is immediate. Suppose

$$f(x) = \sum_{n=-N}^{N} a_n \cdot e_n(x) \qquad \text{and} \qquad g(x) = \sum_{n=-N}^{N} b_n \cdot e_n(x)$$

are trigonometric polynomials, where $N \in \mathbb{Z}_{\geq 0}$. Then,

$$f(x) \cdot g(x) = \sum_{n=-N}^{N} \sum_{m=-N}^{N} a_n b_m \cdot e_n(x) e_m(x) = \sum_{n=-N}^{N} \sum_{m=-N}^{N} a_n b_m \cdot e_{m+n}(x) = \sum_{k=-2N}^{2N} \left(\sum_{n=\max\{-N,k-N\}}^{\min\{N,k+N\}} a_n b_{k-n} \right) \cdot e_k(x).$$

The proof is complete. □

Theorem 2.10. *Let $f \in \mathcal{R}(\mathbb{R})$ be 2π-periodic with $\hat{f}(n) = 0$ for all $n \in \mathbb{Z}$. Then, $f(\theta_0) = 0$ if f is continuous at θ_0.*

Proof. First, suppose f is real-valued. Without loss of generality, suppose $\theta = 0$ and $f(0) > 0$. Fix $0 < \delta \leq \pi/2$ such that $f(x) > f(0)/2$ whenever $|\theta| < \delta$. Let $p(\theta) \coloneqq \epsilon + \cos\theta$, which is a trigonometric polynomial, where $\epsilon > 0$ is chosen sufficiently small such that $|p(\theta)| < 1 - \epsilon/2$ whenever $\delta \leq |\theta| \leq \pi$. Fix $0 < \eta < \delta$ such that $p(\theta) \geq 1 + \epsilon/2$ whenever $|\theta| < \eta$. Define $p_k(\theta) \coloneqq p(\theta)^k$ for $k \in \mathbb{Z}_{\geq 0}$ and fix $B > 0$ such that $|f(\theta)| \leq B$ for all $\theta \in \mathbb{R}$.

We make three observations to estimate the integral $\int_a^b f(\theta) \cdot p_k(\theta)\, \mathrm{d}\theta$ by splitting the domain into three parts, where θ is assumed to satisfy $|\theta| < \eta$, $\eta < |\theta| < \delta$, and $\delta < |\theta| < \pi$ respectively.[1]

[1] We may modify the integrands of the three integrals so that the endpoints evaluate to 0; in this way, we do not change the value of each integral but can assume strict inequalities such as these in estimation.

First, note that
$$\int_{|\theta|\leq\eta} f(\theta)\cdot p_k(\theta) \geq \int_{|\theta|\leq\eta} f(0)/2\cdot(1+\epsilon)/2^k = \eta f(0)\cdot(1+\epsilon/2)^k,$$
where the right-hand side is unbounded as $k\in\mathbb{Z}_{\geq 0}$ varies.

For the second piece, it's enough to conclude

$$\int_{\eta\leq|\theta|\leq\delta} f(\theta)\cdot p_k(\theta)\,\mathrm{d}\theta \geq 0.$$

Lastly, we have
$$\left|\int_{\delta\leq|\theta|} f(\theta)\cdot p_k(\theta)\,\mathrm{d}\theta\right| \leq \int_{\delta\leq|\theta|} |f(\theta)|\cdot|p_k(\theta)|\,\mathrm{d}\theta \leq (2\pi-2\delta)B(1-\epsilon/2)^k,$$
where the right-hand side is bounded.

Hence, $\int_{-\pi}^{\pi} f(\theta)\cdot p_k(\theta)\,\mathrm{d}\theta$ is at least an unbounded number minus a bounded number. This integral, therefore, cannot tend to 0 as $k\longrightarrow\infty$. However, since $p_k(\theta)$ is a trigonometric polynomial by induction on Corollary 2.9, we may write $p_k(\theta)=\sum_{n=S}^{T} c_n\cdot e_n$, and
$$\int_{-\pi}^{\pi} f(\theta)\cdot p_k(\theta)\,\mathrm{d}\theta = 2\pi\sum_{n=S}^{T} c_n\left(\frac{1}{2\pi}\int_{-\pi}^{\pi} f(\theta)\cdot\overline{e_{-n}(\theta)}\,\mathrm{d}\theta\right) = 0.$$

These integrals, then, must tend to 0. In particular, they cannot be unbounded, a contradiction. □

Proposition 2.11. Suppose $f\colon\mathbb{R}\longrightarrow\mathbb{R}$ is periodic and continuous with $\sum_{n=-\infty}^{\infty}|\hat{f}(n)|<\infty$. Then,

$$f(x) = \lim_{N\to\infty}\sum_{n=-N}^{N}\hat{f}(n)\cdot e_n(x) \qquad \text{for all } x\in\mathbb{R},$$

and the convergence is uniform in x.

Before proving this foundational proposition, we remark that periodicity is preserved by pointwise convergence.

Lemma 2.12. Let $P>0$. Suppose $\{f_n\}_{n=1}^{\infty}$ is a pointwise convergent sequence of P-periodic functions from $\mathbb{R}$ to $\mathbb{C}$. Then, the limit is also P-periodic.

