Chapter 8: Some Special Functions

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Supplement. Fourier coefficients in Definition 8.9.

(1) Write

$$f(x) = a_0 + \sum_{n=1}^{N} (a_n \cos(nx) + b_n \sin(nx)), x \in \mathbb{R}$$

(as the textbook Rudin, Principles of Mathematical Analysis, Third Edition). Then

$$a_0 = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(x) dx.$$
$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos(nx) dx, n \in \mathbb{Z}^+.$$
$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin(nx) dx, n \in \mathbb{Z}^+.$$

(2) One might write in one different form,

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{N} (a_n \cos(nx) + b_n \sin(nx)), x \in \mathbb{R}.$$

The only difference between the new one and the old one is a_0, so a_0 should be

$$a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) dx.$$

(3) Again, one might write in one different form,

$$f(x) = \frac{a_0}{\sqrt{2}} + \sum_{n=1}^{N} (a_n \cos(nx) + b_n \sin(nx)), x \in \mathbb{R}.$$

Similarly, a_0 should be

$$a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} \frac{f(x)}{\sqrt{2}} dx.$$

(4) Recall $f(x) = \sum_{-N}^{N} c_n e^{inx}$ ($x \in \mathbb{R}$) where

$$c_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(x) e^{-inx} dx.$$

The relations among a_n, b_n of this textbook and c_n are

$$\begin{aligned} c_0 &= a_0 \\ c_n &= \frac{1}{2}\left(a_n + ib_n\right), n \in \mathbb{Z}^+. \end{aligned}$$

(5) In some textbooks (Henryk Iwaniec, Topics in Classical Automorphic Forms), it is convenient to consider periodic functions f of period 1. Define

$$e(n) = e^{2\pi i x} = \cos(2\pi x) + i\sin(2\pi x).$$

Any periodic and piecewise continuous function f has the Fourier series representation

$$f(x) = \sum_{-\infty}^{\infty} a_n e(nx)$$

with coefficients given by

$$a_n = \int_0^1 f(x)e(-nx)dx.$$

Here is one exercise for this representation. *Show that the fractional part of x, $\{x\} = x - [x]$, is given by*

$$\{x\} = \frac{1}{2} - \sum_{n=1}^{\infty} \frac{\sin(2\pi n x)}{\pi n}.$$

Supplement. Parseval's theorem 8.16.

(1) Given

$$f(x) = a_0 + \sum_{n=1}^{\infty}(a_n\cos(nx) + b_n\sin(nx)), x \in \mathbb{R}.$$

Then

$$\frac{1}{\pi}\int_{-\pi}^{\pi} |f(x)|^2 dx = 2a_0^2 + \sum_{n=1}^{\infty}(a_n^2 + b_n^2).$$

(2) Given

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n\cos(nx) + b_n\sin(nx)), x \in \mathbb{R}.$$

Then

$$\frac{1}{\pi}\int_{-\pi}^{\pi} |f(x)|^2 dx = \frac{a_0^2}{2} + \sum_{n=1}^{\infty}(a_n^2 + b_n^2).$$

(3) Given

$$f(x) = \frac{a_0}{\sqrt{2}} + \sum_{n=1}^{\infty}(a_n \cos(nx) + b_n \sin(nx)), x \in \mathbb{R}.$$

Then

$$\frac{1}{\pi}\int_{-\pi}^{\pi} |f(x)|^2 dx = a_0^2 + \sum_{n=1}^{\infty}(a_n^2 + b_n^2).$$

Exercise 8.1. *Define*

$$f(x) = \begin{cases} e^{-\frac{1}{x^2}} & (x \neq 0), \\ 0 & (x = 0). \end{cases}$$

Prove that f has derivatives of all orders at $x = 0$, and that $f^{(n)}(0) = 0$ for $n = 1, 2, 3, \ldots$

$f(x)$ is an example of non-analytic smooth function, that is, infinitely differentiable functions are not necessarily analytic. In this exercise, we will show that Taylor series of f at the origin converges everywhere to the zero function. So the Taylor series does not equal $f(x)$ for $x \neq 0$. Consequently, f is not analytic at $x = 0$.

Proof.

(1) *Show that*

$$\lim_{x \to 0} g(x)e^{-\frac{1}{x^2}} = 0$$

for any rational function $g(x) \in \mathbb{R}(x)$.

(a) Write $g(x) = \frac{p(x)}{q(x)}$ for some $p(x), q(x) \in \mathbb{R}[x]$, $g(x) \neq 0$.

(b) Write $q(x) = b_m x^m + b_{m-1}x^{m-1} + \cdots + b_0$. $q(x)$ is not identically zero, that is, there exists the unique coefficient of the least power of x in $q(x)$ which is non-zero, say $b_M \neq 0$.

(c) Thus,

$$g(x) = \frac{p(x)/x^M}{q(x)/x^M}.$$

The denominator of $g(x)$ tends to $b_M \neq 0$ as $x \to 0$. By the similar argument in Theorem 8.6(f), we have

$$\frac{p(x)}{x^M}e^{-\frac{1}{x^2}} \to 0 \text{ as } x \to 0.$$

Hence, $\lim_{x \to 0} g(x)e^{-\frac{1}{x^2}} = 0$ for any $g(x) \in \mathbb{R}(x)$.

(2) *Given any real $x \neq 0$, show that*

$$f^{(n)}(x) = g_n(x)e^{-\frac{1}{x^2}}$$

for some rational function $g(x) \in \mathbb{R}(x)$.

(a) Say $g_0(x) = 1 \in \mathbb{R}(x)$.

(b) $\mathbb{R}(x)$ is a field. *Show that $g'(x) \in \mathbb{R}(x)$ for any $g(x) \in \mathbb{R}(x)$.* Write $g(x) = \frac{p(x)}{q(x)}$ for some $p(x), q(x) \in \mathbb{R}[x]$, $q(x) \neq 0$. Thus

$$g'(x) = \frac{p'(x)q(x) - p(x)q'(x)}{q(x)^2}.$$

The numerator of $g'(x)$ is in $\mathbb{R}[x]$ since the differentiation operator on $\mathbb{R}[x]$ is closed in $\mathbb{R}[x]$. Also, the denominator of $g'(x) = q(x)^2 \neq 0$ since $\mathbb{R}[x]$ is an integral domain. Therefore, $g'(x) \in \mathbb{R}(x)$.

(c) Induction on n. For $n = 1$, we have

$$\begin{aligned} f'(x) &= g_0'(x)e^{-\frac{1}{x^2}} + g_0(x) \cdot \left(-\frac{1}{x^2}\right)' e^{-\frac{1}{x^2}} \\ &= \left(g_0'(x) + g_0(x) \cdot \left(-\frac{1}{x^2}\right)'\right) e^{-\frac{1}{x^2}} \\ &= g_1(x)e^{-\frac{1}{x^2}} \end{aligned}$$

where

$$g_1(x) = g_0'(x) + g_0(x) \cdot \left(-\frac{1}{x^2}\right)' \in \mathbb{R}(x).$$

Now assume that the conclusion holds for $n = k$. As $n = k + 1$, similar to the case $n = 1$,

$$f^{(k+1)}(x) = g_{k+1}(x)e^{-\frac{1}{x^2}}$$

where

$$g_{k+1}(x) = g_k'(x) + g_k(x) \cdot \left(-\frac{1}{x^2}\right)' \in \mathbb{R}(x).$$

By induction, the conclusion is true.

