

## 2

# Fourier Trigonometric Series

*"Profound study of nature is the most fertile source of mathematical discoveries."  
Joseph Fourier (1768-1830)*

### 2.1 Introduction to Fourier Series

WE WILL NOW TURN TO THE STUDY of trigonometric series. You have seen that functions have series representations as expansions in powers of  $x$ , or  $x - a$ , in the form of Maclaurin and Taylor series. Recall that the Taylor series expansion is given by

$$f(x) = \sum_{n=0}^{\infty} c_n (x - a)^n,$$

where the expansion coefficients are determined as

$$c_n = \frac{f^{(n)}(a)}{n!}.$$

From the study of the heat equation and wave equation, Fourier showed that there are infinite series expansions over other functions, such as sine functions. We now turn to such expansions and in the next chapter we will find out that expansions over special sets of functions are not uncommon in physics. But, first we turn to Fourier trigonometric series.

We will begin with the study of the Fourier trigonometric series expansion

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi x}{L} + b_n \sin \frac{n\pi x}{L}.$$

We will find expressions useful for determining the Fourier coefficients  $\{a_n, b_n\}$  given a function  $f(x)$  defined on  $[-L, L]$ . We will also see if the resulting infinite series reproduces  $f(x)$ . However, we first begin with some basic ideas involving simple sums of sinusoidal functions.

There is a natural appearance of such sums over sinusoidal functions in music. A pure note can be represented as

$$y(t) = A \sin(2\pi ft),$$

As noted in the Introduction, Joseph Fourier (1768-1830) and others studied trigonometric series solutions of the heat and wave equations.

The temperature,  $u(x, t)$ , of a one dimensional rod of length  $L$  satisfies the heat equation,

$$\frac{\partial u}{\partial t} = k \frac{\partial^2 u}{\partial x^2}.$$

The general solution, which satisfies the conditions  $u(0, t) = 0$  and  $u(L, t) = 0$ , is given by

$$u(x, t) = \sum_{n=0}^{\infty} b_n \sin \frac{n\pi x}{L} e^{-n^2 \pi^2 kt/L^2}.$$

If the initial temperature is given by  $u(x, 0) = f(x)$ , one has to satisfy the condition

$$f(x) = \sum_{n=0}^{\infty} b_n \sin \frac{n\pi x}{L}.$$

The height,  $u(x, t)$ , of a one dimensional vibrating string of length  $L$  satisfies the wave equation,

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}.$$

The general solution, which satisfies the fixed ends  $u(0, t) = 0$  and  $u(L, t) = 0$ , is given by

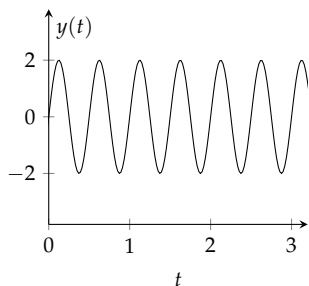
$$u(x, t) = \sum_{n=1}^{\infty} A_n \cos \frac{n\pi ct}{L} \sin \frac{n\pi x}{L} + B_n \sin \frac{n\pi ct}{L} \sin \frac{n\pi x}{L}.$$

If the initial profile and velocity are given by  $u(x, 0) = f(x)$  and  $u_t(x, 0) = g(x)$ , respectively, then one has to satisfy the conditions

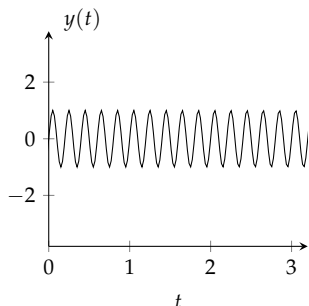
$$f(x) = u(x, 0) = \sum_{n=1}^{\infty} A_n \sin \frac{n\pi x}{L}$$

and

$$g(x) = u_t(x, 0) = \sum_{n=1}^{\infty} \frac{n\pi c}{L} B_n \sin \frac{n\pi x}{L}.$$



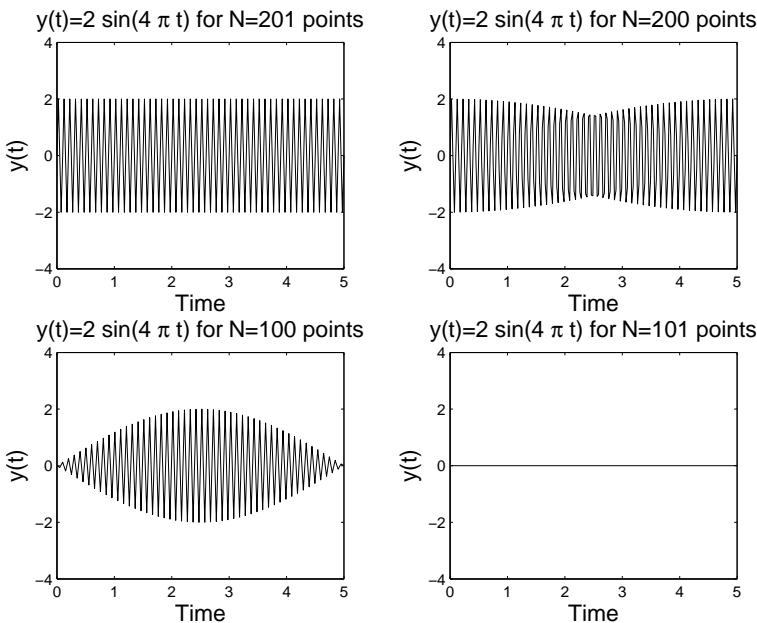
(a)  $y(t) = 2 \sin(4\pi ft)$



(b)  $y(t) = \sin(10\pi ft)$

Figure 2.1: Plots of  $y(t) = A \sin(2\pi ft)$  on  $[0, 5]$  for  $f = 2$  Hz and  $f = 5$  Hz.

Figure 2.2: Problems can occur while plotting. Here we plot the function  $y(t) = 2 \sin 4\pi t$  using  $N = 201, 200, 100, 101$  points.



where  $A$  is the amplitude,  $f$  is the frequency in Hertz (Hz), and  $t$  is time in seconds. The amplitude is related to the volume of the sound. The larger the amplitude, the louder the sound. In Figure 2.1 we show plots of two such tones with  $f = 2$  Hz in the top plot and  $f = 5$  Hz in the bottom one.

In these plots you should notice the difference due to the amplitudes and the frequencies. You can easily reproduce these plots and others in your favorite plotting utility.

As an aside, you should be cautious when plotting functions, or sampling data. The plots you get might not be what you expect, even for a simple sine function. In Figure 2.2 we show four plots of the function  $y(t) = 2 \sin(4\pi t)$ . In the top left, you see a proper rendering of this function. However, if you use a different number of points to plot this function, the results may be surprising. In this example we show what happens if you use  $N = 200, 100, 101$  points instead of the 201 points used in the first plot. Such disparities are not only possible when plotting functions, but are also present when collecting data. Typically, when you sample a set of data, you only gather a finite amount of information at a fixed rate. This could happen when getting data on ocean wave heights, digitizing music, and other audio to put on your computer, or any other process when you attempt to analyze a continuous signal.

Next, we consider what happens when we add several pure tones. After all, most of the sounds that we hear are, in fact, a combination of pure tones with different amplitudes and frequencies. In Figure 2.3 we see what happens when we add several sinusoids. Note that as one adds more and more tones with different characteristics, the resulting signal gets more complicated. However, we still have a function of time. In this chapter we will ask,

“Given a function  $f(t)$ , can we find a set of sinusoidal functions whose sum converges to  $f(t)$ ?”

Looking at the superpositions in Figure 2.3, we see that the sums yield functions that appear to be periodic. This is not unexpected. We recall that a periodic function is one in which the function values repeat over the domain of the function. The length of the smallest part of the domain which repeats is called the period. We can define this more precisely: A function is said to be periodic with period  $T$  if  $f(t + T) = f(t)$  for all  $t$  and the smallest such positive number  $T$  is called the period.

For example, we consider the functions used in Figure 2.3. We began with  $y(t) = 2 \sin(4\pi t)$ . Recall from your first studies of trigonometric functions that one can determine the period by dividing the coefficient of  $t$  into  $2\pi$  to get the period. In this case we have

$$T = \frac{2\pi}{4\pi} = \frac{1}{2}.$$

Looking at the top plot in Figure 2.1 we can verify this result. (You can count the full number of cycles in the graph and divide this into the total time to get a more accurate value of the period.)

In general, if  $y(t) = A \sin(2\pi ft)$ , the period is found as

$$T = \frac{2\pi}{2\pi f} = \frac{1}{f}.$$

Of course, this result makes sense, as the unit of frequency, the hertz, is also defined as  $s^{-1}$ , or cycles per second.

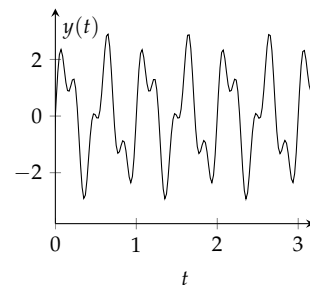
Returning to Figure 2.3, the functions  $y(t) = 2 \sin(4\pi t)$ ,  $y(t) = \sin(10\pi t)$ , and  $y(t) = 0.5 \sin(16\pi t)$  have periods of 0.5s, 0.2s, and 0.125s, respectively. Each superposition in Figure 2.3 retains a period that is the least common multiple of the periods of the signals added. For both plots, this is  $1.0 \text{ s} = 2(0.5) \text{ s} = 5(.2) \text{ s} = 8(.125) \text{ s}$ .

Our goal will be to start with a function and then determine the amplitudes of the simple sinusoids needed to sum to that function. We will see that this might involve an infinite number of such terms. Thus, we will be studying an infinite series of sinusoidal functions.

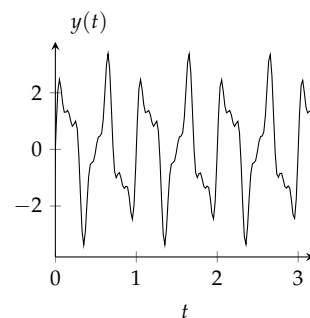
Secondly, we will find that using just sine functions will not be enough either. This is because we can add sinusoidal functions that do not necessarily peak at the same time. We will consider two signals that originate at different times. This is similar to when your music teacher would make sections of the class sing a song like “Row, Row, Row Your Boat” starting at slightly different times.

We can easily add shifted sine functions. In Figure 2.4 we show the functions  $y(t) = 2 \sin(4\pi t)$  and  $y(t) = 2 \sin(4\pi t + 7\pi/8)$  and their sum. Note that this shifted sine function can be written as  $y(t) = 2 \sin(4\pi(t + 7/32))$ . Thus, this corresponds to a time shift of  $-7/32$ .

So, we should account for shifted sine functions in the general sum. Of course, we would then need to determine the unknown time shift as well as the amplitudes of the sinusoidal functions that make up the signal,  $f(t)$ .

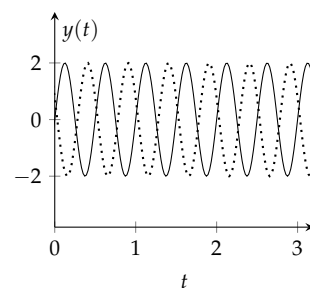


(a) Sum of signals with frequencies  $f = 2 \text{ Hz}$  and  $f = 5 \text{ Hz}$ .

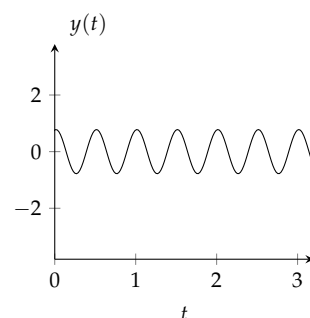


(b) Sum of signals with frequencies  $f = 2 \text{ Hz}$ ,  $f = 5 \text{ Hz}$ , and  $f = 8 \text{ Hz}$ .

Figure 2.3: Superposition of several sinusoids.



(a) Plot of each function.



(b) Plot of the sum of the functions.

Figure 2.4: Plot of the functions  $y(t) = 2 \sin(4\pi t)$  and  $y(t) = 2 \sin(4\pi t + 7\pi/8)$  and their sum.

We should note that the form in the lower plot of Figure 2.4 looks like a simple sinusoidal function for a reason. Let

$$y_1(t) = 2 \sin(4\pi t),$$

$$y_2(t) = 2 \sin(4\pi t + 7\pi/8).$$

Then,

$$\begin{aligned} y_1 + y_2 &= 2 \sin(4\pi t + 7\pi/8) + 2 \sin(4\pi t) \\ &= 2[\sin(4\pi t + 7\pi/8) + \sin(4\pi t)] \\ &= 4 \cos \frac{7\pi}{16} \sin \left( 4\pi t + \frac{7\pi}{16} \right). \end{aligned}$$

<sup>1</sup> Recall the identities (2.9) and (2.10)

$$\begin{aligned} \sin(x + y) &= \sin x \cos y + \sin y \cos x, \\ \cos(x + y) &= \cos x \cos y - \sin x \sin y. \end{aligned}$$

While this is one approach that some researchers use to analyze signals, there is a more common approach. This results from another reworking of the shifted function.

