10
Techniques of Integration

10.1 Powers of Sine and Cosine

Functions consisting of products of the sine and cosine can be integrated by using substitution and trigonometric identities. These can sometimes be tedious, but the technique is straightforward. Some examples will suffice to explain the approach.

EXAMPLE 10.1.1 Evaluate \( \int \sin^3 x \, dx \). Rewrite the function:

\[
\int \sin^3 x \, dx = \int \sin x \sin^2 x \, dx = \int \sin x (1 - \cos^2 x) \, dx.
\]

Now use \( u = \cos x \), \( du = -\sin x \, dx \):

\[
\int \sin x (1 - \cos^2 x) \, dx = \int (1 - u^2) \, du = -u + \frac{1}{2} u^2 + C = -\cos x + \frac{1}{2} \cos^2 x + C.
\]

EXAMPLE 10.1.2 Evaluate \( \int \sin^6 x \, dx \). Use \( \sin^2 x = (1 - \cos(2x))/2 \) to rewrite the function:

\[
\int \sin^6 x \, dx = \int \left( \frac{1 - \cos(2x)}{2} \right)^3 \, dx = \int \frac{1}{8} (1 - 3 \cos 2x + 3 \cos^2 2x - \cos^3 2x) \, dx.
\]

Now we have four integrals to evaluate:

\[
\int 1 \, dx = x
\]

and

\[
\int -3 \cos 2x \, dx = -\frac{3}{2} \sin 2x.
\]

are easy. The \( \cos^3 2x \) integral is like the previous example:

\[
\int \cos^3 2x \, dx = \int \cos 2x \cos^2 2x \, dx = \int \cos 2x (1 - \sin^2 2x) \, dx = \int \frac{1}{2} (1 - u^2) \, du = \frac{1}{2} \left( \frac{u^2}{2} - u \right) + C = \frac{1}{2} \sin 2x - \frac{1}{2} \sin(3x)/3.
\]

And finally we use another trigonometric identity, \( \cos^2 x = (1 + \cos(2x))/2 \):

\[
\int 3 \cos^2 2x \, dx = 3 \int \frac{1 + \cos 4x}{2} \, dx = \frac{3}{2} x + \frac{3}{8} \sin 4x + C.
\]

So at long last we get

\[
\int \sin^6 x \, dx = \frac{2}{15} x - \frac{2}{5} \sin 2x - \frac{1}{15} \sin^3 2x + \frac{3}{10} \sin 4x + C.
\]

EXAMPLE 10.1.3 Evaluate \( \int \sin^2 x \cos^3 x \, dx \). Use the formulas \( \sin^2 x = (1 - \cos(2x))/2 \) and \( \cos^2 x = (1 + \cos(2x))/2 \) to get:

\[
\int \sin^2 x \cos^3 x \, dx = \int \frac{1 - \cos 2x}{2} \cdot \frac{1 + \cos 2x}{2} \, dx.
\]

The remainder is left as an exercise.

Exercises 10.1.

Find the antiderivatives.

1. \( \int \sin^2 x \, dx \)
2. \( \int \sin^4 x \, dx \)
3. \( \int \sin^3 x \, dx \)
4. \( \int \cos^2 x \sin^3 x \, dx \)
5. \( \int \cos^3 x \, dx \)
6. \( \int \sin x \cos^2 x \, dx \)
7. \( \int \cos x \sin^4 x \, dx \)
8. \( \int \sin x (\cos x)^3 \, dx \)
9. \( \int \sec^2 x \cos^3 x \, dx \)
10. \( \int \tan^3 x \sec x \, dx \)

10.2 Trigonometric Substitutions

So far we have seen that it sometimes helps to replace a subexpression of a function by a single variable. Occasionally it can help to replace the original variable by something more complicated. This seems like a "reverse" substitution, but it is really no different in principle than ordinary substitution.