(3) Induction on n. For $n = 1$, by (1) we have

$$f'(0) = \lim_{t \to 0} \frac{e^{-\frac{1}{t^2}} - 0}{t} = 0.$$

Now assume that the statement holds for $n = k$. As $n = k + 1$, by (1)(2) we have

$$f^{(k+1)}(0) = \lim_{t \to 0} \frac{f^{(k)}(t) - f^{(k)}(0)}{t} = \lim_{t \to 0} \frac{g_k(t)e^{-\frac{1}{t^2}} - 0}{t} = 0.$$

Thus, $f^{(n)}(0) = 0$ for $n \in \mathbb{Z}^+$.

□

Exercise 8.2. *Let a_{ij} be the number in the ith row and jth column of the array*

$$\begin{array}{ccccc} -1 & 0 & 0 & 0 & \cdots \\ \frac{1}{2} & -1 & 0 & 0 & \cdots \\ \frac{1}{4} & \frac{1}{2} & -1 & 0 & \cdots \\ \frac{1}{8} & \frac{1}{4} & \frac{1}{2} & -1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{array}$$

so that

$$a_{ij} = \begin{cases} 0 & (i < j), \\ -1 & (i = j), \\ 2^{j-i} & (i > j). \end{cases}$$

Prove that

$$\sum_i \sum_j a_{ij} = -2, \qquad \sum_j \sum_i a_{ij} = 0.$$

Also see Theorem 8.3.

Proof (Brute-force).

$$\begin{aligned} \sum_i \sum_j a_{ij} &= \sum_{i=1}^{\infty} \left(\sum_{j=i} a_{ij} + \sum_{j<i} a_{ij} \right) \\ &= \sum_{i=1}^{\infty} \left(-1 + \sum_{j=1}^{i-1} 2^{j-i} \right) \\ &= \sum_{i=1}^{\infty} (-1 + (1 - 2^{1-i})) \\ &= \sum_{i=1}^{\infty} -2^{1-i} \\ &= -2. \end{aligned}$$

$$\begin{aligned}
\sum_j \sum_i a_{ij} &= \sum_{j=1}^{\infty} \left(\sum_{i=j} a_{ij} + \sum_{i>j} a_{ij} \right) \\
&= \sum_{j=1}^{\infty} \left(-1 + \sum_{i=j+1}^{\infty} 2^{j-i} \right) \\
&= \sum_{j=1}^{\infty} (-1+1) \\
&= \sum_{j=1}^{\infty} 0 \\
&= 0.
\end{aligned}$$

□

Exercise 8.3. *Prove that*

$$\sum_i \sum_j a_{ij} = \sum_j \sum_i a_{ij}$$

if $a_{ij} \geq 0$ for all i and j (the case $+\infty = +\infty$ may occur).

Note. It can be proved by Theorem 8.3 if both summations are finite.

Proof.

(1) Let $\mathscr{F}(I)$ be the collection of all finite subsets of I.

(2) Let

$$s = \sup \left\{ \sum_{(i,j) \in E} a_{ij} : E \in \mathscr{F}(\mathbb{N}^2) \right\}$$

(the case $s = +\infty$ may occur). *It suffices to show that $\sum_i \sum_j a_{ij} = s$.* The case $\sum_j \sum_i a_{ij} = s$ is similar, and thus $\sum_i \sum_j a_{ij} = \sum_j \sum_i a_{ij}$.

(3) *Show that $\sum_i \sum_j a_{ij} \geq s$.* Given any $E \in \mathscr{F}(\mathbb{N}^2)$. It is clear that

$$\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} a_{ij} \geq \sum_{(i,j) \in E} a_{ij}$$

(since $a_{ij} \geq 0$). Thus,

$$\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} a_{ij} \geq \sup \left\{ \sum_{(i,j) \in E} a_{ij} : E \in \mathscr{F}(\mathbb{N}^2) \right\} = s.$$

(4) *Show that* $\sum_i \sum_j a_{ij} \leq s$. (Reductio ad absurdum) If $\sum_i \sum_j a_{ij} > s$, especially $s < \infty$, then there exists $\varepsilon > 0$ such that

$$\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} a_{ij} > s + \varepsilon,$$

or

$$\sum_{i=1}^{n} \sum_{j=1}^{\infty} a_{ij} > s + \varepsilon$$

for some integer n. Consider two possible cases.

(a) If there is some $1 \leq i_0 \leq n$ such that

$$\sum_{j=1}^{\infty} a_{i_0 j} = \infty,$$

then there is some m such that

$$\sum_{j=1}^{m} a_{i_0 j} > s.$$

For $E = \{(i_0, 1), \ldots, (i_0, m)\} \in \mathscr{F}(\mathbb{N}^2)$,

$$\sum_{(i,j) \in E} a_{ij} = \sum_{j=1}^{m} a_{i_0 j} > s,$$

contrary to the supremum of s.

(b) Otherwise, for each $1 \leq i \leq n$ we have

$$\sum_{j=1}^{\infty} a_{ij} < \infty,$$

or there exists some m_i such that

$$\sum_{j=1}^{m_i} a_{ij} > \sum_{j=1}^{\infty} a_{ij} - \frac{\varepsilon}{n}.$$

For $E = \bigcup_{1 \leq i \leq n} \{(i,1), \ldots, (i, m_i)\} \in \mathscr{F}(\mathbb{N}^2)$,

$$\begin{aligned}
\sum_{(i,j) \in E} a_{ij} &= \sum_{i=1}^{n} \sum_{j=1}^{m_i} a_{ij} \\
&> \sum_{i=1}^{n} \left(\sum_{j=1}^{\infty} a_{ij} - \frac{\varepsilon}{n} \right) \\
&= \sum_{i=1}^{n} \sum_{j=1}^{\infty} a_{ij} - \sum_{i=1}^{n} \frac{\varepsilon}{n} \\
&> s + \varepsilon - \varepsilon \\
&= s,
\end{aligned}$$

contrary to the supremum of s.

Therefore, $\sum_i \sum_j a_{ij} \leq s$.

(5) By (3)(4), $\sum_i \sum_j a_{ij} = s$. Similarly, $\sum_j \sum_i a_{ij} = s$. Hence, $\sum_i \sum_j a_{ij} = \sum_j \sum_i a_{ij}$ (including the case $+\infty = +\infty$).

$\square$

Exercise 8.4. *Prove the following limit relations:*

(a) $\lim_{x \to 0} \frac{b^x - 1}{x} = \log b \qquad (b > 0)$.

(b) $\lim_{x \to 0} \frac{\log(1+x)}{x} = 1$.

(c) $\lim_{x \to 0} (1+x)^{\frac{1}{x}} = e$.

(d) $\lim_{n \to \infty} \left(1 + \frac{x}{n}\right)^n = e^x$.

Proof of (a).

$$\begin{aligned}
\lim_{x \to 0} \frac{b^x - 1}{x} &= \lim_{x \to 0} \frac{\exp(x \log b) - 1}{x} \\
&= \frac{d}{dx} \exp(x \log b) \bigg|_{x=0} \\
&= \exp(x \log b) \cdot \log b \big|_{x=0} \\
&= \log b.
\end{aligned}$$

$\square$

Proof of (b).

$$\begin{aligned}\lim_{x\to 0}\frac{\log(1+x)}{x} &= \frac{d}{dx}\log(1+x)\Big|_{x=0}\\ &= \frac{1}{x+1}\Big|_{x=0}\\ &= 1.\end{aligned}$$

□

Proof of (c).

$$\begin{aligned}\lim_{x\to 0}(1+x)^{\frac{1}{x}} &= \lim_{x\to 0}\exp\left(\frac{\log(1+x)}{x}\right)\\ &= \exp\left(\lim_{x\to 0}\frac{\log(1+x)}{x}\right)\\ &= \exp(1)\\ &= e.\end{aligned}$$

□

Proof of (d).

$$\begin{aligned}\lim_{n\to\infty}\left(1+\frac{x}{n}\right)^n &= \lim_{n\to\infty}\left(\left(1+\frac{x}{n}\right)^{\frac{n}{x}}\right)^x\\ &= \left(\lim_{n\to\infty}\left(1+\frac{x}{n}\right)^{\frac{n}{x}}\right)^x\\ &= \left(\lim_{y\to 0}(1+y)^{\frac{1}{y}}\right)^x\\ &= \exp(x).\end{aligned}$$

□

Exercise 8.5. *Find the following limits*

(a) $\lim_{x\to 0}\frac{e-(1+x)^{\frac{1}{x}}}{x}$.

