Fourier Series

4. Integrals

Formula for integration by parts: $\int_a^b u\frac{dv}{dx}dx = [uv]_a^b - \int_a^b \frac{du}{dx}v\,dx$

$f(x)$	$\int f(x)\mathrm{d}x$	$f(x)$	$\int f(x)\mathrm{d}x$
x^n	$\frac{x^{n+1}}{n+1} \quad (n \neq -1)$	$[g(x)]^n g'(x)$	$\frac{[g(x)]^{n+1}}{n+1} \quad (n \neq -1)$
$\frac{1}{x}$	$\ln\lvert x\rvert$	$\frac{g'(x)}{g(x)}$	$\ln\lvert g(x)\rvert$
e^x	e^x	a^x	$\frac{a^x}{\ln a} \quad (a > 0)$
$\sin x$	$-\cos x$	$\sinh x$	$\cosh x$
$\cos x$	$\sin x$	$\cosh x$	$\sinh x$
$\tan x$	$-\ln\lvert\cos x\rvert$	$\tanh x$	$\ln\cosh x$
$\operatorname{cosec} x$	$\ln\left\lvert\tan\frac{x}{2}\right\rvert$	$\operatorname{cosech} x$	$\ln\left\lvert\tanh\frac{x}{2}\right\rvert$
$\sec x$	$\ln\lvert\sec x + \tan x\rvert$	$\operatorname{sech} x$	$2\tan^{-1} e^x$
$\sec^2 x$	$\tan x$	$\operatorname{sech}^2 x$	$\tanh x$
$\cot x$	$\ln\lvert\sin x\rvert$	$\coth x$	$\ln\lvert\sinh x\rvert$
$\sin^2 x$	$\frac{x}{2} - \frac{\sin 2x}{4}$	$\sinh^2 x$	$\frac{\sinh 2x}{4} - \frac{x}{2}$
$\cos^2 x$	$\frac{x}{2} + \frac{\sin 2x}{4}$	$\cosh^2 x$	$\frac{\sinh 2x}{4} + \frac{x}{2}$

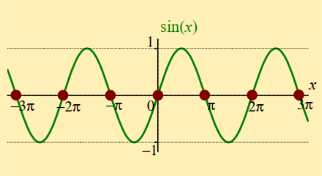
Fourier Series

$f(x)$	$\int f(x)\,\mathrm{d}x$	$f(x)$	$\int f(x)\,\mathrm{d}x$
$\frac{1}{a^2+x^2}$	$\frac{1}{a}\tan^{-1}\frac{x}{a}$ $(a>0)$	$\frac{1}{a^2-x^2}$	$\frac{1}{2a}\ln\left\lvert\frac{a+x}{a-x}\right\rvert$ $(0<\lvert x\rvert<a)$
		$\frac{1}{x^2-a^2}$	$\frac{1}{2a}\ln\left\lvert\frac{x-a}{x+a}\right\rvert$ $(\lvert x\rvert>a>0)$
$\frac{1}{\sqrt{a^2-x^2}}$	$\sin^{-1}\frac{x}{a}$	$\frac{1}{\sqrt{a^2+x^2}}$	$\ln\left\lvert\frac{x+\sqrt{a^2+x^2}}{a}\right\rvert$ $(a>0)$
	$(-a<x<a)$	$\frac{1}{\sqrt{x^2-a^2}}$	$\ln\left\lvert\frac{x+\sqrt{x^2-a^2}}{a}\right\rvert$ $(x>a>0)$
$\sqrt{a^2-x^2}$	$\frac{a^2}{2}\left[\sin^{-1}\left(\frac{x}{a}\right)+\frac{x\sqrt{a^2-x^2}}{a^2}\right]$	$\sqrt{a^2+x^2}$	$\frac{a^2}{2}\left[\sinh^{-1}\left(\frac{x}{a}\right)+\frac{x\sqrt{a^2+x^2}}{a^2}\right]$
		$\sqrt{x^2-a^2}$	$\frac{a^2}{2}\left[-\cosh^{-1}\left(\frac{x}{a}\right)+\frac{x\sqrt{x^2-a^2}}{a^2}\right]$

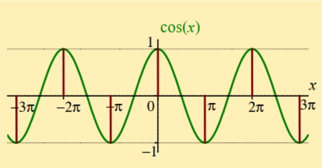
5. Useful trig results

When calculating the Fourier coefficients a_n and b_n , for which $n = 1, 2, 3, \ldots$, the following trig. results are useful. Each of these results, which are also true for $n = 0, -1, -2, -3, \ldots$, can be deduced from the graph of $\sin x$ or that of $\cos x$

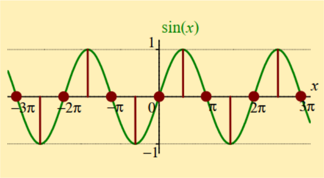
- $\sin n\pi = 0$

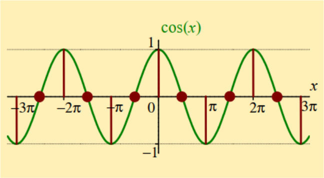


- $\cos n\pi = (-1)^n$



Fourier Series

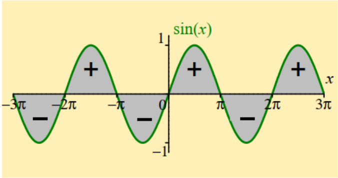




- $\sin n\dfrac{\pi}{2} = \begin{cases} 0 & , n \text{ even} \\ 1 & , n = 1, 5, 9, \dots \\ -1 & , n = 3, 7, 11, \dots \end{cases}$
- $\cos n\dfrac{\pi}{2} = \begin{cases} 0 & , n \text{ odd} \\ 1 & , n = 0, 4, 8, \dots \\ -1 & , n = 2, 6, 10, \dots \end{cases}$

Areas cancel when when integrating over whole periods

- $\int_{2\pi} \sin nx \, \mathrm{d}x = 0$
- $\int_{2\pi} \cos nx \, \mathrm{d}x = 0$



EXERCISE 1.

Let $f(x)$ be a function of period 2π such that

$$f(x) = \begin{cases} 1, & -\pi < x < 0 \\ 0, & 0 < x < \pi\ . \end{cases}$$

a) Sketch a graph of $f(x)$ in the interval $-2\pi < x < 2\pi$

b) Show that the Fourier series for $f(x)$ in the interval $-\pi < x < \pi$ is

$$\frac{1}{2} - \frac{2}{\pi}\left[\sin x + \frac{1}{3}\sin 3x + \frac{1}{5}\sin 5x + ...\right]$$

c) By giving an appropriate value to x, show that

$$\frac{\pi}{4} \quad = \quad 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots$$

EXERCISE 2.

Let $f(x)$ be a function of period 2π such that

$$f(x) = \begin{cases} 0, & -\pi < x < 0 \\ x, & 0 < x < \pi \,. \end{cases}$$

a) Sketch a graph of $f(x)$ in the interval $-3\pi < x < 3\pi$

b) Show that the Fourier series for $f(x)$ in the interval $-\pi < x < \pi$ is

$$\frac{\pi}{4} - \frac{2}{\pi}\left[\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \ldots\right]$$
$$+\left[\sin x - \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x - \ldots\right]$$

c) By giving appropriate values to x, show that

(i) $\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \ldots$ and (ii) $\frac{\pi^2}{8} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \ldots$

EXERCISE 3.

Let $f(x)$ be a function of period 2π such that

$$f(x) = \begin{cases} x, & 0 < x < \pi \\ \pi, & \pi < x < 2\pi \end{cases}.$$

a) Sketch a graph of $f(x)$ in the interval $-2\pi < x < 2\pi$

b) Show that the Fourier series for $f(x)$ in the interval $0 < x < 2\pi$ is

$$\frac{3\pi}{4} - \frac{2}{\pi}\left[\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \dots\right] - \left[\sin x + \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x + \dots\right]$$

c) By giving appropriate values to x, show that

(i) $\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots$ and (ii) $\frac{\pi^2}{8} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \dots$

Exercise 4.