EXAMPLE 10.2.1 Evaluate \( \int \sqrt{1 - x^2} \, dx \). Let \( x = \sin u \) so \( dx = \cos u \, du \). Then

\[
\int \sqrt{1 - x^2} \, dx = \int \sqrt{1 - \sin^2 u} \cos u \, du = \int \cos u \, du = \sin u + C = \sin x + C.
\]

We would like to replace \( \cos u \) by \( \cos x \), but this is valid only if \( \cos x \) is positive, since \( \cos u \) is positive. Consider again the substitution \( x = \sin u \). We could just as well think of this as \( u = \arcsin x \). If we do, then by the definition of the arccosine, \( -\pi/2 \leq u \leq \pi/2 \), so \( \cos u \geq 0 \). Then we continue:

\[
\int \cos u \cos u \, du = \int \cos^2 u \, du = \int \frac{1 + \cos(2u)}{2} \, du = \frac{1}{2} u + \frac{1}{4} \sin(2u) + C = \arcsin x + \frac{1}{2} \arcsin(2 \arcsin x) + C.
\]

This is a perfectly good answer, though the term \( \sin(2 \arcsin x) \) is a bit unpleasant. It is possible to simplify this. Using the identity \( \sin 2x = 2 \sin x \cos x \), we can write \( \sin 2u = 2 \sin u \cos u = 2 \sin(\arcsin x) \sqrt{1 - \sin^2 u} = 2 \sin(\arcsin x) \sqrt{1 - \sin^2(\arcsin x)} = 2x \sqrt{1 - x^2} \). Then the full antiderivative is

\[
\arcsin x + \frac{2x \sqrt{1 - x^2}}{4} + \frac{1}{4} \arcsin(2 \arcsin x) + C = \arcsin x + \frac{2x \sqrt{1 - x^2}}{4} + C.
\]

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This type of substitution is usually indicated when the function you wish to integrate contains a polynomial expression that might allow you to use the fundamental identity \( \sin^2 x + \cos^2 x = 1 \) in one of three forms:

\[
\cos^2 x = 1 - \sin^2 x \quad \sec^2 x = 1 + \tan^2 x \quad \tan^2 x = \sec^2 x - 1.
\]

If your function contains \( 1 - x^2 \), as in the example above, try \( x = \sin u \) if it contains \( 1 + x^2 \), try \( x = \tan u \) and if it contains \( x^2 - 1 \), try \( x = \sec u \). Sometimes you will need to try something a bit different to handle constants other than one.

EXAMPLE 10.2.2 Evaluate \( \int \sqrt{1 - 9x^2} \, dx \). We start by rewriting this so that it looks more like the previous example:

\[
\int \sqrt{1 - 9x^2} \, dx = \int \sqrt{1 - (3x/2)^2} \, dx.
\]

Now let \( 3x/2 = \sin u \) so \( (3/2) \, dx = \cos u \, du \) or \( dx = (2/3) \cos u \, du \). Then

\[
\int 2\sqrt{1 - (3x/2)^2} \, dx = \frac{2}{3} \int \sqrt{1 - \sin^2 u} \, (2/3) \cos u \, du = \frac{4}{9} \int \cos u \, du = \frac{4}{9} u + \frac{4}{3} \sin(3u/2) + C = \frac{4}{9} \arcsin(3x/2) + 2 \sin(3u/2) + C.
\]

But \( 3u/2 = \arcsin(3x/2) \), so

\[
\frac{4}{9} \arcsin(3x/2) + \frac{2}{3} \sin(\arcsin(3x/2)) = \frac{2}{3} \arcsin(3x/2) + \frac{2}{3} \sin(\arcsin(3x/2)) + C = \frac{2}{3} \arcsin(3x/2) + \frac{x^3 - 9x^3}{2} + C.
\]

using some of the work from example 10.2.1.

EXAMPLE 10.2.3 Evaluate \( \int \sqrt{1 + x^2} \, dx \). Let \( x = \tan u \), \( dx = \sec^2 u \, du \), so

\[
\int \sqrt{1 + x^2} \, dx = \int \sqrt{1 + \tan^2 u} \, \sec^2 u \, du = \int \sec^3 u \, du.
\]

Since \( u = \arctan x \), \( -\pi/2 \leq u \leq \pi/2 \) and \( \sec u \geq 0 \), so \( \sqrt{\sec^2 u} = \sec u \). Then

\[
\int \sec^3 u \, du = \int \sec u \, du.
\]

In problems of this type, two integrals come up frequently: \( \int \sec^3 u \, du \) and \( \int \sec u \, du \). Both have relatively nice expressions but they are a bit tricky to discover.
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\[ du = f'(x) \, dx \quad \text{and} \quad dv = g'(x) \, dx \]

To use this technique, we need to identify likely candidates for \( u = f(x) \) and \( dv = g'(x) \, dx \).