Consider the general shifted function

$$y(t) = A \sin(2\pi ft + \phi). \quad (2.1)$$

Note that  $2\pi ft + \phi$  is called the phase of the sine function and  $\phi$  is called the phase shift. We can use the trigonometric identity (2.9) for the sine of the sum of two angles<sup>1</sup> to obtain

$$\begin{aligned} y(t) &= A \sin(2\pi ft + \phi) \\ &= A \sin(\phi) \cos(2\pi ft) + A \cos(\phi) \sin(2\pi ft). \end{aligned} \quad (2.2)$$

Defining  $a = A \sin(\phi)$  and  $b = A \cos(\phi)$ , we can rewrite this as

$$y(t) = a \cos(2\pi ft) + b \sin(2\pi ft).$$

Thus, we see that the signal in Equation (2.1) is a sum of sine and cosine functions with the same frequency and different amplitudes. If we can find  $a$  and  $b$ , then we can easily determine  $A$  and  $\phi$ :

$$A = \sqrt{a^2 + b^2}, \quad \tan \phi = \frac{b}{a}.$$

We are now in a position to state our goal:

#### Goal - Fourier Analysis

Given a signal  $f(t)$ , we would like to determine its frequency content by finding out what combinations of sines and cosines of varying frequencies and amplitudes will sum to the given function. This is called Fourier Analysis.

## 2.2 Fourier Trigonometric Series

AS WE HAVE SEEN IN THE LAST SECTION, we are interested in finding representations of functions in terms of sines and cosines. Given a function  $f(x)$  we seek a representation in the form

$$f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx]. \quad (2.3)$$

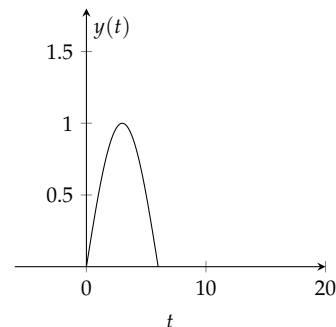
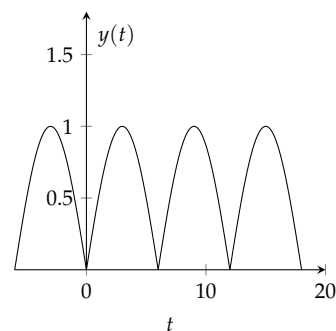
Notice that we have opted to drop the references to the time-frequency form of the phase. This will lead to a simpler discussion for now and one can always make the transformation  $nx = 2\pi f_n t$  when applying these ideas to applications.

The series representation in Equation (2.3) is called a Fourier trigonometric series. We will simply refer to this as a Fourier series for now. The set

of constants  $a_0, a_n, b_n, n = 1, 2, \dots$  are called the Fourier coefficients. The constant term is chosen in this form to make later computations simpler, though some other authors choose to write the constant term as  $a_0$ . Our goal is to find the Fourier series representation given  $f(x)$ . Having found the Fourier series representation, we will be interested in determining when the Fourier series converges and to what function it converges.

From our discussion in the last section, we see that The Fourier series is periodic. The periods of  $\cos nx$  and  $\sin nx$  are  $\frac{2\pi}{n}$ . Thus, the largest period,  $T = 2\pi$ , comes from the  $n = 1$  terms and the Fourier series has period  $2\pi$ . This means that the series should be able to represent functions that are periodic of period  $2\pi$ .

While this appears restrictive, we could also consider functions that are defined over one period. In Figure 2.5 we show a function defined on  $[0, 2\pi]$ . In the same figure, we show its periodic extension. These are just copies of the original function shifted by the period and glued together. The extension can now be represented by a Fourier series and restricting the Fourier series to  $[0, 2\pi]$  will give a representation of the original function. Therefore, we will first consider Fourier series representations of functions defined on this interval. Note that we could just as easily considered functions defined on  $[-\pi, \pi]$  or any interval of length  $2\pi$ . We will consider more general intervals later in the chapter.

(a) Plot of function  $f(t)$ .(b) Periodic extension of  $f(t)$ .Figure 2.5: Plot of the function  $f(t)$  defined on  $[0, 2\pi]$  and its periodic extension.

### Fourier Coefficients

**Theorem 2.1.** *The Fourier series representation of  $f(x)$  defined on  $[0, 2\pi]$ , when it exists, is given by Equation (2.3) with Fourier coefficients*

$$\begin{aligned} a_n &= \frac{1}{\pi} \int_0^{2\pi} f(x) \cos nx \, dx, \quad n = 0, 1, 2, \dots, \\ b_n &= \frac{1}{\pi} \int_0^{2\pi} f(x) \sin nx \, dx, \quad n = 1, 2, \dots \end{aligned} \quad (2.4)$$

These expressions for the Fourier coefficients are obtained by considering special integrations of the Fourier series. We will now derive the  $a_n$  integrals in Equation (2.4).

We begin with the computation of  $a_0$ . Integrating the Fourier series term by term in Equation (2.3), we have

$$\int_0^{2\pi} f(x) \, dx = \int_0^{2\pi} \frac{a_0}{2} \, dx + \int_0^{2\pi} \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx] \, dx. \quad (2.5)$$

We will assume that we can integrate the infinite sum term by term. Then we will need to compute

$$\begin{aligned} \int_0^{2\pi} \frac{a_0}{2} \, dx &= \frac{a_0}{2} (2\pi) = \pi a_0, \\ \int_0^{2\pi} \cos nx \, dx &= \left[ \frac{\sin nx}{n} \right]_0^{2\pi} = 0, \\ \int_0^{2\pi} \sin nx \, dx &= \left[ \frac{-\cos nx}{n} \right]_0^{2\pi} = 0. \end{aligned} \quad (2.6)$$

Evaluating the integral of an infinite series by integrating term by term depends on the convergence properties of the series.

<sup>2</sup> Note that  $\frac{a_0}{2}$  is the average of  $f(x)$  over the interval  $[0, 2\pi]$ . Recall from the first semester of calculus, that the average of a function defined on  $[a, b]$  is given by

$$f_{\text{ave}} = \frac{1}{b-a} \int_a^b f(x) dx.$$

For  $f(x)$  defined on  $[0, 2\pi]$ , we have

$$f_{\text{ave}} = \frac{1}{2\pi} \int_0^{2\pi} f(x) dx = \frac{a_0}{2}.$$

From these results we see that only one term in the integrated sum does not vanish, leaving

$$\int_0^{2\pi} f(x) dx = \pi a_0.$$

This confirms the value for  $a_0$ .<sup>2</sup>

Next, we will find the expression for  $a_n$ . We multiply the Fourier series in Equation (2.3) by  $\cos mx$  for some positive integer  $m$ . This is like multiplying by  $\cos 2x$ ,  $\cos 5x$ , etc. We are multiplying by all possible  $\cos mx$  functions for different integers  $m$  all at the same time. We will see that this will allow us to solve for the  $a_n$ 's.

We find the integrated sum of the series times  $\cos mx$  is given by

$$\begin{aligned} \int_0^{2\pi} f(x) \cos mx dx &= \int_0^{2\pi} \frac{a_0}{2} \cos mx dx \\ &+ \int_0^{2\pi} \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx] \cos mx dx. \end{aligned} \quad (2.7)$$

Integrating term by term, the right side becomes

$$\begin{aligned} \int_0^{2\pi} f(x) \cos mx dx &= \frac{a_0}{2} \int_0^{2\pi} \cos mx dx \\ &+ \sum_{n=1}^{\infty} \left[ a_n \int_0^{2\pi} \cos nx \cos mx dx + b_n \int_0^{2\pi} \sin nx \cos mx dx \right]. \end{aligned} \quad (2.8)$$

We have already established that  $\int_0^{2\pi} \cos mx dx = 0$ , which implies that the first term vanishes.

Next we need to compute integrals of products of sines and cosines. This requires that we make use of some of the well known trigonometric. For quick reference, we list these here.

<b>Useful Trigonometric Identities</b>		
$\sin(x \pm y)$	$= \sin x \cos y \pm \sin y \cos x$	(2.9)
$\cos(x \pm y)$	$= \cos x \cos y \mp \sin x \sin y$	(2.10)
$\sin^2 x$	$= \frac{1}{2}(1 - \cos 2x)$	(2.11)
$\cos^2 x$	$= \frac{1}{2}(1 + \cos 2x)$	(2.12)
$\sin x \sin y$	$= \frac{1}{2}(\cos(x - y) - \cos(x + y))$	(2.13)
$\cos x \cos y$	$= \frac{1}{2}(\cos(x + y) + \cos(x - y))$	(2.14)
$\sin x \cos y$	$= \frac{1}{2}(\sin(x + y) + \sin(x - y))$	(2.15)

We first want to evaluate  $\int_0^{2\pi} \cos nx \cos mx dx$ . We do this using the product identity (2.14). In case you forgot how to derive this identity, we will

quickly review the derivation. Using the identities (2.10), we have

$$\begin{aligned}\cos(A + B) &= \cos A \cos B - \sin A \sin B, \\ \cos(A - B) &= \cos A \cos B + \sin A \sin B.\end{aligned}$$

Adding these equations,

$$2 \cos A \cos B = \cos(A + B) + \cos(A - B).$$

We can use this result with  $A = mx$  and  $B = nx$  to complete the integration. We have

$$\begin{aligned}\int_0^{2\pi} \cos nx \cos mx \, dx &= \frac{1}{2} \int_0^{2\pi} [\cos(m+n)x + \cos(m-n)x] \, dx \\ &= \frac{1}{2} \left[ \frac{\sin(m+n)x}{m+n} + \frac{\sin(m-n)x}{m-n} \right]_0^{2\pi} \\ &= 0.\end{aligned}\tag{2.16}$$

There is one caveat when doing such integrals. What if one of the denominators  $m \pm n$  vanishes? For this problem,  $m + n \neq 0$ , as both  $m$  and  $n$  are positive integers. However, it is possible for  $m = n$ . This means that the vanishing of the integral can only happen when  $m \neq n$ . So, what can we do about the  $m = n$  case? One way is to start from scratch with our integration. (Another way is to compute the limit as  $n$  approaches  $m$  in our result and use L'Hopital's Rule. Try it!)

For  $n = m$  we have to compute  $\int_0^{2\pi} \cos^2 mx \, dx$ . This can also be handled using a trigonometric identity. Using the half angle formula, Equation (2.12), with  $\theta = mx$ , we find

$$\begin{aligned}\int_0^{2\pi} \cos^2 mx \, dx &= \frac{1}{2} \int_0^{2\pi} (1 + \cos 2mx) \, dx \\ &= \frac{1}{2} \left[ x + \frac{1}{2m} \sin 2mx \right]_0^{2\pi} \\ &= \frac{1}{2}(2\pi) = \pi.\end{aligned}\tag{2.17}$$

To summarize, we have shown that

$$\int_0^{2\pi} \cos nx \cos mx \, dx = \begin{cases} 0, & m \neq n, \\ \pi, & m = n. \end{cases}\tag{2.18}$$

This holds true for  $m, n = 0, 1, \dots$  [Why did we include  $m, n = 0$ ?] When we have such a set of functions, they are said to be an orthogonal set over the integration interval. A set of (real) functions  $\{\phi_n(x)\}$  is said to be orthogonal on  $[a, b]$  if  $\int_a^b \phi_n(x)\phi_m(x) \, dx = 0$  when  $n \neq m$ . Furthermore, if we also have that  $\int_a^b \phi_n^2(x) \, dx = 1$ , these functions are called orthonormal.

The set of functions  $\{\cos nx\}_{n=0}^{\infty}$  is orthogonal on  $[0, 2\pi]$ . Actually, the set is orthogonal on any interval of length  $2\pi$ . We can make them orthonormal by dividing each function by  $\sqrt{\pi}$ , as indicated by Equation (2.17). This is sometimes referred to as normalization of the set of functions.

Definition of an orthogonal set of functions and orthonormal functions.

The notion of orthogonality is actually a generalization of the orthogonality of vectors in finite dimensional vector spaces. The integral  $\int_a^b f(x)g(x) dx$  is the generalization of the dot product, and is called the scalar product of  $f(x)$  and  $g(x)$ , which are thought of as vectors in an infinite dimensional vector space spanned by a set of orthogonal functions. We will return to these ideas in the next chapter.