Let $f(x)$ be a function of period 2π such that

$$f(x) = \frac{x}{2} \text{ over the interval } 0 < x < 2\pi.$$

a) Sketch a graph of $f(x)$ in the interval $0 < x < 4\pi$

b) Show that the Fourier series for $f(x)$ in the interval $0 < x < 2\pi$ is

$$\frac{\pi}{2} - \left[\sin x + \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x + \dots\right]$$

c) By giving an appropriate value to x, show that

$$\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \dots$$

Exercise 5.

Let $f(x)$ be a function of period 2π such that

$$f(x) = \begin{cases} \pi - x, & 0 < x < \pi \\ 0, & \pi < x < 2\pi \end{cases}$$

a) Sketch a graph of $f(x)$ in the interval $-2\pi < x < 2\pi$

b) Show that the Fourier series for $f(x)$ in the interval $0 < x < 2\pi$ is

$$\begin{aligned} \frac{\pi}{4} \quad &+ \quad \frac{2}{\pi}\left[\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \dots\right] \\ &+ \quad \sin x + \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x + \frac{1}{4}\sin 4x + \dots \end{aligned}$$

c) By giving an appropriate value to x, show that

$$\frac{\pi^2}{8} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \dots$$

Exercise 6.

Let $f(x)$ be a function of period 2π such that

$$f(x) = x \text{ in the range } -\pi < x < \pi.$$

a) Sketch a graph of $f(x)$ in the interval $-3\pi < x < 3\pi$

b) Show that the Fourier series for $f(x)$ in the interval $-\pi < x < \pi$ is

$$2\left[\sin x - \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x - \dots\right]$$

c) By giving an appropriate value to x, show that

$$\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots$$

EXERCISE 7.

Let $f(x)$ be a function of period 2π such that

$$f(x) = x^2 \text{ over the interval } -\pi < x < \pi.$$

a) Sketch a graph of $f(x)$ in the interval $-3\pi < x < 3\pi$

b) Show that the Fourier series for $f(x)$ in the interval $-\pi < x < \pi$ is

$$\frac{\pi^2}{3} - 4\left[\cos x - \frac{1}{2^2}\cos 2x + \frac{1}{3^2}\cos 3x - \dots\right]$$

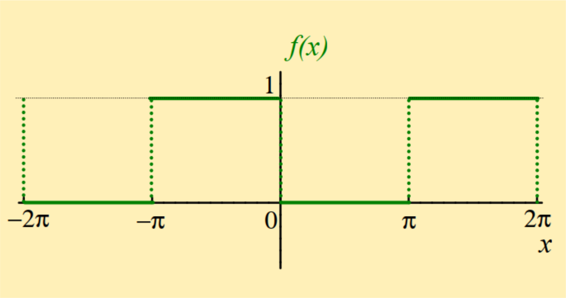
c) By giving an appropriate value to x, show that

$$\frac{\pi^2}{6} = 1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \dots$$

Exercise 1.

$$f(x) = \begin{cases} 1, & -\pi < x < 0 \\ 0, & 0 < x < \pi, \end{cases} \quad \text{and has period } 2\pi$$

a) Sketch a graph of $f(x)$ in the interval $-2\pi < x < 2\pi$



b) Fourier series representation of $f(x)$

STEP ONE

$$\begin{aligned}
a_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\mathrm{d}x &= \frac{1}{\pi}\int_{-\pi}^{0} f(x)\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} f(x)\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{0} 1\cdot\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} 0\cdot\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{0} \mathrm{d}x \\
&= \frac{1}{\pi}\left[x\right]_{-\pi}^{0} \\
&= \frac{1}{\pi}\left(0-(-\pi)\right) \\
&= \frac{1}{\pi}\cdot(\pi) \\
\text{i.e.}\quad a_0 &= 1\,.
\end{aligned}$$

Fourier Series

$$
\begin{aligned}
a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos nx\,\mathrm{d}x &= \frac{1}{\pi}\int_{-\pi}^{0} f(x)\cos nx\,\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} f(x)\cos nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{0} 1\cdot\cos nx\,\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} 0\cdot\cos nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{0} \cos nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\left[\frac{\sin nx}{n}\right]_{-\pi}^{0} = \frac{1}{n\pi}\left[\sin nx\right]_{-\pi}^{0} \\
&= \frac{1}{n\pi}\left(\sin 0 - \sin(-n\pi)\right) \\
&= \frac{1}{n\pi}(0 + \sin n\pi) \\
\text{i.e. } a_n &= \frac{1}{n\pi}(0+0) = 0.
\end{aligned}
$$

Fourier Series

$$\begin{aligned}
b_n &= \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin nx \,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{0} f(x)\sin nx \,\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} f(x)\sin nx \,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{0} 1\cdot\sin nx \,\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} 0\cdot\sin nx \,\mathrm{d}x
\end{aligned}$$

$$\begin{aligned}
\text{i.e.}\quad b_n &= \frac{1}{\pi}\int_{-\pi}^{0} \sin nx \,\mathrm{d}x = \frac{1}{\pi}\left[\frac{-\cos nx}{n}\right]_{-\pi}^{0} \\
&= -\frac{1}{n\pi}[\cos nx]_{-\pi}^{0} = -\frac{1}{n\pi}\left(\cos 0 - \cos(-n\pi)\right) \\
&= -\frac{1}{n\pi}(1-\cos n\pi) = -\frac{1}{n\pi}\left(1-(-1)^n\right),\ \text{see Trig} \\
\text{i.e.}\quad b_n &= \begin{cases} 0 & , n \text{ even} \\ -\frac{2}{n\pi} & , n \text{ odd} \end{cases} \quad ,\ \text{since } (-1)^n = \begin{cases} 1 & , n \text{ even} \\ -1 & , n \text{ odd} \end{cases}
\end{aligned}$$

Fourier Series

We now have that

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx]$$

with the three steps giving

$$a_0 = 1, \;\; a_n = 0\,, \text{ and } \;\; b_n = \begin{cases} 0 & , n \text{ even} \\ -\frac{2}{n\pi} & , n \text{ odd} \end{cases}$$

It may be helpful to construct a table of values of b_n

n	1	2	3	4	5
b_n	$-\frac{2}{\pi}$	0	$-\frac{2}{\pi}\left(\frac{1}{3}\right)$	0	$-\frac{2}{\pi}\left(\frac{1}{5}\right)$

Substituting our results now gives the required series

$$f(x) = \frac{1}{2} - \frac{2}{\pi}\left[\sin x + \frac{1}{3}\sin 3x + \frac{1}{5}\sin 5x + \dots\right]$$

c) Pick an appropriate value of x, to show that

$$\boxed{\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots}$$

Comparing this series with

$$f(x) = \frac{1}{2} - \frac{2}{\pi}\left[\sin x + \frac{1}{3}\sin 3x + \frac{1}{5}\sin 5x + \dots\right],$$

we need to introduce a minus sign in front of the constants $\frac{1}{3}$, $\frac{1}{7}$,...

So we need $\sin x = 1,\ \sin 3x = -1,\ \sin 5x = 1,\ \sin 7x = -1$, etc

The first condition of $\sin x = 1$ suggests trying $x = \frac{\pi}{2}$.

This choice gives	$\sin\frac{\pi}{2}$	$+$	$\frac{1}{3}\sin 3\frac{\pi}{2}$	$+$	$\frac{1}{5}\sin 5\frac{\pi}{2}$	$+$	$\frac{1}{7}\sin 7\frac{\pi}{2}$
i.e.	1	$-$	$\frac{1}{3}$	$+$	$\frac{1}{5}$	$-$	$\frac{1}{7}$

Looking at the graph of $f(x)$, we also have that $f(\frac{\pi}{2}) = 0$.