**EXAMPLE 10.3.1** Evaluate \( \int x \ln x \, dx \). Let \( u = \ln x \) so \( du = \frac{1}{x} \, dx \). Then we must let \( dv = x \, dx \) so \( v = \frac{x^2}{2} \) and

\[
\int x \ln x \, dx = \frac{x^2}{2} \ln x \bigg|_2 + C.
\]

**EXAMPLE 10.3.2** Evaluate \( \int x \sin x \, dx \). Let \( u = x \) so \( du = dx \). Then we must let \( dv = \sin x \, dx \) so \( v = -\cos x \) and

\[
\int x \sin x \, dx = -x \cos x \bigg|_2 + C.
\]

**EXAMPLE 10.3.3** Evaluate \( \int x^2 \, dx \). Of course we already know the answer to this, but we needed to be clever to discover it. Here we'll use the new technique to discover the antiderivative. Let \( u = x^2 \) and \( dv = x \, dx \). Then \( du = 2x \, dx \) and \( v = \frac{x^2}{2} \), and

\[
\int x^2 \, dx = \frac{x^2}{2} \cdot x - \int 2x \cdot \frac{x^2}{2} \, dx + C.
\]

**10.4 Trigonometric Substitutions**

**Exercises 10.2.**

Find the antiderivatives.

1. \( \int \cos x \, dx \rightarrow \)
2. \( \int \sin x \, dx \rightarrow \)
3. \( \int \sqrt{1 - x^2} \, dx \rightarrow \)
4. \( \int \sqrt{1 + x^2} \, dx \rightarrow \)
5. \( \int \frac{1}{\sqrt{1 - x^2}} \, dx \rightarrow \)
6. \( \int \frac{1}{\sqrt{1 + x^2}} \, dx \rightarrow \)
7. \( \int \frac{1}{\sqrt{1 + x^2}} \, dx \rightarrow \)
8. \( \int \frac{1}{\sqrt{x^2 - 1}} \, dx \rightarrow \)
9. \( \int \frac{1}{\sqrt{x^2 + 1}} \, dx \rightarrow \)
10. \( \int \frac{1}{\sqrt{3^2 - x^2}} \, dx \rightarrow \)
11. \( \int \frac{1}{\sqrt{2^2 - x^2}} \, dx \rightarrow \)

**10.5 Integration by Parts**

We have already seen that recognizing the product rule can be useful, when we noticed that

\[
\int \sec^3 u \, du = \sec u \tan u + \int \sec^2 u \, du.
\]

As with substitution, we do not have to rely on insight or cleverness to discover such antiderivatives; there is a technique that will often help us uncover the product rule.

Start with the product rule:

\[
f(x)g(x) = \int f'(x)g(x) \, dx + \int f(x)g'(x) \, dx,
\]

and then

\[
f(x)g'(x) \, dx = f(x)g(x) - \int f'(x)g(x) \, dx.
\]

This may not seem particularly useful at first glance, but it turns out that in many cases we have an integral of the form

\[
f(x)g'(x) \, dx
\]

but that

\[
f(x)g'(x) \, dx
\]

is easier. This technique for turning one integral into another is called integration by parts, and is usually written in more compact form. If we let \( u = f(x) \) and \( v = g(x) \) then

\[
\int u \, dv = uv - \int v \, du.
\]

10.6 Trigonometric Integrals

At first this looks useless—we’re right back to \( \int \sec^3 x \, dx \). But looking more closely:

\[
\int \sec^3 x \, dx = \sec x \tan x - \int \sec x \, dx
\]

\[
\int \sec^3 x \, dx + \int \sec x \, dx = \sec x \tan x + \int \sec x \, dx
\]

\[
2 \int \sec^3 x \, dx = \sec x \tan x + \int \sec x \, dx
\]

10.7 Polar Coordinates

\[
\int 2 \sin x \, dx = -2 \cos x + C
\]

\[
\int x^2 \cos x \, dx = -x^2 \sin x + \int 2x \cos x \, dx
\]

\[
\int x^2 \sin x \, dx = -x^2 \cos x + \int 2x \cos x \, dx
\]

\[
\int x^2 \cos x + \int 2x \cos x \, dx = -x^2 \cos x + 2x \sin x - \int 2 \sin x \, dx
\]

\[
\int x^2 \sin x \, dx = -x^2 \cos x + \int 2x \cos x \, dx
\]

\[
\int x^2 \cos x \, dx = -x^2 \cos x + 2x \sin x + \int 2 \cos x \, dx
\]

\[
\int x^2 \cos x = -x^2 \cos x + 2x \sin x - \int 2 \sin x \, dx
\]

\[
\int x^2 \cos x \, dx = -x^2 \cos x + 2x \sin x + 2 \cos x + C.
\]

