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

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

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 \( \sin 2x = \sin x \cos x + C \), and \( \sin(2\arcsin x) = \frac{3}{4} x - \frac{7}{2} x^3 + \frac{3}{4} x^5 + C \).

**EXAMPLE 10.1.2** Evaluate \( \int \sin^4 x \, dx \). Use \( \sin^4 x = (1 - \cos^2 x)^2 \) to rewrite the function:

\[
\int \sin^4 x \, dx = \int (1 - \cos^2 x)^2 \, dx = \int (1 - \cos^2 x)^2 \, dx.
\]

Now we have four integrals to evaluate:

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

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

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

The remainder is left as an exercise.

**Exercises 10.1.**

Find the antiderivatives.

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

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

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

We would like to replace \( \sqrt{\cos^2 u} \) by \( \cos u \), but this is valid only if \( \cos u \) is positive, since \( \sqrt{\cos^2 u} \) 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 arcsine, \(-\pi/2 \leq u \leq \pi/2\), so \( \cos u \geq 0 \). Then we continue:

\[
\int \sqrt{\cos^2 u} \, du = \int \sqrt{\cos^2 u} \, du = \int \frac{1 + \cos 2u}{2} \, du = \frac{1}{2} \sin 2u + C
\]

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 \( \sin 2x = 2\sin x \cos x \). Then the full antiderivative is

\[
\frac{1}{2} \sin 2u + C = \arcsin x + \frac{2}{3} \sin^2 u + C.
\]

**EXAMPLE 10.2.2** Evaluate \( \sqrt{1 - 4x^2} \). Let \( x = \tan u \), \( dx = \sec^2 u \, du \). Then

\[
\int \sqrt{1 - 4x^2} \, dx = \int \sqrt{1 - \tan^2 u} \, du = \int \sec^2 u \, du = \frac{1}{2} \sec^2 u + C
\]

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

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

using some of the work from example 10.2.1.

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

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

In problems of this type, two integrals come up frequently: \( \int \sec^2 u \, du \) and \( \int \sec u \, du \). Both have relatively nice expressions but they are a bit tricky to discover.
First we do $\int \sec u \, du$, which we will need to compute $\int \sec^3 u \, du$.

\[
\int \sec u \, du = \int \frac{\sec u \, \tan u \, du}{\sec u + \tan u} = \int \frac{\sec^2 u \, du}{\sec u + \tan u}.
\]

Now let $u = \sec t + \tan u$, $du = \sec t \tan u + \sec^2 u \, dt$, exactly the numerator of the function we are integrating. Thus

\[
\int \sec u \, du = \int \frac{\sec^2 u + \sec u \tan u}{\sec u + \tan u} \, du = \int \frac{1}{\sec u + \tan u} \, du = \ln |\sec u + \tan u| + C.
\]

Now for $\int \sec^3 u \, du$:

\[
\sec^3 u = \frac{\sec^2 u}{2} + \frac{\sec^2 u}{2} = \frac{\sec^3 u}{2} + \frac{\tan^2 u + 1}{2} \sec u - \frac{\sec^3 u}{2} \sec u + u + \sec u + u \sec u.
\]

We already know how to integrate $\sec u$, so we just need the first quotient. This is "simply" a matter of recognizing the product rule in action:

\[
\int \sec^3 u \, du = \frac{\sec u \tan u}{2} + \ln |\sec u + \tan u| + C.
\]

So putting these together we get

\[
\int \sec^3 u \, du = \frac{\sec u \tan u}{2} + \ln |\sec u + \tan u| + C,
\]

and reverting to the original variable $x$:

\[
\int \sqrt{1 + x^2} \, dx = \frac{\sec \arctan x \tan \arctan x}{2} + \ln |\sec \arctan x + \tan \arctan x| + C
\]

\[
= \frac{\sqrt{1 + \tan^2 \arctan x}}{2} + \ln |\sqrt{1 + \tan^2 \arctan x} + \tan \arctan x| + C
\]

\[
= \frac{x}{2} \sqrt{1 + x^2} + \ln |x + \sqrt{1 + x^2}| + C.
\]

using $\tan \arctan x = x$ and $\sec \arctan x = \sqrt{1 + \tan^2 \arctan x} = \sqrt{1 + x^2}$. 