Fourier Series

Picking $x = \frac{\pi}{2}$ thus gives

$$0 = \tfrac{1}{2} - \tfrac{2}{\pi}\Big[\sin\tfrac{\pi}{2} + \tfrac{1}{3}\sin\tfrac{3\pi}{2} + \tfrac{1}{5}\sin\tfrac{5\pi}{2} + \tfrac{1}{7}\sin\tfrac{7\pi}{2} + \dots \Big]$$

$$\text{i.e. } 0 = \tfrac{1}{2} - \tfrac{2}{\pi}\Big[1 - \tfrac{1}{3} + \tfrac{1}{5} - \tfrac{1}{7} + \dots \Big]$$

A little manipulation then gives a series representation of $\frac{\pi}{4}$

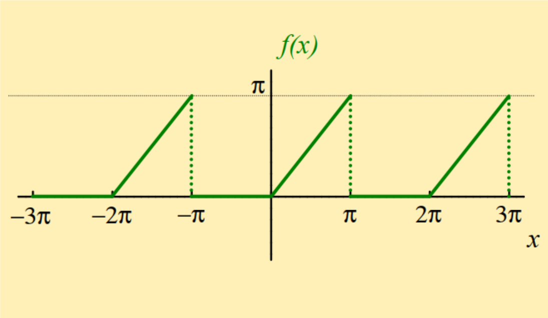
$$\frac{2}{\pi}\left[1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots\right] = \frac{1}{2}$$

$$1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots = \frac{\pi}{4}.$$

Exercise 2.

$$\boxed{f(x) = \begin{cases} 0, & -\pi < x < 0 \\ x, & 0 < x < \pi, \quad \text{and has period } 2\pi \end{cases}}$$

a) <u>Sketch a graph of $f(x)$ in the interval $-3\pi < x < 3\pi$</u>



b) Fourier series representation of $f(x)$

STEP ONE

$$a_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\mathrm{d}x = \frac{1}{\pi}\int_{-\pi}^{0} f(x)\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} f(x)\mathrm{d}x$$

$$= \frac{1}{\pi}\int_{-\pi}^{0} 0\cdot\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} x\,\mathrm{d}x$$

$$= \frac{1}{\pi}\left[\frac{x^2}{2}\right]_0^{\pi}$$

$$= \frac{1}{\pi}\left(\frac{\pi^2}{2} - 0\right)$$

$$\text{i.e. } a_0 = \frac{\pi}{2}.$$

Fourier Series

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos nx\,\mathrm{d}x = \frac{1}{\pi}\int_{-\pi}^{0} f(x)\cos nx\,\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} f(x)\cos nx\,\mathrm{d}x$$

$$= \frac{1}{\pi}\int_{-\pi}^{0} 0\cdot\cos nx\,\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} x\cos nx\,\mathrm{d}x$$

$$\text{i.e. } a_n = \frac{1}{\pi}\int_{0}^{\pi} x\cos nx\,\mathrm{d}x = \frac{1}{\pi}\left\{\left[x\frac{\sin nx}{n}\right]_0^{\pi} - \int_0^{\pi}\frac{\sin nx}{n}\,\mathrm{d}x\right\}$$

(using integration by parts)

$$\begin{aligned}
\text{i.e. } a_n &= \frac{1}{\pi}\left\{\left(\pi\frac{\sin n\pi}{n} - 0\right) - \frac{1}{n}\left[-\frac{\cos nx}{n}\right]_0^{\pi}\right\} \\
&= \frac{1}{\pi}\left\{(\quad 0 \quad - 0) + \frac{1}{n^2}[\cos nx]_0^{\pi}\right\} \\
&= \frac{1}{\pi n^2}\{\cos n\pi - \cos 0\} = \frac{1}{\pi n^2}\{(-1)^n - 1\}
\end{aligned}$$

$$\underline{\text{i.e. } a_n} = \begin{cases} 0 & , n \text{ even} \\ -\frac{2}{\pi n^2} & , n \text{ odd} \end{cases}, \text{ see T}\textsc{rig}.$$

Fourier Series

$$
\begin{aligned}
b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin nx\,\mathrm{d}x &= \frac{1}{\pi}\int_{-\pi}^{0} f(x)\sin nx\,\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} f(x)\sin nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{0} 0\cdot\sin nx\,\mathrm{d}x + \frac{1}{\pi}\int_{0}^{\pi} x\sin nx\,\mathrm{d}x \\
\text{i.e.}\ \ b_n = \frac{1}{\pi}\int_{0}^{\pi} x\sin nx\,\mathrm{d}x &= \frac{1}{\pi}\left\{\left[x\left(-\frac{\cos nx}{n}\right)\right]_0^{\pi} - \int_0^{\pi}\left(-\frac{\cos nx}{n}\right)\mathrm{d}x\right\} \\
&\qquad\qquad\text{(using integration by parts)} \\
&= \frac{1}{\pi}\left\{-\frac{1}{n}\left[x\cos nx\right]_0^{\pi} + \frac{1}{n}\int_0^{\pi}\cos nx\,\mathrm{d}x\right\} \\
&= \frac{1}{\pi}\left\{-\frac{1}{n}(\pi\cos n\pi - 0) + \frac{1}{n}\left[\frac{\sin nx}{n}\right]_0^{\pi}\right\} \\
&= -\frac{1}{n}(-1)^n + \frac{1}{\pi n^2}(0-0),\ \text{see TRIG} \\
&= -\frac{1}{n}(-1)^n
\end{aligned}
$$

Fourier Series

i.e. $\quad b_n = \begin{cases} -\frac{1}{n} & , n \text{ even} \\ +\frac{1}{n} & , n \text{ odd} \end{cases}$

We now have

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx]$$

where $a_0 = \frac{\pi}{2}$, $\quad a_n = \begin{cases} 0 & , n \text{ even} \\ -\frac{2}{\pi n^2} & , n \text{ odd} \end{cases}$, $\quad b_n = \begin{cases} -\frac{1}{n} & , n \text{ even} \\ \frac{1}{n} & , n \text{ odd} \end{cases}$

Constructing a table of values gives

n	1	2	3	4	5
a_n	$-\frac{2}{\pi}$	0	$-\frac{2}{\pi} \cdot \frac{1}{3^2}$	0	$-\frac{2}{\pi} \cdot \frac{1}{5^2}$
b_n	1	$-\frac{1}{2}$	$\frac{1}{3}$	$-\frac{1}{4}$	$\frac{1}{5}$

Fourier Series

This table of coefficients gives

$$\begin{aligned} f(x) = \frac{1}{2}\left(\frac{\pi}{2}\right) \quad &+ \left(-\frac{2}{\pi}\right)\cos x + 0\cdot\cos 2x \\ &+ \left(-\frac{2}{\pi}\cdot\frac{1}{3^2}\right)\cos 3x + 0\cdot\cos 4x \\ &+ \left(-\frac{2}{\pi}\cdot\frac{1}{5^2}\right)\cos 5x + \ldots \\ &+ \sin x - \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x - \ldots \end{aligned}$$

$$\begin{aligned} \text{i.e.}\quad f(x) = \frac{\pi}{4} \quad &- \frac{2}{\pi}\left[\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \ldots\right] \\ &+ \left[\sin x - \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x - \ldots\right] \end{aligned}$$

c) Pick an appropriate value of x, to show that

$$\boxed{\text{(i)}\ \tfrac{\pi}{4} = 1 - \tfrac{1}{3} + \tfrac{1}{5} - \tfrac{1}{7} + \ldots}$$

Comparing this series with

$$f(x) = \frac{\pi}{4} \quad - \frac{2}{\pi}\left[\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \ldots\right] + \left[\sin x - \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x - \ldots\right],$$

the required series of constants does not involve terms like $\frac{1}{3^2}, \frac{1}{5^2}, \frac{1}{7^2}, \ldots$. So we need to pick a value of x that sets the $\cos nx$ terms to zero. The TRIG section shows that $\cos n\frac{\pi}{2} = 0$ when n is odd, and note also that $\cos nx$ terms in the Fourier series all have odd n

i.e. $\quad \cos x = \cos 3x = \cos 5x = \ldots = 0 \quad$ when $x = \frac{\pi}{2}$,

i.e. $\quad \cos\frac{\pi}{2} = \cos 3\frac{\pi}{2} = \cos 5\frac{\pi}{2} = \ldots = 0$