Such repeated use of integration by parts is fairly common, but it can be a bit tedious to accomplish, and it is easy to make errors, especially sign errors involving the subtraction in the formula. There is a nice tabular method to accomplish the calculation that minimizes the chance for error and speeds up the whole process. We illustrate with the previous example. Here is the table:

<table>
<thead>
<tr>
<th>sign</th>
<th>u</th>
<th>du</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>x^2</td>
<td>sin x</td>
</tr>
<tr>
<td>-1</td>
<td>x</td>
<td>-cos x</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td>sin x</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>cos x</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\int x^2 \sin x \, dx & = \int (x^2 \sin x)' \, dx \\
& = x^2 \sin x - \int 2x \cos x \, dx \\
& = x^2 \sin x - 2x \cos x + \int 2 \sin x \, dx.
\end{align*}
\]

\[
\int x^2 \cos x \, dx = \int (x^2 \cos x)' \, dx
\]

\[
= x^2 \cos x + 2x \sin x - \int 2 \cos x \, dx
\]

\[
= x^2 \cos x + 2x \sin x + 2 \cos x + C.
\]
To form the first table, we start with \( u \) at the top of the second column and repeatedly compute the derivative; starting with \( dv \) at the top of the third column, we repeatedly compute the antiderivative. In the first column, we place a "−" in every second row. To form the second table we combine the first and second columns by ignoring the boundary; if you do this by hand, you may simply start with two columns and add a "−" to every second row.

To compute with this second table we begin at the top. Multiply the first entry in column \( u \) by the second entry in column \( dv \) to get \(-x^3 \cos x\), and add this to the integral of the product of the second entry in column \( u \) and second entry in column \( dv \). This gives:

\[-x^2 \cos x + \int 2x \sin x dx,\]

or exactly the result of the first application of integration by parts. Since this integral is not yet easy, we return to the table. Now we multiply twice on the diagonal, \((-x^3)(-\cos x)\) and \((-2x)(-\sin x)\) and then once straight across, \(2)(\sin x)\), and combine these as

\[-x^2 \cos x + 2x \sin x - 2 \sin x dx,


giving the same result as the second application of integration by parts. While this integral is easy, we may return yet once more to the table. Now multiply three times on the diagonal to get \((-x^3)(-(\cos x))\), \((-2x)(-\sin x)\), and \((2)(\cos x)\), and once straight across, \((0)(\cos x)\). We combine these as before to get

\[-x^2 \cos x + 2x \sin x + 2 \cos x + \int 0 dx = -x^2 \cos x + 2x \sin x + 2 \cos x + C.\]

Typically we would fill in the table one line at a time, until the "straight across" multiplication gives an easy integral. If we can see that the \( u \) column will eventually become zero, we can instead fill in the whole table; computing the products as indicated will then give the entire integral, including the "+ \( C \)" as above.

**Exercises 10.3.**

Find the antiderivatives.

1. \( \int x \cos x \, dx \)
2. \( \int x^2 \sin x \, dx \)
3. \( \int x^3 \, dx \)
4. \( \int x^2 \, dx \)
5. \( \int \sin^2 x \, dx \)

**10.4 Rational Functions**

**EXAMPLE 10.4.1** Find \( \int \frac{x^3}{(3 - 2x)^2} \, dx \). Using the substitution \( u = 3 - 2x \) we get

\[
\int \frac{x^3}{(3 - 2x)^2} \, dx = \frac{1}{2} \int \frac{(2x)^3}{u^2} \, du = \frac{1}{16} \int \frac{x^3}{u^2} - 27u - 27x \, du
\]

\[
= \frac{1}{16} \left( \frac{9x^2}{2} + 27x^4 - 27x^2 \ln|3 - 2x| + C \right) - \frac{1}{16} \left( \frac{3(3 - 2x)^2}{2} - \frac{3(3 - 2x)^4}{2} \right) + C
\]

\[
= \frac{1}{16} \left( \frac{9x}{2} + 27x - 27 \ln|3 - 2x| + C \right) - \frac{1}{16} \left( \frac{3(3 - 2x)^2}{2} - \frac{3(3 - 2x)^4}{2} \right) + C
\]

\[
= \frac{1}{16} \left( \frac{9x}{2} + 27x - 27 \ln|3 - 2x| + C \right) - \frac{1}{16} \left( \frac{3(3 - 2x)^2}{2} - \frac{3(3 - 2x)^4}{2} \right) + C
\]