### 10.3 Integration by Parts

#### 10.3.1 Evaluate $\int x \sec x \, dx$.

**Solution:**

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

**Example 10.3.1** Evaluate $\int x \sin x \, dx$. Let $u = \ln x$ so $du = 1/x \, dx$. Then we must let $dv = x \, dx$ so $v = x^2/2$ and

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

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

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

**Example 10.3.3** Evaluate $\int x \cos x \, dx$. 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 $u = x$ and $dv = \cos x \, dx$. Then $du = dx$ and $v = \sin x$ and

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

#### Exercises 10.2

1. $\int \sin x \, dx$ → $-\cos x + C$.
2. $\int x \cos x \, dx$ → $x \sin x + \cos x + C$.
3. $\int \sqrt{x^2 - 1} \, dx$ → $x \sin^{-1} \left( \frac{x}{\sqrt{x^2 - 1}} \right) + C$.
4. $\int \sqrt{x^2 - 4} \, dx$ → $x \sin^{-1} \left( \frac{x}{\sqrt{x^2 - 4}} \right) - \sqrt{x^2 - 4} + C$.
5. $\int \sqrt{x^2 - 1} \, dx$ → $x \sin^{-1} \left( \frac{x}{\sqrt{x^2 - 1}} \right) + C$.
6. $\int \sqrt{x^2 + 1} \, dx$ → $x \sin^{-1} \left( \frac{x}{\sqrt{x^2 + 1}} \right) + \ln |\sqrt{x^2 + 1} + x| + C$.
7. $\int \sqrt{1 + x^2} \, dx$ → $\frac{x}{2} \sqrt{1 + x^2} + \ln |x + \sqrt{1 + x^2}| + C$.
8. $\int \sqrt{1 - x^2} \, dx$ → $\frac{x}{2} \sqrt{1 - x^2} - \frac{1}{2} \sin^{-1} x + C$.
9. $\int \sqrt{1 - x^2} \, dx$ → $\frac{x}{2} \sqrt{1 - x^2} - \frac{1}{2} \sin^{-1} x + C$.
10. $\int \sqrt{1 + x^2} \, dx$ → $\frac{x}{2} \sqrt{1 + x^2} + \ln |x + \sqrt{1 + x^2}| + C$.
11. $\int \frac{1}{\sqrt{1 + x^2}} \, dx$ → $\sin^{-1} x + C$.
12. $\int \frac{1}{\sqrt{x^2 - 1}} \, dx$ → $\sin^{-1} x + C$.

#### 10.3.4 Evaluate $\int x^2 \sin x \, dx$. Let $u = x^3$, $dv = \sin x \, dx$; then $du = 3x^2 \, dx$ and $v = -\cos x$. Now $x^3 \sin x \, dx = -x^3 \cos x + \int 2x \cos x \, dx$. This is better than the original integral, but we need to do integration by parts again. Let $u = 2x$, $dv = \cos x \, dx$; then $du = 2 \, dx$ and $v = \sin x$, and

\[
\int x^2 \sin x \, dx = -x^3 \cos x + \int 2x \cos x \, dx = -x^3 \cos x + 2x \sin x - \int 2 \sin x \, dx = -x^3 \cos x + 2x \sin x + 2 \cos x + C.
\]

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>$u$</th>
<th>$dv$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x^3$</td>
<td>$\sin x$</td>
</tr>
<tr>
<td>$2x$</td>
<td>$-\cos x$</td>
</tr>
<tr>
<td>$x$</td>
<td>$-\sin x$</td>
</tr>
</tbody>
</table>
| $-\frac{1}{2}$ | $0$ |}

<table>
<thead>
<tr>
<th>$u$</th>
<th>$dv$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x^3$</td>
<td>$\sin x$</td>
</tr>
<tr>
<td>$2x$</td>
<td>$-\cos x$</td>
</tr>
<tr>
<td>$x$</td>
<td>$-\sin x$</td>
</tr>
</tbody>
</table>
| $-\frac{1}{2}$ | $0$ |}
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 \( \sim \) 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 \( \sim \) 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 \( x^2 \cos x \), 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, \( (x^2)(-\cos x) \) and \( (-2x)(\sin x) \) and then once straight across, \((2)(\sin x)\), and combine these as