Returning to the integrals in equation (2.8), we still have to evaluate  $\int_0^{2\pi} \sin nx \cos mx dx$ . We can use the trigonometric identity involving products of sines and cosines, Equation (2.15). Setting  $A = nx$  and  $B = mx$ , we find that

Identity (2.15) is found from adding the identities

$$\begin{aligned} \sin(A + B) &= \sin A \cos B + \sin B \cos A, \\ \sin(A - B) &= \sin A \cos B - \sin B \cos A. \end{aligned}$$

$$\begin{aligned} \int_0^{2\pi} \sin nx \cos mx dx &= \frac{1}{2} \int_0^{2\pi} [\sin(n + m)x + \sin(n - m)x] dx \\ &= \frac{1}{2} \left[ \frac{-\cos(n + m)x}{n + m} + \frac{-\cos(n - m)x}{n - m} \right]_0^{2\pi} \\ &= (-1 + 1) + (-1 + 1) = 0. \end{aligned} \tag{2.19}$$

So,

$$\int_0^{2\pi} \sin nx \cos mx dx = 0. \tag{2.20}$$

For these integrals we should also be careful about setting  $n = m$ . In this special case, we have the integrals

$$\int_0^{2\pi} \sin mx \cos mx dx = \frac{1}{2} \int_0^{2\pi} \sin 2mx dx = \frac{1}{2} \left[ \frac{-\cos 2mx}{2m} \right]_0^{2\pi} = 0.$$

Finally, we can finish evaluating the expression in Equation (2.8). We have determined that all but one integral vanishes. In that case,  $n = m$ . This leaves us with

$$\int_0^{2\pi} f(x) \cos mx dx = a_m \pi.$$

Solving for  $a_m$  gives

$$a_m = \frac{1}{\pi} \int_0^{2\pi} f(x) \cos mx dx.$$

Since this is true for all  $m = 1, 2, \dots$ , we have proven this part of the theorem. The only part left is finding the  $b_n$ 's. This will be left as an exercise for the reader.

We now consider examples of finding Fourier coefficients for given functions. In all of these cases, we define  $f(x)$  on  $[0, 2\pi]$ .

**Example 2.1.**  $f(x) = 3 \cos 2x, x \in [0, 2\pi]$ .

We first compute the integrals for the Fourier coefficients:

$$\begin{aligned} a_0 &= \frac{1}{\pi} \int_0^{2\pi} 3 \cos 2x dx = 0, \\ a_n &= \frac{1}{\pi} \int_0^{2\pi} 3 \cos 2x \cos nx dx = 0, \quad n \neq 2, \\ a_2 &= \frac{1}{\pi} \int_0^{2\pi} 3 \cos^2 2x dx = 3, \\ b_n &= \frac{1}{\pi} \int_0^{2\pi} 3 \cos 2x \sin nx dx = 0, \forall n. \end{aligned}$$

The integrals for  $a_0$ ,  $a_n$ ,  $n \neq 2$ , and  $b_n$  are the result of orthogonality. For  $a_2$ , the integral can be computed as follows:

$$\begin{aligned} a_2 &= \frac{1}{\pi} \int_0^{2\pi} 3 \cos^2 2x \, dx \\ &= \frac{3}{2\pi} \int_0^{2\pi} [1 + \cos 4x] \, dx \\ &= \frac{3}{2\pi} \left[ x + \underbrace{\frac{1}{4} \sin 4x}_{\text{This term vanishes!}} \right]_0^{2\pi} = 3. \end{aligned} \quad (2.21)$$

Therefore, we have that the only nonvanishing coefficient is  $a_2 = 3$ . So there is one term and  $f(x) = 3 \cos 2x$ .

Well, we should have known the answer to the last example before doing all of those integrals. If we have a function expressed simply in terms of sums of simple sines and cosines, then it should be easy to write the Fourier coefficients without much work. This is seen by writing out the Fourier series,

$$\begin{aligned} f(x) &\sim \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx]. \\ &= \frac{a_0}{2} + a_1 \cos x + b_1 \sin x + a_2 \cos 2x + b_2 \sin 2x + \dots \end{aligned} \quad (2.22)$$

For the last problem,  $f(x) = 3 \cos 2x$ . Comparing this to the expanded Fourier series, one can immediately read off the Fourier coefficients without doing any integration. In the next example, we emphasize this point.

**Example 2.2.**  $f(x) = \sin^2 x$ ,  $x \in [0, 2\pi]$ .

We could determine the Fourier coefficients by integrating as in the last example. However, it is easier to use trigonometric identities. We know that

$$\sin^2 x = \frac{1}{2}(1 - \cos 2x) = \frac{1}{2} - \frac{1}{2} \cos 2x.$$

There are no sine terms, so  $b_n = 0$ ,  $n = 1, 2, \dots$ . There is a constant term, implying  $a_0/2 = 1/2$ . So,  $a_0 = 1$ . There is a  $\cos 2x$  term, corresponding to  $n = 2$ , so  $a_2 = -\frac{1}{2}$ . That leaves  $a_n = 0$  for  $n \neq 0, 2$ . So,  $a_0 = 1$ ,  $a_2 = -\frac{1}{2}$ , and all other Fourier coefficients vanish.

**Example 2.3.**  $f(x) = \begin{cases} 1, & 0 < x < \pi, \\ -1, & \pi < x < 2\pi, \end{cases}$ .

This example will take a little more work. We cannot bypass evaluating any integrals this time. As seen in Figure 2.6, this function is discontinuous. So, we will break up any integration into two integrals, one over  $[0, \pi]$  and the other over  $[\pi, 2\pi]$ .

$$a_0 = \frac{1}{\pi} \int_0^{2\pi} f(x) \, dx$$

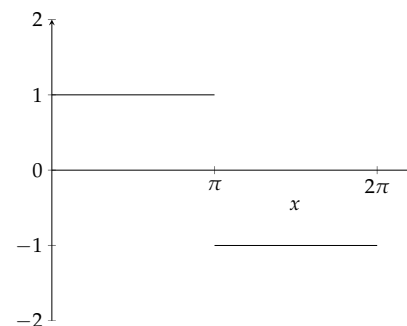


Figure 2.6: Plot of discontinuous function in Example 2.3.

$$\begin{aligned}
&= \frac{1}{\pi} \int_0^\pi dx + \frac{1}{\pi} \int_\pi^{2\pi} (-1) dx \\
&= \frac{1}{\pi}(\pi) + \frac{1}{\pi}(-2\pi + \pi) = 0.
\end{aligned} \tag{2.23}$$

$$\begin{aligned}
a_n &= \frac{1}{\pi} \int_0^{2\pi} f(x) \cos nx \, dx \\
&= \frac{1}{\pi} \left[ \int_0^\pi \cos nx \, dx - \int_\pi^{2\pi} \cos nx \, dx \right] \\
&= \frac{1}{\pi} \left[ \left( \frac{1}{n} \sin nx \right)_0^\pi - \left( \frac{1}{n} \sin nx \right)_\pi^{2\pi} \right] \\
&= 0.
\end{aligned} \tag{2.24}$$

$$\begin{aligned}
b_n &= \frac{1}{\pi} \int_0^{2\pi} f(x) \sin nx \, dx \\
&= \frac{1}{\pi} \left[ \int_0^\pi \sin nx \, dx - \int_\pi^{2\pi} \sin nx \, dx \right] \\
&= \frac{1}{\pi} \left[ \left( -\frac{1}{n} \cos nx \right)_0^\pi + \left( \frac{1}{n} \cos nx \right)_\pi^{2\pi} \right] \\
&= \frac{1}{\pi} \left[ -\frac{1}{n} \cos n\pi + \frac{1}{n} + \frac{1}{n} - \frac{1}{n} \cos n\pi \right] \\
&= \frac{2}{n\pi} (1 - \cos n\pi).
\end{aligned} \tag{2.25}$$

Often we see expressions involving  $\cos n\pi = (-1)^n$  and  $1 \pm \cos n\pi = 1 \pm (-1)^n$ . This is an example showing how to re-index series containing  $\cos n\pi$ .

We have found the Fourier coefficients for this function. Before inserting them into the Fourier series (2.3), we note that  $\cos n\pi = (-1)^n$ . Therefore,

$$1 - \cos n\pi = \begin{cases} 0, & n \text{ even,} \\ 2, & n \text{ odd.} \end{cases} \tag{2.26}$$

So, half of the  $b_n$ 's are zero. While we could write the Fourier series representation as

$$f(x) \sim \frac{4}{\pi} \sum_{\substack{n=1 \\ n \text{ odd}}}^{\infty} \frac{1}{n} \sin nx,$$

we could let  $n = 2k - 1$  in order to capture the odd numbers only. The answer can be written as

$$f(x) = \frac{4}{\pi} \sum_{k=1}^{\infty} \frac{\sin(2k-1)x}{2k-1},$$

Having determined the Fourier representation of a given function, we would like to know if the infinite series can be summed; i.e., does the series converge? Does it converge to  $f(x)$ ? We will discuss this question later in the chapter after we generalize the Fourier series to intervals other than for  $x \in [0, 2\pi]$ .

### 2.3 Fourier Series over Other Intervals

IN MANY APPLICATIONS WE ARE INTERESTED in determining Fourier series representations of functions defined on intervals other than  $[0, 2\pi]$ . In this section, we will determine the form of the series expansion and the Fourier coefficients in these cases.

The most general type of interval is given as  $[a, b]$ . However, this often is too general. More common intervals are of the form  $[-\pi, \pi]$ ,  $[0, L]$ , or  $[-L/2, L/2]$ . The simplest generalization is to the interval  $[0, L]$ . Such intervals arise often in applications. For example, for the problem of a one-dimensional string of length  $L$ , we set up the axes with the left end at  $x = 0$  and the right end at  $x = L$ . Similarly for the temperature distribution along a one dimensional rod of length  $L$  we set the interval to  $x \in [0, 2\pi]$ . Such problems naturally lead to the study of Fourier series on intervals of length  $L$ . We will see later that symmetric intervals,  $[-a, a]$ , are also useful.

Given an interval  $[0, L]$ , we could apply a transformation to an interval of length  $2\pi$  by simply rescaling the interval. Then we could apply this transformation to the Fourier series representation to obtain an equivalent one useful for functions defined on  $[0, L]$ .

We define  $x \in [0, 2\pi]$  and  $t \in [0, L]$ . A linear transformation relating these intervals is simply  $x = \frac{2\pi t}{L}$  as shown in Figure 2.7. So,  $t = 0$  maps to  $x = 0$  and  $t = L$  maps to  $x = 2\pi$ . Furthermore, this transformation maps  $f(x)$  to a new function  $g(t) = f(x(t))$ , which is defined on  $[0, L]$ . We will determine the Fourier series representation of this function using the representation for  $f(x)$  from the last section.

Recall the form of the Fourier representation for  $f(x)$  in Equation (2.3):

$$f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx]. \quad (2.27)$$

Inserting the transformation relating  $x$  and  $t$ , we have

$$g(t) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos \frac{2n\pi t}{L} + b_n \sin \frac{2n\pi t}{L} \right]. \quad (2.28)$$

This gives the form of the series expansion for  $g(t)$  with  $t \in [0, L]$ . But, we still need to determine the Fourier coefficients.

Recall that

$$a_n = \frac{1}{\pi} \int_0^{2\pi} f(x) \cos nx \, dx.$$

We need to make a substitution in the integral of  $x = \frac{2\pi t}{L}$ . We also will need to transform the differential,  $dx = \frac{2\pi}{L} dt$ . Thus, the resulting form for the Fourier coefficients is

$$a_n = \frac{2}{L} \int_0^L g(t) \cos \frac{2n\pi t}{L} \, dt. \quad (2.29)$$

Similarly, we find that

$$b_n = \frac{2}{L} \int_0^L g(t) \sin \frac{2n\pi t}{L} \, dt. \quad (2.30)$$

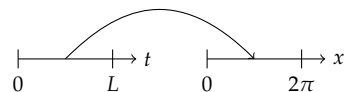


Figure 2.7: A sketch of the transformation between intervals  $x \in [0, 2\pi]$  and  $t \in [0, L]$ .

We note first that when  $L = 2\pi$ , we get back the series representation that we first studied. Also, the period of  $\cos \frac{2n\pi t}{L}$  is  $L/n$ , which means that the representation for  $g(t)$  has a period of  $L$  corresponding to  $n = 1$ .

At the end of this section, we present the derivation of the Fourier series representation for a general interval for the interested reader. In Table 2.1 we summarize some commonly used Fourier series representations.