Proof. It is immediate that for all $x\in\mathbb{R}$, $f(x+P)-f(x)=\lim_{k\to\infty} f_k(x+P)-f_k(x)=\lim 0=0$. □

We now proceed to prove the proposition.

Proof. Without loss of generality, suppose f is 2π-periodic. Let $S_N(x)\coloneqq\sum_{n=-N}^{N}\hat{f}(n)\cdot e_n(x)$ be the N-th partial sum of the Fourier series of f, where $N\in\mathbb{Z}_{\geq 0}$. By Weierstrass' M-test, $\{S_N(x)\}$ converges absolutely and uniformly. Denote the limit as $g(x)$, the Fourier series of f which must be continuous. Hence,

$$\begin{aligned}\widehat{f-g}(n) &= \langle f,e_n\rangle - \langle g,e_n\rangle && \text{(Fubini)}\\ &= \hat{f}(n) - \sum_{m=-\infty}^{\infty}\hat{f}(m)\cdot\langle e_m,e_n\rangle\\ &= \hat{f}(n) - \sum_{m=-\infty}^{\infty}\hat{f}(m)\cdot\delta_{m,n}\\ &= 0.\end{aligned}$$

The lemma implies that g is 2π-periodic as well. Then, $f-g$ is continuous and 2π-periodic, with all zero Fourier coefficients. Therefore, by Theorem 2.10, $f-g$ is identically zero. Therefore, f coincides with its Fourier series g. □

Here is a non-trivial application of Fourier series.

Proposition 2.13. $\sum_{n=1}^{\infty} 1/n^2 = \pi^2/6$.

Proof. Extend $\tilde{f}(x) = |x|$ for $x \in [-\pi, \pi]$ to a 2π-periodic function $f \colon \mathbb{R} \to \mathbb{R}$. Then, f is continuous. Observe that for all non-zero $n \in \mathbb{Z}$,

$$\begin{aligned}
\hat{f}(n) &= \frac{1}{2\pi} \int_0^{\pi} \left(f(x) \cdot \mathrm{e}^{-\mathrm{i}nx} + f(-x)\, \mathrm{e}^{\mathrm{i}nx} \right) \mathrm{d}x \\
&= \frac{1}{\pi} \int_0^{\pi} x \, \mathrm{d}\left(\frac{1}{n} \sin nx \right) \\
&= \frac{1}{\pi n} \left(\cancel{x \sin nx \big|_{x=0}^{\pi}} - \int_0^{\pi} \sin nx \, \mathrm{d}x \right) \\
&= -\frac{1}{\pi n} \int_0^{\pi} \mathrm{d}\left(-\frac{1}{n} \cos nx \right) \\
&= \frac{1}{\pi n^2} (\cos n\pi - 1).
\end{aligned}$$

It is obvious that $\hat{f}(0) = 1/2\pi \cdot 2 \cdot (1/2 \cdot \pi \cdot \pi) = \pi/2$.

Then,

$$\begin{aligned}
f(x) &= \sum_{n=-\infty}^{\infty} \frac{(-1)^n - 1}{\pi n^2} \cdot \mathrm{e}^{\mathrm{i}nx} && ((-1)^n - 1 = -2 \cdot \mathbb{I}[2 \nmid n]) \\
&= \frac{\pi}{2} - \sum_{n=1,3,\ldots} \frac{2}{\pi n^2} \cdot (\mathrm{e}^{\mathrm{i}nx} + \mathrm{e}^{-\mathrm{i}nx}) \\
&= \frac{\pi}{2} - \frac{4}{\pi} \sum_{n=1,3,\ldots} \frac{\cos nx}{n^2}
\end{aligned}$$

In particular, $f(0) = 0$ implies that $\sum_{k=1}^{\infty} 1/(2k-1)^2 = (\pi/2)/(4/\pi) = \pi^2/8$. Now observe that

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \sum_{k=1}^{\infty} \frac{1}{(2k-1)^2} + \sum_{k=1}^{\infty} \frac{1}{(2k)^2} = \frac{\pi^2}{8} + \frac{1}{4} \sum_{k=1}^{\infty} \frac{1}{k^2}.$$

Hence, $\sum_{n=1}^{\infty} \frac{1}{n^2} = (\pi^2/8)/(1 - 1/4) = \pi^2/6$. □

2.2 Convolutions

The concept of convolutions is fundamental to Fourier series and is applicable in greater generality in the context of functions.

Definition 2.14. Let $f, g \colon \mathbb{R} \to \mathbb{C}$ be 2π-periodic and Riemann integrable on $[-\pi, \pi]$. Then, the convolution of f and g, denoted as $f * g \colon \mathbb{R} \to \mathbb{C}$, is defined for all $x \in \mathbb{R}$ as

$$(f * g)(x) \coloneqq \frac{1}{2\pi} \int_{-\pi}^{\pi} f(y) g(x - y) \, \mathrm{d}y.$$

The convolution is well-defined because Riemann integrable functions are closed under pointwise multiplication. The following is immediate.

Proposition 2.15. $*$ is commutative and bilinear over the 2π-periodic functions from $\mathbb{R}$ to $\mathbb{C}$ that are Riemann integrable on $[-\pi, \pi]$.