Fourier Series

Setting $x = \frac{\pi}{2}$ in the series for $f(x)$ gives

$$\begin{aligned}
f\left(\frac{\pi}{2}\right) &= \frac{\pi}{4} - \frac{2}{\pi}\left[\cos\frac{\pi}{2} + \frac{1}{3^2}\cos\frac{3\pi}{2} + \frac{1}{5^2}\cos\frac{5\pi}{2} + \ldots\right] \\
&\quad + \left[\sin\frac{\pi}{2} - \frac{1}{2}\sin\frac{2\pi}{2} + \frac{1}{3}\sin\frac{3\pi}{2} - \frac{1}{4}\sin\frac{4\pi}{2} + \frac{1}{5}\sin\frac{5\pi}{2} - \ldots\right] \\
&= \frac{\pi}{4} - \frac{2}{\pi}[0 \ + \ 0 \ + \ 0 \ + \ldots] \\
&\quad + \left[1 - \frac{1}{2}\underbrace{\sin\pi}_{=0} + \frac{1}{3}\cdot(-1) - \frac{1}{4}\underbrace{\sin 2\pi}_{=0} + \frac{1}{5}\cdot(1) - \ldots\right]
\end{aligned}$$

The graph of $f(x)$ shows that $f\left(\frac{\pi}{2}\right) = \frac{\pi}{2}$, so that

$$\begin{aligned}
\frac{\pi}{2} &= \frac{\pi}{4} + 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \ldots \\
\text{i.e. } \frac{\pi}{4} &= 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \ldots
\end{aligned}$$

Fourier Series

Pick an appropriate value of x, to show that

$$\boxed{\text{(ii)}\ \frac{\pi^2}{8} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \ldots}$$

Compare this series with

$$f(x) = \frac{\pi}{4} \quad - \frac{2}{\pi}\left[\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \ldots\right]$$
$$+ \left[\sin x - \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x - \ldots\right].$$

This time, we want to use the coefficients of the $\cos nx$ terms, and the same choice of x needs to set the $\sin nx$ terms to zero

Picking $x = 0$ gives

$$\sin x = \sin 2x = \sin 3x = 0 \quad \text{and} \quad \cos x = \cos 3x = \cos 5x = 1$$

Note also that the graph of $f(x)$ gives $f(x) = 0$ when $x = 0$

Solutions to exercises 4

So, picking $x = 0$ gives

$$
\begin{aligned}
0 &= \frac{\pi}{4} - \frac{2}{\pi}\left[\cos 0 + \frac{1}{3^2}\cos 0 + \frac{1}{5^2}\cos 0 + \frac{1}{7^2}\cos 0 + \ldots\right] \\
&\quad + \sin 0 - \frac{\sin 0}{2} + \frac{\sin 0}{3} - \ldots \\
\text{i.e. } 0 &= \frac{\pi}{4} - \frac{2}{\pi}\left[1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \ldots\right] + 0 - 0 + 0 - \ldots
\end{aligned}
$$

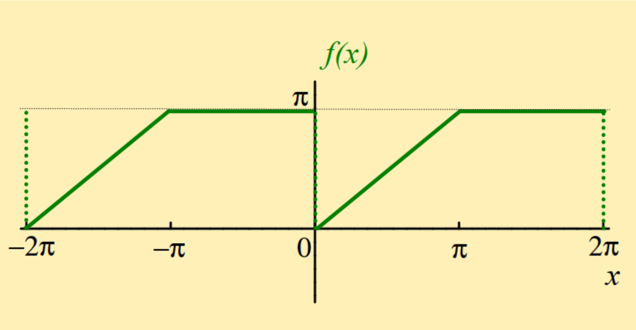
We then find that

$$
\begin{aligned}
\frac{2}{\pi}\left[1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \ldots\right] &= \frac{\pi}{4} \\
\text{and} \qquad 1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \ldots &= \frac{\pi^2}{8}.
\end{aligned}
$$

Exercise 3.

$$f(x) = \begin{cases} x, & 0 < x < \pi \\ \pi, & \pi < x < 2\pi, \end{cases} \quad \text{and has period } 2\pi$$

a) Sketch a graph of $f(x)$ in the interval $-2\pi < x < 2\pi$



Fourier Series

b) <u>Fourier series representation of $f(x)$</u>

STEP ONE

$$
\begin{aligned}
a_0 = \frac{1}{\pi}\int_0^{2\pi} f(x)\mathrm{d}x &= \frac{1}{\pi}\int_0^{\pi} f(x)\mathrm{d}x + \frac{1}{\pi}\int_{\pi}^{2\pi} f(x)\mathrm{d}x \\
&= \frac{1}{\pi}\int_0^{\pi} x\mathrm{d}x + \frac{1}{\pi}\int_{\pi}^{2\pi} \pi \cdot \mathrm{d}x \\
&= \frac{1}{\pi}\left[\frac{x^2}{2}\right]_0^{\pi} + \frac{\pi}{\pi}\Big[x\Big]_{\pi}^{2\pi} \\
&= \frac{1}{\pi}\left(\frac{\pi^2}{2} - 0\right) + \Big(2\pi - \pi\Big) \\
&= \frac{\pi}{2} + \pi \\
\text{i.e. } a_0 &= \frac{3\pi}{}.
\end{aligned}
$$

Fourier Series

$$
\begin{aligned}
a_n &= \frac{1}{\pi}\int_0^{2\pi} f(x)\cos nx \,\mathrm{d}x \\
&= \frac{1}{\pi}\int_0^{\pi} x\cos nx \,\mathrm{d}x + \frac{1}{\pi}\int_{\pi}^{2\pi} \pi\cdot\cos nx \,\mathrm{d}x \\
&= \underbrace{\frac{1}{\pi}\left[\left[x\frac{\sin nx}{n}\right]_0^{\pi} - \int_0^{\pi}\frac{\sin nx}{n}\mathrm{d}x\right]}_{\text{using integration by parts}} + \frac{\pi}{\pi}\left[\frac{\sin nx}{n}\right]_{\pi}^{2\pi} \\
&= \frac{1}{\pi}\left[\frac{1}{n}\left(\pi\sin n\pi - 0\cdot\sin n0\right) - \left[\frac{-\cos nx}{n^2}\right]_0^{\pi}\right] \\
&\qquad + \frac{1}{n}(\sin n2\pi - \sin n\pi)
\end{aligned}
$$

Fourier Series

$$\text{i.e. } a_n = \frac{1}{\pi}\left[\frac{1}{n}\Big(0-0\Big)+\left(\frac{\cos n\pi}{n^2}-\frac{\cos 0}{n^2}\right)\right]+\frac{1}{n}\Big(0-0\Big)$$

$$= \frac{1}{n^2\pi}(\cos n\pi - 1), \quad \text{see TRIG}$$

$$= \frac{1}{n^2\pi}\big((-1)^n - 1\big),$$

$$\text{i.e. } a_n = \begin{cases} -\frac{2}{n^2\pi} & , n \text{ odd} \\ 0 & , n \text{ even.} \end{cases}$$

Fourier Series

$$
\begin{aligned}
b_n &= \frac{1}{\pi}\int_0^{2\pi} f(x)\sin nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_0^{\pi} x\sin nx\,\mathrm{d}x + \frac{1}{\pi}\int_{\pi}^{2\pi} \pi\cdot\sin nx\,\mathrm{d}x \\
&= \underbrace{\frac{1}{\pi}\left[\left[x\left(-\frac{\cos nx}{n}\right)\right]_0^{\pi} - \int_0^{\pi}\left(\frac{-\cos nx}{n}\right)\mathrm{d}x\right]}_{\text{using integration by parts}} + \frac{\pi}{\pi}\left[\frac{-\cos nx}{n}\right]_{\pi}^{2\pi} \\
&= \frac{1}{\pi}\left[\left(\frac{-\pi\cos n\pi}{n}+0\right)+\left[\frac{\sin nx}{n^2}\right]_0^{\pi}\right] - \frac{1}{n}(\cos 2n\pi - \cos n\pi) \\
&= \frac{1}{\pi}\left[\frac{-\pi(-1)^n}{n}+\left(\frac{\sin n\pi - \sin 0}{n^2}\right)\right] - \frac{1}{n}(1-(-1)^n) \\
&= \quad -\frac{1}{n}(-1)^n + \qquad 0 \qquad - \frac{1}{n}(1-(-1)^n)
\end{aligned}
$$