Table 2.1: Special Fourier Series Representations on Different Intervals

<p style="text-align: center;"><b>Fourier Series on <math>[0, L]</math></b></p> $f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos \frac{2n\pi x}{L} + b_n \sin \frac{2n\pi x}{L} \right]. \quad (2.31)$ $a_n = \frac{2}{L} \int_0^L f(x) \cos \frac{2n\pi x}{L} dx. \quad n = 0, 1, 2, \dots,$ $b_n = \frac{2}{L} \int_0^L f(x) \sin \frac{2n\pi x}{L} dx. \quad n = 1, 2, \dots \quad (2.32)$ <p style="text-align: center;"><b>Fourier Series on <math>[-\frac{L}{2}, \frac{L}{2}]</math></b></p> $f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos \frac{2n\pi x}{L} + b_n \sin \frac{2n\pi x}{L} \right]. \quad (2.33)$ $a_n = \frac{2}{L} \int_{-\frac{L}{2}}^{\frac{L}{2}} f(x) \cos \frac{2n\pi x}{L} dx. \quad n = 0, 1, 2, \dots,$ $b_n = \frac{2}{L} \int_{-\frac{L}{2}}^{\frac{L}{2}} f(x) \sin \frac{2n\pi x}{L} dx. \quad n = 1, 2, \dots \quad (2.34)$ <p style="text-align: center;"><b>Fourier Series on <math>[-\pi, \pi]</math></b></p> $f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos nx + b_n \sin nx]. \quad (2.35)$ $a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos nx dx. \quad n = 0, 1, 2, \dots,$ $b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin nx dx. \quad n = 1, 2, \dots \quad (2.36)$
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Integration of even and odd functions over symmetric intervals,  $[-a, a]$ .

Even Functions.

At this point we need to remind the reader about the integration of even and odd functions on symmetric intervals.

We first recall that  $f(x)$  is an even function if  $f(-x) = f(x)$  for all  $x$ . One can recognize even functions as they are symmetric with respect to the  $y$ -axis as shown in Figure 2.8.

If one integrates an even function over a symmetric interval, then one has that

$$\int_{-a}^a f(x) dx = 2 \int_0^a f(x) dx. \quad (2.37)$$

One can prove this by splitting off the integration over negative values of  $x$ ,

using the substitution  $x = -y$ , and employing the evenness of  $f(x)$ . Thus,

$$\begin{aligned} \int_{-a}^a f(x) dx &= \int_{-a}^0 f(x) dx + \int_0^a f(x) dx \\ &= -\int_a^0 f(-y) dy + \int_0^a f(x) dx \\ &= \int_0^a f(y) dy + \int_0^a f(x) dx \\ &= 2 \int_0^a f(x) dx. \end{aligned} \quad (2.38)$$

This can be visually verified by looking at Figure 2.8.

A similar computation could be done for odd functions.  $f(x)$  is an odd function if  $f(-x) = -f(x)$  for all  $x$ . The graphs of such functions are symmetric with respect to the origin, as shown in Figure 2.9. If one integrates an odd function over a symmetric interval, then one has that

$$\int_{-a}^a f(x) dx = 0. \quad (2.39)$$

**Example 2.4.** Let  $f(x) = |x|$  on  $[-\pi, \pi]$ . We compute the coefficients, beginning as usual with  $a_0$ . We have, using the fact that  $|x|$  is an even function,

$$\begin{aligned} a_0 &= \frac{1}{\pi} \int_{-\pi}^{\pi} |x| dx \\ &= \frac{2}{\pi} \int_0^{\pi} x dx = \pi \end{aligned} \quad (2.40)$$

We continue with the computation of the general Fourier coefficients for  $f(x) = |x|$  on  $[-\pi, \pi]$ . We have

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} |x| \cos nx dx = \frac{2}{\pi} \int_0^{\pi} x \cos nx dx. \quad (2.41)$$

Here we have made use of the fact that  $|x| \cos nx$  is an even function.

In order to compute the resulting integral, we need to use integration by parts,

$$\int_a^b u dv = uv \Big|_a^b - \int_a^b v du,$$

by letting  $u = x$  and  $dv = \cos nx dx$ . Thus,  $du = dx$  and  $v = \int dv = \frac{1}{n} \sin nx$ .

Continuing with the computation, we have

$$\begin{aligned} a_n &= \frac{2}{\pi} \int_0^{\pi} x \cos nx dx \\ &= \frac{2}{\pi} \left[ \frac{1}{n} x \sin nx \Big|_0^{\pi} - \frac{1}{n} \int_0^{\pi} \sin nx dx \right] \\ &= -\frac{2}{n\pi} \left[ -\frac{1}{n} \cos nx \right]_0^{\pi} \\ &= -\frac{2}{\pi n^2} (1 - (-1)^n). \end{aligned} \quad (2.42)$$

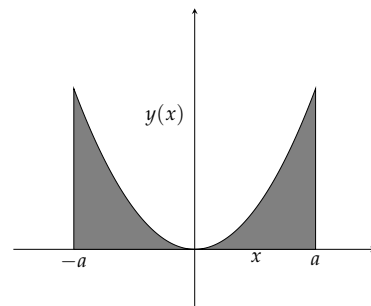


Figure 2.8: Area under an even function on a symmetric interval,  $[-a, a]$ .

Odd Functions.

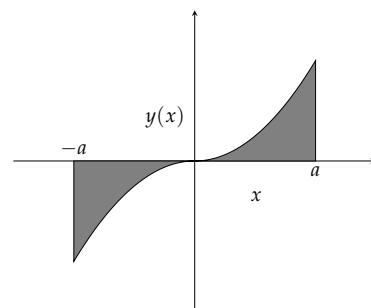


Figure 2.9: Area under an odd function on a symmetric interval,  $[-a, a]$ .

Here we have used the fact that  $\cos n\pi = (-1)^n$  for any integer  $n$ . This leads to a factor  $(1 - (-1)^n)$ . This factor can be simplified as

$$1 - (-1)^n = \begin{cases} 2, & n \text{ odd,} \\ 0, & n \text{ even.} \end{cases} \quad (2.43)$$

So,  $a_n = 0$  for  $n$  even and  $a_n = -\frac{4}{\pi n^2}$  for  $n$  odd.

Computing the  $b_n$ 's is simpler. We note that we have to integrate  $|x| \sin nx$  from  $x = -\pi$  to  $\pi$ . The integrand is an odd function and this is a symmetric interval. So, the result is that  $b_n = 0$  for all  $n$ .

Putting this all together, the Fourier series representation of  $f(x) = |x|$  on  $[-\pi, \pi]$  is given as

$$f(x) \sim \frac{\pi}{2} - \frac{4}{\pi} \sum_{\substack{n=1 \\ n \text{ odd}}}^{\infty} \frac{\cos nx}{n^2}. \quad (2.44)$$

While this is correct, we can rewrite the sum over only odd  $n$  by re-indexing. We let  $n = 2k - 1$  for  $k = 1, 2, 3, \dots$ . Then we only get the odd integers. The series can then be written as

$$f(x) \sim \frac{\pi}{2} - \frac{4}{\pi} \sum_{k=1}^{\infty} \frac{\cos(2k-1)x}{(2k-1)^2}. \quad (2.45)$$

Throughout our discussion we have referred to such results as Fourier representations. We have not looked at the convergence of these series. Here is an example of an infinite series of functions. What does this series sum to? We show in Figure 2.10 the first few partial sums. They appear to be converging to  $f(x) = |x|$  fairly quickly.

Even though  $f(x)$  was defined on  $[-\pi, \pi]$ , we can still evaluate the Fourier series at values of  $x$  outside this interval. In Figure 2.11, we see that the representation agrees with  $f(x)$  on the interval  $[-\pi, \pi]$ . Outside this interval, we have a periodic extension of  $f(x)$  with period  $2\pi$ .

Another example is the Fourier series representation of  $f(x) = x$  on  $[-\pi, \pi]$  as left for Problem 7. This is determined to be

$$f(x) \sim 2 \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} \sin nx. \quad (2.46)$$

As seen in Figure 2.12, we again obtain the periodic extension of the function. In this case, we needed many more terms. Also, the vertical parts of the first plot are nonexistent. In the second plot, we only plot the points and not the typical connected points that most software packages plot as the default style.

**Example 2.5.** It is interesting to note that one can use Fourier series to obtain sums of some infinite series. For example, in the last example, we found that

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

Now, what if we chose  $x = \frac{\pi}{2}$ ? Then, we have

$$\frac{\pi}{2} = 2 \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} \sin \frac{n\pi}{2} = 2 \left[ 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots \right].$$

Figure 2.10: Plot of the first partial sums of the Fourier series representation for  $f(x) = |x|$ .

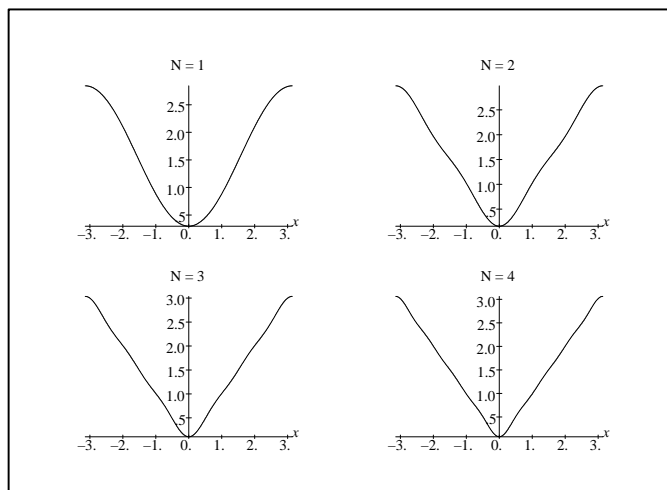


Figure 2.11: Plot of the first 10 terms of the Fourier series representation for  $f(x) = |x|$  on the interval  $[-2\pi, 4\pi]$ .

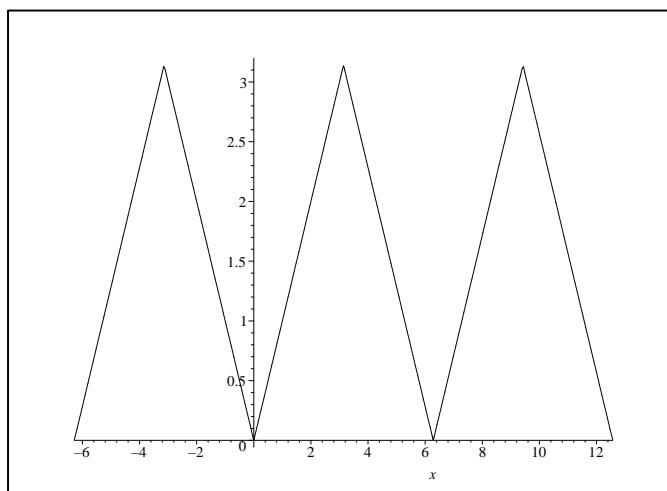
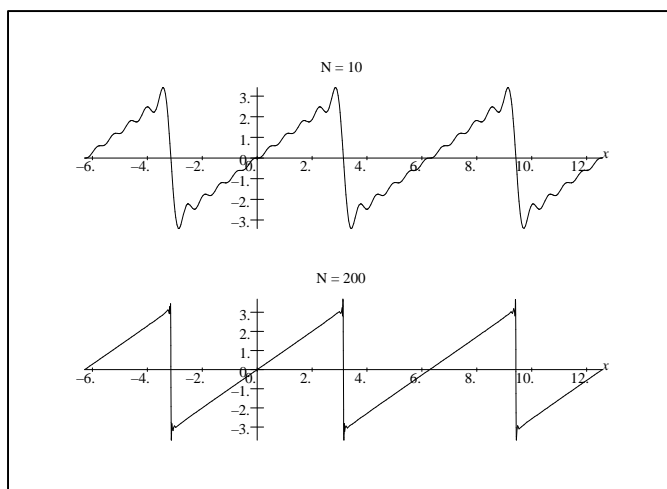


Figure 2.12: Plot of the first 10 terms and 200 terms of the Fourier series representation for  $f(x) = x$  on the interval  $[-2\pi, 4\pi]$ .



This gives a well known expression for  $\pi$ :

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

### 2.3.1 Fourier Series on $[a, b]$

This section can be skipped on first reading. It is here for completeness and the end result, Theorem 2.2 provides the result of the section.

A FOURIER SERIES REPRESENTATION is also possible for a general interval,  $t \in [a, b]$ . As before, we just need to transform this interval to  $[0, 2\pi]$ . Let

$$x = 2\pi \frac{t - a}{b - a}.$$

Inserting this into the Fourier series (2.3) representation for  $f(x)$ , we obtain

$$g(t) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos \frac{2n\pi(t-a)}{b-a} + b_n \sin \frac{2n\pi(t-a)}{b-a} \right]. \quad (2.47)$$

Well, this expansion is ugly. It is not like the last example, where the transformation was straightforward. If one were to apply the theory to applications, it might seem to make sense to just shift the data so that  $a = 0$  and be done with any complicated expressions. However, some students enjoy the challenge of developing such generalized expressions. So, let's see what is involved.