Proof. To show commutativity, note that for all $x \in [-\pi, \pi]$,

$$2\pi \cdot (f * g)(x) = \int_{-\pi}^{\pi} f(t) \cdot g(x - t) \, \mathrm{d}t = \int_{x+\pi}^{x-\pi} f(x - t) \cdot g(t) \; -\mathrm{d}t = \int_{-\pi}^{\pi} g(t) \cdot f(x - t) \, \mathrm{d}t = 2\pi \cdot (g * f)(x).$$

To prove bilinearity, it is sufficient to show that $*$ is linear in the first component. Let $h\colon \mathbb{R} \to \mathbb{C}$ be 2π-periodic and Riemann integrable on $[-\pi, \pi]$ also. Then, for all $c \in \mathbb{C}$ and $x \in \mathbb{R}$,

$$2\pi \cdot ((c \cdot f + g) * h)(x) = \int_{-\pi}^{\pi} (c \cdot f(t) + g(t)) \cdot h(x - t)\, \mathrm{d}t = 2\pi \cdot (c \cdot (f * h)(x) + (g * h)(x)).$$

$\square$

A useful approximation lemma is first presented before proving various properties of convolutions.

Lemma 2.16 (L_1 Approximation)**.** Suppose $f\colon \mathbb{R} \to \mathbb{R}$ is 2π-periodic and Riemann integrable on $[-\pi, \pi]$. Then, there exists a sequence $\{f_k\}_{k=1}^{\infty}$ of 2π-periodic, continuous functions on $\mathbb{R}$ such that

$$\lim_{k\to\infty} \int_{-\pi}^{\pi} |f_k(x) - f(x)|\, \mathrm{d}x = 0.$$

Further, there exists a constant $B > 0$ which uniformly bounds f and f_k in the sense that

$$|f|(\mathbb{R}) \cup \bigcup_{k=1}^{\infty} |f_k|(\mathbb{R}) \subset [-B, B].$$

Proof. Let $k \in \mathbb{Z}_{>0}$ and fix a partition $P = \{x_0, \cdots, x_N\}$ of $[-\pi, \pi]$ such that $U(P, f) - L(P, f) < 1/2k$. Fix $B > 0$ such that $f(\mathbb{R}) \subset [-B, B]$. Denote $I_n \coloneqq [x_{n-1}, x_n)$ for $1 \le n < N$ and $I_N \coloneqq [x_{N-1}, x_N]$. Note that $I_1, \cdots, I_N$, whose endpoints coincide with P, partition $[-\pi, \pi]$.

Define the upper-bound step function $\tilde{f}_k(x) \coloneqq \sum_{n=1}^{N} \sup f([x_{n-1}, x_n]) \cdot \mathbb{I}[x \in I_n]$ on $[-\pi, \pi]$. Observe that $\tilde{f}_k(x) \ge f(x)$ always, and the partition has been chosen so that

$$\int_{-\pi}^{\pi} (\tilde{f}_k(x) - f(x))\, \mathrm{d}x \le U(P, f) - L(P, f) < \frac{1}{2k}.$$

Define $\delta \coloneqq \min\{\min_{1\le i\le N} \Delta x_i/3, 1/8Bk(N+1)\}$ and construct a 2π-periodic, continuous function $f_k\colon \mathbb{R} \to \mathbb{R}$ where, for all $x \in [-\pi, \pi]$,

$$f_k(x) = \begin{cases} \frac{\tilde{f}_k(x_0+\delta)}{\delta} \cdot (x - x_0) & \text{if } x_0 \le x < x_0 + \delta \\ \tilde{f}_k(x) & \text{if } x_{n-1} + \delta \le x < x_n - \delta \text{ for some } 1 \le n \le N \\ \frac{\tilde{f}_k(x_n+\delta) - \tilde{f}_k(x_n-\delta)}{2\delta} \cdot (x - x_n) + \frac{\tilde{f}_k(x_n+\delta) + \tilde{f}_k(x_n-\delta)}{2} & \text{if } x_n - \delta \le x < x_n + \delta \text{ for some } 1 \le n \le N-1 \\ -\frac{\tilde{f}_k(x_N-\delta)}{\delta} \cdot (x - x_N) & \text{if } x_N - \delta \le x \le x_N. \end{cases}$$

In other words, one obtains $f_k(x)$ from $\tilde{f}_k(x)$ by connecting the endpoints of the partition with line segments to make $f(x)$ continuous and forcing $f_k(-\pi) = f_k(\pi) = 0$ without loss of generality for the restriction of periodicity. By construction, $f([-\pi, \pi]) = \tilde{f}_k([-\pi, \pi]) \subseteq f_k([-\pi, \pi]) \subset [-B, B]$. Then,

$$\begin{aligned} \int_{-\pi}^{\pi} |f_k(x) - f(x)|\, \mathrm{d}x &\le \int_{-\pi}^{\pi} (\tilde{f}_k(x) - f(x))\, \mathrm{d}x + \int_{-\pi}^{\pi} |f_k(x) - \tilde{f}_k(x)|\, \mathrm{d}x \\ &< \frac{1}{2k} + \sum_{n=0}^{N} \int_{\max\{x_n-\delta, -\pi\}}^{\min\{x_n+\delta, \pi\}} |f_k(x) - \tilde{f}(x)|\, \mathrm{d}x \\ &< \frac{1}{2k} + (N+1) \cdot 2\delta \cdot 2B \\ &< \frac{1}{k}. \end{aligned}$$