(b) $\lim_{n\to\infty}\frac{n}{\log n}\left[n^{\frac{1}{n}}-1\right]$.

(c) $\lim_{x\to 0}\frac{\tan x - x}{x(1-\cos x)}$.

(d) $\lim_{x\to 0}\frac{x-\sin x}{\tan x - x}$.

Proof of (a). By L'Hospital's rule (Theorem 5.13),

$$\begin{aligned}
\lim_{x \to 0} \frac{e - (1+x)^{\frac{1}{x}}}{x} &= \lim_{x \to 0} \frac{-(1+x)^{\frac{1}{x}} \cdot \frac{\frac{x}{x+1} - \log(x+1)}{x^2}}{1} \\
&= \lim_{x \to 0} \left(-(1+x)^{\frac{1}{x}} \cdot \frac{\frac{x}{x+1} - \log(x+1)}{x^2} \right) \\
&= -\lim_{x \to 0} (1+x)^{\frac{1}{x}} \cdot \lim_{x \to 0} \frac{\frac{x}{x+1} - \log(x+1)}{x^2} \\
&= -e \cdot \lim_{x \to 0} \frac{\frac{x}{x+1} - \log(x+1)}{x^2} && \text{(Exercise 8.4(c))} \\
&= -e \cdot \lim_{x \to 0} \frac{-\frac{x}{(x+1)^2}}{2x} \\
&= e \cdot \lim_{x \to 0} \frac{1}{2(x+1)^2} \\
&= e \cdot \frac{1}{2} \\
&= \frac{e}{2}.
\end{aligned}$$

Here

$$\begin{aligned}
\frac{d}{dx} \left(e - (1+x)^{\frac{1}{x}} \right) &= \frac{d}{dx} \left(e - \exp\left(\frac{\log(x+1)}{x} \right) \right) \\
&= -\exp\left(\frac{1}{x} \log(x+1) \right) \cdot \frac{\frac{1}{x+1} \cdot x - \log(x+1) \cdot 1}{x^2} \\
&= -(1+x)^{\frac{1}{x}} \cdot \frac{\frac{x}{x+1} - \log(x+1)}{x^2},
\end{aligned}$$

and

$$\begin{aligned}
\frac{d}{dx} \left(\frac{x}{x+1} - \log(x+1) \right) &= \frac{(x+1) - x}{(x+1)^2} - \frac{1}{x+1} \\
&= -\frac{x}{(x+1)^2}.
\end{aligned}$$

$\square$

Proof of (b).

(1) Let $x = \frac{\log n}{n}$. Note that $\lim_{n \to \infty} \frac{\log n}{n} = 0$.

(2)

$$\begin{aligned}
\lim_{n\to\infty} \frac{n}{\log n}\left[n^{\frac{1}{n}} - 1\right] &= \lim_{n\to\infty} \frac{n}{\log n}\left[\exp\left(\frac{\log n}{n}\right) - 1\right] \\
&= \lim_{x\to 0} \frac{\exp(x) - 1}{x} && ((1)) \\
&= \frac{d}{dx}\exp(x)\bigg|_{x=0} \\
&= \exp(x)|_{x=0} \\
&= 1.
\end{aligned}$$

□

Proof of (c) (L'Hospital's rule). By L'Hospital's rule (Theorem 5.13) three times,

$$\begin{aligned}
\lim_{x\to 0} \frac{\tan x - x}{x(1-\cos x)} &= \lim_{x\to 0} \frac{\sec^2 x - 1}{1 - \cos x + x\sin x} \\
&= \lim_{x\to 0} \frac{2\sec x(\tan x \sec x)}{\sin x + \sin x + x\cos x} \\
&= \lim_{x\to 0} \frac{2\tan x \sec^2 x}{2\sin x + x\cos x} \\
&= \lim_{x\to 0} \frac{2[\sec^2 x \sec^2 x + \tan x \cdot 2\sec x(\tan x \sec x)]}{2\cos x + \cos x - x\sin x} \\
&= \lim_{x\to 0} \frac{2\sec^4 x + 2\sec^2 x \tan^2 x}{3\cos x - x\sin x} \\
&= \frac{2}{3}.
\end{aligned}$$

□

Proof of (c) (Taylor series). Since

$$\begin{aligned}
\cos x &= 1 - \frac{x^2}{2} + O(x^4) \\
\tan x &= x + \frac{x^3}{3} + O(x^5),
\end{aligned}$$

we have

$$\lim_{x\to 0} \frac{\tan x - x}{x(1-\cos x)} = \lim_{x\to 0} \frac{\frac{x^3}{3} + O(x^5)}{\frac{x^3}{2} + O(x^5)} = \frac{2}{3}.$$

□

Proof of (d) (L'Hospital's rule). By L'Hospital's rule (Theorem 5.13) three times,

$$\begin{aligned}
\lim_{x\to 0} \frac{x-\sin x}{\tan x - x} &= \lim_{x\to 0} \frac{1-\cos x}{\sec^2 x - 1} \\
&= \lim_{x\to 0} \frac{\sin x}{2\sec x(\tan x \sec x)} \\
&= \lim_{x\to 0} \frac{\sin x}{2\tan x \sec^2 x} \\
&= \lim_{x\to 0} \frac{\cos x}{2\tan x \sec^2 x} \\
&= \lim_{x\to 0} \frac{\cos x}{2[\sec^2 x \sec^2 x + \tan x \cdot 2\sec x(\tan x \sec x)]} \\
&= \lim_{x\to 0} \frac{\cos x}{2\sec^4 x + 2\sec^2 x \tan^2 x} \\
&= \frac{1}{2}.
\end{aligned}$$

□

Proof of (d) (Taylor series). Since

$$\begin{aligned}
\sin x &= x - \frac{x^3}{6} + O(x^5) \\
\tan x &= x + \frac{x^3}{3} + O(x^5),
\end{aligned}$$

we have

$$\lim_{x\to 0} \frac{x-\sin x}{\tan x - x} = \lim_{x\to 0} \frac{\frac{x^3}{6} + O(x^5)}{\frac{x^3}{2} + O(x^5)} = \frac{1}{2}.$$

□

Exercise 8.6. *Suppose $f(x)f(y) = f(x+y)$ for all real x and y.*

(a) *Assuming that f is differentiable and not zero, prove that*

$$f(x) = e^{cx}$$

where c is a constant.

(b) *Prove the same thing, assuming only that f is continuous.*

Part (b) implies part (a). We prove part (b) directly.

Proof of (b).

(1) Since $f(x)$ is not zero, there exists $x_0 \in \mathbb{R}$ such that $f(x_0) \neq 0$. So $f(0)f(x_0) = f(x_0)$, or $f(0) = 1$ by cancelling $f(x_0) \neq 0$.

(2) Next, $f(\frac{n}{m}) = f(\frac{1}{m})^n$ for $m \in \mathbb{Z}$, $n \in \mathbb{Z}^+$. Since f is continuous at $x = 0$, f is positive in the neighborhood of $x = 0$. That is, there exists $N \in \mathbb{Z}^+$ such that $f(\frac{1}{m}) > 0$ whenever $|m| \geq N$. So, $f(\frac{n}{m}) = f(\frac{1}{m})^n > 0$. (Since $f(\frac{n}{m}) = f(\frac{kn}{km})$ for any $k \in \mathbb{Z}^+$, we can rescale m to km such that $|km| \geq N$.) That is, f is positive on $\mathbb{Q}$. Since $\mathbb{Q}$ is dense in $\mathbb{R}$ and f is continuous on $\mathbb{R}$, f is positive on $\mathbb{R}$.