First, we apply the addition identities for trigonometric functions and rearrange the terms.

$$\begin{aligned} g(t) &\sim \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos \frac{2n\pi(t-a)}{b-a} + b_n \sin \frac{2n\pi(t-a)}{b-a} \right] \\ &= \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \left( \cos \frac{2n\pi t}{b-a} \cos \frac{2n\pi a}{b-a} + \sin \frac{2n\pi t}{b-a} \sin \frac{2n\pi a}{b-a} \right) \right. \\ &\quad \left. + b_n \left( \sin \frac{2n\pi t}{b-a} \cos \frac{2n\pi a}{b-a} - \cos \frac{2n\pi t}{b-a} \sin \frac{2n\pi a}{b-a} \right) \right] \\ &= \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ \cos \frac{2n\pi t}{b-a} \left( a_n \cos \frac{2n\pi a}{b-a} - b_n \sin \frac{2n\pi a}{b-a} \right) \right. \\ &\quad \left. + \sin \frac{2n\pi t}{b-a} \left( a_n \sin \frac{2n\pi a}{b-a} + b_n \cos \frac{2n\pi a}{b-a} \right) \right]. \quad (2.48) \end{aligned}$$

Defining  $A_0 = a_0$  and

$$\begin{aligned} A_n &\equiv a_n \cos \frac{2n\pi a}{b-a} - b_n \sin \frac{2n\pi a}{b-a} \\ B_n &\equiv a_n \sin \frac{2n\pi a}{b-a} + b_n \cos \frac{2n\pi a}{b-a}, \quad (2.49) \end{aligned}$$

we arrive at the more desirable form for the Fourier series representation of a function defined on the interval  $[a, b]$ .

$$g(t) \sim \frac{A_0}{2} + \sum_{n=1}^{\infty} \left[ A_n \cos \frac{2n\pi t}{b-a} + B_n \sin \frac{2n\pi t}{b-a} \right]. \quad (2.50)$$

We next need to find expressions for the Fourier coefficients. We insert the known expressions for  $a_n$  and  $b_n$  and rearrange. First, we note that under the transformation  $x = 2\pi\frac{t-a}{b-a}$ , we have

$$\begin{aligned} a_n &= \frac{1}{\pi} \int_0^{2\pi} f(x) \cos nx \, dx \\ &= \frac{2}{b-a} \int_a^b g(t) \cos \frac{2n\pi(t-a)}{b-a} \, dt, \end{aligned} \quad (2.51)$$

and

$$\begin{aligned} b_n &= \frac{1}{\pi} \int_0^{2\pi} f(x) \sin nx \, dx \\ &= \frac{2}{b-a} \int_a^b g(t) \sin \frac{2n\pi(t-a)}{b-a} \, dt. \end{aligned} \quad (2.52)$$

Then, inserting these integrals in  $A_n$ , combining integrals, and making use of the addition formula for the cosine of the sum of two angles, we obtain

$$\begin{aligned} A_n &\equiv a_n \cos \frac{2n\pi a}{b-a} - b_n \sin \frac{2n\pi a}{b-a} \\ &= \frac{2}{b-a} \int_a^b g(t) \left[ \cos \frac{2n\pi(t-a)}{b-a} \cos \frac{2n\pi a}{b-a} - \sin \frac{2n\pi(t-a)}{b-a} \sin \frac{2n\pi a}{b-a} \right] dt \\ &= \frac{2}{b-a} \int_a^b g(t) \cos \frac{2n\pi t}{b-a} \, dt. \end{aligned} \quad (2.53)$$

A similar computation gives

$$B_n = \frac{2}{b-a} \int_a^b g(t) \sin \frac{2n\pi t}{b-a} \, dt. \quad (2.54)$$

Summarizing, we have shown that:

**Theorem 2.2.** *The Fourier series representation of  $f(x)$  defined on  $[a, b]$  when it exists, is given by*

$$f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos \frac{2n\pi x}{b-a} + b_n \sin \frac{2n\pi x}{b-a} \right]. \quad (2.55)$$

with Fourier coefficients

$$\begin{aligned} a_n &= \frac{2}{b-a} \int_a^b f(x) \cos \frac{2n\pi x}{b-a} \, dx. \quad n = 0, 1, 2, \dots, \\ b_n &= \frac{2}{b-a} \int_a^b f(x) \sin \frac{2n\pi x}{b-a} \, dx. \quad n = 1, 2, \dots \end{aligned} \quad (2.56)$$

## 2.4 Sine and Cosine Series

IN THE LAST TWO EXAMPLES ( $f(x) = |x|$  and  $f(x) = x$  on  $[-\pi, \pi]$ ), we have seen Fourier series representations that contain only sine or cosine terms. As we know, the sine functions are odd functions and thus sum to odd functions. Similarly, cosine functions sum to even functions. Such

occurrences happen often in practice. Fourier representations involving just sines are called sine series and those involving just cosines (and the constant term) are called cosine series.

Another interesting result, based upon these examples, is that the original functions,  $|x|$  and  $x$ , agree on the interval  $[0, \pi]$ . Note from Figures 2.10 through 2.12 that their Fourier series representations do as well. Thus, more than one series can be used to represent functions defined on finite intervals. All they need to do is agree with the function over that particular interval. Sometimes one of these series is more useful because it has additional properties needed in the given application.

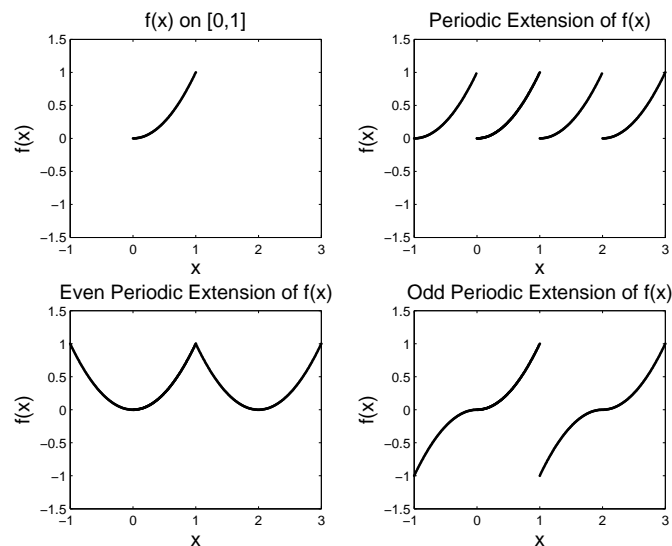
We have made the following observations from the previous examples:

1. There are several trigonometric series representations for a function defined on a finite interval.
2. Odd functions on a symmetric interval are represented by sine series and even functions on a symmetric interval are represented by cosine series.

These two observations are related and are the subject of this section. We begin by defining a function  $f(x)$  on interval  $[0, L]$ . We have seen that the Fourier series representation of this function appears to converge to a periodic extension of the function.

In Figure 2.13, we show a function defined on  $[0, 1]$ . To the right is its periodic extension to the whole real axis. This representation has a period of  $L = 1$ . The bottom left plot is obtained by first reflecting  $f$  about the  $y$ -axis to make it an even function and then graphing the periodic extension of this new function. Its period will be  $2L = 2$ . Finally, in the last plot, we flip the function about each axis and graph the periodic extension of the new odd function. It will also have a period of  $2L = 2$ .

Figure 2.13: This is a sketch of a function and its various extensions. The original function  $f(x)$  is defined on  $[0, 1]$  and graphed in the upper left corner. To its right is the periodic extension, obtained by adding replicas. The two lower plots are obtained by first making the original function even or odd and then creating the periodic extensions of the new function.



In general, we obtain three different periodic representations. In order to

distinguish these, we will refer to them simply as the periodic, even, and odd extensions. Now, starting with  $f(x)$  defined on  $[0, L]$ , we would like to determine the Fourier series representations leading to these extensions. [For easy reference, the results are summarized in Table 2.2]

<p><b>Fourier Series on <math>[0, L]</math></b></p> $f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos \frac{2n\pi x}{L} + b_n \sin \frac{2n\pi x}{L} \right]. \quad (2.57)$ $a_n = \frac{2}{L} \int_0^L f(x) \cos \frac{2n\pi x}{L} dx. \quad n = 0, 1, 2, \dots,$ $b_n = \frac{2}{L} \int_0^L f(x) \sin \frac{2n\pi x}{L} dx. \quad n = 1, 2, \dots \quad (2.58)$ <p><b>Fourier Cosine Series on <math>[0, L]</math></b></p> $f(x) \sim a_0/2 + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi x}{L}. \quad (2.59)$ <p>where</p> $a_n = \frac{2}{L} \int_0^L f(x) \cos \frac{n\pi x}{L} dx. \quad n = 0, 1, 2, \dots \quad (2.60)$ <p><b>Fourier Sine Series on <math>[0, L]</math></b></p> $f(x) \sim \sum_{n=1}^{\infty} b_n \sin \frac{n\pi x}{L}. \quad (2.61)$ <p>where</p> $b_n = \frac{2}{L} \int_0^L f(x) \sin \frac{n\pi x}{L} dx. \quad n = 1, 2, \dots \quad (2.62)$	<p>Table 2.2: Fourier Cosine and Sine Series Representations on <math>[0, L]</math></p>
----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	-----------------------------------------------------------------------------------------

We have already seen from Table 2.1 that the periodic extension of  $f(x)$ , defined on  $[0, L]$ , is obtained through the Fourier series representation

$$f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos \frac{2n\pi x}{L} + b_n \sin \frac{2n\pi x}{L} \right], \quad (2.63)$$

where

$$a_n = \frac{2}{L} \int_0^L f(x) \cos \frac{2n\pi x}{L} dx. \quad n = 0, 1, 2, \dots,$$

$$b_n = \frac{2}{L} \int_0^L f(x) \sin \frac{2n\pi x}{L} dx. \quad n = 1, 2, \dots \quad (2.64)$$

Given  $f(x)$  defined on  $[0, L]$ , the even periodic extension is obtained by simply computing the Fourier series representation for the even function

$$f_e(x) \equiv \begin{cases} f(x), & 0 < x < L, \\ f(-x) & -L < x < 0. \end{cases} \quad (2.65)$$

Even periodic extension.

Since  $f_e(x)$  is an even function on a symmetric interval  $[-L, L]$ , we expect that the resulting Fourier series will not contain sine terms. Therefore, the series expansion will be given by [Use the general case in Equation (2.55) with  $a = -L$  and  $b = L$ .]:

$$f_e(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi x}{L}. \quad (2.66)$$

with Fourier coefficients

$$a_n = \frac{1}{L} \int_{-L}^L f_e(x) \cos \frac{n\pi x}{L} dx. \quad n = 0, 1, 2, \dots \quad (2.67)$$

However, we can simplify this by noting that the integrand is even and the interval of integration can be replaced by  $[0, L]$ . On this interval  $f_e(x) = f(x)$ . So, we have the Cosine Series Representation of  $f(x)$  for  $x \in [0, L]$  is given as

$$f(x) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi x}{L}. \quad (2.68)$$

where

$$a_n = \frac{2}{L} \int_0^L f(x) \cos \frac{n\pi x}{L} dx. \quad n = 0, 1, 2, \dots \quad (2.69)$$

Similarly, given  $f(x)$  defined on  $[0, L]$ , the odd periodic extension is obtained by simply computing the Fourier series representation for the odd function

$$f_o(x) \equiv \begin{cases} f(x), & 0 < x < L, \\ -f(-x) & -L < x < 0. \end{cases} \quad (2.70)$$

The resulting series expansion leads to defining the Sine Series Representation of  $f(x)$  for  $x \in [0, L]$  as

$$f(x) \sim \sum_{n=1}^{\infty} b_n \sin \frac{n\pi x}{L}, \quad (2.71)$$

where

$$b_n = \frac{2}{L} \int_0^L f(x) \sin \frac{n\pi x}{L} dx. \quad n = 1, 2, \dots \quad (2.72)$$

**Example 2.6.** In Figure 2.13, we actually provided plots of the various extensions of the function  $f(x) = x^2$  for  $x \in [0, 1]$ . Let's determine the representations of the periodic, even, and odd extensions of this function.

For a change, we will use a CAS (Computer Algebra System) package to do the integrals. In this case, we can use Maple. A general code for doing this for the periodic extension is shown in Table 2.3.

**Example 2.7. Periodic Extension - Trigonometric Fourier Series** Using the code in Table 2.3, we have that  $a_0 = \frac{2}{3}$ ,  $a_n = \frac{1}{n^2\pi^2}$ , and  $b_n = -\frac{1}{n\pi}$ . Thus, the resulting series is given as

$$f(x) \sim \frac{1}{3} + \sum_{n=1}^{\infty} \left[ \frac{1}{n^2\pi^2} \cos 2n\pi x - \frac{1}{n\pi} \sin 2n\pi x \right].$$

Fourier Cosine Series.

Odd periodic extension.

Fourier Sine Series Representation.

In Figure 2.14, we see the sum of the first 50 terms of this series. Generally, we see that the series seems to be converging to the periodic extension of  $f$ . There appear to be some problems with the convergence around integer values of  $x$ . We will later see that this is because of the discontinuities in the periodic extension and the resulting overshoot is referred to as the Gibbs phenomenon, which is discussed in the last section of this chapter.