Hence, $\int_{-\pi}^{\pi} |f_k(x) - f(x)|\, \mathrm{d}x$ tends to 0 as $k \to \infty$ by the comparison test. $\square$

Corollary 2.17. Suppose $f\colon \mathbb{R} \to \mathbb{C}$ is 2π-periodic and Riemann integrable on $[-\pi, \pi]$. Then, there exists a sequence $\{f_k\}_{k=1}^{\infty}$ of 2π-periodic, continuous functions on $\mathbb{R}$ such that

$$\lim_{k\to\infty} \int_{-\pi}^{\pi} |f_k(x) - f(x)| \,\mathrm{d}x = 0.$$

Further, there exists a constant $B > 0$ which uniformly bounds f and f_k in the sense that

$$|f|(\mathbb{R}) \cup \bigcup_{k=1}^{\infty} |f_k|(\mathbb{R}) \subset [-B, B].$$

The proof is immediate by considering the real and imaginary parts separately and is hence omitted.

We now have sufficient machinery regarding several useful properties of the convolution. To establish properties regarding all Riemann integrable functions, we first restrict our attention to continuous such functions before applying the approximation lemma above for generalization.

Lemma 2.18. Suppose $f, g, h\colon \mathbb{R} \to \mathbb{C}$ are 2π-periodic and continuous. Then,

- $f * g$ is 2π-periodic and continuous
- $(f * g) * h = f * (g * h)$
- $\widehat{f * g}(n) = \hat{f}(n) \cdot \hat{g}(n)$ for all $n \in \mathbb{Z}$.

Proof. To see that $f * g$ is 2π-periodic, one notes, for all $x \in \mathbb{R}$,

$$(f * g)(x + 2\pi) - (f * g)(x) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(t) \cdot \cancel{(g(x + 2\pi - t) - g(x - t))} \,\mathrm{d}t = 0.$$

To see that $f * g$ is continuous, we show the stronger condition of uniform continuity. Fix $B > 0$ such that $|f|(\mathbb{R}) \cup |g|(\mathbb{R}) \subset [-B, B]$. Let $\epsilon > 0$ and fix $\delta > 0$ such that $|g(x) - g(y)| < \epsilon/B$ whenever $|x - y| < \delta$, where $x, y \in \mathbb{R}$ by the (uniform) continuity of g. Consequently, if $|x - y| < \delta$, then

$$|(f * g)(x) - (f * g)(y)| \le \frac{1}{2\pi} \int_{-\pi}^{\pi} |f(t)| \cdot |g(x - t) - g(y - t)| \,\mathrm{d}t < B \cdot \frac{\epsilon}{B} = \epsilon.$$

Associativity is similarly obtained by expanding

$$\begin{aligned}
4\pi^2((f * g) * h)(x) &= \int_{-\pi}^{\pi} 2\pi (f * g)(t) \cdot h(x - t) \,\mathrm{d}t \\
&= \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} f(s) \cdot g(t - s) \cdot h(x - t) \,\mathrm{d}s \,\mathrm{d}t && \text{(Fubini)} \\
&= \int_{-\pi}^{\pi} f(s) \cdot \left(\int_{-\pi}^{\pi} g(t - s) \cdot h(x - t) \,\mathrm{d}t \right) \mathrm{d}s && (v = t - s) \\
&= \int_{-\pi}^{\pi} f(s) \cdot \left(\int_{-\pi \cancel{- s}}^{\pi \cancel{- s}} g(v) \cdot h(x - s - v) \,\mathrm{d}v \right) \mathrm{d}s \\
&= \int_{-\pi}^{\pi} f(s) \cdot 2\pi (g * h)(x - s) \,\mathrm{d}s \\
&= 4\pi^2 (f * (g * h))(x).
\end{aligned}$$

Lastly, for all $n \in \mathbb{Z}$, one has

$$\begin{aligned}
4\pi^2 \widehat{f * g}(n) &= \int_{-\pi}^{\pi} 2\pi (f * g)(x) \cdot \mathrm{e}^{-\mathrm{i}nx} \, \mathrm{d}x \\
&= \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} f(t) \cdot g(x-t) \cdot \mathrm{e}^{-\mathrm{i}nx} \, \mathrm{d}t \, \mathrm{d}x && \text{(Fubini)} \\
&= \int_{-\pi}^{\pi} f(t) \cdot \mathrm{e}^{-\mathrm{i}nt} \cdot \left(\int_{-\pi}^{\pi} g(x-t) \cdot \mathrm{e}^{-\mathrm{i}n(x-t)} \, \mathrm{d}x \right) \mathrm{d}t \\
&= \left(\int_{-\pi}^{\pi} f(t) \cdot \mathrm{e}^{-\mathrm{i}nt} \, \mathrm{d}t \right) \cdot \left(\int_{-\pi \cancel{-t}}^{\pi \cancel{-t}} g(x) \cdot \mathrm{e}^{-\mathrm{i}nx} \, \mathrm{d}x \right) \\
&= 2\pi \hat{f}(n) \cdot 2\pi \hat{g}(n).
\end{aligned}$$

The proof is finished. $\square$

It is true, though not at all straightforward, that all these properties hold for f, g being more generally Riemann integrable rather than continuous. We first approximate the convolution and obtain the result of continuity immediately.