We now proceed to the case in which the denominator is a quadratic polynomial. We can always factor out the coefficient of \( x^2 \) and put it outside the integral, so we can assume that the denominator has the form \( x^2 + bx + c \). There are three possible cases, depending on how the quadratic factors: either \( x^2 + bx + c = (x - r)(x - s) \), \( x^2 + bx + c = (x - r)^2 \), or it doesn’t factor. We can use the quadratic formula to decide which of these we have, and to factor the quadratic if it is possible.

**EXAMPLE 10.4.2** Determine whether \( x^2 + x + 1 \) factors, and factor it if possible. The quadratic formula tells us that \( x^2 + x + 1 = 0 \) when

\[
x = \frac{1 \pm \sqrt{1 - 4}}{2}
\]

Since there is no square root of \(-3\), this quadratic does not factor.

**EXAMPLE 10.4.3** Determine whether \( x^2 - x - 1 \) factors, and factor it if possible. The quadratic formula tells us that \( x^2 - x - 1 = 0 \) when

\[
x = \frac{1 \pm \sqrt{5}}{2}
\]

Therefore

\[
x^2 - x - 1 = \left( x - \frac{1 \pm \sqrt{5}}{2} \right) \left( x - \frac{1 - \sqrt{5}}{2} \right)
\]

**10.4.5** Evaluate \( \int \frac{x^3}{(x - 2)(x + 3)} \, dx \). We start by writing \( \frac{7x - 6}{(x - 2)(x + 3)} \) as the sum of two fractions. We want to end up with

\[
7x - 6 = \frac{A}{x - 2} + \frac{B}{x + 3}
\]

If we go ahead and add the fractions on the right hand side we get

\[
7x - 6 = \frac{(A + B)x + 3A - 2B}{(x - 2)(x + 3)}
\]

So all we need to do is find \( A \) and \( B \) so that \( 7x - 6 = (A + B)x + 3A - 2B \), which is to say, we need \( T = A + B \) and \( -6 = 3A - 2B \). This is a problem you’ve seen before: solve a
system of two equations in two unknowns. There are many ways to proceed; here's one: If $7 = 3 + 4t$ then $B = 7 - A$ and so $-6 = 3A - 2B = 3A - 2(7-A) = 3A - 14 + 2A = 5A - 14$. This is easy to solve for $A$: $A = 8/5$, and then $B = 7 - A = 7/5 - 8/5 = 7/5$. Thus

$$\int \frac{7x - 6}{(x - 3)} \, dx = \int \frac{8}{5} \cdot \frac{1}{x - 3} - \frac{27}{5} \cdot \frac{1}{x - 3} \, dx = \frac{4}{5} \ln |x - 2| - \frac{27}{5} \ln |x + 3| + C.$$ 

The answer to the original problem is now

$$\int \frac{x^4}{(x - 2)(x + 3)} \, dx = \int x - 1 + \int \frac{7x - 6}{(x - 2)(x + 3)} \, dx = \frac{7}{3} x + \frac{1}{3} \ln |x - 2| - \frac{27}{5} \ln |x + 3| + C. \quad \blacksquare$$

Now suppose that $x^2 + bx + c$ doesn’t factor. Again we can use long division to ensure that the numerator has degree less than 2, then we complete the square.