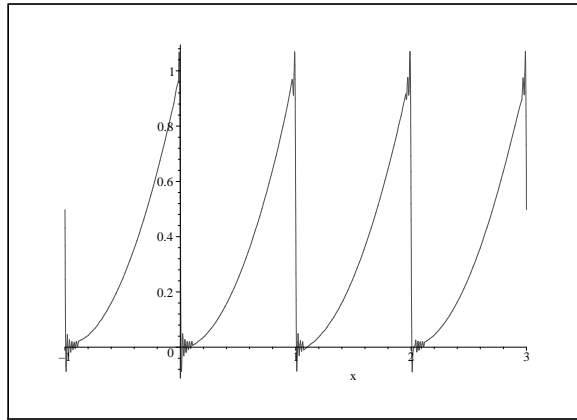


Figure 2.14: The periodic extension of  $f(x) = x^2$  on  $[0, 1]$ .

```
> restart:
> L:=1:
> f:=x^2:
> assume(n, integer):
> a0:=2/L*int(f, x=0..L);
                                a0 := 2/3
> an:=2/L*int(f*cos(2*n*Pi*x/L), x=0..L);
                                1
                                an := -----
                                2  2
                                n~ Pi
> bn:=2/L*int(f*sin(2*n*Pi*x/L), x=0..L);
                                1
                                bn := - -----
                                n~ Pi
> F:=a0/2+sum((1/(k*Pi)^2)*cos(2*k*Pi*x/L)
              -1/(k*Pi)*sin(2*k*Pi*x/L), k=1..50):
> plot(F, x=-1..3, title='Periodic Extension',
       titlefont=[TIMES, ROMAN, 14], font=[TIMES, ROMAN, 14]);
```

Table 2.3: Maple code for computing Fourier coefficients and plotting partial sums of the Fourier series.

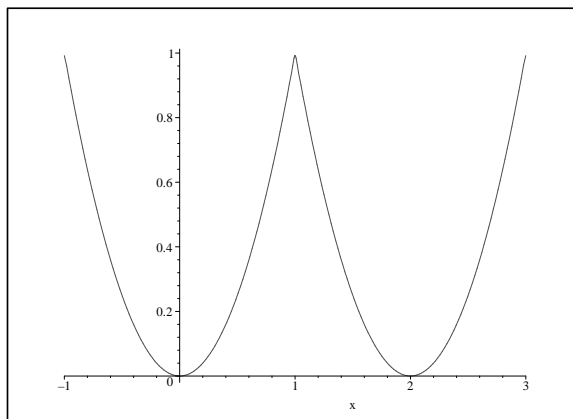
### Example 2.8. Even Periodic Extension - Cosine Series

In this case we compute  $a_0 = \frac{2}{3}$  and  $a_n = \frac{4(-1)^n}{n^2\pi^2}$ . Therefore, we have

$$f(x) \sim \frac{1}{3} + \frac{4}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \cos n\pi x.$$

In Figure 2.15, we see the sum of the first 50 terms of this series. In this case the convergence seems to be much better than in the periodic extension case. We also see that it is converging to the even extension.

Figure 2.15: The even periodic extension of  $f(x) = x^2$  on  $[0, 1]$ .



### Example 2.9. Odd Periodic Extension - Sine Series

Finally, we look at the sine series for this function. We find that

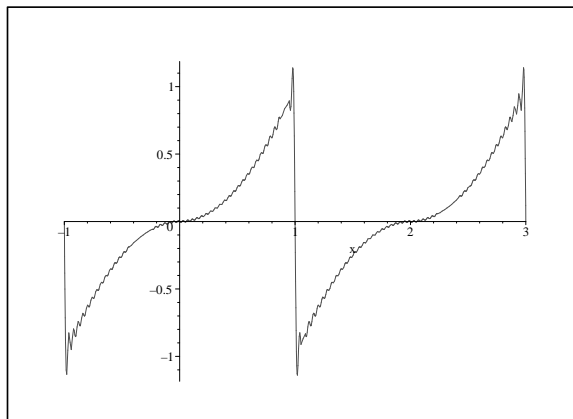
$$b_n = -\frac{2}{n^3\pi^3}(n^2\pi^2(-1)^n - 2(-1)^n + 2).$$

Therefore,

$$f(x) \sim -\frac{2}{\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^3} (n^2\pi^2(-1)^n - 2(-1)^n + 2) \sin n\pi x.$$

Once again we see discontinuities in the extension as seen in Figure 2.16. However, we have verified that our sine series appears to be converging to the odd extension as we first sketched in Figure 2.13.

Figure 2.16: The odd periodic extension of  $f(x) = x^2$  on  $[0, 1]$ .



## 2.5 The Gibbs Phenomenon

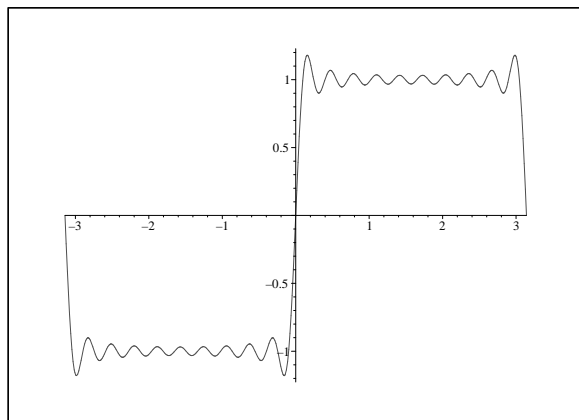
WE HAVE SEEN THE GIBBS PHENOMENON when there is a jump discontinuity in the periodic extension of a function, whether the function originally had a discontinuity or developed one due to a mismatch in the values of the endpoints. This can be seen in Figures 2.12, 2.14, and 2.16. The Fourier series has a difficult time converging at the point of discontinuity and these graphs of the Fourier series show a distinct overshoot which does not go away. This is called the Gibbs phenomenon<sup>3</sup> and the amount of overshoot can be computed.

In one of our first examples, Example 2.3, we found the Fourier series representation of the piecewise defined function

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

to be

$$f(x) \sim \frac{4}{\pi} \sum_{k=1}^{\infty} \frac{\sin(2k-1)x}{2k-1}.$$



In Figure 2.17, we display the sum of the first ten terms. Note the wiggles, overshoots and undershoots. These are seen more when we plot the representation for  $x \in [-3\pi, 3\pi]$ , as shown in Figure 2.18.

We note that the overshoots and undershoots occur at discontinuities in the periodic extension of  $f(x)$ . These occur whenever  $f(x)$  has a discontinuity or if the values of  $f(x)$  at the endpoints of the domain do not agree.

One might expect that we only need to add more terms. In Figure 2.19 we show the sum for twenty terms. Note the sum appears to converge better for points far from the discontinuities. But, the overshoots and undershoots are still present. Figures 2.20 and 2.21 show magnified plots of the overshoot at  $x = 0$  for  $N = 100$  and  $N = 500$ , respectively. We see that the overshoot

<sup>3</sup> The Gibbs phenomenon was named after Josiah Willard Gibbs (1839-1903) even though it was discovered earlier by the Englishman Henry Wilbraham (1825-1883). Wilbraham published a soon forgotten paper about the effect in 1848. In 1889 Albert Abraham Michelson (1852-1931), an American physicist, observed an overshoot in his mechanical graphing machine. Shortly afterwards J. Willard Gibbs published papers describing this phenomenon, which was later to be called the Gibbs phenomena. Gibbs was a mathematical physicist and chemist and is considered the father of physical chemistry.

Figure 2.17: The Fourier series representation of a step function on  $[-\pi, \pi]$  for  $N = 10$ .

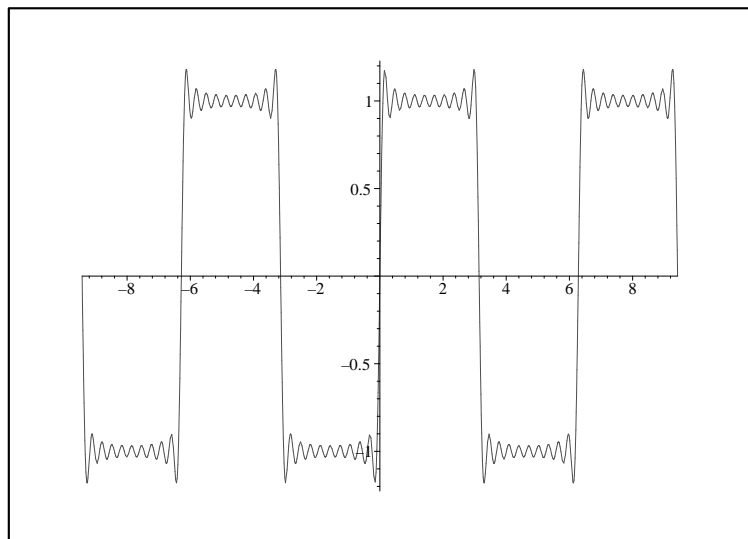


Figure 2.18: The Fourier series representation of a step function on  $[-\pi, \pi]$  for  $N = 10$  plotted on  $[-3\pi, 3\pi]$  displaying the periodicity.

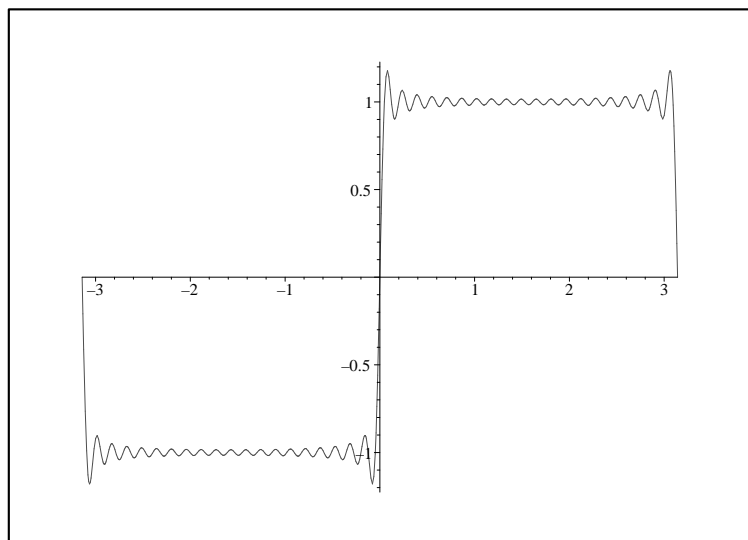


Figure 2.19: The Fourier series representation of a step function on  $[-\pi, \pi]$  for  $N = 20$ .

persists. The peak is at about the same height, but its location seems to be getting closer to the origin. We will show how one can estimate the size of the overshoot.

We can study the Gibbs phenomenon by looking at the partial sums of general Fourier trigonometric series for functions  $f(x)$  defined on the interval  $[-L, L]$ . Writing out the partial sums, inserting the Fourier coefficients, and rearranging, we have

$$\begin{aligned}
 S_N(x) &= a_0 + \sum_{n=1}^N \left[ a_n \cos \frac{n\pi x}{L} + b_n \sin \frac{n\pi x}{L} \right] \\
 &= \frac{1}{2L} \int_{-L}^L f(y) dy + \sum_{n=1}^N \left[ \left( \frac{1}{L} \int_{-L}^L f(y) \cos \frac{n\pi y}{L} dy \right) \cos \frac{n\pi x}{L} \right. \\
 &\quad \left. + \left( \frac{1}{L} \int_{-L}^L f(y) \sin \frac{n\pi y}{L} dy \right) \sin \frac{n\pi x}{L} \right] \\
 &= \frac{1}{L} \int_{-L}^L \left\{ \frac{1}{2} \right. \\
 &\quad \left. + \sum_{n=1}^N \left( \cos \frac{n\pi y}{L} \cos \frac{n\pi x}{L} + \sin \frac{n\pi y}{L} \sin \frac{n\pi x}{L} \right) \right\} f(y) dy \\
 &= \frac{1}{L} \int_{-L}^L \left\{ \frac{1}{2} + \sum_{n=1}^N \cos \frac{n\pi(y-x)}{L} \right\} f(y) dy \\
 &\equiv \frac{1}{L} \int_{-L}^L D_N(y-x) f(y) dy
 \end{aligned}$$

We have defined

$$D_N(x) = \frac{1}{2} + \sum_{n=1}^N \cos \frac{n\pi x}{L},$$

which is called the  $N$ -th Dirichlet kernel .