Lemma 2.19. Suppose $f, g \colon \mathbb{R} \to \mathbb{C}$ are 2π-periodic and Riemann integrable on $[-\pi, \pi]$. If $\{f_k\}_{k=1}^{\infty}$ and $\{g_k\}_{k=1}^{\infty}$ are taken from Lemma 2.16 to approximate f and g respectively, then $f_k * g_k$ converges uniformly to $f * g$.

Proof. Let $\epsilon > 0$ and fix $K \in \mathbb{Z}_{>0}$ such that $\int_{-\pi}^{\pi} |f_k(t) - f(t)| \, \mathrm{d}t$ and $\int_{-\pi}^{\pi} |g_k(t) - g(t)| \, \mathrm{d}t$ are both less than ϵ whenever $k \geq K$. Then, for any such $k \geq K$, one has, for all $x \in \mathbb{R}$,

$$\begin{aligned}
|(f_k * g_k)(x) - (f * g)(x)| &\leq |((f_k - f) * g_k)(x)| + |(f * (g_k - g))(x)| \\
&\leq \frac{1}{2\pi} \left(\sup |g_k| (\mathbb{R}) \cdot \int_{-\pi}^{\pi} |f_k(t) - f(t)| \, \mathrm{d}t + \sup |f| (\mathbb{R}) \cdot \int_{-\pi}^{\pi} |g_k(t) - g(t)| \, \mathrm{d}t \right) \\
&\leq \frac{\max\{\sup |g_k| (\mathbb{R}), \sup |f| (\mathbb{R})\}}{2\pi} \cdot \epsilon,
\end{aligned}$$

so the convergence of $f_k * g_k$ to $f * g$ is uniform. $\square$

Corollary 2.20. Suppose $f, g \colon \mathbb{R} \to \mathbb{C}$ are 2π-periodic and Riemann integrable on $[-\pi, \pi]$. Then, $f * g$ is 2π-periodic and continuous.

Proof. That $f * g$ is continuous is immediate from the preceding lemma coupled with the continuity of each $f_k * g_k$. Periodicity follows from the same argument as in Lemma 2.18. $\square$

We also show that uniform convergence implies L^1 convergence.

Lemma 2.21. Suppose $\{f_k\}_{k=1}^{\infty}$ is a sequence of 2π-periodic functions from $\mathbb{R}$ to $\mathbb{C}$ that are Riemann integrable on $[-\pi, \pi]$. If $\{f_k\}$ converges uniformly to $f \colon \mathbb{R} \to \mathbb{C}$, then $\lim\limits_{k \to \infty} \int_{-\pi}^{\pi} |f_k(x) - f(x)| \, \mathrm{d}x = 0$.

Proof. Let $\epsilon > 0$ and fix $K \in \mathbb{Z}_{>0}$ such that $|f_k(x) - f(x)| < \epsilon / 2\pi$ for all $x \in \mathbb{R}$ and $k \geq K$. Then, for all such $k \geq K$ one has

$$\int_{-\pi}^{\pi} |f_k(x) - f(x)| \, \mathrm{d}x < 2\pi \cdot \frac{\epsilon}{2\pi} = \epsilon.$$

The proof is complete. $\square$

Proposition 2.22. Suppose $f, g, h \colon \mathbb{R} \to \mathbb{C}$ are 2π-periodic and Riemann integrable on $[-\pi, \pi]$. Then,

- $(f * g) * h = f * (g * h)$
- $\widehat{f * g}(n) = \hat{f}(n) \cdot \hat{g}(n)$ for all $n \in \mathbb{Z}$.

Proof. Fix sequences of functions $\{f_k\}$, $\{g_k\}$, and $\{h_k\}$ for f, g, and h respectively from Lemma 2.16. To show associativity, observe that for all $x \in \mathbb{R}$,

$$\begin{aligned}
&2\pi \left|(f * g) * h - (f_k * g_k) * h_k\right|(x) \\
&\leq 2\pi \cdot \left|(f * g) * (h - h_k)\right|(x) + 2\pi \cdot \left|(f * g - f_k * g_k) * h_k\right|(x) \\
&\leq \int_{-\pi}^{\pi} \underbrace{\left|(f * g)(t)\right|}_{\text{cont. hence bounded}} \left|(h - h_k)(x - t)\right| \,\mathrm{d}t + \int_{-\pi}^{\pi} \left|(f * g - f_k * g_k)(t)\right| \cdot \underbrace{\left|h_k(x - t)\right|}_{\text{bounded}} \,\mathrm{d}t \\
&\leq C \cdot \int_{-\pi}^{\pi} \left|h(x - t) - h_k(x - t)\right| \,\mathrm{d}t + C \cdot \int_{-\pi}^{\pi} \left|(f * g)(x) - (f_k * g_k)(t)\right| \,\mathrm{d}t,
\end{aligned}$$