Fourier Series

$$\text{i.e. } b_n = -\frac{1}{n}(-1)^n - \frac{1}{n} + \frac{1}{n}(-1)^n$$

$$\text{i.e. } b_n = -\frac{1}{n}.$$

We now have

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

where $a_0 = \frac{3\pi}{2}$, $a_n = \begin{cases} 0 & , n \text{ even} \\ -\frac{2}{n^2\pi} & , n \text{ odd} \end{cases}$, $b_n = -\frac{1}{n}$

Constructing a table of values gives

n	1	2	3	4	5
a_n	$-\frac{2}{\pi}$	0	$-\frac{2}{\pi}\left(\frac{1}{3^2}\right)$	0	$-\frac{2}{\pi}\left(\frac{1}{5^2}\right)$
b_n	-1	$-\frac{1}{2}$	$-\frac{1}{3}$	$-\frac{1}{4}$	$-\frac{1}{5}$

This table of coefficients gives

$$f(x) = \tfrac{1}{2}\left(\tfrac{3\pi}{2}\right) + \left(-\tfrac{2}{\pi}\right)\left[\cos x + 0\cdot\cos 2x + \tfrac{1}{3^2}\cos 3x + \ldots\right]$$

$$+ \left(-1\right)\left[\sin x + \tfrac{1}{2}\sin 2x + \tfrac{1}{3}\sin 3x + \ldots\right]$$

$$\text{i.e. } f(x) = \frac{3\pi}{4} - \frac{2}{\pi}\left[\cos x + \tfrac{1}{3^2}\cos 3x + \tfrac{1}{5^2}\cos 5x + \ldots\right]$$

$$- \left[\sin x + \tfrac{1}{2}\sin 2x + \tfrac{1}{3}\sin 3x + \ldots\right]$$

and we have found the required series.

c) Pick an appropriate value of x, to show that

$$\boxed{\text{(i) } \frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots}$$

Compare this series with

$$f(x) = \frac{3\pi}{4} - \frac{2}{\pi}\left[\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \dots\right]$$
$$- \left[\sin x + \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x + \dots\right]$$

Here, we want to set the $\cos nx$ terms to zero (since their coefficients are 1, $\frac{1}{3^2}$, $\frac{1}{5^2}$, ...). Since $\cos n\frac{\pi}{2} = 0$ when n is odd, we will try setting $x = \frac{\pi}{2}$ in the series. Note also that $f(\frac{\pi}{2}) = \frac{\pi}{2}$

This gives

$$\frac{\pi}{2} = \frac{3\pi}{4} - \frac{2}{\pi}\left[\cos\frac{\pi}{2} + \frac{1}{3^2}\cos 3\frac{\pi}{2} + \frac{1}{5^2}\cos 5\frac{\pi}{2} + \dots\right]$$
$$- \left[\sin\frac{\pi}{2} + \frac{1}{2}\sin 2\frac{\pi}{2} + \frac{1}{3}\sin 3\frac{\pi}{2} + \frac{1}{4}\sin 4\frac{\pi}{2} + \frac{1}{5}\sin 5\frac{\pi}{2} + \dots\right]$$

and

$$\frac{\pi}{2} = \frac{3\pi}{4} - \frac{2}{\pi}\left[0 + 0 + 0 + \ldots\right]$$
$$- \quad \left[(1) + \tfrac{1}{2}\cdot(0) + \tfrac{1}{3}\cdot(-1) + \tfrac{1}{4}\cdot(0) + \tfrac{1}{5}\cdot(1) + \ldots\right]$$

then

$$\frac{\pi}{2} = \frac{3\pi}{4} - \left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \ldots\right)$$

$$1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \ldots = \frac{3\pi}{4} - \frac{\pi}{2}$$

$$1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \ldots = \frac{\pi}{4}, \qquad \text{as required.}$$

<u>To show that</u>

$$\boxed{\text{(ii)}\ \frac{\pi^2}{8} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \ldots},$$

We want zero $\sin nx$ terms and to use the coefficients of $\cos nx$

Setting $x = 0$ eliminates the $\sin nx$ terms from the series, and also gives

$$\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \frac{1}{7^2}\cos 7x + \ldots = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \ldots$$

(i.e. the desired series).

The graph of $f(x)$ shows a discontinuity (a "vertical jump") at $x = 0$

The Fourier series converges to a value that is **half-way** between the two values of $f(x)$ around this discontinuity. That is the series will converge to $\frac{\pi}{2}$ at $x = 0$

$$\text{i.e. } \frac{\pi}{2} = \frac{3\pi}{4} - \frac{2}{\pi}\left[\cos 0 + \frac{1}{3^2}\cos 0 + \frac{1}{5^2}\cos 0 + \frac{1}{7^2}\cos 0 + \ldots\right] - \left[\sin 0 + \frac{1}{2}\sin 0 + \frac{1}{3}\sin 0 + \ldots\right]$$

$$\text{and } \frac{\pi}{2} = \frac{3\pi}{4} - \frac{2}{\pi}\left[1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \ldots\right] - [0 + 0 + 0 + \ldots]$$

Fourier Series

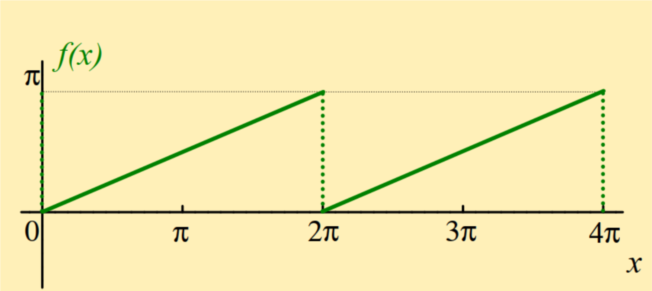
Finally, this gives

$$\begin{aligned} -\frac{\pi}{4} &= -\frac{2}{\pi}\left(1+\frac{1}{3^2}+\frac{1}{5^2}+\frac{1}{7^2}+\dots\right) \\ \text{and} \quad \frac{\pi^2}{8} &= 1+\frac{1}{3^2}+\frac{1}{5^2}+\frac{1}{7^2}+\dots \end{aligned}$$

Exercise 4.

$\boxed{f(x) = \frac{x}{2}, \text{ over the interval } 0 < x < 2\pi \text{ and has period } 2\pi}$

a) Sketch a graph of $f(x)$ in the interval $0 < x < 4\pi$



b) Fourier series representation of $f(x)$

STEP ONE

$$
\begin{aligned}
a_0 &= \frac{1}{\pi}\int_0^{2\pi} f(x)\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_0^{2\pi} \frac{x}{2}\,\mathrm{d}x \\
&= \frac{1}{\pi}\left[\frac{x^2}{4}\right]_0^{2\pi} \\
&= \frac{1}{\pi}\left[\frac{(2\pi)^2}{4} - 0\right] \\
\text{i.e. } a_0 &= \pi.
\end{aligned}
$$

Fourier Series

STEP TWO

$$
\begin{aligned}
a_n &= \frac{1}{\pi}\int_0^{2\pi} f(x)\cos nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_0^{2\pi} \frac{x}{2}\cos nx\,\mathrm{d}x \\
&= \frac{1}{2\pi}\underbrace{\left\{\left[x\frac{\sin nx}{n}\right]_0^{2\pi} - \frac{1}{n}\int_0^{2\pi}\sin nx\,\mathrm{d}x\right\}}_{\text{using integration by parts}} \\
&= \frac{1}{2\pi}\left\{\left(2\pi\frac{\sin n2\pi}{n} - 0\cdot\frac{\sin n\cdot 0}{n}\right) - \frac{1}{n}\cdot 0\right\} \\
&= \frac{1}{2\pi}\left\{(0-0) - \frac{1}{n}\cdot 0\right\} \quad \text{, see Trig} \\
\text{i.e. } a_n &= 0.
\end{aligned}
$$