(3) Now let $c = \log f(1)$ (which is well-defined since $f > 0$). We write $f(1)$ in the two ways. Firstly, $f(1) = f(\frac{n}{n}) = f(\frac{1}{n})^n$ where $n \in \mathbb{Z}^+$. Secondly, $f(1) = e^c = (e^{\frac{c}{n}})^n$. Since the positive n-th root is unique (Theorem 1.21), $f(\frac{1}{n}) = e^{\frac{c}{n}}$ for $n \in \mathbb{Z}^+$. By $f(x)f(-x) = f(0) = 1$ or $f(-x) = \frac{1}{f(x)}$, $f(-\frac{1}{n}) = \frac{1}{e^{\frac{c}{n}}} = e^{-\frac{c}{n}}$ for $n \in \mathbb{Z}^+$. Therefore,

$$f\left(\frac{1}{m}\right) = e^{\frac{c}{m}} \text{ where } m \in \mathbb{Z}.$$

(4) By using $f(\frac{n}{m}) = f(\frac{1}{m})^n$ for $m \in \mathbb{Z}$, $n \in \mathbb{Z}^+$ again, $f(\frac{n}{m}) = e^{c\frac{n}{m}}$ where $m \in \mathbb{Z}, n \in \mathbb{Z}^+$, or

$$f(x) = e^{cx} \text{ where } x \in \mathbb{Q}.$$

Since $g(x) = f(x) - e^{cx}$ vanishes on a dense set of $\mathbb{Q}$ and g is continuous on $\mathbb{R}$, g vanishes on $\mathbb{R}$. Therefore, $f(x) = e^{cx}$ for $x \in \mathbb{R}$.

□

Supplement. *Proof of (a).*

(1) Since $f(x)$ is not zero, there exists $x_0 \in \mathbb{R}$ such that $f(x_0) \neq 0$. So $f(0)f(x_0) = f(x_0)$, or $f(0) = 1$ by cancelling $f(x_0) \neq 0$.

(2) Since f is differentiable, for any $x \in \mathbb{R}$,

$$\begin{aligned} f'(x) &= \lim_{h \to 0} \frac{f(x+h) - f(x)}{h} \\ &= \lim_{h \to 0} \frac{f(x)f(h) - f(x)}{h} \\ &= f(x) \lim_{h \to 0} \frac{f(h) - 1}{h} \\ &= f(x) \lim_{h \to 0} \frac{f(h) - f(0)}{h} \\ &= f(x)f'(0). \end{aligned}$$

Let $c = f'(0)$ be a constant. Then $f'(x) = cf(x)$. So $f(x) = e^{cx}$ for $x \in \mathbb{R}$. (To see this, let $g(x) = \frac{f(x)}{e^{cx}}$ be well-defined on $\mathbb{R}$. $g(0) = 1$. $g'(x) = 0$ since $f'(x) = cf(x)$. So $g(x)$ is a constant, or $g(x) = 1$ since $g(0) = 1$. Therefore, $f(x) = e^{cx}$ on $\mathbb{R}$.)

□

Supplement. Cauchy's functional equation.

(1) *(Cauchy's functional equation.) Suppose $f(x) + f(y) = f(x + y)$ for all real x and y. Assuming that f is continuous, prove that $f(x) = cx$ where c is a constant.*

Notice that we cannot let $g(x) = \log f(x)$ and apply Cauchy's functional equation on $g(x)$ to prove Exercise 8.6 since $f(x)$ is not necessary positive and thus $g(x) = \log f(x)$ might be meaningless. However, this wrong approach gives you some useful ideas such as you need to prove that $f(x)$ is positive first, and $f(x)$ should be equal to e^{cx} where $c = g(1) = \log f(1)$.

(2) *Suppose $f(xy) = f(x) + f(y)$ for all positive real x and y. Assuming that f is continuous, prove that $f(x) = c \log x$ where c is a constant.*

(3) *Suppose $f(xy) = f(x)f(y)$ for all positive real x and y. Assuming that f is continuous and positive, prove that $f(x) = x^c$ where c is a constant.*

(4) *Suppose $f(x + y) = f(x) + f(y) + xy$ for all real x and y. Assuming that f is continuous, prove that $f(x) = \frac{1}{2}x^2 + cx$ where c is a constant.*

(5) *(USA 2002.) Suppose $f(x^2 - y^2) = xf(x) - yf(y)$ for all real x and y. Assuming that f is continuous, prove that $f(x) = cx$ where c is a constant.*

Supplement. *Show that the only automorphism of $\mathbb{Q}$ is the identity.*

Proof. Given any $\sigma \in \mathrm{Aut}(\mathbb{Q})$.

(1) *Show that $\sigma(1) = 1$.* Since $1^2 = 1$, $\sigma(1)\sigma(1) = \sigma(1)$. $\sigma(1) = 0$ or 1. There are only two possible cases.

   (a) Assume that $\sigma(1) = 0$. So

   $$\sigma(a) = \sigma(a \cdot 1) = \sigma(a) \cdot \sigma(1) = \sigma(a) \cdot 0 = 0$$

   for any $a \in \mathbb{Q}$. That is, $\sigma = 0 \in \mathrm{Aut}(\mathbb{Q})$, which is absurd.

   (b) Therefore, $\sigma(1) = 1$.

(2) *Show that $\sigma(n) = n$ for all $n \in \mathbb{Z}^+$.* Write $n = 1 + 1 + \cdots + 1$ (n times 1). Applying the additivity of σ, we have

$$\sigma(n) = \sigma(1) + \sigma(1) + \cdots + \sigma(1) = 1 + 1 + \cdots + 1 = n.$$

(Might use induction on n to eliminate $\cdots$ symbols.)

(3) *Show that $\sigma(n) = n$ for all $n \in \mathbb{Z}$.* By the additivity of σ, $\sigma(-n) = -\sigma(n) = -n$ for $n \geq 0$. The result is established.

For any $a = \frac{n}{m} \in \mathbb{Q}$ $(m, n \in \mathbb{Z},\ n \neq 0)$, applying the multiplication of σ on $am = n$, that is, $\sigma(a)\sigma(m) = \sigma(n)$. By (3), we have $\sigma(a)m = n$, or

$$\sigma(a) = \frac{m}{n} = a$$

provided $n \neq 0$, or σ is the identity. $\square$

Exercise 8.7. PLACEHOLDER.

Exercise 8.8. *For $n = 0, 1, 2, \ldots,$ and x real, prove that*

$$|\sin(nx)| \leq n|\sin x|.$$

Note that this inequality may be false for other values of n. For instance,

$$\left|\sin\left(\frac{1}{2}\pi\right)\right| > \frac{1}{2}|\sin\pi|.$$

Proof. Induction on n.

(1) Note that
$$\sin(a+b) = \sin a\cos b + \cos a\sin b$$
for any $a, b \in \mathbb{R}$.

(2) $n = 0, 1$ are clearly true.

(3) Assume the induction hypothesis that for the single case $n = k$ holds, meaning
$$|\sin(kx)| \leq k|\sin x|$$
is true. It follows that
$$\begin{aligned}
|\sin((k+1)x)| &= |\sin(kx)\cos x + \cos(kx)\sin x| && ((1)) \\
&\leq |\sin(kx)||\cos x| + |\cos(kx)||\sin x| && \text{(Triangle inequality)} \\
&\leq |\sin(kx)| + |\sin x| && (|\cos(\cdot)| \leq 1) \\
&\leq k|\sin x| + |\sin x| && \text{(Induction hypothesis)} \\
&\leq (k+1)|\sin x|.
\end{aligned}$$

$\square$

Exercise 8.9 (The Euler-Mascheroni constant).