where $C \coloneqq \max\{\sup |f * g|(\mathbb{R}), \sup |h_k|(\mathbb{R})\}$. Observe that $\int_{-\pi}^{\pi} |h(x - t) - h_k(x - t)| \,\mathrm{d}t = \int_{-\pi}^{\pi} |h(t) - h_k(t)| \,\mathrm{d}t$ tends to 0 by construction. Further, the uniform convergence of $f_k * g_k$ to $f * g$ implies $\int_{-\pi}^{\pi} |(f * g)(t) - (f_k * g_k)(t)| \,\mathrm{d}t \to 0$ by Lemmata 2.19 and 2.21. Then, both terms must converge to 0, and $|(f * g) * h - (f_k * g_k) * h_k| \to 0$.

By the same reasoning, $|f * (g * h) - f_k * (g_k * h_k)| = |(g * h) * f - (g_k * h_k) * f_k| \to 0$. Therefore, $|(f * g) * h - f * (g * h)| \leq |(f * g) * h - (f_k * g_k) * h_k| + |f_k * (g_k * h_k) - f * (g * h)| \to 0$ as $k \to \infty$. Note that $|(f * g) * h - f * (g * h)|$ is a constant w.r.t. k and hence must be 0.

To show the second item, fix $n \in \mathbb{Z}$ and first consider $\left|\widehat{f_k - f}(n)\right| \leq 1/2\pi \cdot \int_{-\pi}^{\pi} |f_k(x) - f(x)| \cdot \cancel{\left|e^{-inx}\right|} \,\mathrm{d}x$, which tends to 0 by construction; similarly, $|\widehat{g_k - g}(n)| \to 0$ as $k \to \infty$. So,

$$\left|\widehat{f * g - f_k * g_k}(n)\right| \leq \frac{1}{2\pi} \int_{-\pi}^{\pi} \left|(f * g - f_k * g_k)(x)\right| \,\mathrm{d}x \to 0$$

as has been shown when proving the first item, and

$$|\hat{f}_k(n) \cdot \hat{g}_k(n) - \hat{f}(n) \cdot \hat{g}(n)| \leq |\hat{f}_k(n)| \cdot |\widehat{g_k - g}(n)| + \left|\widehat{f_k - f}(n)\right| \cdot |\hat{g}(n)| \to 0$$

because $\hat{f}_k(n)$ is bounded uniformly in k and $|\hat{g}(n)|$ is a constant in k.

Therefore,

$$\left|\widehat{f * g}(n) - \hat{f}(n) \cdot \hat{g}(n)\right| \leq \left|\widehat{f * g - f_k * g_k}(n)\right| + \left|\hat{f}_k(n) \cdot \hat{g}_k(n) - \hat{f}(n) \cdot \hat{g}(n)\right| \to 0$$

as $k \to \infty$. Since the left-hand side is a constant w.r.t. k, it must be 0. □

While tedious, the same techniques apply over and over again. The properties of commutativity, bilinearity, and associative are no surprise. It is however noteworthy that the convolution of integrable functions is necessarily continuous. Convolutions truly "smoothen" functions.

2.3 Kernels

We now define some kernels—sequences of functions commonly used to convolve with a given function. A prototypical family of kernels, known as the Dirichlet kernels, are defined as follows.

Definition 2.23. For $N \in \mathbb{Z}_{\geq 0}$, the N-th Dirichlet kernel, denoted as $D_N : \mathbb{R} \to \mathbb{C}$, is the trigonometric polynomial defined as $D_N(x) \coloneqq \sum_{n=-N}^{N} e^{inx}$.

We first provide a closed-form expression.

Proposition 2.24. Let $N \in \mathbb{Z}_{\geq 0}$. Then N-th Dirichlet kernel is

$$D_N(x) = \frac{\sin((N + 1/2)x)}{\sin(x/2)} \qquad \text{for all } x \neq 0.$$

Proof. We sum the finite geometric series

$$\begin{aligned} D_N(x) &= \sum_{n=-N}^{N} \mathrm{e}^{\mathrm{i}nx} \\ &= \mathrm{e}^{\mathrm{i}(-N)x} \cdot \frac{1-\mathrm{e}^{\mathrm{i}(2N+1)x}}{1-\mathrm{e}^{\mathrm{i}x}} \\ &= \frac{\mathrm{e}^{-\mathrm{i}(N+1/2)x} - \mathrm{e}^{\mathrm{i}(N+1/2)x}}{\mathrm{e}^{\mathrm{i}(-1/2)x - \mathrm{e}^{\mathrm{i}(1/2)x}}} \\ &= \frac{\sin((N+1/2)x)}{\sin(x/2)}. \end{aligned}$$

The proof is finished. □

The Dirichlet kernels naturally appear when considering the partial sums of a Fourier series.