**EXAMPLE 10.5.6** Evaluate $\int \frac{x + 1}{x^2 + 4x + 8} \, dx$. The quadratic denominator does not factor. We could complete the square and use a trigonometric substitution, but it is simpler to rearrange the integrand:

$$\int \frac{x + 1}{x^2 + 4x + 8} \, dx = \int \frac{x + 2 - 1}{x^2 + 4x + 8} \, dx - \int \frac{1}{x^2 + 4x + 8} \, dx.$$

The first integral is an easy substitution problem, using $u = x^2 + 4x + 8$:

$$\int \frac{x + 2}{x^2 + 4x + 8} \, dx = \int \frac{1}{u} \, du = \frac{1}{2} \ln |x^2 + 4x + 8|.$$

For the second integral we complete the square:

$$x^2 + 4x + 8 = (x + 2)^2 + 4 = \frac{1}{4} \left( \frac{x + 2}{2} \right)^2 + 1,$$

making the integral

$$\frac{1}{2} \int \frac{1}{x^2 + 4} \, dx.$$

Using $u = \frac{x + 2}{2}$ we get

$$\frac{1}{2} \int \frac{1}{u^2 + 1} \, du = \frac{1}{2} \arctan \left( \frac{x + 2}{2} \right).$$

The final answer is now

$$\int \frac{x + 1}{x^2 + 4x + 8} \, dx = \frac{1}{2} \ln |x^2 + 4x + 8| + \frac{1}{2} \arctan \left( \frac{x + 2}{2} \right) + C. \quad \blacksquare$$

### 10.5 Numerical Integration

The areas of all trapezoids we get

$$f(x_0) + f(x_1) \Delta x + f(x_2) + f(x_3) \Delta x + \cdots + f(x_{n-1}) + f(x_n) \Delta x = \frac{f(x_0)}{2} + f(x_1) + f(x_2) + \cdots + f(x_{n-1}) + \frac{f(x_n)}{2} \Delta x.$$

This is usually known as the Trapezoidal Rule. For a modest number of subintervals this is not too difficult to do with a calculator; a computer can easily do many subintervals.

![Figure 10.5.2 A single trapezoid.](image)

In practice, an approximation is useful only if we know how accurate it is; for example, we might need a particular value accurate to three decimal places. When we compute a particular approximation to an integral, the error is the difference between the approximation and the true value of the integral. For any approximation technique, we need an error estimate; a value that is guaranteed to be larger than the actual error. If $A$ is an approximation and $E$ is the associated error estimate, then we know that the true value of the integral is between $A - E$ and $A + E$. In the case of our approximation of the integral, we want $E = E(\Delta x)$ to be a function of $\Delta x$ that gets small rapidly as $\Delta x$ gets small. Fortunately, for many functions, there is such an error estimate associated with the trapezoidal approximation.

**THEOREM 10.5.1** Suppose $f$ has a second derivative $f''$ everywhere on the interval $[a, b]$, and $|f''(x)| \leq M$ for all $x$ in the interval. With $\Delta x = (b - a)/n$, an error estimate for the trapezoidal approximation is

$$E(\Delta x) = \frac{b - a}{12} M (\Delta x)^2 = \frac{(b - a)^3}{12n^2} M.$$

Let’s see how we can use this.

### Exercises 10.4

1. \[ \int \frac{x}{x^2 + 1} \, dx \]
2. \[ \int x^2 \, dx \]
3. \[ \int e^x \, dx \]
4. \[ \int e^{-x} \, dx \]
5. \[ \int e^{3x} \, dx \]
6. \[ \int e^{-2x} \, dx \]
7. \[ \int x^2 \, dx \]
8. \[ \int x^2 + 10x + 22 \, dx \]
9. \[ \int 2x^2 - x - 3 \, dx \]
10. \[ \int x^3 + 8x \, dx \]

### 10.5 Numerical Integration

We have now seen some of the most generally useful methods for discovering antiderivatives, and there are others. Unfortunately, some functions have no simple antiderivatives; in such cases if the value of a definite integral is needed it will have to be approximated. We will see two methods that work reasonably well and yet are fairly simple; in some cases more sophisticated techniques will be needed.

Of course, we already know one way to approximate an integral: if we think of the integral as computing an area, we can add up the areas of some rectangles. While this is quite simple, it is usually the case that a large number of rectangles is needed to get acceptable accuracy. A similar approach is much better: we approximate the area under a curve over a small interval as the area of a trapezoid. In figure 10.5.1 we see an area under a curve approximated by rectangles and by trapezoids; it is apparent that the trapezoids give a substantially better approximation on each subinterval.