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

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 \( (x^2)(-\cos x) \), \( (-2x)(\sin x) \), and \((2)(\cos x)\), and once straight across, \((0)(\cos x)\). We combine these as above 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 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. \( \int x \cos x \, dx \Rightarrow \)
2. \( \int x^2 \cos x \, dx \Rightarrow \)
3. \( \int x^3 \cos x \, dx \Rightarrow \)
4. \( \int x^2 \sin x \, dx \Rightarrow \)
5. \( \int \sin x \, dx \Rightarrow \)

**10.4 Rational Functions**

If \( x^2 + bx + c = (x - r)^2 \) then we have the special case where we already have seen, that can be handled with a substitution. The other two cases require different approaches.

If \( x^2 + bx + c = (x - r)(x - s) \) we have an integral of the form

\[
\int \frac{p(x)}{(x - r)(x - s)} \, dx
\]

where \( p(x) \) is a polynomial. The first step is to make sure that \( p(x) \) has degree less than 2.

**EXAMPLE 10.4.4**

Rewrite \( \int \frac{x^3}{(x - 3)(x + 3)} \, dx \) in terms of an integral with a numerator that has degree less than 2. To do this we use long division of polynomials to discover that

\[
\frac{x^3}{(x - 3)(x + 3)} = \frac{x^3 + 6x^2 + 27x + 81}{x^2 + 9} = x + 6 + \frac{27x + 81}{x^2 + 9}.
\]

It is clear that the second term is an integral of the form \( \frac{27x + 81}{x^2 + 9} \), so

\[
\int \frac{x^3}{(x - 3)(x + 3)} \, dx = \int (x + 6) \, dx + \int \frac{27x + 81}{x^2 + 9} \, dx.
\]

Now consider the following simple algebra of fractions:

\[
\frac{A}{x - a} + \frac{B}{x - b} = \frac{A(x - b) + B(x - a)}{(x - a)(x - b)} = \frac{(A + B)x - Aa - Bb}{(x - a)(x - b)}.
\]

That is, adding two fractions with constant numerator and denominators \((x - a)\) and \((x - b)\) produces a fraction with denominator \((x - r)(x - s)\) and a polynomial of degree less than 2 for the numerator. We want to reverse this process: starting with a single fraction, we want to write it as a sum of two simpler fractions. An example should make it clear how to proceed.

**EXAMPLE 10.4.5**

Evaluate \( \int \frac{x}{(x - 2)(x + 3)} \, dx \) as the sum of two fractions. We want to end up with

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

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

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

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 \( 7 = A + B \) 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 $7 = 3 + 4$ then $B = 7 - A$ and so $B = 3 + 4 = 3 - 2(7 - A) = 3 - 4 + 2A = 7 - 4 + 2A$. This is easy to solve for $A$: $A = 8/5$, and then $B = 7 - 4/5 = 7/5$. Thus

$$
\int 2(3x - 6) \, dx = \int 8/5 \, 3x - 6 \, dx = 8/5 \ln|3x - 6| + C.
$$

The answer to the original problem is now

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

EXAMPLE 10.4.6 Evaluate $\int \frac{x + 1}{x^2 + 4x + 8} \, dx$. The quadratic denominator does not factor. Again we can use long division to ensure that the numerator has degree less than 2, then we complete the square.

$$
\frac{x + 1}{x^2 + 4x + 8} = \frac{x + 1}{(x + 2)^2 + 4}.
$$

Hence the proper substitution is $u = x + 2$, so $du = dx$. Also $x = u - 2$.

$$
\int \frac{x + 1}{(x + 2)^2 + 4} \, dx = \int \frac{u - 1}{u^2 + 4} \, du = \frac{1}{2} \int \frac{u}{u^2 + 4} \, du - \frac{1}{2} \int \frac{1}{u^2 + 4} \, du.
$$

The first integral is an easy substitution problem, using $u = x + 2$.

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

Making the integral

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

For the second integral we complete the square:

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

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 10.4.6 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:

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

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

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

For the second integral we complete the square:

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

Making the integral

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

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.

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 $t_a + t_{b+1}1/2 \Delta x$. If we add up

Exercise 10.5.1. Evaluate $\int x^2 \, dx$.