Definition 2.25. Let $f\colon \mathbb{R} \to \mathbb{C}$ be 2π-periodic and Riemann integrable on $[-\pi,\pi]$. For $N \in \mathbb{Z}_{\geq 0}$, let $S_N(f)\colon \mathbb{R} \to \mathbb{C}$ be the trigonometric polynomial defined as

$$S_N(f) = \sum_{n=-N}^{N} \hat{f}(n) \cdot \mathrm{e}^{\mathrm{i}nx} \qquad \text{for all } x \in \mathbb{R}.$$

Proposition 2.26. Let $f\colon \mathbb{R} \to \mathbb{C}$ be 2π-periodic and Riemann integrable on $[-\pi,\pi]$. Then, $S_N(f) = f * D_N$ for all $N \in \mathbb{Z}_{\geq 0}$.

Proof. For all $x \in \mathbb{R}$, one has

$$S_N(f) = \frac{1}{2\pi}\int_{-\pi}^{\pi} f(t) \cdot \sum_{n=-N}^{N} \mathrm{e}^{\mathrm{i}n(x-t)}\,\mathrm{d}t = (f * D_N)(x).$$

The proof is complete. □

We use the term "kernels" synonymously with functions. Some reasonable properties of (sequences of) kernels are quite commonplace, and we call such kernels well-behaved or an approximation to the identity.

Definition 2.27. A sequence of 2π-periodic functions $\{K_n\}_{n=1}^{\infty}$ from $\mathbb{R} \to \mathbb{C}$, also called kernels, are said to be well-behaved or to approximate the identity if

(−) For all $n \in \mathbb{Z}_{>0}$,

$$\frac{1}{2\pi}\int_{-\pi}^{\pi} K_n(x)\,\mathrm{d}x = 1.$$

(=) There exists $M > 0$ such that for all $n \in \mathbb{Z}_{>0}$,

$$\int_{-\pi}^{\pi} |K_n(x)|\,\mathrm{d}x \leq M.$$

(≡) For all $\delta > 0$,

$$\lim_{n\to\infty}\int_{\delta\leq|x|\leq\pi} |K_n(x)|\,\mathrm{d}x = 0$$

Note that the second item is a consequence of the first for non-negatively-valued kernels, which we shall also frequently encounter. In this case, one can view the well-behaved kernels as distributions on a circle that eventually peak "infinitely" at 0—approximating the Dirac δ function, in an informal sense. The utility of such kernels is seen in the following theorem.

Theorem 2.28 (Approximation to the Identity)**.** *Let $\{K_n\}_{n=1}^{\infty}$ be a family of well-behaved kernels and suppose $f\colon \mathbb{R} \to \mathbb{C}$ is 2π-periodic and integrable on $[-\pi,\pi]$. Then, for all $x \in \mathbb{R}$ where f is continuous,*

$$\lim_{n\to\infty}(f * K_n)(x) = f(x).$$

Further, if f is continuous everywhere, then the convergence $f * K_n \to f$ is uniform.

Proof. Suppose $x \in \mathbb{R}$ is given, where f is continuous at x. Let $B > 0$ where $f(\mathbb{R}) \subset [-B, B]$. Fix $M > 0$ from item ($\equiv$) of Definition 2.27.

Let $\epsilon > 0$ be arbitrary. Fix $\delta > 0$ such that $|f(x-y) - f(x)| < \epsilon/2M$ whenever $|y| \le \delta$. Fix also $N \in \mathbb{Z}_{>0}$ such that $\int_{\delta \le |y| \le \pi} |K_n(y)|\, \mathrm{d}y < \epsilon/4B$ whenever $n \ge N$. Then, for all such $n \ge N$,

$$\begin{aligned}
|(f * K_n)(x) - f(x)| &= \frac{1}{2\pi}\left|\int_{-\pi}^{\pi} K_n(y)\cdot f(x-y)\,\mathrm{d}y - \int_{-\pi}^{\pi} K_n(y)\cdot f(x)\,\mathrm{d}y\right| && (-)\\
&\le \frac{1}{2\pi}\int_{-\pi}^{\pi} |K_n(y)|\cdot|f(x-y)-f(x)|\,\mathrm{d}y\\
&= \frac{1}{2\pi}\int_{|y|\le\delta} |K_n(y)|\cdot|f(x-y)-f(x)|\,\mathrm{d}y + \frac{1}{2\pi}\int_{\delta\le|y|\le\pi} |K_n(y)|\cdot|f(x-y)-f(x)|\,\mathrm{d}y\\
&\le \frac{M}{2\pi}\cdot\frac{\epsilon}{2M} + \frac{2B}{2\pi}\cdot\frac{\epsilon}{4B} && (1/2\pi < 1)\\
&< \epsilon/2 + \epsilon/2 = \epsilon.
\end{aligned}$$

This concludes the first part of the proof. For the second part, suppose f is continuous and hence uniformly continuous. Then, the choice of $\delta > 0$ can be made independent of x, and the desired bound by ϵ still holds. Therefore, the convergence is uniform in this case. □

2.4 The Cesàro Sum

Note that the Dirichlet kernels are not well-behaved since, in particular, $D_N(0) = 1 + \cdots + 1 = 2N + 1$ is unbounded. If they were, then their approximation to the identity can be used to investigate the convergence of Fourier series with significant aid. We may then consider other senses in which the Fourier series converge, which may correspond to other kernels which are well-behaved. This is indeed the case with regards to the Cesàro sum.