![Figure 10.5.1 Approximating an area with rectangles and with trapezoids.](image)

As with rectangles, we divide the interval into $n$ equal subintervals of length $\Delta x$. A typical trapezoid is pictured in figure 10.5.2; it has area $\frac{f(x_i) + f(x_{i+1})}{2} \Delta x$. If we add up

### Exercises 10.5.2

1. Approximate $\int e^{-x^3} \, dx$ to two decimal places. The second derivative of $f = e^{-x^3}$ is $(4x^2 - 2)e^{-x^3}$, and it is not hard to see that on $[0, 1], |(4x^2 - 2)e^{-x^3}| \leq 2$

We begin by estimating the number of subintervals we are likely to need. To get two decimal places of accuracy, we will certainly need $E(\Delta x) < 0.005$ as

$$\frac{1}{\sqrt{500}} < 0.005 \quad \Rightarrow \quad n \approx 500 \quad \Rightarrow \quad n \geq 500.$$

5.77 $\approx \sqrt{300}$ $\Rightarrow \quad n$ with $n = 6$, the error estimate is thus $1/\sqrt{6} < 0.0047$. We compute the trapezoidal approximation for six intervals:

$$\left( \frac{f(0)}{2} + f(1/6) + f(2/6) + \cdots + f(5/6) + f(6) \right) \frac{1}{2} \approx 0.74512.$$
by using something other than a straight line? The obvious candidate is a parabola: if we can approximate a short piece of the curve with a parabola with equation \( y = ax^2 + bx + c \), we can easily compute the area under the parabola.

There are an infinite number of parabolas through any two given points, but only one through three given points. If we find a parabola through three consecutive points \((x_i, f(x_i)), (x_{i+1}, f(x_{i+1})), (x_{i+2}, f(x_{i+2}))\) on the curve, it should be quite close to the curve over the whole interval \([x_i, x_{i+2}]\), as in figure 10.5.3. If we divide the interval \([a, b]\) into an even number of subintervals, we can then approximate the curve by a sequence of parabolas, each covering two of the subintervals. For this to be practical, we would like a simple formula for the area under one parabola, namely, the parabola through \((x_i, f(x_i)), (x_{i+1}, f(x_{i+1})), \) and \((x_{i+2}, f(x_{i+2}))\). That is, we should attempt to write down the parabola \( y = ax^2 + bx + c \) through these points and then integrate it, and hope that the result is fairly simple. Although the algebra involved is messy, this turns out to be possible. The algebra is a bit within the capability of a good computer algebra system like Sage, so we will present the result without all of the algebra, you can see how to do it in this Sage worksheet.

To find the parabola, we solve these three equations for \(a, b,\) and \(c\):

\[
\begin{align*}
  f(x_i) &= a(x_i + \Delta x)^2 + b(x_i + \Delta x) + c \\
  f(x_{i+1}) &= a(x_{i+1})^2 + b(x_{i+1}) + c \\
  f(x_{i+2}) &= a(x_{i+2})^2 + b(x_{i+2}) + c
\end{align*}
\]

Not surprisingly, the solutions turn out to be quite messy. Nevertheless, Sage can easily compute and simplify the integral to get

\[
\int_{x_i + \Delta x}^{x_{i+1} - \Delta x} \left( ax^2 + bx + c \right) dx = \frac{\Delta x}{3} \left( f(x_i) + 4f(x_{i+1}) + f(x_{i+2}) \right) - \frac{\Delta x}{3} \left( f(x_{i+1}) + 4f(x_{i+2}) + f(x_i) \right)
\]

Now the sum of the areas under all parabolas is

\[
\frac{\Delta x}{3} \sum_{i=0}^{n} \left( f(x_i) + 4f(x_{i+1}) + f(x_{i+2}) \right) + \frac{\Delta x}{3} \sum_{i=0}^{n} \left( f(x_{i+1}) + 4f(x_{i+2}) + f(x_i) \right)
\]

This is slightly more complicated than the formula for trapezoids; we need to remember the alternating 2 and 4 coefficients; note that it must be even for this to make sense. This approximation technique is referred to as Simpson’s Rule.