(a) *Put* $s_N = 1 + \frac{1}{2} + \cdots + \frac{1}{N}$. *Prove that*

$$\lim_{N\to\infty} (s_N - \log N)$$

exists. (The limit, often denoted by γ*, is called Euler's constant. Its numerical value is* $0.5772\ldots$*. It is not known whether* γ *is rational or not.)*

(b) *Roughly how large must* m *be so that* $N = 10^m$ *satisfies* $s_N > 100$*?*

Proof of (a) (Theorem 3.14).

(1) Note that

$$\begin{aligned}
&\frac{1}{1+\frac{1}{n}} \leq \frac{1}{x} \leq 1 \text{ for } x \in \left[1, 1+\frac{1}{n}\right] \\
\Longrightarrow &\int_1^{1+\frac{1}{n}} \frac{dx}{1+\frac{1}{n}} \leq \int_1^{1+\frac{1}{n}} \frac{dx}{x} \leq \int_1^{1+\frac{1}{n}} dx & \text{(Theorem 6.12(b))} \\
\Longrightarrow &\frac{1}{n+1} \leq \int_1^{1+\frac{1}{n}} \frac{dx}{x} \leq \frac{1}{n} \\
\Longrightarrow &\frac{1}{n+1} \leq \log\left(1+\frac{1}{n}\right) \leq \frac{1}{n}. & \text{(Equation (39) on page 180)}
\end{aligned}$$

(2) Define

$$\gamma_n = s_n - \log n.$$

It suffices to show that $\{\gamma_n\}$ is monotonic and bounded (Theorem 3.14).

(3) *Show that* $\{\gamma_n\}$ *is decreasing.*

$$\begin{aligned}
\gamma_{n+1} - \gamma_n &= (s_{n+1} - \log(n+1)) - (s_n - \log n) \\
&= (s_{n+1} - s_n) - (\log(n+1) - \log n) \\
&= \frac{1}{n+1} - \log\left(\frac{n+1}{n}\right) \\
&= \frac{1}{n+1} - \log\left(1+\frac{1}{n}\right) \\
&\leq 0. & ((1))
\end{aligned}$$

Note. $\gamma_n \leq \cdots \leq \gamma_1 = 1$ for all $n = 1, 2, 3, \ldots$.

(4) *Show that* $\gamma_n \geq 0$ *for all* $n = 1, 2, 3, \ldots$. Since

$$\begin{aligned}
\log n &= \sum_{k=1}^{n-1} (\log(k+1) - \log k) \\
&= \sum_{k=1}^{n-1} \log \frac{k+1}{k} \\
&= \sum_{k=1}^{n-1} \log \left(1 + \frac{1}{k}\right) \\
&\leq \sum_{k=1}^{n-1} \frac{1}{k} \qquad ((1)) \\
&= s_{n-1},
\end{aligned}$$

we have

$$\gamma_n = s_n - \log n \geq s_n - s_{n-1} = \frac{1}{n} > 0.$$

By (3)(4), $\{\gamma_n\}$ converges to $\lim_{N \to \infty}(s_N - \log N) = \gamma$. $\square$

Supplement. *Show that if* $f \geq 0$ *on* $[0, \infty)$ *and* f *is monotonically decreasing, and if*

$$c_n = \sum_{k=1}^{n} f(k) - \int_1^n f(x)dx,$$

then $\lim_{n \to \infty} c_n$ *exists.* (Exercise 10 of Section 5.2 in the textbook: *R Creighton Buck, Advanced Calculus, 3rd edition.* See page 235.) If this exercise is true, we can get the existence of γ by taking $f(x) = \frac{1}{x}$.

(1) Note that

$$f(n+1) \leq \int_n^{n+1} f(x)dx \leq f(n).$$

(2) *Show that* $\{c_n\}$ *is decreasing.*

$$c_{n+1} - c_n = f(n+1) - \int_n^{n+1} f(x)dx \leq 0.$$

(3) *Show that* $c_n \geq 0$. Since $f(k) \geq \int_k^{k+1} f(x)dx$,

$$\begin{aligned}
\sum_{k=1}^{n} f(k) &\geq \sum_{k=1}^{n} \int_k^{k+1} f(x)dx \\
&= \int_1^{n+1} f(x)dx \\
&\geq \int_1^n f(x)dx. \qquad (f \geq 0)
\end{aligned}$$

So that $c_n = \sum_{k=1}^{n} f(k) - \int_1^n f(x)dx \geq 0$.

(4) By (2)(3), $\{c_n\}$ converges (Theorem 3.14).

$\square$

Proof of (a) (Limit comparison test). Inspired by this paper: *Philippe Flajolet and Ilan Vardi, Zeta Function Expansions of Classical Constants.*

(1) Rewrite

$$\gamma_n + \log n - \log(n+1) = \sum_{k=1}^{n} \left(\frac{1}{k} - \log\left(1 + \frac{1}{k}\right)\right)$$

(similar to the argument in (a)(4)(Theorem 3.14)). Let

$$c_k = \frac{1}{k} - \log\left(1 + \frac{1}{k}\right).$$

(2) *Show that*

$$\lim_{k\to\infty} \frac{c_k}{\frac{1}{k^2}} = \frac{1}{2}.$$

In fact,

$$\begin{aligned}
&\lim_{k\to\infty} \frac{c_k}{\frac{1}{k^2}} \\
=&\lim_{x\to 0} \frac{x - \log(1+x)}{x^2} && (\text{Put } x = \frac{1}{k}) \\
=&\lim_{x\to 0} \frac{1 - \frac{1}{1+x}}{2x} && (\text{L'Hospital's rule}) \\
=&\lim_{x\to 0} \frac{1}{2(x+1)} \\
=&\frac{1}{2}.
\end{aligned}$$

(3) By limit comparison test or comparison test, $\sum c_k$ converges since $\sum \frac{1}{k^2}$ converges. Also,

$$\lim_{n\to\infty} \log n - \log(n+1) = 0.$$

Therefore, $\lim_{n\to\infty} \gamma_n$ exists.

$\square$

Note. This proof is based on **limit comparison test** (Theorem 8.21) in this textbook: *Tom. M. Apostol, Mathematical Analysis, 2nd edition.* It is easy to prove by the original comparison test.

Proof of (a) (Comparison test).

(1) Note that

$$0 \leq x - \log(x+1) \leq \frac{x^2}{2}$$

for all $x \geq 0$.

(2) Write

$$c_n = \frac{1}{n} - \log\left(1 + \frac{1}{n}\right).$$

as in the the proof of (a) (Limit comparison test). By (1),

$$|c_n| \leq \frac{1}{2n^2}$$

for all $n = 1, 2, \ldots$. Hence, by the comparison test (Theorem 3.25(a), $\sum c_n$ converges since $\sum \frac{1}{n^2}$ converges (to $\frac{\pi^2}{6}$). Use the same argument in the proof of (a) (Limit comparison test), since

$$\gamma_n + \log n - \log(n+1) = \sum c_n \text{ and } \lim_{n\to\infty} \log n - \log(n+1) = 0,$$

we have the existence of $\lim \gamma_n = \gamma$.

$\square$

Proof of (a) (Uniformly convergence of $\sum \frac{x}{n(x+n)}$). (One example to Exercise 7 of Section 6.2 in the textbook: *R Creighton Buck, Advanced Calculus, 3rd edition*. See pages 270 to 271.)