We now prove

**Lemma 2.1.** *The  $N$ -th Dirichlet kernel is given by*

$$D_N(x) = \begin{cases} \frac{\sin((N+\frac{1}{2})\frac{\pi x}{L})}{2 \sin \frac{\pi x}{2L}}, & \sin \frac{\pi x}{2L} \neq 0, \\ N + \frac{1}{2}, & \sin \frac{\pi x}{2L} = 0. \end{cases}$$

*Proof.* Let  $\theta = \frac{\pi x}{L}$  and multiply  $D_N(x)$  by  $2 \sin \frac{\theta}{2}$  to obtain

$$\begin{aligned}
 2 \sin \frac{\theta}{2} D_N(x) &= 2 \sin \frac{\theta}{2} \left[ \frac{1}{2} + \cos \theta + \cdots + \cos N\theta \right] \\
 &= \sin \frac{\theta}{2} + 2 \cos \theta \sin \frac{\theta}{2} + 2 \cos 2\theta \sin \frac{\theta}{2} + \cdots + 2 \cos N\theta \sin \frac{\theta}{2} \\
 &= \sin \frac{\theta}{2} + \left( \sin \frac{3\theta}{2} - \sin \frac{\theta}{2} \right) + \left( \sin \frac{5\theta}{2} - \sin \frac{3\theta}{2} \right) + \cdots \\
 &\quad + \left[ \sin \left( N + \frac{1}{2} \right) \theta - \sin \left( N - \frac{1}{2} \right) \theta \right]
 \end{aligned}$$

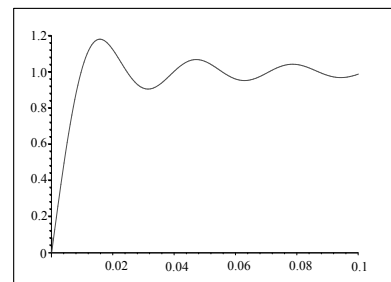


Figure 2.20: The Fourier series representation of a step function on  $[-\pi, \pi]$  for  $N = 100$ .

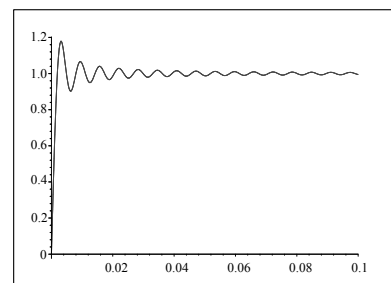


Figure 2.21: The Fourier series representation of a step function on  $[-\pi, \pi]$  for  $N = 500$ .

$$= \sin\left(N + \frac{1}{2}\right)\theta. \quad (2.73)$$

Thus,

$$2 \sin \frac{\theta}{2} D_N(x) = \sin\left(N + \frac{1}{2}\right)\theta.$$

If  $\sin \frac{\theta}{2} \neq 0$ , then

$$D_N(x) = \frac{\sin\left(N + \frac{1}{2}\right)\theta}{2 \sin \frac{\theta}{2}}, \quad \theta = \frac{\pi x}{L}.$$

If  $\sin \frac{\theta}{2} = 0$ , then one needs to apply L'Hospital's Rule as  $\theta \rightarrow 2m\pi$ :

$$\begin{aligned} \lim_{\theta \rightarrow 2m\pi} \frac{\sin\left(N + \frac{1}{2}\right)\theta}{2 \sin \frac{\theta}{2}} &= \lim_{\theta \rightarrow 2m\pi} \frac{\left(N + \frac{1}{2}\right) \cos\left(N + \frac{1}{2}\right)\theta}{\cos \frac{\theta}{2}} \\ &= \frac{\left(N + \frac{1}{2}\right) \cos(2m\pi N + m\pi)}{\cos m\pi} \\ &= \frac{\left(N + \frac{1}{2}\right)(\cos 2m\pi N \cos m\pi - \sin 2m\pi N \sin m\pi)}{\cos m\pi} \\ &= N + \frac{1}{2}. \end{aligned} \quad (2.74)$$

□

We further note that  $D_N(x)$  is periodic with period  $2L$  and is an even function.

So far, we have found that the  $N$ th partial sum is given by

$$S_N(x) = \frac{1}{L} \int_{-L}^L D_N(y-x) f(y) dy. \quad (2.75)$$

Making the substitution  $\xi = y - x$ , we have

$$\begin{aligned} S_N(x) &= \frac{1}{L} \int_{-L-x}^{L-x} D_N(\xi) f(\xi+x) d\xi \\ &= \frac{1}{L} \int_{-L}^L D_N(\xi) f(\xi+x) d\xi. \end{aligned} \quad (2.76)$$

In the second integral, we have made use of the fact that  $f(x)$  and  $D_N(x)$  are periodic with period  $2L$  and shifted the interval back to  $[-L, L]$ .

We now write the integral as the sum of two integrals over positive and negative values of  $\xi$  and use the fact that  $D_N(x)$  is an even function. Then,

$$\begin{aligned} S_N(x) &= \frac{1}{L} \int_{-L}^0 D_N(\xi) f(\xi+x) d\xi + \frac{1}{L} \int_0^L D_N(\xi) f(\xi+x) d\xi \\ &= \frac{1}{L} \int_0^L [f(x-\xi) + f(\xi+x)] D_N(\xi) d\xi. \end{aligned} \quad (2.77)$$

We can use this result to study the Gibbs phenomenon whenever it occurs. In particular, we will only concentrate on the earlier example. For this case, we have

$$S_N(x) = \frac{1}{\pi} \int_0^\pi [f(x-\xi) + f(\xi+x)] D_N(\xi) d\xi \quad (2.78)$$

for

$$D_N(x) = \frac{1}{2} + \sum_{n=1}^N \cos nx.$$

Also, one can show that

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

Thus, we have

$$\begin{aligned} S_N(x) &= \frac{2}{\pi} \int_0^x D_N(\xi) d\xi - \frac{2}{\pi} \int_{\pi-x}^{\pi} D_N(\xi) d\xi \\ &= \frac{2}{\pi} \int_0^x D_N(z) dz + \frac{2}{\pi} \int_0^x D_N(\pi - z) dz. \end{aligned} \quad (2.79)$$

Here we made the substitution  $z = \pi - \xi$  in the second integral.

The Dirichlet kernel for  $L = \pi$  is given by

$$D_N(x) = \frac{\sin(N + \frac{1}{2})x}{2 \sin \frac{x}{2}}.$$

For  $N$  large, we have  $N + \frac{1}{2} \approx N$ ; and for small  $x$ , we have  $\sin \frac{x}{2} \approx \frac{x}{2}$ . So, under these assumptions,

$$D_N(x) \approx \frac{\sin Nx}{x}.$$

Therefore,

$$S_N(x) \rightarrow \frac{2}{\pi} \int_0^x \frac{\sin N\xi}{\xi} d\xi \quad \text{for large } N, \text{ and small } x.$$

If we want to determine the locations of the minima and maxima, where the undershoot and overshoot occur, then we apply the first derivative test for extrema to  $S_N(x)$ . Thus,

$$\frac{d}{dx} S_N(x) = \frac{2 \sin Nx}{\pi x} = 0.$$

The extrema occur for  $Nx = m\pi$ ,  $m = \pm 1, \pm 2, \dots$ . One can show that there is a maximum at  $x = \pi/N$  and a minimum for  $x = 2\pi/N$ . The value for the overshoot can be computed as

$$\begin{aligned} S_N(\pi/N) &= \frac{2}{\pi} \int_0^{\pi/N} \frac{\sin N\xi}{\xi} d\xi \\ &= \frac{2}{\pi} \int_0^{\pi} \frac{\sin t}{t} dt \\ &= \frac{2}{\pi} \text{Si}(\pi) \\ &= 1.178979744 \dots \end{aligned} \quad (2.80)$$

Note that this value is independent of  $N$  and is given in terms of the sine integral,

$$\text{Si}(x) \equiv \int_0^x \frac{\sin t}{t} dt.$$

## 2.6 Multiple Fourier Series

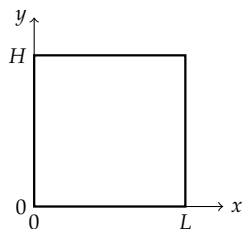


Figure 2.22: The rectangular membrane of length  $L$  and width  $H$ . There are fixed boundary conditions along the edges.

FUNCTIONS OF SEVERAL VARIABLES CAN HAVE FOURIER SERIES REPRESENTATIONS as well. We motivate this discussion by looking at the vibrations of a rectangular membrane. You can think of this as a drumhead with a rectangular cross section as shown in Figure 2.22. We stretch the membrane over the drumhead and fasten the material to the boundary of the rectangle. The height of the vibrating membrane is described by its height from equilibrium,  $u(x, y, t)$ .

**Example 2.10.** *The vibrating rectangular membrane.*

The problem is given by the two-dimensional wave equation in Cartesian coordinates,

$$u_{tt} = c^2(u_{xx} + u_{yy}), \quad t > 0, 0 < x < L, 0 < y < H, \quad (2.81)$$

a set of boundary conditions,

$$\begin{aligned} u(0, y, t) = 0, \quad u(L, y, t) = 0, \quad t > 0, \quad 0 < y < H, \\ u(x, 0, t) = 0, \quad u(x, H, t) = 0, \quad t > 0, \quad 0 < x < L, \end{aligned} \quad (2.82)$$

and a pair of initial conditions (since the equation is second order in time),

$$u(x, y, 0) = f(x, y), \quad u_t(x, y, 0) = g(x, y). \quad (2.83)$$

The general solution is obtained in a course on partial differential equations using what is called the Method of Separation of Variables. One assumes solutions of the form  $u(x, y, t) = X(x)Y(y)T(t)$  which satisfy the given boundary conditions,  $u(0, y, t) = 0$ ,  $u(L, y, t) = 0$ ,  $u(x, 0, t) = 0$ , and  $u(x, H, t) = 0$ . After some work, one finds the general solution is given by a linear superposition of these product solutions. The general solution is

$$u(x, y, t) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} (a_{nm} \cos \omega_{nm}t + b_{nm} \sin \omega_{nm}t) \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H}, \quad (2.84)$$

where

$$\omega_{nm} = c \sqrt{\left(\frac{n\pi}{L}\right)^2 + \left(\frac{m\pi}{H}\right)^2}. \quad (2.85)$$

Next, one imposes the initial conditions just like we had indicated in the side note at the beginning of this chapter for the one-dimensional wave equation. The first initial condition is  $u(x, y, 0) = f(x, y)$ . Setting  $t = 0$  in the general solution, we obtain

$$f(x, y) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} a_{nm} \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H}. \quad (2.86)$$

This is a double Fourier sine series. The goal is to find the unknown coefficients  $a_{nm}$ .

The coefficients  $a_{nm}$  can be found knowing what we already know about Fourier sine series. We can write the initial condition as the single sum

$$f(x, y) = \sum_{n=1}^{\infty} A_n(y) \sin \frac{n\pi x}{L}, \quad (2.87)$$

The general solution for the vibrating rectangular membrane.

where

$$A_n(y) = \sum_{m=1}^{\infty} a_{nm} \sin \frac{m\pi y}{H}. \quad (2.88)$$

These are two Fourier sine series. Recalling from Chapter 2 that the coefficients of Fourier sine series can be computed as integrals, we have

$$\begin{aligned} A_n(y) &= \frac{2}{L} \int_0^L f(x, y) \sin \frac{n\pi x}{L} dx, \\ a_{nm} &= \frac{2}{H} \int_0^H A_n(y) \sin \frac{m\pi y}{H} dy. \end{aligned} \quad (2.89)$$

Inserting the integral for  $A_n(y)$  into that for  $a_{nm}$ , we have an integral representation for the Fourier coefficients in the double Fourier sine series,

$$a_{nm} = \frac{4}{LH} \int_0^H \int_0^L f(x, y) \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H} dx dy. \quad (2.90)$$

We can carry out the same process for satisfying the second initial condition,  $u_t(x, y, 0) = g(x, y)$  for the initial velocity of each point. Inserting the general solution into this initial condition, we obtain

$$g(x, y) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} b_{nm} \omega_{nm} \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H}. \quad (2.91)$$

Again, we have a double Fourier sine series. But, now we can quickly determine the Fourier coefficients using the above expression for  $a_{nm}$  to find that

$$b_{nm} = \frac{4}{\omega_{nm} LH} \int_0^H \int_0^L g(x, y) \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H} dx dy. \quad (2.92)$$

This completes the full solution of the vibrating rectangular membrane problem. Namely, we have obtained the solution

$$u(x, y, t) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} (a_{nm} \cos \omega_{nm} t + b_{nm} \sin \omega_{nm} t) \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H}, \quad (2.93)$$

where

$$a_{nm} = \frac{4}{LH} \int_0^H \int_0^L f(x, y) \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H} dx dy, \quad (2.94)$$

$$b_{nm} = \frac{4}{\omega_{nm} LH} \int_0^H \int_0^L g(x, y) \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H} dx dy, \quad (2.95)$$

and the angular frequencies are given by

$$\omega_{nm} = c \sqrt{\left(\frac{n\pi}{L}\right)^2 + \left(\frac{m\pi}{H}\right)^2}. \quad (2.96)$$

In this example we encountered a double Fourier sine series. This suggests a function  $f(x, y)$  defined on the rectangular region  $[0, L] \times [0, H]$  has a double Fourier sine series representation,

$$f(x, y) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} b_{nm} \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H}, \quad (2.97)$$

The Fourier coefficients for the double Fourier sine series.