STEP THREE

$$
\begin{aligned}
b_n &= \frac{1}{\pi}\int_0^{2\pi} f(x)\sin nx\,\mathrm{d}x = \frac{1}{\pi}\int_0^{2\pi}\left(\frac{x}{2}\right)\sin nx\,\mathrm{d}x \\
&= \frac{1}{2\pi}\int_0^{2\pi} x\sin nx\,\mathrm{d}x \\
&= \frac{1}{2\pi}\underbrace{\left\{\left[x\left(\frac{-\cos nx}{n}\right)\right]_0^{2\pi} - \int_0^{2\pi}\left(\frac{-\cos nx}{n}\right)\mathrm{d}x\right\}}_{\text{using integration by parts}} \\
&= \frac{1}{2\pi}\left\{\frac{1}{n}\left(-2\pi\cos n2\pi + 0\right) + \frac{1}{n}\cdot 0\right\}, \text{ see TRIG} \\
&= \frac{-2\pi}{2\pi n}\cos(n2\pi) \\
&= -\frac{1}{n}\cos(2n\pi) \\
\text{i.e. } b_n &= -\frac{1}{n} \quad , \text{ since } 2n \text{ is even (see TRIG)}
\end{aligned}
$$

Fourier Series

We now have

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx]$$

where $a_0 = \pi, \; a_n = 0, \; b_n = -\frac{1}{n}$

These Fourier coefficients give

$$\begin{aligned} f(x) &= \frac{\pi}{2} + \sum_{n=1}^{\infty} \left(0 - \frac{1}{n} \sin nx\right) \\ \text{i.e. } f(x) &= \frac{\pi}{2} - \left\{ \sin x + \frac{1}{2} \sin 2x + \frac{1}{3} \sin 3x + \dots \right\}. \end{aligned}$$

c) Pick an appropriate value of x, to show that

$$\boxed{\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \dots}$$

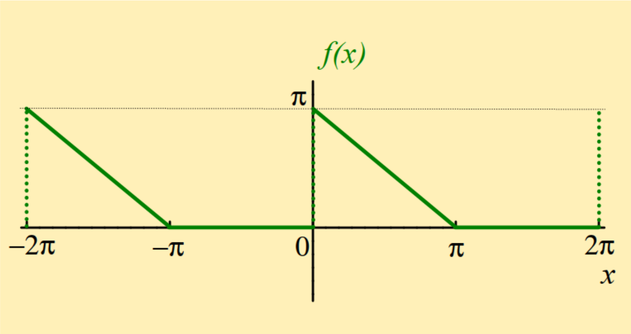
Setting $x = \frac{\pi}{2}$ gives $f(x) = \frac{\pi}{4}$ and

$$\begin{aligned}
\frac{\pi}{4} &= \frac{\pi}{2} - \left[1 + 0 - \frac{1}{3} + 0 + \frac{1}{5} + 0 - \dots\right] \\
\frac{\pi}{4} &= \frac{\pi}{2} - \left[1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \dots\right] \\
\left[1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \dots\right] &= \frac{\pi}{4} \\
\text{i.e.} \quad 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \dots &= \frac{\pi}{4}.
\end{aligned}$$

Exercise 5.

$$\boxed{f(x) = \begin{cases} \pi - x & , 0 < x < \pi \\ 0 & , \pi < x < 2\pi, \text{ and has period } 2\pi \end{cases}}$$

a) Sketch a graph of $f(x)$ in the interval $-2\pi < x < 2\pi$



b) Fourier series representation of $f(x)$

STEP ONE

$$
\begin{aligned}
a_0 &= \frac{1}{\pi}\int_0^{2\pi} f(x)\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_0^{\pi} (\pi - x)\,\mathrm{d}x + \frac{1}{\pi}\int_{\pi}^{2\pi} 0\cdot\mathrm{d}x \\
&= \frac{1}{\pi}\left[\pi x - \frac{1}{2}x^2\right]_0^{\pi} + 0 \\
&= \frac{1}{\pi}\left[\pi^2 - \frac{\pi^2}{2} - 0\right] \\
\text{i.e. } a_0 &= \frac{\pi}{2}.
\end{aligned}
$$

Fourier Series

STEP TWO

$$
\begin{aligned}
a_n &= \frac{1}{\pi}\int_0^{2\pi} f(x)\cos nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_0^{\pi} (\pi - x)\cos nx\,\mathrm{d}x + \frac{1}{\pi}\int_\pi^{2\pi} 0\cdot\mathrm{d}x \\
\text{i.e. } a_n &= \frac{1}{\pi}\underbrace{\left\{\left[(\pi - x)\frac{\sin nx}{n}\right]_0^\pi - \int_0^\pi (-1)\cdot\frac{\sin nx}{n}\,\mathrm{d}x\right\}}_{\text{using integration by parts}} + 0 \\
&= \frac{1}{\pi}\left\{(0-0) + \int_0^\pi \frac{\sin nx}{n}\mathrm{d}x\right\} \quad \text{, see TRIG} \\
&= \frac{1}{\pi n}\left[\frac{-\cos nx}{n}\right]_0^\pi \\
&= -\frac{1}{\pi n^2}\left(\cos n\pi - \cos 0\right) \\
\text{i.e. } a_n &= -\frac{1}{\pi n^2}\left((-1)^n - 1\right) \quad \text{, see TRIG}
\end{aligned}
$$

$$\text{i.e. } a_n = \begin{cases} 0 & , n \text{ even} \\ \frac{2}{\pi n^2} & , n \text{ odd} \end{cases}$$

STEP THREE

$$\begin{aligned}
b_n &= \frac{1}{\pi}\int_0^{2\pi} f(x)\sin nx \,\mathrm{d}x \\
&= \frac{1}{\pi}\int_0^{\pi} (\pi - x)\sin nx \,\mathrm{d}x + \int_{\pi}^{2\pi} 0\cdot \mathrm{d}x \\
&= \frac{1}{\pi}\left\{\left[(\pi - x)\left(-\frac{\cos nx}{n}\right)\right]_0^{\pi} - \int_0^{\pi}(-1)\cdot\left(-\frac{\cos nx}{n}\right)\mathrm{d}x\right\} + 0 \\
&= \frac{1}{\pi}\left\{\left(0 - \left(-\frac{\pi}{n}\right)\right) - \frac{1}{n}\cdot 0\right\}, \text{ see Trig} \\
\text{i.e. } b_n &= \frac{1}{n}.
\end{aligned}$$

Fourier Series

In summary, $a_0 = \frac{\pi}{2}$ and a table of other Fourier cofficients is

n	1	2	3	4	5
$a_n = \frac{2}{\pi n^2}$ (when n is odd)	$\frac{2}{\pi}$	0	$\frac{2}{\pi}\frac{1}{3^2}$	0	$\frac{2}{\pi}\frac{1}{5^2}$
$b_n = \frac{1}{n}$	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{5}$

$$
\begin{aligned}
\therefore\ f(x) &= \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx] \\
&= \frac{\pi}{4} + \frac{2}{\pi}\cos x + \frac{2}{\pi}\frac{1}{3^2}\cos 3x + \frac{2}{\pi}\frac{1}{5^2}\cos 5x + \dots \\
&\quad + \sin x + \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x + \frac{1}{4}\sin 4x + \dots \\
\text{i.e. } f(x) &= \frac{\pi}{4} + \frac{2}{\pi}\left[\cos x + \frac{1}{3^2}\cos 3x + \frac{1}{5^2}\cos 5x + \dots\right] \\
&\quad + \sin x + \frac{1}{2}\sin 2x + \frac{1}{3}\sin 3x + \frac{1}{4}\sin 4x + \dots
\end{aligned}
$$

c) To show that $\boxed{\frac{\pi^2}{8} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \dots}$,

note that, as $x \to 0$, the series converges to the half-way value of $\frac{\pi}{2}$,

$$\text{and then} \quad \frac{\pi}{2} = \frac{\pi}{4} + \frac{2}{\pi}\left(\cos 0 + \frac{1}{3^2}\cos 0 + \frac{1}{5^2}\cos 0 + \dots\right) + \sin 0 + \frac{1}{2}\sin 0 + \frac{1}{3}\sin 0 + \dots$$

$$\frac{\pi}{2} = \frac{\pi}{4} + \frac{2}{\pi}\left(1 + \frac{1}{3^2} + \frac{1}{5^2} + \dots\right) + 0$$