(1) Let

$$f_n(x) = \frac{x}{n(x+n)} = \frac{1}{n} - \frac{1}{x+n}$$

defined on $E = [0, 1]$.

(2) Note that

$$|f_n(x)| \leq \frac{1}{n^2}$$

for all $x \in [0, 1]$. Since $\sum \frac{1}{n^2}$ converges, $\sum f_n$ converges uniformly on $[0, 1]$ (Theorem 7.10).

(3) Corollary to Theorem 7.16 implies that

$$\begin{aligned}
\int_0^1 \sum_{n=1}^{\infty} \frac{x}{n(x+n)} dx &= \sum_{n=1}^{\infty} \int_0^1 \frac{x}{n(x+n)} dx \\
&= \sum_{n=1}^{\infty} \int_0^1 \left(\frac{1}{n} - \frac{1}{x+n} \right) dx \\
&= \sum_{n=1}^{\infty} \left(\frac{1}{n} - \log \frac{n+1}{n} \right) \\
&= \lim_{N \to \infty} \left(\sum_{n=1}^{N} \frac{1}{n} - \log(N+1) \right) \\
&= \lim_{N \to \infty} (s_N - \log(N+1))
\end{aligned}$$

exists. Since $\lim_{N \to \infty} (\log(N+1) - \log N) = 0$,

$$\begin{aligned}
\gamma &= \lim_{N \to \infty} (s_N - \log N) \\
&= \lim_{N \to \infty} (s_N - \log(N+1)) + \lim_{N \to \infty} (\log(N+1) - \log N)
\end{aligned}$$

exists.

□

Proof of (a) (Existence of $\int_1^\infty \frac{\{x\}}{x^2} dx$).

(1) Define $\{x\} = x - [x]$ where $[x]$ is the greatest integer $\leq x$ (Exercise 6.16). *Show that*

$$\int_1^\infty \frac{\{x\}}{x^2} dx < \infty.$$

Use the similar argument in Exercise 6.16(b). Since $\frac{\{x\}}{x^2} \leq \frac{1}{x^2}$ on $[1, \infty)$ and $\int_1^\infty \frac{1}{x^2} dx = 1$ exists, the result is established (Theorem 6.12(b)).

(2) *Show that*

$$\int_1^N \frac{[x]}{x^2} dx = s_N - 1.$$

Use the similar argument in Exercise 6.16(a),

$$\begin{aligned}
\int_1^N \frac{[x]}{x^2}dx &= \sum_{k=1}^{N-1} \int_k^{k+1} \frac{[x]}{x^2}dx \\
&= \sum_{k=1}^{N-1} \int_k^{k+1} \frac{k}{x^2}dx \\
&= \sum_{k=1}^{N-1} \int_k^{k+1} \frac{k}{x^2}dx \\
&= \sum_{k=1}^{N-1} \frac{1}{k+1} \\
&= \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{N} \\
&= s_N - 1.
\end{aligned}$$

Supplement (Euler's summation formula). (Theorem 7.13 in the textbook: *Tom. M. Apostol, Mathematical Analysis, 2nd edition.*) *If f has a continuous derivative f' on $[a, b]$, then we have*

$$\sum_{a<n\leq b} f(n) = \int_a^b f(x)dx + \int_a^b f'(x)\{x\}dx + f(a)\{a\} - f(b)\{b\},$$

where $\sum_{a<n\leq b}$ means the sum from $n = [a] + 1$ to $n = [b]$. When a and b are integers, this becomes

$$\sum_{n=a}^{b} f(n) = \int_a^b f(x)dx + \int_a^b f'(x)\left(\{x\} - \frac{1}{2}\right)dx + \frac{f(a)+f(b)}{2}.$$

By taking $f(x) = \frac{1}{x}$ we can get the same result.

(3) *Show that*

$$\int_1^N \frac{\{x\}}{x^2}dx = \log N - s_N + 1 = 1 - \gamma_N.$$

In fact,

$$\begin{aligned}
\int_1^N \frac{\{x\}}{x^2}dx &= \int_1^N \frac{x-[x]}{x^2}dx \\
&= \int_1^N \frac{1}{x}dx - \int_1^N \frac{[x]}{x^2}dx \\
&= \log N - (s_N - 1) \\
&= \log N - s_N + 1 \\
&= 1 - \gamma_N.
\end{aligned}$$

(4) Since
$$\lim_{N \to \infty} \int_1^N \frac{\{x\}}{x^2} dx = \int_1^\infty \frac{\{x\}}{x^2} dx$$
exists (by (1)), $\gamma = \lim \gamma_N$ exists.

$\square$

Proof of (b). By $s_n - \log n > 0$ in (a)(4)(Theorem 3.14), it suffices to choose $N = 10^m$ such that $s_N \geq \log(N+1) > 100$, or
$$m > \frac{\log(\exp(100) - 1)}{\log 10},$$
or choose m satisfying
$$m > \frac{100}{\log 10} > \frac{\log(\exp(100) - 1)}{\log 10},$$
or $m = 44$. $\square$

Note. The exact value of N is
$$15092688622113788323693563264538101449859497 \approx 1.509 \times 10^{43}.$$

Exercise 8.10. *Prove that $\sum \frac{1}{p}$ diverges; the sum extends over all primes.*

There are many proofs of this result. We provide some of them.

Proof (Due to hint). Given N.

(1) *Show that*
$$\sum_{n \leq N} \frac{1}{n} \leq \prod_{p \leq N} \left(1 - \frac{1}{p}\right)^{-1}.$$

By the unique factorization theorem on $n \leq N$,
$$\sum_{n \leq N} \frac{1}{n} \leq \prod_{p \leq N} \left(1 + \frac{1}{p} + \frac{1}{p^2} + \cdots\right) = \prod_{p \leq N} \left(1 - \frac{1}{p}\right)^{-1}.$$

(2) By (1) and the fact that $\sum \frac{1}{n}$ diverges, there are infinitely many primes.

(3) *Show that*
$$\prod_{p \leq N} \left(1 - \frac{1}{p}\right)^{-1} \leq \exp\left(\sum_{p \leq N} \frac{2}{p}\right).$$

By applying the inequality $(1-x)^{-1} < e^{2x}$ where $x \in (0, \frac{1}{2}]$ on any prime p,

$$\left(1-\frac{1}{p}\right)^{-1} < \exp\left(\frac{2}{p}\right).$$

Now multiplying the inequality over all primes $p \leq N$ and noticing that $\exp(x) \cdot \exp(y) = \exp(x+y)$, we have

$$\prod_{p \leq N} \left(1-\frac{1}{p}\right)^{-1} \leq \exp\left(\sum_{p \leq N} \frac{2}{p}\right).$$

(4) By (1)(3),

$$\sum_{n \leq N} \frac{1}{n} \leq \exp\left(\sum_{p \leq N} \frac{2}{p}\right).$$

Since $\sum_{n \leq N} \frac{1}{n}$ diverges, the result holds.