Exercise 10.5.2. Approximate $\int e^{-x^2} \, dx$ to two decimal places. The second derivative of $f = e^{-x^2}$ is $(4x^2 - 2)e^{-x^2}$, and it is not hard to see that on $[0,1]$, $(4x^2 - 2)e^{-x^2} \leq 2$.

Centering at $x = 0$, we can use Simpson’s Rule to approximate

$$
\int x^2 \, dx = \frac{x^3}{3} + C.
$$

Unfortunately, the first rounds to 0.74 and the second rounds to 0.75, so we can’t be sure of the correct value in the second decimal place; we need to pick a larger $n$. As it turns out, we need to go to $n = 12$ to get two bounds that both round to the same value, which turns out to be 0.75. For comparison, using 12 rectangles to approximate the area gives 0.7727, which is considerably less accurate than the approximation using six trapezoids.
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 \((x_0, f(x_0)), (x_1, f(x_1)), (x_2, f(x_2))\) on the curve, it should be quite close to the curve over the whole interval \([x_0, x_2]\); 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 \((x_0, f(x_0)), (x_1, f(x_1)), (x_2, f(x_2))\). 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 well 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 \(c\):

\[
\begin{align*}
   f(x_0) &= a(x_0 - \Delta x)^2 + b(x_0 - \Delta x) + c \\
   f(x_1) &= a(x_1)^2 + b(x_1) + c \\
   f(x_2) &= a(x_2)^2 + b(x_2) + c
\end{align*}
\]

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

\[
\int_{x_0}^{x_2} \frac{\Delta x}{3} f(x_0) + 4f(x_1) + f(x_2) dx = \frac{\Delta x}{3} \left[ f(x_0) + 4f(x_1) + f(x_2) \right].
\]

This is just slightly more complicated than the formula for trapezoids; we need to remember the alternating 2 and 4 coefficients; note that you 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:

\[ E(\Delta x) = \frac{h^4}{180} f''''(x) \]

\[ \frac{h}{2} = \text{the number of subintervals} \]

10.6 Additional exercises

In the following problems, compute the trapezoid 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 algebra system 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. \( \int_0^1 x^2 \, dx \) 
2. \( \int_0^1 \sin x \, dx \) 
3. \( \int_0^1 x^3 dx \) 
4. \( \int_0^1 \frac{1}{x^2} \, dx \) 
5. \( \int_0^1 \frac{1}{x} \, dx \) 
6. \( \int_0^1 \sqrt{x+1} \, dx \) 
7. \( \int_0^1 \frac{1}{\sqrt{x}} \, dx \) 
8. \( \int_0^1 \frac{1}{\sqrt{1-x^2}} \, dx \) 
9. \( \int_0^1 x \sin x^2 \, dx \)
10. Using Simpson’s rule on a parabola \( f(x) \), even with just two subintervals, gives the exact value of the integral, because the parabolas used to approximate \( f \) will be \( f \) itself. Remarkably, Simpson’s rule also computes the integral of a cubic function \( f(x) = ax^3 + bx^2 + cx + d \) exactly. Show this by using that

\[
\int_0^1 f(x) \, dx = \frac{1}{2} \left( f(0) + 4f\left(\frac{1}{2}\right) + f(1) \right).
\]

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. \( \int_0^1 x + 1 \, dx \) 
2. \( \int_0^1 (x + 1)^2 \, dx \) 
3. \( \int_0^1 e^x + 16x \, dx \) 
4. \( \int_0^1 \sin x \cos x \, dx \) 
5. \( \int_0^1 \tan \theta \sin^2 \theta \, d\theta \) 
6. \( \int_0^1 \tan \theta + 1 \, d\theta \) 
7. \( \int_0^1 \frac{1}{\sqrt{1+e^{bx}}} \, dx \) 
8. \( \int_0^1 \frac{1}{\sqrt{1+e^{bx}}} \, dx \) 
9. \( \int_0^1 \cos bx \, dx \) 
10. \( \int_0^1 \cos bx \, dx \) 
11. \( \int_0^1 \frac{1}{\sqrt{1+e^{bx}}} \, dx \) 
12. \( \int_0^1 \cos bx \, dx \)