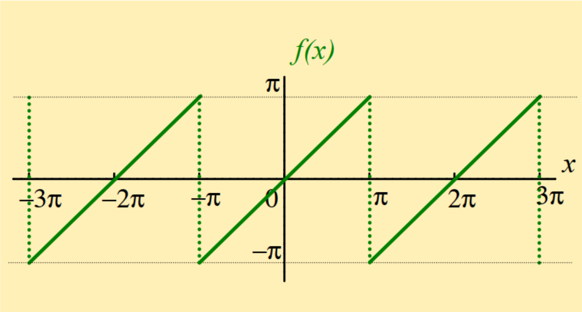
$$\frac{\pi}{4} = \frac{2}{\pi}\left(1 + \frac{1}{3^2} + \frac{1}{5^2} + \dots\right)$$

$$\text{giving} \quad \frac{\pi^2}{8} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \dots$$

Exercise 6.

$$\boxed{f(x) = x, \text{ over the interval } -\pi < x < \pi \text{ and has period } 2\pi}$$

a) Sketch a graph of $f(x)$ in the interval $-3\pi < x < 3\pi$



b) Fourier series representation of $f(x)$

STEP ONE

$$
\begin{aligned}
a_0 &= \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{\pi} x\,\mathrm{d}x \\
&= \frac{1}{\pi}\left[\frac{x^2}{2}\right]_{-\pi}^{\pi} \\
&= \frac{1}{\pi}\left(\frac{\pi^2}{2}-\frac{\pi^2}{2}\right) \\
\text{i.e. } a_0 &= 0.
\end{aligned}
$$

Fourier Series

STEP TWO

$$
\begin{aligned}
a_n &= \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos nx \,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{\pi} x\cos nx \,\mathrm{d}x \\
&= \frac{1}{\pi}\underbrace{\left\{\left[x\frac{\sin nx}{n}\right]_{-\pi}^{\pi} - \int_{-\pi}^{\pi}\left(\frac{\sin nx}{n}\right)\mathrm{d}x\right\}}_{\text{using integration by parts}} \\
\text{i.e. } a_n &= \frac{1}{\pi}\left\{\frac{1}{n}(\pi\sin n\pi - (-\pi)\sin(-n\pi)) - \frac{1}{n}\int_{-\pi}^{\pi}\sin nx\,\mathrm{d}x\right\} \\
&= \frac{1}{\pi}\left\{\frac{1}{n}(0-0) - \frac{1}{n}\cdot 0\right\}, \\
&\qquad \text{since} \quad \sin n\pi = 0 \quad \text{and} \quad \int_{2\pi}\sin nx\,\mathrm{d}x = 0, \\
\text{i.e. } a_n &= 0.
\end{aligned}
$$

STEP THREE

$$\begin{aligned}
b_n &= \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{\pi} x\sin nx\,\mathrm{d}x \\
&= \frac{1}{\pi}\left\{\left[\frac{-x\cos nx}{n}\right]_{-\pi}^{\pi} - \int_{-\pi}^{\pi}\left(\frac{-\cos nx}{n}\right)\mathrm{d}x\right\} \\
&= \frac{1}{\pi}\left\{-\frac{1}{n}\left[x\cos nx\right]_{-\pi}^{\pi} + \frac{1}{n}\int_{-\pi}^{\pi}\cos nx\,\mathrm{d}x\right\} \\
&= \frac{1}{\pi}\left\{-\frac{1}{n}\left(\pi\cos n\pi - (-\pi)\cos(-n\pi)\right) + \frac{1}{n}\cdot 0\right\} \\
&= -\frac{\pi}{n\pi}\left(\cos n\pi + \cos n\pi\right) \\
&= -\frac{1}{n}\left(2\cos n\pi\right) \\
\text{i.e. } b_n &= -\frac{2}{n}(-1)^n.
\end{aligned}$$

Fourier Series

We thus have

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

with $a_0 = 0,\ a_n = 0,\ b_n = -\frac{2}{n}(-1)^n$

and

n	1	2	3
b_n	2	-1	$\frac{2}{3}$

Therefore

$$\begin{aligned} f(x) &= b_1 \sin x + b_2 \sin 2x + b_3 \sin 3x + \ldots \\ \text{i.e. } f(x) &= 2\left[\sin x - \frac{1}{2} \sin 2x + \frac{1}{3} \sin 3x - \ldots \right] \end{aligned}$$

c) Pick an appropriate value of x, to show that

$$\boxed{\tfrac{\pi}{4} = 1 - \tfrac{1}{3} + \tfrac{1}{5} - \tfrac{1}{7} + \dots}$$

Setting $x = \frac{\pi}{2}$ gives $f(x) = \frac{\pi}{2}$ and

$$\frac{\pi}{2} = 2\left[\sin\frac{\pi}{2} - \frac{1}{2}\sin\frac{2\pi}{2} + \frac{1}{3}\sin\frac{3\pi}{2} - \frac{1}{4}\sin\frac{4\pi}{2} + \frac{1}{5}\sin\frac{5\pi}{2} - \dots\right]$$

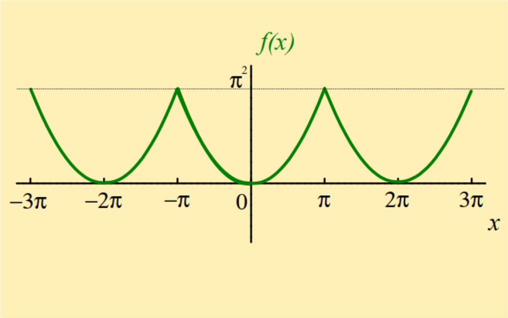
This gives

$$\begin{aligned}
\frac{\pi}{2} &= 2\left[1 + 0 + \frac{1}{3}\cdot(-1) - 0 + \frac{1}{5}\cdot(1) - 0 + \frac{1}{7}\cdot(-1) + \dots\right] \\
\frac{\pi}{2} &= 2\left[1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots\right] \\
\text{i.e.}\quad \frac{\pi}{4} &= 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots
\end{aligned}$$

Exercise 7.

$$\boxed{f(x) = x^2, \text{ over the interval } -\pi < x < \pi \text{ and has period } 2\pi}$$

a) Sketch a graph of $f(x)$ in the interval $-3\pi < x < 3\pi$



b) Fourier series representation of $f(x)$

STEP ONE

$$\begin{aligned} a_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\mathrm{d}x &= \frac{1}{\pi}\int_{-\pi}^{\pi} x^2\,\mathrm{d}x \\ &= \frac{1}{\pi}\left[\frac{x^3}{3}\right]_{-\pi}^{\pi} \\ &= \frac{1}{\pi}\left(\frac{\pi^3}{3} - \left(-\frac{\pi^3}{3}\right)\right) \\ &= \frac{1}{\pi}\left(\frac{2\pi^3}{3}\right) \\ \text{i.e. } a_0 &= \frac{2\pi^2}{3}. \end{aligned}$$