Definition 2.29. Suppose $\{c_k\}_{k=1}^{\infty}$ is a sequence of complex numbers. The formal sum $\sum_{k=1}^{\infty} c_k$ is said to be Cesàro summable to $\lim_{n\to\infty} \sigma_n$ if the sequence $\{\sigma_n\}_{n=1}^{\infty}$ converges, where $\sigma_n \coloneqq (S_1 + \cdots + S_n)/n$ and $S_n \coloneqq c_1 + \cdots + c_n$ for $n \in \mathbb{Z}_{>0}$.

Cesàro summability is more general than the convergence of partial sums.

Proposition 2.30. Suppose the series $\sum_{k=1}^{\infty} c_k$ of complex numbers converges to $s \in \mathbb{C}$. Then, $\sum_{k=1}^{\infty} c_k$ is Cesàro summable to s.

Proof. Fix $B' > 0$ such that $|S_n| \le B'$ for all n, and let $B \coloneqq B' + |s| > 0$ be such that $|S_n - s| \le B$ for all n.

Let $\epsilon > 0$ be arbitrary. Fix $K \in \mathbb{Z}_{>0}$ such that for all $k \ge K$, $|S_k - s| < \epsilon/2$. Let $N \coloneqq \max\{\lceil 2BK/\epsilon\rceil, K\} \in \mathbb{Z}_{>0}$. Then, for all $n \ge N \ge K$, one has

$$\begin{aligned}
|\sigma_n - s| &\le \frac{1}{n}(|S_1 - s| + \cdots + |S_K - s|) + \frac{1}{n}(|S_{K+1} - s| + \cdots + |S_n - s|)\\
&< \frac{K}{n}\cdot B + \frac{n-K}{n}\cdot\epsilon/2 && (n \ge N \ge 2BK/\epsilon \Rightarrow K/n\cdot B \le \epsilon/2)\\
&< \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.
\end{aligned}$$

The proof is complete. □

Corollary 2.31. In Definition 2.29, for all $n \in \mathbb{Z}_{>0}$,

$$S_n - \sigma_n = \frac{0}{n}\cdot c_1 + \frac{1}{n}\cdot c_2 + \cdots + \frac{n-1}{n}\cdot c_n.$$

A theorem of Tauber states that, with suitable conditions on the summands, the Cesàro sum coincides with the limit of the partial sums.

Lemma 2.32. For all $n \in \mathbb{Z}_{>0}$, $S_n - \sigma_n = \frac{1}{n}c_2 + \cdots + \frac{n-1}{n}c_n$.

Proof. First, notice that the sets $\{(k,j) \in \mathbb{Z}^2 \mid 1 \le k \le n \wedge 1 \le j \le k\}$ and $\{(k,j) \in \mathbb{Z}^2 \mid 1 \le j \le n \wedge j \le k \le n\}$ coincide. Thus,

$$S_n - \sigma_n = \sum_{k=1}^{n} c_k - \frac{1}{n}\sum_{k=1}^{n}\sum_{j=1}^{k} c_j = \sum_{k=1}^{n} c_k - \frac{1}{n}\sum_{j=1}^{n}\sum_{k=j}^{n} c_j = \sum_{k=1}^{n}\left(1 - \frac{n-k+1}{n}\right) c_k = \frac{1}{n}c_2 + \cdots + \frac{n-1}{n}c_n.$$

The proof is finished. □

Theorem 2.33 (Tauber). *If $\sum_{n=1}^{\infty} c_n$ is Cesàro summable to $\sigma \in \mathbb{C}$ and $|c_n| = o(1/n)$ (that is, $nc_n \to 0$), then $\sum c_n$ converges to σ.*

Proof. Fix $B > 0$ such that $n \cdot |c_n| \le B$, and hence $|c_n| \le B/n \le B$, for all n.

Let $\epsilon > 0$ be arbitrary. Fix $K_1, K_2 \in \mathbb{Z}_{>0}$ such that, respectively, $k \cdot |c_k| < \epsilon/4$ for all $k \ge K_1$ and $|\sigma_k - \sigma| < \epsilon/2$ for all $k \ge K_2$; then, define $K \coloneqq \max\{K_1, K_2\}$ and $N \coloneqq \max\{\lceil 4K^2B/\epsilon \rceil, K\}$.

Then, for all $n \ge N \ge K$,

$$\begin{aligned}
|S_n - \sigma| &\le |\sigma_n - \sigma| + |S_n - \sigma_n| \\
&< \frac{\epsilon}{2} + \left(\frac{0}{n} \cdot |c_1| + \cdots + \frac{K-1}{n} \cdot |c_K|\right) + \left(\frac{K}{n^2} \cdot n\,|c_{K+1}| + \cdots + \frac{n-1}{n^2} \cdot n\,|c_n|\right) \\
&< \frac{\epsilon}{2} + \underbrace{\frac{K}{n} \cdot K \cdot B}_{\le \epsilon/4} + \underbrace{\frac{1}{n} \cdot (n-K)}_{<1} \cdot \frac{\epsilon}{4}.
\end{aligned}$$

The first underbraced portion is at most $\epsilon/4$ because we have chosen $n \ge N \ge 4K^2B/\epsilon$. Therefore, $|S_n - \sigma| < \epsilon$. □