The full solution of the vibrating rectangular membrane.

where

$$b_{nm} = \frac{4}{LH} \int_0^H \int_0^L f(x, y) \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H} dx dy \quad n, m = 1, 2, \dots \quad (2.98)$$

Of course, we would expect some of the same convergence problems already seen with Fourier series.

**Example 2.11.** Find the double Fourier sine series representation of  $f(x, y) = xy$  on the unit square.

For this example, we seek the series representation

$$f(x, y) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} b_{nm} \sin n\pi x \sin m\pi y. \quad (2.99)$$

We compute the Fourier coefficients:

$$\begin{aligned} b_{nm} &= 4 \int_0^1 \int_0^1 f(x, y) \sin n\pi x \sin m\pi y dx dy \\ &= 4 \int_0^1 \int_0^1 xy \sin n\pi x \sin m\pi y dx dy \\ &= 4 \left( \int_0^1 x \sin n\pi x dx \right) \left( \int_0^1 \sin m\pi y dy \right) \\ &= 4 \left[ -\frac{\cos n\pi}{n\pi} \right] \left[ -\frac{\cos m\pi}{m\pi} \right] \\ &= \frac{4(-1)^{n+m}}{nm\pi^2}. \end{aligned}$$

Therefore,

$$xy \sim 4 \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{(-1)^{n+m}}{nm\pi^2} \sin n\pi x \sin m\pi y. \quad (2.100)$$

We could just as well seek a double Fourier cosine series on  $[0, L] \times [0, H]$ ,

$$\begin{aligned} f(x, y) &\sim \frac{a_{00}}{4} + \frac{1}{2} \sum_{n=1}^{\infty} a_{n0} \cos \frac{n\pi x}{L} + \frac{1}{2} \sum_{m=1}^{\infty} a_{0m} \cos \frac{m\pi y}{H} \\ &\quad + \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} a_{nm} \cos \frac{n\pi x}{L} \cos \frac{m\pi y}{H}, \end{aligned} \quad (2.101)$$

where the Fourier coefficients are given by

$$a_{nm} = \frac{4}{LH} \int_0^H \int_0^L f(x, y) \cos \frac{n\pi x}{L} \cos \frac{m\pi y}{H} dx dy, \quad n, m = 0, 1, \dots \quad (2.102)$$

The more general double Fourier trigonometric series on  $[0, L] \times [0, H]$  would take the form

$$\begin{aligned} f(x, y) &\sim \frac{a_{00}}{4} + \frac{1}{2} \sum_{n=1}^{\infty} \left[ a_{n0} \cos \frac{2n\pi x}{L} + b_{n0} \sin \frac{2n\pi x}{L} \right] \\ &\quad + \frac{1}{2} \sum_{m=1}^{\infty} \left[ a_{0m} \cos \frac{2m\pi y}{H} + b_{0m} \sin \frac{2m\pi y}{H} \right] \\ &\quad + \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} a_{nm} \cos \frac{2n\pi x}{L} \cos \frac{2m\pi y}{H}, \end{aligned}$$

$$\begin{aligned}
& + \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} b_{nm} \sin \frac{2n\pi x}{L} \sin \frac{2m\pi y}{H}, \\
& + \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} c_{nm} \cos \frac{2n\pi x}{L} \sin \frac{2m\pi y}{H}, \\
& + \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} d_{nm} \sin \frac{2n\pi x}{L} \cos \frac{2m\pi y}{H}. \tag{2.103}
\end{aligned}$$

The corresponding double Fourier coefficients would take the form you might expect.

### Problems

1. Write  $y(t) = 3 \cos 2t - 4 \sin 2t$  in the form  $y(t) = A \cos(2\pi ft + \phi)$ .
2. Determine the period of the following functions:
  - a.  $f(x) = \cos \frac{x}{3}$ .
  - b.  $f(x) = \sin 2\pi x$ .
  - c.  $f(x) = \sin 2\pi x - 0.1 \cos 3\pi x$ .
  - d.  $f(x) = |\sin 5\pi x|$ .
  - e.  $f(x) = \cot 2\pi x$ .
  - f.  $f(x) = \cos^2 \frac{x}{2}$ .
  - g.  $f(x) = 3 \sin \frac{\pi x}{2} + 2 \cos \frac{3\pi x}{4}$ .
3. Derive the coefficients  $b_n$  in Equation (2.4).
4. Let  $f(x)$  be defined for  $x \in [-L, L]$ . Parseval's identity is given by

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

Assuming the the Fourier series of  $f(x)$  converges uniformly in  $(-L, L)$ , prove Parseval's identity by multiplying the Fourier series representation by  $f(x)$  and integrating from  $x = -L$  to  $x = L$ . [In Section 5.6.3 we will encounter Parseval's equality for Fourier transforms which is a continuous version of this identity.]

5. Consider the square wave function

$$f(x) = \begin{cases} 1, & 0 < x < \pi, \\ -1, & \pi < x < 2\pi. \end{cases}$$

- a. Find the Fourier series representation of this function and plot the first 50 terms.
- b. Apply Parseval's identity in Problem 4 to the result in part a.
- c. Use the result of part b to show  $\frac{\pi^2}{8} = \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2}$ .

6. For the following sets of functions: (i) show that each is orthogonal on the given interval, and (ii) determine the corresponding orthonormal set. [See page 43.]

a.  $\{\sin 2nx\}$ ,  $n = 1, 2, 3, \dots$ ,  $0 \leq x \leq \pi$ .

b.  $\{\cos n\pi x\}$ ,  $n = 0, 1, 2, \dots$ ,  $0 \leq x \leq 2$ .

c.  $\{\sin \frac{n\pi x}{L}\}$ ,  $n = 1, 2, 3, \dots$ ,  $x \in [-L, L]$ .

7. Consider  $f(x) = 4 \sin^3 2x$ .

a. Derive the trigonometric identity giving  $\sin^3 \theta$  in terms of  $\sin \theta$  and  $\sin 3\theta$  using DeMoivre's Formula.

b. Find the Fourier series of  $f(x) = 4 \sin^3 2x$  on  $[0, 2\pi]$  without computing any integrals.

8. Find the Fourier series of the following:

a.  $f(x) = x$ ,  $x \in [0, 2\pi]$ .

b.  $f(x) = \frac{x^2}{4}$ ,  $|x| < \pi$ .

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

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

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

9. Find the Fourier series of each function  $f(x)$  of period  $2\pi$ . For each series, plot the  $N$ th partial sum,

$$S_N = \frac{a_0}{2} + \sum_{n=1}^N [a_n \cos nx + b_n \sin nx],$$

for  $N = 5, 10, 50$  and describe the convergence (Is it fast? What is it converging to?, etc.) [Some simple Maple code for computing partial sums is shown in the notes.]

a.  $f(x) = x$ ,  $|x| < \pi$ .

b.  $f(x) = |x|$ ,  $|x| < \pi$ .

c.  $f(x) = \cos x$ ,  $|x| < \pi$ .

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

10. Find the Fourier series of  $f(x) = x$  on the given interval. Plot the  $N$ th partial sums and describe what you see.

a.  $0 < x < 2$ .

b.  $-2 < x < 2$ .

c.  $1 < x < 2$ .

**11.** The result in Problem 8b above gives a Fourier series representation of  $\frac{x^2}{4}$ . By picking the right value for  $x$  and a little arrangement of the series, show that [See Example 2.5.]

a.

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

b.

$$\frac{\pi^2}{8} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \cdots$$

Hint: Consider how the series in part a. can be used to do this.

c. Use the Fourier series representation result in Problem 8e to obtain the series in part b.

**12.** Sketch (by hand) the graphs of each of the following functions over four periods. Then sketch the extensions of each of the functions as both an even and odd periodic function. Determine the corresponding Fourier sine and cosine series and verify the convergence to the desired function using Maple.

a.  $f(x) = x^2, 0 < x < 1$ .

b.  $f(x) = x(2 - x), 0 < x < 2$ .

c.  $f(x) = \begin{cases} 0, & 0 < x < 1, \\ 1, & 1 < x < 2. \end{cases}$

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

**13.** Consider the function  $f(x) = x, -\pi < x < \pi$ .

a. Show that  $x = 2 \sum_{n=1}^{\infty} (-1)^{n+1} \frac{\sin nx}{n}$ .

b. Integrate the series in part a and show that

$$x^2 = \frac{\pi^2}{3} - 4 \sum_{n=1}^{\infty} (-1)^{n+1} \frac{\cos nx}{n^2}.$$

c. Find the Fourier cosine series of  $f(x) = x^2$  on  $[0, \pi]$  and compare it to the result in part b.

d. Apply Parseval's identity in Problem 4 to the series in part a for  $f(x) = x$  on  $-\pi < x < \pi$ . This gives another means to finding the value  $\zeta(2)$ , where the Riemann zeta function is defined by

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}.$$

**14.** Consider the function  $f(x) = x, 0 < x < 2$ .

a. Find the Fourier sine series representation of this function and plot the first 50 terms.

- b. Find the Fourier cosine series representation of this function and plot the first 50 terms.
- c. Apply Parseval's identity in Problem 4 to the result in part b.
- d. Use the result of part c to find the sum  $\sum_{n=1}^{\infty} \frac{1}{n^4}$ .

**15.** Differentiate the Fourier sine series term by term in Problem 14. Show that the result is not the derivative of  $f(x) = x$ .

**16.** The temperature,  $u(x, t)$ , of a one-dimensional rod of length  $L$  satisfies the heat equation,

$$\frac{\partial u}{\partial t} = k \frac{\partial^2 u}{\partial x^2}.$$

- a. Show that the general solution,

$$u(x, t) = \sum_{n=0}^{\infty} b_n \sin \frac{n\pi x}{L} e^{-n^2 \pi^2 k t / L^2},$$

satisfies the one-dimensional heat equation and the boundary conditions  $u(0, t) = 0$  and  $u(L, t) = 0$ .

- b. For  $k = 1$  and  $L = \pi$ , find the solution satisfying the initial condition  $u(x, 0) = \sin x$ . Plot six solutions on the same set of axes for  $t \in [0, 1]$ .
- c. For  $k = 1$  and  $L = 1$ , find the solution satisfying the initial condition  $u(x, 0) = x(1 - x)$ . Plot six solutions on the same set of axes for  $t \in [0, 1]$ .

**17.** The height,  $u(x, t)$ , of a one-dimensional vibrating string of length  $L$  satisfies the wave equation,

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}.$$

- a. Show that the general solution,

$$u(x, t) = \sum_{n=1}^{\infty} A_n \cos \frac{n\pi c t}{L} \sin \frac{n\pi x}{L} + B_n \sin \frac{n\pi c t}{L} \sin \frac{n\pi x}{L},$$

satisfies the one-dimensional wave equation and the boundary conditions  $u(0, t) = 0$  and  $u(L, t) = 0$ .

- b. For  $c = 1$  and  $L = 1$ , find the solution satisfying the initial conditions  $u(x, 0) = x(1 - x)$  and  $u_t(x, 0) = x(1 - x)$ . Plot five solutions for  $t \in [0, 1]$ .
- c. For  $c = 1$  and  $L = 1$ , find the solution satisfying the initial condition

$$u(x, 0) = \begin{cases} 4x, & 0 \leq x \leq \frac{1}{4}, \\ \frac{4}{3}(1 - x), & \frac{1}{4} \leq x \leq 1. \end{cases}$$

Plot five solutions for  $t \in [0, 0.5]$ .

18. Show that

$$u(x, y, t) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} (a_{nm} \cos \omega_{nm} t + b_{nm} \sin \omega_{nm} t) \sin \frac{n\pi x}{L} \sin \frac{m\pi y}{H},$$

where

$$\omega_{nm} = c \sqrt{\left(\frac{n\pi}{L}\right)^2 + \left(\frac{m\pi}{H}\right)^2},$$

satisfies the two-dimensional wave equation

$$u_{tt} = c^2(u_{xx} + u_{yy}), \quad t > 0, 0 < x < L, 0 < y < H,$$

and the boundary conditions,

$$\begin{aligned} u(0, y, t) = 0, \quad u(L, y, t) = 0, \quad t > 0, \quad 0 < y < H, \\ u(x, 0, t) = 0, \quad u(x, H, t) = 0, \quad t > 0, \quad 0 < x < L, \end{aligned}$$

19. Find the double Fourier sine series representation of the following:

- $f(x, y) = \sin \pi x \sin 2\pi y$  on  $[0, 1] \times [0, 1]$ .
- $f(x, y) = x(2 - x) \sin y$  on  $[0, 2] \times [0, \pi]$ .
- $f(x, y) = x^2 y^3$  on  $[0, 1] \times [0, 1]$ .

20. Derive the Fourier coefficients in the double Fourier trigonometric series in Equation (2.103).