STEP TWO

$$
\begin{aligned}
a_n &= \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos nx \,\mathrm{d}x \\
&= \frac{1}{\pi}\int_{-\pi}^{\pi} x^2\cos nx \,\mathrm{d}x \\
&= \underbrace{\frac{1}{\pi}\left\{\left[x^2\frac{\sin nx}{n}\right]_{-\pi}^{\pi} - \int_{-\pi}^{\pi} 2x\left(\frac{\sin nx}{n}\right)\mathrm{d}x\right\}}_{\text{using integration by parts}} \\
&= \frac{1}{\pi}\left\{\frac{1}{n}\left(\pi^2\sin n\pi - \pi^2\sin(-n\pi)\right) - \frac{2}{n}\int_{-\pi}^{\pi} x\sin nx\,\mathrm{d}x\right\} \\
&= \frac{1}{\pi}\left\{\frac{1}{n}(0-0) - \frac{2}{n}\int_{-\pi}^{\pi} x\sin nx\,\mathrm{d}x\right\}, \text{ see }\textsc{Trig} \\
&= \frac{-2}{n\pi}\int_{-\pi}^{\pi} x\sin nx\,\mathrm{d}x
\end{aligned}
$$

$$
\begin{aligned}
\text{i.e. } a_n &= \frac{-2}{n\pi}\underbrace{\left\{\left[x\left(\frac{-\cos nx}{n}\right)\right]_{-\pi}^{\pi} - \int_{-\pi}^{\pi}\left(\frac{-\cos nx}{n}\right)\mathrm{d}x\right\}}_{\text{using integration by parts again}} \\
&= \frac{-2}{n\pi}\left\{-\frac{1}{n}\left[x\cos nx\right]_{-\pi}^{\pi} + \frac{1}{n}\int_{-\pi}^{\pi}\cos nx\,\mathrm{d}x\right\} \\
&= \frac{-2}{n\pi}\left\{-\frac{1}{n}\Big(\pi\cos n\pi - (-\pi)\cos(-n\pi)\Big) + \frac{1}{n}\cdot 0\right\} \\
&= \frac{-2}{n\pi}\left\{-\frac{1}{n}\Big(\pi(-1)^n + \pi(-1)^n\Big)\right\} \\
&= \frac{-2}{n\pi}\left\{\frac{-2\pi}{n}(-1)^n\right\}
\end{aligned}
$$

Fourier Series

$$\text{i.e. } a_n = \frac{-2}{n\pi}\left\{-\frac{2\pi}{n}(-1)^n\right\}$$

$$= \frac{+4\pi}{\pi n^2}(-1)^n$$

$$= \frac{4}{n^2}(-1)^n$$

$$\text{i.e. } a_n = \begin{cases} \frac{4}{n^2} & , n \text{ even} \\ \frac{-4}{n^2} & , n \text{ odd.} \end{cases}$$

Fourier Series

STEP THREE

$$
\begin{aligned}
b_n &= \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin nx\,\mathrm{d}x = \frac{1}{\pi}\int_{-\pi}^{\pi} x^2 \sin nx\,\mathrm{d}x \\
&= \underbrace{\frac{1}{\pi}\left\{\left[x^2\left(\frac{-\cos nx}{n}\right)\right]_{-\pi}^{\pi} - \int_{-\pi}^{\pi} 2x\cdot\left(\frac{-\cos nx}{n}\right)\mathrm{d}x\right\}}_{\text{using integration by parts}} \\
&= \frac{1}{\pi}\left\{-\frac{1}{n}\left[x^2\cos nx\right]_{-\pi}^{\pi} + \frac{2}{n}\int_{-\pi}^{\pi} x\cos nx\,\mathrm{d}x\right\} \\
&= \frac{1}{\pi}\left\{-\frac{1}{n}\left(\pi^2\cos n\pi - \pi^2\cos(-n\pi)\right) + \frac{2}{n}\int_{-\pi}^{\pi} x\cos nx\,\mathrm{d}x\right\} \\
&= \frac{1}{\pi}\left\{-\frac{1}{n}\underbrace{\left(\pi^2\cos n\pi - \pi^2\cos(n\pi)\right)}_{=0} + \frac{2}{n}\int_{-\pi}^{\pi} x\cos nx\,\mathrm{d}x\right\} \\
&= \frac{2}{\pi n}\int_{-\pi}^{\pi} x\cos nx\,\mathrm{d}x
\end{aligned}
$$

Fourier Series

$$
\begin{aligned}
\text{i.e. } b_n &= \frac{2}{\pi n} \underbrace{\left\{ \left[x \frac{\sin nx}{n} \right]_{-\pi}^{\pi} - \int_{-\pi}^{\pi} \frac{\sin nx}{n} \, \mathrm{d}x \right\}}_{\text{using integration by parts}} \\
&= \frac{2}{\pi n} \left\{ \frac{1}{n} \left(\pi \sin n\pi - (-\pi) \sin(-n\pi) \right) - \frac{1}{n} \int_{-\pi}^{\pi} \sin nx \, \mathrm{d}x \right\} \\
&= \frac{2}{\pi n} \left\{ \frac{1}{n} (0 + 0) - \frac{1}{n} \int_{-\pi}^{\pi} \sin nx \, \mathrm{d}x \right\} \\
&= \frac{-2}{\pi n^2} \int_{-\pi}^{\pi} \sin nx \, \mathrm{d}x \\
\text{i.e. } b_n &= 0.
\end{aligned}
$$

Fourier Series

$$\therefore\ f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx]$$

where $\qquad a_0 = \frac{2\pi^2}{3}, \qquad a_n = \begin{cases} \frac{4}{n^2} & , n \text{ even} \\ \frac{-4}{n^2} & , n \text{ odd} \end{cases}, \qquad b_n = 0$

n	1	2	3	4
a_n	$-4(1)$	$4\left(\frac{1}{2^2}\right)$	$-4\left(\frac{1}{3^2}\right)$	$4\left(\frac{1}{4^2}\right)$

$$\text{i.e. } f(x) = \frac{1}{2}\left(\frac{2\pi^2}{3}\right) - 4\left[\cos x - \frac{1}{2^2}\cos 2x + \frac{1}{3^2}\cos 3x - \frac{1}{4^2}\cos 4x \ldots\right]$$

$$+ [0 + 0 + 0 + \ldots]$$

$$\text{i.e. } f(x) = \frac{\pi^2}{3} - 4\left[\cos x - \frac{1}{2^2}\cos 2x + \frac{1}{3^2}\cos 3x - \frac{1}{4^2}\cos 4x + \ldots\right].$$

Fourier Series

c) To show that $\boxed{\frac{\pi^2}{6} = 1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \dots}$,

use the fact that $\cos n\pi = \begin{cases} 1 & , n \text{ even} \\ -1 & , n \text{ odd} \end{cases}$

i.e. $\cos x - \frac{1}{2^2}\cos 2x + \frac{1}{3^2}\cos 3x - \frac{1}{4^2}\cos 4x + \dots$ with $x = \pi$

gives $\cos \pi - \frac{1}{2^2}\cos 2\pi + \frac{1}{3^2}\cos 3\pi - \frac{1}{4^2}\cos 4\pi + \dots$

i.e. $(-1) - \frac{1}{2^2}\cdot(1) + \frac{1}{3^2}\cdot(-1) - \frac{1}{4^2}\cdot(1) + \dots$

i.e. $-1 - \frac{1}{2^2} - \frac{1}{3^2} - \frac{1}{4^2} + \dots$

$$= -1 \cdot \underbrace{\left(1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \dots\right)}_{\text{(the desired series)}}$$

Fourier Series

The graph of $f(x)$ gives that $f(\pi) = \pi^2$ and the series converges to this value.

Setting $x = \pi$ in the Fourier series thus gives

$$\begin{aligned}
\pi^2 &= \frac{\pi^2}{3} - 4\left(\cos\pi - \frac{1}{2^2}\cos 2\pi + \frac{1}{3^2}\cos 3\pi - \frac{1}{4^2}\cos 4\pi + \dots\right) \\
\pi^2 &= \frac{\pi^2}{3} - 4\left(-1 - \frac{1}{2^2} - \frac{1}{3^2} - \frac{1}{4^2} - \dots\right) \\
\pi^2 &= \frac{\pi^2}{3} + 4\left(1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \dots\right) \\
\frac{2\pi^2}{3} &= 4\left(1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \dots\right) \\
\text{i.e. } \frac{\pi^2}{6} &= 1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \dots
\end{aligned}$$