As with the trapezoid method, this is useful only with an error estimate:

\[E(\Delta x) = \frac{b-a}{180} f^{(4)}(z) \Delta x^4, \quad |f^{(4)}(z)| \leq M,\]

where \(a, b\) are the endpoints of the interval, \(\Delta x = (b-a)/n\), and \(f^{(4)}(z)\) is the maximum value of the fourth derivative of \(f\) on the interval. With \(\Delta x = (b-a)/n\), an error estimate for Simpson’s approximation is

\[E(\Delta x) = \frac{b-a}{180} f^{(4)}(z) \Delta x^4 = \frac{(b-a)^5 M}{180^4 n^4}.\]

**THEOREM 10.5.3** Suppose \(f\) has a fourth derivative \(f^{(4)}\) everywhere on the interval \([a, b]\), and \(|f^{(4)}(z)| \leq M\) for all \(z\) in the interval. With \(\Delta x = (b-a)/n\), an error estimate for Simpson’s approximation is

\[E(\Delta x) = \frac{b-a}{180} f^{(4)}(z) \Delta x^4 = \frac{(b-a)^5 M}{180^4 n^4}.\]

**EXAMPLE 10.5.4** Let us again approximate \(\int_a^b e^{-x^2} dx\) to two decimal places. The fourth derivative of \(f = e^{-x^2}\) is \((16x^2 - 48x^2 + 12)e^{-x^2}\); on \([0, 1]\) this is at most 12 in absolute value. We begin by estimating the number of subintervals we are likely to need. To get two decimal places of accuracy, we will certainly need \(E(\Delta x) < 0.005\), but taking a cue from our earlier example, let’s require \(E(\Delta x) < 0.001\):

\[
\frac{1}{180(12)} \left( \frac{b-a}{n} \right)^4 < 0.001
\]

So we try \(n = 4\), since we need an even number of subintervals. Then the error estimate is \(12\Delta x^4/4^4 < 0.0003\) and the approximation is

\[
(f(0) + 4f(1/4) + 2f(1/2) + 4f(3/4) + f(1)) / (12/4^4) \approx 0.746855.
\]

So the true value of the integral is between 0.746855 – 0.0003 = 0.746555 and 0.746855 + 0.0003 = 0.747155, both of which round to 0.75.

---

**Exercises 10.5.**

In the following problems, compute the trapezoidal and Simpson approximations using 4 subintervals, and compute the error estimate for each. (Finding the maximum values of the second and fourth derivatives can be challenging for some of these, you may use a graphing calculator or computer software to estimate the maximum values.) If you have access to Sage or similar software, approximate each integral to two decimal places. You can use this Sage worksheet to get started.

1. \(\int_1^2 x \, dx \)  
2. \(\int_0^1 x^2 \, dx \)  
3. \(\int_1^2 x^3 \, dx \)  
4. \(\int_1^2 \frac{1}{x} \, dx \)  
5. \(\int_1^2 \frac{1}{x^2} \, dx \)  
6. \(\int_0^\frac{\pi}{2} \sin x \, dx \)  
7. \(\int_0^{\pi/2} \cos x \, dx \)  
8. \(\int_1^3 \sqrt{x^2 + 1} \, dx \)  
9. \(\int_0^\pi \cos^2 x \, dx \)  
10. \(\int_1^2 \frac{1}{\sqrt{x}} \, dx \)  
11. Using Simpson’s rule on a parabola \(f(x)\), even with just two subintervals, gives the exact value of the integral, because the parabola used to approximate \(f\) will be \(f\) itself. Remarkably, Simpson’s rule also computes the integral of a cubic function \(f(x) = ax^3 + bx^2 + cx \) exactly. Show this is true by showing that

\[
\int_{x_1}^{x_2} f(x) \, dx = \frac{x_2 - x_1}{2} (f(x_1) + 4f((x_2 + x_1)/2) + f(x_2)).
\]

This does require a bit of messy algebra, so you may prefer to use Sage.

**10.6 Additional exercises**

These problems require the techniques of this chapter, and are in no particular order. Some problems may be done in more than one way:

1. \(\int (t + 1) \, dt \)  
2. \(\int (t^2 - 9)^{1/2} \, dt \)  
3. \(\int (t^3 + 16) \, dt \)  
4. \(\int \sin^3 \cos x t \, dt \)  
5. \(\int \tan^2 x \, dx \)  
6. \(\int \frac{1}{t^2 + 1} \, dx \)  
7. \(\int \frac{1}{\sin^2 x} \, dx \)  
8. \(\int \frac{\cos x}{\sin x} \, dx \)  
9. \(\int \cos x \, dx \)  
10. \(\int \sin x \, dx \)  
11. \(\int \frac{1}{\sqrt{1 - x^2}} \, dx \)  
12. \(\int \cos^2 x \, dx \)