$\square$

Proof (Due to Kenneth Ireland and Michael Rosen). The proof in Kenneth Ireland and Michael Rosen, A Classical Introduction to Modern Number Theory, Second Edition (Theorem 3 in Chapter 2) does not use the inequality $(1-x)^{-1} < e^{2x}$ ($x \in (0, \frac{1}{2}]$) directly. Instead, the authors take the logarithm on $(1-p^{-1})^{-1}$ and estimate it. (So the length of proof is longer than the proof due to hint.) That is,

$$\begin{aligned}
-\log\left(1-p^{-1}\right) &= \sum_{n=1}^{\infty} \frac{p^{-n}}{n} \\
&= \frac{1}{p} + \sum_{n=2}^{\infty} \frac{p^{-n}}{n} \\
&< \frac{1}{p} + \sum_{n=2}^{\infty} p^{-n} \\
&= \frac{1}{p} + \frac{p^{-2}}{1-p^{-1}} \\
&< \frac{1}{p} + 2 \cdot \frac{1}{p^2}.
\end{aligned}$$

Now we sum over all primes $p \leq N$,

$$\log\left(\prod_{p \leq N} \left(1-\frac{1}{p}\right)^{-1}\right) < \sum_{p \leq N} \frac{1}{p} + 2 \sum_{p \leq N} \frac{1}{p^2}.$$

So

$$\log \sum_{n \leq N} \frac{1}{n} < \sum_{p \leq N} \frac{1}{p} + 2 \sum_{p \leq N} \frac{1}{p^2}.$$

Notice that $\sum \frac{1}{n}$ diverges and $\sum \frac{1}{p^2}$ converges (since $\sum \frac{1}{n^2}$ converges). Therefore, $\sum \frac{1}{p}$ diverges. $\square$

Proof (Due to I. Niven). It is an exercise in Kenneth Ireland and Michael Rosen, A Classical Introduction to Modern Number Theory, Second Edition. See Exercise 27 in Chapter 2.

(1) *Show that $\sum' \frac{1}{n}$, the sum being over square free integers, diverges.* For any positive integers n, we can write $n = a^2 b$ where $a \in \mathbb{Z}^+$ and b is a square free integer. Given N,

$$\sum_{n \leq N} \frac{1}{n} \leq \left(\sum_{a=1}^{\infty} \frac{1}{a^2} \right) \left({\sum_{b \leq N}}' \frac{1}{b} \right).$$

Notice that $\sum_{a=1}^{\infty} \frac{1}{a^2}$ converges. Since $\sum_{n \leq N} \frac{1}{n} \to \infty$ as $N \to \infty$, $\sum'_{b \leq N} \frac{1}{b} \to \infty$ as $N \to \infty$.

(2) *Show that*

$$\prod_{p \leq N} (1 + \frac{1}{p}) \to \infty \text{ as } N \to \infty.$$

By the unique factorization theorem on $n \leq N$,

$$\prod_{p \leq N} \left(1 + \frac{1}{p} \right) \geq {\sum_{n \leq N}}' \frac{1}{n}.$$

Since ${\sum_{n \leq N}}' \frac{1}{n} \to \infty$ as $N \to \infty$ by (1), the conclusion is established.

(3) By applying the inequality $e^x > 1 + x$ on any prime p,

$$\exp \left(\frac{1}{p} \right) > 1 + \frac{1}{p}.$$

Now multiplying the inequality over all primes $p \leq N$ and noticing that $\exp(x) \cdot \exp(y) = \exp(x + y)$, we have

$$\exp \left(\sum_{p \leq N} \frac{1}{p} \right) > \prod_{p \leq N} \left(1 + \frac{1}{p} \right).$$

By (2), $\exp \left(\sum_{p \leq N} \frac{1}{p} \right) \to \infty$ as $N \to \infty$, or $\sum_{p \leq N} \frac{1}{p} \to \infty$ as $N \to \infty$.

□

Exercise 8.11. *Suppose $f \in \mathscr{R}$ on $[0, A]$ for all $A < \infty$, and $f(x) \to 1$ as $x \to +\infty$. Prove that*

$$\lim_{t \to 0} t \int_0^\infty e^{-tx} f(x) dx = 1 \qquad (t > 0),$$

It is similar to Exercise 3.14(a).

Proof. Given any $\varepsilon > 0$.

(1) The integral $\int_0^\infty e^{-tx} f(x) dx$ is well-defined. (It suffices to show that $\int_0^\infty e^{-tx} f(x) dx$ converges absolutely in the sense of Exercise 6.8. It is quite easy since $f(x) \to 1$ as $x \to +\infty$ and well-behavior of $\int_{A_0}^\infty e^{-tx} f(x) dx$ for any $A_0 > 0$.)

(2) Note that

$$t \int_0^\infty e^{-tx} dx = 1$$

for any $t > 0$.

(3) Since $f(x) \to 1$ as $x \to +\infty$, there is $A_0 > 0$ such that

$$|f(x) - 1| < \frac{\varepsilon}{64} \text{ whenever } x \geq A_0.$$

(4) Since $f \in \mathscr{R}$ on $[0, A_0]$, f is bounded on $[0, A_0]$, or $|f| \leq M$ on $[0, A_0]$ for some M (Theorem 6.7(c)).

(5) As $t > 0$,

$$\begin{aligned}
&\left| \left(t \int_0^\infty e^{-tx} f(x) dx \right) - 1 \right| \\
=&\left| t \int_0^\infty e^{-tx} (f(x) - 1) dx \right| && ((2)) \\
\leq& t \int_0^\infty e^{-tx} |f(x) - 1| dx && ((1) \text{ with Theorem 6.13}) \\
=& t \int_0^{A_0} e^{-tx} |f(x) - 1| dx + t \int_{A_0}^\infty e^{-tx} |f(x) - 1| dx \\
\leq& t \int_0^{A_0} (M+1) dx + t \int_{A_0}^\infty e^{-tx} |f(x) - 1| dx && ((3) \text{ and } e^{-tx} \leq 1) \\
\leq& t \int_0^{A_0} (M+1) dx + t \int_{A_0}^\infty e^{-tx} \frac{\varepsilon}{64} dx && ((4)) \\
=& tA_0(M+1) + \exp(-A_0 t) \frac{\varepsilon}{64} \\
\leq& tA_0(M+1) + \frac{\varepsilon}{64}. && (e^{-tx} \leq 1)
\end{aligned}$$

Since t is arbitrary, take $t = \frac{\varepsilon}{89A_0(M+1)} > 0$ to get

$$\left| \left(t \int_0^\infty e^{-tx} f(x) dx \right) - 1 \right| < \frac{\varepsilon}{89} + \frac{\varepsilon}{64} < \varepsilon,$$

or

$$\lim_{t \to 0^+} t \int_0^\infty e^{-tx} f(x) dx = 1.$$

$\square$

Exercise 8.12. *Suppose* $0 < \delta < \pi$,

$$f(x) = \begin{cases} 1 & \text{if } |x| \leq \delta, \\ 0 & \text{if } \delta < |x| \leq \pi, \end{cases}$$

and $f(x + 2\pi) = f(x)$ *for all* x.

(a) *Compute the Fourier coefficients of* f.

(b) *Compute that*

$$\sum_{n=1}^\infty \frac{\sin(n\delta)}{n} = \frac{\pi - \delta}{2} \qquad (0 < \delta < \pi).$$

(c) *Deduce from Parseval's theorem that*

$$\sum_{n=1}^{\infty} \frac{(\sin(n\delta))^2}{n^2\delta} = \frac{\pi - \delta}{2}.$$

(d) *Let* $\delta \to 0$ *and prove that*

$$\int_0^{\infty} \left(\frac{\sin x}{x}\right)^2 dx = \frac{\pi}{2}.$$

(e) *Put* $\delta = \frac{\pi}{2}$ *in (c). What do you get?*

It is a centered square pulse around $x = 0$ with shift δ. Besides, $f(x)$ is an even function.

Proof of (a).

$$\begin{aligned} c_0 &= \frac{1}{2\pi}\int_{-\pi}^{\pi} f(x)dx \\ &= \frac{1}{2\pi}\int_{-\delta}^{\delta} dx \\ &= \frac{\delta}{\pi}. \end{aligned}$$

For $0 \neq n \in \mathbb{Z}$,

$$\begin{aligned} c_n &= \frac{1}{2\pi}\int_{-\pi}^{\pi} f(x)e^{-inx}dx \\ &= \frac{1}{2\pi}\int_{-\delta}^{\delta} e^{-inx}dx \\ &= \frac{1}{2\pi}\cdot\frac{2\sin(n\delta)}{n} \\ &= \frac{\sin(n\delta)}{n\pi}. \end{aligned}$$

□

Supplement. Find a_n and b_n of this textbook.
By (a), $a_0 = \frac{\delta}{\pi}$, $a_n = \frac{2\sin(n\delta)}{n\pi}$, $b_n = 0$ for $n \in \mathbb{Z}^+$. Surely, we can compute a_n

and b_n $(n > 0)$ directly. Since $f(x)$ is an even function, $b_n = 0$. And

$$\begin{aligned} a_n &= \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos(nx)dx \\ &= \frac{2}{\pi}\int_{0}^{\delta} \cos(nx)dx \\ &= \frac{2\sin(n\delta)}{n\pi}. \end{aligned}$$

Proof of (b). Given $x = 0$, there are constants $\delta' = \delta > 0$ and $M = 1 < \infty$ such that

$$|f(0+t) - f(0)| \leq M|t|$$

for all $t \in (-\delta', \delta')$. By Theorem 8.14,

$$\sum_{-\infty}^{\infty} c_n = f(0).$$

Notice that $c_{-n} = c_n$ for $n \in \mathbb{Z}^+$, so

$$\begin{aligned} \frac{\delta}{\pi} + 2\sum_{n=1}^{\infty} \frac{\sin(n\delta)}{n\pi} &= 1 \\ \sum_{n=1}^{\infty} \frac{\sin(n\delta)}{n} &= \frac{\pi - \delta}{2}. \end{aligned}$$

□

We can also use the expression a_n and b_n to prove the same thing. Besides, taking $\delta = 1$ yields

$$\sum_{n=1}^{\infty} \frac{\sin n}{n} = \frac{\pi - 1}{2}.$$

Proof of (c). Since $f(x)$ is a Riemann-integrable function with period 2π, by Parseval's theorem

$$\frac{1}{2\pi}\int_{-\pi}^{\pi} |f(x)|^2 dx = \sum_{-\infty}^{\infty} |c_n|^2.$$

So

$$\frac{\delta}{\pi} = \frac{\delta^2}{\pi^2} + 2\sum_{n=1}^{\infty} \frac{(\sin(n\delta))^2}{n^2\pi^2},$$

or

$$\sum_{n=1}^{\infty} \frac{(\sin(n\delta))^2}{n^2\delta} = \frac{\pi - \delta}{2}.$$

$\square$

Notices that
$$\sum_{n=1}^{\infty}\frac{(\sin n)^2}{n^2}=\frac{\pi-1}{2}$$
as $\delta=1$.

Proof of (d). Given $\varepsilon>0$. By Exercise 6.8,
$$\int_0^{\infty}\left(\frac{\sin x}{x}\right)^2 dx$$
exists. So there exists $b>0$ such that
$$\left|\int_0^{b}\left(\frac{\sin x}{x}\right)^2 dx-\int_0^{\infty}\left(\frac{\sin x}{x}\right)^2 dx\right|<\frac{\varepsilon}{4}$$
By Supplement in Chapter 6, there exists $\delta>0$ such that for any partition $P_m=\{0,\frac{b}{m},\frac{2b}{m},\dots,\frac{(m-1)b}{m},b\}$ of $[0,b]$ with $\|P\|=\frac{b}{m}<\delta$, or $m>\frac{b}{\delta}$, we have
$$\left|\sum_{n=1}^{m}\frac{(\sin\left(n\frac{b}{m}\right))^2}{(n\frac{b}{m})^2}\cdot\frac{b}{m}-\int_0^{b}\left(\frac{\sin x}{x}\right)^2 dx\right|<\frac{\varepsilon}{4},$$
$$\left|\sum_{n=1}^{m}\frac{(\sin\left(n\frac{b}{m}\right))^2}{n^2\frac{b}{m}}-\int_0^{b}\left(\frac{\sin x}{x}\right)^2 dx\right|<\frac{\varepsilon}{4}.$$

For simplicity we resize δ to $\delta<\pi$ to make $0<\frac{b}{m}<\delta<\pi$. Besides, since $\sum_{n=1}^{\infty}\frac{1}{n^2}$ converges, there exists $N>0$ such that
$$\left|\sum_{n=1}^{\infty}\frac{(\sin\left(n\frac{b}{m}\right))^2}{n^2\frac{b}{m}}-\sum_{n=1}^{m}\frac{(\sin\left(n\frac{b}{m}\right))^2}{n^2\frac{b}{m}}\right|<\frac{\varepsilon}{4}$$
whenever $m\geq N$. By (c),
$$\left|\frac{\pi-\frac{b}{m}}{2}-\sum_{n=1}^{m}\frac{(\sin\left(n\frac{b}{m}\right))^2}{n^2\frac{b}{m}}\right|<\frac{\varepsilon}{4}$$
whenever $m\geq N$. Last, it is easy to get
$$\left|\frac{\pi}{2}-\frac{\pi-\frac{b}{m}}{2}\right|<\frac{\varepsilon}{4}$$
whenever $m>\frac{2b}{\varepsilon}$. Now we have
$$\left|\frac{\pi}{2}-\int_0^{\infty}\left(\frac{\sin x}{x}\right)^2 dx\right|<\varepsilon$$

whenever $m > \max(\frac{b}{\delta}, N, \frac{2b}{\varepsilon})$. Since ε is arbitrary, $\int_0^\infty \left(\frac{\sin x}{x}\right)^2 dx = \frac{\pi}{2}$. □

Proof of (e).

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

Write

$$\begin{aligned}\sum_{n=1}^{\infty} \frac{1}{n^2} &= \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} + \sum_{n=1}^{\infty} \frac{1}{(2n)^2} \\ &= \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} + \frac{1}{4}\sum_{n=1}^{\infty} \frac{1}{n^2},\end{aligned}$$

so

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{4}{3}\sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} = \frac{\pi^2}{6}.$$

□

Exercise 8.13. *Put $f(x) = x$ if $0 \le x < 2\pi$, and apply Parseval's theorem to conclude that*

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{\pi}{6}.$$

Proof.

$$\begin{aligned}c_0 &= \frac{1}{2\pi}\int_0^{2\pi} x dx \\ &= \pi,\end{aligned}$$

For $n \neq 0$,

$$\begin{aligned}c_n &= \frac{1}{2\pi}\int_0^{2\pi} xe^{-inx} dx \\ &= \frac{1}{2\pi}\left(\left[-\frac{1}{in}xe^{-inx}\right]_{x=0}^{x=2\pi} - \int_0^{2\pi} -\frac{1}{in}e^{-inx}dx\right) \\ &= \frac{i}{n}.\end{aligned}$$

Since $f(x)$ is a Riemann-integrable function with period 2π, by Parseval's theorem

$$\frac{1}{2\pi}\int_{-\pi}^{\pi} |f(x)|^2 dx = \sum_{-\infty}^{\infty} |c_n|^2.$$

So

$$\frac{1}{2\pi} \cdot \frac{(2\pi)^3}{3} = \pi^2 + 2\sum_{n=1}^{\infty} \frac{1}{n^2},$$

or

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{\pi^2}{6}.$$

$\square$

Supplement. *Put $f(x) = x^n$ if $n \in \mathbb{Z}^+$ and $0 \leq x < 2\pi$. Might get*

$$\zeta(2n) = \sum_{k=1}^{\infty} \frac{1}{k^{2n}} = \frac{(-1)^{n+1} B_{2n} (2\pi)^{2n}}{2(2n)!}.$$

Exercise 8.14-8.31. PLACEHOLDER.